Unmanned System Technologies

Agbotiname Lucky Imoize ·
Sardar M. N. Islam · T. Poongodi ·
Lakshmana Kumar Ramasamy ·
B. V. V. Siva Prasad *Editors*

Unmanned Aerial Vehicle Cellular Communications

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Editors

Agbotiname Lucky Imoize
Department of Electrical and Electronics Engineering, Faculty of Engineering
University of Lagos
Lagos, Nigeria

Sardar M. N. Islam
Institute for Sustainable Industries and Liveable Cities (ISILC), VU Research, Victoria University
Melbourne, VIC, Australia

T. Poongodi
School of Computing Science and Engineering
Galgotias University
Delhi-NCR, Delhi, India

Lakshmana Kumar Ramasamy
Faculty of Computer Information Science
Higher Colleges of Technology
United Arab Emirates

B. V. V. Siva Prasad
Computer Science Engineering, School of Engineering
Malla Reddy University
Hyderabad, Telangana, India

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Preface

The design and applications of adaptable unmanned aerial vehicles (UAVs) to operate in diverse and harsh environmental conditions are gaining quantum leap. Designing efficient UAVs to address several complex connectivity issues and improve the overall efficiency of beyond 5G wireless communication systems is the central focus. This book gives new insights into the real-world scenarios of the design, development, application, and associated benefits of UAVs in future wireless communication systems. Chapter 1 explores the historical perspectives and introduction to UAV cellular communications. Chapter 2 considers UAV cellular communication in 5G new radio wireless standards. Specifically, 3GPP updates and new 5G NR features for aerial devices are broached. Chapter 3 torchlights 5G NR massive MIMO for efficient and robust UAV cellular communications.

Chapter 4 presents the concept of an intelligent reflecting surface (IRS)-assisted UAV communication system. Emerging physical layer technologies corresponding to IRS-assisted UAV systems and their benefits and challenges are highlighted. The chapter covers joint optimization approaches to the UAV trajectory and IRS passive beamforming. In Chap. 5, the focus is on artificial intelligence–empowered models for UAV communications. In Chap. 6, RIS-assisted UAV cellular communication is discussed with practical scenarios. The chapter demonstrates that RIS can partially control the wireless transmission channels and provide more favorable propagation characteristics. Chapter 7 presents cell-free massive MIMO architecture for UAV cellular communications. The chapter highlights the effectiveness of CF-mMIMO in delivering improved spectral and energy-efficient UAV cellular communication. New expressions for UL and DL data transmission phases are derived for the achievable lower and upper spectral efficiency bounds.

Chapter 8 examines UAV-assisted reconfigurable intelligent surface (RIS) for energy-efficient reliable communication. Intelligent and blind UAV-assisted RIS schemes are proposed to increase energy efficiency. Analytical closed-form average bit error probability expressions are derived. Intelligent UAV-assisted RIS can convert a wireless fading environment into a superior communication environment, offering a low average bit error rate at extremely low SNR conditions. The idea of using blockchain technology to support UAV cellular communications is presented in Chap. 9. Chapter 10 dissects unmanned aerial vehicle cellular communication with the non-terrestrial networks. The channel model and the vertical height of the UAV for both ground users and base stations are analyzed.

In Chap. 11, design and performance issues in UAV cellular communications are elaborated. Specifically, the chapter highlights some strategies for UAV design and performance optimization. Chapter 12 presents the evolution and significance of unmanned aerial vehicles and discusses the importance of UAVs to society and industry. Finally, Chap. 13 provides an overview of the energy consumption of unmanned aerial vehicles used in cellular communications. The chapter remarks that cleaner energy sources and energy-efficient batteries will hold great promise for UAV applications in future wireless communication systems.

Bochum, North Rhine-Westphalia, Germany Agbotiname Lucky Imoize

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About the Editors

Agbotiname Lucky Imoize (Senior Member, IEEE) is a lecturer in the Department of Electrical and Electronics Engineering, University of Lagos, Nigeria. He received BEng (Honors) in electrical and electronics engineering from Ambrose Alli University, Nigeria, in 2008, and MSc in electrical and electronics engineering from the University of Lagos, Nigeria, in 2012. Before joining the University of Lagos, he was a lecturer at Bells University of Technology, Nigeria. He worked as a core network products manager at ZTE Nigeria Limited from 2011 to 2012 and as a network switching subsystem engineer at Globacom, Nigeria, from 2012 to 2017. Imoize was awarded the Fulbright Fellowship as a visiting research scholar at the Wireless@VT Lab in the Bradley Department of Electrical and Computer Engineering, Virginia Tech., USA, where he worked under the supervision of Prof. R. Michael Buehrer from 2017 to 2018. He is currently a research scholar at Ruhr University Bochum, Germany, under the Nigerian Petroleum Technology Development Fund (PTDF) and the German Academic Exchange Service (DAAD) through the Nigerian–German Postgraduate Program. He is a registered engineer with the Council for the Regulation of Engineering in Nigeria (COREN) and a Nigerian Society of Engineers (NSE) member. He has co-edited one book and coauthored over 80 papers in peer-reviewed journals and conferences. His research interests are beyond 5G and 6G wireless communications, chaotic communications, and wireless security systems.

Sardar M. N. Islam is currently a professor, ISILC, at Victoria University**,** Australia. He is also a Distinguished Visiting Professor of Artificial Intelligence at Unsri and a distinguished visiting professor at AURAK, 2019–2021. Professor Islam adopts a global and humanistic approach in his research and academic works. He has undertaken rigorous scientific studies of emerging computer science issues and other disciplines. His scholarly work has gained international acclaim resulting in through honors and awards, visiting or adjunct professorial appointments in different countries, appointment in editorial roles of journals, and keynote speeches at international conferences in several countries. He has published 31 scholarly academic books in different disciplines, including computer science. Each of these books makes significant scientific contributions to the literature. These books are published by prestigious publishers in highly regarded book series. He has also published about 250 *articles*, including some of the top leading international journal articles in his specialized research areas, including computer science.

T. Poongodi is currently working as a professor in the School of Computing Science & Engineering at the Galgotias University, Delhi–NCR, India. She received her PhD degree in information technology (Information and Communication Engineering) from Anna University, Tamil Nadu, India. Her current research interests include network security, wireless ad hoc and sensor networks, Internet of Things (IoT), computer networks, and blockchain technology for emerging communication networks. Dr. T. Poongodi has authored more than 40 book chapters, some of which have been published by reputed publishers such as Springer, Elsevier, IET, Wiley, De-Gruyter, CRC Press, and IGI global, and presented at more than 30 international journals and conferences. She has published more than 10 books on the Internet of Things, data analytics, blockchain technology, artificial intelligence, machine learning, and healthcare informatics, published by reputed publishers such as Springer, IET, Wiley, CRC Taylor & Francis, and Apple Academic Press. She adopts a universal and humanistic approach in her academic and research works. She has undertaken meticulous scientific studies of emerging issues in several disciplines in her research. She has many years of academic work experience in teaching and multi-disciplinary research. Professor Dr. T. Poongodi has also received invitations to address international conferences as a keynote speaker. She is a member of the Institute of Electrical and Electronics Engineers (IEEE), IEEE Women in Engineering (WIE), Association for Computing Machinery (ACM), the International Association of Engineers (IAENG), the Institute of Research Engineers and Doctors (IRED), and the International Association of Computer Science and Information Technology (IACSIT).

Lakshmana Kumar Ramasamy is head of the Center of Excellence for Artificial Intelligence and Machine Learning at Hindusthan College of Engineering and Technology, Tamil Nadu, India. He completed Postdoctoral Fellowship at Thu Dau Mot University, Vietnam. He is also working as an offshore director for R&D (AI) in a Canada-based company (ASIQC) in the Vancouver region of British Columbia, Canada. He represents the Technical Group Committee of the National Cyber Defence Research Centre (NCDRC), Government of India. He holds certification in data science from John Hopkins University, USA. He is certified as an Amazon Cloud Architect from Amazon Web Services. He is the founding member of IEEE SIG of Big Data for Cyber Security and Privacy. Dr. Ramasamy serves as a core member in the editorial advisory board of the artificial intelligence group in Cambridge Scholars Publishing, UK. He is a member of IEEE. He is also the ACM Distinguished Speaker and IEEE brand ambassador.

B. V. V. Siva Prasad works as an assistant professor at Malla Reddy University, Hyderabad, Telangana. He completed Postdoctoral Fellowship at Thu Dau Mot University, Vietnam. Currently, he holds 5 patents for his works, has published more than 30 research papers, is the author of 5 books, has chaired multiple conferences, and has received many awards. He has acted as session chair for different national and international conferences conducted in engineering. He has reviewed almost five theses till now. He has published 10 Scopus-indexed papers and 20 conference papers in IEEE, Springer, Elsevier. Dr. Prasad is also an editorial member of nearly 10 international journals and a review committee member for around 20 national and international journals. He is an Empanelled Fellow Member of Nikhil Bharat Shiksha Parishad. Dr. Prasad has been appointed as senior member in the Iranian Neuroscience Society-Fars Chapter (SM-FINSS). He is a member of IEEE, CSI, ISTE, IAENG, CSTA, and the International Association of Engineers. Currently, he holds 6 patents for his works. Presently, he is guiding 5 PhD scholars, and has guided 25 PG projects until now as well as trained 80 graduates and more than 200 BTech students. Dr. Prasad has conducted more than 1000 competitive exams like IBPS with the help of TCS. He is also a placement coordinator for a few engineering colleges.

Chapter 1
Historical Perspectives and Introduction to UAV Cellular Communications

T. Poongodi, Aradhna Saini, Gaurav Dhuriya, and Vaishali Gupta

Abstract With the progression in drone innovation, in only a couple of years, robots will help people in every space. Yet, there are many difficulties to be handled, communication being the main one. This chapter is aimed at giving the essentials of UAV and knowledge on the most recent Unmanned Aerial Vehicle (UAV) communication advances by examining appropriate modules, radio wires, resource dealing with stages (plan, acquire, use maintain, dispose), and network models. Moreover, we investigate procedures, for example, artificial intelligence and ways of improving existing specialized strategies for robots. Board strength and encryption methods for ensuring secure communications are also evaluated. In addition, utilization of UAV networks for various logical purposes, going from route to reconnaissance, ultra-solid and low-latency communication, border processing and business related to man-made reasoning are investigated, specifically, the multifaceted interchange between UAV, progressed cell communication, and the internet of things. This chapter discusses about the challenges, applications, and future research directions in UAV communications.

Keywords Cellular networks · Communication technologies · Wireless sensor networks · Vehicular transmission · Antenna · Security threats

1.1 Introduction to UAV Cellular Communications

Consumer unmanned aerial vehicles (UAVs) are utilized for anything from remote sensing to find-and-rescue to delivering packages. Based on a Federal Aviation Administration forecast, the utilization of drones would double by 2022, from an

T. Poongodi (✉) · V. Gupta
School of Computing Science and Engineering, Galgotias University, Greater Noida, Uttar Pradesh, India

A. Saini · G. Dhuriya
Department of Computer Science and Engineering, Noida Institute of Engineering and Technology, Greater Noida, Uttar Pradesh, India

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assessed 1.1 million units in 2017. New use cases are predicted to increase in the future, which boosts the growth of UAVs.

The evolution of the UAV market is likely to create new and exciting commercial prospects for cellular operators, as the variety of real-time instances could be beneficial for linking the UAVs to cellular or mobile networks to achieve effective coordination and bi-directional transmissions. Based on a particular study, it was discovered that improving the line-of-sight (LoS) among aerial UEs and Base Stations (BSs) will considerably raise the level of system interference, necessitating novel solutions to support both aerial and ground use [1].

Wireless network operators are particularly interested in the once-in-a-lifetime potential of creating flying wireless relay and BSs placed on UAVs that could dynamically relocate themselves to improve the area coverage, spectrum efficiency, and quality of experience (QoE). Most of the suppliers have brought the prototypes to test in the field to show that such UAV-mounted flying BSs can perform.

The compatibility of the available wireless technologies, such as Wi-Fi, ZigBee, Bluetooth, cellular, and WiMAX can be investigated for several UAV applications.

1.2 Categories of UAV and Their Characteristics

Drones, or unmanned aerial vehicles, come in a variety of sizes and specifications. Moreover, they can be quickly deployed whenever necessary, making them interesting candidates for cellular communication. The characteristics of a few common drones are listed and explained in this section, with a particular emphasis on the effect of UAV-assisted cellular communications.

Payload Payload is the maximum weight that a drone can carry, i.e., the measurement of its lifting capability. Several accessories can be carried with a larger payload, but at the cost of a larger drone, shorter flight time, and higher battery capacity [2]. Video cameras and various sensors are common payloads that could be utilized for surveillance, reconnaissance, or commercial reasons. Drones can also carry cellular devices such as tablets or mobile phones that weigh less than a kilogram when aiding cellular communications. It can also mount BSs or remote radio heads to deliver cellular services.

Drones are classified into three categories based on the flying mechanisms:

Multi-rotor, also called rotary-winged drones, which may lift off and land vertically and levitate above the set spot for consistent wireless service in particular locations. Because of their great maneuverability, they are well suited to supporting wireless cellular communications; consequently, they can precisely distribute BSs at the necessary spots or fly in a predetermined trajectory. They consume a lot of power and have limited mobility, as they constantly want to combat gravity.

Fixed-wing can easily slide through the air, as a result of which they are more energy efficient and effective at carrying heavier payloads. They can also benefit from sliding to travel faster. Fixed-wing drones have the disadvantages of (a) requiring a landing field to take off because vertical take-off and landing are not practicable, and (b) being unable to hover over a fixed spot. Drones with fixed wings are considerably more costly than those with multiple rotors.

Hybrid fixed have been recently introduced to the market as a compromise between the two types of drones discussed above. The Parrot Swing is a perfect example of this wing drone because it can take off vertically, glide through the air fast to its goal, and then hover with four rotors.

Range and Altitude A drone's range means the distance from which it may be operated remotely. Small drones have a range of tens of meters, whereas larger drones have a range of hundreds of kilometers [3]. The height to which a drone can fly, irrespective of country-specific limitations, is referred to as altitude. Because a UAV BS must differ its altitude to improve base coverage and fulfill varied QoS requirements, the maximum flying height for a specific drone is a significant metric for UAV-based wireless communications. Furthermore, aerial platforms can be divided into two categories based on height:

Low-altitude platforms (LAPs): these platforms are commonly used to aid wireless cellular communications because of significant factors such as less expensive and rapid deployment. Moreover, LAPs typically afford shortest range LoS connectivity, which improves the communication process dramatically.

High-altitude platforms (HAPs): cellular connectivity could also be provided by HAPs, such as balloons. HAPs have a larger coverage area than LAPs and can stay in the air for much longer. HAP deployment, on the other hand, is more complicated, and they are primarily thought of as a way of bringing internet access to wide strips of the world's population that are not currently served by cellular networks. Furthermore, the employment of HAPs in cellular communications may result in a complete network shutdown due to unusually high inter-cell interference.

Flight Time and Speed Small drones fly at rates of less than 15 m/s, although large drones can achieve speeds of up to 100 m/s. If the trajectory necessitates numerous rotations, the speed of a UAV BS/relay must be carefully examined when flying in a prescribed route to maximize its spectral efficiency and energy. The trade-off between the speed and turning agility of a drone is investigated. The flight time or endurance of a drone refers to how long it can stay in the air without recharging or replenishing.

In smaller commercial drones, flying time is around 20–30 min, but larger drones can fly for several hours. For instance, with hybrid-electric power sources, the Sky front Tailwind drone can fly for up to 4.5 h [4]. Nonetheless, the greatest practical constraints to its large-scale deployment in cellular networks is the short persistence of existing UAVs.

Power Supply The power source of a drone has a considerable impact on its durability. Although most commercial drones are powered by rechargeable batteries, certain larger drones could be driven by fuels such as gas for extensive flying periods. Drones that are powered by solar energy are also a viable option. The power source for drone-mounted BSs must sustain the drone's functionality as well as the on-board equipment such as the amplifier, antenna array, and circuits. And, a standard aerial BS, for example, entails a maximum transmission power of 5 W, which should be provided by the on-board energy supply.

UAV, Satellite, and marine communication would be linked into terrestrial cellular networks to enable continuous network access in order to attain ubiquitous coverage.

UAV communication networks are seen as a viable alternative to enhance the QoS and increase the scope of present networks in hostile environments because of their LoS high-low altitude channel, low cost with better adaptability.

Unmanned aerial vehicles, often called drones, have been used in a variety of applications for nearly a century. UAVs are widely employed in military applications such as armed attack and remote surveillance, as they can be controlled remotely and no pilots are required on board. Commercial UAVs have become increasingly popular in recent years as manufacturing technology has improved and costs have decreased.

Unmanned aerial vehicles are being employed for surveillance and reconnaissance, as well as transportation management, public safety, search and rescue, and data collection. UAV-assisted communication has emerged as a possible technology for future 6G networks, because of the lower usage of communication devices, better adaptability, and low price of UAVs. Furthermore, UAVs differ drastically from traditional terrestrial communication nodes as a novel component of the 6G networks [5]. The following are the new features of UAV-based communication systems compared with terrestrial systems:

1. High altitude. The altitude of UAVs is frequently higher than that of traditional base stations and mobile clients. Typically, the remote connectivity established between the base node and the UAV is unimpeded. As a result, the air-ground channel has minimum scattering and route loss compared with the traditional terrestrial channel. And, LoS channels have both advantages and disadvantages for air-ground communications.

   Compared with nonline-of-sight (NloS) terrestrial communications, the LoS dominating channels provide greater dependability and lessen the chance of losing the pathway in high–low altitude communications. In a wireless network, however, the LoS channels cause substantial interference with other neighboring nodes. To leverage the LoS-dominant high–low altitude wireless channels, the location of the UAV in 3D space must be analyzed.
2. Greater movability. Under traditional terrestrial communications, the positions of the nodes are generally anchored at a particular site. For UAV communications, UAVs can also be wirelessly instructed to move at higher speeds in physical areas. Then, the UAV can be used for launching wireless networks in a variety

of ways. This trait is more beneficial in times of crisis, which include uses in military and disaster relief, where a quick response is required. Furthermore, the UAV's mobility can be used to approach closer to the target user for improved channel gain and to avoid barriers. As a result, the UAV's trajectory can be customized to enhance the communication performance.

3. Limited energy: because of its weight and size limitations, tiny UAVs have limited on-board energy compared with terrestrial communication networks, which have adequate power sources. Furthermore, UAVs must afford power for both bi-directional transmissions and impulsion at the same time. Furthermore, the power consumed by impulsion to keep the UAV upward and support its mobility is substantially more than the energy consumed by communication. As a result, the endurance period of a small UAV is limited. Finally, although the UAV is appropriate for rapid deployment in difficult environments, it necessitates an energy-efficient structure to extend its lifetime.

1.3 Enabling UAV Communication and Network Technologies

To build up a legitimate UAV communication network, communication modules and conventions are of the utmost significance. Different techniques are proposed by the exploration local area in which a couple of basic factors, for example, radio wire configuration, network design, and executive platform citation needed, were thought of. In this segment, communication modules, various systems administration plans, and usage of the internet of things in various parts of robot communication are examined [5]. In Fig. 1.1, different types of drone and antennas holding different modules used in UAV communication are shown.

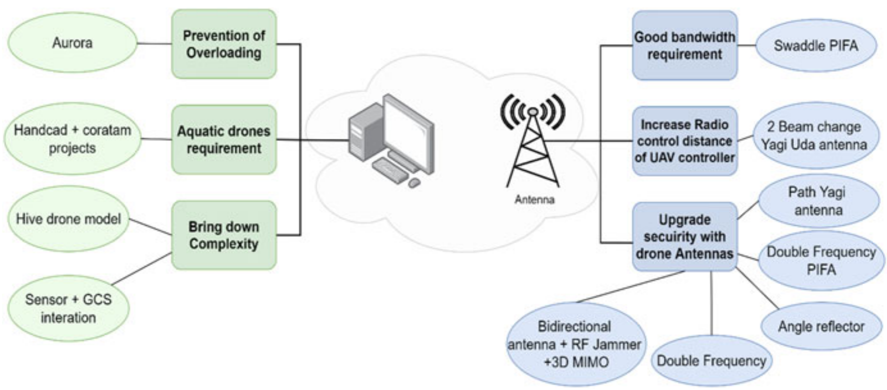

Fig. 1.1 Drones and antennas holding different modules

1.3.1 Communication Modules

A number of investigative works are committed to reviewing communication development. In particular, accuracy is eventually considered as a significant factor in UAV communications. Some of the existing remote modes including WiMAX, LTE, and ZigBee, are compliant with these guidelines [6]. Multiple-input and multiple-output (MIMO) used orthogonal frequency division multiplexing (OFDM) to duplicate the information sent exactly to the last of the compilers for further reduction and computer complexity. In any case, encouraging the highest possible benchmark can be another reason for promoting a communication system.

1.3.2 Antenna Design

Proficient radio wire configuration is fundamental to signal trade and data exchange among drones. It is imperative to conceive a strategy that maximises the execution of radio wire pictures by considering the need for data transmission capacity. Miniaturized Printed experiments found that the printed systems were very good, especially the Planar Inverted-F Antenna (PIFA). The UAV selector is a handle-shaft-mounted annular group that obtains cables through two bars that convert the radio cable to an active 2.4 GHz frequency, with a range of radio power forward to improve the UAV's operational range [7]. The direct Yagi receiving cable has also been used to focus on the development of gadget power. A review center around the line of sight (LOS) security feature and the nLOS (non-line of sight) risk factors. Using the telephone gadgets received, for example, duplicate PIFA, directional radio cables, and electronic drawing point indicators, the framework can differentiate between attacks on novice users.

1.3.3 Resource Management Forums

Experimentation has continued to promote platforms that can be pre-owned by analysts and designers to perform tasks easily. Distant from the Human Manifesto, AuRoRA, has been worn as a transmission route that breaks the deck for servo motors in automobiles as demonstrated. This approach prevents the heavy load of a sole PC by synchronizing flight information with control signals. Whatever the case, in the area of multi-machine technology, being in charge of various UAVs can be a daunting job and direct coordination between them is needed. A set of instructions for programming a group of robots includes a substation with specific responsibilities for the setup of various sensory components. Robots were mounted on a sensory network, part of which was surrounded by the ground control station (GCS). The transmission base was organized utilizing live stream, control, information, and collaborative channels, supporting video to send letters between drones and a ground control station. The ad hoc network is heterogeneous for the

Table 1.1 Drone transmission (different platforms and algorithms)

Algorithm	Domain	Functionality	Source
AuRoRA	Resource handling	1. Fills in as earth station 2. Avoids putting undue pressure on one person	13
Karma	Resource handling	1. Shift complex integrates errand to focal hive PC	16
AFAR	Drone network	1. Uses geological data and flooding	77
IACO	Path planning	1. Can effectively address portable agent steering issue 2. Robust and self-versatile	78
VerifierBee	Path planning	1. Gives shortest way for TLVP	48
DMPC	Multi-UAV system	1. In view of XBee communication	49
LinHAE	Cryptography	1. Direct homographic verification for regulators	52
RFly	Drone network	1. Merges with existing RFID infrastructure 2. Protects stage and season of future data packets	64
LEAP	Optimization of latency	1. Concentrates on the energy limit impediment of robot base station	25

cooperation of aquatic drones and the capacity of aquatic drones for maritime tasks projects, engaging in controlling a large number of aquatic robots and transmission between them. Important objectives of the program were to authorize mobile ad hoc networks to be carried at minimal cost for sea robots (2.4 GHz repeat performance). The Yagi directional radio cable has also been used to focus on the development of gadget power. A review center around the non line of sight (LoS) security feature and non line of sight (NLoS) risk factors. In the case of certainty, an RF scrambler with a double-stranded radio and a 3 dimensional multiple input multiple output (3D MIMO) detector would be used to ensure that it would not be tested again [8].

1.3.4 Networking Technologies for UAV Transmission Model

The large part of the trial effort has zeroed in on the dissimilar pieces of mechanical affiliations, which have achieved new better turns of events and invigorating associations. The full mix of microwave access (WiMAX) association as a consistently better approach to zero in on the advancement of distant communications such as ZigBee, WiFi, XBee, and WiMAX, in the light of the SHERPA network rules [9]. When properly adapted, drones may join the adaptive forward area-based routing estimation (AFAR) of robots using a geographic information system to focus in on floods. Assessment with the destination-sequenced distance-vector (DSDV) directing meeting guaranteed a high level of AFAR-D mass transmission. An advanced framework is required for the board structure router-movable information-centric networking especially in crafted by writing inside a separated network [10]. Ongoing upgrade of flying switches and transmission harvests were used to further develop adaptability and proficiency. A number-crunching technique called improved ant colony optimization was utilized for the assortment of versatile robots. One more piece of resource allotment isolates the best band to recreate individual robots in order to give the biggest number of robots to work the fundamental communication band while simultaneously staying away from interferences. Thinking about radar and robot closure, Yang proceeded to foster a much bigger band of robots utilizing an objective band contrasting with the absolute character of robots by expanding the size of the basic limit district. The high blockage was recognized on the radio power unit in the 2.4-GHz remote band. Advancement techniques and their trial results have shown Wi-Fi shortcomings in this band because of the huge range of control devices utilized by this band previously [11]. Despite the danger, a clever and practical strategy was almost variant using unexpected writing throughout the development of the multi-robot alliance. With the assistance of the group, a trailblazer plane is monitored by an individual, and different robots autonomously follow the trailblazer utilizing Wi-Fi signal power. The UAV-type activity has started to attract interest in standard applications. The fact that there have been numerous UAV swarm shows that the degree of private activity has been restricted. More often than not, each and every UAV is overseen at the same time by the GCS. The current UAV series shows utilization of one of two normal kinds of multi-report development from an association-based plan amount engineer or a plan with a unique assignment status. The flying ad hoc network (FANET), in which the communication issue disturbing the robots' working reach was tended to [12]. The new hand-held FANET can likewise be utilized to control robots that serve the primary edge (GCS). The "return to the following bouncing robot" plot is valuable in the systems administration of separate robots on associated drones. Likewise, business networks examined where a solid association involving autonomous flight wireless (AFW) areas of interest with delay tolerant networks (DTN) and never die networks (NDN) is utilized to screen imagined remote channels and send messages to distant areas [13].

1.3.5 UAV-Assisted Wireless Sensor Networks and UAV-Assisted Vehicular Transmission Model

Integrating robots into a wireless sensor network (WSN) is a daunting task because of a thick sensory structure in a large area. Standing WSN networks are not able to function effectively with progressive injury categories. The WSN and UAV recommendations were made in view of the advanced manifestations of the three misadventure management categories, namely, pre-misadventure preparedness, debacle testing, and fiasco feedback and healing. Flexible information on UAVs was integrated into the WSN. The guiding system was defined in the case of route selection and the Communications Regulatory Authority (CRA) using a separate controlled calculation. D2D can be a productive medium between UAV communications. A review of the ongoing development in D2D development is shown in Uchida et al. [14]. D2D communication and re-use and power control utilizing a multi-player defilement model were developed and researched. Studies show that gadgets capable of mobile networking can track different gadgets in the affected areas. In addition, the mobile site can be used for high data transfer and building private networks. Other research [15] has introduced a robot that has helped Decentralized Autonomous Vehicle Network engineering to install drones and ground vehicle systems, using robots to improve base installation, car-to-car access, network performance, and information integration capabilities.

Some inventive work has been done on vehicular ad hoc networks (VANETs). Arrangements such as UAVR-S (aeronautical communications) and UAVR-G (ground-to-air). The specially appointed association of moving UAVs as transmission is sent when the impressions are poor or the vehicular alcove site region is too low to be in any way ready to coordinate the majority. A lightweight forward-back is planned as a remuneration for minor authoritative postponements, and a lightweight forward back is arranged as compensation for tiny authoritative postponements [16]. The foundation of the UAV helped by an exceptionally planned vehicular (VANET) system is said to be the vehicle-drone hybrid vehicular offhand network (VDNet), utilizing UAVs to work with the exchange of data among vehicles and to fill a critical role. The First Responder Network Authority (First-Net) astute robot utilizes a device, which sends communication between the essential channel and end-to-end devices. Sporting outcomes show that a robot is necessary as long as the necessary path or communication power surpasses the pre-decided breaking point. Figure 1.2 show the UAV communication network.

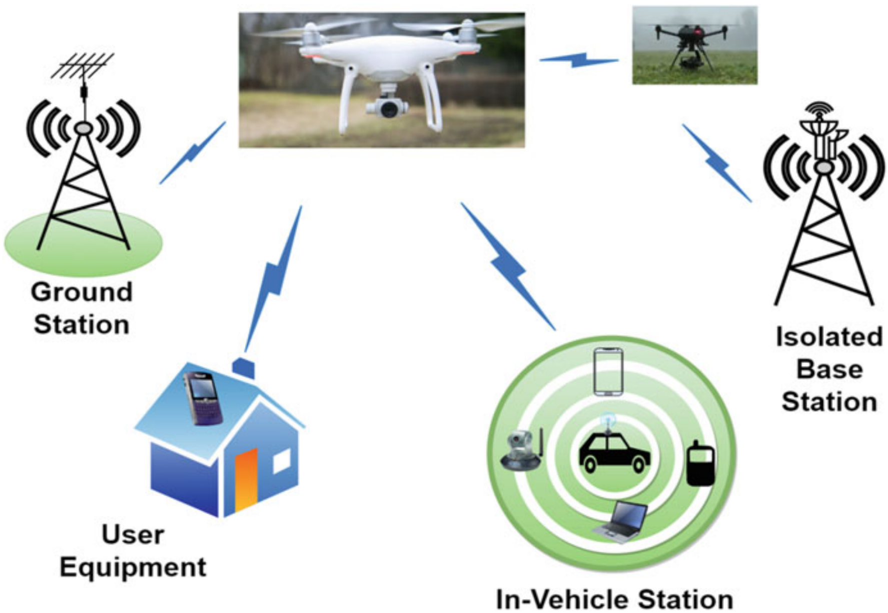

Fig. 1.2 Unmanned aerial vehicle communication network (proposed cellular-connected)

1.4 Artificial Intelligence Technologies for Future UAV Transmission Model

Fifth-age (5G) and past interchanges are fundamentally described by:

(i) Monstrous network,
(ii) Ultra-unwavering quality and low idleness,
(iii) Expanded throughput.

Fulfilling all these targets related to the quick development of Internet of Things (IoT) applications addresses a difficult undertaking, particularly under exceptionally powerful and diverse conditions. A reliable methodology for embracing UAVs as aeronautical client hardware. In particular, UAV-related correspondences might additionally foster the organization execution under emergency conditions by offering fast help recovery and by offloading in extraordinarily pressed circumstances. These characteristics have raised a reasonable worry on the part of the standardization organizations [17] and the scholarly community. Besides, the combination of artificial intelligence (AI) and machine learning (ML) methods in remote networks can use knowledge to resolve different issues. In this way, the mix of AI/ML and UAVs gives an impression of being firmly consistent across rules, applications, and organizational levels, bringing to simplified complexity and exceptional performance benefits. In the accompanying sub-sections, a short presentation on the areas of ML and UAVs is introduced, applicable overviews are discussed, recognizing the present gap in the literature that has propelled the present work.

1.4.1 UAV Features

As interest in far-reaching broadband administration, worldwide inclusion, and pervasive access has developed, nonterrestrial networks (NTNs) can firmly uphold the grounded terrestrial backhaul networks. One of the primary parts of NTNs, the LAPs, are meant to work with different regular citizens, business, administrative aims, and IoT applications, ranging from security and military tasks to diversion and broadcast communications. UAVs, a critical representative sort of LAPs, are typically small automated airplanes utilized for brief periods (a few hours) permitting the quick arrangement of a multi-jump communication spine in testing applications with no faculty included, for example, public security, search and salvage missions, observation investigation, crisis interchanges in post-debacle circumstances or surprising occasions, visual surveillance, metropolitan traffic reconnaissance, accuracy horticulture, and media traffic checking [18–20]. It is important that the statistical surveying conjectures, which deals with UAVs, surpassed $12 billion of business every year by 2021, whereas the Federal Aviation Administration forecast that UAVs would gain around 2.4 million units by 2022.

Clearly, such a commercial scale and elements have been the main thrust with regard to the advancement of UAVs. Recently, incredible interest has be attracted by normalization bodies, ventures, and the academic world toward the utilization of UAVs as flying BSs, portable transfers, or independent conveyance hubs for providing short periods of inactivity and exceptionally dependable interchanges in urban communities, across rural regions, and over rustic landscapes.

Contingent upon these flying instruments, UAVs may be characterized as multi-rotor drones, remotely piloted vehicles, firm-wing drones, half and half fixed/revolving wing drones, robot planes, and pilotless airplanes, and can vary in size from small toys to huge military airplanes [18–20]. Additionally, the payloads of UAVs, including communication radars, gear, sensors, and cameras, vary in weight and clearly determined size, flight length, and battery limit. Attributable to their novel qualities, UAVs are equipped to provide pervasive and savvy remote access over huge inclusion regions at heights and humble elevations, and with a high opportunity of view (LOS) associated with the ground hubs, whereas they guarantee fast arrangement and development on request [18–20]. Aside from utilizing few UAVs, a multitude of UAVs can likewise agreeably attempt to complete complex undertakings in altogether huge regions and particularly in checking and observation applications, through the FANETs [21], in which different UAVs convey in an especially appointed way, can successfully extend the availability and communication range in situations with terrestrial network limitations, i.e., distant hubs, exceptionally portable hubs, and profoundly scattered hubs. All things considered, challenges with regard to the portability, assets of the executives, and control of the UAVs are forced, particularly because of enormous UAV swarms and the changeability of its sorts, when the fruitful and long-haul activity of UAV-focused networks requires successful obstruction moderation alongside coordination and interoperability between heterogeneous remote frameworks. In addition, the restricted perseverance of the UAVs with deference not exclusively to the systems administration and on-board handling of errands but also to power interest in its motors and flight control at present consists of primarily pragmatic variables limiting the full-capacity sending of UAVs in National Television Standards Committee. Prolongation of drone lifetime is a main issue, emphatically connected with flight qualities and mission boundaries.

In any case, contrasting with terrestrial remote networks, UAV networks have numerous unmistakable elements, such as profoundly unique network geographies, circles, or flight paths, and associated communication hubs. Once the power supply is restricted, an energy-productive plan of airborne frameworks regarding the way of arranging and battery booking is likewise expected to expand the flight term. Additionally, the portability and the individual Doppler shift is expanded and the QoS in information transmissions might be out of harmony or balance. In general, the communication necessities should be adjusted to the rate and nature of the information transmission to accomplish the ideal exhibition measurements. Furthermore, existing regular interchange strategies include innate restrictions, especially on account of mind-boggling communication situations, where unforeseen and nonlinear peculiarities win. As unique and strategic UAV-based communications lead to specific intricacy, vulnerability, and serious levels of changeability, AI/ML is the primary innovation that empowers in a general sense different dynamic abilities to acquire an appropriate UAV situation and direction.

1.4.2 Machine Learning and Artificial Intelligence

Simulated intelligence has been viewed as the study of preparing machines to mimic human errands. There are numerous applications that AI has been engaged with, including mechanical vehicles, discourse acknowledgment, machine interpretation, and as of late, remote communication. In addition, a particular subdivision of AI is the strategies that are utilized for preparing machines in how to realize, which starts another structure known as ML. Under this specific circumstance, ML can provide arrangements in situations where countless gadgets at the same time expect admittance to the network's assets in a heterogeneous, dynamic, and slightly way, in IoT communication. In this regard, smart administration ought to be acted on in the whole network to adapt to the different requesting prerequisites of this clever kind of administration. The ML is to adaptively and progressively deal with the network's assets in an ideal way. Thus, ML calculations have been proposed as a proficient methodology for standing up to this multitude of disconnected difficulties coming from the IoT environment.

As a rule, ML depends on the sample acknowledgment structure and its principle thought is to take advantage of the connection among a quantity of information as well as past great activity groupings for adjusting to the ecological changes with next to no sort of human intercession. Obviously, the benefit presented by the ML system in the activity of the remote network is that it will empower networking components to screen, and anticipate different communication-related boundaries, for example, remote channel conduct, traffic designs, client setting, and gadget areas.

Machine learning is arranged into different classes.

- *Supervised learning*: in this, the calculations use informational indexes, in which information and the ideal result are accessible. Consequently, this sort of calculation must be utilized in situations where enough named information is accessible to be taken advantage of.
- *Unsupervised learning*: the unsupervised learning calculations likewise expect information to be accessible for preparation, which, notwithstanding, do exclude the marked result. Consequently, in this sort of learning, grouping or a sample revelation is executed on the accessible information.
- *Semi-supervised learning*: a halfway methodology with regard to the idea of accessible data is followed by semi-regulated learning estimation. In this sort of technique, unlabeled and labeled data are utilized for the planning.
- *Reinforcement learning*: in this technique, the situations are tackled by utilizing grouping of activities that utilize the experimentation rule. Accordingly, the principal thought of this kind of learning is drastically unique when contrasted

with those recently referenced, which exploit authentic information. All things being equal, reinforcement learning calculations are prepared by the recently taken choices toward tackling the issue. The reinforcement learning calculations are utilized in different situations in the space of remote network advancement.

Moreover, a particular class of ML is deep learning (DL) and in DL, different layers are utilized to assemble an AI network that can settle on smart choices with no sort of human intercession. DL calculations can be used when restricted manual obstruction is required, at the expense of higher numerical necessities. In any case, DL and AI/ML techniques are generally utilized in different remote interchange situations to work on various boundaries of the network.

Alongside the developing number of modern answers for remote networks in recent years, a few ongoing studies zeroing in on the transaction of AI, ML, and remote communications are given. Different investigations have claimed the use of ML for working on the presentation of remote networks. A short portrayal of the utilization of DL in a design in view of the zero-stack structure, which is reliable ethereal advanced mechanics engineering with the normal parts connected with discernment, direction, route, and control of automated rotorcraft frameworks, with various automated specialists comprising various deliberation levels of automated aeronautical automated frameworks, similar to social, intelligent, and deliberative layers, among others. The DL calculations are utilized in four bearings, including extraction, arranging, situational mindfulness, and control of movement. The arrangement is restricted to the learning type of the calculation and the area of use for ethereal robot frameworks that utilize explicit sensors. It concentrates on the utilization of deep reinforcement learning for quite a long time, and communication angles, for example, control of rate and networking access, offloading and changing out, security and availability conservation, directing, assets, and information assortment. Now and again, the UAV is considered as a specialist for cellular network, similar to a base station, a sensor, a portal, a client, an network regulator. Deep Q-learning, deep Q-networks, and a liquid state machine are sub-types of analyzing calculations that are used for the previously mentioned problems of the UAV situations. Fairly extensive study from the select point of DL applications in versatile and remote networks is portrayed in Bekmezci et al. [22]. The creators give groupings to various characteristics, for example, versatile large information, information and portability investigation, client limitation, security and network control. Nonetheless, the utilization of UAV networks isn't thought about. Simultaneously, a few of the DL procedures that are examined can be of significance to UAV networks. Then, a concise outline of ML procedures for remote enormous information examination. One of the main objectives is connected to UAVs, not discussing AI/ML perspectives. Other work discusses the fact that the AI/ML complex machinery for computations in 5G and post-5G networks are essential for the advancement of 6G networks. The basic utilization of self-supporting networks in 6G needs low-inactivity, more highly unwavering quality, and versatile AI, alongside a dependable foundation, depending on the incorporation of UAVs and ground network hubs.

In networks comprising ground-based and ethereal vehicles, there have been different overviews introducing potential uses of AI/ML, to begin with, the abuse of AI for vehicle-to-everything applications, including examinations of AI calculations. In addition, in independent driving, the review sorts the most generally involved AI strategies into Swarm Insight, ML, DL, master frameworks, and arranging, planning, and enhancement, where one might track down similitudes to the conspicuous UAV arrangement. A portion of the recommended widely available or exclusive programming apparatuses can likewise be utilized in UAV communications, and yet the vast majority of them consider usage such as wellbeing, network clogging, routing, security, content conveyance, and edge processing [23]. All the more explicitly, UAV-related angles of remote networks are for the most part examined for purpose of the board in a calamity disregarding ML upgrades, whereas ML is essentially considered for medical service applications within the space of inconsistency identification for patients [18]. A few recently established methods come to mind (e.g., non-orthogonal multiple access (NOMA), furthermore, millimeter-wave band transmissions), whereas the categorization of various procedures acts as far as the actual layer; network layer; and joint communication, processing, and reserving, thinking about the BS type and the quantity of UAVs. Nonetheless, just a predetermined number of deals are incorporated with the utilization of ML in UAV networks [20]. In the last option, just two stages are introduced utilizing ML calculations for direction and situation. For the UAV networks, Machine Learning is currently just being included as a possible future research route for normalization, guidelines, and safety perspectives.

According to the network protection perspective, one might observe a concentration on AI/ML. The three cyber–physical system (CPS) parts in the UAV network that the overview breaks down are communication, calculation, and command. As for the ML methods, the creator's group have open-source programming activities and libraries, fundamentally zeroing in on the machine observation region. The creators momentarily notice the utilization of ML and RL at the actual sheet and direct, proportioned, at the calculation and communication parts. With respect to the calculation and control parts, insightful calculations are examined for calculation-improved flight and arrangement control. The creators provide planning of UAV network availability, QoS, safety, planning difficulties, and prerequisites for a digital–physical security request. The use of ML is introduced for things such as identification and picture acknowledgment, as well concerning intriguing future examination regions, for example, crash avoidance, range detecting, channel assessment, and Energy Board. The principal objective [24] is to lay out the remote and security challenges that emerge with regard to UAV-based conveyance frameworks, continuous sight and sound streaming, and smart transportation frameworks. To address such difficulties, artificial neural networks (ANNs)-based arrangement plans are presented. The creators consider the security at higher levels of communication. With respect to remote difficulties and pertinent AI/ML arrangements, each utilization case follows an alternate methodology and ANN-based arrangement. Likewise, the creators provide a conversation on actual communication level issues, such as obstruction of the executives. Finally, [19] a complete report on the utilization of

UAVs in remote communications and networks from the cyber–physical (CP) safety viewpoint. Two primary instances of the use of UAVs are examined: elevated remote BSs for 5G and past petitions that supplement increasing remote communication frameworks and cell-associated clients that utilize existing remote foundations. For each case of utilization, trouble sign, petitions, and essential unlocked issues are noted, alongside the numerical devices and methods required for tending to the difficulties. With respect to the latter, the instructional exercise devotes just a little part to examining the increasing field of ML, fundamentally for arranging direction and route.

Most of the reviews either center around ML for various remote network conditions or predict the mix in an UAV-build network, talking about its future prospective. To begin with, it centers around AI for mechanical requests, involving both dual- polarization hubs and UAVs. In these situations, UAVs can work on the availability and safety of several robot groups toward proficiently playing out their undertakings. Man-made intelligence/ML strategies for advanced aviation mechanics incorporate:

- ANN for postponement, network, and safety advancement, as well as channel forecast;
- Molecule flock enhancement for deciding UAV direction;
- DL for further developing UAV availability; and
- ML for client content solicitation expectation from the UAVs.

Then, at that point, it centers around a diverse communication framework involving air (UAV), space (satellite), and ground sections, in particular, the space–air–ground incorporated network, which is used for tracking down DL, fundamentally CNNs, and various AI/ML and DL designs and preparation techniques can further develop the execution of the network. Then, the instructional [24] gives an order of ANNs to remote interchanges. Among a few uses (e.g., reserving, different radio access technology, and IoT), the creators allude to UAVs and talk about RL for inclusion, availability, direction, assets, and ways of arranging improvements. A common instance to put in AI/ML is thought of, where UAVs are essential for storing empowered BSs. At long last, recurrent neural network and particularly echo state network calculations at the origin get analyzed for adaptability projections.

1.5 Cyber–Physical Security of UAV-Based Cellular Communications

Nowadays, security has become a crucial issue for any electronic communication system, especially in a UAV-aided wireless communication system where UAVs as embedded devices are equipped with data computing devices and require wireless communication. Interconnection of the cyber and physical world gives rise to an even more serious security problem. As a result, UAV-based wireless communication systems are more exposed to security risks because of the broadcast nature of wireless communication and inbuilt air-to-ground LoS channel. For example, UAVs that rely primarily on commercial GPS systems for positioning are vulnerable to jamming and spoofing and these attacks lead to the crash or capture of critical UAVs by malicious users. As UAVs, also referred to as drones, play an increasingly important role in multiple domains such as terrorism, military, public, and civilian, and for various purposes, it is important to ensure that UAV0based wireless communication systems are secure.

1.5.1 CPS Security Vulnerabilities

Open Ports

Many UAVs have open ports, which provide data to streaming services that are usually connected to a device or a computer. Open ports such as Telnet and FTP can be common and an adversary could crash or attack a drone by accessing those open ports. Human errors are the most common cause of open port vulnerabilities, which may be quickly fixed. Exceptions should be dealt with on an individual basis.

Cellular Communication Links

Unmanned aerial vehicles commonly use cellular communication as wireless communication and the literature shows a wide number of Wi-Fi vulnerabilities that can be used to target drones. As a result, adversaries use wireless abilities to acquire remote access or control of a drone, as well as potentially impair the functioning of the drone. This results in damage or a loss of control. One study [25] also exposed the vulnerability of the telemetry connection of a commercial drone.

Encryption Methods

In UAV security, encryption techniques should be employed extensively: a single vulnerability can endanger the entire system. Malicious attackers are particularly interested in data linkages and communication. Attackers attempt to acquire unauthorized access to a network via a logical or physical violation in order to retrieve sensitive information, resulting in a privacy violation. Attackers can intercept data streaming that again leads to violation of privacy and confidentiality.

GPS Exploitation

The global positioning system (GPS) is a global public service for global geolocation. An attacker can track a drone by exploiting GPS navigation system, which results in a breach of location privacy. GPS is the easiest way to keep track of drones and schedule automated flights. Military GPS employs M-code transmission signals, which are designed to be secure and resistant to jamming. Civilian communications are open to the public and can be intercepted by any GPS receiver, which is a common component in UAVs. The literature shows that drones are more vulnerable to GPS jamming.

Physical Threats
An adversary can launch physical attacks on drones by obtaining access to a drone on the ground, capturing a flying drone, or controlling drones after successfully launching cyber-attacks. Physical threats are usually associated with other security vulnerabilities. Physical attacks can be avoided if other security attacks are fixed.

1.5.2 CPS Security Threats

Cyber physical security threats can be seen as a combination of CPS cyber or physical security threats. Here, cyber and physical threats for UAV-assisted cellular communication or radio links are identified and presented.

1.5.2.1 Cyber Threats

The vulnerabilities of UAV cellular communication can lead to cyber-attacks that compromise data confidentiality, integrity, or availability.

GPS Jamming
Jamming is a frequent method of integrity attacks, where adversaries emit fake radio frequency signals that cause interference in the receiving process at the receiver end. GPS jamming is one of the significant security threats for drones. In 2012, a small drone collapsed and caused casualties as a result of GPS jamming of the legitimate receiver [26]. A common strategy against jamming attempts is to improve the signal-to-noise ratio. However, this is always constrained by how much power the transmitter can deliver and how effective receiver algorithms can reduce noise at the receiver end.

GPS Spoofing
Spoofing of GPS is a common attack on drones. Attackers can impersonate other entities by providing fake information. The adversaries can control drones by delivering untrue GPS signals with more power than the real ones. In spoofing, attackers are able to spoof sensors by sending fake signals to the control system. In order to prevent GPS spoofing attacks, jamming-to-noise sensing and multi-antenna defense solutions might be used. Another way of protecting public GPS from spoofing is authentication. Owing to its open nature, public GPS is not designed to be secure. The sole defense solution against GPS spoofing is authentication, which can be achieved using a suitable encryption mechanism.

Sniffing
In sniffing, attackers intercept and log the target's network communications. As the small and pilot drones communicate wirelessly, they communicate publicly. To exacerbate the problem, no encrypted or secure channels are employed. Sniffing

attacks on drones are trivial because security is virtually non-existent. Sniffing attacks on small UAVs lead to replay attacks and probable reconnaissance.

Eavesdropping
Eavesdropping compromises the confidentiality aspect of security. In this type of attack, by intercepting sensor data, the attacker gains unauthorized access to confidential information. It is easy to obtain transmitted information directly from the channels because connections mostly employ wireless channels. As a protection, appropriate encryption and physical layer security mechanisms could be implemented.

Hijacking
Hijacking compromises the availability of data where an adversary takes over a radio connection. As radio connections between drones and GCSs are all wireless links, attackers could use de-authentication management frames to break the connection between a drone and related GCS in order to launch hijacking attacks to take over a drone remotely. Effective detection algorithms and encryption techniques could be employed in defense against de-authentication attacks.

Denial or Disruption of Service
In order to attempt a denial of service (DoS) attack, attackers send a large number of fake requests to the server in order to make the network congested. Consequently, the system appears unavailable and disallows legitimate users to access their service. A DoS attack can be launched in three ways: flooding, spoofing, and buffer overflow.

1.5.2.2 Physical Threats

Attackers can also launch physical attacks on drones in addition to cyber-attacks, which is one more security concern for UAV systems. In order to conduct physical attacks, adversaries must first get access to drones, which can be done in one of two ways:

- First, adversaries can either capture a flying drone or acquire access to a damaged or out-of-battery drone that is on the ground.
- Second, adversaries can gain access to drones by effectively launching cyber-attacks.

The following factors can be used to categorize physical threats.

Physical Damage
Power-generating stations such as power grid, power plants, and base stations are mostly highly secured by employing well-guarded implementation for access controls, authorization, and authentication. However, the problem is with power-generating substations or base stations that are under- or unprotected. As there is less protection, transmission channels are prone to sabotage attacks and disruption.

However, physical invasion or theft by adversaries is almost impossible to prevent, but it is possible to reduce the chance of theft and lessen its effect.

Substation Failure
A major case of concern is when a malicious attacker causes many substation failures. The major urban areas could face complete black out for several hours if the smart grid is severely damaged.

Repair
Repairing is a self-fixing process based on the capacity to detect faults or interruptions, isolate the issue, and transmit signals to the interrelated control system to rearrange the backup resources automatically and continue the service required. Here, the aim is to achieve a rapid recovery as soon as possible. On the other hand, critical components have either no or limited backup capabilities. Therefore, self-healing can be seen as a result that can respond more quickly to severe damages.

1.6 Future Research Directions

1.6.1 Future UAV Networks

Communication procedures and management systems referred to in this review are all important for UAV collaboration and efficiency. Future innovations during intra-UAV communications will emerge from a logical new construction. LoRa and LoWPAN have similarly emerged in the expected development of UAV literature in the short term. Difficulties identified as a result of recurring disappointment, rate fluctuations, high elevation production, and portability could be addressed by communication along with outlined activity of network development outlined activity. It is clear that over time, ability, network, and steady performance need to be upgraded. Full flight time, command over geological areas in the past, and predictability of information should be improved. The conservation and use of power is currently a test of modern intelligence, especially in the case of many UAVs where consecutive information transfer is required and associated with subordinates.

1.6.2 UAV Mobile Networks

The use of the cellular network, the development of channel attributes in high-speed UAVs, and texts linking components, for example, downlink circuit board and uplink traffic, will be unlocked matter for future UAV documentation. The contribution of 5G along with latest specialized technologies, for example, NOMA, industrial internet of UAV and many more [27], appear to be an encouraging output facilitating faster combination, and convenience. Then again, analysts in the scientific and industrial communities are currently researching accurate models of the UAV-linked cellular network using a variety of processes.

1.6.3 UAV Books for the Future

The future of UAVs combined with the development of the 5G network and the IoT will have a strong impact on acute urban environments for business and security motives. Nonetheless, it is vital to consider the standards and guidelines identified for use in the terms of applications. In developing an understanding of UAV literature, computer thinking, the introduction of new books, and safety play important roles in future UAVs. Apart from that, it is common to restrict the use of UAVs to evolution, extraction, caregivers' services, and agriculturally connected activities; however, it will incorporate public health, section, re-inspection, and safety. It is common knowledge that with the continuous development of intelligent urban communities, 5G, IoT, and man-made brain power, UAVs will become much stronger and more stable.

1.7 Conclusion

Remote communication innovation for both indoor and outdoor communication is turning out to be more pervasive, therefore prompting progress in UAV communication. This chapter audits late UAV enhancements in communication advances. The incorporation of 5G innovation will provide more secure and more solid networks. By testing the convenience of UAVs in assorted topographical areas, it was seen that dependable and safe communication highlights are as yet a test of UAV communication. Innovations such as FANET, NDN, AFW, and DTN help with synchronization and the minimization of dormancy. This chapter breaks down the UAV communication advancements for both equipment and calculation-based programming, including receiving wire exhibits and transmission to the executives, and usage of unified and decentralized strategies.

Accessible strategies and numerous layers of communication have been executed mostly to augment security highlights. Be that as it may, because of the imperatives of force utilization and dormancy-connected matters, execution is currently in an observation phase and requires some development. Ability utilization is difficult for UAVs. A short audit of force and improvement procedures for UAVs has been given, including different strategies proposed by scientists, such as Advances in Control and Optimization of Dynamical Systems, power enhancement of information/yield gadgets, and investigation of battery life. The immense variety of usefulness shows that the future opportunities for communication identified between the drone and intra-drone are basically limitless. The fundamental parts of UAV networks and frameworks are communication, mechanical design, and streamlining calculations. The ideal equilibrium of robot type, application, and communication innovation ought to have the option to create protected, solid, and incredible robots with long flying times and negligible communication dormancy.

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T. Poongodi, is currently working as a Professor in the School of Computing Science & Engineering at the Galgotias University, Delhi – NCR, India. She received her Ph.D. degree in Information Technology (Information and Communication Engineering) from Anna University, Tamil Nadu, India. Her current research interests include Network Security, Wireless Ad Hoc and Sensor Networks, Internet of Things (IoT), Computer Networks, and Blockchain Technology for emerging communication networks. Dr. T. Poongodi is the author of over 40+ book chapters, including some reputed publishers such as Springer, Elsevier, IET, Wiley, De Gruyter, CRC Press, IGI global, and 30+ international journals and conferences. She has published 10+ books in the areas of Internet of Things, Data Analytics, Blockchain Technology, Artificial Intelligence, Machine Learning, and Healthcare Informatics, published by Springer, IET, Wiley, CRC Taylor & Francis, and Apple Academic Press. She adopts a universal and humanistic approach in her academic and research works. She has undertaken meticulous scientific studies of emerging issues in several disciplines. She has many years of academic work experience in teaching, and multi-disciplinary research. Professor Dr. T. Poongodi has also received invitations to address international conferences as a keynote speaker. She is a member of The Institute of Electrical and Electronics Engineers (IEEE), IEEE Women in Engineering (WIE), Association for Computing Machinery (ACM), the International Association of Engineers (IAENG), the Institute of Research Engineers and Doctors (IRED), and International Association of Computer Science and Information Technology (IACSIT).

Aradhna Saini, is an Assistant Professor at Noida Institute of Engineering and Technology, Greater Noida, India. She has completed an M.Tech with honors at the School of Computing Science and Engineering at Galgotias University, Delhi – NCR, India. She has completed a B.Tech with honors in Computer Science and Engineering from Rajasthan Technical University, Rajasthan, India. She has taken part in conferences and written book chapters. She is working on Machine Learning and Data Science. The computer languages she is interested in are Python, C, Java, R, and data mining.

Gaurav Dhuriya, is an Assistant Professor at Noida Institute of Engineering and Technology, Greater Noida, India. He has completed an M.Tech with honors at the School of Computing Science and Engineering at Galgotias University, Delhi – NCR, India. He has completed a B.Tech in Computer Science and Engineering from Uttar Pradesh Technical University, U.P., India. He is working on Machine Learning, Artificial Intelligence, and Data Science. The computer languages he is interested in are Python, C, Java, and R. He is well versed in software such as LaTex, MS Word, Tableau, and draw.io.

Vaishali Gupta, is working as an Assistant Professor at the School of Computer Science and Engineering, Galgotias University, NCR Delhi, India. She is pursuing a Ph.D. in the area of machine learning from Indira Gandhi Delhi Technical University for Women, Delhi, India. She completed an M.Tech from Amrita School of Engineering, Bangalore, in 2010. She has 13 years of teaching experience in the field of computer science and engineering. Her areas of interest and research are Artificial Intelligence, Machine Learning, Neural Networks, and Big Data Analytics. She has presented research papers at various National/International Conferences and has also published research papers and book chapters in reputed journals and edited books respectively.

Chapter 2
UAV Cellular Communication in 5G New Radio Wireless Standards

Oluwagbemiga Omotayo Shoewu, Lateef Adesola Akinyemi, and Richard Edozie

Abstract Very recently, unmanned aerial vehicles (UAVs) have aroused the interest of wireless networking researchers. 3GPP's new radio (NR) is the global standard for the 5G air interface. By delivering 5G base stations to underserved areas, UAVs can help improve 5G mobile networks allowing bandwidth-intensive services like extremely high-definition (EHD) video streaming and additional multimedia services. More so, inherent 3D mobility, autonomy, and intelligent placement of UAVs make them ideal for a wide range of wireless applications. This chapter presents and looks at 3GPP updates and new 5G NR features for aerial devices. Furthermore, a use case scenario was considered where secondary users reuse spectrum resource channels of primary users for both uplink and downlink 5G communication. The simulation for a range of frequency between 3400 and 3800 MHz with an input impedance of 50 ohms produced a delivery ratio of UAV for a range of users. The UAV 1 and UAV 3 showed decreasing form at approximately 20 users and flatten up at convergence form as the number of users increases.

Keywords Massive MIMO · mmWave · UAV-to-UAV · Cellular-bound system · AI · Intelligent reprogrammable surfaces · Terahertz-based communications · 3GPP · 5G

2.1 Introduction

The unmanned aerial vehicles (UAVs), often known as drones or aircraft, are devices controlled remotely by pre-programmed operation systems or a person, making them fly unmanned. UAV characteristics, including high mobility, ease of deployment, and most importantly, autonomous operation, make them exciting solutions for a wide range of applications, including various environmental, commercial, and

O. O. Shoewu (✉) · L. A. Akinyemi · R. Edozie
Faculty of Engineering, Lagos State University, Lagos, Nigeria
e-mail: Oluwagbemiga.shoewu@lasu.edu.ng; Lateef.akinyemi@lasu.edu.ng

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military missions. Wireless communications involving UAVs have seen a spike of attention, owing to two ideologies encapsulated by the phrases “what can UAVs do for networks?” and “what can networks do for UAVs?” UAVs enhance cellular networks by hauling base stations (BSs) that can be quickly dispatched, cheaply maintained, and easily maneuvered [1, 2]. Base stations (BSs) carried by UAVs will make available good solutions to some challenges in the cellular communication area, such as the following:

- By guaranteeing better coverage in remote areas and locations.
- Densification of the network regarding steady congested regions.
- Adequate small latency will be reached/fulfilled by avoiding the compression and expansion of video in layers that require higher data rates.

Nevertheless, for UAV-mounted base stations (BSs) to become a reality, several issues associated with UAV-mounted base stations (BSs) should be tackled. The issues needed to be addressed include effective management of mounted UAV-based base station and their effective consumption of energy extended to the working principles of the futuristic network. Hence, the amount of UAVs utilized and deployed for industrial and public benefits will skyrocket in the coming decades [3, 4]. Aside from communicating large amount of data in actual period with base stations, the UAVs should be managed with a practically limitless aerial navigation. This chapter presents a solid manufacturing use which is anticipated and necessitating a robust wireless cellular authorization which explains how 3GPP plans enable it and some future scenarios. Looking at the development of UAVs, an increase in size of UAVs ranging from civil purposes for site surveillance to military uses is observed. Similarly, in terms of the amount of data they generate while transiting to and from the ground control stations in real-time is observed. We will look at how concrete industrial UAV application is expected to necessitate a solid and stable wireless cellular connection and then explain its future uses. Hence, the following are some factors influencing UAV communication system.

2.2 Factors Influencing UAV Communication: Drawbacks

Because UAVs move swiftly and flexibly, it is hard to communicate with them while they are in flight using a wired connection. Even when using a wireless connection, there are several drawbacks, such as the following:

(i) Spectrum/bandwidth efficiency: The bandwidth efficiency of a communication system means that the piece of information rate which is capable of transferring over a range of assigned bandwidth referring to the transmission of data is critical. When it comes to data transmissions, bandwidth is critical. A greater data rate allows for faster data delivery [5].
(ii) Tolerance: As soon as the UAVs travel through the air, it is required of UAVs to possess energy to make them stay aloft, and this energy can be regarded to being

limited as a resource mainly for tiny/miniature UAV systems. Furthermore, in the case when transmission of data is carried out by UAVs, the available/used energy in the aircraft determines the range and transmission rate. There are various areas that could be concentrated on in the military application field, such as relay capabilities and data security [6, 7].

Despite the factors influencing UAV communication system as highlighted above, there are several benefits to using wireless networking with UAVs which are summarized as follows:

(i) Owing to LOS propagation technique and requirements, UAVs provide high on-demand service and communication that is of high quality.
(ii) UAVs serve as an end user of sensing devices and data integration which are dynamically placed/situated in any location that appeals to the environment.
(iii) UAVs modify flying parallel routes/tracks in order to enhance networking wirelessly and thereby resulting to good communication system.
(iv) UAVs are capable of carrying and conveying massive amounts of data [8].

2.3 Literature Review

Researchers have been proposing and developing strategies to address technical concerns and obstacles in UAV systems. Controlling single and many UAVs is one of these strategies. Hence, this section gives a comprehensive literature review regarding UAVs and its applications in wireless communications. In [9], the authors worked on the analysis on multiple-antenna techniques for UAV communication systems. The analysis was further extended to different aspects of communication systems such as multiple-antenna schemes. Furthermore, it was concluded that enhancement of the cellular communication system to UAVs could be achieved via the use of multiple-antenna schemes. Additionally, in the work [10], the study was focused on the application of cell-free massive multiple-input multiple-output (MIMO) in fifth-generation (5G) and beyond 5G wireless networks as a survey. In this work, the significance of the UAV as an enabler in 5G network system and application was highlighted in great detail. In [11], the authors also canvassed and highlighted the significance of UAV communications by employing multiple antennas as veritable scheme in military application and other human endeavors as far as communications system is concerned. Apart from the works of authors as stated above, the authors in [12] did carry out research on the significant role of the future of technologies in securing UAV-inspired autonomous devices such as vehicles. More importantly and specifically, the authors centered their work on data-based security in which the blockchain technology was leveraged on as the basis of the work. Hence, the significant roles of other technologies such as artificial intelligence to provide support in terms security to the UAV-based scheme were highlighted in that work. Some far-reaching future works and challenges were put forward as well. Also, in [13], a similar work to UAV was carried out. In that work, it majorly focused on the joint communication and trajectory optimization for multi-UAV-inspired mobile internet of vehicles (IoVs). In summary, the authors were able to expertly and diligently obtain striking results numerically regarding the performance of the use of the multi-UAV-based mobile IoVs using joint communication and trajectory optimization approach. More so, in [14–17], the authors worked and highlighted the importance of UAV-based system using various AI and machine learning (ML) techniques in 5G and beyond 5G. Moving forward, techniques such as AI, ML, and federated learning (FL) in 6G technology will be the essential drivers and enablers in this era called 6G. Hence, there is a need to key in to these technologies to autonomously control devices and seamlessly make human work less laborious.

2.3.1 UAV System Functions and Requirements

The purpose is to communicate between small unmanned aerial vehicles (UAVs), referred to as "mini" UAVs, using wireless technology by considering several essential elements and realistic settings [9]. In terms of range and altitude, a tiny UAV can fly for less than 10 km with an angle of no more than 300 m. It is estimated that the power will last around 2 hours. The mini UAV can be loaded with up to 30 kg of cargo total weight. Text-based data, such as mission directives or flight status information, is used to send the information. When another unmanned aerial vehicle (UAV) receives a command, it responds by sending feedback [10–12].

It is vital to the software the UAV's onboard HW components. It offloads them at the network's edge to optimize UAV-based BSs' autonomous energy-efficient mission planning by leveraging modern communication networks' edge and low latency capabilities and developments in UAV technology [13–15]. Using this approach, high computational flight data may be analyzed in real time to optimize autonomous flight operations, including recharging, moving, and hovering. These actions together make up an autonomous mission.

Mobile networks' fifth-generation (5G) system offers low delay and allow component softwarization. The splitting of these among nodes in terms of computing capabilities and network edges (eMBB) support MEC natively at higher gigabits per second in terms of speed with support of URRLC and incorporate ground and non-terrestrial networks such as satellites, allowing advanced optimization techniques to be used in real time throughout the mission (such as flying level, wind speed, battery status, and distance from charging base are all variables to consider) [16–20]. Exercising these complex optimization techniques allows the flight controller to make on-the-fly best choices for defining the flight plan, which reduces superfluous actions and notions by the UAV while also ensuring an effortless hovering fight, which reduces energy consumption. To assist the relevant businesses in their ongoing development, efforts at standardization efforts are gradually integrating UAVs with 5G networks [21, 22].

However, the UAVs should travel at around 10 meters per second (maximum). It is well known that data decreases with increasing distance. A data greater than 100Kps is required for optimal performance. To simulate communication, one network device would be selected. It is necessary to assess the relevant demands regarding the number of bits employed per second, dependability delay, and speed supported by UAV and the height and location/siting precision. Following sequence of introductory section, an assessment will be carried out via the following section. The assessment will lead to a solution for selecting the appropriate protocol and equipment for the real-life task. The previously terrestrial-based cellular system is rapidly affected with aerial users and innovative manufacturing UAV ones [23, 24].

The 3GPP has highlighted use cases which would enable 5G. It is categorized into three types:

(a) Command and control links (C2C)
(b) UAVs as radio access nodes
(c) Payload data links

(a) *C2C (command and control) links*: From now on, commercial UAV owners will begin employing command and control links to provide delivery of goods ordered by the client's houses. To connect with the UAV, a controller can be used provided that UAV and the controller are 5G compliant. A set of paths will be provided by UAV traffic management (UTM) to owners once they have been granted permission to fly their UAV. A UAV owner may be asked to direct the UAV at times. This could be before reaching cruise altitude, delivering a shipment, or witnessing a roadside accident [25–29]. Therefore, the uplink-based video feedback from the UAVs employs direct steering control mechanism. They differ depending on the nature of the controller whether it is visibly based line of sight or not. The UTM can further fly autonomously, providing paths in geometrically based four-dimensional (4D) polygon structure in which the UAV sends back recurring and at fixed intervals location data for tracking purposes and applications [30–32].
(b) *Unmanned aerial vehicles as enabler and radio access points*: In some cases, for example, observation and surveillance on borders, artificial aid such as emergency with base stations (BSs), can be immediately deployed to provide radio access to the surrounding area. The same could be true for coverage of hotspot events, in which the demand for broadband services spikes unexpectedly. In spite of the fact that particular requirements regarding this scenario are yet to be fully established by regulatory bodies such as 3GPP, it is anticipated that one will be able to combine by demanding C2C and data requirement (payload) [33, 34].
(c) *Payload data links*: UAVs are projected to provide consumers with virtual reality experiences using video live transmission such as through a 360-degree spherical-view cameras that will capture and upload 8K video in real time to a

cloud server. Users can watch a live video broadcast using remote VR glasses. This use case requires precise placement in densely populated areas, high bit rates, and low latency. In densely populated areas where standard satellite technology may be inaccurate, a superfluous location of counterbalance may trigger and initiate system of collision, thereby reducing the performance of the UAVs. Hence, a measure is expected to be used by UAVs to counteract this threat, with a four-way inspired 4K complete-angle camera data being transmitted to an AI controller that would then issue timely control instructions [34].

2.3.2 UAV Communication Architecture

For UAVs to be used, they have to connect to infrastructures such as network backbones. The two communication modes of UAVs that best describes the architecture of UAVs are as follows:

(a) U2U (UAV-to-UAV)

Collaboration is a crucial component of UAV systems in network environment which support and offer services relating to components. It is significant because UAV outfits with various technologies to communicate with other types of UAVs as well as robotics. Because in aerial flight, UAVs essentially in mobile communication serve as MANET. Hence in a MANET environment, every single UAV is regarded as a mobile point/node. Furthermore, an open system interconnection (OSI) framework is commonly employed in research that comprises the open system interconnection (OSI) model, namely, physical, data link, network, transport, and application stages. Additionally, the application incorporates both presentation and session layers. Therefore, the common and generic IEEE 802.11 protocol (a set of rules) can be employed in both layers, namely, physical and data link [39–42].

(b) U2I (UAV-to-Infrastructure)

Another significant part of UAV network concept is the UAV-to-infrastructure (U2I) communication system. Cooperative UAV devices are intended to relate and interact with other devices using UAV-to-UAV (U2U) protocol. Furthermore, data interaction internet and infrastructural network (IN) capabilities are required. This is employed for gathering U2U data from alternative forms of UAVs, thereby exchanging them with the IN using wide wireless area networks (WWAN) and wireless local area network (WLAN) protocols accessible in that geographical area [43].

2.3.3 Consideration of Factors in UAV Communication System

When UAVs communicate, some factors should be considered, including the following:

(a) Embryonic/starting approach and selection of cells
(b) Challenges such as interference experienced by UAVs

(a) Embryonic/Starting Approach and Selection of Cells
Cellular-connected unmanned aerial vehicles (UAVs) must connect to the network firstly to receive and transmit packets of payload data. Cellular base stations (BSs) emit synchronization signal blocks (SSBs) on a regular basis to aid in the finding of their surroundings. Up until the introduction of the long-term evolution (LTE)-enhanced pro networks, the BS antenna pattern is employed to determine the value of the radiation of SSB signals. In a typical cellular network with downtilted base stations, it shows that devices flying higher than the base stations might only detect SSB signals via the sidelobes of the antennas on the BSs. Its preceding behavior does not only present a significant issue when UAVs seek to connect to the network for the first time, but it also presents a significant challenge when UAVs are flown at normal speeds and required to select and resect their serving cell [44].
(b) Interference Challenges
Once UAVs have been connected to the network, the network must ensure that the signal quality is consistent and sufficient to allow for reliable C2 and data transmissions to take place.

2.4 Impact of 5G in UAV

It is possible to provide stable connectivity for flying vehicles while simultaneously minimizing consumption of power, weight and scale, and requirements while also improving UAV multimedia provision. 3GPP has stated that the new 5G core networks would use cloud-based service-based architecture (SBA). The SBA will encompass all the future network (5G and beyond) services and identity and security, session management, and end-user traffic accumulation, among other things. It underlines the need of network function virtualization (NFV), with capabilities positioned with MEC infrastructure. The fifth-generation core network's major goal ensures segregation of the control plane from the data plane including network characteristics.

5G networks may be able to do this. This is achieved by using multilayer networks and multiple access channels. To achieve this, it uses a more intelligent radio access network (RAN) design that is not constrained by base station closeness or complexity of the design. Part of the technical parameters that are used to keep 5G networks is contained in the preceding infrastructure complexity.

(i) The delay in the radio access network (RAN) is significantly reduced by 5G NR when paired with MEC [20] potentialities in the proximity of the radio facility. It allows for ultralow latency on the C2 link. The C2 connection can achieve low delay (latency) by using MEC [20] near the radio network. Since MEC is closer to the computer and the end-users, it provides benefits like high bandwidth, low latency, and immediate access to RAN data. The UAV pilot version in terms of drones will also be mounted at the MEC, ensuring extremely minimal/small delay communication for the C2 link, as envisaged in this book chapter. Hence, the nature of the software used for offloading and piloting at the computing node of the network reduces additional energy consumed by the UAV, making it more energy-efficient.

(ii) Software-Defined Network and Network Function Virtualization

Network function virtualization (NFV) that softwarizes equipment network functionalities like bridges, firewalls, and routers establishes as virtualized occurrences alongside the fifth-generation (5G) network typically at its boundaries using the MEC physical structures. The SDN is an additional 5G promoter that is being developed. According to the findings of this research, the virtualization process has an impact on a variety of parts which are removed from the UAV, including C2 parts and the pilot. It is common for the NFV to be used alongside SDN that adds foundation for energetic and enterprising broadcast of network points or nodes as the case may be, thereby allowing for disconnection and detachment of both the data plane and control planes to the overall network [21].

(iii) Network slicing (NS): The NS allows numerous virtual network system to be run concurrently over an allocated physical resource which is referred to as a virtual network fabric. To meet the performance demands of a wide range of networks and devices, such as those used in athletic events, festival parties, and other social gatherings, 5G incorporates three kinds of novel cases: URLLC, eMBB, and enormous machine-type communications (mMTC). As a result, NS is a useful function for unmanned aerial vehicles. Hence, it does create a safe slice of flying vehicle control that does not rely on ground contact with payloads, like video broadcasting to the surface.

(iv) Frequency and 5G spectrum: The UAV connections regarding 4-GHz long-term evolution has already been extensively explored, while 5-GHz new radio (NR) provides significantly more capabilities. The current 5G radio technology utilizes a number of different frequency ranges (NR). Generally speaking, mmWave is defined as the range of frequencies from 30 to 300 GHz which can be used to communicate between and unmanned aerial vehicle (UAV) and a distant command center with high capacity and low delay. Hence, 3GPP 5G NR standard has become a focal part of the standard owing to the great possibilities of communication in millimeter wave (mmWave) band range and other frequencies usually above 6 GHz. However, communicating system in mmWave regions and other frequencies above 6 GHz could be regarded as inefficient on long-distance communication system. Therefore, the subdivided 6-GHz spectrums are often reused in 5G in more densely populated locations, and these frequencies could be employed to enable long-range independent beyond-visual-line-of-sight (BVLOS) flights.

(v) Transmission in form of beamforming: The particular characteristics of unmanned aerial vehicles (UAVs), for instance, their 3D-spaced nimbleness and their significant power, scale, and weight limits, provide new challenges for 5G broadcasting communications. A beamforming technology is necessary to improve the capability of signal reception in UAVs, and 5G provides this technological benefit. It is therefore possible to assess the greatest efficient communication channel to users by using 5G MIMO-based system.

2.5 Connections Linking the Different Nodal Points of the UAV-Based Communication System

Figure 2.1 depicts the different protocols employed at various connections in communication system such as U2I and U2U and different linkages themselves. It is possible to utilize protocols such as IEEE 802.11 series in U2U link because it is a well-established standard that has been evolved over the years [43].

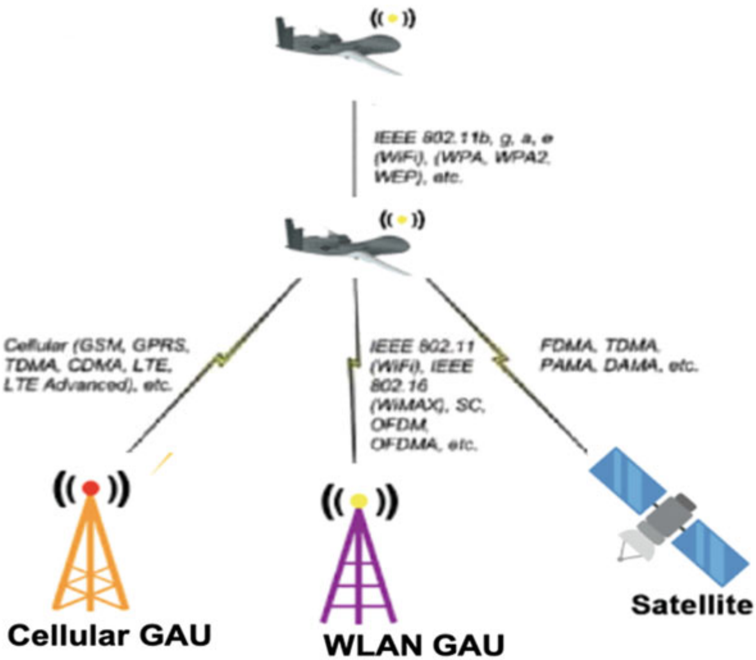

Fig. 2.1 The system architecture of UAV-based system

2.6 UAV Structure Functionalities, Demands, and Services

It is important to underline the cooperative networking aspect of the system demands since communication in such a system and associated application is a critical component of the communication process.

(i) UAVs Are Able to Communicate with One Another

Collaboration is critical in UAV-based systems, especially in networking service and support components. Therefore, it is significant because UAVs will function with various networking technologies. Also, most of the unmanned aerial vehicles find it difficult to be in touch directly with one another or the BS. Operationally, unmanned aerial vehicles (UAVs) exhibit a varied range of uses with different communication and networking demands. Various communication channels may also be offered. Cellular, satellite, and line-of-sight communication links are examples, as they are real-time mobile-based ad hoc networks and latency-tolerant networks with data-transmitting devices [34].

(ii) Sensing with UAVs

Many collaborative UAVs are applied to detect an area or examine a network's infrastructures utilizing sensors such as heat sensors and among others. Hence, it is envisaged that these service-based applications will necessitate effective-detection among a large number of UAVs. Because individual UAVs can perform some sensing tasks, it is more structured and dependable to deploy a group of UAVs to coordinate operations and collect accurate and reliable data [34].

(iii) Acting with the Assistance of Unmanned Aerial Vehicles (UAVs)

UAVs are required for some applications, such as agricultural and military missions. Several unmanned aerial vehicles (UAVs) can work together to finalize tasks in these applications. In agriculture, for example, a large number of unmanned aerial vehicles (UAVs) could quickly spray pesticides or seed large fields. The autonomous collaboration reduces (or eliminates) overlaps and speeds up task completion without human intervention.

(iv) Unmanned Aerial Vehicles (UAVs) as Transmission Relay Points

Unmanned aerial vehicles (UAVs) can be represented as relay nodes, connecting detached MANET clusters. Nodes from different disconnected clusters can communicate using a UAV. To communicate, the UAV is placed in between the two clusters. In large MANETs, one or more unmanned aerial vehicles can perform this function, increasing communication efficiency and dynamics. This method allows a MANET to span a large geographic area, but depending on the usage, the nodes may need to be clustered in different locations. If multiple UAVs are required, effective algorithms that enhance UAV points' placement must be developed to reduce the number of UAVs demanded while providing strong and dependable connections for all MANET clusters.

(v) Unmanned Aerial Vehicles (UAVs) as Network Gateways

In remote or disaster-ravaged locations, unmanned aerial vehicles can connect to backbone networks, internets, or infrastructural communication. This is useful in disaster-stricken or remote areas. This function can help restore cellular, internet, or satellite coverage when it is severely or critically needed. In terms of search and rescue, this connectivity could help. Unmanned aerial vehicles (UAVs) can be employed to perform this task quickly and efficiently.

(vi) Data Storage Using Unmanned Aerial Vehicles (UAVs)

The following reasons are important even though some UAV applications will transmit data collected directly to the base station. First, because the acquired data requires a lot of bandwidth, it may not always be available for transfer from UAVs to base stations. There is no need to upload data collected to the base station immediately because it will be accessed and processed after the operation. The collected data can be saved in the onboard storage devices. This reduces the amount of time spent moving data back and forth among the base station and the sensor. Unmanned aerial vehicles can be homogeneous or heterogeneous in terms of storage and data collection. Depending on the application, UAVs may collect the same or different amounts of data. If the amount of data collected by different UAVs is not equal, or if the storage capacity of the UAVs varies, then a collaborative data storage method involving multiple UAVs is required.

(vii) Data Processing Using Unmanned Aerial Vehicles (UAVs)

High-performance computing applications such as video processing, high-resolution image processing, pattern recognition, stream data mining, and online task scheduling can be performed by collaborative unmanned aerial vehicles (UAVs) equipped with high-end computer units. A single-computer component in a single-UAV or multiple computer systems in multiple UAVs can perform high-performance data processing. To be successful, the latter scenario requires that the available processors in the sky efficiently exploit one of the distributed processing methodologies. This is critical when UAVs are flying in remote locations far from base stations and immediate action is required. On a battlefield, an unmanned aerial vehicle (UAV) may be needed to identify an enemy unit near friendly units. Pattern recognition and image processing are required to quickly locate and destroy the adversary. This process cannot afford to wait for data to be sent to a remote base station and then receive feedback. It must be completed immediately. The nearby UAVs could thus coordinate their efforts to finish the analysis and respond appropriately.

(viii) Control That Is Distributed Rather Than Centralized

Many unmanned aerial vehicles require a unique set of real-time control operations. Different control techniques are required for the coordination of many unmanned aerial vehicles (UAVs), efficient use of UAV resources, safe operations, and fault tolerance. Centralizing these tasks is difficult. This is for three reasons. Because control signals may not always connect UAVs, not all UAVs are connected to the GCS at all times, and a centralized control system may act as a communication and security bottleneck [42, 44]. For all of these reasons, distributed and collaborative controls are preferable to centralized controls.

Reduce the reliance between the access network and the core network (CN) and modularize the function architecture to enable us to achieve effective and scalable network slicing. However, these network functions (NFs) include the following:

- The access and mobility management function (AMF) manages access and mobility.
- The session management function (SMF) sets up sessions following policy.
- The data traffic for users is being handled and forwarded by the user plane function.
- The authentication server function (AUSF) handles the authentication part of the system.
- The policy control function (PCF) manages the charging rules and policy.
- The unified data management function (UDMF) unifies subscriber information for both fixed and mobile access networks.
- The network slice selection function (NSSF) allows users to select a network slice instance.
- The network repository function (NRF) manages the registration and finding of NF services.
- The network exposure function (NEF) is in charge of exposing capabilities and events.

2.7 Consequences of Spectrum Sharing

In an underlay configuration, UAVs are only used to access 1 MHz. The power control factor of UAV has little effect on the overlay because both UAV signal power and overall interference increase. Using 5G core SBA, GPP implemented a reference model for unmanned aerial vehicles (UAVs) based on 3GPP TR 22.825 that allows controllers to operate UAVs outside of the visual line of sight (BVLOS). The 3GPP scheme thus benefits UAVs in the areas of authorization, coverage, monitoring, and quality-of-service support, among other things. The 3GPP design also enables UAS traffic management to connect to UAV and query its identity and meta-data (e.g., general safety measures and agencies).

2.8 Artificial Intelligence (AI) Modeling UAV Communications

One of the key components of future 6G networks will be the widespread use of AI frameworks across all aspects of cellular system architecture [43]. We describe two well-known and unique use cases where AI frameworks greatly benefit UAV cellular communications.

(i) UAV Mobility Management Using Artificial Intelligence

A unique and strong solution for mobility management assistance is discussed in Sect. 2.1. While LTE includes new radio resource control signaling for this purpose, the problem's complexity and dynamic nature necessitates the application of machine learning and artificial intelligence technologies. In this context, reinforcement learning appears to be well suited for optimizing handover decisions and reducing unnecessary handovers.

Consider another scenario where a flexible Q-learning algorithm is used to balance the number of handovers per UAV with their observed RSRP values (to be increased or expanded). The algorithm makes decision on whether or not a UAV in a certain position and trajectory should perform a handover.

- Aerial Channel Modeling Using Artificial Intelligence

Despite their importance, non-ray-tracing accessible channel models regarding UAV communication system in the millimeter wave band are unavailable for practical use. For example, current 3GPP flying-based channel models are only scaled for frequencies under 6 GHz. The first measurements-based mmWave aerial channel model is still statistically unexploited in relation to the multipath channel, which is important for enabling wireless coverage in various situations. Other publications lack a 3D spatial channel model and thus are unable to conduct a comprehensive assessment of the performance of UAVs connected to mmWave networks.

Because millimeter wave systems depend essentially on directed communication at the transmitter and the receiver, a channel model must lay out empirical descriptions of all channel characteristics. These statistics must include the total path components, arrival and departure angles, and gains and delays, among other things. Modern data-driven machine learning technologies are becoming more appealing for this problem. For indoor mmWave channel modeling, neuronal networks produce values that indicate a deviation from the trained set of data almost identical to learning-based planning and prediction tools.

Data-driven machine learning algorithms are appealing because they allow for unique and painstaking/thorough performance evaluations of unmanned aerial vehicle (UAV) communications. Artificial intelligence-based methods could also generalize standard mobility management schemes, allowing for new UAV-aware network design and operation options. It also includes a large ray-tracing-based urban dataset for training and a 3D spatial channel model derived from the training data.

2.9 Infrastructure for 5G Experimentation

Given the variety of advancements that 5G offers to UAVs, this chapter focuses on the provision of 5G MEC capabilities, which allow a UAV to offload the softwarized UAV flight plan and controller at the edge of the network, thereby increasing the energy efficiency of the UAV mission while also supporting sophisticated and resource-demanding autonomous flight plans (e.g., AI driven) for BVLOS missions. Abstract: Detailed information on the 5G infrastructure, as depicted in Fig. 2.3, is provided in this section. This infrastructure was used for the purposes of this paper in order to realize the deployment of the softwarized flight controller at the edge of a 5G network and to further validate the feasibility of providing C2 connectivity to a UAV over 5G.

2.10 Infrastructure for the Mobile Core Network

The Amarisoft core network installed in the 5G testing facility was employed in this book chapter. The core is compatible with 5G NR Release 15 for 5G SA mode. Connectivity with gNBs is achieved by the standard NG interface, which employs the NGAP and GTP-U protocols to achieve this. Built inside the 5GC are modules for handling user-experience procedures and allowing direct access to the internet protocol (IP) network, including AMF, AUSF, SMF, and UPF. With integrated SGW, PGW, and HSS for 5G NSA mode, the core implements the MME element of the network. It also supports numerous eNBs over a standard S1 interface (S1AP and GTP-U protocols). This component of the architecture supports UE operations such as authentication, security setup, detach, attach, updating of tracking field, service access, radio-bearer establishment, and paging. The usage of USIM cards with the XOR, Mileage, and TUAK algorithms can be used by UEs for identity authentication.

2.11 Infrastructure for 5G Radio Access Networks

Amarisoft provides RF front end hardware in the form of PCIe SDR boards, which are operated by the NR. Cells can be run on the eNB/gNB simultaneously, and each cell can be configured individually while sharing the same S1 interface with the core network. The newly acquired system features three PCIe SDR cards, which allow it to support up to three LTE networks simultaneously: 2×2 cells or two cells, the first of which utilizes LTE technology and the second of which uses 5G technology.

It is a fully software-implemented LTE/NR base station (eNodeB/gNodeB) that runs on an x86 Linux-based host and supports up to 100 simultaneous connections. The host generates a baseband signal, which is transferred from the digital to analog

Table 2.1 Simulation parameters and values

Ports	4 × 4 MIMO 3400–3800 MHz ports
Range of frequency	3400–3800 MHZ
Sub-bands regarding peak gain	7.7 dBi
Gain	7.3 dBi
Beamwidth for Azimuth at −3 dB	72.8°
Beamwidth for elevation angle at −3 dB	71.5°
Downtilt value	7.7 dBi
Peak measurement for CPD	7.3 dBi
Ratio of front to back at 180°	73°
Isolation for port-to-port cross-polar	72°
Standing wave ratio	7.7 dBi
Input power continuous wave	49 watts
Angle of polarization	Dual-based polarization 45
Input impedance	50 Ohms

conversion to a radio front end via the radio interface. For the reception, the reverse is done. The RAN communicates with the LTE core network via the standard S1 interface and with the 5GS core network via the standard NG interface, both of which are industry standards.

Furthermore, the NR is compliant with Release 15 and can support both FDD and TDD transmission modes. The bandwidth configuration ranges from 5 to 50 MHz, with MIMO variants available for up to 4 × 46 channels. For the downlink transmission channel, modulation schemes up to 256 QAM are supported, and for the uplink channel, modulation schemes up to 64 QAM are supported. The spacing between data subcarriers can be varied between 15 and 120 kHz.

Last but not least, an eight-port small-cell antenna was employed, with four wideband ports covering the frequency range of 1695–2690 MHz and four wideband ports covering the frequency range of 3400–3800 MHz. Two distinct sets of 4 × 4 multiple-input multiple-output (MIMO) functionality are supplied by the small-cell antenna over the frequencies of 1695–2690 MHz and 3400–3800 MHz ports, with the 4 × 4 high band ports for 3400–3800 MHz being provided in Table 2.1.

2.12 Numerical Simulation Results

This section highlights briefly the numerical results obtained via simulation. Numerical simulation and results are depicted in Fig. 2.2, indicating the delivery ratio of UAV for a range of users. This simulation focuses on the energy efficiency and mean total power of a single-tier 5G UAV network communication network comprising a set of primary and secondary users. The results are presented in Figs. 2.3 and 2.4, respectively, for energy efficiency and power. The aim is to assign secondary users spectrum resource which minimizes the primary users' energy cost.

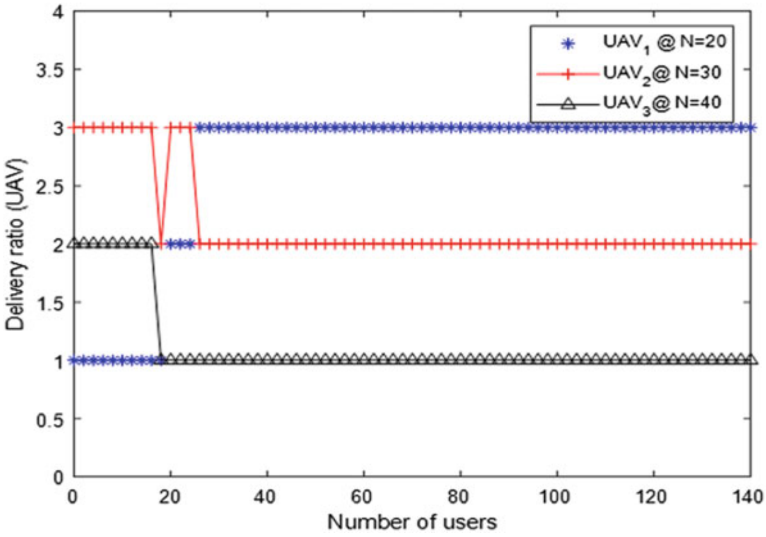

Fig. 2.2 Delivery ratio for UAV simulation results against the number of users

We consider a use case where secondary users reuse the spectrum resource channel of primary users for both uplink and downlink communication. Hence, our energy-efficient resource allocation model for future wireless network is implemented as follows:

2.13 Interpretation of Numerical Results

Figure 2.2 shows the graph of delivery ratio for UAV against the number of users deployed to enjoy offered services by the system. It can be inferred that UAV 1 and UAV 3 show some decreasing form at approximately 20 users and flatten up as convergence form as the number of users increases. Additionally, in Fig. 2.3, the mean total energy efficiency (EE) of the network is plotted against the radius of the deployment region of the respective UAV. In this work, the analytical (mean EE) is employed, and one of the metaheuristic algorithms called genetic algorithm (GA) is applied to evaluate the performance of this study. It is further observed that both the analytical and GA schemes follow the same pattern with a GA having a slim comparative advantage over the analytical approach. This may be due to some parameter settings during the simulation process.

Furthermore, in Fig. 2.4, the mean total power of the network is plotted against the radius. At approximate 50 m, it was observed that both schemes intercepted and afterward diverged. This sudden drift can be associated with the settings of parameters during the simulation. In our future study in this area, we intend to investigate

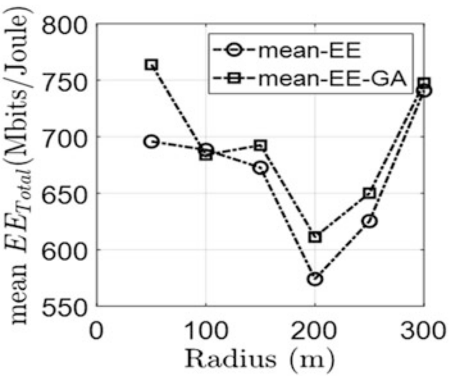

Fig. 2.3 The simulation results of delivery ratio for mean total energy efficiency versus radius

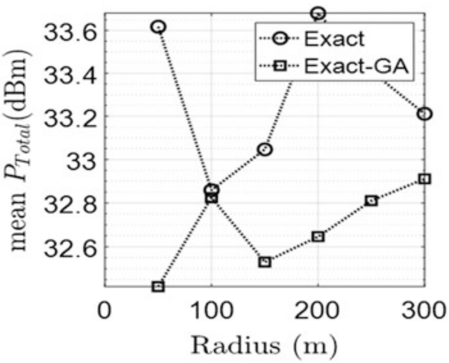

Fig. 2.4 The simulation results of delivery ratio for mean total power versus radius

further and compare more metaheuristics such as the ant colony approach, particle swarm optimization (PSO), grey wolf scheme, and so on depending on the nature of the formulated problem in order to make informed conclusion regarding this.

2.14 Conclusion

While progress has been made in the knowledge of unmanned aerial vehicle cellular communications over the previous few years, there are still numerous fundamental hurdles to overcome. In this chapter, both academic and industrial viewpoints have been combined, embarking on a journey that brought us from 5G to 6G UAV application cases, needs, and enabling technologies, and then back to the beginning. It was demonstrated, through demonstrable results, how NR advancements will significantly assist in meeting the rigorous control and payload data requirements of network-connected unmanned aerial vehicles (UAVs) throughout this decade. Among these are beamformed control signals, which make UAV cell selection and handovers easier when compared to sidelobe-based association signals. mMIMO in conjunction with UAV-aware null steering or UAV-based beamforming is required to ensure stable cellular connectivity in both ultrawideband and dense ultra-high-density scenarios. Surprisingly, NR mmWave networks can also provide adequate coverage of the sky, owing to a favorable mix of antenna side lobes and strong reflections, as demonstrated in this chapter.

A variety of communication protocols and technologies were also examined, including those employed in different connections and layers of a UAV-based networking architecture. In addition, we presented a case study in which unmanned aerial vehicles (UAVs) were used to collect data from a WSN in an efficient manner. More particularly, we examined the usage of unmanned aerial vehicles (UAVs) for data gathering in various WSN topologies, such as LSNs, cluster and geometric WSNs, and other topologies. This book chapter also looked at some of the data gathering tactics employed during the process. As unmanned aerial vehicles (UAVs) continue to develop rapidly, it is projected that they will be employed in a growing variety of applications impacting every part of our lives, including government, industry, the environment, and the general public. Efficient and seamless communication in UAV-based networks is critical to ensuring that the usage of unmanned aerial vehicles (UAVs) and their safe deployment and operation achieve the levels of efficacy and success predicted and sought.

With a shift in gears to the next decade, equipping air taxis with sufficient data transfer capacity and a minimal lack of connectivity will necessitate adopting of a 6G paradigm shift by 2030. NTNs have the potential to solve the unavoidable ground coverage gaps that can currently imperil a UAV operation, while also handling the more mobility UAVs across their vast coverage area. Cell-free architectures and reconfigurable smart wireless environments have the potential to convert interference into useful signal and increase UAV coverage, resulting in a huge improvement in worst-case performance and, consequently, improved overall reliability. AI is already being used to enable aerial channel modeling. It will also aid in the design and operation of optimal UAV-aware networks in the future, such as for mobility management. Finally, THz frequencies can provide large bandwidths for unmanned aerial vehicles, enabling MIMO even in low-bandwidth environments. Since adopting these technologies to UAVs is a difficult task, this chapter also identified several unsolved issues and presented well-founded recommendations for much-needed future research. In the expectation that this chapter will stimulate fresh research and technological advancements, the wireless community will be one step closer to the fly-and-connect era.

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Oluwagbemiga Omotayo Shoewu, studied BSc Electronic and Computer Engineering and has a MSc in Electrical Engineering and PhD in Electronics and Telecommunications Engineering. He also studied postgraduate diploma in Education. He is a Member of the IEEE and IET, Founder of Wireless Communication Research Group (WCRG) at the Lagos State University, Lagos, Nigeria. He is pioneer in radio wave propagation for cellular networks in dryland and wetland terrains and wireless communication systems design. His research has influenced many international researchers. He and his students invented the SOUP, SPOUSE, and BASKET mobile applications for wireless communication systems.

Lateef Adesola Akinyemi, is a lecturer and researcher of electronic and computer engineering at the Department of Electronic and Computer Engineering, Faculty of Engineering, Lagos State University, Lagos, Nigeria. He obtained a BSc (First Class Hons.) Electronic and Computer Engineering (Computational Electronics) at Lagos State University, Lagos, Nigeria; a Master of Science in Electronic and Computer Engineering at Lagos State University, Lagos, Nigeria, and a Master of Science in Electrical and Electronics Engineering (Communication Engineering Option), University of Lagos, Akoka, Nigeria; and a PhD in Electrical Engineering, Department of Electrical Engineering, Faculty of Engineering and the Built Environment, University of Cape Town, Western Cape, South Africa. His research areas are wireless communications (radio resource allocations management, optimization algorithms, heuristic algorithms and proof of concepts and its applications, computational electronics and analysis, wavelets and frames, electromagnetic fields and waves, numerical techniques (SFDM, CFDM, DFT), modelling and simulations of quantum-inspired nanoparticles and devices, microwave engineering and antennas, machine learning and data science).

Richard Edozie, is a graduate from Lagos State University, Nigeria, where he studied BSc Electronic and Computer Engineering. He was also an undergraduate research assistant with the Wireless Communication Research Group (WCRG) at the Lagos State University, Nigeria. He is a Member of the IEEE and has publications in the area of Wireless Communications.

Chapter 3
5G NR Massive MIMO for Efficient and Robust UAV Cellular Communications

Yasar Moidutty, P. Ihsana Muhammed, and N. M. Sreenarayanan

Abstract In the latest reviews, a driverless automated engine has obtained extensive citation toward the smooth movement of equipment, enterprise, and study societies because of the fast boom in a wide variety of electronic hardware. Especially, driverless automated engines are getting forced toward offering an improved strategy to dependable and cost-powerful Wi-Fi connectivity toward the range. The growth of driverless automated engines will have seemed like an opportunity to supplement toward present mobile structures, to reap better passing performance along with stronger insurance in spite of the carriers of 5G. Anyway with large band spectrum for huge wireless communication devices will be a great barrier for futuristic device to pass messages in present scenario. By providing various transmission path way for the communication of machine to machine systems and other vehicular activities it is going to be high demand for the upcoming wireless connections bands to provide proper channel for future approaches. So within the limits of previous communication technologies, the 5G spectrums must provide a large area in the field of vehicles for its wireless network transmissions, various transmitting methods will be additionally made in the manner toward the great connectivity of driverless automated engines to help Wi-Fi-limited providers for destiny fifth-generation and past Wi-Fi hardware. Therefore, cutting-edge achievements withinside the upgradation of 5G unused spectrum communications into supported vehicles through Wi-Fi networks. With higher concepts, methods to categorize the present studies' troubles are projected, through thinking about various contemporary solutions. Therefore, it offers short assessment of fifth-generation communications for driverless automated engines supported by Wi-Fi connectors

Y. Moidutty
Artificial Intelligence & Data Science, Royal College of Engineering & Technology, APJ Abdul Kalam Technological University, Thiruvananthapuram, Kerala, India

P. Ihsana Muhammed
Computer Science and Engineering, Royal College of Engineering & Technology, APJ Abdul Kalam Technological University, Thiruvananthapuram, Kerala, India

N. M. Sreenarayanan (✉)
Computing Science and Engineering, Galgotias University, Greater Noida, India

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using various aspects, i.e., major hardware design benefits along with demanding situations in addition to capability types of equipment. So, with the design at the mentioned method, similar upgradation must come with the element through the present- day troubles, answers, and grounded demanding situations in a rising area on 5G UAV designs.

Keywords Dynamic spectrum sharing

Acronym

DSS Dynamic spectrum sharing

3.1 Introduction

In order to exceed the limits of networks, it needs to exaggerate the conditions of networks of virtual abilities. Therefore, it must do a great experiment in the field of virtual resource spectrums.

Here the study sets out to achieve the following objectives: enlighten the audience on an overall view of UAV communications, evaluate MIMO technology (spatial multiplexing), and input toward high-speed data efficiency in a 5G network

By setting up 3GPP (third-generation partnership project) telecommunications protocols, the 5G NR properties clear how 5G NR edge devices (modules, phones, wireless connectivity, and connection protocols) and 5G NR network infrastructure (small cells, base stations, and other Different Radio Access Network equipment) send and receive data. So, it has to find the method of using radio waves to send data to each other [1, 14]. Less latency than previous radio access technologies must be preferred. The 5GCN improves the 5G networks' [2, 4] whole performance. However, 5GCN is not a radio access technology like 5G NR, but rather connectivity. It allows access to other technologies like LTE, 3G, H+, etc [3, 12].

UAV describes the connection of sensors with the internet, between the connections in cities and villages. It also determines the connection of uploading and downloading, huge areas, and even over large machines.

OFDM LTE technique is a multicarrier scheme in which a carrier frequency is subdivided into subcarriers. These subsets of subcarriers are transmitted simultaneously at different frequencies to each receiver. Carriers are closely spaced to one another; data is carried at a low rate and is placed orthogonal such that the carrier spacing is inversely proportional to the period. This is achieved so as to eliminate the occurrence of interference and cross-talk between overlapping frequencies. This extends the property for sending and connecting devices over a carrier channel. The OFDM transmission scheme is mostly suitable for downlinks transmission because of the volume of points required by the mobile device to transmit uplink data.

Normally 5G NR uses the frequency of 400 MHz and 6 GHz, which are also called a sub-6 spectrum (frequencies under 6 GHz). The DSS creates a link between the bands of the spectrum as LTE, LTE-M, and NB-IoT. All these technologies provide far betterment in the special related fields like military, medical science, weather forecasting, other drones, virtual reality, and augmented reality, etc.

3.2 Massive MIMO

3.2.1 What Is Massive MIMO?

Multiple-input multiple-outputs refer the connectivity between various networks using a base station and user equipment. There are basically two MIMO technologies—single-user MIMO and MU-MIMO—and some other techniques like doubling MIMO (2 × 2 MIMO), or quadrupling MIMO (4 × 4 MIMO) for the use of the peak throughput of a single user which is also present as shown in Fig. 3.1.

With low-power devices, more data with high quality is used to transmit using these technologies in MIMO Fig. 3.2. And it is enhanced for both upload and download links. For both 4G and 5G technologies, usage of antenna systems (AAS) was an advancement for large-scale deployments [6]. So, this cost-efficient AAS makes an advantage of transmitting data between urban and rural areas where the buildings are huge, where the toots of connectivity are very less both vertical and horizontal.

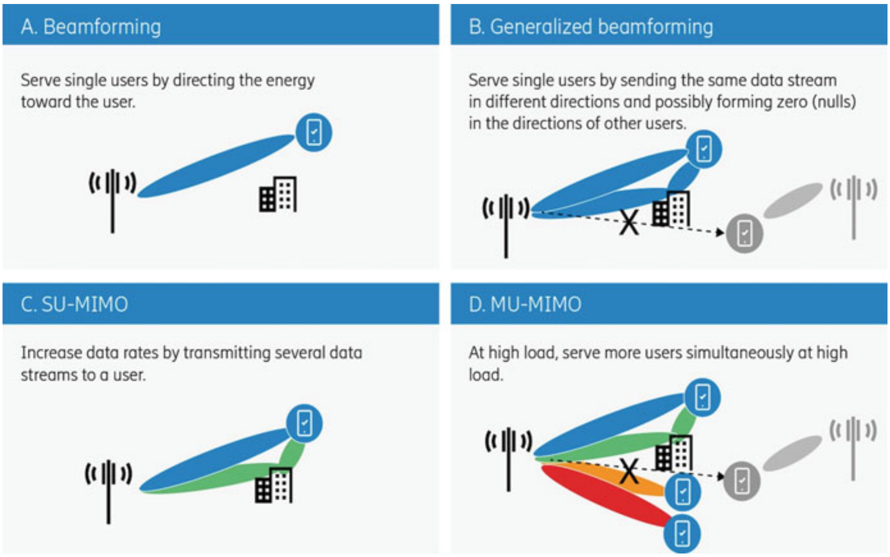

Fig. 3.1 MU MIMO defines for multiple streaming of the data using the resources

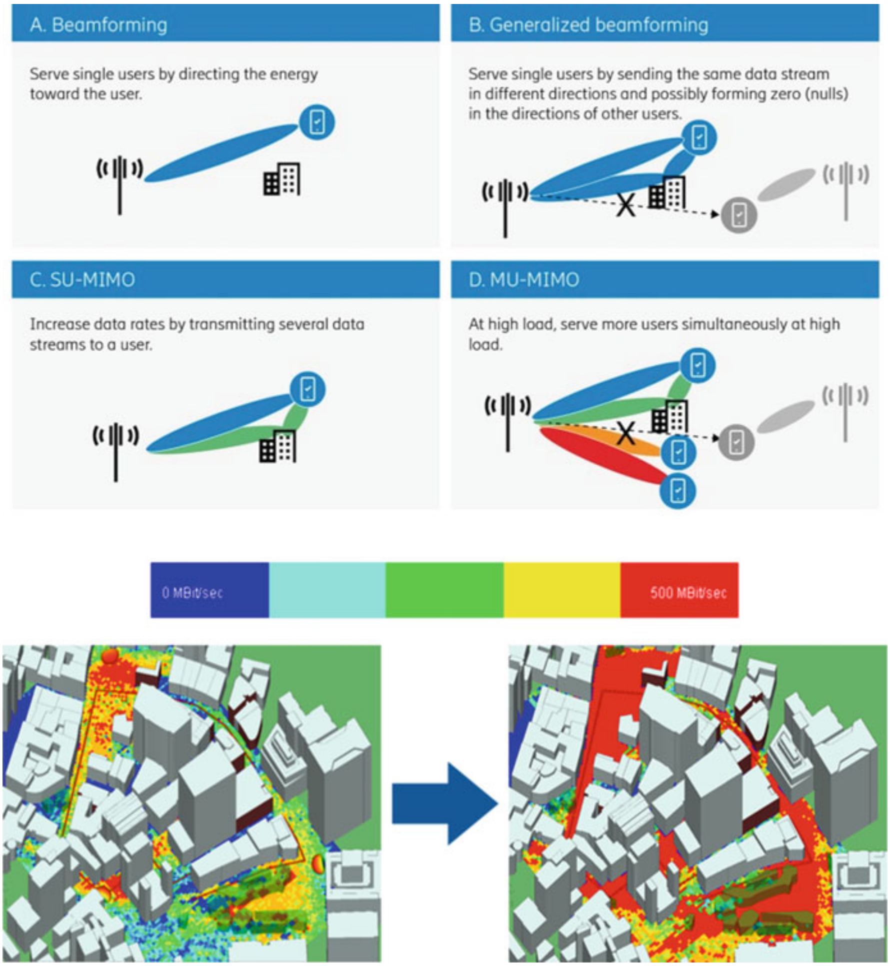

Fig. 3.2 Low-power devices, more data with high quality is used to transmit using these technologies in MIMO

So along with 5G are future technologies; this AAS will be a great boom for society and other technical needs.

3.2.2 Spatial Multiplexing

The spatial multiplexing (SM) technique in MIMO employs large antennas at both transmitting along with the receiving ends; it has purportedly been dubbed the future of new generation wireless communication systems as a result of its capacity to transmit and receive high data rates. The high demand for high data rates by consumers has set in motion the drive to incorporate MIMO technology into every communication system in order to cancel out the multipath interference limitation of conventional wireless transmissions. This chapter is aimed at elucidating on MIMO technology and how efficiently it transmits data in the fifth-generation realm of data communication [5, 11].

Spatial multiplexing uses singular value decomposition (SVD). Spatial value decomposition increases throughput in the parallel transfer of data. SVD splits the channel into various multiple streams. Throughput actually depends on the SINR.

Mobile network operators (MNOs) and service providers make use of the radio frequency (RF) spectrum in providing the bandwidth for subscribers. However, the finite nature of the RF band allocated to each MNO makes it a huge challenge in satisfying subscribers' needs for wider bandwidth. Therefore, other means of maximizing RF allocation have been sought after by MNOs. New mobile cellular technologies are currently being studied to map out a 4G cellular communications system which will be characterized in terms of high speed, capacity, range, and efficiency among other characteristics [8].

Spatial multiplexing can be likened to frequency reuse in cellular voice communications where different users can use a particular frequency at the same time but must be on different cells which are far apart from each other. Spatial multiplexing is such that each signal occupies a space at a given time in the same cell. When combined with the OFDM transmission scheme, cells are multiplied and mapped orthogonally between one another, thereby eliminating the occurrence of interference in each cell.

In spatial multiplexing technology, every stream of data sent via a transmitting antenna is referred to as a "layer," and each layer will contain as much data as contained in a single 5G transmission. This means that spatial multiplexing can result in exponential multiplication of throughput, thus, increasing data speed and capacity massively.

There are three major factors which mobile operators can use to increase data rates and build on the consistency of LTE networks. These factors are as follows:

- Maximizing multipath conditions in a cell space
- Configuring eNodeBs such that they conform with the MIMO settings
- Ensuring that user equipment take full advantage of the LTE network

Putting these three major factors into play will result in increased throughput, thereby improving customer satisfaction and return of investment for service providers.

Spatial multiplexing is a characteristic of MIMO, used to increase data capability by exploiting the number of multipath channel propagation to hold additional traffic, i.e., each and every carrier wave, and which is traveling through different paths that holds their own multiple independent traffic antennas to antennas using the same carrier frequency. However, in spite of the advantage of higher capacity, the maximum data stream that can be transmitted is affected by physical state confines according to the Shannon-Hartley law.

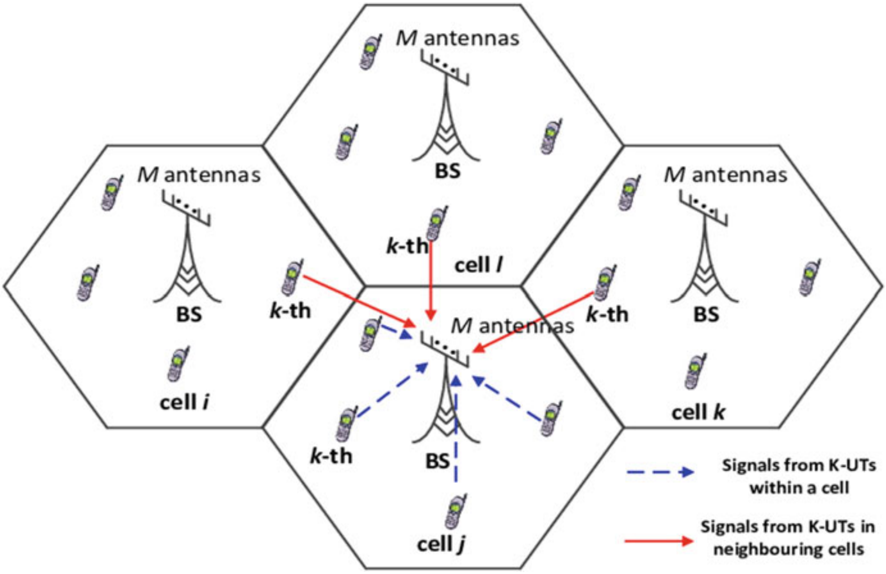

Fig. 3.3 Massive MIMO using larger antennas which increases throughput with more user tracking

3.2.3 Beamforming

Narrow beams are achieved with massive MIMO using larger antennas [1], which increases throughput with more user tracking which is shown in Fig. 3.3.

- Increases throughputs.
- Multiplexing gain: increases capacity.
- High-energy efficiency.
- Spectral efficiency: large antennas for a single user.
- Increased robustness and reliability: more antennas give less bound, intra- cell interference, fading of signal, and uncorrelated noise.
- Cost reduction: for low energy, RF amplifiers with minimum cost in the milli-Watt range can be used [7].

3.2.4 Multiuser MIMO

This is a radio frequency technology that uses two or more antennas to pass wireless streams on the same frequency. The MIMO provides diversity when it about to transmission techniques and as SIMO is also always referred to as receive diversity and MISO, the service antenna is present in more advanced cellular network systems. The reason for using a multiple-stream transmission service antenna is because it pillar stems from the scattering of RF-signals. In other words, as RX and TX signals are transmitted via the same medium, and these signal streams are in constant collision with objects which reflects these signals, thereby altering the path of these signals most especially in a heavily sense environment, as a result of this, attenuation (degradation of RF signals) occur. Therefore, the use of multiple antennas can recompense for the constant loss of signal. In addition, using multiple antennas boosts SNR. The MIMO achieves this by combining the unique fading characteristics and the path of every signal via its own antenna (signals will have different propagation paths because their antennas are different) and taking the best signals at both Tx and RX because the antennas transmit the same signals via different paths. This increases the signal-to-noise ratio, which can be used to boost throughput (data transfer rates) by properly modulating the signals using 16QAM/64QAM to achieve high data rates.

MIMO smart antenna systems have been seen implemented in modern wireless standards, such as the IEEE 802.11n, LTE, and WiMAX systems to name a few. It provides enhanced data transfer rates regardless of the interference, signal fading, and multipath fading.

MIMO technology can work both as MISO and SIMO combined which results in achieving a massive boost in SNR (Fig. 3.4). However, when the maximum SNR has been achieved, boosting the SNR further will only result in a marginal increase in throughput gains; therefore, the increase in SNR has its own limit. Consequently, because there is a limit to the amount of throughput that can be achieved when the SNR is at its highest, the LTE uses a technique known as spatial multiplexing to

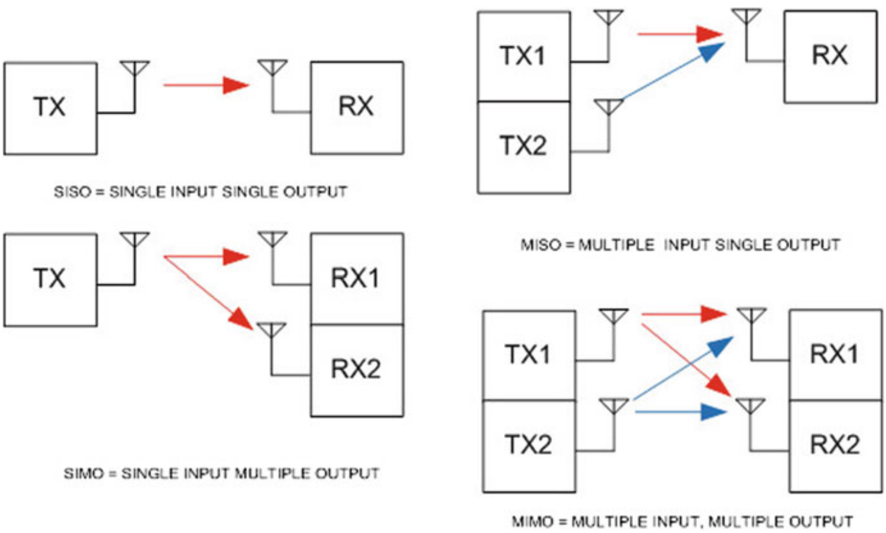

Fig. 3.4 SISO, MIMO, MISO, and SIMO

further achieve throughput obtain even SNR is at its maximum. Spatial multiplexing is a special technique that permits each and every transmitting service antenna to transmit multiple data streams to various receiving antennas at the same times and through the same set of frequency within the same platform sector.

The return of investment and a commercial windfall of any technology reside in its attributes and form a technical standpoint; multiple-input multiple-output smart antenna systems are interoperable with most of the modern wireless standards available; this includes the IEEE 802.11n, LTE, third-generation partnership project (3GPP), and Wi-MAX. The continuous increase in demand for high-throughputs is one of the major problems which led to the development of the MIMO transmission technique because it yields high data rates even in severe conditions of interference, multipath, and signal fading. Mobile network operators can cash in on the use of this technology.

3.2.5 Performance Factor

Mm wave spectrum given arises for 5G technology due to the massive availability of spectral space for connection and data passage. But because of the large number of carrier frequencies are present, free space loss is more. Due to some atmospheric conditions like rain and fog, the losses are somewhat higher in an extra-higher-frequency spectrum. Attenuation with heavy rainfall for millimeter wave frequencies occurs with attenuation of 2 dB rain at 73 GHz. Blockage and shadowing will be more for mm wave due to the large wavelength. Therefore with the atmospheric attenuation, high propagation loss, directivity, and sensitivity to blockage loss happen. Proper modeling and other engineering structures can be given for detecting path loss and related parameters.

5G delivers higher capacity performance in the recent test even in video streaming, machine-to-machine connections.

Figure 3.5 shows a comparison between 4G and 5G.

The performance factor mainly depends on battery performance. Since the connectivity is more, the battery will be drained at the earliest.

So, the possible method is to develop the most associated energy-storing batteries.

3.3 MIMO Architecture

More than 4G and other communication, 5G is mostly supported by the products. A common equivalent frequency is steered in a different direction without increasing spectrum usage. These measures can increase SNR and channel capacity.

The increasing number of digital signal processors and other spatial techniques increases the data transfers.

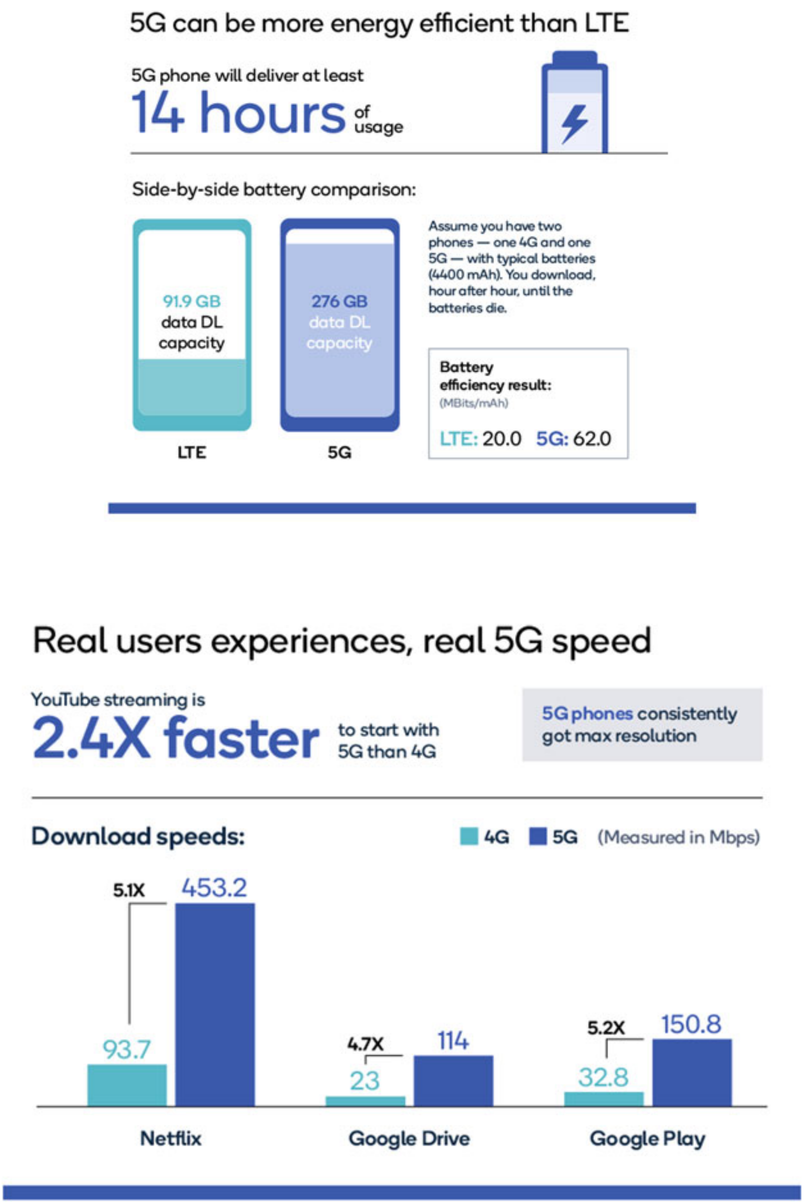

Fig. 3.5 5G delivers higher capacity performance in the recent test even in video streaming, machine-to-machine connections

Time division duplexing enhances the channel capacity including the transmission of various frequencies. The MIMO degree is shown by the number of transmitters and the number of receivers, i.e., 4 × 4 (Fig. 3.6).

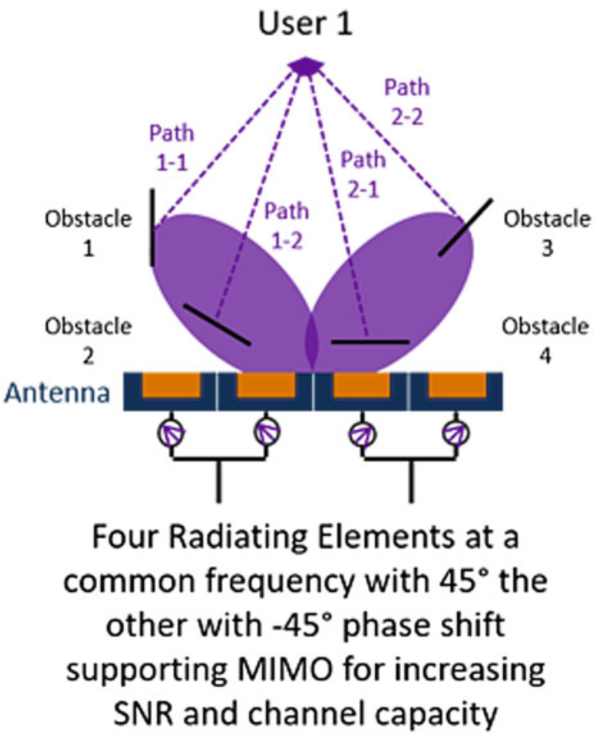

Fig. 3.6 MIMO phase shift

3.3.1 5G Core Architecture

Modern 5G composes and utilizes cloud-aligned, service-based architecture (SBA) that performs interface including security, authentication, session management, and aggregation of traffic from end devices [5].

Hardware features and functionality of 5G depend on the new deployment with the new core. Careful planning and implementation make it more user-friendly than the previous version of data connections.

North American, Asian, and European countries have already integrated 5G and its testing. Mostly preferred rural-urban areas and other non-connective areas of places will be more efficient by the use of 5G.

Developing and developed nations, including China, Japan, and India, are heavily making use of 5G and its appliances [9]. Hardware antennas and other infrastructures make large heavy duties from software and other manufacturing companies in order to welcome 5G infrastructures. An example scenario is shown in Fig. 3.7.

Large changes are coping with machine-to-machine connections. Factories and medical equipment will be more reliable to 5G [10]. However, robots' mass

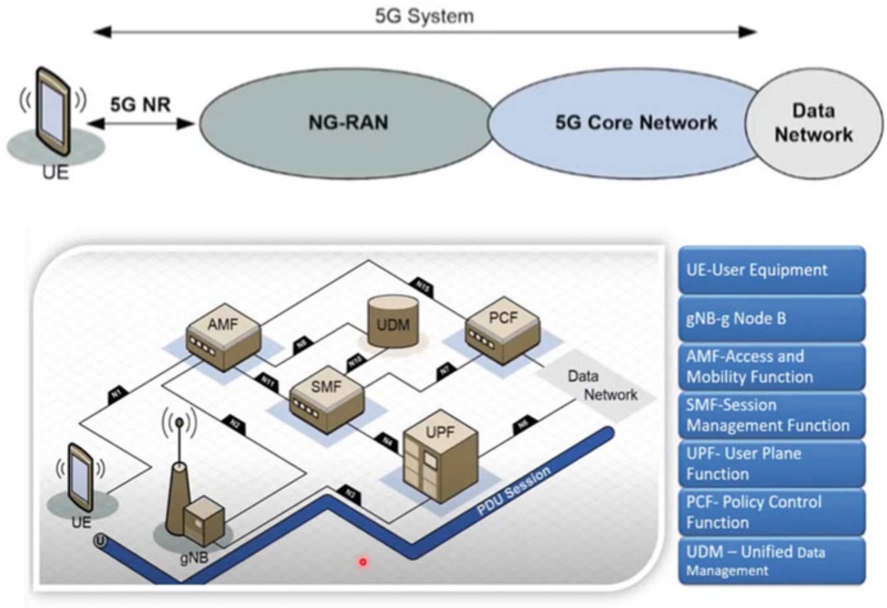

Fig. 3.7 Factory automation and production

production instrumentation units which pave way for industrial IoT facilities will be having advancement with 5G. Industry 4.0 and IoT production with wireless sensor networks will be the most trending terms in 5G. Virtual reality and augmented reality appliances will be more boon to society. This requires less time in production, an increase in IoT appliances with more production units in factories and industries.

The United Nations organization, the International Telecommunication Union Radiocommunication Sector (ITU-R), addresses the main capabilities to define the requirements for 5G systems.

3.3.2 Channel Estimation

The estimation is supported by Maxwell's equation. The propagation is not time-invariant. When the time is considered as short, then it can be considered as time-invariant. The approximately time-invariant time is the coherence time (TC).

The channel is in a time-invariant system as it is an incoherent time. Due to multiple propagations in time delay, dispersion will be present spreading out the signal over time. Coherent bandwidth may vary due to various reasons.

MIMO techniques help us to increase a large number of data transfers at high rates.

The antennas are basically designed in three-dimensional x-, y-, and z axes. Then, channel estimation for multiuser uplinks is the preamble phase, in which orthogonal and spatial optimal rotation is calculated. Overlapping is eliminated using these designs. At the second phase, rotational directions are formulated and the rest are done. This system reduces the computational complexity of traditional systems, and it does not degrade the required performance also. More number of array antennas is required for decreasing computational complexity. Parameter angle is calculated for the antenna connection.

3.3.3 Beam Propagation

It is a method of sending more number of radiations at the same wavelength and phase in a single antenna with higher streaming rates.

It depends on the arrangement of antennas in lobes of various directions. Beamforming with two and four elements is shown in Fig. 3.8.

3.3.4 Uplink-Downlink Transformation

In normal satellite-driven telecommunication, especially a downlink is a link from a satellite to the ground receivers. An uplink acts like a link from the ground systems to a top satellite which is as shown in Fig. 3.9.

Radiations are transmitted from station to UAVs and vice versa at different times and frequencies. At various points, more antennas are connected where antennas are located called MIMO.

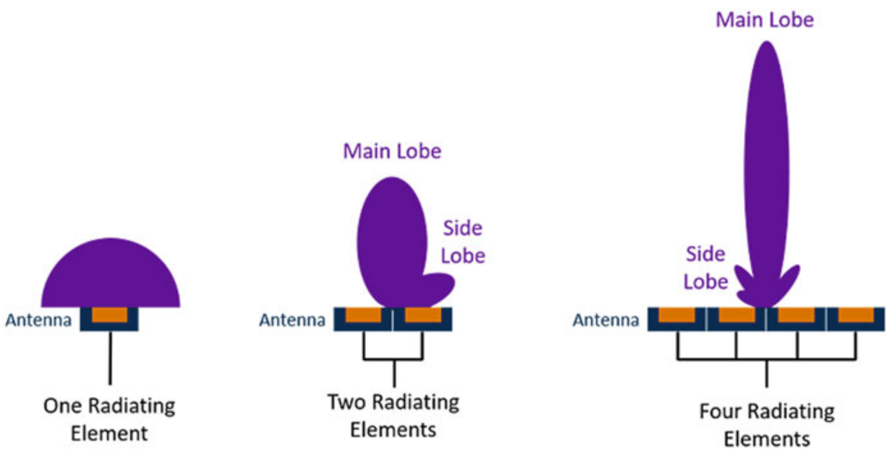

Fig. 3.8 Beamforming with two and four radiating elements

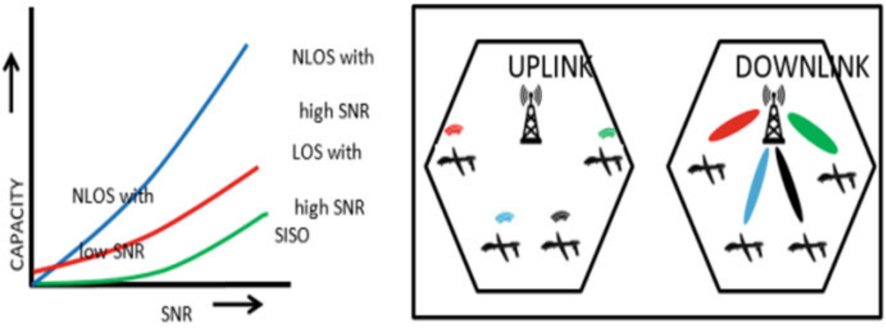

Fig. 3.9 Uplink and downlink

3.3.5 2 × 2 and 4 × 4 MIMO

New multi band 5G QuPanel antenna family supports structures of MIMO 4 × 4 and MIMO 2 × 2 for bands up to 3800 MHz. Fifth-generation/LTE directional MIMO 4 × 4 high-gain antenna is predicted for 4G LTE mainly and 5G but is adaptable with 2G and 3G as well. The service antenna significantly improves the stream signal in rural/remote/suburban and various locations where the communication signal is weaker. That antenna is predicted to be installed on the buildings (on the pole or the wall). Due to large working stream frequency range, service antenna is the universal state client for fifth-generation bands n77 and n78 and LTE bands like LTE-3800/3400/2600/2300/2100/1900/1800/800/700. It's compatible with Teltonika and other MIMO 4 × 4 5G/LTE/3G/2G modems and routers.

1 × 1 MIMO connects one antenna with one wireless stream.
2 × 2 MIMO connects two antennas with two MIMO streams.
3 × 3 MIMO connects three antennas with three MIMO streams.
4 × 4 MIMO connects 4 antennas with 42 MIMO streams.

3.4 Multiuser MIMO (MU-MIMO)

MU-MIMO helps to increase the speed of transmission for connecting multiple devices.

3.4.1 Energy and Spectral Efficiency

It transmits and sends data within equal time and speed. If you have a 2 × 2 phone and 4 × 4 router, it will be difficult to communicate.

Thirty GHz and 300 GHz frequencies in the spectrum are known as the millimeter wave, and their wavelengths are from 1 to 10 mm. Twenty-four GHz and 100 GHz are now given in different parts of the world. In more populated areas, it's fine, but for larger areas, it will be very tough to transmit and receive data [17].

3.4.2 Favorable Propagation

The channel vectors of UAV must be orthogonal vectors. Due to beamforming gaining less interference happens. So focusing the signal toward the UAV creates less interference which is leaked into different directions. If UAVs are in fewer directions, it shows less interference only.

3.4.3 Multicell Multiuser MIMO

Using low-power consumption with higher-throughput and energy efficiency, maximum coverage for users is provided using this technique. As designed earlier, this method provides 100 times greater connectivity than LTE [3].

For the method of time division duplex (TDD), a number of antennas and users are made with associating algorithm. Estimation of data transfer of uplink and downlink is done [2]. It considers that all of these service channels are more constant throughout the coherence time span of length which is expressed in absolute symbols and swap independently in all intervals. In every time span, these symbols are used for channel propagation estimation in the uplink; these symbols are absolutely dedicated for the data stream transmission.

3.4.4 MU-MIMO Benefits

In spatial stream multiplexing mode style, data set streams in transit can be received and acknowledged by one single user (single-user MIMO), or it can be received by numerous users (multiuser MIMO). While SU-MIMO increases the throughput of one system user, MU-MIMO allows increasing the overall system capability as opposed to maximizing the information/data stream transfer rate of one user [13].

The eNodeBs often switches between SU-MIMO and MU-MIMO based on channel conditions and the user's equipment ability to update the system on its real-time conditions, and this can only be achieved by taking advantage of the spatial dimension of the resource blocks. This spatial dimension is such that each transmitting service antenna transmits various data set streams, while each receiving service antenna will receive all the streams transmitted by each antenna, thereby

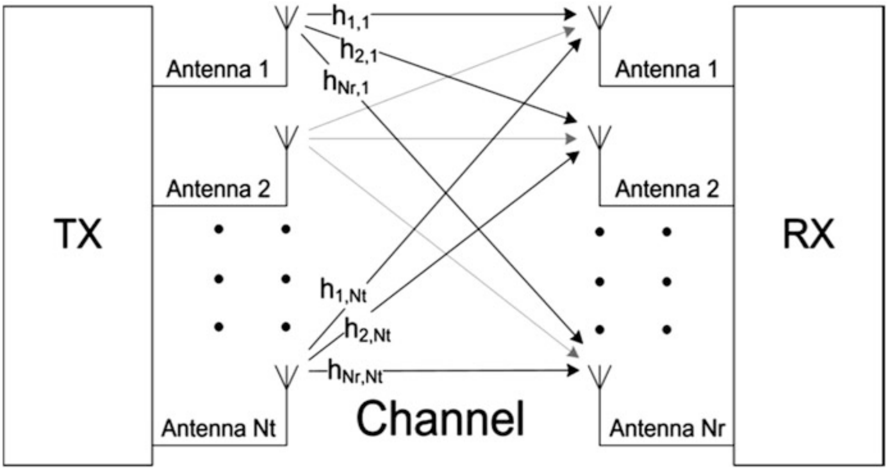

Fig. 3.10 Spatial multiplexing channel matrix

forming a matrix of channels. Thus the channel matrix can be used to determine a specific transmission (Fig. 3.10).

In relation to the figure above, Nt is depicted to be the number of transmitting antennas, while Nr is the number of receiving antennas. This creates 2×2 matrixes for the reference point of any LTE MIMO transmission scenario. It is important to note that the channel coefficients between a transmitter (x) and a receiver (y) can be written as (Hx, y) which can be used to calculate all propagation paths between the transmitter and the receiver. The matrix rank {Nt, Nr} specifies the minimum number of streams and which can be successfully transmitted and received over a MIMO channel.

3.5 Massive MIMO Challenges

3.5.1 Pilot Contamination

TDD (time-division duplex) is suggested immensely as a quality mode aspect to obtain timely channel state information in massive-scale MIMO systems. And the application of non-orthogonal state pilot techniques, proposed for service channel parameters multi-cell feature TDD networks, reduction of coherence time lacks in a vital source series of pilot contamination. Properties of hardware and transceivers determine the results of pilot contamination.

Multiplexing gain helps in increasing the capacity more.

The large antenna arrays decrease the uplink (UL) and downlink (DL) signals. It increases energy efficiency by which the UL energy of each adaptive UT can bring down inversely aggregate proportional to the number of service antennas at these stations. Spectral efficiency is increased by adding more antennas and service devices in massive MIMO with accuracy and multiplexing to increase the latency time and data rates [15].

More number of service antennas also permits for obtaining more number of transmission channel system. Also, if the total number of service antenna count increases uncorrelated noise, passive loss and fast fading are reduced to a great extent. For simple linear processing due to base station antennas much greater than the UT antenna, simplest linear pre-coders and detectors are used. Due to less energy consumption, more antennas allows the usage of low- cost RF amplifiers in the milli-Watt range which helps to reduce cost in radio frequency (RF) power components.

3.5.2 Unfavorable Propagation

The current and primary obstacle preventing wide-scale massive MIMO adoption, in addition to the specific spectrum holdings by different carriers, is the cost of implementation. Initial 5G networks are typically non-standalone, which means they are built on the existing 4G LTE and node infrastructure. Because the existing infrastructure cannot physically hold the number of antennas required to meet “massive” MIMO capacity, network operators will need to build standalone networks in order to accomplish full-scale adoption.

Building a new, standalone infrastructure takes time and carries significant hardware and installation expense. (For a full understanding of standalone versus non-standalone architecture, read our recent FAQ entry on the subject.) Until large-scale 5G, standalone networks are up and running, it will not see widespread massive MIMO in action.

Massive MIMO is one of the many 5G-related technologies that, when combined, will helpfully support the high demand of data consumption and increased connectivity of our world now and into the future. While massive MIMO cannot support the coming era of 5G alone, it will be a crucial component to achieving fast and seamless connectivity in homes, businesses, and on the go.

3.5.3 Implementation Challenges

Challenges within the hardware requirements are very high since the antenna for MIMO application and 5G-related techniques are very high. Regarding the radiation, demerits on humans will be tougher than normal connectivity procedures.

3.6 Future of 5G

Implementation of 5G results in the transformation of data to various aspects. Along with the technology of LTE and 3G, it enhances the most secured regions of transmission and reception of data.

No mobile next-generation network upgrade has been easy. In hindsight, they only look simplistic in comparison to the ever-expanding scope of 5G and the seemingly endless interconnected initiatives that must all advance in parallel. The biggest takeaway for 2021 is that clear pathways ahead continue to be forged. Considerable progress is being made worldwide, even in the face of adversity, complexity, and the discovery of new unknowns. Spirent is proud to be a driving force of these ambitious efforts [20].

5G technologies elaborate targets among previous technologies of 4G, 3G, and other previous connections. It does not compromise the versions of previous communications as LTE did in its previous versions [21].

Since all the data, including hardware and software, are virtually connected using protocols, the need for secured appliances is greater in the field of communications for proper monitoring and other security-related matters.

Aside from the smart antenna systems used in fixed and cellular transmission, MIMO is the mechanism behind the RADAR communications system [18]. The passive radar makes use of an advanced signal processing mechanism to ascertain the distance between itself and a distant object by means of calculating its reflection of radio signals sent to it. The passive radar was employed conventionally in the Second World War to detect Nazi aircrafts inbound the United Kingdom. In conventional radar, a transmitter sends beams of radio signals in the form of waves in many directions. If any target (aircraft) is within the radius of that transmission, the signal will be reflected back to the receiving antenna. The mechanism behind the radar is a derivative of the MIMO technique [19].

In disasters including flood, cyclones, and other calamities, predicting techniques can be done using these technologies. The main advantage of 5G is its connection is not only provided for data connections but also for machines and automatic vehicles, including UAVs. Also 5G parameters supports high bandwidth, high capacity, high speed, low advances in ultra-low latency, high-density coverage, high availability, low device energy consumption, high throughput, etc. for proper channel of communication within less latency time [16].

3.7 Conclusion

MIMO technology is a significant element of new-generation wireless technologies because it yields high gains and throughputs as compared to other technologies. In addition to high-throughputs, its ability to turn around the deficiency (multipath interference) of wireless technology has positioned it as the future of modern wireless transmission technology.

5G is mainly focusing on cloud-based technologies.

For the next industrial internet-of-things revolution, 5G is going to be among the most tremendous data-passing techniques for high-speed data rate applications like industry, online surgeries, medicals, farming, and irrigation.

As mobile operators build 5G networks on the public cloud, they find themselves traversing entirely new terrain. Every function and service must be tested and validated, over and over. The stakes are high with compliance, capacity, and performance all on the line. Help is on the way in the form of 5G network validation on AWS, combined with Spirent's groundbreaking Landslide 5GC Automation Package, which is now proven for point-rapid testing and validation of deployments and continuous network updates (CI/CD).

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Yasar Moidutty, has got 3 years of academic experience and is currently working as Assistant Professor and Trainer in the Department of Artificial Intelligence & Data Science, Royal College of Engineering & Technology, under APJ Abdul Kalam Technological University, Kerala. He is currently pursuing the Ph.D. degree from VIT, Vellore. He has completed his Under Graduation B. Tech., in Electronics and Instrumentation Engineering in 2017 from College of Engineering Vadakara, under CAPE, Govt. of Kerala, and Post-Graduation M. Tech., in Instrumentation Technology, in 2019 from Cochin University of Science and Technology. He has published more than 5 research articles in International Journals & Conferences and delivered guest lectures on various topics. His research interests include Artificial Intelligence, Machine Learning, Robotics, Embedded Systems, Sensors, and IoT.

P. Ihsana Muhammed, has got 10 years of academic experience and is currently working as Assistant Professor in the Department of Computing Science and Engineering, Royal College of Engineering & Technology, under APJ Abdul Kalam Technological University, Kerala. She has completed her Under Graduation B. Tech., in 2009 in Computer Science and Engineering from Calicut University and Post-Graduation M. E., in 2014 in Computer Science and Engineering from Anna University, Chennai. She has published more than 5 research articles in International Journals & Conferences and delivered guest lectures on various topics. Her research interests include Artificial Intelligence, Machine Learning, and Information security.

N. M. Sreenarayanan, has got 7 years of academic experience and is currently working as Assistant Professor and Trainer in the Department of Computing Science and Engineering, Galgotias University, Greater Noida, India. He is currently pursuing the Ph.D. degree from Galgotias University. He has completed his Under Graduation B. Tech., in 2013 and Post-Graduation M. Tech., in 2016 in Computer Science and Engineering from Calicut University. He has published more than 20 research articles in International Journals & Conferences and delivered guest lectures on various topics. His research interests include Artificial Intelligence, Machine Learning, and Emotional Intelligence.

Chapter 4
An Overview of Intelligent Reflecting Surface Assisted UAV Communication Systems

Samarendra Nath Sur, Debdatta Kandar, Agbotiname Lucky Imoize, and Rabindranath Bera

Abstract In order to realize the concept of massive wireless connectivity and Internet of Everything (IoE), the scientific community is focusing on technological evolution that will reach out to every corner of the world. In this context, intelligent reflecting surface (IRS) and unmanned aerial vehicle (UAV) are two prominent technologies aiming to magnify the wireless communication networks' performance in terms of achievable data rate, reliability, security, extended coverage, and more. But all these come with some challenges. In this chapter, the authors have provided an overview of the challenges corresponding to the UAV communication system. We also discuss the possible emerging physical layer technologies corresponding to IRS-assisted UAV (IRS-UAV) systems along with their benefits and challenges. Particularly we discuss the joint optimization approaches related to the UAV trajectory and IRS passive beamformation. Finally, a case study is presented to demonstrate the importance of active and passive beamformation for a IRS-UAV system to improve the overall sum rate of the network.

Keywords IRS · UAV · Phase shift · MIMO · NOMA · Beamformation · Optimization · Channel · Coverage · SWARM · Deployment

S. N. Sur (✉) · R. Bera
Department of Electronics and Communication Engineering, Sikkim Manipal Institute of Technology, Sikkim Manipal University, Majitar, Sikkim, India

D. Kandar
Department of Information Technology, North-Eastern Hill University, Shillong, Meghalaya, India

A. L. Imoize
Department of Electrical and Electronics Engineering, Faculty of Engineering, University of Lagos, Lagos, Nigeria

Department of Electrical Engineering and Information Technology, Institute of Digital Communication, Ruhr University, Bochum, Germany

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4.1 Introduction

Future generation communication systems are aiming to provide global coverage with ubiquitous connectivity over 3D space, ultra-high data rate, energy efficiency, ultra-high reliability, and ultra-low latency. The UAV-assisted communication (UAVAC) is considered to be the building block for the next generation communication system and also as a vital component towards achieving the goal of *connected world*. It has the potential to provide high-speed communication to diverse applications over a large coverage area. With the advancement in manufacturing technology and the reduction in cost, UAVs have received significant attention from the researchers and are considered for cargo delivery, pesticide spraying, search and rescue, traffic monitoring, and so on [1–5].

A summary of UAV-based applications is presented in Fig. 4.1. The UAVAC system becomes particularly important in the case of the disaster relief operation and service recovery as under such a situation the conventional terrestrial solution becomes challenging because of its high operational expenditure.

Despite great potential, there are some severe challenges such as variable altitude, high and changeable mobility, shadowing, rain attenuation, various environmental components, operational frequencies, etc. Particularly there is no control over the propagation channel between the ground station and UAV and that impacts the performance of the UAVAC systems. And also mitigation of interference in the case of multi-UAVs assisted architecture is a great concern [3].

To encounter those issues IRS emerge as a breakthrough technology [6–9]. It has the capability of actively modifying the incident electromagnetic wave (EM). In the

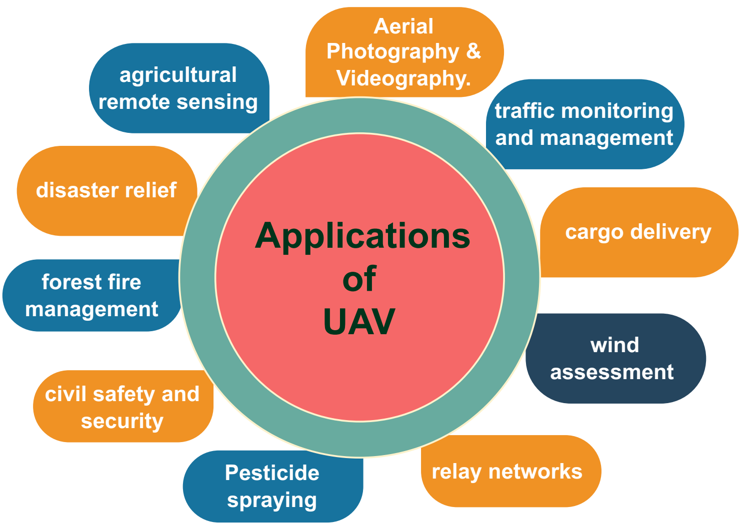

Fig. 4.1 Application of UAV

UAVAC system energy is a major constraint but IRS exploits the benefits of joint active and passive beamformation to minimize the requirement of transmit power. Therefore, it makes the system more energy efficient [10]. The optimized phase distribution and strategic deployment of IRS have the potential to improve the LoS probability [11], extend the coverage area [12], security of the communication link [13], ability to suppress interference [6], and so on. Furthermore, the deployment flexibility [7] makes the IRS a suitable choice to integrate with the existing wireless networks.

Thus the integration of UAV and IRS paves the path for providing ubiquitous communication services. It aims to enhance spectral efficiency (SE), energy efficiency (EE), physical layer security (PLS), reduction in information leakage, etc. However, the integration of IRS into the UAVAC system brings both opportunities and challenges. In this chapter, the authors have provided a brief overview of such opportunities and challenges. From extensive research, it is clear that such a system is bound to face challenges related to network characterization to performance optimization. This chapter also includes a brief discussion on the working of IRS and UAV communication network architectures and corresponding challenges. At the later stage of this chapter, it provides a case study on IRS-UAV system considering a simplistic model.

The major outlines of this chapter are presented as follows:

- A brief description of the IRS system and system models is presented here.
- A brief overview of the UAV communication system is presented here along with a comprehensive analysis of the associated challenges.
- An extensive review of the IRS-UAV systems, particularly with THz communication, NOMA, SWIPT, PLS, is presented here. It also highlights the associated challenges related to trajectory and beamforming optimization.
- It also includes a case study related to the performance analysis of the IRS-UAV system with joint active and passive beamformation optimization.

Organization Section 4.2 highlights the basic concept of the IRS along with a system model corresponding to the IRS-assisted communication system for uplink and downlink. Section 4.3 briefly describes the architecture and associated challenges corresponding to UAVAC system. An extensive literature review on IRS-UAV system is presented in Sect. 4.4. Section 4.5 presents a case study related to the IRS-UAV system.

4.2 Intelligent Reflecting Surfaces

The IRS technology is envisioned as the key player for the 6G and beyond communication system. The idea of IRS is to intelligently control the wireless environment and by virtue of that it helps to enhance the system performance. It consists of real-time controllable planer array with a large number of low-cost

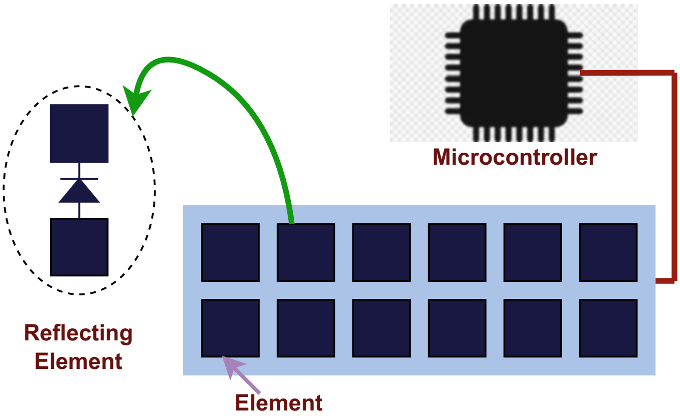

Fig. 4.2 IRS with PIN diode for controlling EM reflection

passive elements as in Fig. 4.2. The sole purpose of IRS is to direct the waves towards the destination by introducing a phase shift to the incoming electromagnetic (EM) wave. This smart controlling of the propagation environment leads to the improvement of the system performance [14, 15]. Although there are some studies presenting the concept of active elements based IRS [16]. The authors in [17] have proposed passive and active elements based IRS for improving the network performance.

The concept of IRS is basically based on the meta-materials. The meta-surface consists of meta-atoms that have the ability to transform the impinging EM waves. The transformation ability of the surface is relied on the properties of these discrete elements and also on the structural arrangement within the array [18]. In other words, the IRS surface is a reconfigurable frequency selective surface with thin meta-material film. Apart from manipulating the incident RM waves, it produces very low noise applications. The unique features of IRS make it a suitable candidate for indoor and outdoor applications. The tunability of the surface is realized by inserting positive-intrinsic negative (PIN) diodes [19], varactor-tuned resonators, liquid crystal, and also by exploiting the MEMS technologies. In the case of a PIN switch assisted controlling, the bias voltage across the PIN diode enables two distinct states (ON/OFF) for the IRS. During OFF state, the incident EM wave gets absorbed. But the surface enjoys the reflective property under ON state condition [14]. The equivalent circuit corresponding to a discrete IRS element is represented in Fig. 4.3. The baseband equivalent signal model at each element of a N elements IRS can be expressed as $Y_n = \alpha_n e^{j\phi_n} X_n$; $n = 1, ..., N$, where $\alpha_n \in [0, 1]$: reflection amplitude; $\phi_n \in [0, 2\pi]$: phase shift;$\alpha_n = 0$ represents absorption and $\alpha_n = 1$ represents full reflection.

The IRS controller plays an important role to carry forward the reconfiguration request and effective distribution of the phase shift information to all the discrete

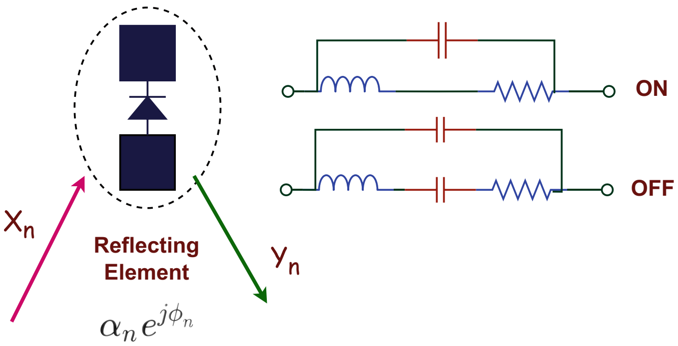

Fig. 4.3 Reflection element and equivalent circuit

elements. In IRS, the controller is realized by utilizing field-programmable gate array (FPGA) [19], a direct current (DC) source [20], or a micro-controller [21].

As the future wireless network is aiming to give more emphasis on green technologies and in this regard IRS is considered to be the perfect candidate for the same. The passive nature of the IRS makes it more energy efficient in comparison to other upcoming technologies. Although there are some works related to the involvement of the active elements to gather the channel state information more efficiently. Therefore, IRS is a perfect candidate for the future generation of green communication technology for sustainable development. Another exceptional advantage of IRS is its complementary nature to support other well-established technologies like massive MIMO, backscatter communication, millimeter wave, THz communication, etc. Additionally, IRS with full-duplex (FD) multiplexing enables new degrees of freedom, which enable the path for designing next-generation wireless communication systems with improved spectrum efficiency and low-cost hardware configuration.

The following sections discuss the mathematical model corresponding to IRS-assisted communication system for uplink and downlink scenarios.

4.2.1 System Model: Uplink Multiuser and Multi-IRS-Aided System

Figure 4.4 shows a multi IRS-assisted communication network for uplink under multiuser (MU) scenario. As in Fig, it consists of L IRSs with N_r discrete elements, K users with N_u antennas and BS with N_{bs} antennas. As presented in the signal model, between the users and the BS, there exists a direct path and several indirect paths. And there is a cascaded channel via the reflection at the IRS. In above figure, $h_{UB_k} \in \mathbb{C}^{N_{bs} \times N_u}$ represents the propagation channel between the kth user and the BS. And $h^l_{UR_k} \in \mathbb{C}^{N_r \times N_u}$ denotes the path matrix between the kth user and lth IRS.

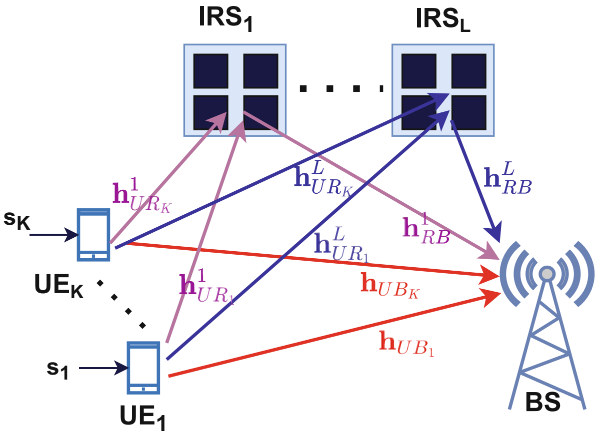

Fig. 4.4 Simple IRS-assisted communication system

Similarly, $h^l_{RB} \in \mathbb{C}^{N_{bs} \times N_r}$ is the channel matrix related to the path between the lth IRS and BS. Therefore, the channels $h^l_{UR_k}$ and h^l_{RB} formed cascaded channel model. The benefits of IRS can be exploited by proper design of the phase matrix and the phase shift vector $\boldsymbol{\psi} = \rho\ diag\left(e^{j\phi_1}, ..., e^{j\phi_{N_r}}\right)$,where $\phi_i \in [0, 2\pi]$,$i = 1, ..., N_r$, is the phase shift corresponding to the ith elements of IRS and $\rho \in [0, 1]$ is the reflection coefficient. The phase matrix corresponding to the lth IRS is denoted by $\boldsymbol{\psi}^l$. Considering the system as in Fig. 4.4 the received signal at BS corresponding to the transmitted signal $\mathbf{s}_k$ from the kth user is

$$\mathbf{y} = \sum_{k=1}^{K} \left(\mathbf{h}_{UB_k} + \sum_{l=1}^{L} \mathbf{h}^l_{RB} \boldsymbol{\psi}^l \mathbf{h}^l_{UR_k} \right) \mathbf{p}_k \mathbf{s}_k + \mathbf{n} \tag{4.1}$$

where $\mathbf{n}$ denotes the complex additive white Gaussian noise (AWGN) and $\mathbf{p}_k$ represents the precoding matrix corresponding to the kth user. The signal can be estimated ($\hat{\mathbf{s}}$) at the BS by utilizing appropriate filter ($\mathbf{W}$), i.e., $\hat{\mathbf{s}} = \mathbf{W}^H \mathbf{y}$.

4.2.2 System Model: Downlink Multiuser and Multi-IRS-Aided System

Figure 4.5 shows a multi IRS-assisted communication network for downlink under MU scenario. As in Fig, it consists of L IRSs with N_r discrete elements, K users with N_u antennas and BS with N_{bs} antennas. Here, BS allocate $N_{s,k}$ streams for each users and $\mathbf{s}_k$ is the signal transmitted towards the kth user.

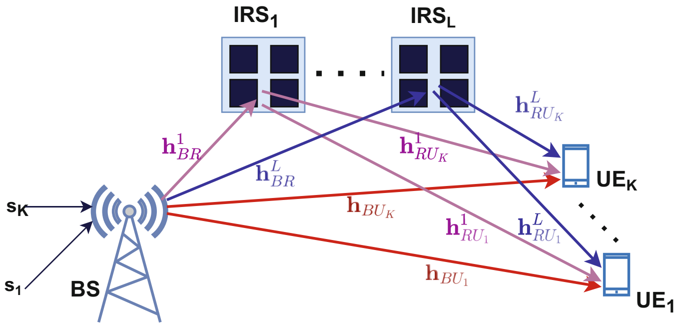

Fig. 4.5 Simple IRS-assisted communication system

In above figure, $h_{BU_k} \in \mathbb{C}^{N_{bs} \times N_u}$ represents the propagation path vector between the kth user and BS. And $h^l_{RU_k} \in \mathbb{C}^{N_{bs} \times N_r}$ denotes the propagation path vector between the kth user and lth IRS. Similarly, $h^l_{BR} \in \mathbb{C}^{N_r \times N_u}$ is the response of propagation path between lth IRS and BS. Similarly, considering the system as in Fig. 4.5 the received signal at the kth user corresponding to the transmitted signal $\mathbf{s}_u$ can be represented by

$$\mathbf{y}_k = \left(\mathbf{h}_{BU_k} + \sum_{l=1}^{L} \mathbf{h}^l_{RU_k} \boldsymbol{\psi}^l \mathbf{h}^l_{BR} \right) \sum_{k=1}^{K} \mathbf{p}_k \mathbf{s}_k + \mathbf{n}_k \tag{4.2}$$

where $\mathbf{n}$ denotes the complex valued AWGN and $\mathbf{p}_k$ represents the precoding matrix corresponding to the kth user employed by BS. The signal corresponding to each user can be estimated ($\hat{\mathbf{s}_k}$) by utilizing appropriate filter ($\mathbf{W}_k$), i.e., $\hat{\mathbf{s}_k} = \mathbf{W}_k^H \mathbf{y}_k$.

4.3 UAV Communication System

Future generation communication system is looking for reliable, secure, energy-efficient technology which can support massive device connectivity with high data rate and very low latency. UAVs are expected to be an important ingredient for future generation wireless networks, which have the potential to facilitate wireless high-speed broadcast. Over the past few years, design and analysis of the UAVAC system [22, 23] becomes the hot research topic. The concept of cellular-connected UAVs [24] enables the option to provide the service to multiple applications via aerial nodes. The concept of the Flying ad-hoc network (FANETs) [25] is explored by exploiting a swarm of UAVs to broadband wireless communications over a large geographical area. The major attributes of the UAVAC system are as in Fig. 4.6.

The increasing demand for diverse IoT-based applications makes it necessary to engage in the development of an integrated space-air-ground-based network. In

Fig. 4.6 Major attributes of UAV-assisted communication

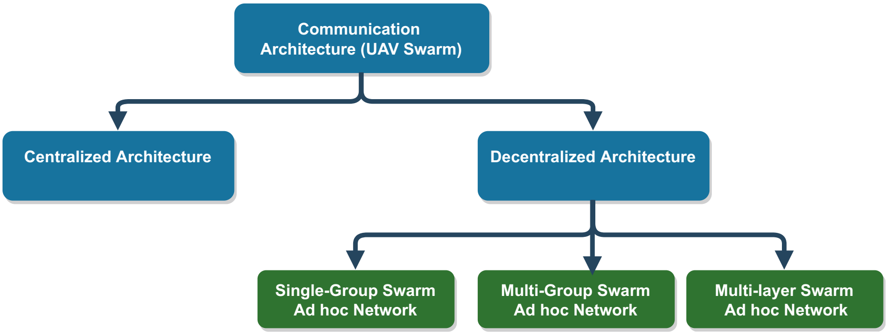

Fig. 4.7 UAV (swarm) assisted communication system architecture categories

this context, UAV plays an important role. From the deployment point of view, the swarm of multi-UAVs is advantageous in comparison to the single-UAV-based system. But the reliability and the performance of such a multi-UAV-based communication system is influenced by many factors such as coordination strategies, mission planning strategies, control mechanism, etc. [26]. In general, a multi-UAV system consists of UAVs of smaller in size and works in a coordinated manner. These UAVs are generally configured to deliver the required services co-operatively and extend the coverage by acting as relays. Therefore, communication architecture plays a significant role in mutual collaboration and control. The different categories of UAVAC system architecture are presented in Fig. 4.7,

The centralized approach is appropriate for a small coverage area and for a relatively simple mission or objective. In this architecture, a fixed network infrastructure acts as the central nodes and all the UAVs are connected with it directly for exchanging the control signals. Although it is a simple and stable architecture but it is less preferable because of its dependency on the single central node, which may lead to the Single Point of Failure (SPOF). In this swarm ad-hoc network the communication link between the swarm and infrastructure is established via a dedicated UAV (gateway-UAV). Apart from gate UAVs, all other UAVs are small in size with less payload and only communicate with the UAVs in the swarm. This architecture enables the swarm to act more collaboratively and thereby improves the efficiency and the coverage of the network [27].

Based on the mission requirements, the small UAVs (Intra-swarm communication architecture) are arranged differently like ring architecture, star architecture, and meshed architecture. But for the practical and more challenging application, it is required to have diverse UAVs in a network. And that is the main limitation of this kind of architecture. This gives rise to the demand for multi-group and multi-layer architecture. The multi-group architecture is nothing but the integration of centralized and single swarm architecture. This architecture is suitable when there is a requirement for a variety of UAVs. This diversification comes with challenges regarding the robustness of this architecture and the latency of the network [28]. Multi-layer swarm architecture is another kind of architecture to support different types of UAVs and it is the most advanced architecture of all. This is basically a layered architecture, where adjacent UAVs of the same types build up an ad-hoc network (first layer). These groups interact with each other via the gateway-UAV and it constitutes the second layer. And at the third layer, the nearest gateway-UAV communication with the infrastructure. This architecture ensures that it is free of SPOF. Therefore, it is considered to be a more reliable and robust network architecture [29].

Considering the requirement of high-speed operation, highly dynamic nature of connectivity, and the requirement of providing support over large coverage area, the decentralized approach is considered to be the best. It is free from the dependency on the infrastructure and UVAs are communicating with each other in an ad-hoc manner [30].

Extensive research works established the fact that the UAVAC system has great potential to support the future generation communication system goal. But all these come with some key challenges as mentioned in Fig. 4.8. This section discusses the key challenges as mentioned in Fig. 4.8. *Channel Model:* As in [31], the authors have demonstrated that UAV-to-ground channels are much more complex in nature than ground communication channels. And also the blockage probability is more in comparison to the air-to-air channel. Therefore, the conventional models are not applicable for the characterization. Lots of research works are reported to characterize the UAV-to-ground channel [32] and it is very vital from the point of view of understanding and evaluating the system performance. *Deployment Strategies:* UAV deployment as an aerial-BS has emerged as a promising and an encouraging solution for the future generation communications systems to provide reliable and secure communication links over a larger geographical area.

Fig. 4.8 Challenges: UAV communication

The high-mobility feature of UAV is proved to be advantageous for the strategic deployment [33]. Therefore, its 3D-deployment is considered to be a key challenges for a UAVAC system. *Path Planning:* In the case of swarm networks, optimal path planning, and trajectory control are challenging tasks. Proper planning and efficient control of trajectory in the utmost importance to ensure seamless connectivity [34]. *Altitude:* The performance of the UAVAC is greatly influenced by the operational altitudes of the UAVs [35]. It is necessary to optimize the altitude UAVs to provide maximum coverage on the ground. And for the same, it is important to take the tread-off between the LoS and path loss into account. *Interference management:* In swarm network UAVs, ground cellular networks and air to ground channels suffer from co-channel interference. And the mobility of the UAVs results in Doppler shifts and that results in inter-carrier interference. Hence proper and efficient interference management is very much required to maintain the system QoS. *SWAP constraint:* For mission-specific applications the SWAP are the challenging constraints to address as they put limits on the communication capabilities. Therefore, smaller size, lighter weight, and more power efficient hardware need to be designed for effective deployment. *Security:* The integrated network is vulnerable to malicious attacks. Particularly, the central SDN controlling unit is very much exposed to cyberattacks [36]. Therefore, ensuring the security of the integrated network is still a challenging task. The security and privacy issues of UAVs are generally originated from the attached sensor, related hardware, integrated software, and communication links. *Back-haul Cellular Network:* One of the major requirements of the UAV-assisted network is to have the high-speed back-haul link between the gateway-UAV and the core network. This requirement puts a limit on the QoS. *Swarm operation and coordination:*The Swarm of UAVs is the key element for next-generation communication systems. It can operate through centralized and distributed control. And also with multiple layers of UAV networks. Through substantial research works it is observed that the multi-layer UAV ad-hoc network is the most efficient architecture but coordination and collaboration among different layers is one of the key challenges [37].

Lots of efforts are imparted to improve the UAVAC system by exploiting the efficient design of the physical layer. The key enabling technologies are presented in Fig. 4.9. Researchers have explored the possibilities of utilizing millimeter wave (mmWave) and Tera-Hz (THz) bands to exploit larger bandwidth to enhance the data rate. At the same time, massive multi-input and multi-output (Massive MIMO) and cognitive radio (CR) is considered for UAV communication to enhance spectral

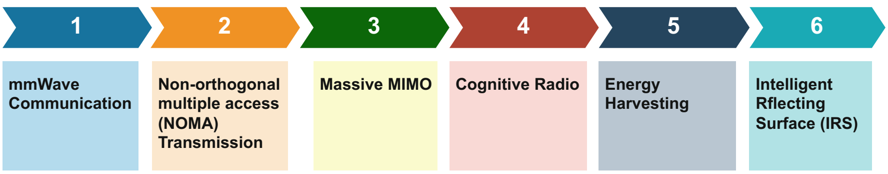

Fig. 4.9 Physical layer technologies: UAV communication

efficiency. The addition of CR with the UAV communication system makes the system more intelligent in a way to provide the desired service to the intended users by suppressing the interference from the undesired users. Moving towards the energy-efficient communication system, the concept of energy harvesting and the integration of IRS with UAV plays an important role. As part of the scope of this chapter, the authors have addressed the IRS-assisted communication system in the next section.

In the context of the UAVAC system, IRS can play a significant role to improve the security, reliability, and robustness of the link. To improve the system performance the efficient deployment of IRS, optimal phase shift design for IRS, and resource allocation needs to be investigated. In this chapter (Sect. 4.1), we have summarized the works related to IRS-UAV communication system.

4.4 IRS-UAV Communication

The academic and research community intensively engaged in exploring the possibilities of IRS-UAV technology [38–40]. [41] demonstrate the utility of IRS for improving the UAV-assisted cellular communications by proper deployment. Furthermore, as in [42], IRS-UAV consumed considerably less power than an active relay and at the same time provide improved performance by exploiting the optimization of UAV trajectory and resource allocation. This section briefly reviews the works cater for IRS-UAV networks (as in Fig. 4.10), challenges, and future directions.

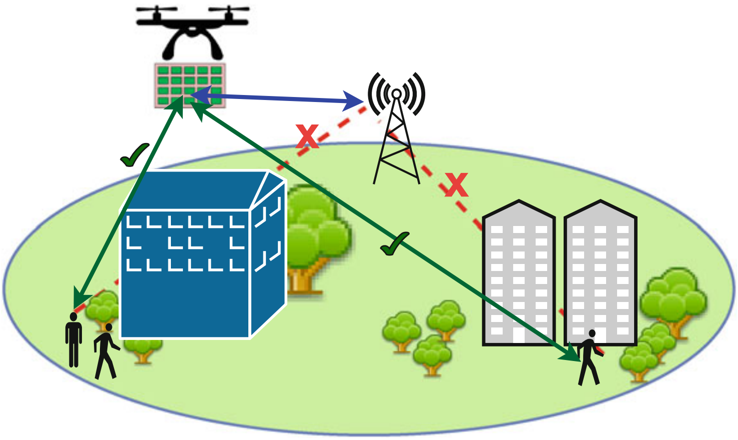

Fig. 4.10 IRS-UAV network

4.4.1 IRS-THz-UAV Communications

Researchers are exploring the THz communication for its potential to enhance the wireless capacity [43, 44]. The THz communication system offers secure and reliable communication links by exploiting its highly directional transmission. But along with such benefits, there are some challenges such as high-frequency selective nature, high path loss, water-vapor absorption, and relative air composition [43, 45]. IRS is considered to be the potential solution for compensating the high path loss and emerged as one of the key technology to remove the barriers of relatively unreliable and costly conventional THz communication. The integration of IRS and UAV pave the way for realizing the THz communication for the omni-bearing coverage [46].

4.4.2 IRS-NOMA-UAV Communications

For a UAVAC system, UAV-mounted BSs are generally provide service to a large number of ground users, and for this purpose non-orthogonal multiple access (NOMA) plays a pivotal role. Although the performance of other multiple access techniques has also been analyzed. As in [42] TDMA scheme is utilized and in [47] OFDMA scheme is adopted. The authors in [48–54] have investigate the performance of the IRS-UAV-NOMA communication networks. In [48], the authors have demonstrated the utility of joint optimization of 3D placement for the maximization of the sum rate of the multi-UAV networks. The proposed optimization techniques involve the parameters like transmit power corresponding to UAVs, the reflection coefficients of the IRS elements, and the NOMA decoding orders among users. It demonstrated that in comparison with the orthogonal multiple access (OMA) scheme, NOMA is more efficient in terms of sum rate. Similarly, [50], the authors have utilized the joint optimization and demonstrated that NOMA is more beneficial than OMA in terms of SE and EE. By exploiting the proper deployment strategy and optimal power allocation, it is possible to extend the coverage of the network, and the same is demonstrated in [51]. With the motivation of improving the sum rate, in [52], the authors have utilized Deep Reinforcement Learning (DRL) Based Optimization for a IRS-UAV-NOMA downlink network. In[53], the authors have analyzed the performance of IRS-UAV-power domain(PD)-NOMA by exploiting reinforcement learning (RL) based algorithms for optimizing trajectory, sub-carrier, and power variables.

4.4.3 IRS-SWIPT-UAV Communications

Recently, wireless power transfer has gained substantial attraction from the research community as it has been established as an effective solution for recharging the low-powered IoT devices and sensors [55]. It is possible by harvesting RF energy from surrounding sources. In this context, SWIPT has gained significant attention. By exploiting this technology, data and power can be transferred using EM waves for information decoding (ID)or energy harvesting (EH).

Because of the unique features of UAV technology is an ideal choice for assisting SWIPT and extensive research is going on in this regard. It is particularly important when the ID and EH devices are spread over a large area or disaster area. And by exploiting this it is possible to avoid the near-far problems. Additionally, IRS-UAV-SWIPT technology has the capability to significantly enhance the performance of ID and EH by exploiting the optimized beamformation. Not only that, it induces an additional degree of freedom, such as 3D trajectory optimization of UAV, consumption of power optimization for IRS-UAV, phase vector optimization for ID and EH, and so on, to enhance the performance of SWIPT. Therefore, the integration of IRS with UAN-SWIPT technology will improve the energy transmission efficiency and the coverage of the network. As in [56, 57] the authors have proposed a IRS-UAV-SWIPT scheme for energy harvesting across the IoT devices. The proposed schemes rely on joint optimization for maximizing the network sum rate. As a part of joint optimization formulation, researchers are considering the UAV trajectory, the EH scheduling of connected devices, phase shift vector corresponding to IRS, IRS reflection coefficient, transmission power allocation, and power splitting ratio. The authors in [58] demonstrated that IRS consumed a little fraction of incident power, mostly un-reflected signals for self-powered. Therefore, IRS-UAV SWIPT technology is capable to provide efficient energy harvesting and very high information transfer capacity.

4.4.4 IRS-PLS-UAV Communication

UAVAC system has the potential to improve the PLS of terrestrial cellular networks. The secrecy rate performance of UAVAC system is presented in [59]. This is due to the fact that UAV established dominant LoS links between an aerial and ground node. And also by properly utilizing the UAV, it is possible to support legitimate users and can act as friendly jammers for eavesdroppers. This will protect the privacy and security of legitimate users. From the security point of view, IRS would be beneficial and can be used in a UAV to enable networks to tackle any security threats. By intelligently configuring a phase matrix corresponding to the IRS elements one can orient a stronger beam towards the legitimate users to increase the SNR whereas producing destructive interference towards the eavesdroppers.

4.5 Challenges

4.5.1 *Channel Model and Estimation*

The channel model plays an important role to design and exploring the effectiveness of the communication system. In the case of a IRS-UAV communication system, it is very much important to characterize the path loss, the air molecule scattering, propagation fading impact, shadowing effect, etc. With the integration of IRS with the UAV-assisted communication, the accurate modeling of the IRS-UAV channel additionally depends on the number of the IRS elements, the geometric configuration of then IRS, IRS materials, etc. The situation becomes more challenging its dynamic mobility. Therefore, it is very much evident that the IRS-UAV channel modeling is more challenging and needs sophisticated formulation.

Although the IRS offers several advantages but its passive nature makes the channel estimation task more difficult. This problem can be resolved by utilizing a few low-powered active elements that enable channel sensing capabilities. Therefore, proper design and segmentation of passive and active elements also play an important role to gather the CSI.

4.5.2 *IRS Controlling*

The effectiveness of the IRS depends on how we are controlling the IRS, more specifically the phases corresponding to each element. This generates the requirements of proper synchronization and reliable control link. But the dynamic and time-varying nature of the IRS-UAV channel makes the task more difficult. Therefore, more emphasis should be given towards the developing proper controlling signal and its processing keeping the overhead burden in check.

4.5.3 *Trajectory and Beamforming Optimization*

This section addresses the trajectory and beamforming optimization problems and summarizes the related works carried out over the last few years with aim of improving the UAVAC system. Apart from eavesdropping, jamming is also a point of concern for the communication system. IRS provides the solution for such kind of threat. And it is proved to be beneficial to improve the overall system performance under a severe jamming environment. To ensure the reliability and the security, it is required to jointly optimize the trajectory of UAVs along with the IRS passive beamforming. This is considered to be one of the major challenges. In this regards placing of UAV is also an important factor. To ensure the optimal performance under a quasi-static condition, the UAV is to be placed at an altitude by keeping a trade-off between the LoS probability and the path loss [2, 3]. This critical optimality condition can be deviated by leveraging the proper deployment of IRS and passive beamforming. In the case of high-mobility UAVs, joint optimization of trajectory and beamforming is the best solution for optimal performance. The optimization problem regarding this is extensively investigated in [50, 60–68]. [60] utilized the beamforming power, phase shift matrix at IRS and trajectory of UAVs to boost the secrecy rate performance. Here the proposed IRS-UAV scheme demonstrated a 20% higher secrecy rate than the system with the eavesdropping elimination method. As in [61], the system average achievable rate is improved by exploiting the joint optimization technique. Similarly, in [65], the authors have utilized the benefits of joint optimization to improve the data rate for the high-speed train. In[63], the authors have considered multiple IRSs and a multi-antenna UAV system to improve the received power by jointly optimizing the passive/active beamforming, and the trajectory. As in [64], the joint optimization of UAV trajectory, IRS passive beamforming has the ability to improve secrecy rate performance and the transmit power corresponding to the legitimate user. Furthermore, in [67, 68] the authors have exploited joint optimization of UAV trajectory, passive beamforming, and ground node power allocation to improve the achievable average rate in presence of malicious jamming. The problem of the conventional optimization techniques is their complexity but the complexity problem can be addressed by utilizing machine learning/ artificial intelligence techniques. [62] demonstrates a deep Q-network (DQN)-based method suitable for the system with hardware limit and also with discrete trajectory and phase shift design. And also a deep deterministic policy gradient (DDPG)-based approach for the system with continuous trajectory and phase shift design. It also demonstrates that the proposed approach performs better than the other traditional benchmarks. Extending further in [50], the authors have addressed the energy consumption minimizing problem for IRS-UAV NOMA system by exploiting decaying deep Q-network (D-DQN).

4.6 Case Study: IRS-UAV Communication

This section deals with the performance analysis of IRS-UAV communication system with IRS passive and active beamforming.

4.6.1 System Model

For this study, we consider one simplified IRS-UAV communication network. The system (Fig. 4.11) performance is analyzed in absence of a direct link between the BS [acting as source (S)] and the receivers/destinations (Ds). A communication path is established between the S and Ds via a reflected path from the aerial-IRS(AIRS). Here, the BS is equipped with N antennas and D is with one antenna. And also

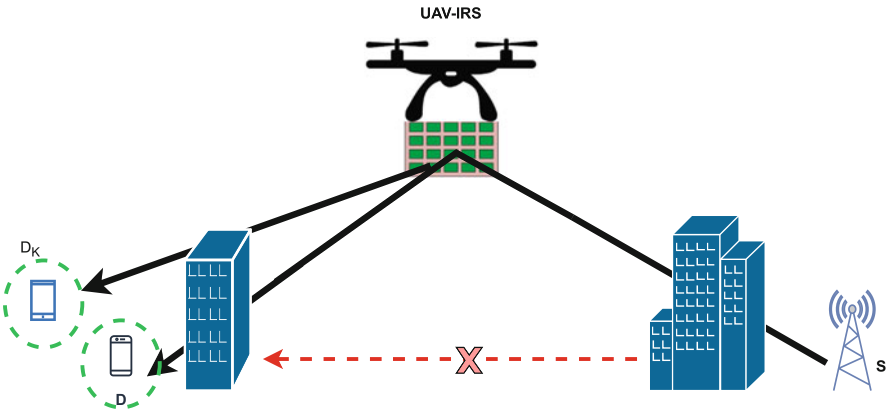

Fig. 4.11 IRS-UAV communication

the AIRS (R) is consist of M number of reflecting elements. This system designed is to provide the service to the K users (destinations). The aim of this chapter is to improve the sum rate of the system by jointly optimizing the active and passive beamforming. The optimized beamforming not only improves the sum rate but also reduces the transmit power requirements.

Here we consider,$\mathbf{h}_{SR}$, represents the channel between BS and AIRS unit, having dimension $(M \times N)$ and $\mathbf{h}_{RD_k} \in \mathbb{C}^{M\times 1}$ is the channel between the AIRS unit and the kth D. The properties of AIRS are characterized via the phase shift matrix $\boldsymbol{\psi} = \rho\ diag\left(e^{j\phi_1}, ..., e^{j\phi_M}\right)$,where $\phi_i \in [0, 2\pi]$,$i = 1, ..., M$, is the phase shift corresponding to the ith elements of AIRS and $\rho \in [0, 1]$ is the reflection coefficient. Therefore, the overall channel matrix between the BS and kth D can be expressed as $\overline{\mathbf{h}_k} = \mathbf{h}_{RD_k}\boldsymbol{\psi}\mathbf{h}_{SR}$. The received signal vector $\mathbf{y}$ is given by

$$\mathbf{y}_k = (\mathbf{h}_{RD_k}\boldsymbol{\psi}\mathbf{h}_{SR})\mathbf{s}_k + \mathbf{n}_k \tag{4.3}$$

where $\mathbf{s}_k$ denote the transmitted signal vector from S with covariance matrix $\mathbf{Q} = \mathbb{E}[\mathbf{ss}^H] = 1$.

Under MU scenario, the received signal at the kth D can be represented by

$$\mathbf{y}_k = \mathbf{h}_{RD_k}{}^H\boldsymbol{\psi}^H\mathbf{h}_{SR}\mathbf{p}_k\mathbf{s}_k + \mathbf{h}_{RD_k}{}^H\boldsymbol{\psi}^H\mathbf{h}_{SR}\sum_{j=1,j\neq k}^{K}\mathbf{p}_j\mathbf{s}_j + \mathbf{n}_k \tag{4.4}$$

where s_k is the transmitted signal from the BS to kth D with normalized power. Here, n_k is the AWGN vector at the kth D. Here the precoding matrix is represented by $\mathbf{P} = [p_1, ..., p_k]$ and the precoding vector for the signal from BS to kth D is denoted as p_k. The entire system is under the constraint of total transmitted power at the BS and can expressed as $tr(\mathbf{PP}^H) \leq P_{max}$. Here, we consider the composite channel model to have a more realistic analysis. Here the small scale fading channel

(S_c) characteristic is governed by Nakagami-m distribution and inverse-Gamma distribution is exploited to design large scale shadowing (L_c) effect. The probability density function (PDF) corresponding to the Nakagami-m channel can be expressed as

$$f_{S_c}(x; m, \Omega) = 2\left(\frac{m}{\Omega}\right)^m \frac{1}{\Gamma(m)} x^{2m-1} e^{\frac{-m}{\Omega}x^2}, x > 0 \tag{4.5}$$

where m is the Nakagami-m fading parameter (shape) and Ω is the spread parameter. Similarly, the PDF corresponding to inverse-Gamma distribution can be expressed as

$$f_{L_c}(x; \alpha, \beta) = \frac{\beta^\alpha}{\Gamma(\alpha)} x^{-\alpha-1} e^{\frac{-\beta}{x}}, x > 0 \tag{4.6}$$

where $\alpha(> 1)$ and β represent the shape and spread parameter of the distribution, respectively. Considering the above setup, the channel capacity corresponding to kth D can be expressed as

$$C_k = \log_2 det\left(\mathbf{I} + \frac{1}{\sigma_n^2}\bar{\mathbf{h}}Q\bar{\mathbf{h}}^H\right) \tag{4.7}$$

As in (4.7), the channel capacity of the IRS-assisted communication system is greatly influenced by $\boldsymbol{\psi}$ and also depends on the covariance matrix $\mathbf{Q}$. The achievable sum rate of the system as in Fig. 4.2 is

$$R_{sum} = \sum_{k=1}^{K} C_k \tag{4.8}$$

In this chapter, the system performance is evaluated by exploiting the joint optimization. For the network as presented in Fig. 4.2, the signal to interference noise ratio (γ_k) for the kth D can be given as

$$\gamma_k = \frac{\left|\mathbf{h}_{RD_k^H}\boldsymbol{\psi}^H\mathbf{h}_{SR}\mathbf{p}_k\right|^2}{\sum_{j=1,j\neq k}^{K}\left|\mathbf{h}_{RD_k^H}\boldsymbol{\psi}^H\mathbf{H}_{SR}\mathbf{p}_j\right|^2 + \sigma_n^2} \tag{4.9}$$

As in [69, 70], the weighted sum rate problem can be defined as

$$\underset{\mathbf{P},\,\boldsymbol{\psi}}{max} f(\mathbf{P}, \boldsymbol{\psi}) = \sum_{k=1}^{K} \omega_k \log_2(1 + \gamma_k) \tag{4.10}$$

$$tr(\mathbf{P}\mathbf{P}^H) \leq P_{max} \tag{4.11}$$

The continuous phase set

$$\theta_m = exp\,(j\psi_m|\,\psi_m \in [0, 2\pi]) \tag{4.12}$$

Here, weight ω_k is applied to the kth D. The system performance can be enhanced by optimizing the $\mathbf{P}$ and $\boldsymbol{\psi}$. In this chapter, the authors have demonstrated the influence of optimized ZF precoder over the system performance.

As 1st step, the authors have considered the task of optimizing the active beamforming. As in [69, 70],under the power constraint the precoding matrix optimization problem can be defined as

$$\underset{\mathbf{P}}{max}\, f(\mathbf{P}) = \sum_{k=1}^{K} \frac{\overline{\eta}_k \left|\overline{\mathbf{G}}_k^H \mathbf{P}_k\right|^2}{\sum_{j=1}^{k} \left|\overline{\mathbf{G}}_k^H \mathbf{P}_j\right|^2 + \sigma_n^2} \tag{4.13}$$

where $\overline{\mathbf{G}}_k^H = \mathbf{h}_{RD_k}^H \boldsymbol{\psi}^H \mathbf{h}_{SR}$. And as solution, for each D, the optimized precoding matrix can be obtained as

$$\mathbf{p}_{k_{opt}} = \sqrt{\overline{\eta}_k}\,\beta_k \left(\mu I_N + \sum_{i=1}^{K} |\beta_i|^2\, \overline{\mathbf{G}_i}\, \overline{\mathbf{G}}_i^H\right)^{-1} \overline{\mathbf{G}}_k \tag{4.14}$$

where $\boldsymbol{\eta} = [\eta_1, \ldots.., \eta_K]^T$ is the auxiliary vector obtained from the Lagrangian dual transformation [69, 70] and $\overline{\eta}_k = \omega_k\,(1 + \eta_k)$. And $\boldsymbol{\beta} = [\beta_1, \ldots.., \beta_K]^T$ is the auxiliary vector extracted by utilizing the quadratic transform (QT) technique [70]. And μ is the Lagrange multiplier related to the power constraint as mentioned in 4.11.

After the active beamforming optimization, the authors have considered the problem of optimization of passive beamforming. Similar to (4.13) the optimization problem for $\boldsymbol{\theta}$ can be defined as follows

$$\underset{\boldsymbol{\theta}}{max}\, f\,(\boldsymbol{\theta}) = \sum_{k=1}^{K} \frac{\overline{\eta}_k \left|\boldsymbol{\theta}^H \mathbf{v}_{k,k}\right|^2}{\sum_{j=1}^{K} \left|\boldsymbol{\theta}^H \mathbf{v}_{k,j}\right|^2 + \sigma_n^2} \tag{4.15}$$

Now to have the optimal solution can be achieved by exploiting QT. The QT process introduced the auxiliary vector $\boldsymbol{\rho} = [\rho_1, \ldots, \rho_K]^T$. The optimal solution for ρ_k [69] can be extracted by following the Lagrange multiplier method and can be expressed as

$$\rho_{k_{opt}} = \frac{\sqrt{\overline{\eta}_k}\,\boldsymbol{\theta}^H\, \mathbf{v}_{k,k}}{\sum_{j=1}^{K} \left|\boldsymbol{\theta}^H\, \mathbf{v}_{k,j}\right|^2 + \sigma_n^2} \tag{4.16}$$

Here, $\mathbf{v}_{k,j} = \mathbf{h}_{RD_k}^H \mathbf{h}_{SR} \mathbf{P}_j$. Following the same approach as in[69], the optimized θ for a given ρ can be obtained as follows

$$\theta_{opt} = \left(\sum_{k=1}^{K} \left(|\rho_k|^2 \right) \sum_{j=1}^{K} \mathbf{v}_{k,j} \mathbf{v}_{k,j}^H + \sum_{k=1}^{M} \gamma_k \boldsymbol{\varrho}_k \boldsymbol{\varrho}_k^H \right)^{-1} \left(\sum_{k=1}^{K} \sqrt{\alpha_k}\, \rho_k^* \mathbf{v}_{k,k} \right) \tag{4.17}$$

where $\varrho_k \in \mathbb{R}^{M \times 1}$ is an elementary vector consist of one in the kth position and zeros elsewhere and γ_k is associated with the constraint $|\theta_k|^2 \leq 1$.

Here in this chapter the authors have demonstrated the potential of joint optimization techniques for boosting the system performance.

4.6.2 Simulated Results

The sum-rate performance of the system (as in Fig. 4.11) with joint optimization is evaluated in this section. The performance is evaluated through the numerical simulation using the MATLAB platform considering the parameters as mentioned in Table 4.1. The aim is the analyze the sum-rate improvement due to the joint optimization.

Figure 4.12 represents the sum-rate performance of the IRS-UAV communication system as a function of M. As in the figure, with the increase in M, the system sum-rate performance of the system increases. And also the influence of the number of BS antennas (N) over the system performance is observed. For example, with $M = 70$, the system sum rates are 18.16 bits/sec/Hz and 23.04 bits/sec/Hz for system with $N = 32$ and $N = 64$, respectively. It is clear from the figure that joint optimization significantly improves the system performance. as compared with un-optimized linear precoders along with random phase distribution for the passive beamforming. As in the figure, for fixed BS antennas (say, $N = 64$), the system

Table 4.1 Configurations

Parameters	Value(s)
Base station antennas (N)	[32,64]
IRS elements (M)	[10:80]
User terminals (D) antenna	1
Antenna array structure at BS	ULA with $\lambda/2$ antenna spacing
Transmitted power	30 dB
Cascaded channel model	Nakagami-m and Inverse-Gamma
Number of users (K)	[2]
DOA/AOA phase quantization	$B = 4, 2$
Precoding algorithms	ZF

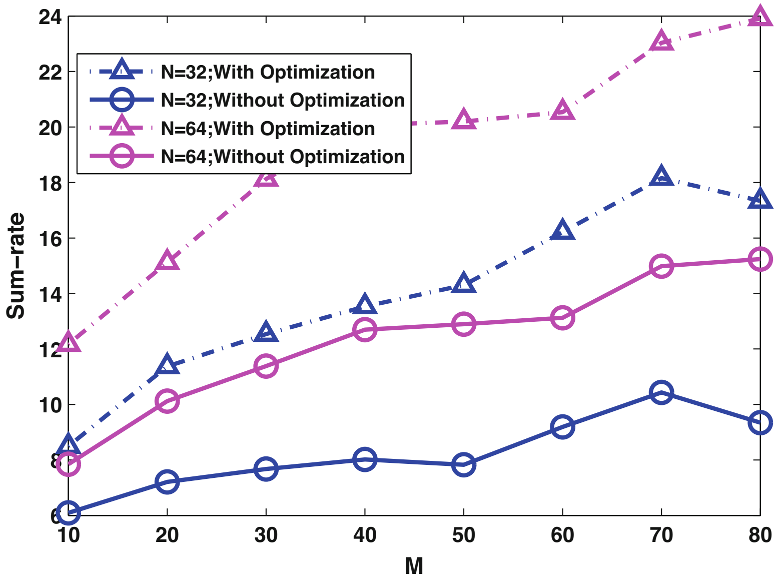

Fig. 4.12 Sum-rate variation with M

sum rates are 23.04 bits/sec/Hz and 14.98 bits/sec/Hz in case of with and without optimization, respectively.

Figure 4.13 represents the sum-rate performance of the system as a function of the number of elements (M) with the variation in fading and shadowing parameters (m and α, respectively). The influence of m and α on the system performance is clearly visible. An increase in m improves the channel condition and the same is true for α. Like Fig. 4.12, it also represents the performance gain due to optimization. For example, with $(m = 2.0, \alpha = 3.0)$ and $M = 80$, the sum rate with and without optimization is 20.33 bits/sec/Hz and 12.13 bits/sec/Hz, respectively. And this presents a significant performance gain. Figure 4.14 represents the sum-rate performance of the system as a function of SNR with the variation of m and α. Influence of m and α on the system performance is clearly visible in Figs. 4.13 and 4.14. For SNR = 10 dB and with $\alpha = 3.0$, the system sum rate is 24.68 bits/sec/Hz for $m = 3.0$ and 15.86 bits/sec/Hz for $m = 1.0$ under the optimized condition. This is because for higher m value, the Nakagami distribution moves towards the Rician distribution.

From the above simulated results, one can conclude that for a AIRS system, optimization of passive and active beamforming plays an important role and it can significantly improve the system sum rate.

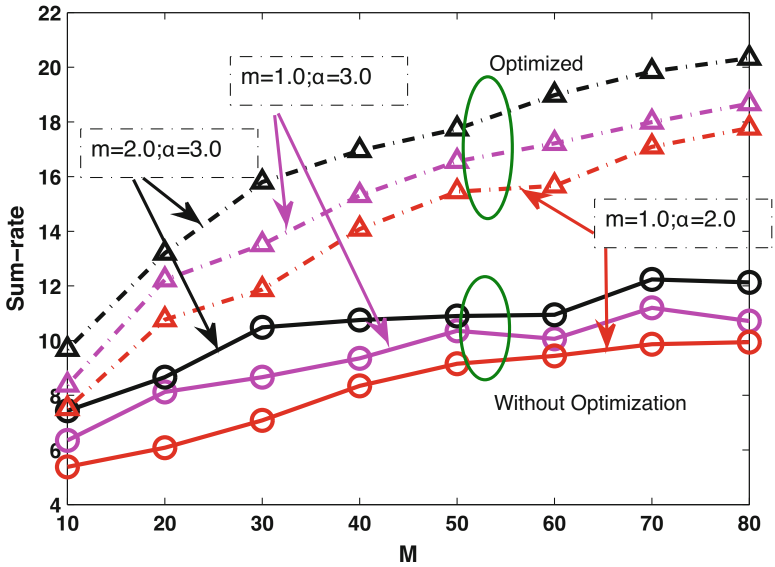

Fig. 4.13 Sum-rate variation with M under different fading condition

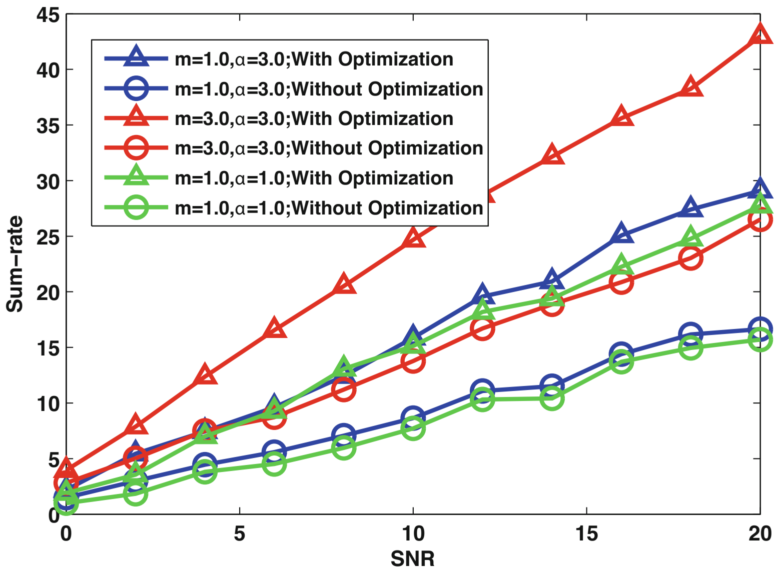

Fig. 4.14 Sum-rate variation with SNR under different fading condition

4.7 Conclusion

This chapter provides a comprehensive overview of the IRS-UAV communication system. Apart from reviewing the research works related to UAVAC systems and IRS-UAV communication systems it also addresses the challenges involved for its successful implementation. It also highlights the works related to the emerging physical layer technologies for the realization of the user demand. Through extensive research works, it is already established that the concept of IRS can be a revolutionary idea for improving the performance of UAVAC systems. Particularly joint optimization of UAV trajectory and IRS passive beamformation plays an important role to boost the system performance. Therefore, IRS-UAV communication system is a promising solution for the future generation communication system and has the potential to improve the sum rate of the networks, the energy efficiency of the system, the security and reliability of the network. In this chapter, the authors have analyzed the performance of the IRS-UAV communication system with joint beamforming optimization to demonstrate the importance of optimization for sum-rate maximization. As a part of future work, the performance of the IRS-assisted multi-UAVs network with joint trajectory and IRS passive beamformation can be explored.

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Samarendra Nath Sur (Senior Member, IEEE) received B.Sc degree in Physics (Hons.) from the University of Burdwan in 2007. He received M.Sc. degree in Electronics Science from Jadavpur University in 2007 and M.Tech degree in Digital Electronics and Advanced Communication from Sikkim Manipal University in 2012 and Ph.D degree in MIMO signal processing from National Institute of Technology (NIT), Durgapur. Since 2008, he has been associated with the Sikkim Manipal Institute of Technology, India, where he is currently an assistant professor in the Department of Electronics & Communication Engineering. His current research interests include Broadband Wireless Communication (MIMO and Spread Spectrum Technology), Advanced Digital Signal Processing, and Remote Sensing, Radar Image/Signal Processing (Soft Computing). He is a senior Member of the Institute of Electrical and Electronics Engineers (IEEE), IEEE-IoT, IEEE Signal Processing Society, Institution of Engineers (India)(IEI) and International Association of Engineers (IAENG). He has published more than 73 SCI/Scopus indexed international journal and conference papers. He is the recipient of the University Medal & Dr. S.C. Mukherjee Memorial Gold Centered Silver Medal from Jadavpur University in 2007. He is also a regular reviewer of repute journals, namely IEEE, Springer, Elsevier, Taylor and Francis, IET, Wiley, etc. He is currently editing several books with Springer Nature, Elsevier, and Routledge & CRC Press. He is also serving as Guest editor for topical collection/special issues of the journal like Springer Nature, MDPI and Hindawi.

Debdatta Kandar (Member, IEEE) received the Ph.D. (Engg.) degree from the Department of Electronics and Telecommunication Engineering, Jadavpur University, Kolkata, West Bengal, India, in 2011, the Postdoctoral degree from the Department of Electrical and Electronics Engineering Technology, University of Johannesburg, South Africa. He has more than 20 years of professional experience. He is currently working as a Professor with the Department of Information Technology, North-Eastern Hill University, Meghalaya, India. His research interests include wireless mobile communication, artificial intelligence, soft computing, and radar operation. He has successfully guided several Ph.D., M.Tech., and B.Tech. students. He has national and international journals, conference proceedings, book chapters, and edited books. For his research work, he was a recipient of the Young Scientist Award from Union Radio Science International (URSI GA-2005) at Vigyan Bhaban, Delhi, India.

Agbotiname Lucky Imoize (Senior Member, IEEE) is a Lecturer in the Department of Electrical and Electronics Engineering, University of Lagos, Nigeria. He received B.Eng (Honours) in Electrical and Electronics Engineering from Ambrose Alli University, Nigeria in 2008, and M.Sc in Electrical and Electronics Engineering from the University of Lagos, Nigeria in 2012. Before joining the University of Lagos, he was a Lecturer at Bells University of Technology, Nigeria. He worked as a core network products manager at ZTE Nigeria Limited from 2011–2012 and as a Network Switching Subsystem Engineer at Globacom, Nigeria, from 2012–2017. Imoize was awarded the Fulbright Fellowship as a Visiting Research Scholar at the Wireless@VT Lab in the Bradley Department of Electrical and Computer Engineering, Virginia Tech., USA, where he worked under the supervision of Prof. R. Michael Buehrer from 2017–2018. He is currently a Research Scholar at Ruhr University Bochum, Germany, under the Nigerian Petroleum Technology Development Fund (PTDF) and the German Academic Exchange Service (DAAD) through the Nigerian-German Postgraduate Program. He is a Registered Engineer with the Council for the Regulation of Engineering in Nigeria (COREN) and a Nigerian Society of Engineers (NSE) member. He has co-edited one book and coauthored over 80 papers in peer-reviewed journals and conferences. His research interests are beyond 5G and 6G wireless communications, chaotic communications, and wireless security systems.

Rabindranath Bera Born in 1958 at Kolaghat, West Bengal, India. Received his B. Tech, M. Tech & Ph.D degree from the Institute of Radiophysics & Electronics, The University of Calcutta in year 1982, 1985, and 1997, respectively. Currently working as Professor (EX-Reader, C.U., EX-Dean (R&D), Head of the Department) at Dept. of Artificial Intelligence and Data Science Engineering. Sikkim Manipal Institute of Technology, Sikkim Manipal University. Prof. Bera involved with the indigenous system development includes Radar, Radiometers, Communication Systems since 1988 at the Institute of Radio Physics & Electronics, Calcutta University in a project on Millimeter Wave Wireless System Development ranging up to 140 GHz sponsored by Ministry of Information Technology (MIT) and rewarded as 'BOSE FELLOW' by URSI, Japan. of India. During this 30 years of extensive and dedicated zeal, Prof. Bera has so far completed more than 7 very high end projects costing more than 15 crores serving MIT, AICTE, DRDO, TISCO, DST and others and formed a core group involving Ph.D. students, Teachers, Scientists, lots of M.Tech / B.Tech students. 15 Ph.D. students awarded their degree under his supervision. He has published few books, book chapters more than 120 International Journals of repute, more than 150 International Conference papers.

Chapter 5
Artificial Intelligence Empowered Models for UAV Communications

Nilanjana Pradhan, Roohi Sille, and Shrddha Sagar

Abstract UAVs and AI are used for a variety of tasks, including object detection, segmentation, tracking, facial recognition, fire and smoke detection, and so on. Drones can collect data from sensors thanks to AI, resulting in a smart, agile model for businesses and consumers. AI technology aids UAVs in identifying things while in flight, resulting in data collection and analysis on the ground. UAVs can recognize and track objects using a neural network, which is considered the foundation model of AI. Drones also help in conducting risky work in construction sites and monitoring agricultural activities. UAVs use a variety of methods from machine learning, which is a subset of artificial intelligence. Deep learning, a subset of machine learning, is also included, which aids with object detection and image recognition. This chapter discusses the usage of artificial intelligence techniques in real-world scenarios. It also discusses usage of UAV in various fields. Better connectivity, a good prediction system, and increased UAV network performance are all made possible by combining AI, ML, and DL. Because they capture photographs via drones and large data is smoothly linked with multiple commercial applications, AI-based platforms offer a lot of potentials.

Keywords Artificial intelligence · Machine learning · Deep learning · UAV

5.1 Introduction

Automation includes not only automated autos but also automated trucks, autonomous watercraft, and automated unmanned aerial vehicles (UAVs). In the subject of automating UAV communications for recognizing objects, fire and smoke analysis, segmentation, and tracking [1], there has been a lot of research.

N. Pradhan (✉) · S. Sagar
Galgotias University, Greater Noida, India

R. Sille
University of Petroleum and Energy Studies, Dehradun, India

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The development of autonomous vehicles for public usage has accelerated in the last decade. The automated devices aid in the automation and control of network traffic. Artificial intelligence has emerged as a powerful technique for enabling automated human decision-making in unmanned aerial vehicles [2] for this automation. Not only is research being conducted using the same AI methodologies, but it is also being conducted on altering the architecture, training on a huge number of datasets, and retrieving the outputs.

There has recently been a significant investment in the development of unmanned aerial vehicles (UAVs) and multi-UAV systems that can collaborate and accomplish missions more efficiently. As a result, new and upcoming technologies, such as 5G and beyond, have a lot of potential for UAVs with sensors delivering IoT services that need the execution of computationally heavy activities [3]. Unmanned aerial vehicles (UAVs) are employed for both civilian and military purposes since they improve connectivity and accessibility. The information for the targeted area is collected and analyzed using a collection of UAVs and cameras. UAVs may easily communicate, exchange, and process sensor-gathered data using a distributed network before delivering it to the preprocessing stage. Due to the massive amount of data transmitted, it consumes a lot of energy and has a lot of latency [4]. In a real-time scenario, artificial intelligence efficiently processes massive volumes of data. UAV datasets include not just photos but also video streaming, for which deep learning algorithms have shown to be state-of-the-art.

Communications, control algorithms, and sensing equipment are all part of a UAV network. For some specific targets, many UAVs work together in a network. Each UAVs equipped with cameras collect visual sensory data for each target (Fig. 5.1). The corresponding sensing data is subsequently swapped for various targets throughout the network. Two architectures are used to share information: dispersed and centralized. The distributed network's nodes aid in the exchange of information as well as the UAVs perform processing and decision-making processes. UAVs can reduce communication overhead and enhance robustness to maintain neighbor connections by using distributed networks. In a centralized network, a central processor handles all duties such as data collection, computation, and command delivery to other nodes. The disadvantage of a centralized network is that the central processor has a single point of failure and additional nodes are only connected to this central unit. Control algorithms, in addition to information sharing, are a major concern for many UAV operations. Because UAVs must generally operate at low altitudes in urban environments due to regulatory limits, UAV-based surveillance systems face various challenges.

To avoid collisions during UAV formation, control algorithms assist in assessing and recognizing impediments present in the target locations. A control method for a team of micro-UAVs was proposed based on the leader-follower technique [4]. The proposed method performed well in terms of maintaining formation shape and smooth movement.

When combined with deep learning techniques, UAV networks have shown to be the most effective surveillance system application. [4] describes a UAV-based platform for crop drought mapping. Multiple unmanned aerial vehicles (UAVs) are

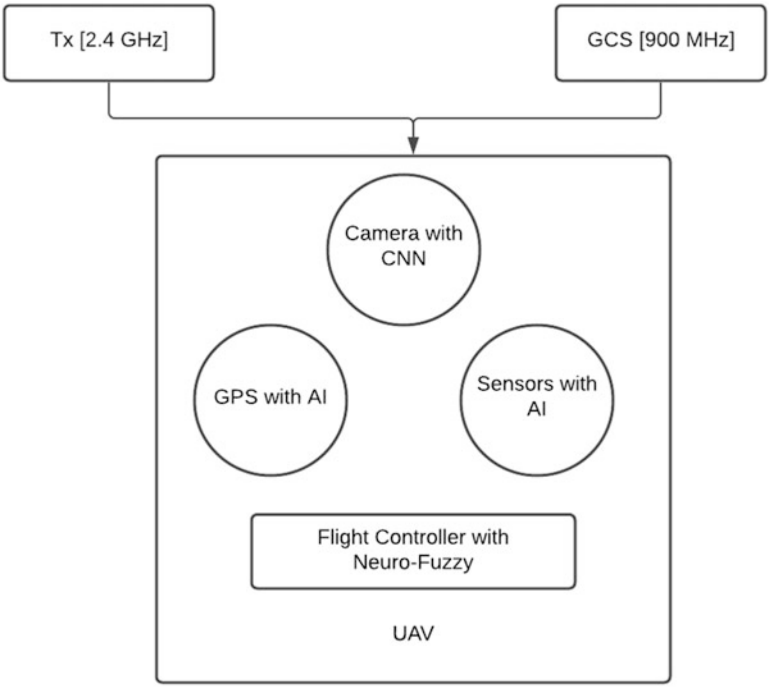

Fig. 5.1 UAV model with embedded AI [5]

employed to monitor and detect traffic congestion in develops a framework for wildfire monitoring based on numerous UAV systems.

Convolutional neural networks are used by UAVs for object detection, mostly in video surveillance. CNNs have been shown to be more accurate in recognizing moving objects with more precision and accuracy. The architecture of CNNs is improved by the introduction of many hidden layers within the architecture [6]. Deeper CNNs can extract features from moving objects with less redundancy, ensuring the acquired image's quality. CNNs incorporated in UAVs have been utilized not only to detect but also to classify the numerous items that have entered the path. Furthermore, the existing state-of-the-art deep learning techniques are effective, but they require a lot of computational resources that affect fetching real-time results. For real-time object detection, quick processing along with low energy consumption is required [7].

Recent research is focused on enhancing the efficiency of the UAV's network by incorporating artificial intelligence techniques for multiple tasks such as object detection, object classification, etc. [8] (Fig. 5.2).

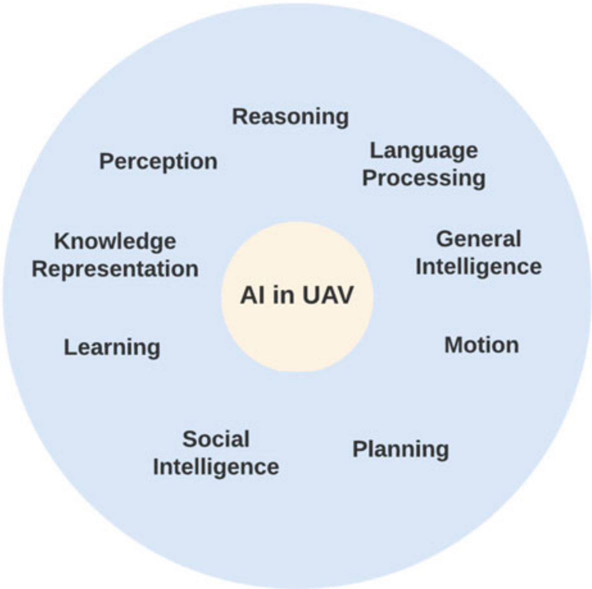

Fig. 5.2 The role of AI in UAV [9]

5.2 Literature Review

Immense research is going on in the field of unmanned aerial vehicles or drones with the emergence of artificial intelligence and deep learning algorithms. These algorithms are facilitating the drones to extract limited and useful features only rather than fetching unnecessary data. More precisely, the shortcomings faced by AV technology such as real-time navigation, visibility, mapping, content uploading, and maneuvering could be supported by UAV technology. Convolutional neural networks are usually preferred for fetching the images and videos of the obstacles arriving in front of drones and helping them to find a clear way out. With the help of CNNs, the redundant information is removed, and it helps in low energy consumption.

A flocking control algorithm is deployed to lead the group of UAVs in the working fields and to avoid obstacles if needed [10]. The method also reduces the training time and classification time compared to existing methods, such as YOLO detection. The overall proposed methods help reduce the storage capacity, transmission bandwidth, and performance in the surveillance application of UAVs. The application of the method helps to reduce approximately 90% of the excess. To collect and analyze UAV-fetched data for plants and trees, a cloud-based and AI-based application has been proposed. This is an interactive application that retrieves information about plant locations, including leftover spaces between plants and dead plants. It makes data processing and visualization easier and encourages

Table 5.1 Literature survey of AI in UAV

References	Technique	Advantage
[16]	Flocking control algorithm	Reduce the training time, storage capacity, transmission bandwidth, and performance in surveillance application of UAVs
[17]	Cloud- and AI-based technique (Agroview application)	Attained less tree detection error
[18]	UAV wireless network (UAWN)	Overcame the challenges imposed by the random fluctuation of wireless channels, blocking, and user mobility effects
[27]	Hierarchical hybrid continuous and discrete action (HHCDA) deep reinforcement learning method	Decreases the request reject rate and average delay by 31.5% and 20% and increases the energy efficiency by 40%

the use of unmanned aerial vehicles in agriculture. A cloud-based and AI-based technique (Agroview application) was developed to automatically process, analyze, and visualize UAV-collected data for individual tree monitoring and assessment. This interactive application included a machine vision algorithm based on deep learning that successfully detected individual plants on aerial maps. An experiment on a large commercial citrus orchard yielded a tree detection error of 2.29% (175,977 trees; 1871 acres; normal and high-density spacing) [11].

Artificial intelligence (AI) enabled unmanned aerial vehicle (UAV)-aided wireless networks (UAWN) which are proposed to overcome the challenges posed by random fluctuation of wireless channels, blocking, and user mobility effects. The potential of AI techniques in UAV-assisted wireless networks is investigated. Both big data-assisted feature extraction and machine learning-assisted optimization solutions improve the quality of service for users. The key advantages of AI-enabled networks were identified when compared to traditional UAWN (Table 5.1).

5.2.1 Unmanned Aerial Vehicles (UAVs) and Artificial Intelligence Are Revolutionizing Wildlife Monitoring and Conservation

Monitoring sea turtles, black bears, large land mammals (e.g., elephants), marine mammals (e.g., dugongs [12]), and birds, such as snow geese (21), is an example of current uses of UAVs for wildlife management. In addition, UAVs can be used to support anti-poaching operations for rhinos. These digital and thermal imaging sensors allow for high-definition video recording and closer animal imaging than manned aerial surveys. It was concluded that a UAV could overcome "safety, cost, statistical integrity, and logistics" issues associated with manned aircraft for wildlife monitoring by conducting more than 30 missions over 2 years. Autonomous tracking of radio-tagged animals is another advancement in this field.

The use of unmanned aerial vehicles (UAVs) to conduct wildlife monitoring surveys has proven to be effective, but in many cases, the extensive post-processing effort required negates any convenience or time savings afforded by the use of UAVs in the field. Because of this, for UAVs to be a truly effective wildlife monitoring tool, they must be able to automatically detect and count animals in the imagery collected by UAVs. Automated image classification for wildlife monitoring is being developed. As an example, van Gemert et al. evaluated the use of UAVs and advanced object detection techniques for the detection of animals, demonstrating a promising solution for conservation purposes [13]. With 93.3% accuracy in an altitude range of 3–10 m, researchers used thermal imagery and an algorithm to classify between animal and nonanimal objects, which was achieved using a structure that was elevated rather than a drone. A system of a UAV equipped with thermal image acquisition as well as a video processing pipeline to perform automated detection, classification, and tracking of wildlife in a forest setting is described in this paper, which further addresses the issue of automated wildlife detection in UAV imagery.

For counting and tracking algorithms to count, track, and classify wildlife on the ground control station computer, we implemented two algorithms. Depending on the image or video's content, a different strategy is needed. Color, size, and position thresholds can be used to identify an object of interest in a photograph of, say, a koala, deer, or kangaroo. If the image is less clear, for example, if the object is an irregular shape, with no apparent color, of variable size, or in multiple positions, more complex algorithms are needed. For ease of access to open-source computer vision libraries, such as OpenCV, the algorithms were written in the Python programming language using the SimpleCV framework [14]. The pixel intensity threshold (PIT) approach is an algorithm that uses the wildlife's heat signature to create a good contrast between the target wildlife and the background. Because of the high contrast, an intensity threshold can be set to eliminate the background and highlight the subject at hand. For all pixels below or equal to the threshold, the intensity threshold is set to 0 and all pixels above the threshold to 255, respectively. This corresponds to the black and white colors, respectively, of an image when using the term "binarization" or "image segmentation" [15].

5.2.2 Unmanned Aerial Vehicles in Agriculture

UAVs are rapidly replacing satellites and other aircraft in the field of agriculture. Initially, unmanned aerial vehicles (UAVs) were used for military and surveillance purposes. Images taken by unmanned aerial vehicles can be of high quality at a low cost compared to images taken by other types of vehicles, such as satellites and aircraft. However, UAVs fly at lower altitudes, allowing them to acquire clear images more quickly and easily than traditional aircraft. Thus, the use of UAVs in agriculture is increasing at a rapid pace. Controllers, sensors, and communication methods were used in previous studies. The various types of platforms—fixed-wing and rotary-wing unmanned aerial vehicles (UAVs)—dominate the UAV market. The appearance of a fixed-wing unmanned aerial vehicle (UAV) is very similar to that of an airplane. It is propelled by a combination of thrust and aerodynamic lift. The most common use of fixed-wing drones is for spraying and photography, but they can also be used for other purposes. Helicopters and multirotor UAVs both have rotary wings. A large propeller sits atop the helicopter's body. In addition to spraying, it is also used for aerial photography [16]. Many multirotor models are referred to by their rotor count, such as a quadcopter, which has four rotors. There are six rotors on each of the hexacopter and eight rotors on the octocopter respectively. The number of rotors is determined by the amount of payload and the size of the UAV. For spraying, octocopters, helicopters, and fixed-wing aircraft have the largest payload capacity (9.5 kg). Quadcopter and hexacopter payloads range from 1.25 to 2.6 kg, making them smaller and lighter than helicopters. These devices are employed for reconnaissance and mapping purposes. In terms of payload capacity, fixed-wing and rotary-wing UAVs are the most capable, followed by helicopter-style drones (22 kg) [17]. Precision agriculture is becoming increasingly popular with the use of fixed- and rotary-wing UAVs. Pollen-moisture distribution and precision control are two common applications for multirotor UAVs. MAVLink is a standard protocol for connecting unmanned aerial vehicles (UAVs) to a ground station (GCS). UAV and GCS applications communicate with each other via physical means, such as through the use of a computer (e.g., Raspberry Pi, Arduino, and UDOO) or a control platform (e.g., Pixhawk and Ardupilot). Using GNSS, MAVLink transmits the UAV's location and speed. If the UAV is within line-of-sight, it can communicate up to 2 km away from the GCS, depending on the specifications [18]. When communication is lost, unmanned aerial vehicles (UAVs) are programmed to return to their starting point. Enabling return-to-launch mode helps prevent accidents. Communication between the GCS and UAVs is physically possible via ZigBee and radio frequency modules. Phone apps, for example, can be used to extend the range of communication. There is also a shift in cellular technology occurring right now, from 4G to 5G, which has the potential to greatly improve communication and data processing speeds, both of which will be helpful for high-definition mapping [19].

The field of unmanned aerial vehicles (UAVs) is rapidly evolving. The speed of communication has greatly improved. The speed with which data is processed has vastly improved. The reach of a worker's control is extended as communication range increases [20]. UAVs and UGVs are currently using simultaneous localization and mapping (SLAM) technology, which is based on autonomous driving. SLAM technology uses a camera and/or LiDAR to map in real time. While autonomously travelling or performing tasks, it recognizes its location and detects obstacles. Because it is self-contained, the technology does not require the use of existing controllers and is both efficient and practical. We are getting closer to smart agricultural capability as a result of these developments. Harvesting has been tested thanks to the development of soft grippers. It's far from perfect, but the tools and techniques are getting better. A UAV's robotic arms can be fitted with soft grippers. The harvesting actions can then be learned and controlled using a camera attached to the gripper [21]. UAV and UGV teams are being studied for combined agricultural tasks using swarm-control techniques. Multi-robot technology will most likely be possible in the next few years. The agricultural UAV market has virtually no limits. Research and development in its infancy still face numerous obstacles and limitations. An overview of agricultural UAVs that have been developed or are currently being studied is presented in this paper. A variety of limitations, applications, and current trends in agricultural UAVs are also discussed, as is the direction in which research will go in the future. A closer look at UAV hardware for agricultural purposes was done first (platform types, components/sensors, and communication) to be more specific. In addition, we discussed agricultural UAV operation modeling, control systems, and control (such as linear, nonlinear, learning-based, and swarm) [22]. The use of agricultural UAVs for mapping, spraying, planting, and monitoring has been thoroughly investigated and classified as a field of application. This was followed by a detailed discussion of potential applications, the limitations (such as batteries and user interface), and future technology trends in harvesting, precision mapping, and developing countries (communications, SLAM, aerial manipulator, and multi-robot systems). Using a multi-robot system, we were able to circumvent the problems and drawbacks that come with a robot-based smart farming system [23].

5.2.3 Fuzzy Logic Approach for Unmanned Aerial Vehicles

The approach of fuzzy logic imitates decision-making in humans. Unlike two-valued Boolean logic, fuzzy logic is multivalued. It deals with degrees of membership and degrees of truth [24]. A fuzzy rule can be defined as a conditional statement in the form IF x is A, then y is B, where x and y are linguistic variables and A and B are linguistic values determined by fuzzy sets on the universe of discourses X and Y, respectively. For a fuzzy expert system to achieve implementation abilities, a system has to be able to obtain a single crisp solution for the output variable by first aggregating all output fuzzy sets into a single output fuzzy set and then demulsifying the resulting fuzzy set into a single number. This is achieved through the fuzzy inference systems (FIS) [25]. FIS is a process of mapping from a given input to an output, using the theory of fuzzy sets. The two main types of FIS are Mamdani and Sugeno systems discussed in the next sections. The structure of any Mamdani system looks as follows: If x is A and y is B, then z is C, where x and y are linguistic input variables and is Z is the linguistic output. These input and output variables could be stated in language form. An example of that can be stating temperature measures as being "cold, medium, and hot" or distance measures as "far, intermediate, and close" and so on. The Mamdani inference process is performed in four steps: Input variables are fuzzed out. The second step is to evaluate the rules. The rule output is aggregated here. Defuzzification is the fourth step. The Mamdani method for capturing expert knowledge is widely accepted. As a result of this feature, users can describe their expertise in a more human-like way. This paper uses a Mamdani-type FIS to capture human knowledge and allow the UAV to make autonomous decisions in the data generation (predefined UAV mission). There is a significant computational burden associated with this FIS, however [26].

Here is how the Sugeno model works: If x and y are fuzzy sets on the universe of discourse, then the output of the mathematical function is known as $f(x, y)$ (x, y). When applied to dynamic nonlinear systems, Sugeno's method is highly efficient and works well with optimization and adaptive techniques. There is no better candidate for a hybrid system than this one, as it will both explain and learn from collected data (experience). In [27], grammatical evolution was used to evolve the structure of fuzzy rules, and the rules were visualized in parallel coordinates. Accordingly, grammatical evolution is used to evolve fuzzy rules for both normal and abnormal traffic classifications based on the KDD99 intrusion dataset. The non-linear response of the laser lap welding process is identified using the grammatical evolution approach. Because of this, it is possible to build intelligent systems by merging neural networks and fuzzy logic into one single integrated system. The parallel computation and learning abilities of neural networks can be combined with the human-like knowledge representation and explanation abilities of fuzzy systems. In the proposed explainable artificial intelligence (XAI), we aim to improve explainability while maintaining high learning performance for a variety of machine learning techniques. The performance (predictive accuracy) and explainability of machine learning are inherently at odds. Deep learning and decision trees are often the least explainable and the most accurate methods (e.g., deep learning) [28]. This paper introduces the use of a combination of fuzzy logic (highly explainable) and neural networks to address the performance versus explainability trade-off (accurate prediction) [29]. This is the first time that ANFIS has been proposed to develop an XAI system, to the best of our knowledge. There are two types of machine learning algorithms: those that learn from previous data and those that learn from expert knowledge (make predictions). Thus, the research hypothesis is as follows:

Using the original decision-making model's output data as input into a new explainable model, and the original decision-making model's inputs as outputs in the explainable model, the explainable model's outputs will serve as reasoning for actions taken during the decision-making process. Because of this, it is important to provide a rationale for a decision. A machine learning algorithm that can both learn and explain why it is making a prediction is the goal of this paper [30].

5.2.4 Machine Learning and UAV

Researchers have been studying unmanned aerial vehicles (UAVs) for the past few years, and since then, UAVs have become commonplace in civilian and military environments. Many researchers have tried to use UAVs as an ideal platform for inspecting, delivering, monitoring, and so on, as well as other purposes. The application of machine learning to unmanned aerial vehicles (UAVs) for autonomous flight, in particular, has allowed UAVs to perform their assigned tasks more efficiently. Machine learning has a long history and a wide range of classifications, and this paper focuses on the current state of the art when it comes to autonomous flight of unmanned aerial vehicles (UAVs). In the literature, we provide control strategies such as parameter tuning, adaptive control for uncertain environments, real-time path planning, and object recognition [31].

In computer learning, artificial intelligence (AI) was coined by Alan Turing in 1950 after the first computers were created. A series of questions and answers were put forth by him as an attempt to separate machines from people, which he called the "Turing test." It was considered "intelligent" like a human if the computer passed the exam. It wasn't until 1956 that the field of artificial intelligence was recognized as a legitimate academic discipline. Originally, AI was defined as an intelligent agent capable of learning and problem-solving in a changing environment, as well as adapting to it. Many researchers have attempted to apply AI to a variety of fields over the past 60 years, but the technology has yet to reach its full potential because of a lack of understanding about how computational capacity is limited by environmental factors. There was a noticeable rise in AI in the 2000s as the Internet became more widely used, sensors became more common, and big data became more accessible. Natural language processing, knowledge representation, automated reasoning, and machine learning are just some of the areas where AI has been studied in recent years. Artificial intelligence (AI) is advancing in many areas, including machine learning. Without having to write any code, machine learning has been used by many researchers to identify patterns in data and predict future outcomes. Autonomous flight and intelligent behaviour in particular are being studied with UAVs through the use of machine learning. Using machine learning, UAVs can address a wide range of issues, including intelligent control strategy and object detection. There are three main types of machine learning: supervised, unsupervised, and reinforcement learning. Supervised learning is the most common machine learning technique. Observing input-output pairs teaches an agent a function that maps output to input. So the agent is looking for ways to label the output based on the presence of the input. A classification problem occurs when the output is one of the limited number of possible "classes" for an input x, which is the case in this case. When the output is continuous, the issue is referred to as a regression problem. There is no labelling of output in unsupervised learning (UL). As a result, instead of receiving labelled data, an agent focuses on observation and pattern recognition in the real world. Hidden patterns, structures, or features can be found in the data by using a data mining approach. Using clustering as a case study, unsupervised learning can be demonstrated. The agent can identify several clusters by simply glancing at the data and then classifying each piece of data into the appropriate cluster. Learning from feedback is the primary goal of reinforcement learning (RL). A reward is the term for this type of feedback. The process is repeated until the agent decides on the best course of action to maximize their expected total reward [32]. As a result, reinforcement learning's goal is to learn an optimal environment policy based on observed rewards. It is assumed that a Markov decision process (MDP) exists, which includes the set of states S, actions A, rewards R, and transition probabilities T that represent a system's dynamics. T(s,a,s) = P(s|s, a) describes the impact of actions on the state. The next state and reward are determined solely by the previous states and actions, and no additional information about the previous states or actions is available. When it comes to forecasting the future, the state is considered to be the only statistic that matters. One of the most commonly used machine learning techniques is called "deep learning," and it's based on human intelligence. DL algorithms use neural networks (NNs), which are hierarchies of simple neurons, to explain complex systems. It is possible to classify DL algorithms based on their characteristics: supervised, unsupervised, and reinforcement learning. Machine learning advancements have made it possible to operate self-flying UAVs on their own. For UAVs, we focus primarily on the most recent advancements in autonomous flight and object recognition. Prior research shows the timeline of previous studies. In the real world, even with highly nonlinear dynamics and uncertainty, a UAV's control strategy is essential for autonomous flight. Researchers are now looking into ways to use machine learning to improve control strategies [33].

5.2.5 Robotics and UAV

A timeline of earlier investigations into UAVs and machine learning resulted in the study of various fields that we classify into three categories i.e. parameter tuning, adaptive control and real-time path planning and navigation [16]. Tuning of parameters: In the simplest application of machine learning, parameter tuning for the objective function in the control system is used. Parameter tuning is critical for UAV controllers in real time if they are to quickly adapt to new environments. PID controller parameter tuning using machine learning algorithms has been studied in several studies. Using feedforward neural networks (FNNs), an approximator coefficient that approximates the PID controller's response can be obtained. Fifteenth-order generalization of the integer-order PID controller is achieved by exploiting the non-integer orders of Laplace variables, which provides additional complexity. Although the PID controller performed similarly in the simulation, it required far less computation than the real-world controller. However, because the demonstration is limited to linear models, it is necessary to test more complex models. By optimizing control parameters, an intelligent PID control based on radial basis function (RBF) neural network (NN) enables the PID controller in UAVs for autonomous flight. In the RBF NN, the input layer, a single hidden layer, and the output layer are all feedforward networks. A radial basis Gaussian function is used as the network activation function of the hidden layer in the RBF NN. To better control pitch angle, the RBF NN algorithm outperformed traditional PID control in a simulated environment. The algorithm must be applied to both roll and yaw angles, and both angles must be controlled at the same time for future progress. RBF NN-based PID control algorithm overcomes the PID method's nonlinearity and parameter uncertainty [34]. This algorithm can adapt and learn on the fly. A quadrotor's attitude and position controllers are designed to follow the predicted trajectory. After a wind disturbance, the RBF NN-based PID algorithm recovered faster than the conventional PID algorithm and reduced 17% of overshoot. Tracking and anti-disturbance performance were not improved by the PID algorithm. To overcome the proposed method's shortcomings, it will be interesting. Santos et al. used the learning automata (LA) algorithm to adjust the PID controller parameters for quadcopter attitude and path tracking controllers. Learning automata, one of the reinforcement learning methods, is an adaptive decision-making method that learns the optimal action from a set of actions through repeated interactions with a random environment. The parameters of controllers were adjusted for a nonlinear UAV, taking into account nonlinear disturbances, using LA. The simulations performed nonlinear tracking and flip maneuvers, while the experiments tested position tracking performance. Even in the presence of wind and ground effects, simulation results showed a better performance than the conventional method of adjusting a controller. Using simulated tests as a benchmark, the experiments showed that tracking performance was not significantly different.

Optimal weighting parameters of the objective function for quadcopter trajectory planning based on model predictive control (MPC): To get the most out of an autonomous vehicle's energy consumption, MPC-based techniques require a lot of computing power. Tracking error performance was improved by selecting a weighted cost function over time. It is planned to test the tuning methods on a quadcopter in the future.

Adaptive control based on neural networks: There has been various applications of adaptive control algorithms based on neural networks (NNs) for autonomous flight in UAVs. There is an increasing interest in adaptive control stems from its ability to handle changes in system dynamics and mitigate uncertainty. Based on the intelligent behavior of the human brain, NN consists of many simple, connected processors called neurons, each producing a sequence of real-valued activations. This yields great advantages in high-dimensional data representation and processing; therefore, NN has been widely used to solve complicated adaptive control problems of UAVs for autonomous flight.

5.2.6 Prospects of the Development of Unmanned Aerial Vehicles (UAVs)

Rapidly developing technology has become both a boon and a curse on entrepreneurs. While it expanded business opportunities, it turned out that some market positions were quickly becoming obsolete due to improved navigation and flight software. The industry now began to select the most profitable business plans, and survival tactics included shifting the company's focus, including finding new target customers. Airware, the highest-paid startup, originally developed cloud software and autopilot systems for agricultural drones. They had to fly over land and collect data on crop conditions and assess field humidity and pest availability. But most farmers are not yet in a position to use such information, and companies need to look for new ways to use their drones. UAVs have been established in the past, especially during the last decade. Generally, it can be stated that the WTO will play a major role in armed conflicts of the twenty-first century using conventional means of defeat. At the same time, local wars and regional military conflicts show the growing role of UAVs, a promising type of military equipment used for various military tasks: from the strategic and operational level to the tactical level, including flights in the interests of individual servicemen. The newly designed UAVs with new systematic architecture, construction methods, sensors, and algorithms will be optimized and adapted for various uses in the next 10 years or so. The composition of the laboratory should facilitate for modeling and debugging, and it includes hardware based on a real digital control system and software in the form of mathematical models of flight dynamics and specialized control software. The complex should also supplement with the necessary control and verification equipment (rotary table, aneroid-membrane test equipment, etc.) and measuring equipment [35].

5.2.7 Smart Agricultural Irrigation Using Unmanned Aerial Vehicles

An application of modern and accurate information and communication technology to difficult agricultural tasks or processes is called “smart agriculture” or “precision agriculture.” Many new wireless applications, ranging from environmental monitoring to health and medical monitoring, are enabled by the Internet of things (IoT). Data from sensors measuring various parameters such as soil moisture and humidity is collected and monitored remotely via mobile applications developed for smart agriculture via IoT. Decisions can be made, or devices, such as water pumps, can be actuated remotely. The farmers’ workload will be lessened as a result of better utilization of available resources and low-cost equipment. The use of AI techniques, such as neural networks, fuzzy logic controllers, and more recently deep learning models, can assist farmers and specialists by analyzing agricultural and environmental data. Smart agriculture’s biggest challenges are crop monitoring and disease detection, which must be done continuously. We will use IoT and unmanned aerial vehicles (UAVs) to propose only two solutions to the problems of field monitoring and irrigation automation in this study (UAVs) [35].

Drones are other names for unmanned aircraft systems (UAS), which include UAVs. Drones are flying robots that can be piloted from a distance. It used to be that unmanned aerial vehicles (UAVs) were only used in warfare or intelligence gathering by the military, but that is no longer the case. Civilian uses of drones have recently expanded to include everything from search-and-rescue to traffic monitoring to weather forecasting to delivery services. UAVs, or unmanned aerial vehicles, have been shown in numerous studies to play an important role in agricultural monitoring and forecasting. Using thermal or infrared imaging cameras and a cloud-of-things (CoT) network, drones can also perform intelligent irrigation monitoring. In addition, the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) report that manual spraying of pesticides in the field causes dangerous diseases for farmworkers. As a result, UAVs are an excellent option for spraying pesticides automatically while also reducing the risk of environmental and health issues for farmers.

5.2.8 Internet of Things (IOT)-Enabled Unmanned Aerial Vehicles

Computer vision and machine learning for damage detection and to render an image for a machine's perception, computer vision, or image processing is the most popular choice. Numerous image processing-related studies have been done to inspect buildings or construction sites, both indoor and outdoor. This section will review the most recent findings. A lot of progress has been made over the past two decades in the field of computer vision technique design for the inspection of construction sites both offline and online. Many algorithms, such as the convolution neural network (CNN), were developed during this period and used to detect cracks in metal surfaces. A nondestructive image processing algorithm is proposed to monitor the defects of historical buildings; one can see the research contribution. Building structures were the primary focus of the research. It was also found that it is extremely difficult for an automated system to identify defects without taking into account physical variables like temperature and humidity.

Automating the process of defect analysis and detection using these physical parameters necessitates an extraordinary approach (machine learning tactics). In the literature, cost-effective and deep learning-oriented damage analysis strategies can be found. There were over 30,000 iterations and 3 hours of training for the CNNs in this method. It was found that the proposed method yielded high-accuracy results and reliable identification. The algorithm's only flaw was that it had to be trained on an unknown fault or irregular defect before it could be used. Similarly, spalling and corrosion were used to identify earthquakes. In real time, the results had an accuracy rate of more than 86%. The authors of this work suggested using unmanned aerial vehicles to carry out the entire large-scale inspection at a reduced cost and time.

The only way to combine machine learning algorithms with image processing strategies and perform fault/defect analysis and identification with high accuracy and speed is through hybridization. Artificial neural networks and CNNs have proven to be useful in a variety of fields, so they are being considered for use in UAVs to improve real-time response times. For large-scale construction site inspection and surveillance, there were several trending techniques [35].

These constraints can be addressed in this manner, including network scalability and computing constraints, as well as a wide range of applications. Not only can this setback be overcome, but these three critical Internet-of-things expectations can be further enhanced by introducing IoT-enabled UAVs. A surge in the Internet of things (IoT) has taken place over the past few years, and it has been utilized in many different areas. With the Internet of things (IoT), the system can be connected to a variety of Internet capabilities. Machine-to-machine communication is most commonly used by us. Consequently, the paper suggests that a supervisor of the entire construction site use a base station system to communicate with the drone and monitor the progress of work. IoT and AI and computer vision algorithms are increasingly being combined to produce better results over the past decade. A major reason this manuscript discusses IoT-enabled drones is that IoT can analyze data extracted from images captured by drones and better measure the overall progress at the site. This ability is commonly referred to as “automated” in the field of intelligence. Construction site automation has been around for a while, but it’s still in its infancy compared to the concept of automated intelligence. The primary goal of using IoT is to process and analyze the enormous amounts of data generated by a UAV-enabled camera. Using automated intelligence, one must meet the following three constraints to get reliable results.

Scalability of the network refers to a network’s ability to grow indefinitely without sacrificing its current level of coverage. Assuring the best algorithm for extracting data and determining the result is known as intelligence. A wide range of sensors can support data diversity.

Convolutional neural network CNNs are feedforward neural networks having multiple hidden layers. CNN comprises convolutional layers, pooling layer, ReLu layer, dropout layer, and fully connected layers. CNN is part of a deep learning algorithm in which the neural network layers are organized hierarchically. The initial layers such as convolutional, pooling, and ReLu act as a feature extractor, whereas the last layers such as fully connected layers perform classification, segmentation, and object detection. The pooling layers help in the downsampling of unwanted features from various feature maps. ReLu or leaky ReLu acts as an activation function. The dropout layer helps in solving the overfitting issues (Fig. 5.3) [36].

5.3 Conclusion and Future Scope

This chapter concludes the use of UAVs in real-time scenarios, and artificial intelligence techniques have improved the accuracy of UAVs. AI techniques have not only been used for object detection but also image segmentation, recognition, monitoring, reasoning, planning, etc. Usage of AI-empowered techniques has

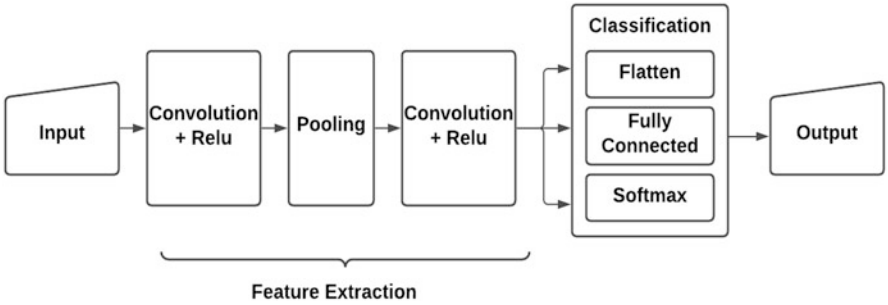

Fig. 5.3 CNN model for UAV's camera

enhanced the output of UAVs in every field such as military, agriculture, autonomous flight, research, and development. Deep learning algorithms have proven to be the state of the art in improving the performance of UAVs. Mostly, convolutional neural networks are used for image segmentation, object detection, and recognition. Fuzzy-based neural networks are also used for reasoning and predictive planning of motion in UAVs. Recently research is going on in the field of developing hybrid models combining fuzzy logic and deep learning algorithms to easily predict the object's motion and self-driving capability of drones or UAVs. AI-built drones would not only detect, classify, and segment the object but also help the UAVs in accurate and precise monitoring and planning of the UAVs to take appropriate action in advance. All the movement control of UAVs will be controlled with the help of AI instead of manually handled.

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Nilanjana Pradhan, is a PhD Scholar at Galgotias University, Greater Noida, India. She has an extensive experience of 14 years as an Assistant Professor in Computer Science. Prior to joining Galgotias University, she was at the University of Petroleum and Energy Studies as an Assistant Professor (CSE) and as a Machine Learning Professor at Pune Institute of Business Management, a reputed institute under the affiliation of Pune University. She completed B.Tech in Information Technology from the University of Calcutta, West Bengal, India. She holds an M.Tech in Information Technology from the West Bengal University of Technology. Currently, she is pursuing a PhD in Alzheimer disease prediction modelling using machine learning and deep learning concepts at Galgotias University, Greater Noida, India.

Roohi Sille, completed an M.Tech in Artificial Intelligence and Neural Networks from the University of Petroleum and Energy Studies, Dehradun, India, in 2014. She holds a B.Tech in Biomedical Engineering from Bundelkhand University, Jhansi, Uttar Pradesh, India, in 2012. She is currently working as Assistant Professor at UPES, Dehradun, India. Her research area is in machine learning, deep learning, and image processing, and she has 7 years of experience in teaching.

Shrddha Sagar, is a Professor in the School of Computing Science and Engineering, Galgotias University, NCR, Delhi, India. She received a PhD degree in Computer Science from Banasthali University, Jaipur, India. She has more than 14 years of experience in teaching and research. Her current research areas are artificial intelligence, the Internet of things, machine learning, and big data. Dr. Shrddha Sagar is the author of over 10+ book chapters published by some reputed publishers such as Springer, Elsevier, Wiley, CRC Press, and IGI global and 25+ international journals and conferences. She adopts a universal and humanistic approach in her academic and research works. She has undertaken meticulous scientific studies of emerging issues in several disciplines in her research. Professor Shrddha Sagar has also received invitations to address international conferences as a keynote speaker. She is a Senior Member of the Institute of Electrical and Electronics Engineers (IEEE), IEEE Women in Engineering (WIE), Member of ACM, Life Member at IAENG, Life Member at IRED, and Fellow Member at IACSIT.

Chapter 6
Reconfigurable Intelligent Surface (RIS)-Assisted UAV Cellular Communication

P. Ihsana Muhammed, Yasar Moidutty, N. M. Sreenarayanan, and V. M. Meera

Abstract An *unmanned aerial vehicle*, *UAV*, is an aerial vehicle without a directing pilot and is controlled remotely by humans. UAVs have applications in emergency rescue missions, surveillance, package delivery, and weather and traffic management. UAVs can also be used to improve the characteristics of wireless or mobile communication technologies. It can also be used as a wireless access point in wireless ground communications. To turn the above applications into reality, UAV requires control over wireless transmission channels to operate remotely and safely. The radio propagation standard characteristics in which it operates are entirely different from the conventional ground users (GUEs). Considering all these challenges, studies have been taking place with the aim of cooperating with UAV communication in today's wireless mobile networks. Reconfigurable intelligent surfaces are emerging hardware technology that can be used to improve transmission medium characteristics and improve energy efficiency. RIS can be used in wireless networks to generate a smart radio environment. By using RIS, it enables the user to configure the transmission of electromagnetic waves in a user-programmable manner. RIS can receive radio signals from the transmitter and beamform inactively toward the receiver by inciting a manageable phase shift. This increases the signal energy and improves the data rate also. RIS can control the wireless transmission channels partially and provide us with more favorable propagation characteristics. For this reason, it is well suited for UAV cellular communications by which it is possible to improve the communication quality and provide a reconfigurable propagation environment.

P. Ihsana Muhammed · V. M. Meera
Computer Science and Engineering, Royal College of Engineering & Technology, APJ Abdul Kalam Technological University, Thiruvananthapuram, Kerala, India

Y. Moidutty
Artificial Intelligence & Data Science, Royal College of Engineering & Technology, APJ Abdul Kalam Technological University, Thiruvananthapuram, Kerala, India

N. M. Sreenarayanan (✉)
Computing Science and Engineering, Galgotias University, Greater Noida, Uttar Pradesh, India

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Keywords Unmanned aerial vehicle · Channel modeling · UAV cellular communication · RSS-assisted UAV · Tackling propagation · Propagation pathloss · Propagation modeling · Spectrum sharing · Massive multiple access · Reconfigurable intelligent surfaces

6.1 Introduction

It is expected that the number of network connections and networked devices will reach up to 28.5 billion by the year 2022, as per the report of Cisco in the year 2019. Of these 28.5 networked devices, 12.3 billion consist of mobile devices and connections. This drastic growth of connections will result in the data traffic growing up to 77 exabytes per month by 2022. And further, this is expected by 2030; it will reach 5016 exabytes per month. This is surely a big challenge for current mobile communication networks. This enlightens the significance of the evolution and progression of portable communication technologies. As a result of years of studies, the first fifth-generation (5G) communication standard has been completed in 2018. But studies during the 5G standards show that no technology supports 5G applications altogether. So in the last few years, innovative wireless transmission technologies have been investigated to support 5G applications and to meet these large demands of mobile network devices.

In the recent years, studies and research are going on to improve service quality and simplify the transceiver architecture of mobile communication. Spatial modulation is one of the popular methods that emerged as the result of these studies. Another study resulted in media-based modulation. In this media-based modulation, information is encoded into identifiable radiation patterns by using reconfigurable antennas. In all these abovementioned methods, different signatures are generated from the interaction of the received signals, which are used to transmit data with lesser complexity.

As per the studies, 5G is not able to support the enormous demand for mobile communication by 2030. The mMIMO and mmWave are the two common techniques used in 5G today. These existing techniques mainly concentrate on sender and receiver system design to avoid adverse conditions in the propagation environment. The mMIMO technology makes use of the spatial domain by setting the number of antennas to facilitate multiple user communication using the same measure of frequency, resource, and time. The mmWaves use the abundant number of spare spectrum in high-frequency bands, which in turn resolves insufficiency issues of the spectrum at microwave frequencies. Even though mMIMO and mmWaves enhance the efficiency of the spectrum, the cost of hardware and complexity are the main difficulties in their implementation. In addition to that, mmWaves are highly endangered to path loss and signal blockage.

UAVs are commonly used in emergency search and rescue missions, surveillance, package delivery, weather, and traffic management and can also be used to improve the characteristics of wireless or mobile communication technologies. It can also be used as a wireless access point or as a relay node in wireless ground communications. UAVs can be used to enhance communication quality due to their high mobility. The LoS transmission channel links dominated between the top UAVs and the ground-controlled devices since UAVs transmit from a high altitude. Considering the abovementioned things, UAV communication is preferred beyond fifth-generation B5G and sixth-generation (6G) networks.

Recently, an innovative, cost-effective, revolutionary, and brand-new technology has emerged, known as reconfigurable intelligent surface (RIS) which is capable of configuring a wireless medium. Special electromagnetic raw material that is significantly electronically controlled and has unique proper wireless communication capabilities is used for RISs manufacturing. The main difference of RIS from other technologies which are currently being used is that it can make the environment controllable. RIS has similarities with the currently deployed SM-based systems but also differs. RIS aims to improve the signal strength at the receiver by controlling the propagation channel. In the current wireless network technology, it is not possible for the operators to control the propagation environment. But RIS provides a smart environment which turns the wireless network into a reconfigurable one, making it possible for the operators to control the transferring and processing of information. RIS also enables us to control the propagation path loss from refraction, reflection, and scattering of EM signals. Hence it can be used to avoid device-to-device interference and helps to achieve necessary data rates.

RIS-assisted UAV communication is a big advancement in the field of wireless transmissions, and it will help to reduce the complexity of the wireless transmission medium as shown in Fig. 6.1. As depicted in Fig. 6.1, the RIS-assisted drones or UAV systems are capable to improve the channel transmission quality status in

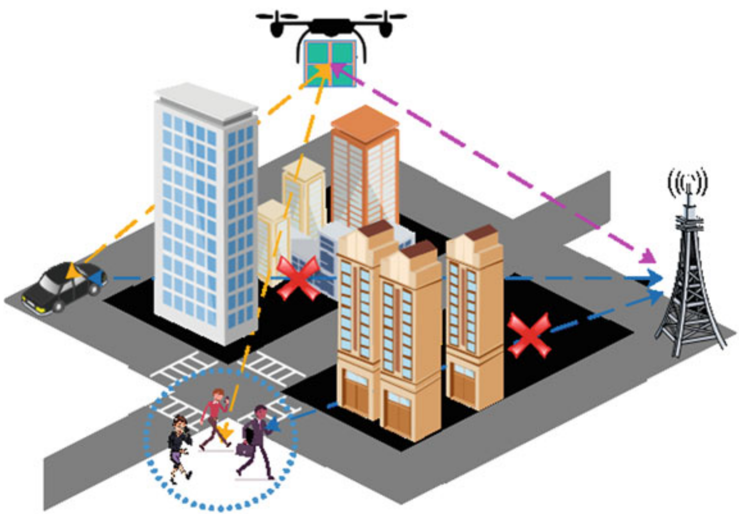

Fig. 6.1 RIS-assisted UAV communication

remote urban areas. RIS-assisted UAV communication consumes less power than other related technologies. So RIS-assisted UAV is an energy-efficient method. RIS-assisted UAV can also be used to improve the throughput of the communication which in turn improves cellular communication.

6.2 Propagation Path Loss

Unlike wired transmission medium which is stationary and predictable, the wireless transmission medium is random, which makes it difficult to analyze. In wireless transmission, the communication medium channel between the transmitter and the corresponding receiver differs from LoS to one that is prevented by mountains, foliage, and buildings. It limits the performance of the system. This is the type of medium, in which a mobile radio signal traveling may cause path loss and medium losses. The propagation path loss is the reduction in the power of the transmitted signal when it travels through the medium. Path loss causes the power of the received signal less than the power of the transmitted signal. The distance between the sender and the receiver, antenna gain, power of the transmission signal, and frequency of operation are the factors that affect the received signal power. Path loss may cause the transmission path to reconstruct. This may result in transmitting similar data again and may cause high energy consumption. Designing and developing a mobile communication channel calculation of the path loss that may experience in the channel is essential. Mathematically path loss can be expressed as

$$\text{path loss (dB)} = 20 \log 10 \left(4\pi d/\lambda\right).$$

There are various reasons for path loss which include the following:

- Reflection
- Diffraction
- Multipath

Reflection happens when EM wave comes into collision with an obstacle having a large size compared to the wavelength of that signal. Diffraction happens when the transmission channel between the sender and the receiver is prevented by an obstacle with pointed edges. Scattering happens when the channel in which the signal traverse met with large number of entities having a small size compared to the wavelength of the signal. A sample scenario is shown in Fig. 6.2.

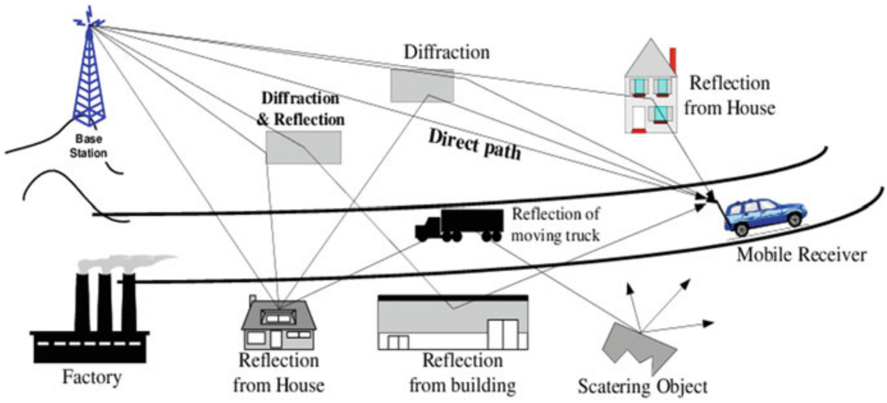

Fig. 6.2 Propagation path loss

6.2.1 Path Attenuation

Path attenuation is the loss in power of the transmitted signal when it propagates through space. When the signal propagates in space, without any other effects, the free space loss causes the signal to attenuate when it spreads out. The most basic model to represent the path is the free space propagation model state. The major relationship between P_t (transmitted power) and P_r (received power) is

$$P_\mathrm{r} = P_\mathrm{t} G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2$$

where G_t is the transmitter-antenna gain, G_r is the receiver-antenna gain, d is the transmitter and receiver distance, and λ is the signal wavelength.

6.2.2 Path Loss Due to Reflection

Reflection is a feature of electromagnetic signal to deflect a flat surface and propagate in a different direction. Reflection happens when the electromagnetic wave collides on an obstacle having large dimensions compared to the wavelength of that signal. Under 1 GHz, it will reflect from the ionosphere and can propagate waves at long distance compared to the ordinary LoS transmissions. Above 1 GHz, the low-wavelength signal will be reflected by smooth objects.

6.2.3 Path Loss Due to Diffraction

Another property of electromagnetic waves is diffraction which bends the signal. When a signal comes across an object in the path, it bends, and losses occur. The more rounded the object, the more the radio signal tends to diffract. Diffraction happens when the transmission channel between the sender and the receiver is prevented by an object with pointed edges. This happens during long-distance communication and at lower wavelengths. When the object becomes more pointed, the chances of causing diffraction are also higher.

6.2.4 Channel Modeling

The wireless channel medium is highly variable due to several interrelated phenomena. Managing this variability is really a big challenge. Also, estimation of the transmission medium accuracy is important to achieve reliable communication. So many interrelated factors have to be considered during the design of the transmission path. Therefore, it is essential to have a model to represent the channel and thereby find out the efficiency of the communication channel. The ability to evaluate the techniques implemented to address these real-life applications decides the design is accurate or not. Channel modeling requires accurate data for identifying path loss, scattering, and fading effects and also helps in evaluating the performance characteristics of the channel. All theoretical concepts of channel modeling can be implemented within the software. The channel models must consider the basic characteristics of communication and also need to support the processes in which the evaluation is to be carried out. A model needs to be tested correctly before developing the systems. Developing a mobile communication system without channel modeling is risky, and sometimes it is not feasible.

6.3 Propagation Models

The typical model UAV communication scenarios mainly consist of following three categories:

- UAV to GS/UE
- UAV to BS
- UAV to UAV

The key features of these communication scenarios are summarized as follows:

- UAV to GS/UE

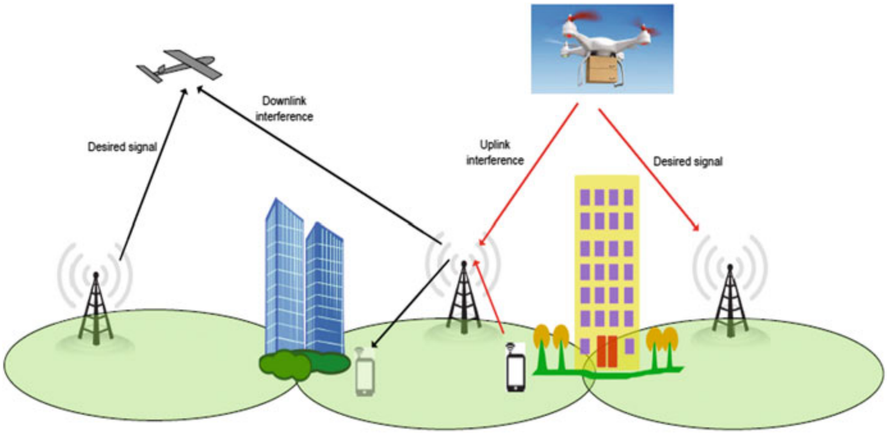

Fig. 6.3 UAV-BS communication

This refers to the command and control channel between GS and UAV, operating in unlicensed bands such as 2.4 and 5 GHz. Subsequently, the UAV is considered an auxiliary or alternative of TBS, serving ground UEs as an ABS. Therefore, the operating bands on this link range from hundreds of megahertz (MHz) to millimeter-wave (mmWave) bands, in which L-band for control and non-payload communication (CNPC) links and C-band for payload communication links are recommended by the International Telecommunication Union.

- UAV to BS

To guarantee reliable beyond line-of-sight (BLOS) communication links in very-long-distance flights, UAVs are expected to be aerial users of almost ubiquitous TBSs in cellular networks, which are known as cellular-connected UAV (CC-UAV) communications, since the TBS is equipped with downtilt directional sector antennas and deployed in fixed heights, which differs from the GS/UE, which is shown in Fig. 6.3.

- UAV to UAV

For many use cases such as aerial relay and flying ad hoc network, intercommunications between UAVs are necessary. Compared with conventional vehicular communication, UAV-to-UAV communications exhibit more challenges since drones can fly with highly variable heights in the three-dimensional (3D) space, comparably, generally travelling along with linear trajectory on the two-dimensional (2D) plane. Regarding propagation channels, the air-to-air and air-to-ground channels are involved in the communication links mentioned above. A2G channels include UAV-to-GS/UE and UAV-to-BS scenarios. It is undeniable that an accurate channel model is paramount for implementing reliable communication links.

In general, UAV communication can be of two types: air-to-air communication and air-to-ground communication. In addition to the transmission of data, it is necessary to transmit control and command information also. For that, the air-to-ground transmission channel must have two types of channels. The first type of link is of high capacity which is used to carry the payload. And the second type is used for carrying control and command.

The air-to-air link is a multipath channel with a LoS component. This transmission link is characterized as a two-ray model. And the transmission link fading is characterized by the Rician distribution in which the K factor calculates the strength of the line-of-sight component. It is measured as 15 dB for the air-to-air links.

6.3.1 Propagation Mechanism

The basic UAV communication architecture consists of two types of communication links. One is used for transmitting control and command information and another for payload. It is called control and non-payload communication link and the data link, respectively.

- Control and Non-Payload Communication Link

The CNPC links require a low data rate and it is needed for the safe operation. It is used for sharing safety information like control and command information between UAVs and mainly UAVs and other ground stations. The CNPC data can be classified into three types as shown below.

- Command and control from GS to UAVs
- UAV status report from UAVs to ground
- Information among UAVs

Since CNPC links are used to transmit critical data, it operates in a protected spectrum. Usually, a secondary CNPC link is also employed using satellite to provide backup and improve reliability. An authentication mechanism is also implemented in CNPC links to provide security and prevent unauthorized access.

- Data Link

The data link is used to transmit the actual payload to the ground stations (GS) and base stations (BS). UAV must support different types of communication such as the following:

(i) Mobile-to-UAV communication
(ii) UAV-to-BS communication
(iii) UAV-to-UAV communication

Data links are high-capacity communication links. Their capacity ranges between Kbps and Gbps depending on the application. Data links have high tolerance in terms of latency compared to that of control and non-payload communication links. Data links are able to reuse the existing band assigned for the application.

In UAV communication, CNPC and data link support two types of communication channels. They are as follows:

- UAV-to-Ground Channel

Usually, the line-of-sight links are used for UAV-to-ground channels, but they are blocked by obstacles like buildings or terrain. UAV-to-ground channel communication causes by multipath components due to reflection, diffraction, and scattering. In sea or deserts, the two-ray model is used. The stochastic Rician model is another largely used model.

- UAV-to-UAV Channel

The line-of-sight communication is mainly used in UAV-to-UAV channels. Multipath fading is very minimal in UAV-to-UAV communication compared to UAV-to-ground and ground-to-ground channels. They also have high Doppler frequency and large relative velocity among UAVs. Due to these features, mmWave communication is used in UAV-to-UAV channels.

6.3.2 Rural Area Propagation Model

In rural areas, enough electricity to meet the requirements of 5G is not available. So it has to make use of solar panels and batteries. The MU-MIMO communication mechanism is used in 5G rural communication in order to increase the downlink data rate. Commonly two types of architectures are considered for 5G rural communication. The first one is large cell-based, which covers hundreds of square kilometers. In the second architecture, basic radio functionalities are implemented on top of a UAV, and high-level functionalities are implemented at the ground site. The low-level features, such as a remote radio head (RRH), are hosted on the DHW carried by the UAV, and the high-level ones, like a base band unit (BBU) and/or mobile edge computing (MEC), are hosted by the DHW and CHW installed at the ground site.

6.3.3 Urban Area Propagation Model

In urban areas, between the sender and the receiver, no line-of-sight communication occurs. They suffer from diffraction loss due to the buildings and other obstacles which is shown in Fig. 6.4. The signal travels through different paths and interaction between these signals causing multipath fading. The strength of the signal attenuates as the distance between the sender and the receiver increases.

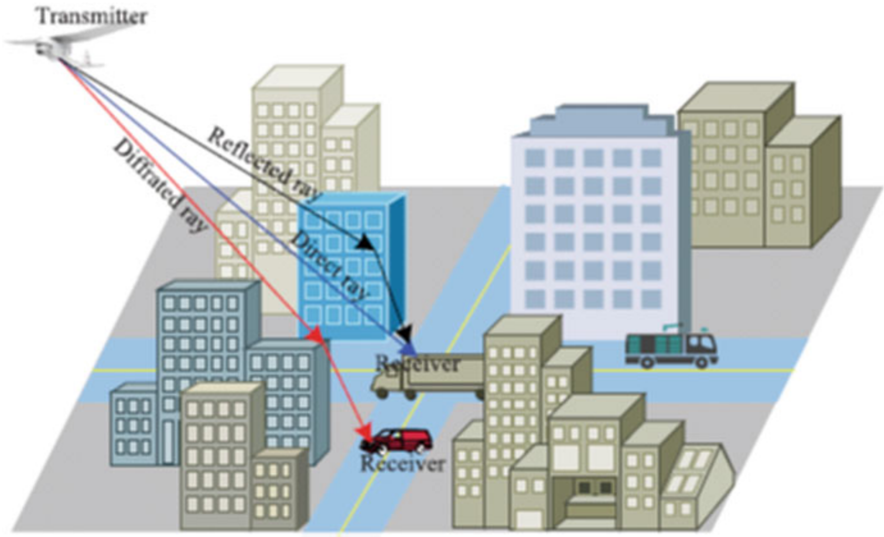

Fig. 6.4 Urban communication scenario

6.3.4 Propagation Challenges

The special features of UAVs and their flights directly induce some key challenges in channel modeling, compared with traditional cellular or vehicular communications. The key factors are not only related to external factors, including frequency, environment, and weather, but also dependent on the internal characteristics of UAVs and ground terminals. The key challenges are in detail as follows.

- Variable Heights

Based on the flying altitude, aerial platforms are divided into the high-altitude platform (HAP) with altitudes ranging between 17 and 32 km and the low-altitude platform (LAP) with altitudes below 5 km. Notably, the Federal Aviation Administration (FAA) has stipulated that the maximum allowable altitude of a UAV weighing less than 55 pounds (25 kg) is 400 feet (121.92 m) above the ground level. Moreover, as the potential next regulatory limit, the 3GPP selected the maximum altitude as 300 m for LTE/5G-supported UAV communications. Thereby, a robust UAV communication system should adapt to different heights or both UAV and ground terminals, which requires researchers to accurately quantify the impact of altitude on channel characteristics. Specifically, the height-dependent channel models are indispensable.

- Changeable Mobility

UAVs can be roughly divided into the fixed-wing (FW) and rotor-wing (RW) kinds. The main difference lies in that RW-UAVs can hover in the air with zero speed, whereas FW-UAVs need to maintain the aerodynamic lift by maintaining certain mobility. Overall, the mobilities of UAVs and ground terminals such as vehicles are highly changeable. However, the high-speed mobility is adverse to reliable transmission, since the propagation channels are vulnerable to spatio temporal non-stationarity.

- Flying Fluctuations

Extremely stable flights are impractical for any kind of UAVs. Thus, the impacts of fluctuating/jittering/wobbling flight of UAVs on wireless channels should be carefully considered. The small variation in the UAV-UE distance led by unstable flight can cause a large phase offset of multipath components (MPCs) and thus severely affects the channel coherence time. Besides, it is meaningful to consider different flying states for UAVs, such as taxiing, en-route, takeoffs, and landing, since these states may cause different levels of fluctuations.

- Fuselage Shadowing

The shadowing effects due to the blockage in the flight may cause signal interruption. Obviously, the shadowing is highly related to the fuselage size and flying altitude of the UAV as well as the antenna placement. Thus, in the large-scale fading model, these influences should be comprehensively considered.

- Rain Attenuation

The rainfall, as a common weather condition, will lead to significant level of attenuation mainly due to various scattering and absorption for frequencies always above 10 GHz. As an example, the rain attenuation was measured at 37.3 to 39.2 GHz with a span between the range 48 and 497 m in [1]. The outcomes mainly focus on the attenuation ranges from 1.5 dB to 9 dB for different rainfall rates. It brings another challenge for UAV mmWave links.

- Various Environments and Frequencies

UAVs can fly in various environments, such as built-up, overwater, forest, mountain, and other remote or harsh environments. Since the density, height, distribution, and electromagnetic parameters of scatterers are distinct in these environments, multi-environment measurements for UAV channels are essential. Besides, the diversity of the frequency is also of significance for channel modeling. The frequency bands used in UAV communications vary from sub-6 GHz to mmWave bands, which require more effort to characterize the impact of diverse bands on channel characteristics.

6.4 Channel Propagation Models

The most used 5G technologies are mMIMO and mmWave communications. These technologies' main aim is to design a system that is able to adjust to the changing environment. The mMIMO technology makes use of the spatial domain. In this method, a set of antennas are used to provide transmission to multiple users by means of parallel communication. The mmWaves are a large number of the unused spectrum with high frequency thereby solving the spectrum scarcity problem. The main disadvantage of mMIMO and mmWave are high hardware cost and complexity. mmWave is also susceptible to signal blockage and path loss.

During the past few years, studies and research is going on to improve the quality of service and simplify the transceiver-receiver system design. Spatial modulation is one of the popular methods that emerged as the result of these studies. Another study resulted in media-based modulation. This media-based modulation information is encoded into identifiable radiation patterns by using reconfigurable antennas. In all these abovementioned methods, from the received signal interaction, different signatures are generated, which are in turn used to transmit data with lesser complexity.

6.4.1 Basic MIMO Channel Propagation

MIMO or multiple-input multiple-output communication transmits data as the number of signals through several antennas parallel at a time, using a single channel. In this method, a set of antennas are used to enhance signal strength and quality. Data to be transmitted is divided into multiple data streams at the transceiver and are combined together at the receiver side. There will be another MIMO radio that will be configured at the receiver side similar to that of a transceiver. The receiver is designed in such a way that it can find out the difference in the received time of each signal and also the noise that occurred in each signal. By doing this, MIMO can achieve redundancy in data transmission. The main advantages of MIMO over SISO configurations are listed as follows:

1. By generating the number of data streams from a data, MIMO can reduce packet data loss. This in turn improves video and audio quality.
2. MIMO can enhance signal strength because at the receiver side, multiple data streams are received and combined together at the receiver.
3. System throughput is improved.

MIMO makes use of multiple antennas to transmit and receive a number of data streams at a time. The radio manufacturer is the one who determines the number of antennas required by the system. A 4×4 MIMO is shown in Fig. 6.5.

6.4.2 Channel Model Requirement

A channel model is used to represent the channel in order to find out the efficiency of the communication channel. To evaluate the performance of the currently used

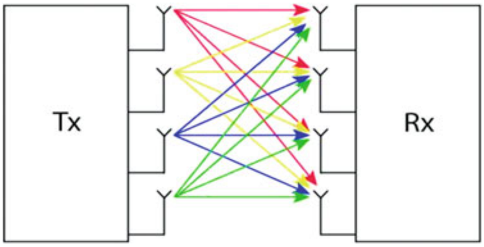

Fig. 6.5 4 × 4 MIMO

wireless network, the third-generation partnership project (3GPP) specified a model to UAV. The main features of this model are listed as follows:

- UAV Spatial Placement

Based on the amount of density of major UAVs in the particular network, the 3GPP defines five different cases. Per cellular sector, it considers the placement of devices out of 15 mobile devices $N_{\text{aerial}} = \{0, 0.1, 1, 3, 5\}$. Airborne devices with 160 km/h speed are distributed uniformly in the range of 0 and 300.

- LOS Probability

According to the increase in height of UAVs, the probability for the line-of-sight communication between GSs and UAVs grows. In the urban macro scenario, there exists a line-of-sight communication between UAVs at a height of 100 meters and all the BSs.

- Path Loss

The inbuilt 3GPP model uses one of the fact that as UAVs increase their height, the path loss composed of exponent of ground-to-aerial acting links generally decreases. UAVs in the line of sight with their base stations endure a path loss which is similar to a free space propagation. It majorly depends on the heights of the UAVs.

- Shadowing

Considering UAV in the line of sight with base station, for increasing UAV heights, shadowing gain diminishes.

- Fast-Fading Model

Here three different variations of different implementation complexity are considered. They are as follows:

1. A cluster delay-based channel model for urban and macro areas' reflection from the roof of the building is employed.
2. In the second variant, the mean and standard deviation in the delay occurred at the departure, and arrival time is adjusted also the K factor.
3. In the third approach which is the simplest one, the K factor is adjusted.

There exist several issues in the air-to-ground channel modeling. They are listed as follows:

1. There must have a realistic channel model that measures real values.
2. A precise UAV-to-UAV channel model must record the variations that occurred in time and the Doppler effect which is caused by the movement of the UAV.
3. It is also necessary to consider the multipath fading in the air-to-air communication.

In the case of RIS-assisted UAV channel modeling, in order to develop accurate models, we have to look into a number of factors. These include RIS-associated fabrication linked material, the several devices connected, the model geometry structure of the RIS, and aerial-to-ground distance. UAV and RIS will make the channel modeling a complex one. Since the UAV is an aerial node, its rotation and movement cause modification in aerial connected shadowing and modified based on its serial movement and orientation, and a rapid dynamic mobility pattern will cause temporal and spatial variation. It makes it hard to define a proper channel model for RIS-assisted UAVs.

6.4.3 Reconfigurable Intelligent Surface

Reconfigurable intelligent surfaces are emerging hardware technology that can be used to improve transmission medium characteristics and improve energy efficiency. RIS can be used in wireless networks to generate a smart radio environment. RIS consists of an integrated electronic circuit that is used as a reflecting surface. This circuit is having a number of elements that can be controlled by a varactor diode which is programmable. This property can be used to control the multipath effects.

RIS is a programmable planar surface that consists of passive reflecting elements whose size is smaller than the wavelength of the signal. A smart controller can be used in RIS in order to control transmission and reception. RIS reflects the incident signal which is received from a base station by having a phase shift that can be controlled by a user using a controller. This reflected signal can be added to the originally received signal from BS in order to strengthen the signal at the receiver. The important characteristics of RIS communication are listed as follows:

- RIS does not need a dedicated energy source, and it is passive.
- The signals received by RIS can be software programmed.
- RIS can work at any frequency level and have a full-band response.
- They are not susceptible to noise and do not require any power amplifiers and analog-to-digital converters, vice versa.
- RIS can be easily installed indoors and outdoors with ease.

RIS-assisted wireless communication is used for noise cancellation and to achieve programmable output signals. Compared to currently used methods, RIS has an advantage of cost and energy efficiency since it does not need any dedicated power source.

In RIS-based information transmission, the RIS receives the signal generated from other devices and is used to transmit the same by modulating the signal.

6.4.4 RIS-Assisted Wireless Communication

The RIS (reconfigurable intelligent surface) is an innovative technology and is capable to reconfigure a wireless medium as user needs. In a smart radio environment, more than one RIS is used in order to improve the system's performance. There are mainly two types of implementations that exist for RIS. They are reflectarray-based implementation and metasurface-based implementation. Irrespective of the type of implementation, RIS will remain passive and does not emit power on its own and enable the propagation of user-programmable.

- *Reflectarray-Based Implementation*

The easiest way for RIS implementation is by using reflectarray. In reflectarray implementation, the antenna is controlled by the user to backscatter and phase shift the signal. The effect on individual elements of the transmitted signal is very less, but elements can be used to control the signal effectively. For this method to be effective, around a thousand of antenna elements are required. This reflectarray RIS implementation is similar to backscattering. The main differences between the backscattering and reflect array implementation are as follows:

- In backscatter communication, in order to transmit information to the receiver, reflections from the reflectors are used. But RIS does not transmit information; it only helps to transmit the data.
- Even though the element in reflectarray is similar to that of the backscatter element, RIS elements work together according to the environment in which it is propagated.

This reflectarray implementation has a simple transceiver-receiver system design leaving the complexity to RIS and controller.

- *Metasurface-Based RIS Implementation*

Metasurface-based RIS implementation is an advanced implementation. By metasurface, it means having a 2D planar type of metamaterial which is not naturally found but is developed for applications to replace expensive lenses. A metasurface consists of meta-atoms that are closely spaced. The gap between two nearby meta-atoms will be much lesser or smaller than that of wavelength. At first, the designs of metasurfaces depend on static meta-atoms and are not possible to be modified after the fabrication. Now the designs are based on semiconductors that are possible to reconfigure in real time. By tuning mechanically, electrically, and thermally in the integrated components, it achieves reconfigurability. A metasurface-based RIS implementation consists of various tiles, in which each tile is a reconfigurable metasurface, where the size is larger than that of the wavelength.

6.4.5 Channel Propagation Problem

In RIS-assisted UAV communication systems, a large number of RIS elements are used which vary from few to hundreds and more and will create signaling overhead. This system experiences shadowing and fading, which in turn affect the phase shift modification. So in order to limit signaling overhead and to provide a static control link, new solutions are required.

6.5 Applications

The RIS-assisted UAV communication systems are used to improve the coverage and reliability of UAV communication systems. The main applications of RIS-assisted UAV communications are as follows:

- Extended coverage
- Increased capacity
- Massive multiple access
- Spectrum sharing

6.5.1 Extended Coverage

Using ABS and AR techniques for extended coverage, aerial communications cause large signal overhead. So RIS is the best possible alternative for this. Intelligent omni-surface (IOS), a special case of RIS, which has antenna connected elements, is kept on two sides of the metasurface to receive and reflect the signals from both directions. Reflecting on the incident signals from both sides can extend the coverage of 360 degrees. In UAV this can be achieved by keeping an IOS and by flying at suitable heights. The main advantage of using IOS is that the transmitted signal from RIS to the receivers can be controlled by inducing phase shifts on both sides. The UAV trajectory optimization and other phase shift vectors are for reaching the various desired locations, irrespective of static and mobile stations, and extending the cell device coverage in various desired direction as illustrated in Fig. 6.6.

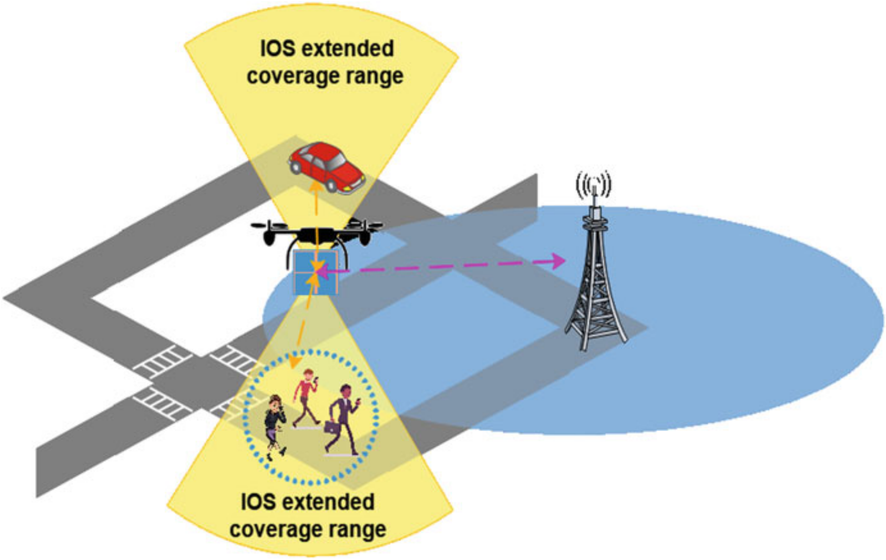

Fig. 6.6 RIS-assisted UAV for extended coverage

6.5.2 Increased Capacity

Between UEs and BSs, in order to increase the data rate on uplink and downlink, AR is used. An alternative method to improve channel capacity and throughput is RIS-assisted UAV communication. In ARs, the half-duplex communication mode is used commonly in order to improve the efficiency of the spectrum. But RIS operates in full-duplex mode. The self-relaying RIS strategy can remove the self-interference and amplification of noise due to its passive nature. Interference cancellation is achieved by inducing phase shifts and thereby inversing or weakening the interference signal by the RIS controller. By optimizing the phase shifts of the antenna elements, RIS-assisted UAV can be used to achieve scattering of line-of-sight links for several ground UEs. By using this, the spectrum's efficiency can be improved than the existing solutions. Combining static RIS with multiple UAVs makes it is possible to achieve scalability also.

6.5.3 Massive Multiple Access

By 2025, it is expected that the number of IoT devices will reach 75 billion and thereby causing a spectrum scarcity. So there is a need to provide enough connection to these IoT devices to connect and interact. The current urban scenario makes it more complex because, in the urban area, there is a need to provide a large number of

IoT devices both indoor and outdoor. The shadowing and nonavailability of reliable links in urban areas also add difficulty to this. This need for massive access can be solved effectively by integrating RIS with UAV. The indoor and outdoor virtual reality applications are suspected to suffer three problems. They are as follows:

- Large data transfers require high consumption of energy.
- Multipath communication.
- Interference from nearby VR devices.

These problems can be solved by using RIS-assisted UAV communication methods. In this method, RIS makes use of joint optimization of phase shift vectors together with UAV altitude and trajectory to improve the capacity and coverage which in turn provide massive connectivity.

6.5.4 Spectrum Sharing

RIS is an excellent choice for providing spectrum sharing because RIS is able to reduce the interference where the devices transmit data simultaneously using the same frequency band. Currently used spectrum sharing techniques makes use of cognitive radio and require reliable and efficient spectrum sensing techniques. In complex channel conditions, these techniques require high energy, and more often reliability is not ensured. That's why RIS-assisted UAV systems are used to improve the system capacity by spectrum sharing. The advantages and feasibility of RIS-assisted UAV system to provide indoor spectrum sharing are shown in Fig. 6.7. In this method, capacity is increased by providing multiple accesses in the shared spectrum and by controlling the interference among the users by phase shift controllers. Spectrum-shared strategy by RIS-assisted UAV method is used to

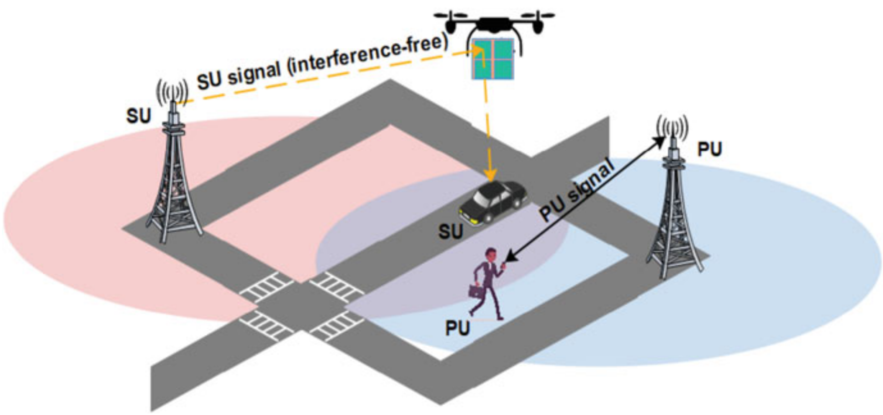

Fig. 6.7 Spectrum Sharing

improve the secondary user capacity without compromising the quality of service for primary users. The wireless networking performance in real time is optimized by the parameters explaining UAV mechanics which is shown in Fig. 6.7. Here it is necessary to consider how latitude, longitude, and altitude coordinates have an effect on the performance of RIS phase shifting and thereby system capacity.

6.6 Conclusion

Reconfigurable intelligent surface is an emerging hardware technology that can be used to improve transmission medium characteristics and to improve energy efficiency. RIS enables the user to configure the transmission of electromagnetic waves in a user-programmable manner. RIS can receive radio signals from the transmitter and beamform passively toward the receiver by inducing a manageable phase shift. Thereby, RIS does not require additional power for signal transmission contrary to the traditional methods that need additional power for signal transmission and regeneration. For this reason, it is well suited for UAV cellular communications by which it is possible to improve the communication quality and provide a reconfigurable propagation environment. This increases the signal energy and improves the data rate also. RIS can control the wireless transmission channels partially and provide us with more favorable propagation characteristics. The RIS-assisted UAV communications reduced the complexity of wireless channels. Compared to the massive MIMO method, the hardware cost and power consumption are very less in RIS. Since RIS is lightweight, it can be easily mounted on walls and ceilings. RIS-assisted UAV relay system significantly improves the coverage and reliability of UAV communication systems. The performance of RIS-assisted UAV communication can be improved by using artificial intelligence and machine learning algorithms. Machine learning algorithms can be used in RIS for improving the spectrum efficiency and to predict the channel estimation properly which in turn leads to autonomous decision-making in RIS-assisted UAV communications.

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P. Ihsana Muhammed has got 10 years of academic experience and is currently working as Assistant Professor in the Department of Computing Science and Engineering, Royal College of Engineering and Technology, under APJ Abdul Kalam Technological University, Kerala. She has completed her undergraduate degree in B.Tech. in 2009 in Computer Science and Engineering from Calicut University and postgraduate M.E., in 2014 in Computer Science and Engineering from Anna University, Chennai. She has published more than five research articles in international journals and conferences and delivered guest lectures on various topics. Her research interests include artificial intelligence, machine learning, and information security.

Yasar Moidutty has got 3 years of academic experience and is currently working as Assistant Professor and Trainer in the Department of Artificial Intelligence and Data Science, Royal College of Engineering and Technology, under APJ Abdul Kalam Technological University, Kerala. He is currently pursuing a Ph.D. degree from VIT, Vellore. He has completed his undergraduate degree in B.Tech. in Electronics and Instrumentation Engineering in 2017 from the College of Engineering Vadakara, under CAPE, Government of Kerala, and postgraduate degree in M.Tech., in Instrumentation Technology, in 2019 from Cochin University of Science and Technology. He has published more than five research articles in international journals and conferences and delivered guest lectures on various topics. His research interests include artificial intelligence, machine learning, robotics, embedded systems, sensors, and IoT.

N. M. Sreenarayanan has got 7 years of academic experience and is currently working as Assistant Professor and Trainer in the Department of Computing Science and Engineering, Galgotias University, Greater Noida, India. He is currently pursuing a Ph.D. degree from Galgotias University. He has completed his undergraduate degree in B.Tech. in 2013 and postgraduate degree in M.Tech. in 2016 in Computer Science and Engineering from Calicut University. He has published more than 20 research articles in international journals and conferences and delivered guest lectures on various topics. His research interests include artificial intelligence, machine learning, and emotional intelligence.

V. M. Meera has got 9 years of academic experience and is currently working as Assistant Professor in the Department of Computing Science and Engineering, Royal College of Engineering and Technology, under APJ Abdul Kalam Technological University, Kerala. She has completed her undergraduate degree in B.Tech. in 2009 in Computer Science and Engineering from Cochin University of Science and Engineering, Kochi, and postgraduate degree in M. Tech., in 2012 in Computer Science and Engineering from Cochin University of Science and Engineering, Kochi. She has published more than five research articles in international journals and conferences and delivered guest lectures on various topics. Her research interests include cyber security, artificial intelligence, machine learning, and information security.

Chapter 7
Cell-Free Massive MIMO Architecture for UAV Cellular Communications

Hope Ikoghene Obakhena, Agbotiname Lucky Imoize, Michael Adedosu Adelabu, Francis Ifeanyi Anyasi, and K. V. N. Kavitha

Abstract Unmanned aerial vehicle (UAV)-aided communications have emerged as a promising paradigm for providing capacity enhancement and coverage expansion in terrestrial mobile communication systems. However, due to the infancy in research and the stringent requirements of the state-of-the-art, spectral and energy-efficiency (EE) issues remain a prime challenge. Recently, cell-free massive multiple-input multiple-output (CF-mMIMO), consisting of arbitrarily allocated access points (APs) linked to a central processing unit (CPU), has been in the limelight, particularly because of its distinctive benefits toward achieving optimal

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H. I. Obakhena (✉)
Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology, Ambrose Alli University, Ekpoma, Nigeria

Department of Electrical and Electronics Engineering, Faculty of Engineering, University of Benin, Ugbowo, Nigeria
e-mail: obakhenahope@aauekpoma.edu.ng

A. L. Imoize
Department of Electrical and Electronics Engineering, Faculty of Engineering, University of Lagos, Lagos, Nigeria

Department of Electrical Engineering and Information Technology, Institute of Digital Communication, Ruhr University, Bochum, Germany
e-mail: aimoize@unilag.edu.ng

M. A. Adelabu
Department of Electrical and Electronics Engineering, Faculty of Engineering, University of Lagos, Akoka, Lagos, Nigeria
e-mail: madelabu@unilag.edu.ng

F. I. Anyasi
Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology, Ambrose Alli University, Ekpoma, Nigeria
e-mail: francisanyasi@aauekpoma.edu.ng

K. V. N. Kavitha
Department of Communication Engineering, School of Electronics Engineering (SENSE), Vellore Institute of Technology, Vellore, Tamil Nadu, India
e-mail: kvnkavitha@vit.ac.in

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EE and spectral gains. This chapter provides a comprehensive discussion on the feasibility as well as the effectiveness of CF-mMIMO in providing an improved spectral and energy-efficient UAV cellular network. First, an exposition into the evolution from the classical cell-based structure to the novel CF structure is presented. Next, elaborate discussions on the system model, propagation model, channel estimation, and communication process of UAV-aided CF-mMIMO networks are provided. Further, novel expressions for the achievable lower and upper spectral efficiency (SE) bounds for UL and DL data transmission phases are derived. Finally, analytical and numerical results derived through intensive computer simulations and open research issues are presented to inform future research directions toward achieving reliable UAV communications.

Keywords 5G wireless networks · Massive MIMO · Cell-free massive MIMO · Unmanned aerial vehicles · Energy efficiency · Spectral efficiency · Access points · Rician fading channel · Cellular communication · Drone

Abbreviation

5G	Fifth generation
6G	Sixth generation
AP	Access point
AWGN	Additive white gaussian noise
B5G	Beyond 5G
BS	Base station
CB	Conjugate beamforming
CDF	Cumulative distribution function
CF	Cell-free
CPU	Central processing unit
CSI	Channel state information
D2D	Device-to-device
DL	Downlink
EE	Energy efficiency
GUE	Ground user
HE	Harvested energy
IoT	Internet-of-Things
LB	Lower bound
LMMSE	Linear minimum mean squared error
LoS	Line-of-sight
m	Meter
MF	Matched filtering
mm	Millimeter
mMIMO	Massive multiple-input multiple-output
MMSE	Minimum mean squared error
ms	Millisecond
MS	Mobile stations
NOMA	Non-orthogonal multiple access
QoS	Quality of service
SC	Small-cell

SE	Spectral efficiency
SINR	Signal-to-interference-plus-noise ratio
SNR	Signal-to-noise ratio
TDD	Time division duplex
UAV	Unmanned aerial vehicles
UB	Upper bound
UC	User-centric
UE	User equipment
UL	Uplink
UT	User terminals
WPT	Wireless power transfer
ZF	Zero forcing

7.1 Introduction

In the current decade, the phenomenal popularity of portable devices, device-to-device (D2D) communications, Internet-of-Things (IoT) applications, and social platforms has drastically increased the demands of ubiquitous communication services and wireless data traffic. Future fifth-generation (5G) and beyond network is envisaged to support an excess density of users, allow for increased throughput, and is expected to provide pervasive interconnectivity of virtually everything across the universe into the Internet [1, 2]. Thanks to the distinctive combination of the so-called mm (millimeter)wave spectrum and large-scale antenna arrays (i.e., MIMO), extra degrees of freedom in terms of SE and EE have been realized [3, 4]. mMIMO exploits aggressive spatial multiplexing, signal coprocessing at multiple network AP and is characterized by a few hundreds of antennas at the base station (BS) to corporately coordinate single or multiple user equipment (UEs) simultaneously in a time frequency that is recognized as a promising component to cater for the increasing demand. Nevertheless, one of the foremost fundamental limitations inherent in conventional cellular mMIMO systems is the SE degradation owing to large variability in the quality of service (QoS) coupled with intercell interference, particularly for users at the cell boundaries [5]. As a result, there has been an exponential increase in research efforts toward mitigating/eliminating intercell interference in cellular networks.

CF-mMIMO, introduced in [6], has emerged as a key candidate architecture in future fully networked society to alleviate the cell-edge performance issues and guarantee substantive increment in 95% likely per-user throughput of unlucky users. In this type of architecture, a dearth of user terminals (UTs), randomly deployed in a wide coverage area, is simultaneously served by a plethora of low-complexity antenna APs, all linked via a backhaul to a CPU that coordinates the communication. The CF-mMIMO technology leverages the channel hardening and favorable propagation conditions of the centralized mMIMO through the use of simple signal processing such as zero-forcing (ZF), matched filtering (MF), and conjugate beamforming (CB) schemes, yielding a uniformly good service to the served UE [7]. Importantly, such systems are capable of providing higher coverage probability by utilizing macro-diversity due to coherent processing across APs [8].

Recently, the enthusiasm to harness the civil and public potentials presented by UAVs has impelled the telecommunications industry and academia to explore unprecedented use cases of the state-of-the-art [9]. Benefitting from salient attributes such as on-demand deployment, high maneuverability, long-range connectivity, and low-latency transmission [10, 11], UAVs have found rapid deployment in diverse applications such as package delivery, inspection and surveillance, aerial photography, emergency response, traffic control, scientific data collection, and agriculture [12, 13]. Interestingly, UAV-assisted communications have also attracted substantial research interest due to their distinctive advantages such as aerial communication platforms, enhanced network capability, wireless broadcasting, and high-rate information transmission [14]. Moreover, UAVs are envisioned to be an integral candidate technology and complement to the forthcoming future communication systems. Besides, UAVs can be flexibly employed as flying BSs and/or mobile relays to ensure reliable connectivity between ground targets in highly congested scenarios and to provide capacity enhancement [15, 16]. However, UAV communications suffer from new difficulties including asymmetric QoS, UE's throughput constraint, power limitations (UAV's battery energy constraint), aerial-terrestrial system interference, resource allocation, and trajectory control. Particularly, SE, measured by the ratio of data rate to bandwidth and EE and measured by the ratio of transmitted bits to the total power consumption, has emerged as a dominant design index for practical next-generation wireless systems and triggered an exponential increase in research [17, 18].

UAV-assisted CF-mMIMO network, which is an emerging technology, has been identified as an inevitable mainstream to realize an unprecedented spectral and energy-efficient gain in broadband communication systems. By exploiting the distinctive benefits presented by the subsystems, considerable performance improvement over cellular-connected UAVs is anticipated concerning high-rate wireless connectivity, coverage, throughput, and reliability [19]. As a result, the UAV-assisted CF-mMIMO network has skyrocketed research interest in industry and academia. Results from prior works on the beneficial combination of UAVs and CF-mMIMO manifest that proper interplay between both systems can greatly improve the net throughput, SE, and EE of UAV cellular communications [20, 21]. Nonetheless, not many works jointly optimize the SE and EE of UAV cellular communications. Consequently, this chapter presents a comprehensive discussion on spectral efficient and green networking strategies in UAV cellular communications using CF-mMIMO architectures. Specifically, the goal of this chapter is to enhance the perspective and preliminary results presented in [21]. The main contributions of the chapter are summarized as follows:

1. We present a detailed overview of the CF-mMIMO architecture, highlighting their background, configuration details, and mathematical modeling.
2. We explore viable characteristics, use cases, and associated communication requirements of UAVs.

3. We present an exhaustive analysis of UAV-assisted CF-mMIMO networks, with special emphasis on their prospects, system model, propagation model, channel estimation, and communication process.
4. We present an exhaustive analysis of the achievable SE bounds for UAV-assisted CF-mMIMO exploiting linear minimum mean squared error (LMMSE) channel estimation.
5. We perform computer simulations and numerical analysis to assess the performance of the state-of-the-art.
6. We present open research problems and highlight interesting scopes for future investigation.

The remainder of the chapter is organized as follows: The "Related Work" section features the literature review. The "Cell-Free Massive MIMO" section presents a brief discussion on the background, architecture, and mathematical modeling of cell-free massive MIMO. The "UAV Characteristics" section provides an insight into the characteristics, use cases, and associated communication requirements of UAVs. The system description, mathematical modeling, and performance analysis of UAV-assisted CF-mMIMO systems are presented in the "UAV-Assisted Cell-Free Massive MIMO Network" section. Moreover, instructive insights into the simulation results are delineated in the "Numerical Results and Discussion" section. Finally, we draw a concise conclusion and outline clear paths for further research in the "Conclusion" section.

7.2 Related Work

Wireless communications with UAVs, although still in the early stages of development, have attracted significant interest from researchers. More precisely, standardization bodies, industries, and academia are exploring unprecedented possibilities, prototypes, mathematical models, and algorithmic solutions to maximize the potentials of UAV-aided communication systems and ultimately boost rate transmission, wireless broadcast, and coverage [22, 23]. While a significant number of studies have characterized the performance of UAV-assisted communication, not many works simultaneously optimize the SE and EE of UAV cellular communication. Thus, there is a need for an insightful chapter to extend preliminary results and harness the full potentials of the state-of-the-art. The limitations of some existing literature and the authors' contribution to filling the knowledge gap are outlined in Table 7.1.

Table 7.1 Limitations of some existing surveys

Reference	Focus and coverage	Limitations	Contributions
[18]	Provides a novel insight into the performance of network-connected UAV communications, with emphasis on the design aspects and associated challenges	The study is limited to cellular network deployment Although EE optimization was discussed, SE optimization was omitted	Enhances perspective by characterizing UAV-enabled CF-mMIMO deployment Derives insightful mathematical expressions for the SE bounds of the proposed system
[20]	The work presents a detailed analysis of the performance of CF and user-centric (UC) architectures in enhancing UAV-enabled communication	Challenges with EE are not accounted for Future research directions are not discussed in-depth	Novel insight into the DL-harvested energy (HE) of UAVs is presented A clear path to support cutting-edge research is reported
[21]	Examined the possibility of enhancing UAV communications using CF and UC mMIMO. The survey takes into consideration the presence of ground users (GUEs) and adopts a Rician channel model	Challenges with EE constraints were omitted Mathematical modeling of CF architecture not accounted for	Provides a holistic overview of the DL HE of UAVs and reports exciting trends for future work An in-depth exposition into the system model of a typical CF architecture is presented
[19]	Presents an exhaustive analysis of the interplay between wireless communications with UAVs and CF-mMIMO, concerning the effects of wireless power transfer and hardware impairments	Mathematical modeling of CF architecture is not discussed	A robust discussion on CF architecture and system modeling is presented
[24]	Presents a detailed analysis of the capability of multiple antennas in supporting UAV cellular communication	The study is limited to cellular-connected UAV communication	Adopts a CF framework to enhance UAV cellular communication
[13]	Considered exhaustively the performance of non-orthogonal multiple access (NOMA)-assisted UAV network, to increase connectivity and realize superior SE	The study is focused on multicell mMIMO setups SE and EE optimization are not accounted for	Enhances perspective by characterizing UAV-enabled CF-mMIMO deployment Provides instructive insights into the SE and EE of the proposed system
[25]	Analyzed the performance of a cellular network integrated with UAV-to-UAV communication under two spectrum sharing strategies	The scope is restricted to cellular architectures	Adopts a CF framework to enhance UAV cellular communication
[26]	Characterized the performance of a federated learning framework in maximizing the communication efficiency of UAV-aided communication systems	The survey is centered on heterogeneous cellular networks SE and EE are not clearly outlined	Enhances perspective by characterizing UAV-aided CF-mMIMO setup Outlines a clear roadmap to optimize the SE and EE of the proposed system

7.3 Cell-Free Massive MIMO

In recent decades, mMIMO has appeared as a promising candidate to support various innovative services such as online gaming, video calling, social media applications, and the IoT [27, 28]. With globalization, the demand for wireless networks with no limitation is skyrocketing. Particularly, the growth in mobile data traffic, pervasive connectivity of devices, and a wide range of technology like a mobile cloud, holographic optical elements, and human digital interaction devices are envisioned to be highly colossal [29, 30]. To relieve the stress on the classical cell-based structure which has raised concerns as to their inability to effectively support ultrareliable low latency, massive connectivity, extremely high-data-rate, and ubiquitous coverage, CF-mMIMO has emerged as an innovative paradigm to match the requirements of 5G-and-beyond systems and guarantee sustainable evolution [31, 32]. The main novelty is the elimination of the traditional concept of the "cell" altogether through the use of an enormous count of APs, which simultaneously serve several UE by coherent joint transmission. Interestingly, CF-mMIMO inherits many of the attractive attributes of the classical centralized mMIMO using simple linear processing schemes, thus yielding a high level of coverage probability and low path losses [33]. Moreover, as noticed by [8], these networks are shown to provide a considerable performance improvement as opposed to the conventional small-cell (SC) systems and co-located antenna systems. Figure 7.1 presents the architecture of a typical CF-mMIMO network.

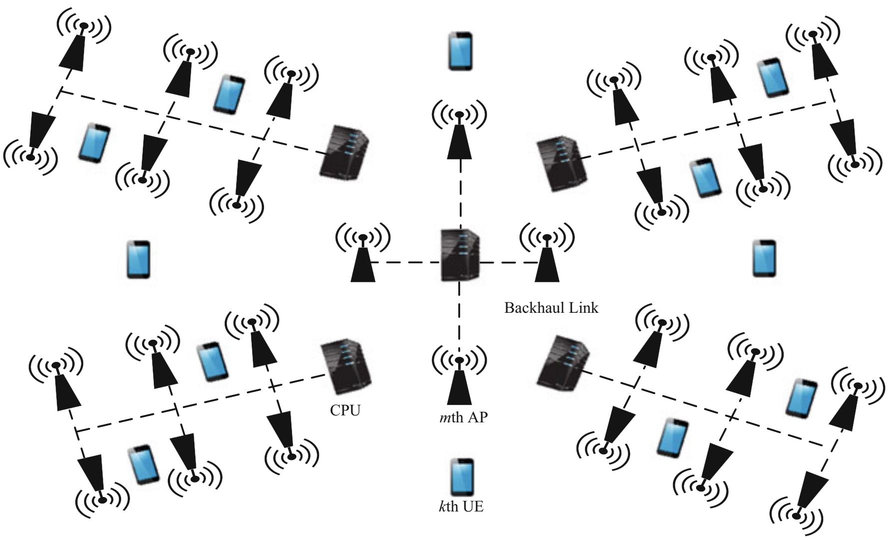


Fig. 7.1 Architecture of a typical cell-free massive MIMO network

7.3.1 System Model of a Cell-Free Massive MIMO System

A CF-mMIMO system stochastically allocated in a large serving area without boundaries and working in the same time/frequency resource is considered within this framework. We assume that M arbitrarily allocated APs, each equipped with N_{ap} antennas, jointly serve k single-antenna UEs with $M > k$. A CPU is connected with all APs via a fronthaul network, wherein power control coefficients, channel estimates, and precoding vectors are collected and distributed. What is more, the channel reciprocity of a time division duplex (TDD) protocol is exploited. Let the channel coefficient vector between UE k and AP m be specified by $N \times 1$, which can be represented as (7.1)

$$\boldsymbol{h}_{mk} = \sqrt{\beta_{mk}}\boldsymbol{d}_{mk}, \tag{7.1}$$

where β_{mk} denotes the effects of shadow fading and path loss, herein referred to as large-scale fading coefficient, and $\boldsymbol{d}_{mk}$ reflects the small-scale fading vector. Moreover, this framework assumes that $[\boldsymbol{d}_{mk}]_n \sim \mathcal{CN}(0,1)$. The TDD protocol with coherence time divided between UL and DL data transmission and pilots is depicted in Fig. 7.2. Further, the associated communication protocols—UL pilot training, UL data transmission, DL pilot training, and DL data transmission—are considered.

7.3.1.1 Uplink Pilot Training

The UL channel state information (CSI) is evaluated using each user's pilot signal in this phase. Let $\psi_k \in \mathbb{C}^{\tau \times 1}$ specify the pilot assigned to user k, where τ represents the length of each training stage with $\tau \ll T_{coher}$, and $\|\varnothing_k\|^2 = 1$. By adopting reused pilots, the system's signal-to-interference-plus-noise ratio (SINR), popularly referred to as pilot contamination, will be alleviated. Thus, it is assumed that the numerous access terminals are simultaneously served by a pilot assignment algorithm from the CPU. The received signal at AP m after K users transmit the pilot signals is given as (7.2)

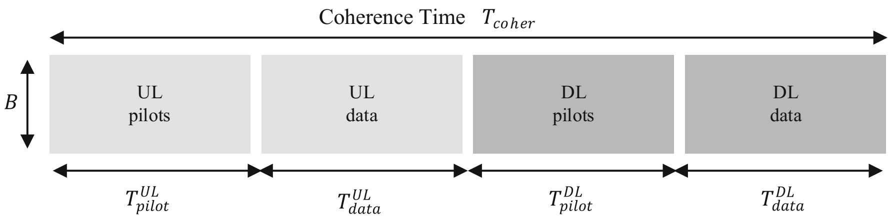


Fig. 7.2 Illustration of TDD system where the coherence time is divided into different phases for uplink (UL) and downlink (DL)

$$\boldsymbol{x}_{m,l} = \sqrt{\tau\rho_l}\sum_{k=1}^{K}\boldsymbol{h}_{mk}\varnothing_k^D + \boldsymbol{n}_{m,l}, \tag{7.2}$$

where ρ_l accounts for the transmit signal-to-noise ratio (SNR) and $\boldsymbol{n}_{m,\,l}$ represents the (7.3) accounts for an $N \times \tau$ noise matrix

$$\boldsymbol{n}_{m,l} \sim \mathbb{C}\mathcal{N}(0, N\boldsymbol{I}_\tau). \tag{7.3}$$

To estimate $\boldsymbol{h}_{mk}$, $\boldsymbol{x}_{m,\,l}$ is remodeled by AP m as expressed in (7.4)

$$\breve{\boldsymbol{x}}_{mk,l} = \boldsymbol{x}_{m,l}\emptyset_k = \sqrt{\tau\rho_l}\sum_{i=1}^{K}\boldsymbol{h}_{mi}\emptyset_i^D\emptyset_k + \boldsymbol{n}_{m,l}\emptyset_k. \tag{7.4}$$

Therefore, the minimum mean squared error (MMSE) estimation of $\boldsymbol{h}_{mk}$ is obtained as (7.5)

$$\widehat{\boldsymbol{h}}_{mk} = \mathbb{E}\{\boldsymbol{h}_{mk}\breve{\boldsymbol{x}}_{mk,l}^D\}/\left(\mathbb{E}\left\{\left|\breve{\boldsymbol{x}}_{mk,l}\right|^2\right\}\right).\breve{\boldsymbol{x}}_{mk,l} = c_{mk}\breve{\boldsymbol{x}}_{mk,l}, \tag{7.5}$$

where

$$c_{mk} = \frac{\sqrt{\tau\rho_l}\beta_{mk}}{\tau\rho_l\sum_{i=1}^{K}\beta_{mi}\left|\varnothing_i^D\varnothing_k\right|^2 + 1} \tag{7.6}$$

The associated channel estimation error vector is represented as (7.7)

$$\tilde{\boldsymbol{h}}_{mk} = \boldsymbol{h}_{mk} - \hat{\boldsymbol{h}}_{mk} \tag{7.7}$$

In addition, the statistics of (7.5) and (7.7) are expressed as (7.8) and (7.9)

$$\widehat{\boldsymbol{h}}_{mk} \sim \mathbb{C}\mathcal{N}(\mathbf{0}, \sigma_{mk}\,.\,\mathbf{I}_N\,), \tag{7.8}$$

$$\widetilde{\boldsymbol{h}}_{mk} \sim \mathbb{C}\mathcal{N}(\mathbf{0}, (\beta_{mk} - \sigma_{mk})\,.\,\mathbf{I}_N\,), \tag{7.9}$$

where

$$\sigma_{mk} = \frac{\tau\rho_l\beta_{mk}^2}{\tau\rho_l\sum_{i=1}^{K}\beta_{mi}\left|\varnothing_i^D\varnothing_k\right|^2 + 1} \tag{7.10}$$

7.3.1.2 Uplink Data Transmission

Let v_k specify the data signal forwarded by user k, where $\mathbb{E}\left\{|v_k|^2\right\} = 1$. Therefore, the received signal at AP m is expressed as (7.11)

$$\boldsymbol{x}_{m,g} = \sqrt{\rho_p}\sum_{k=1}^{K}\boldsymbol{h}_{mk}\sqrt{\eta_k}v_k + \boldsymbol{n}_{m,g}, \tag{7.11}$$

where ρ_p accounts for the SNR corresponding to the data signal. Likewise, the power control coefficient is denoted by $0 \leq \eta_k \leq 1$, and $\boldsymbol{n}_{m,\,g}$ represents a vector of additive white Gaussian noise (AWGN) at AP m. Employing a backhaul link, the obtained signal $\boldsymbol{x}_{m,\,g}$ is forwarded to the CPU. Let $\hat{\mathbf{H}}$ be specified by $\hat{\mathbf{H}} = \left[\hat{\boldsymbol{h}}_1, \hat{\boldsymbol{h}}_2, \ldots, \hat{\boldsymbol{h}}_K\right] \in \mathbb{C}^{MN\times K}$, where $\hat{\boldsymbol{h}}_k = \left[\hat{\boldsymbol{h}}_{1k}, \hat{\boldsymbol{h}}_{2k}, \ldots, \hat{\boldsymbol{h}}_{Mk}\right]^T$. In this context, a ZF receiver $\mathrm{A} = \hat{\mathbf{H}}\left(\hat{\mathbf{H}}^D\hat{\mathbf{H}}\right)^{-1}$ is adopted to observe the data signal of UE k and is expressed as (7.12)

$$X_k = \sqrt{\rho_p}\boldsymbol{a}_k^D\sum_{i=1}^{K}\sqrt{\eta_i}\boldsymbol{h}_i v_i + \boldsymbol{a}_k^D\boldsymbol{n}$$

$$= \sqrt{\rho_p\eta_k}v_k + \sqrt{\rho_p}\sum_{i\neq k}^{K}\sqrt{\eta_i}\boldsymbol{a}_k^D\tilde{\boldsymbol{h}}_i v_i + \boldsymbol{a}_k^D\boldsymbol{n}, \tag{7.12}$$

where $\boldsymbol{h}_k = [\boldsymbol{h}_{1k}, \boldsymbol{h}_{2k}, \ldots, \boldsymbol{h}_{Mk}]^T$, $\tilde{\boldsymbol{h}}_k = \left[\tilde{\boldsymbol{h}}_{1k}, \tilde{\boldsymbol{h}}_{2k}, \ldots, \tilde{\boldsymbol{h}}_{Mk}\right]^T$, $\boldsymbol{n} = [\boldsymbol{n}_{1,\,d}, \boldsymbol{n}_{2,\,d}, \ldots, \boldsymbol{n}_{M,\,g}]^{\boldsymbol{T}}$, and $\boldsymbol{a}_k$ denote the k-th column of $\mathbf{A}$. Therefore, v_k can be deduced via X_k.

7.3.1.3 Downlink Pilot Training

In this phase, the beamforming of pilots to the UEs is performed using a fully distributed CB scheme. Let the DL pilot signal beamformed to UE k be represented as $\sqrt{\tau_{d,l}}\varphi_k \in \mathbb{C}^{\tau_{d,l}}$, $k = 1, \ldots, K$, where $\|\varphi_k\|^2 = 1$, and let $\tau_{d,\,l}$ denote the DL pilot length. Moreover, for this particular study, any two DL pilot signals are assumed to be either identical or mutually orthonormal, and the expression is given by (7.13)

$$\varphi_k^G\varphi_{k'} = \begin{cases} 1, & \text{if } \varphi_k = \varphi_{k'}, \\ 0, & \text{Otherwise,} \end{cases} \tag{7.13}$$

Then, the $\tau_{d,l} \times 1$ DL pilot vector forwarded by the mth AP is specified by (7.14)

$$\boldsymbol{w}_{m,l} = \sqrt{\tau_{d,l}\rho_{d,l}} \sum_{k=1}^{K} \sqrt{\eta_{mk}} \hat{h}_{mk}^{*} \varphi_k, \tag{7.14}$$

where $\rho_{d,l}$ accounts for the SNR corresponding to the DL pilot symbol. What's more, the power expended by a single AP on DL pilots for each coherence interval is expressed as (7.15)

$$\mathsf{E}\left\{\left\|\boldsymbol{w}_{m,l}\right\|^2\right\} = \tau_{d,l}\rho_{d,l}\mathsf{E}\left\{\left\|\sum_{k=1}^{K}\sqrt{\eta_{mk}}\hat{h}_{mk}^{*}\varphi_k\right\|^2\right\}$$

$$= \tau_{d,l}\rho_{d,l}\sum_{k=1}^{K}\eta_{mk}\delta_{mk} + \tau_{d,l}\rho_{d,l}\sum_{k=1}^{K}\sum_{k^{'}\neq k}^{K}\sqrt{\eta_{mk}\eta_{mk^{'}}}\varphi_k^{G}\varphi_{k^{'}}\mathsf{E}\left\{\hat{h}_{mk}\hat{h}_{mk^{'}}^{*}\right\} \tag{7.15}$$

With regard to the UL pilot contamination, it is worth noting that $\mathsf{E}\left\{\hat{h}_{mk}\hat{h}_{mk^{'}}^{*}\right\} \neq 0$ only if $\psi_{k^{'}} = \psi_k$. While the pilot assignment is constrained for analytical convenience, orthogonal DL pilots are allocated to any set of users k and $k^{'}$ using the same UL pilot, i.e., $\varphi_k^{G}\varphi_{k^{'}} = 0$, if $\psi_{k^{'}} = \psi_k$. As a result, the second term in (7.15) is zero and is expressed as (7.16)

$$\tau_{d,l}\rho_{d,l}\sum_{k=1}^{K}\sum_{k^{'}\neq k}^{K}\sqrt{\eta_{mk}\eta_{mk^{'}}}\varphi_k^{G}\varphi_{k^{'}}\mathsf{E}\left\{\hat{h}_{mk}\hat{h}_{mk^{'}}^{*}\right\} = 0. \tag{7.16}$$

Then, the resulting $\tau_{d,l} \times 1$ DL pilot vector received by the kth user is specified by (7.17)

$$\boldsymbol{x}_{dl,k} = \sqrt{\tau_{d,l}\rho_{d,l}}\sum_{k^{'}=1}^{K} a_{kk^{'}}\varphi_{k^{'}} + z_{dl,k}, \tag{7.17}$$

where a_{kk} accounts for the effective DL channel and $z_{dl,k}$ accounts for the receiver noise vector.

7.3.1.4 Downlink Data Transmission

In this context, we take into consideration the assumption that channel estimates are treated as the true channels. Further, via the APs, maximum ratio transmission is adapted to forward signals to all UEs. Then, the signal forwarded from the mth AP is expressed as (7.18)

$$w_m = \sqrt{\rho_d \kappa_t} \sum_{k'=1}^{K} \left(\sqrt{\delta_{mk'}} \hat{h}^*_{mk'} q_{k'} \right) + \eta^d_{mt}, \tag{7.18}$$

where ρ_d specifies the normalized transmit power and δ_{mk} accounts for the DL power control coefficient between the kth UE and the mth AP. Besides, the hardware impairment inherent in the transceiver η^d_{mt}, η^d_{ky} is reflected by (7.19) and (7.20)

$$\eta^d_{mt} \mid \{h_{mk}\} \sim \mathcal{CN}\left(0, (1-\kappa_t)\rho_d \sum_{k'=1}^{K} \delta_{mk'} \left|\hat{h}^*_{mk'}\right|^2\right), \tag{7.19}$$

$$\eta^d_{ky} \sim \mathcal{CN}\left(0, \rho_d^2 (1-\kappa_y) \sum_{m=1}^{M} |h_{mk}|^2 \sum_{k'=1}^{K} \delta_{mk'} \left|\hat{h}^*_{mk'}\right|^2\right). \tag{7.20}$$

Then, the corresponding signal received by the kth user from all APs is expressed by (7.21)

$$y_{dk} = \sqrt{\kappa_y} \sum_{m=1}^{M} h_{mk} w_m + \eta^d_{ky} + z_{dk}$$

$$= \sqrt{\rho_d \kappa_t \kappa_y} \sum_{m=1}^{M} \sum_{k'=1}^{K} \delta_{mk'}^{1/2} h_{mk} \hat{h}^*_{mk'} q_{k'} + \sqrt{\kappa_y} \sum_{m=1}^{M} h_{mk} \eta^d_{mt} + \eta^d_{ky} + z_{dk}, \tag{7.21}$$

where $z_{dk} \sim \mathcal{CN}(0, \sigma_d^2)$ reflects the AWGN.

7.4 UAV Characteristics

UAVs, popularly referred to as drones, have sparked great interest from academia, industries, and standardization bodies due to the significant momentum and rapid development of manufacturing business, control technology, seamless wireless communication, and military applications [34]. On the standpoint of superior flexibility of movement, high mobility and versatility, and autonomy, UAVs have found extensive use cases in a proliferation of fields ranging from videography, aerial photography, forensics, cargo distribution, precision agriculture, military and security operations, to civil emergency services [35, 36]. It is also critical to note that UAVs are emerging as suitable platforms for airborne communications. More precisely, they can be deployed as novel aerial UEs or function as a flying BS, mobile relay, and autonomous communicating nodes. This is because of their dynamic deployment abilities, a strong likelihood of line-of-sight (LoS) connection with the GUEs, and capability of forming UAV-based swarm networks [37, 38]. Concerning the payload, which measures the lifting capability of a UAV and directly connects with the size, flight duration, and battery capacity of the drone, the payload of drones typically ranges from tens of grams to at least a few kilograms. More so, in terms of their flying mechanism, drones can either be multi-rotor, fixed-wing, or rotary-wing drones (also known as a hybrid fixed drones) [39]. Figure 7.3 presents a pictorial representation of UAV use cases and key requirements. In addition,

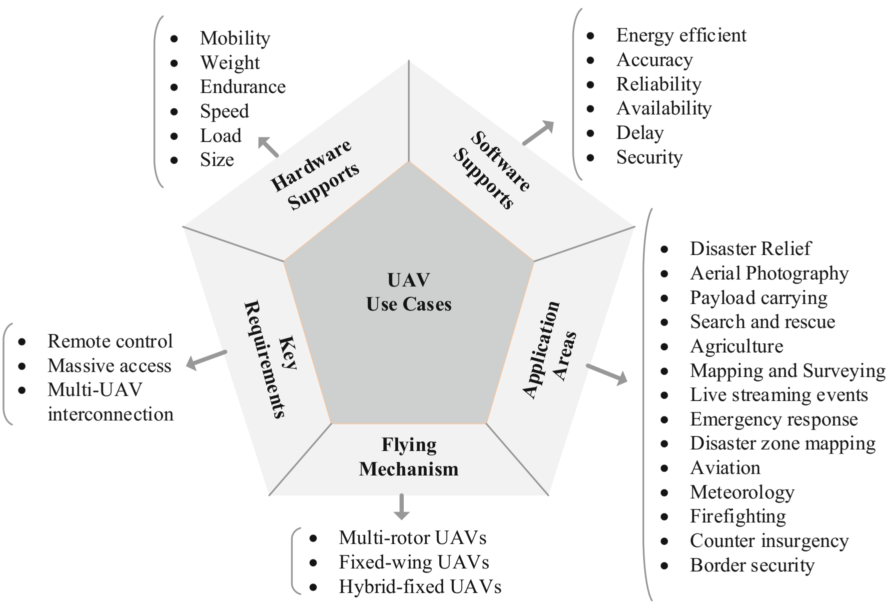


Fig. 7.3 UAV use cases and key requirements

Table 7.2 presents a summary of UAV communication requirements, and Table 7.3 presents a detailed insight into communication requirements for conventional UAV applications.

7.5 UAV-Assisted Cell-Free Massive MIMO Network

In recent years, the CF architecture, which depicts a useful embodiment and a practical incarnation of the network mMIMO, has received tremendous attention due to its potential to remedy the mediocre cell-edge problem prevalent in classical cell-based structures and guarantee an unprecedented high-coverage ratio. In such systems, a plethora of low-power and distributed single- or multiple-antenna APs jointly serve a dearth of UE, yielding low-path losses and higher macro-diversity. Thus, CF-mMIMO has been hailed as a novel wireless networking candidate for future wireless communication [31]. In parallel to the continued progress in this exciting research direction, UAVs have also seen dramatic deployment in a proliferation of fields. UAV-assisted wireless communication is envisaged to be a key candidate technology in the forthcoming B5G and sixth-generation (6G) mobile communications [9, 40].

UAV communication with CF-mMIMO architecture has become a hot research area mainly because of the potential of CF-mMIMO architecture in outperforming traditional cellular mMIMO systems. For instance, UAV-mounted flying BSs are a promising approach to maximize the performance of CF-mMIMO and ultimately space-air-ground networks [20]. The authors in [20] explored extensively the capability of CF-mMIMO in supporting GUEs and UAVs. Reference [19] considered critically the performance of UAV-aided CF-mMIMO networks enhanced by wireless power transfer (WPT). The paper revealed a robust improvement in the 95% likely UL SE compared to that of cellular mMIMO and SC. Reference [41] considers a severely hardware-impaired UAV-assisted CF-mMIMO and advocate using a block quadratic transformation technique to maximize the EE. It suffices that the SE is moderately improved for UAVs operating at a larger height. Interestingly, the authors in [42] analyze the possibility of CF cognitive satellite-UAV networks in serving wide-area IoT devices. Being fully aware of the UAVs' stringent reliability requirements and communication and mobility energy consumption, we propose to enhance preliminary findings delineated in [21]. Following a similar approach, we consider LMMSE channel estimation and assume a Rician fading channel. Figure 7.4 illustrates the architecture of a CF-mMIMO network in the presence of both ground and UAV users.

Table 7.2 UAV communication requirement [12]

	Data type	Data rate	Reliability	Latency	Critical?
DL	Radio control	–	–	–	✓
	Synchronization	–	–	–	✓
	Command and control	60–100 kbps	10^{-3} packet error rate	50 ms	✓
UL	Command and control	60–100 kbps	10^{-3} packet error rate	–	✓
	Application data	Up to 50 mbps	–	Similar to terrestrial user	✗

Table 7.3 Communication requirements for conventional UAV applications [12]

UAV application	Height coverage in meter (m)	Payload traffic latency in millisecond (ms)	Payload data rate (UL/DL)
Search and rescue	100 m	500 ms	6 mbps/300 kbps
Surveillance	100 m	3000 ms	10 mbps/300 kbps
Drone filming	100 m	500 ms	30 mbps/300 kbps
Drone delivery	100 m	500 ms	200 kbps/300 kbps
Access point	500 m	500 ms	50 mbps/50 mbps
Precision agriculture	300 m	500 ms	200 kbps/300 kbps
Drone fleet show	200 m	100 ms	200 kbps/200 kbps
Infrastructure inspection	100 m	3000 ms	10 mbps/300 kbps

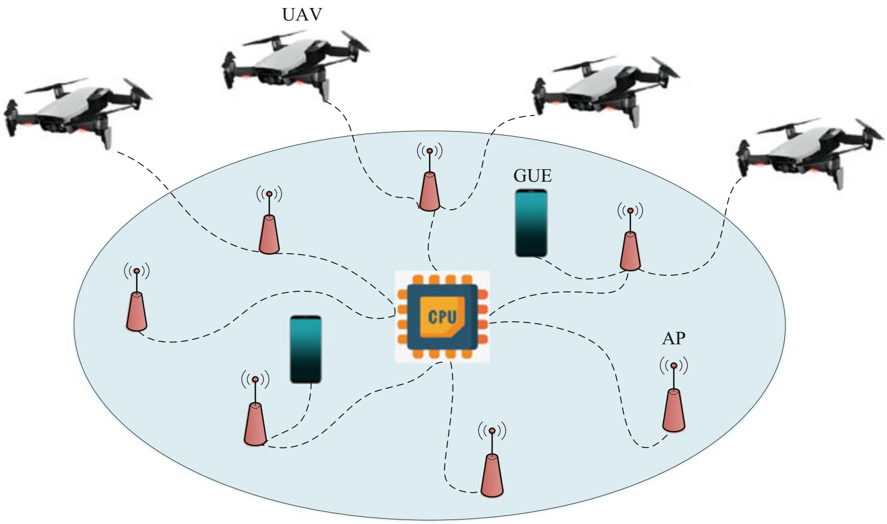


Fig. 7.4 UAV Communications with cell-free massive MIMO

7.5.1 System Model of UAV-Assisted Cell-Free Massive MIMO Network

In this context, a CF architecture comprising $\mathcal{L}$ APs, $\mathcal{G}$ legacy GUEs, and $\mathfrak{A}$ UAVs is considered. We assume that each AP is supplied with a uniform linear array comprising N_{ap} antennas and that GUEs and UAV users are supplied with a single antenna. For simplicity, we denote both GUEs and UAV users by the term *users*. Through a fronthaul link, the N_{ap} antennas are linked to a CPU, wherein processing tasks are performed and communication is coordinated. Let N_{L}, N_{G}, and N_{U} denote the cardinalities of the $\mathcal{L}$ APs, $\mathcal{G}$ GUEs, and $\mathfrak{A}$ UAVs, respectively. We define $\mathcal{K} = \mathcal{G} \cup \mathfrak{A}$ and use $K \triangleq N_{\mathrm{G}} + N_{\mathrm{U}}$ to reflect the UTs in the network. Moreover, let $\mathcal{K}_l$ denote the array of users served by the lth AP with reference to a physical resource block, and let K_l specify its cardinality. Likewise, let $\mathcal{L}_k$ with cardinality L_k specify the array of Aps serving the kth user. In the following, we consider three coherence phases, namely, UL data transmission, UL channel estimation, and DL data transmission. Interestingly, the set $\mathcal{K}_l$ of users corresponding to the lth AP is evaluated on the premise that each AP transmits signals to all users in the network, viz., $\mathcal{K}_l = \mathcal{K}$ and $\forall l = 1, \ldots, N_{\mathrm{L}}$ and the set $\mathcal{L}_k = \mathcal{L}$ and $\forall k = 1, \ldots, K$.

7.5.2 Propagation Model

In this context, a Rician fading model comprising a predominant LoS segment alongside a Rayleigh-distributed component is assumed to represent the small-scale fading. Let $\mathbf{h}_{k,l} \in \mathbb{C}^{N_{ap}}$ specify the channel between the kth UE and the lth AP. Then, the channel between the kth UE and the lth AP is expressed as (7.22)

$$\mathbf{h}_{k,l} = \sqrt{\frac{\beta_{k,l}}{K_{k,l}+1}}\left[\sqrt{K_{k,l}}\mathrm{e}^{j\vartheta_{k,l}}\boldsymbol{l}\left(\theta_{k,l}\right)+\mathbf{d}_{k,l}\right], \tag{7.22}$$

where $\beta_{k,\,l}$ denotes a scalar coefficient accounting for the shadowing effects and channel path-loss, $K_{k,\,l}$ denotes the Rician K component, $\vartheta_{k,\,l}$ represents a phase rotation for the direct path and is essentially a $\mathfrak{U}\left[0, 2\pi\right]$ random variable, $\mathbf{d}_{k,l} \in \mathbb{C}^{N_{ap}}$ embodies the i.i.d. $\mathcal{CN}\ (0, 1)$ small-scale fading coefficients from the kth user to the lth AP, and $\boldsymbol{l}\left(\theta_{k,l}\right) \in \mathbb{C}^{N_{ap}}$ accounts for the AP antenna array steering vector characterized at the angle $\theta_{k,\,l}$. Moreover, we reflect by $\boldsymbol{q}_{l,\,\ell}$ the vector specifying the placement of the ℓth antenna element at the lth AP. Let $\widetilde{\boldsymbol{q}}_k$ reflect the vector specifying the position of the kth UE. Thus, for vector $\boldsymbol{l}(\theta_{k,\,l})$, the ℓth entry is obtained as (7.23), with $\ell = 1, \ \ldots, N_{ap}$

$$\left[\boldsymbol{l}\left(\theta_{k,l}\right)\right]_{\ell} = \mathrm{e}^{-j\frac{2\pi}{\lambda}\left(\left\|\boldsymbol{q}_{l,1}-\widetilde{\boldsymbol{q}}_k\right\|-\left\|\boldsymbol{q}_{l,\ell}-\widetilde{\boldsymbol{q}}_k\right\|\right)}. \tag{7.23}$$

As a step further, we characterize the Rician factor K with reference to the specific link type (UAV-to-AP channel). We assume here that the Rician K factor $K_{k,\,l}$ is dependent on the UAV-AP distance and is expressed as (7.24)

$$K_{k,l} = \frac{\rho\mathrm{LoS}\left(s_{k,l}\right)}{1-\rho\mathrm{LoS}\left(s_{k,l}\right)}, \tag{7.24}$$

where $s_{k,\,l}$ accounts for the link length between the kth UE and the lth AP and $\rho\mathrm{LoS}(s_{k,\,l})$ reflects the probability that the distance between the kth UE and the lth AP is LoS.

7.5.3 Uplink Channel Estimation

In the following, it is assumed that the GUEs and UAV users employ a single channel for channel estimation. Further, the length of the UL and DL phases of GUEs is identical to that of UAV users for data transmission. We denote by $\mathbf{h}_{ge,\,l}$ the channel coefficient between the GUE and the lth AP. Then, the fading channel $\mathbf{h}_{ge,\,l}$ is specified by (7.25)

$$\mathbf{h}_{ge,l} \sim \mathcal{CN}\left(0, \mathbf{R}_{ge,l}\right), l = 1, \dots, L, \tag{7.25}$$

where $\mathbf{R}_{ge,l} \in \mathbb{C}^{N_{ap} \times N_{ap}}$ reflects the spatial correlation matrix and $\beta_{ge,\,l} = \mathrm{tr}\,(\mathbf{R}_{ge,\,l})/N_{ap}$ reflects the large-scale fading coefficient. By exploiting MMSE estimation, the channel estimation $\hat{\mathbf{h}}_{ge,l}$ is given as (7.26)

$$\hat{\mathbf{h}}_{ge,l} = \sqrt{\rho_{ge}}\, \mathbf{R}_{ge,l} \boldsymbol{\varphi}_{ge,l} \boldsymbol{q}_l, \tag{7.26}$$

where the signal transmit power of GUE is defined by ρ_{ge}, $\boldsymbol{\varphi}_{ge,l} = \left(\rho_{ge}\mathbf{R}_{ge,l} + \sigma^2 \mathbf{I}_{N_{ap}}\right)^{-1}$, and $\boldsymbol{q}_l = \mathbf{h}_{ge,l}\sqrt{\rho_{ge}} + \boldsymbol{n}_l$ denotes the received signal between GUE and AP l. Interestingly, the distributed form of $\hat{\mathbf{h}}_{ge,l}$ can be modeled as (7.27)

$$\hat{\mathbf{h}}_{ge,l} \sim \mathcal{CN}\left(0, \mathbf{D}_{ge,l}\right), \tag{7.27}$$

where $\mathbf{D}_{ge,\,l} = \rho_{ge}\mathbf{R}_{ge,\,l}\varphi_{ge,\,l}\mathbf{R}_{ge,\,l}$.

7.5.4 *The Communication Process*

7.5.4.1 Uplink Training

Let τ_c specify the dimension of the channel coherence length in terms of time frequency samples, and let the dimension of the UL training phase in terms of time frequency samples be specified by τ_p, where $\tau_c > \tau_p$. What is more, let the pilot sequence forwarded by the kth user be specified by $\gamma_k \in \mathbb{C}^{\tau_p}$, on the assumption that $\|\gamma_k\|^2 = 1, \ \ \forall\, k$. Thus, we express by $(N_{ap} \times \tau_p)$-dimensional matrix the received signal at the lth AP during the UL training, which is obtained as (7.28)

$$\boldsymbol{X}_l = \sum_{k \in \kappa} \sqrt{\eta_k} \boldsymbol{h}_{k,l} \gamma_k^D + \boldsymbol{Y}_l, \tag{7.28}$$

where η_k specifies the power utilized during the training phase by user k and $\boldsymbol{Y}_l \in \mathbb{C}^{N_{ap} \times \tau_p}$, with i.i.d. $\mathcal{CN}\left(0, \sigma_y^2\right)$ entries accounting for the out-of-cell interference and thermal noise augmentation at the lth AP. From prior studies on users' pilot sequences [8], it is obvious that the lth AP can perform estimation of the channel vectors $\left\{\boldsymbol{h}_{k,l}\right\}_{k \in \kappa_l}$ and is expressed as (7.29)

$$\hat{\boldsymbol{x}}_{k,l} = \boldsymbol{X}_l \gamma_k = \sqrt{\eta_k} \boldsymbol{h}_{k,l} + \sum_{\substack{i=1 \\ i \neq k}}^{K} \sqrt{\eta_i} \boldsymbol{h}_{i,l} \gamma_i^D \gamma_k + \boldsymbol{Y}_l \gamma_k. \tag{7.29}$$

Regarding the vectors $\boldsymbol{l}(\theta_{k,\ l})\ \forall\ l$ and k and large-scale fading coefficients $\beta_{k,\ l}$, the LMMSE estimate of the channel $\boldsymbol{h}_{k,\ l}$ is obtained as (7.30)

$$\hat{\boldsymbol{h}}_{k,l} = \boldsymbol{G}_{k,l} \hat{\boldsymbol{x}}_{k,l}, \tag{7.30}$$

where $\boldsymbol{H}_{k,\ l}$, $\boldsymbol{G}_{k,\ l}$, and $\boldsymbol{B}_{k,\ l}$ can be expressed as (7.31), (7.32), and (7.33), respectively,

$$\boldsymbol{H}_{k,l} = \frac{\beta_{k,l}}{K_{k,l}+1} \left[K_{k,l} \boldsymbol{l}\left(\theta_{k,l}\right) \boldsymbol{l}^D \left(\theta_{k,l}\right) + \mathbf{I}_{N_{ap}} \right], \tag{7.31}$$

$$\boldsymbol{G}_{k,l} = \sqrt{\eta_k} \boldsymbol{H}_{k,l} \boldsymbol{B}_{k,l}^{-1} \in \mathbb{C}^{N_{ap} \times N_{ap}}, \tag{7.32}$$

$$\boldsymbol{B}_{k,l} = \sum_{i \in \kappa} \eta_i \beta_{i,\ l} \boldsymbol{H}_{i,l} \left| \gamma_i^D \gamma_k \right|^2 + \sigma_y^2 \mathbf{I}_{N_{ap}}. \tag{7.33}$$

7.5.4.2 Uplink Data Transmission

In this framework, channel estimation by users is nonexistent, and as such, the transmitted data symbols are free from any channel-dependent phase offset. Therefore, the received N_{ap}-dimensional vector at the lth AP in a comprehensive symbol interval is given by (7.34)

$$\overline{\boldsymbol{x}}_l = \sum_{k \in \kappa} \sqrt{\eta_k^{\mathrm{UL}}} \boldsymbol{h}_{k,l} w_k^{\mathrm{UL}} + \boldsymbol{y}_l, \tag{7.34}$$

where η_k^{UL} accounts for the UL transmit power of user k, w_k^{UL} accounts for the data symbols of user k, and $\boldsymbol{y}_l \sim \mathcal{CN}\left(0, \sigma_y^2 \mathbf{I}\right) \in \mathbb{C}^{N_{ap}}$ accounts for the AWGN vector. Accordingly, the forwarded data by users in κ_a is decoded by each AP, resulting in the formation of the statistics $t_{l,k} = \hat{\boldsymbol{h}}_{k,l}^D \overline{\boldsymbol{x}}_l$ by the lth AP, for each $k \in \kappa_l$. As a result, the CPU provides soft estimates for the signal transmitted by the UEs and is given by (7.35)

$$\hat{w}_k^{\mathrm{UL}} = \sum_{l \in \mathcal{L}_k} t_{l,k}, \qquad k \in \kappa \tag{7.35}$$

which can be further simplified as (7.36)

$$\hat{w}_k^{\mathrm{UL}} = \sum_{l \in \mathcal{L}_k} \sqrt{\eta_k^{\mathrm{UL}}} \hat{\boldsymbol{h}}_{k,l}^D \boldsymbol{h}_{k,l} w_k^{\mathrm{UL}} + \sum_{j \in \kappa/k} \sum_{l \in \mathcal{L}_k} \sqrt{\eta_j^{\mathrm{UL}}} \hat{\boldsymbol{h}}_{k,l}^D \boldsymbol{h}_{j,l} w_j^{\mathrm{UL}} + \sum_{l \in \mathcal{L}_k} \hat{\boldsymbol{h}}_{k,l}^D \boldsymbol{y}_l \tag{7.36}$$

7.5.4.3 Downlink Data Transmission

In the following, the users perform channel estimation, and as such, CB is introduced by the APs. Consequently, the forwarded signal by the lth AP in a comprehensive symbol interval is given by (7.37)

$$\boldsymbol{v}_l = \sum_{k \in \kappa_l} \sqrt{\eta_{k,l}^{\mathrm{DL}}} \hat{\boldsymbol{h}}_{k,l} w_k^{\mathrm{DL}}, \tag{7.37}$$

where $\boldsymbol{v}_l$ is the N_{ap}-dimensional vector, w_k^{DL} accounts for the DL data symbol of user k, and $\eta_{k,l}^{\mathrm{DL}}$ accounts for the power correlation between the lth AP and user k. Denoting by η_l^{DL} the total power forwarded by the lth AP, the condition in (7.38) must be obeyed:

$$\mathbb{E}\left[\|\boldsymbol{v}_l\|^2\right] = \sum_{k \in \kappa_l} \eta_{k,l}^{\mathrm{DL}} \phi_{k,l} \leq \eta_l^{\mathrm{DL}}, \tag{7.38}$$

here $\phi_{k,l} = \mathbb{E}\left[\hat{\boldsymbol{h}}_{k,l}^D \hat{\boldsymbol{h}}_{k,l}\right] = \sqrt{\eta_k} \boldsymbol{tr}\left(\boldsymbol{H}_{k,l} \boldsymbol{G}_{k,l}\right)$.

At this point, channel estimation by the users is unnecessary since all APs transmit a phase-aligned signal to each user. Consequently, soft estimates for data symbol are forwarded to user k and is expressed as (7.39)

$$\begin{aligned} \hat{w}_k^{\mathrm{DL}} &= \sum_{l \in \mathcal{L}} \boldsymbol{h}_{k,l}^D \boldsymbol{v}_l + q_k \\ &= \sum_{l \in \mathcal{L}_k} \sqrt{\eta_{k,l}^{\mathrm{DL}}} \boldsymbol{h}_{k,l}^D \hat{\boldsymbol{h}}_{k,l} w_k^{\mathrm{DL}} + \sum_{j \in \kappa/k} \sum_{l \in \mathcal{L}_j} \sqrt{\eta_{j,l}^{\mathrm{DL}}} \boldsymbol{h}_{k,l}^D \hat{\boldsymbol{h}}_{j,l} w_j^{\mathrm{DL}} + q_k, \end{aligned} \tag{7.39}$$

where $q_k \sim \mathcal{CN}\left(0, \sigma_q^2\right)$ accounts for the AWGN.

7.5.5 Performance Analysis

In this context, insightful mathematical expressions are presented for the lower and upper SE bounds. Meanwhile, we consider UL and DL data transmission phases.

7.5.5.1 Downlink Data Transmission: Lower and Upper SE Bounds

1. *Lower Bound*

To determine the lower bound (LB) for the DL SE, we assume that each user simply knows the channel statistics and not the channel realizations. Therefore, the soft estimate forwarded to user k in (7.39) can be remodeled as (7.40)

$$\hat{w}_k^{\mathrm{DL}} = \underbrace{\mathbb{E}\left[\sum_{l\in\mathcal{L}_k}\sqrt{\eta_{k,l}^{\mathrm{DL}}}\boldsymbol{h}_{k,l}^{D}\hat{\boldsymbol{h}}_{k,l}\right]w_k^{\mathrm{DL}}}_{G_k} + \underbrace{\left(\sum_{l\in\mathcal{L}_k}\sqrt{\eta_{k,l}^{\mathrm{DL}}}\boldsymbol{h}_{k,l}^{D}\hat{\boldsymbol{h}}_{k,l} - \mathbb{E}\left[\sum_{l\in\mathcal{L}_k}\sqrt{\eta_{k,l}^{\mathrm{DL}}}\boldsymbol{h}_{k,l}^{D}\hat{\boldsymbol{h}}_{k,l}\right]\right)w_k^{\mathrm{DL}}}_{B_k}$$
$$+ \sum_{j\in\kappa/k}\underbrace{\sum_{l\in\mathcal{L}_j}\sqrt{\eta_{j,l}^{\mathrm{DL}}}\boldsymbol{h}_{k}^{D}\hat{\boldsymbol{h}}_{j,l}w_j^{\mathrm{DL}}}_{I_{k,j}} + q_k, \tag{7.40}$$

where G_k accounts for the desired signal strength, B_k accounts for the beamforming gain uncertainty, and $I_{k,j}$ accounts for the interference generated by user k. As in reference [43], we regard the total of the second, third, and fourth summands in (7.40) as "actual noise." Based on the knowledge that uncorrelated Gaussian noise reflects the most extreme instance, the LB for the DL SE of user k is obtained as (7.41)

$$SE_{k,\ LB}^{DL} = \frac{\tau_d}{\tau_c}\log_2\left(1 + \frac{|G_k|^2}{\mathbb{E}\left[|B_k|^2\right] + \sum_{j\in\kappa/k}\mathbb{E}\left[\left|I_{k,j}\right|^2\right] + \sigma_q^2}\right), \tag{7.41}$$

where τ_d is expressed as $\tau_d = \tau_c - \tau_\rho - \tau_u$ and τ_u accounts for the span of each coherence interval for the DL and UL data transmission phases (in time frequency domain). Although a wide range of expectations over the random channel realizations exist in (7.41), which is deterministic, obtaining these expectations in closed form is unrealizable but may be used as a starting point. Remarkably, an LB for the DL SE is available in closed form using CB and LMMSE and is expressed as (7.42)

$$SE_{k,\ LB}^{DL} = \frac{\tau_d}{\tau_c}\log_2\left(1 + \overline{SINR}_{k,DL}\right), \tag{7.42}$$

where $\overline{SINR}_{k,DL}$ is given by (7.43)

$$\overline{SINR}_{k,DL} = \left(\sum_{l\in\mathcal{L}_k}\sqrt{\eta_{k,l}^{\mathrm{DL}}}\phi_{k,l}\right)^2 \times \left\{\sum_{l\in\mathcal{L}_k}\eta_{k,l}^{\mathrm{DL}}\left(\eta_k\lambda_{k,l}^{(k)}-\phi_{k,l}^2\right)+\sum_{j\in\kappa}\sqrt{\eta_j}\sum_{l\in\mathcal{L}_j}\eta_{j,l}^{\mathrm{DL}}\mathrm{tr}\left(\boldsymbol{H}_{j,l}\boldsymbol{G}_{j,l}^{D}\boldsymbol{H}_{k,l}\right)+\sigma_q^2 + \sum_{j\in\kappa/k}\eta_k\left\{\sum_{l\in\mathcal{L}_j}\left[\eta_{j,l}^{\mathrm{DL}}\lambda_{k,l}^{(j)}+\sum_{\substack{b\in\mathcal{L}_j\\ b\neq l}}\sqrt{\eta_{j,l}^{\mathrm{DL}}}\sqrt{\eta_{j,b}^{\mathrm{DL}}}\mathrm{tr}\left(\boldsymbol{G}_{j,l}\boldsymbol{H}_{k,l}\right)\mathrm{tr}\left(\boldsymbol{G}_{j,b}^{D}\boldsymbol{H}_{k,b}\right)\right]\right\}\left|\gamma_k^{D}\gamma_j\right|^2\right\}^{-1} \tag{7.43}$$

and $\lambda_{k,l}^{(j)}$ is expressed as (7.44)

$$\lambda_{k,l}^{(j)} = \left(\frac{\beta_{k,l}}{K_{k,l}+1}\right)^2\mathrm{tr}^2\ \left(\boldsymbol{G}_{j,l}\right)+2K_{k,l}\left(\frac{\beta_{k,l}}{K_{k,l}+1}\right)^2\Re\left\{\mathrm{tr}\left(\boldsymbol{l}^{D}\ \left(\theta_{k,l}\right)\ \boldsymbol{G}_{j,l}\boldsymbol{l}\ \left(\theta_{k,l}\right)\ \boldsymbol{G}_{j,l}^{D}\right)\right\}. \tag{7.44}$$

2. *Upper Bound*

To determine the upper bound (UB) for the DL SE, we consider the received signal in (7.39). By mathematical analysis, the UB expression for the SE is given by (7.45), and the expectation is based on the realizations of the fast-fading channel

$$SE_{k,\ UB}^{DL} = \frac{\tau_d}{\tau_c}\mathbb{E}\left[1+\frac{\left|\sum_{l\in\mathcal{L}_k}\sqrt{\eta_{k,l}^{\mathrm{DL}}}\ \boldsymbol{h}_{k,l}^{D}\hat{\boldsymbol{h}}_{k,l}\right|^2}{\sum_{j\in\kappa/k}\left|\sum_{l\in\mathcal{L}_j}\sqrt{\eta_{j,l}^{\mathrm{DL}}}\ \boldsymbol{h}_{k,l}^{D}\hat{\boldsymbol{h}}_{j,l}\right|^2+\sigma_q^2}\right]. \tag{7.45}$$

7.5.5.2 Uplink Data Transmission: Lower and Upper SE Bounds

1. *Lower Bound*

With the aid of mathematical computations, (7.36) can be transformed into (7.46)

$$\hat{w}_k^{\mathrm{UL}} = \sum_{l\in\mathcal{L}_k}\sqrt{\eta_k^{\mathrm{UL}}}\hat{\boldsymbol{h}}_{k,l}^{D}\boldsymbol{h}_{k,l}w_k^{\mathrm{UL}}+\sum_{j\in\kappa/k}\sum_{l\in\mathcal{L}_k}\sqrt{\eta_j^{\mathrm{UL}}}\hat{\boldsymbol{h}}_{k,l}^{D}\boldsymbol{h}_{j,l}w_j^{\mathrm{UL}}+\sum_{l\in\mathcal{L}_k}\hat{\boldsymbol{h}}_{k,l}^{D}\boldsymbol{y}_l. \tag{7.46}$$

We assume that the CPU performs detection solely based on statistical information of the channel coefficient. As such, (7.46) can be remodeled as (7.47)

$$\hat{w}_k^{\mathrm{UL}} = \underbrace{\mathbb{E}\left[\sum_{l\in\mathcal{L}_k}\sqrt{\eta_k^{\mathrm{UL}}}\hat{\boldsymbol{h}}_{k,l}^{D}\boldsymbol{h}_{k,l}\right] w_k^{\mathrm{UL}}}_{\widetilde{G}_k}$$

$$+\underbrace{\left(\sum_{l\in\mathcal{L}_k}\sqrt{\eta_k^{\mathrm{UL}}}\hat{\boldsymbol{h}}_{k,l}^{D}\boldsymbol{h}_{k,l} - \mathbb{E}\left[\sum_{l\in\mathcal{L}_k}\sqrt{\eta_k^{\mathrm{UL}}}\hat{\boldsymbol{h}}_{k,l}^{D}\boldsymbol{h}_{k,l}\right]\right) w_k^{\mathrm{UL}}}_{\widetilde{B}_k}$$

$$+\sum_{j\in\kappa/k}\underbrace{\sum_{l\in\mathcal{L}_k}\sqrt{\eta_j^{\mathrm{UL}}}\hat{\boldsymbol{h}}_{k,l}^{D}\boldsymbol{h}_{j,l}w_j^{\mathrm{UL}}}_{\widetilde{I}_{k,j}} + \underbrace{\sum_{l\in\mathcal{L}_k}\hat{\boldsymbol{h}}_{k,l}^{D}\boldsymbol{y}_l}_{\widetilde{N}_k}. \tag{7.47}$$

Following a similar approach as the one detailed above, we regard the total of the second, third, and fourth summands in (7.47) as "actual noise," where the uncorrelated Gaussian noise is assumed to reflect the most extreme case. In light of the above, the LB for the UL SE of user k in the system is obtained as (7.48)

$$SE_{k,\ LB}^{UL} = \frac{\tau_u}{\tau_c}\log_2\left(1+\frac{\left|\widetilde{G}_k\right|^2}{\mathbb{E}\left[\left|\widetilde{B}_k\right|^2\right]+\sum_{j\in\kappa/k}\mathbb{E}\left[\left|\widetilde{I}_{k,j}\right|^2\right]+\mathbb{E}\left[\left|\widetilde{N}_k\right|^2\right]}\right). \tag{7.48}$$

In this case, (7.48) provides numerous expectations over random channel realizations and is deterministic. By exploiting the distinctive combination of LMMSE channel estimation and MF detection, an LB for the UL SE of the kth UE is obtainable in closed form, and the result is given by (7.49)

$$SE_{k,\ LB}^{UL} = \frac{\tau_u}{\tau_c}\log_2\left(1+\overline{SINR}_{k,\ UL}\right), \tag{7.49}$$

where $\overline{SINR}_{k,\ UL}$ is specified by (7.50)

$$\overline{SINR}_{k,UL} = \eta_k^{\mathrm{UL}} \left(\sum_{l \in \mathcal{L}_k} \phi_{k,l} \right)^2$$
$$\times \left\{ \eta_k^{\mathrm{UL}} \sum_{l \in \mathcal{L}_k} \left(\eta_k \overset{\sim(k)}{\lambda}_{k,l} - \phi_{k,l}^2 \right) + \sum_{j \in \kappa} \eta_j^{\mathrm{UL}} \sqrt{\eta_k} \sum_{l \in \mathcal{L}_k} \mathrm{tr} \left(\boldsymbol{H}_{k,l} \boldsymbol{G}_{k,l}^D \boldsymbol{H}_{j,l} \right) + \sigma_y^2 \sum_{l \in \mathcal{L}_k} \phi_{k,l} \right.$$
$$\left. + \sum_{j \in \kappa / k} \eta_j^{\mathrm{UL}} \eta_j \left\{ \sum_{l \in \mathcal{L}_k} \left[\overset{\sim(k)}{\lambda}_{j,l} + \sum_{\substack{b \in \mathcal{L}_k \\ b \neq l}} \mathrm{tr} \left(\boldsymbol{G}_{k,l}^D \boldsymbol{H}_{j,l} \right) \mathrm{tr} \left(\boldsymbol{G}_{k,b} \boldsymbol{H}_{j,b} \right) \right] \right\} \left| \gamma_j^D \gamma_k \right|^2 \right\}^{-1}, \tag{7.50}$$

and $\overset{\sim(k)}{\lambda}_{j,l}$ is specified by (7.51)

$$\overset{\sim(k)}{\lambda}_{j,l} = \left(\frac{\beta_{j,l}}{K_{j,l}+1} \right)^2 \mathrm{tr}^2 \left(\boldsymbol{G}_{k,l} \right) + 2K_{j,l} \left(\frac{\beta_{j,l}}{K_{j,l}+1} \right)^2 \Re \left\{ \mathrm{tr} \left(\boldsymbol{l}^D \left(\theta_{j,l} \right) \boldsymbol{G}_{k,l} \boldsymbol{l} \left(\theta_{j,l} \right) \boldsymbol{G}_{k,l}^D \right) \right\}. \tag{7.51}$$

2. *Upper Bound*

The UB bound for the UL SE is computed using similar techniques to the ones outlined above. By straightforward manipulation of (7.36), the UB expression for the UL SE is given by (7.52)

$$SE_{k,\ UB}^{UL} = \frac{\tau_u}{\tau_c} \mathbb{E} \left[1 + \frac{\eta_k^{\mathrm{UL}} \left| \sum_{l \in \mathcal{L}_k} \hat{\boldsymbol{h}}_{k,l}^D \boldsymbol{h}_{k,l} \right|^2}{\sum_{j \in \kappa / k} \eta_j^{\mathrm{UL}} \left| \sum_{l \in \mathcal{L}_k} \hat{\boldsymbol{h}}_{k,l}^D \boldsymbol{h}_{j,l} \right|^2 + \sigma_y^2 \sum_{l \in \mathcal{L}_k} \left\| \hat{\boldsymbol{h}}_{k,l} \right\|^2} \right]. \tag{7.52}$$

7.6 Numerical Results and Discussion

By adopting an insightful simulation setup, we analyze the performance of the proposed UAV-aided CF architecture. To minimize boundary effects, we consider a square of size 100 m by 100 m wrapped around the edges. In this scenario, we report the UL SE and DL HE of three distinct topologies, namely, CF-mMIMO, SCs, and cellular mMIMO, considering the time slot 1 resulting from the initial phase pilot power at time slot 0 coming from the considered UAV. To establish an accurate comparison of the three different network topologies, the total radiated

Table 7.4 Simulation parameters

Parameter	Value
Number of APs N_{L}	20
Number of UAVs N_{U}	1
Carrier frequency f_c	2 GHz
Bandwidth B	20 MHz
Reference channel power gain	−40 dB
Noise variance σ^2	−96 dBm
Signal transmit power of GUE	1 dBm
Initial pilot transmit power ρ [0]	1 dBm
Length of channel coherence block T_{coher}	2 ms[4]
Number of channel users τ_c	200
Constant velocity of UAV V_{hor}	20 m/s
User antennas	Omnidirectional with 0 dBi gain
Spatial correlation angular standard deviation	10°

power is assumed to be equal in all scenarios, i.e., the DL transmit power is specified by $\rho_d^{sc}[n] = \mathcal{L}\rho_d^{cf}[n]$ and $\rho_d^{cf}[n] = \rho_d^{c}[n] = 30$dBm. It is worthy of note that the effect of spatial correlation is moderate due to the strong LoS segment in various network topologies. The curves representing the APs and UAV locations are generated with over 4000 instances. Table 7.4 presents a report of the simulation parameters.

Figure 7.5 illustrates the cumulative distribution functions (CDFs) of the UL SE of UAVs for the following network topologies—CF-mMIMO, SCs, and cellular mMIMO with $\Gamma = 0.5$ and Q $= 0.98$, where Γ and Q reflect the time-splitting factor and the hardware quality factor, respectively. The results of Fig. 7.5 manifest that a twofold and fivefold improvement regarding median and 95% likely UL SE is obtainable with the proposed CF architecture as opposed to cellular mMIMO. This is a result of cooperative signal processing and a dramatic decrease in the average distance between APs and UAVs in scenarios with CF networks. Remarkably, in scenarios with cellular mMIMO, when the distance between the UAV and the cellular BS grows small, considerable levels of SE gains can be obtained. However, the overall performance diminishes when the distance becomes very large, particularly at the cell edges. Additionally, a considerable performance gap is shown to exist between CF-mMIMO and SC systems. This is because SC systems result in poor antenna diversity gain arising from SE-maximizing APs solely serving the UAV. By introducing GUEs, the SE performance of UAVs as illustrated in Fig. 7.5b is significantly impacted, due to GUE-generated interference.

Figure 7.6 depicts the CDF of the DL GUE rates for CF-mMIMO and multicell mMIMO systems. The results of Fig. 7.6 illustrate a significant performance difference between CF-mMIMO and multicell mMIMO deployment in scenarios with and without UAVs. This is because of the presence of intercell interference, which hugely impacts the potential of mMIMO setups. Fortunately, we can also observe approximate preservation in performance for CF architecture in scenarios

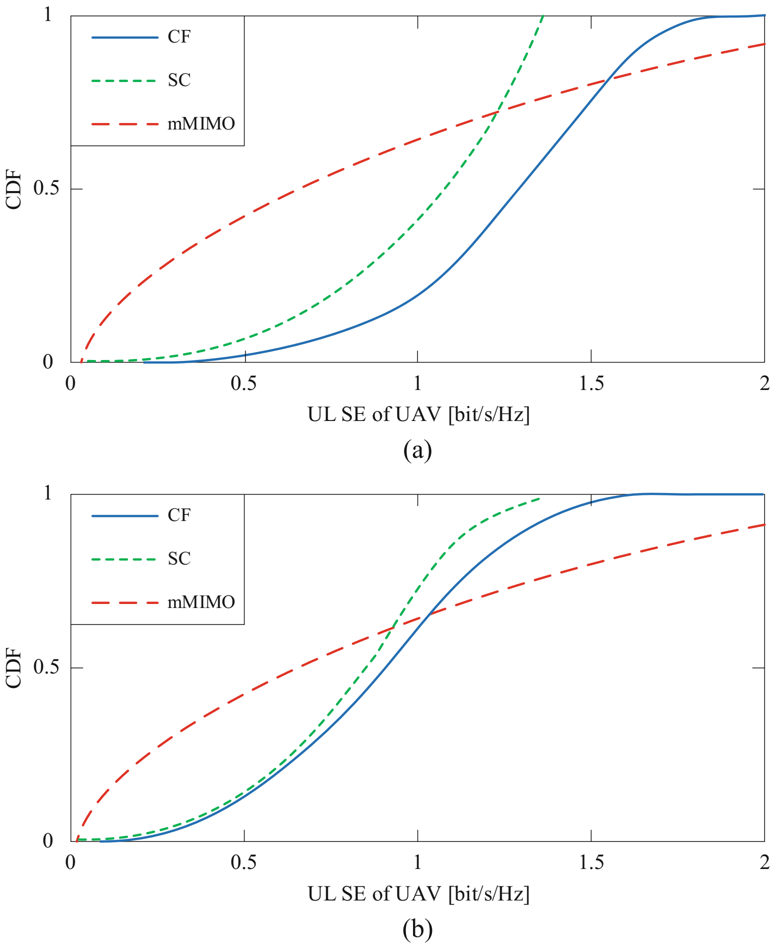


Fig. 7.5 CDF of UL SE of UAV in (i) CF-mMIMO, (ii) SC, and (iii) cellular mMIMO ($\mathcal{L} = 20$, $N_{ap} = 2$, $\Gamma = 0.5$, $Q = 0.98$, $H = 20$ m). **(a)** Without GUE. **(b)** With GUE

with UAVs, due to the adequate management of UL pilot contamination resulting from UAVs through insightful LMMSE channel estimation.

Figure 7.7 reflects the relation between the time-splitting factor Γ and the median UL SE of UAV in CF-mMIMO with varying values of N_{ap} and H, where H denotes the possible height for the UAV. Also, we assume that $\mathcal{L} = 20$ and $Q = 0.98$. We can observe that the median UL SE of UAV is significantly maximized followed by a substantial degradation when the value of Γ changes from 0 to 1. The reason is that the transition of Γ from 0 to 1 indicates no information transmission and ultimately no energy harvesting. Furthermore, the results of Fig. 7.7 manifest that a substantive gain in SE is achieved by increasing N_{ap} and reducing the possible height of UAV.

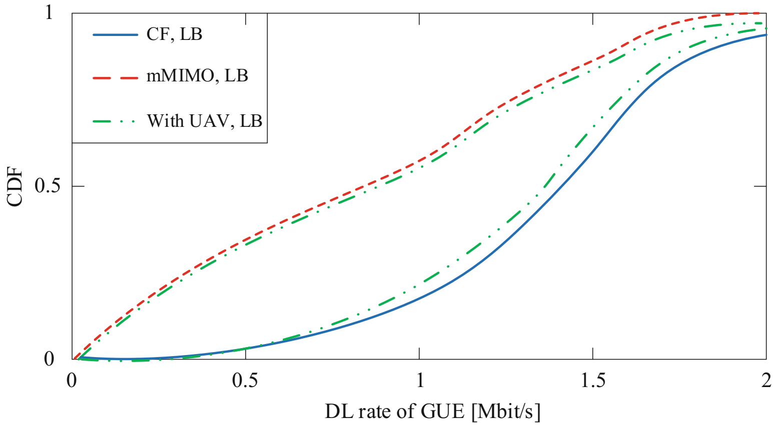
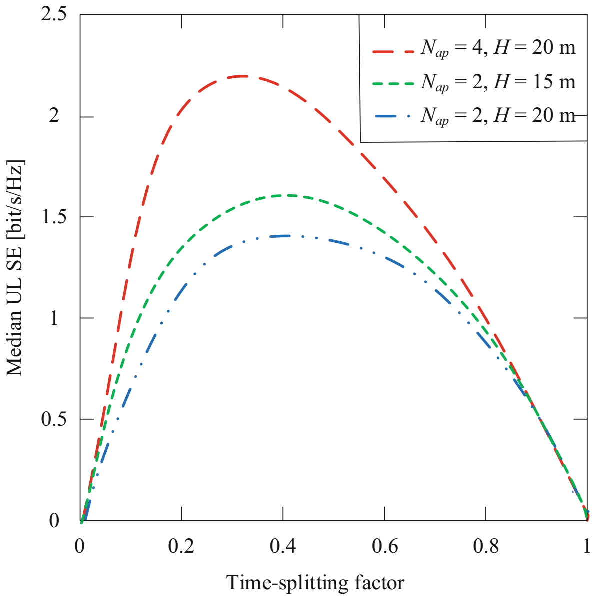


Fig. 7.6 CDF of DL rates of GUEs in (i) CF-mMIMO and (ii) cellular mMIMO ($\mathcal{L} = 20$, $N_{ap} = 2$, $\Gamma = 0.5$, Q = 0.98, $H = 20$ m)

Fig. 7.7 Relation between the time-splitting factor Γ and the median UL SE of UAV in CF-mMIMO with varying values of N_{ap} and H ($\mathcal{L} = 20$, Q = 0.98)



Moreover, it is shown that lower values of Γ are critical for the operating point of SE and to achieve the desired balance.

In Fig. 7.8, the CDF of DL HE of UAV in the considered systems, namely, CF-mMIMO, SCs, and cellular mMIMO, is depicted. It is worth noting that the expression $\rho_d^{sc}[n] = \mathcal{L}\rho_d^{cf}[n]$ is employed to achieve a modest comparison between CF and SC architectures. Similar to the case outlined above, a twofold and threefold improvement concerning median and 95% likely DL HE is obtainable

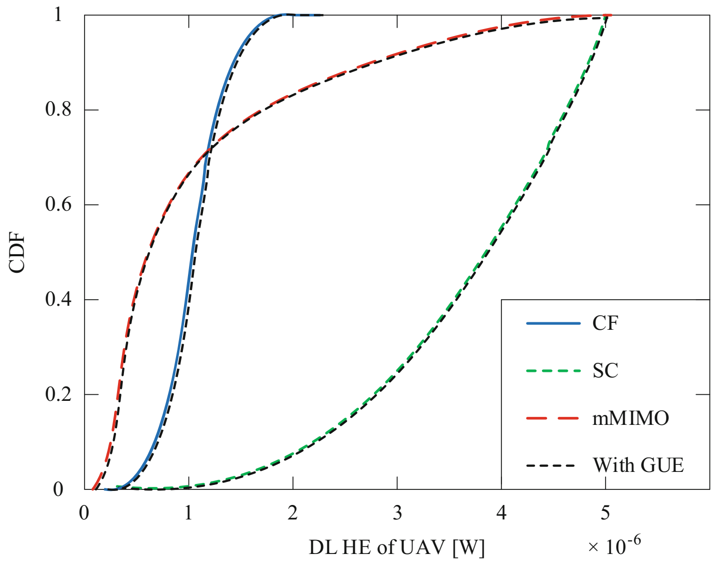


Fig. 7.8 CDF of DL HE of UAV in (i) CF-mMIMO, (ii) SC, and (iii) cellular mMIMO ($\mathcal{L} = 20$, $N_{ap} = 2$, $\Gamma = 0.5$, Q = 0.98, $H = 20$ m)

with the proposed CF architecture as opposed to cellular mMIMO. This is a result of the proximity between the UAV and antennas in scenarios with CF-mMIMO. Also, compared with CF-mMIMO, the SC system improves the median DL HE significantly. Nonetheless, concerning SE gains which is a critical performance index, CF-mMIMO significantly outperforms SC systems whose performance is poor in practical applications.

7.7 Conclusion

In this chapter, we characterized the use of CF-mMIMO architecture as a compelling solution to support UAV cellular communications which are envisioned to be of substantive importance in the space-air-ground network. More precisely, we proposed to improve the achievable spectral and EE in UAV cellular communications by exploiting the distinctive benefits presented by CF-mMIMO architectures. Foundational knowledge of CF-mMIMO architecture, viable characteristics, use cases, and associated communication requirements of UAVs are discussed. Moreover, extensive analysis on the background, architecture, and system modeling of UAV-aided CF-mMIMO networks is provided. By exploiting LMMSE channel estimation, novel expressions for the achievable lower and upper SE bounds for UL and DL data transmission phases are derived. Numerical analysis and computer simulations revealed a considerable boost in performance with the proposed CF-mMIMO architecture compared to multicell mMIMO networks and SC systems. Specifically, we have demonstrated that CF-mMIMO architecture may provide a robust enhancement in the realization of spectral and energy-efficient UAV cellular communications. Future research is integral to examine sophisticated power control techniques and the effect of hardware impairments at multiple UAVs.

7.7.1 Scope for Future Works

The concept of the UAV-aided CF-mMIMO system is still at a very infant stage of development, and several open research issues exist. This section attempts to unearth research challenges and provide promising directions to stimulate cutting-edge interest and unlock the full potentials of UAV-aided CF-mMIMO communications. The open research issues are highlighted as follows:

I. *Power control and interference coordination:* Power control and interference coordination are of paramount importance to provide seamless connectivity, manage the strong cross-link interference resulting from LoS-dominated air-ground channels, and ultimately improve the performance of systems [44]. However, this exciting area has not received a commensurate level of research interest. Therefore, there is a need for more sophisticated power control techniques and novel frameworks to manage the stringent requirements of UAV-enabled CF-mMIMO networks.

II. *NOMA-based UAV-aided CF-mMIMO:* NOMA has become an inevitable mainstream to overcome the prime challenge of high-spectrum efficiency and massive connectivity in 5G and B5G wireless communication networks via successive interference cancellation [13]. However, serving a multitude of users with multiple-antenna techniques introduces a performance bottleneck in terms of channel ordering. The design of cutting-edge channel ordering in NOMA-based UAV-aided CF-mMIMO is an interesting area worth investigating.

III. *mmWave communications:* The exponential increase in spectrum crowding coupled with the rapid proliferation of data-intensive applications encourages the exploitation of a new chunk of frequency spectrum available at 30–300 GHz (mmWave frequency band). Fortunately, mmWave UAV-aided CF-mMIMO is expected to provide a high probability of LoS channels and manage the stringent requirements of future wireless networks [45]. However, the extremely high propagation loss, large array beamforming gain, and doppler frequency compensation reflect critical challenges in mmWave UAV-aided CF-mMIMO and require further research.

IV. *Energy efficiency:* The cruising duration, endurance, and persistency of operation of UAV-based communications are significantly impacted by the availability of energy. A positive relationship exists between the sustenance of various operations such as sensing/transmission of data, flight control, and the capacity-limited battery (onboard energy) storage. Although several practical recharging solutions and energy consumption optimization techniques have been explored, the battery depletion problem and the challenge of guaranteeing prolonged and sustainable communication service remain an open research issue and is an interesting area worth exploring.

V. *Wireless power transfer:* Providing perpetual energy supplies to UAV-aided CF-mMIMO in all circumstances is critical and challenging. The novel energy delivering technology called WPT is envisioned to realize the ultimate performance limits [46]. Unfortunately, ensuring the efficiency of WPT is an arduous task owing to the length between the energy transmitters and receivers. Therefore, optimization techniques to enhance the WPT efficiency are a crucial aspect worthy of further investigation.

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Hope Ikoghene Obakhena, received the B.Eng. degree in Electrical and Electronics Engineering from Ambrose Alli University, Nigeria, in 2019. He is currently pursuing an M.Eng. degree with the Department of Electronics and Telecommunication Engineering, University of Benin, Nigeria. He emerged as the second-best Engineering Graduate in Nigeria in 2019. He is currently with the Department of Electrical and Electronics Engineering, Ambrose Alli University, Nigeria, as a Graduate Assistant. His research interests include 5G and beyond 5G wireless networks, signal processing, physical-layer secure communications, and artificial intelligence.

Agbotiname Lucky Imoize, (Senior Member, IEEE) is a Lecturer in the Department of Electrical and Electronics Engineering, University of Lagos, Nigeria. He received B.Eng. (Honors) in Electrical and Electronics Engineering from Ambrose Alli University, Nigeria, in 2008, and M.Sc. in Electrical and Electronics Engineering from the University of Lagos, Nigeria, in 2012. Before joining the University of Lagos, he was a Lecturer at Bells University of Technology, Nigeria. He worked as a Core Network Products Manager at ZTE Nigeria Limited from 2011 to 2012 and as a Network Switching Subsystem Engineer at Globacom, Nigeria, from 2012 to 2017. Imoize was awarded the Fulbright Fellowship as a Visiting Research Scholar at the Wireless@VT Lab in the Bradley Department of Electrical and Computer Engineering, Virginia Tech., USA, where he worked under the supervision of Prof. R. Michael Buehrer from 2017 to 2018. He is currently a Research Scholar at Ruhr University Bochum, Germany, under the Nigerian Petroleum Technology Development Fund (PTDF) and the German Academic Exchange Service (DAAD) through the Nigerian-German Postgraduate Program. He is a Registered Engineer with the Council for the Regulation of Engineering in Nigeria (COREN) and a Nigerian Society of Engineers (NSE) member. He has co-edited 1 book and coauthored over 80 papers in peer-reviewed journals and conferences. His research interests are beyond 5G and 6G wireless communications, chaotic communications, and wireless security systems.

Michael Adedosu Adelabu, obtained M.Sc. degree in Electronics and Telecommunications from Wroclaw Technical University, Wroclaw, Poland, in 1984; Postgraduate Diploma, PGD in Computer Science from the University of Lagos, Akoka, Yaba, Lagos, in 1991; and Ph.D. in Electrical and Electronics Engineering (Communications) 2016 from the University of Lagos. He taught briefly at Abubakar Tafawa Balewa University at the University of Lagos since 1993. His research interests include mobile communication systems, electromagnetics, consumer electronics technology, digital signal processing, and microwave engineering. He also has a passion for electronic circuits and systems and renewable energy systems. He has authored and co-authored papers in peer-reviewed journals and learned conferences. He is a COREN Registered Engineer, Fellow of the Nigerian Society of Engineers, and Senior Member of the Institute of Electrical and Electronics Engineers (USA).

Francis Ifeanyi Anyasi, is a Professor of Electronics and Telecommunication in the Department of Electrical and Electronics Engineering, Ambrose Alli University, Nigeria, where he received the B.Eng. degree in Electrical and Electronics Engineering and the Ph.D. degree in Telecommunications Engineering in 1996 and 2008, respectively. He is currently the Dean of the Faculty of Engineering and Technology, Ambrose Alli University, Nigeria. He has also served as the Foundation Program Coordinator, Director of Academic Planning and Industrial Training Unit in the same institution, in 2005, 2014, and 2018, respectively. He is a COREN Registered Engineer and a corporate member of the Nigerian Society of Engineers. He has co-authored over 70 papers in peer-reviewed journals and conference proceedings, and he has authored 2 books. His research interests span telecommunications engineering, antennas and propagation, digital signal processing, massive MIMO technology, and advanced electronic circuits and systems.

K. V. N. Kavitha is an Associate Professor in the Department of Communication Engineering, School of Electronics Engineering, Vellore Institute of Technology, Vellore, India. She is a Member of IEEE, the International Association of Computer Science and Information Technology, and IAENG. She received BE in Electronics and Communication Engineering from Madras University, India, in 1998; MBA in Human Resource Management from Annamalai University, India, in 2003; and ME in Applied Electronics from Anna University, India, in 2006. She received a Doctorate (Ph.D.) in Wireless Communication from VIT University, India, in 2018. Before joining VIT University, she was a Senior Lecturer at Arunai Engineering College, India. She worked as a faculty at Arunai Engineering College, India, from 1999 to 2007. She guided International Internship Project, ESIGELEC University, France, in 2008. She has given over 20 invited talks in conferences and seminars. She has reviewed over 100 articles in journals and conferences. She is an Editorial Board Member in various journals. She has co-authored over 50 papers in peer-reviewed journals and conferences. Her research interests are beyond 5G and 6G wireless communications, signal processing, IoT, networking, and wireless security systems.

Chapter 8
Unmanned Aerial Vehicle-Assisted Reconfigurable Intelligent Surface for Energy Efficient and Reliable Communication

Vinoth Babu Kumaravelu, Hindavi Kishor Jadhav, Anjana B. S., Vishnu Vardhan Gudla, Arthi Murugadass, and Agbotiname Lucky Imoize

Abstract Unmanned aerial vehicle (UAV) is one of the airborne components, which can establish a flexible infrastructure to support seamless connectivity requirements of the sixth-generation (6G) standard. Modern UAVs are equipped with communication and signal processing capabilities. Hence, it can act as a base station or relay station to support reliable communication. In order to improve energy efficiency, reconfigurable intelligent surfaces (RIS) can be employed on UAVs or the communication chain. The physical parameters, such as phase shifts of reflecting units, can be adjusted to enhance the signal-to-noise ratio (SNR) through software control. RIS can directly provide the additional array gain without complex precoding and radio frequency (RF) level processing. Due to this, a smaller number of onboard antennas are sufficient for UAVs to offer the required array gain for users. In this work, intelligent and blind UAV-assisted RIS schemes are proposed

V. B. Kumaravelu (✉) · H. K. Jadhav · Anjana B. S.
Department of Communication Engineering, School of Electronics Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, India
e-mail: vinothbab@gmail.com; hindavikj@gmail.com; anjanaalakkatt@gmail.com

V. V. Gudla
Department of Electronics and Communication Engineering, Aditya Engineering College, Surampalem, Andhra Pradesh, India
e-mail: vsquare.tarus@gmail.com

A. Murugadass
Department of Computer Science and Engineering (AI & ML), Sreenivasa Institute of Technology and Management Studies, Chittoor, Andhra Pradesh, India
e-mail: arthimdas@gmail.com

A. L. Imoize
Department of Electrical and Electronics Engineering, Faculty of Engineering, University of Lagos, Lagos, Nigeria

Department of Electrical Engineering and Information Technology, Institute of Digital Communication, Ruhr University, Bochum, Germany
e-mail: aimoize@unilag.edu.ng

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to increase energy efficiency. In contradiction to the blind scheme, the knowledge of the dual-hop channel is assumed to be available at UAV in an intelligent UAV-assisted RIS scheme, which maximizes the SNR. The analytical closed-form average bit error probability (ABEP) expressions are derived to validate our claims. Through simulation results, it is observed that intelligent UAV-assisted RIS can convert wireless fading environment into superior communication environment, which can offer a low average bit error rate (ABER) at extremely low SNR conditions.

Keywords Array gain · Average bit error probability (ABEP) · Average bit error rate (ABER) · Blind UAV-assisted RIS · Diversity gain · Dual-hop communication · Intelligent UAV-assisted RIS · Reconfigurable intelligent surfaces (RIS) · Sixth-generation (6G) · Unmanned aerial vehicle (UAV)

8.1 Introduction

8.1.1 Motivation

Wireless communication has a tremendous growth in the last few decades. In 2018, the first commercial fifth-generation (5G) standard was introduced. As per the Ericsson Mobility Report (June 2021), there will be 580 million subscriptions for 5G networks by the end of 2021 [1]. Around 160 network service providers have deployed 5G communication until now, and several smartphone manufacturing companies have launched more than 300 5G-supporting smartphones. In the 5G subscription count, Northeast Asia, North America, and Western Europe hold first, second, and third positions. Compared to fourth-generation (4G) subscriptions, the growth of 5G is very fast. Fixed wireless access (FWA) is offered by more than 70% of service providers.

As per Cisco annual report (2020), 70% of the world population will acquire mobile connectivity, and 10% will have 5G connectivity by 2023 [2]. For fixed broadband, the speed is expected to reach 110.4 Mbps. For the mobile network, the speed is expected to reach 43.9 Mbps, approximately three times higher than the speed of 2018. By then, the average connection speed of 5G will become 575 Mbps.

6G has tremendous applications. With the invention of 6G, smart homes, smart cities, augmented reality (AR), virtual reality (VR), and mixed reality will become more user-friendly. With the deployment of 6G, the automotive system will become more efficient, and self-driving cars are expected to be more common [3]. The 6G deployment expects a low latency, high data rate, and reliable communication.

Now let us look at the requirements of 5G and 6G. Spectral and energy efficiency of 5G is 10 times more than 4G, whereas, in 6G, it should be 1000 times more. The rate requirement of 5G is 1 Gbps, but in 6G, it is expected to be 1 Tbps. One ms is the end-to-end delay of 5G, and in 6G it will be just below 0.1 ms. The processing delay of 5G is 100 ns, whereas in 6G it should be 10 ns. 5G uses sub-6 GHz and millimeter wave (30–100 GHz) bands. 6G must use sub-6 GHz, millimeter wave, sub-millimeter wave (more than 100 GHz), and THz (300 GHz to 10 THz) bands [4]. The main key element of 5G technology is massive Multiple-input multiple-output (MIMO), where the major 6G-enabling technology is RIS. The authors of [5] highlighted novel 6G use cases like precision agriculture, tourism, transportation, media, and education. They also looked into 6G's ability to contribute to global sustainability. This study also highlights the major challenges and areas of future investigation.

The global mobile traffic will cross 77 exabytes by 2022. The current cellular standards may not accommodate these demands. In order to meet the expected demands, various possible solutions like migration to millimeter wave, sub-millimeter wave, and THz bands; relay-assisted communication; non-reconfigurable passive reflectors; and smart nearly passive surfaces are proposed in the literature [6]. RIS will be a cost- and energy-effective, green and sustainable solution for 6G [7]. RIS is suitable for Internet of things (IoT), device-to-device (D2D) communications, visible light communications (VLC), machine-to-machine (M2M) communications, etc. [8–10]. MIMO has the potential to provide tremendous spectral and energy efficiency [11]. MIMO serves as the cornerstone for RIS.

8.1.2 Multiple-Input Multiple-Output (MIMO)

MIMO is a significant milestone for developing wireless communication systems, which is commonly used in third-generation (3G) and 4G standards. MIMO system consists of multiple antennas at the transmitter and multiple antennas at the receiver. Multiple antennas lead to diversity, which increases the reliability. The data rate increases by transmitting several information bits in parallel, known as spatial multiplexing. It can also offer array gain and beamforming gain. The MIMO system needs high resource requirements and hardware complexity compared to a single-antenna conventional system. It has many RF chains; therefore, it increases power consumption. MIMO requires complex signal processing algorithms compared to a single-antenna system. In [11], physical, analytical, and standardized MIMO channel models are studied in detail. The sustained high data rate and reliable communication between UAVs and users are required to ensure increased UAVs utilization in the future. To achieve this goal, UAVs can be integrated to current cellular networks. Supporting UAVs with cellular connections presents new challenges and opportunities for study. One way to improve cellular communication capability for UAVs is to use multiple antennas [12, 13].

8.1.3 Multiuser MIMO

In practice, it is hard to achieve considerable multiplexing gains through point-to-point MIMO [14]. Multiuser (MU) MIMO allows multiple users to communicate simultaneously. It operates as a point-to-multipoint MIMO on the downlink and as a multipoint-to-point MIMO on the uplink. Users do not cooperate in MU-MIMO because everyone has their own signal to transmit. Instead than focusing on a single capacity, each user is concerned with their own performance. Every user has his or her own power budget. The channel matrix is modelled very differently, where each column can be modelled as a single-input multiple-output (SIMO) channel. MU-MIMO inspired the concept of non-orthogonal multiple access (NOMA). MU-MIMO provides each user with beamforming gain at a lower loss owing to MU interference. Massive connectivity with larger sum capacity is enabled via MU-MIMO, which is essential for next-generation networks.

8.1.4 Massive MIMO

Massive MIMO is the extended version of MIMO. In massive MIMO, base stations are equipped with a large number of antennas (typically, more than 64). The capacity of massive MIMO improves with the number of antennas. It has high spectral and energy efficiency than conventional MIMO [14]. Reliability is high due to diversity, and it is resistant to small-scale fading. For network operators, massive MIMO is the best solution to improve network capacity. Beamforming in massive MIMO is accurate, so radio signals focus on the specific user equipment. Better coverage is obtained by beamforming, and it will reduce the interference and increase the signal strength. Due to these properties, massive MIMO has become the pillar of 5G.

Practical implementation of massive MIMO has been started all over the world. In 2018, Ericsson designed AIR 6468 for 4G long-term evolution (LTE) networks. It consists of 64 antennas and 64 digital transceivers for uplink and downlink channels. Each antenna in AIR 6468 radiates 1.85 W power. In 2018, other telecom companies also started to implement massive MIMO. With the support of massive MIMO, UAV-assisted cellular communication becomes more reliable and efficient [15].

Massive MIMO uses many antennas to improve spectral efficiency. But it will increase hardware complexity and cost. Many antenna arrays are not suitable for future networks to improve energy efficiency. This is because energy consumption rises with the number of RF chains used [16]. Signal processing complexity is high due to the use of many antennas and the multiplexing of user equipment. The practical deployment of massive MIMO antenna arrays is a complicated task.

8.1.5 Spatial Modulation

The modulation order of typical digital modulation schemes should be increased to improve spectral efficiency. To ensure the required reliability, this necessitates a high transmit power. In spatial modulation (SM), the antenna indices, in addition to the standard signal constellation, carry information. In order to attain the needed spectral efficiency, lower-order modulation methods are sufficient. This lowers the required transmit power to achieve the desired reliability. In SM, only one RF chain will be active at a time. Therefore, by introducing SM, we can reduce the number of RF chains active, which leads to a reduction in power consumption. SM maps a group of information bits into two information-carrying units. The spectral efficiency of SM is specified by

$$\gamma_{\mathrm{SM}} = \log_2 (N_T) + \log_2(M) \text{ bpcu} \tag{8.1}$$

Here N_T is the number of transmitting antennas and M is the constellation order. The first $\log_2(N_T)$ bits choose the transmit antenna, and last $\log_2(M)$ bits choose a symbol to be transmitted. For example, $N_T = 4$ and $M = 2$, leading to a spectral efficiency of $\gamma_{\mathrm{SM}} = 3$ bpcu. Since there are four transmit antennas, we need a minimum of two bits to uniquely identify them. This results in a spectral efficiency of 2. The conventional modulation with $M = 2$ can offer a spectral efficiency of 1. We will obtain a spectral efficiency of 3 bpcu for each transmission. The detailed explanations for SM-assisted transmission is elaborated in [17–20].

SM consumes low power. Because a single transmit antenna is active at a time, inter-symbol interference can be avoided. Therefore the complexity of the detector can be reduced. SM achieves high spectral efficiency, but it is not very high as expected [17–20].

8.2 Reconfigurable Intelligent Surfaces (RIS)

It is a promising technique for future wireless communication. The transmitted electromagnetic (EM) waves experience several unmanageable alterations while propagating in a wireless environment [21]. The effects like absorption, reflections, refractions, diffractions, and free space path loss highly affect the system's performance. These characteristics are not controllable. RIS is a metasurface consisting of an array of meta-atoms. It can scatter the incoming wave with a controllable phase shift. By using RIS, we can create a controllable wireless environment. It will improve signal quality and energy efficiency. It can flexibly manipulate EM waves in the communication channel to enhance performance [22]. It can fully absorb the incoming wave. It can steer the beam toward the desired user. It can also manipulate the polarization. RIS is also known as intelligent reflecting surface (IRS), large-scale intelligent surfaces (LIS), hypersurface tile, digitally controllable scatterers, and software-controlled meta-surfaces [22–24]. Through simulations, the effectiveness of RIS-assisted communication is evaluated in [21]. RIS can support MIMO communications without the additional requirement of RF chains [25]. This drastically reduces power consumption.

RIS requires only small operational power for implementation. Therefore, it can be easily implemented on building walls. If there is no line of sight (LoS) between source and destination due to shadowing, the transmitter can beamform the signal toward the user through RIS. RIS act as a non-amplifying relay, so it reradiates the signal without any amplification. RIS ensures lower energy consumption than traditional amplify-and-forward (AF) relays [24, 26]. Relays are active elements, which needs a dedicated power supply. It consists of digital-to-analog converters, mixers, power amplifiers, analog-to-digital converters, low noise amplifiers, etc. Hence, deployment of relays is expensive and time- and power-consuming. When full duplex (FD) relaying is used, complexity is increased further. RIS is configured with switches or varactors [27–29]. These are inexpensive and low-powered electronic components. The electronic components used in relays lead to additive noise. The AF relays amplify noise in addition to signal. In decode-and-forward (DF) relays, the received signal is detected first to remove the effect of noise and interference. Then the signal is regenerated and transmitted to the destination. This is power inefficient solution with higher signal processing complexity. RISs are passive reflectors not affected by additive noise. It does not amplify or regenerate the signal.

As per two-ray ground reflection model, the received power can be expressed as [24]

$$P_{\mathrm{rx}} = P_{\mathrm{tx}} G_{\mathrm{t}} G_{\mathrm{r}} \left(\frac{h_{\mathrm{tx}}^2 h_{\mathrm{rx}}^2}{d_0^4} \right) \tag{8.2}$$

Here P_{tx} is the transmitted power. G_{t} and G_{r} represent the source and destination antenna gains, respectively. h_{tx} and h_{rx} are the heights of source and destination respectively. d_0 is the distance between the source and destination. The received signal power increases with an increase in transmitted power and is inversely proportional to the fourth power of the distance. Therefore, a small change in distance will have a huge impact on the received power. There is a degradation of received power when the distance between transmitter and receiver is very high. Due to uncontrollable reflection, only a small fraction of transmit power is received at the receiver.

Let us consider RIS-assisted wireless communication as in Fig. 8.1. RIS can manipulate the incoming wave and optimize the phase of the reflected wave. Then the received power due to RIS with N reflecting elements is approximated as [24].

$$P_{\mathrm{rx}} \approx (N+1)^2 P_{\mathrm{tx}} \left(\frac{\lambda}{4\pi d_0} \right)^2 \tag{8.3}$$

Here λ represents the wavelength. By comparing (8.2) and (8.3), received power is inversely proportional to the square of the source and destination separation distance for RIS-assisted communication. The conventional two-ray ground reflection model's received power decays with the fourth power of distance. Therefore, we can improve the received signal strength by using RIS-assisted communication.

The use cases of RIS are energy focusing and energy nulling. Figure 8.2 represents energy focusing use case of RIS. There is a direct path between the source and the destination. Transmitter sends the signal to a user. The same signal

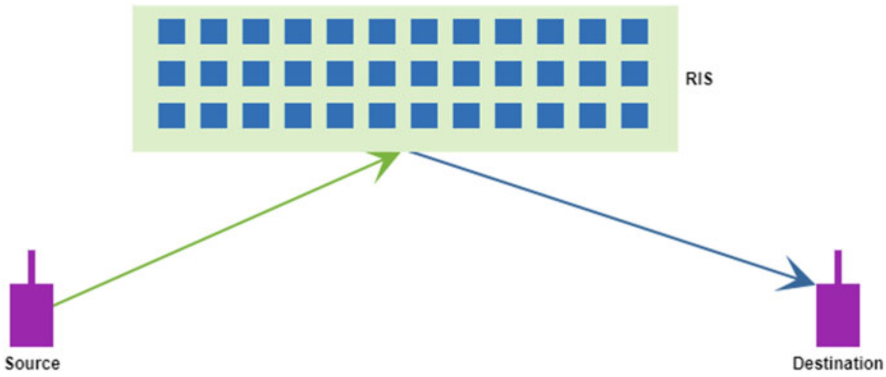


Fig. 8.1 RIS-assisted communication

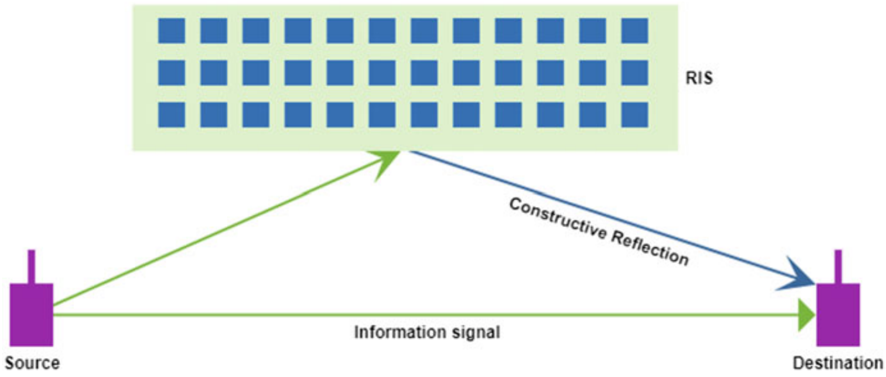


Fig. 8.2 Energy focusing use case of RIS

is reflected through RIS. The signal is adjusted so that these two signals are constructively added and focused on the desired user. As a result of constructive interference, we get a stronger signal. To improve the SNR, RIS is used here. Figure 8.3 represents the energy-nulling use case of RIS. When the transmitter transmits a signal to user 1, it leaks to user 2 as well. Using a RIS, we can control the signal bouncing off it. It will adjust the phase of the signal so that at user 2, it is destructively added and at user 1 constructively added. Therefore user 2 gets almost zero signal. Due to constructive interference, we get a stronger signal at user 1 [23].

There are multiple other objectives/use cases of RIS. Few of them are listed here [21]:

- Minimize inter-user interference
- Optimize the quality of service (QoS)
- Provide secure air path
- Block unauthorized users
- Wireless power transfer

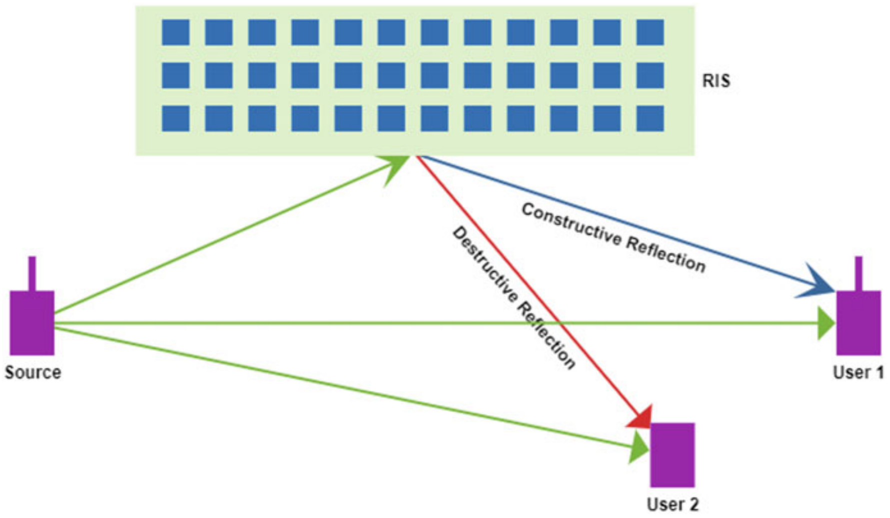


Fig. 8.3 Energy nulling use case of RIS

Since RIS only shifts the phases, the attainable rates are reasonably limited. In order to address this issue, a new RIS architecture is proposed to attain amplitude/phase diversifying modulation [27]. This eases MIMO-quadrature amplitude modulation (QAM) transmission design. The hardware constraints on RIS and the corresponding effect on the system's performance are also analyzed. The proposed RIS-assisted MIMO-QAM prototype is also tested over the air. In [7], the working principle of RIS is introduced. It also proposes different optimization frameworks to maximize energy efficiency, achievable rate, coverage ratio, secrecy rate, etc. This work also analyzes the performance in terms of capacity, achievable uplink and downlink rates, outage probability, the effect of hardware impairments on capacity, etc. This work highlights various research issues associated with RIS like resource allocation, localization, combined RF-VLC, health forethoughts, etc.

In [28], multiple RISs are placed on improving the capacity of single-user multiple-input single-output (MISO) downlink transmission. By exploiting the channel state information (CSI), the phase shift matrices of all placed RIS are configured. The proposed system observes convincing gains when the randomness associated with the channel is low. In [25], the precoding matrix at the base station and phase shift matrix at RIS are designed using deep reinforcement learning. The proposed neural network learns from the environment and slowly enhances its behavior. It offers significant gains over the two state-of-the-art benchmarks. By setting appropriate parameters for the neural network, the convergence rate and performance can be improved substantially.

In [29], RIS is deployed in the LoS of a multi-antenna base station to support multiple single-antenna users. It has been proven that the spectral efficiency gains are improved unprecedentedly with the number of passive reflective elements. Here, the optimal linear precoder, which maximizes the SNR under power constraint, is discussed. Through simulations, it has been observed that the RIS with a smaller number of reflective elements outperform half-duplex relays. In contrast, the RIS with larger reflective elements outperforms full-duplex relays.

8.2.1 UAV-Assisted RIS

Most of the literature focuses on terrestrial RIS, where RIS is mounted on facades of buildings, walls, ceilings, furniture, etc. [30]. Practically, it is difficult to find a location for RIS deployment. It involves various reasons like the willingness of owners, site rent, the effect of urban landscape, etc. The RIS located at facades and walls may serve users located on one side of the building. The source and destination terminals are expected to be available on the same side of RIS. The RIS may not serve the destination terminal available on the other side of the building. The half-space reflection by conventional terrestrial RIS is illustrated in Fig. 8.4, where T_1 represents the source and R_1 and R_2 represent the destinations. In urban environments, even with RIS, the signals produced by the source should undergo multiple reflections before it reaches the destination. There will be significant attenuation due to multiple reflections and scattering in undesired directions. This is illustrated in Fig. 8.5. Here T and R represent the source and destination, respectively.

In order to address the above issues, a three-dimensional aerial RIS (ARIS) is proposed, where RIS is deployed on aerial vehicles like balloons, UAVs, etc. [30]. It can reflect intelligently from the sky. It can quickly establish an LoS communication with all ground nodes [31]. This leads stronger channel compared to terrestrial RIS. It empowers full-angle reflection, i.e., can reflect signals between any two terminals on the ground. The full-angle reflection by UAV-assisted RIS is illustrated in Fig. 8.6. This can cover the destination terminals on the other side of the buildings. The

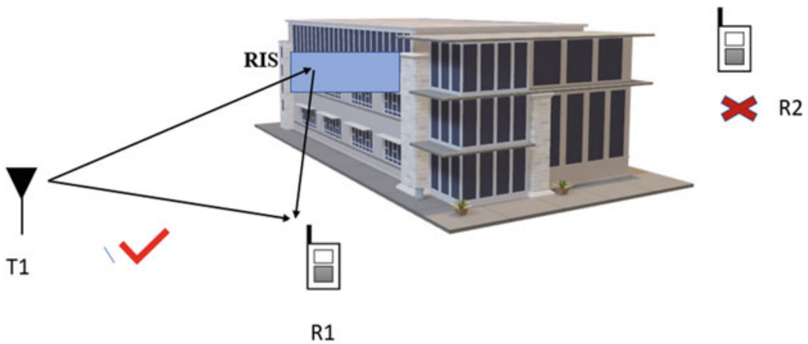


Fig. 8.4 Half-space reflection by the conventional terrestrial RIS

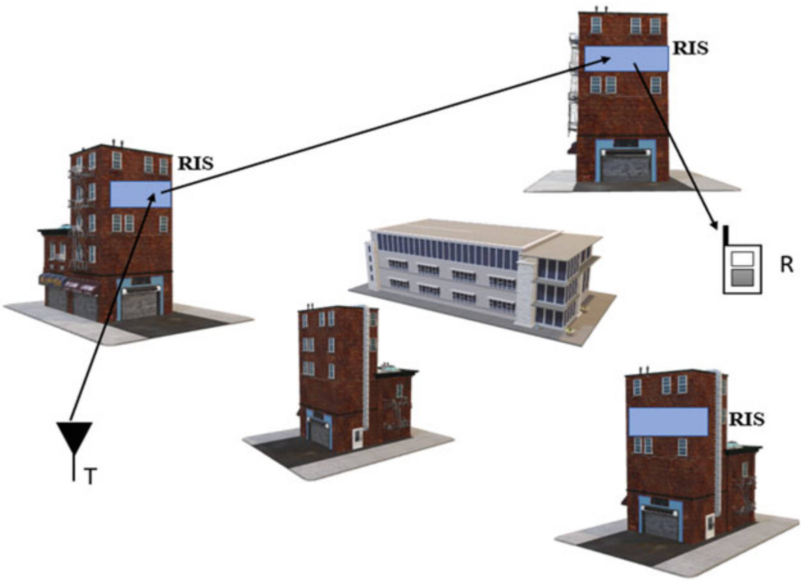
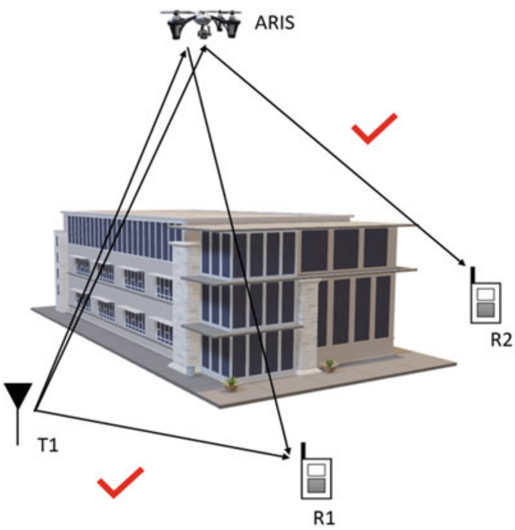


Fig. 8.5 Multiple reflections by the conventional terrestrial RIS

Fig. 8.6 Full-angle reflection by UAV-assisted RIS



UAV-assisted RIS enables single reflection. This hugely reduces the power loss with multiple reflections. This is illustrated in Fig. 8.7. Due to the above benefits, we have considered UAV-assisted RIS communication in this work. The deployment of RIS on UAV is beyond the scope of this work. We also assume tethered UAVs, which can have a permanent physical link from the building to provide power.

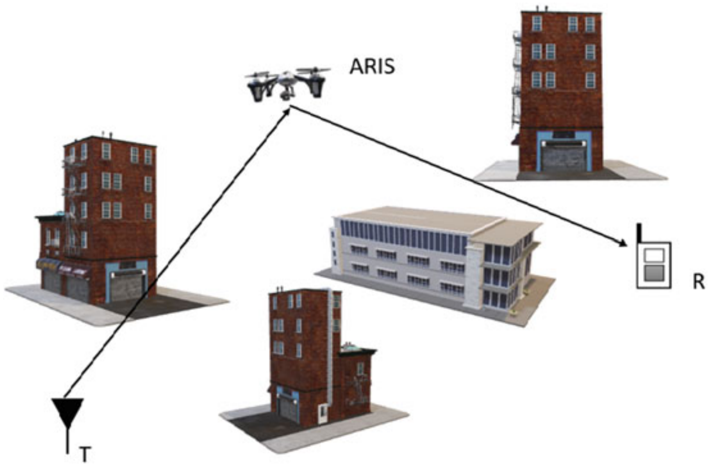


Fig. 8.7 Single reflection by UAV-assisted RIS

8.3 The Proposed UAV-Assisted RIS Schemes

A simple UAV-assisted RIS scheme is depicted in Fig. 8.8, which comprises a source, RIS-mounted UAV, and a destination. Here a power-driven (tethered) UAV with N number of reflective elements acts as an RIS. The source and destination terminals are assumed to have a single antenna. Basar et al. proposed two RIS-assisted schemes (intelligent and blind) for future wireless communications [24, 32]. They also derived analytical ABEP expressions for both schemes. The proposed schemes are validated only for binary phase shift keying (BPSK). We developed two UAV-assisted RIS schemes by keeping this work as a base.

8.3.1 Intelligent UAV-Assisted RIS Scheme

The UAV-assisted RIS is assumed to have accurate CSI in this dual-hop communication. Hence, it can post and pre-compensate the phase distortions for maximizing the SNR [24, 32]. Considering the effect of channel estimation error and channel information feedback delay is out of the scope of this work.

The channel gain between source and k th passive reflector of RIS is denoted by $p_k = \beta_k e^{j\Phi_k}$, where β_k and Φ_k are the corresponding magnitude and phase. The channel gain between k th passive reflector of RIS and destination is given by $q_k = \Upsilon_k e^{j\psi_k}$, where Υ_k and ψ_k are the corresponding magnitude and phase.

The net signal reflected by N reflecting elements is given by [24]

$$y = \left[\sum_{k=1}^{N} p_k q_k e^{-j\theta_k}\right] s + \omega \tag{8.4}$$

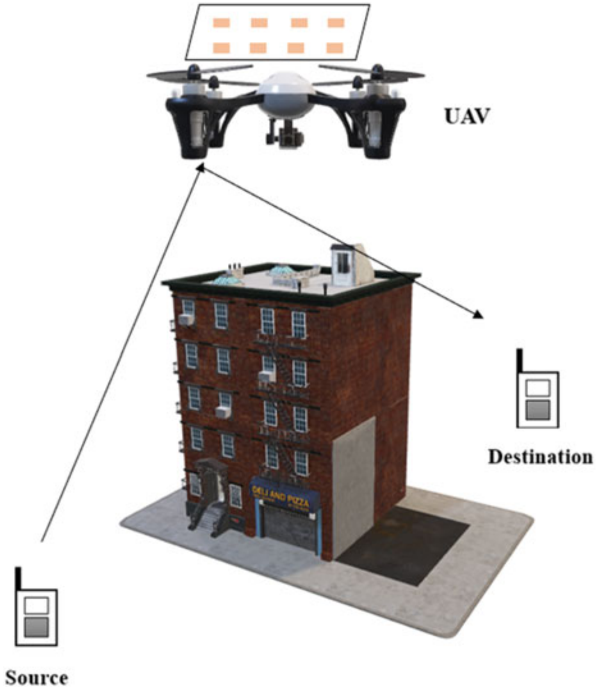


Fig. 8.8 UAV-assisted RIS scheme

where s is the transmitted signal and ω is the additive white Gaussian noise (AWGN) having zero mean and variance σ_{ω}^{2}. Here θ_k is the phase adjusted by the k th RIS element in order to minimize the interference, which is given by

$$\theta_k = \phi_k + \psi_k \tag{8.5}$$

Instantaneous SNR for the described model is calculated as follows

$$\Gamma = \frac{\left|\sum_{k=1}^{N} \beta_k \Upsilon_k \mathrm{e}^{-j(\theta_k - \phi_k - \psi_k)}\right|^2 E_S}{N_{\mathrm{o}}} \tag{8.6}$$

where E_S is the average energy of the transmitted symbols. SNR is maximized by generating the phase (θ_k) by software control so that the phase interference becomes zero.

$$\Gamma = \frac{\left(\sum_{k=1}^{N} \beta_k \Upsilon_k\right)^2 E_S}{N_{\mathrm{o}}} = \frac{G^2 E_S}{N_{\mathrm{o}}} \tag{8.7}$$

β_k and Υ_k both follow Rayleigh distribution, and they are independent. The mean and variance of $\beta_k \Upsilon_k$ are given as [33]

$$E\left[\beta_k \Upsilon_k\right] = \frac{\pi}{4} \tag{8.8}$$

$$\mathrm{Var}\left[\beta_k \Upsilon_k\right] = 1 - \frac{\pi^2}{16} \tag{8.9}$$

From (8.7), it is clear that phase effects are completely nullified when we substitute (8.5) in (8.6). In (8.7), it is given that SNR is directly proportional to the square of the magnitude of the channel gain. Hence, the SNR is maximum in this transmission scheme. If N is large enough ($N \geq 1$), then as per central limit theorem (CLT), Gaussian distribution is followed by G. For the large values of N, the mean and variance of these variables become

$$E\left[G\right] = \frac{N\pi}{4} \tag{8.10}$$

$$\mathrm{Var}\left[G\right] = N\left(1 - \frac{\pi^2}{16}\right) \tag{8.11}$$

The instantaneous SNR follows noncentral Chi-square distribution with one degree of freedom. The corresponding moment generation function (MGF) is [34]

$$M_\Gamma\left(\eta\right) = \left(\frac{1}{1 - \frac{\eta\left(16-\pi^2\right)NE_S}{8N_0}}\right)^{\frac{1}{2}} \exp\left(\frac{\frac{\eta\pi^2N^2E_S}{16N_0}}{1 - \frac{\eta\left(16-\pi^2\right)NE_S}{8N_0}}\right) \tag{8.12}$$

For M-ary phase-shift keying (PSK) modulation, the average symbol error probability (ASEP) is calculated as follows [35]:

$$p_e = \frac{1}{\pi}\int\limits_0^{\pi(M-1)/M} M_\Gamma\left(-\frac{\sin^2(\pi/M)}{\sin^2 t}\right)\mathrm{dt} \tag{8.13}$$

For BPSK, (8.13) simplifies to

$$p_e = \frac{1}{\pi}\int\limits_0^{\pi/2}\left(\frac{1}{1 + \frac{\left(16-\pi^2\right)NE_S}{8\ \sin^2 t N_0}}\right)^{\frac{1}{2}} \exp\left(\frac{\frac{-\pi^2N^2E_S}{16\sin^2 t N_0}}{1 + \frac{\left(16-\pi^2\right)NE_S}{8\sin^2 t N_0}}\right)\mathrm{d}t \tag{8.14}$$

The upper bound is calculated for $t = \frac{\pi}{2}$ [32]

$$P_e \leq \frac{1}{2}\left(\frac{1}{1 + \frac{\left(16-\pi^2\right)NE_S}{8N_o}}\right)^{\frac{1}{2}} \exp\left(\frac{\frac{-\pi^2N^2E_S}{16N_o}}{1 + \frac{\left(16-\pi^2\right)NE_S}{8N_o}}\right) \tag{8.15}$$

8.3.2 Blind UAV-Assisted RIS Scheme

In this transmission technique, RIS does not know the channel phases [24, 32]. Blind transmission cannot overcome the effect of phases as they are unknown. SNR maximization is not possible in this technique. Hence, the performance of the blind transmission scheme is poor when compared with the intelligent transmission scheme. Assuming $\theta_k = 0$, the received signal is expressed as

$$y = \left[\sum_{k=1}^{N} p_k q_k\right] s + \omega \tag{8.16}$$

In terms of MGF, the received Γ for the higher value of N is given as

$$M_\Gamma(\eta) = \left(\frac{1}{1-\frac{\eta N E_S}{N_0}}\right) \tag{8.17}$$

For the blind transmission, the ABEP is given by

$$p_e = \frac{1}{\pi}\int_0^{\pi/2}\left(\frac{1}{1+\frac{NE_S}{\sin^2 t N_0}}\right)dt = \frac{1}{2}\left(1-\sqrt{\frac{\frac{NE_S}{N_0}}{1+\frac{NE_S}{N_0}}}\right) \tag{8.18}$$

8.4 Simulation Results and Discussions

The proposed intelligent and blind UAV-assisted RIS schemes are simulated in this section. Initially, the number of passive reflective elements are varied by fixing the modulation order. Later, the modulation order is varied by fixing the number of reflective elements. We assume RIS on tethered UAV in this work, which will not move. The simple Rayleigh fading channel is considered for dual-hop communication. For simplicity, the altitude, shadowing factors, etc. are not considered while modelling the channel. The effect of correlation between the RIS mirrors is also ignored.

In Fig. 8.9, the ABER performance of intelligent UAV-assisted RIS scheme by varying the number of passive reflective elements is plotted. The simulations are performed for BPSK modulation. Increasing the number of reflecting elements increases the SNR gains. To achieve an ABER $\left(P_e^t\right)$ of 10^{-5}, $N = 8$, $N = 16$, $N = 32$, $N = 64$, $N = 128$, $N = 256$, and $N = 512$ systems require SNR of ~−1 dB, ~−9 dB, ~−17 dB, ~−24 dB, ~−30 dB, ~−36 dB, and ~−43 dB, respectively. An intelligent UAV-assisted RIS scheme performs better than a classical wired AWGN channel. It transforms the wireless fading environment into a reliable environment. This remarkable gain is due to the cancellation of phase distortions at UAV-assisted RIS.

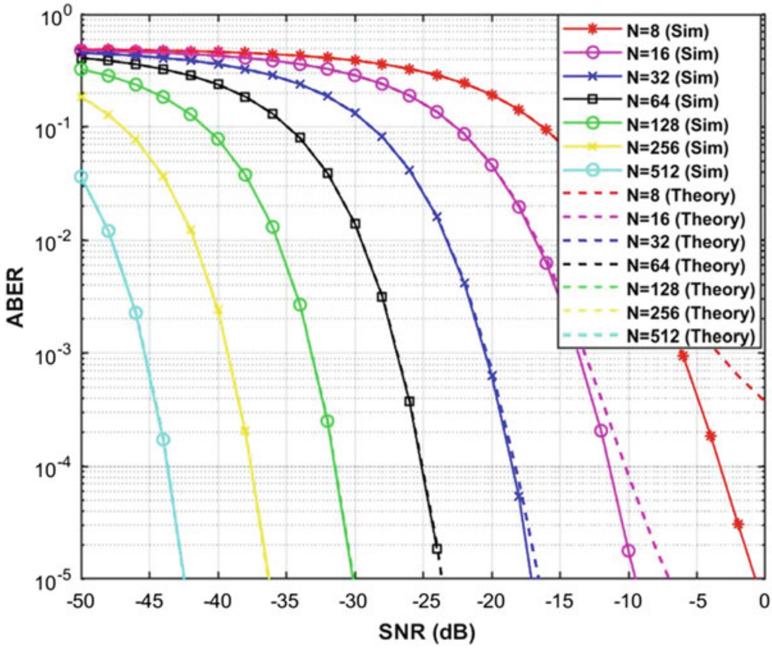


Fig. 8.9 ABER performance of intelligent UAV-assisted RIS scheme for varying number of passive reflective elements and $M = 2$

The simulation results are compared with the theoretical ABEP expressions derived in (8.14). For a smaller number of reflecting elements, the ABER and ABEP results are deviating. Once N increases, the deviation decreases. From $N = 32$, the ABER and ABEP results are tightly matching. This is due to the CLT approximations used to derive (8.14). For a sufficiently large number of passive reflecting elements, G converges to Gaussian distribution. This validates the accuracy of our simulation results.

In Fig. 8.10, the exact ABEP performance of the intelligent UAV-assisted RIS scheme is compared with its upper bound in (8.15) by varying the number of passive reflective elements. There is a slight deviation between exact and upper bound results for low SNR regions. But there is a closer match at high SNR regions.

In Fig. 8.11, the ABER performance of blind UAV-assisted RIS scheme by varying the number of passive reflective elements is plotted. The simulations are performed assuming BPSK modulation. Increasing the number of RIS elements increases the SNR gains. To achieve an ABER of 10^{-5}, $N = 8$, $N = 16$, $N = 32$, $N = 64$, $N = 128$, $N = 256$, and $N = 512$ systems require SNR of 35 dB, 32 dB, 29 dB, 25 dB, 23 dB, 20 dB, and 15 dB, respectively. The UAV-assisted RIS does not have the knowledge of dual-hop channels. Hence, the received SNR cannot be maximized by eliminating the phase terms. The simulation results are compared with the theoretical ABEP expression in (8.18). The ABER and ABEP results are

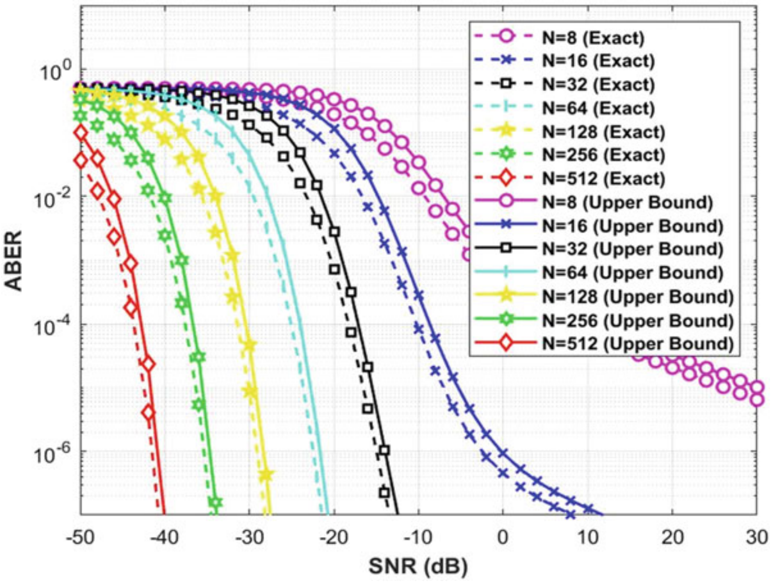


Fig. 8.10 Exact versus upper bound ABEP performance comparisons of intelligent UAV-assisted RIS scheme for varying number of passive reflective elements and $M = 2$

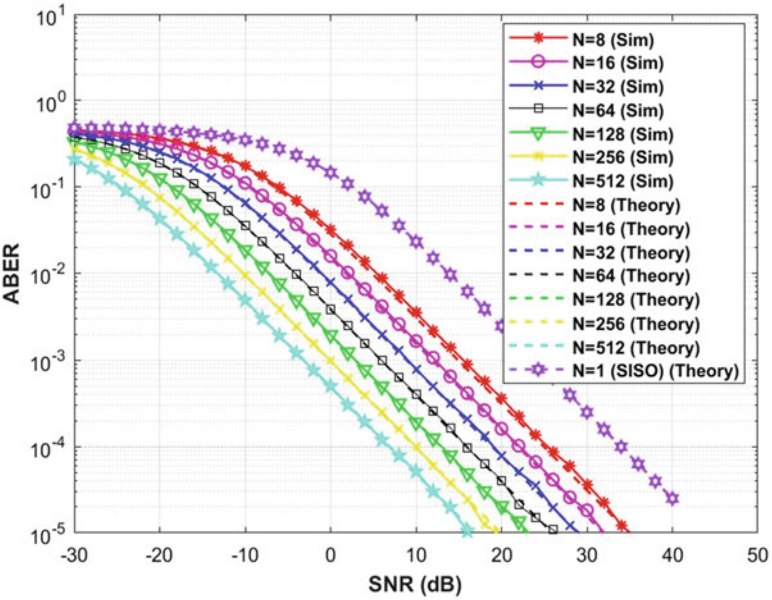


Fig. 8.11 ABER performance of blind UAV-assisted RIS scheme for varying number of passive reflective elements and $M = 2$

Table 8.1 The gain in SNR of intelligent UAV-assisted RIS scheme over blind UAV-assisted RIS scheme for the various number of reflecting elements, considering $M = 2$

$M = 2$ and $P_e^t = 10^{-5}$			
Number of reflecting elements (N)	Intelligent UAV-assisted RIS scheme	Blind UAV-assisted RIS scheme	Gain in SNR (dB)
8	~−1	~35	~36
16	~−9	~32	~41
32	~−17	~29	~46
64	~−24	~25	~49
128	~−30	~23	~53
256	~−36	~20	~56
512	~−43	~15	~58

tightly matching. This validates the accuracy of our simulation results. For $N = 1$, the blind UAV-assisted RIS scheme behaves like the single-input single-output (SISO) Rayleigh fading model. When the number of reflecting elements increases, even the blind scheme performs better than the SISO system. This is mainly due to the array gain.

The gain in SNR of intelligent UAV-assisted RIS scheme over blind UAV-assisted RIS scheme for the various number of reflecting elements, considering $M = 2$, is listed in Table 8.1. The performance of an intelligent UAV-assisted RIS scheme is far better than a blind UAV-assisted RIS scheme. As an intelligent UAV-assisted RIS scheme has the knowledge of channel phases in advance, it can maximize the SNR by cancelling the phase distortions of the channel. The SNR gains of intelligent scheme increase with N over the blind scheme.

In Fig. 8.12, the ABER performance of intelligent UAV-assisted RIS scheme by varying the modulation order is plotted. The simulations are performed for $N = 4$. The increase in modulation order increases the SNR required to achieve the target ABER. In order to achieve an ABER of 10^{-5}, $M = 2$, $M = 4$, $M = 8$, $M = 16$, $M = 32$, and $M = 64$ systems require SNR of ~ 11 dB, ~ 14 dB, ~ 18 dB, ~ 24 dB, ~ 30 dB, and ~ 35 dB, respectively. $M = 64$ system requires ~ 25 dB more than $M = 2$ system for achieving the same target ABER.

In Fig. 8.13, the ABER performance of blind UAV-assisted RIS scheme by varying the modulation order is plotted. The simulations are performed for $N = 4$. The increase in modulation order increases the SNR required to achieve the target BER. In order to achieve an ABER of 10^{-5}, $M = 2$, $M = 4$, $M = 8$, $M = 16$, $M = 32$, and $M = 64$ systems require SNR of ~ 36 dB, ~ 39 dB, ~ 42 dB, ~ 49 dB, ~ 54 dB, and ~ 58 dB, respectively. $M = 64$ system requires ~ 22 dB more than $M = 2$ system for achieving the same target ABER. The gain in SNR of intelligent UAV-assisted RIS scheme over blind UAV-assisted RIS scheme for various M-ary modulation schemes, considering $N = 4$, is listed in Table 8.2. As the phase distortions of the channels are compensated by intelligent UAV-assisted RIS, it performs better than blind UAV-assisted RIS scheme.

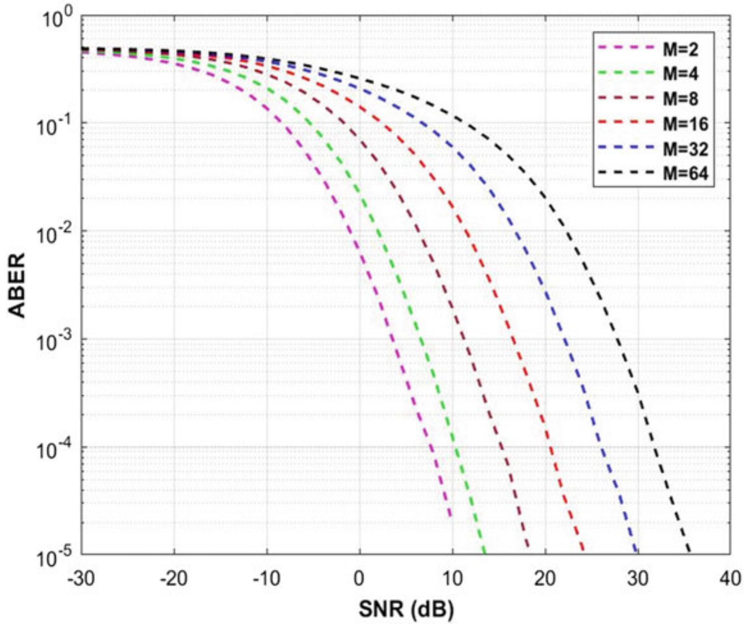


Fig. 8.12 ABER performance of intelligent UAV-assisted RIS scheme for varying modulation order and $N = 4$

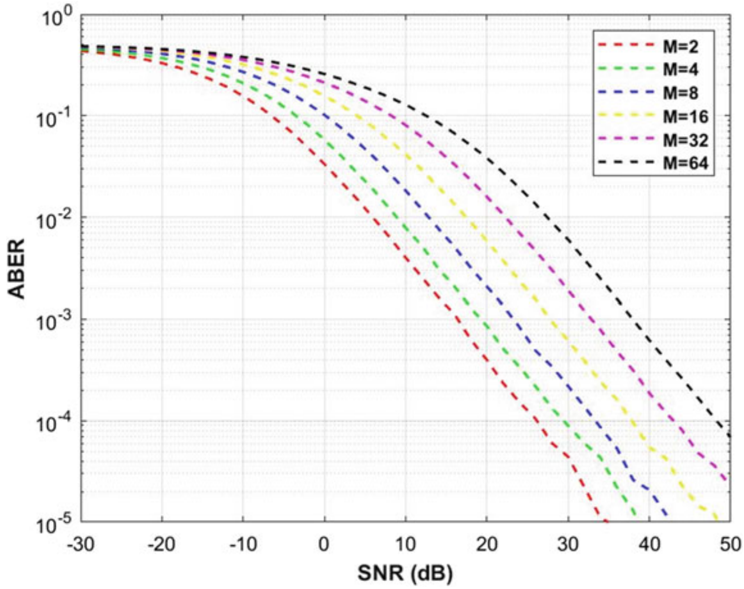


Fig. 8.13 ABER performance of blind UAV-assisted RIS scheme for varying modulation order and $N = 4$

Table 8.2 The gain in SNR of intelligent UAV-assisted RIS scheme over blind UAV-assisted RIS scheme for various M-ary modulation schemes, considering $N = 4$

$N = 4$ and $P_e^t = 10^{-5}$			
Modulation order (M)	Intelligent UAV-assisted RIS scheme	Blind UAV-assisted RIS scheme	Gain in SNR (dB)
2	~11	~36	~25
4	~14	~39	~25
8	~18	~42	~24
16	~24	~49	~25
32	~30	~54	~24
64	~35	~58	~23

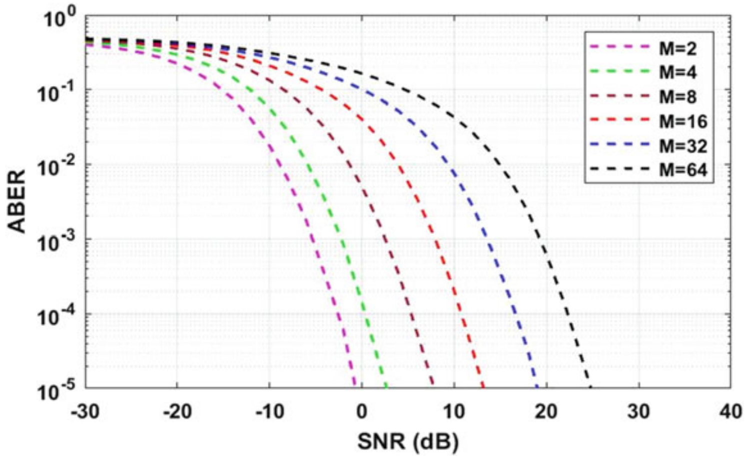


Fig. 8.14 ABER performance of intelligent UAV-assisted RIS scheme for varying modulation order and $N = 8$

In Fig. 8.14, the ABER performance of intelligent UAV-assisted RIS scheme by varying the modulation order is plotted. The simulations are performed for $N = 8$. The increase in modulation order increases the SNR required to achieve the target ABER. To achieve an ABER of 10^{-5}, $M = 2$, $M = 4$, $M = 8$, $M = 16$, $M = 32$, and $M = 64$ systems need SNR of ~−1 dB, ~ 3 dB, ~ 7 dB, ~ 13 dB, ~ 18.5 dB, and ~ 25 dB, respectively. $M = 64$ system requires ~ 26 dB more than $M = 2$ system for achieving the same target ABER.

In Fig. 8.15, the ABER performance of blind UAV-assisted RIS scheme by varying the modulation order is plotted. The simulations are performed for $N = 8$. The increase in modulation order increases the SNR required to achieve the target BER. In order to achieve an ABER of 10^{-5}, $M = 2$, $M = 4$, $M = 8$, $M = 16$, $M = 32$, and $M = 64$ systems require SNR of ~ 28 dB, ~ 31 dB, ~ 35 dB, ~ 42 dB, ~ 46 dB, and ~ 51 dB, respectively. $M = 64$ system requires ~ 23 dB more than $M = 2$ system for achieving the same target ABER. Increasing the number of passive reflective

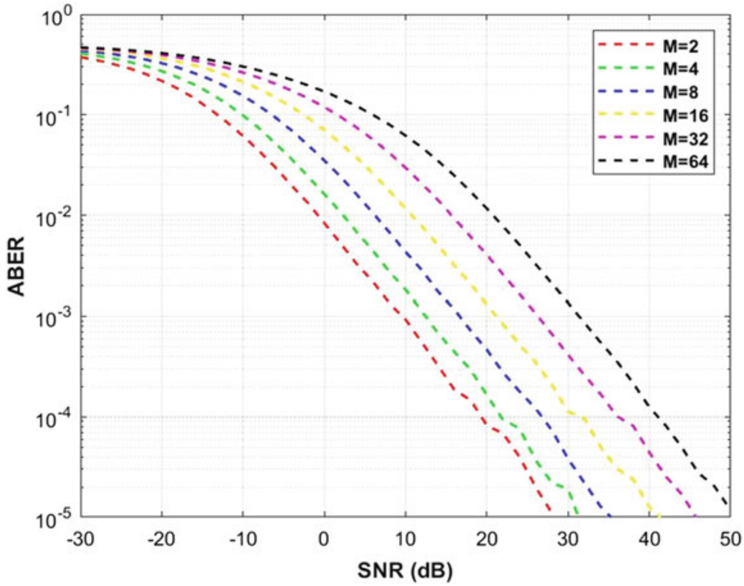


Fig. 8.15 ABER performance of blind UAV-assisted RIS scheme for varying modulation order and $N = 8$

Table 8.3 The gain in SNR of intelligent UAV-assisted RIS scheme over blind UAV-assisted RIS scheme for various M-ary modulation schemes, considering $N = 8$

$N = 8$ and $P_e^t = 10^{-5}$			
Modulation order (M)	Intelligent UAV-assisted RIS scheme	Blind UAV-assisted RIS scheme	Gain in SNR (dB)
2	~-1	~28	~29
4	~3	~31	~28
8	~7	~35	~28
16	~13	~42	~29
32	~18.5	~46	~28
64	~25	~51	~26

elements from $N = 4$ to $N = 8$ improves the ABER performance of both intelligent and blind UAV-assisted RIS schemes for all modulation orders.

The gain in SNR of intelligent UAV-assisted RIS scheme over blind UAV-assisted RIS scheme for various M-ary modulation schemes, considering $N = 8$, is listed in Table 8.3. As the phase distortions of the channels are compensated by intelligent UAV-assisted RIS, it performs better than blind UAV-assisted RIS scheme.

In Fig. 8.16, the ABER performance of intelligent UAV-assisted RIS scheme by varying the modulation order is plotted. The simulations are performed for $N = 16$. The increase in modulation order increases the SNR required to achieve the target ABER. In order to achieve an ABER of 10^{-5}, $M = 2$, $M = 4$, $M = 8$, $M = 16$,

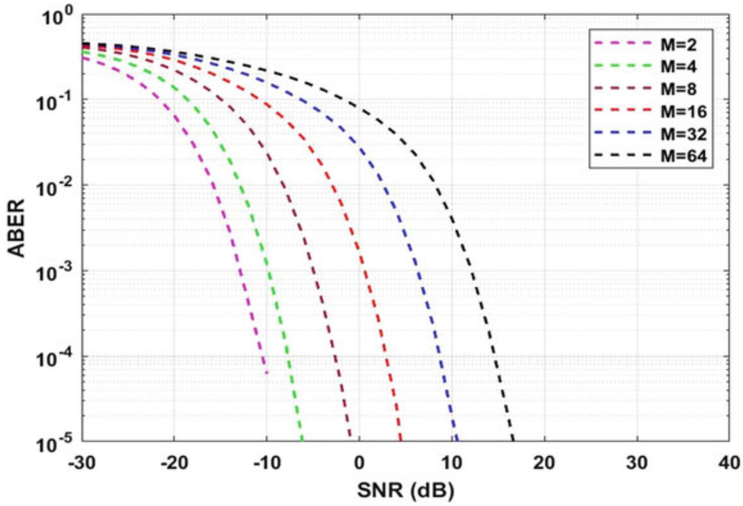


Fig. 8.16 ABER performance of intelligent UAV-assisted RIS scheme for varying modulation order and $N = 16$

$M = 32$, and $M = 64$ systems require SNR of ~−8 dB, ~−6 dB, ~−1 dB, ~ 5 dB, ~ 10.5 dB, and ~ 16 dB, respectively. $M = 64$ system requires ~ 24 dB more than $M = 2$ system for achieving the same target ABER.

In Fig. 8.17, the ABER performance of blind UAV-assisted RIS scheme by varying the modulation order is plotted. The simulations are performed for $N = 16$. The increase in modulation order increases the SNR required to achieve the target BER. In order to achieve an ABER of 10^{-5}, $M = 2$, $M = 4$, $M = 8$, $M = 16$, $M = 32$, and $M = 64$ systems require SNR of ~ 23 dB, ~ 28 dB, ~ 30 dB, ~ 35 dB, ~ 40 dB, and ~ 45 dB, respectively. $M = 64$ system requires ~ 22 dB more than $M = 2$ system for achieving the same target ABER. It is clear that increasing the number of passive reflective elements from $N = 4$ and $N = 8$ to $N = 16$, increases the ABER performance of all modulation orders for both intelligent and blind UAV-assisted RIS schemes. The gain in SNR of intelligent UAV-assisted RIS scheme over blind UAV-assisted RIS scheme for various M-ary modulation schemes, considering $N = 16$, is listed in Table 8.4.

In Fig. 8.18, the ABER performance of intelligent UAV-assisted RIS scheme by varying the modulation order is plotted. The simulations are performed for $N = 64$. The increase in modulation order increases the SNR required to achieve the target ABER. To achieve an ABER of 10^{-5}, $M = 2$, $M = 4$, $M = 8$, $M = 16$, $M = 32$, and $M = 64$ systems require SNR of ~− 23 dB, ~-20 dB, ~-15 dB, ~− 9 dB, ~-4 dB, and ~ 3 dB, respectively. $M = 64$ system requires ~ 26 dB more than $M = 2$ system for achieving the same target ABER.

In Fig. 8.19, the ABER performance of blind UAV-assisted RIS scheme by varying the modulation order is plotted. The simulations are performed for $N = 64$. The increase in modulation order increases the SNR required to achieve the target

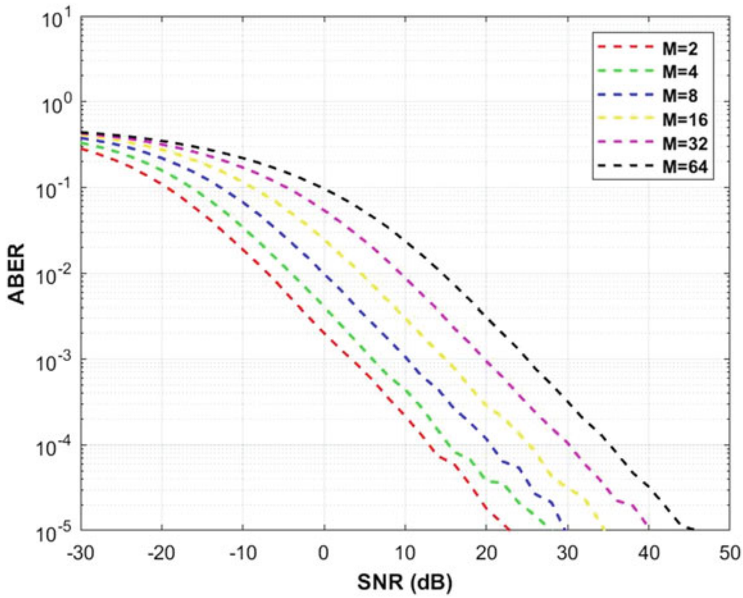


Fig. 8.17 ABER performance of blind UAV-assisted RIS scheme for varying modulation order and $N = 16$

Table 8.4 The gain in SNR of intelligent UAV-assisted RIS scheme over blind UAV-assisted RIS scheme for various M-ary modulation schemes, considering $N = 16$

$N = 16$ and $P_e^t = 10^{-5}$			
Modulation order (M)	Intelligent UAV-assisted RIS scheme	Blind UAV-assisted RIS scheme	Gain in SNR (dB)
2	~−8	~23	~31
4	~−6	~28	~34
8	~−1	~30	~31
16	~5	~35	~30
32	~10.5	~40	~30
64	~16	~45	~29

BER. To achieve an ABER of 10^{-5}, $M = 2$, $M = 4$, $M = 8$, $M = 16$, $M = 32$, and $M = 64$ systems require SNR of ~ 9 dB, ~ 12 dB, ~ 18 dB, ~ 22 dB, ~ 28 dB, and ~ 33 dB, respectively. $M = 64$ system requires ~ 24 dB more than $M = 2$ system for achieving the same target ABER. It is clear that increasing the number of passive reflective elements from $N = 4$, $N = 8$, and $N = 16$ to $N = 64$, increases the ABER performance of all modulation orders for both intelligent and blind UAV-assisted RIS schemes. The gain in SNR of intelligent UAV-assisted RIS scheme over blind UAV-assisted RIS scheme for various M-ary modulation schemes, considering $N = 64$, is listed in Table 8.5.

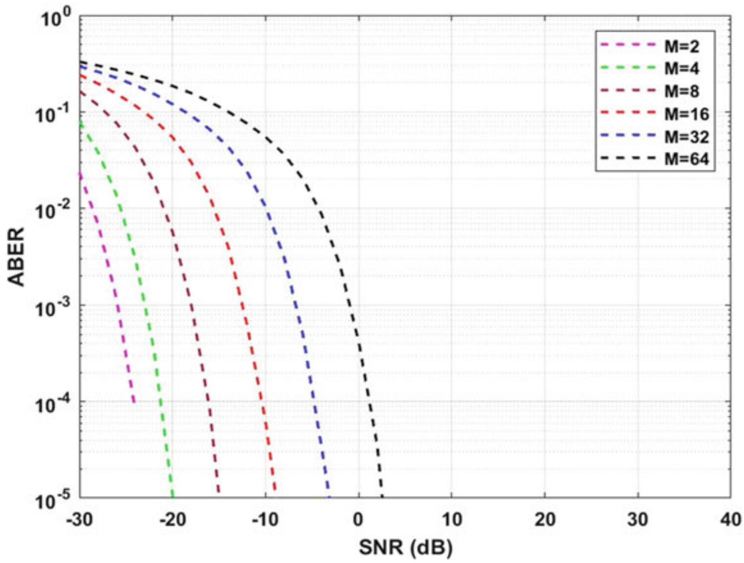


Fig. 8.18 ABER performance of intelligent UAV-assisted RIS scheme for varying modulation order and $N = 64$

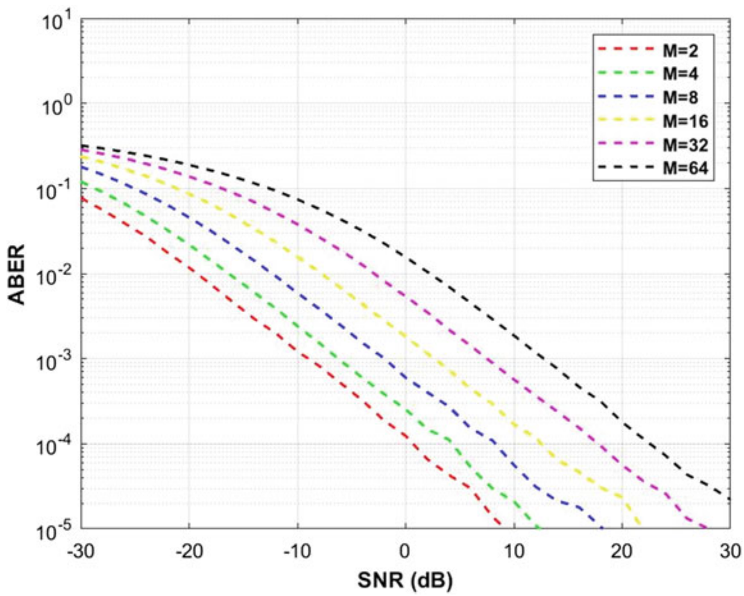


Fig. 8.19 ABER performance of blind UAV-assisted RIS scheme for varying modulation order and $N = 64$

Table 8.5 The gain in SNR of intelligent UAV-assisted RIS scheme over blind UAV-assisted RIS scheme for various M-ary modulation schemes, considering $N = 64$

$N = 64$ and $P_e^t = 10^{-5}$			
Modulation order (M)	Intelligent UAV-assisted RIS scheme	Blind UAV-assisted RIS scheme	Gain in SNR (dB)
2	~−23	~9	~32
4	~−20	~12	~32
8	~−15	~18	~33
16	~−9	~22	~31
32	~−4	~28	~32
64	~3	~33	~30

8.5 Conclusion

In this chapter, intelligent and blind UAV-assisted RIS schemes are proposed to increase the energy efficiency of next-generation networks. The intelligent UAV-assisted RIS scheme performs better than the wired AWGN system. The analytical upper bound and exact ABEP expressions are derived for BPSK modulation. There is a slight deviation between ABER and ABEP results for a smaller number of reflecting elements. For a higher number of reflecting elements, the deviation between ABER and ABEP results reduces and closely matches. This shows the accuracy of our simulation results. It is also observed that increasing the number of RIS elements increases the SNR gains. The intelligent UAV-assisted RIS scheme outperforms the blind UAV-assisted RIS scheme. This is due to the compensation of phase distortion at the RIS. The simulations were repeated by varying the modulation order while fixing the number of reflecting elements. It is observed that an increase in modulation order degrades the ABER performance. As the proposed schemes drastically improve energy efficiency, they could be a potential candidate for next-generation networks.

8.5.1 Scope for Future Works

The following aspects can be the future works:

- The analytical upper bound and exact ABEP expressions need to be derived for higher-order PSK and QAM constellations.
- The effect of channel estimation error and channel information feedback delay can be considered while evaluating the performance of an intelligent UAV-assisted RIS scheme.
- Machine learning (ML)-/deep learning-based channel estimation schemes can compensate for phase distortions at RIS.

- The ideal continuous phase shifters can be replaced with discrete phase shifters.
- The effect of correlation between RIS mirrors can be considered while evaluating the performance of intelligent and blind UAV-assisted RIS schemes [36].
- The appropriate channel models for tethered and untethered UAVs can be considered while designing the system.
- This idea can be combined with spatial modulation (SM) [37, 38] and NOMA [31, 39, 40] schemes.

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Vinoth Babu Kumaravelu is presently working as an Associate Professor Senior in the Department of Communication Engineering, School of Electronics Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, India. In 2014, he received his Ph.D. in MIMO-OFDM-based wireless communication from Vellore Institute of Technology, Vellore, India. In 2009, he graduated with an M.Tech. in Communication Engineering from Vellore Institute of Technology, Vellore, India. During his M.Tech. degree, he won the gold medal. He was awarded merit scholarships twice during his master's degree at Vellore Institute of Technology for securing high grades. Wireless communications, digital communications, and signal processing are among his areas of interest. Spatial modulation, RIS, NOMA, wireless sensor networks, Internet of things, device-to-device communication, small cells, and vehicular ad hoc networks are some of the areas in which he is presently working. He is the author for the books *Communication Engineering* and *Digital Communications* published by Magnus Publications, India. He is one of the guest editors for Hindawi's special issues, "Artificial Intelligence Techniques for Joint Sensing and Localization in Future Wireless Networks" and "Emerging Technologies and Applications of Wireless Power Transfer".

Hindavi Kishor Jadhav is currently pursuing Ph.D. degree in machine learning-based transit antenna selection techniques for next-generation networks from Vellore Institute of Technology, Vellore. She has also received her master's degree in Communication Engineering from Vellore Institute of Technology, Vellore, in 2020. She has developed a cost-effective algorithm for FMCW RADAR during her internship at NXP semiconductors, Bangalore. Her research interests include reconfigurable intelligent surfaces, index modulation techniques, and radar signal processing.

Anjana B. S. has completed her M.Tech. in Communication Engineering from Vellore Institute of Technology, Vellore, Tamil Nadu, in 2022. She has completed her B.Tech. degree in Electronics and Communication from LBS College of Engineering, Kasaragod, Kerala, India. Her research interests include reconfigurable intelligent surfaces and polar codes.

Vishnu Vardhan Gudla is presently working as Assistant Professor in the Department of Electronics and Communication Engineering, Aditya Engineering College, Surampalem, Andhra Pradesh, India. He has completed his Ph.D. degree in the area of spatial/index modulation-based wireless communication techniques from Vellore Institute of Technology, Vellore, Tamil Nadu, in 2021. He also got his M.Tech. degree in Communication Engineering from Vellore Institute of Technology, Vellore, in 2015. Previously, he also received senior research fellowship (SRF) from the Council of Scientific and Industrial Research (CSIR), India. His research interests include wireless communication, spatial/index modulation techniques, and cognitive radio.

Arthi Murugadass is presently working as an Associate Professor and Head in the Department of Computer Science and Engineering (AI and ML), Sreenivasa Institute of Technology and Management Studies, Chittoor, Andhra Pradesh, India. She has completed her Ph.D. from Vellore Institute of Technology, Vellore, India, in 2017 and M.E. (CSE) and B.E. (CSE) degrees from Anna University, Chennai, India, in 2012 and 2010, respectively. She has more than 25 Scopus publications. She is one of the authors for the books *Communication Engineering* and *Digital Communications*, published by Magnus Publications. She is presently working in the areas of heterogeneous wireless networks, wireless sensor networks, Internet of things, device-to-device communication.

Agbotiname Lucky Imoize (Senior Member, IEEE) is a Lecturer in the Department of Electrical and Electronics Engineering, University of Lagos, Nigeria. He received B.Eng. (Honors) in Electrical and Electronics Engineering from Ambrose Alli University, Nigeria, in 2008, and M.Sc. in Electrical and Electronics Engineering from the University of Lagos, Nigeria, in 2012. Before joining the University of Lagos, he was a Lecturer at Bells University of Technology, Nigeria. He worked as a core network products manager at ZTE Nigeria Limited from 2011 to 2012 and as a Network Switching Subsystem Engineer at Globacom, Nigeria, from 2012 to 2017. Imoize was awarded the Fulbright Fellowship as a Visiting Research Scholar at the Wireless@VT Lab in the Bradley Department of Electrical and Computer Engineering, Virginia Tech., USA, where he worked under the supervision of Prof. R. Michael Buehrer from 2017 to 2018. He is currently a Research Scholar at Ruhr University Bochum, Germany, under the Nigerian Petroleum Technology Development Fund (PTDF) and the German Academic Exchange Service (DAAD) through the Nigerian-German Postgraduate Program. He is a Registered Engineer with the Council for the Regulation of Engineering in Nigeria (COREN) and a Nigerian Society of Engineers (NSE) member. He has co-edited 1 book and coauthored over 80 papers in peer-reviewed journals and conferences. His research interests are beyond 5G and 6G wireless communications, chaotic communications, and wireless security systems.

Chapter 9
Blockchain Technology Enabling UAV Cellular Communications

S. Suganthi, G. Nagarajan, and T. Poongodi

Abstract Unmanned Aerial Vehicle (UAV) is a technology which has been found useful in many application areas and is mainly used for the purpose of data collection and surveillance. They are very useful in reaching out inaccessible areas without endangering the safety of the working personnel However, security of the data collected and the UAV themselves are a major concern in implementing the system as they are prone to many security attacks. Hence, the confidentiality, availability and integrity of the data collected and transmitted over the UAV network should be preserved for high reliability of its functioning. Thus, blockchain technology with immutable ledger along with other key characteristics, when integrated with UAVs is found to be much effective in providing data security. This chapter explores the basics of blockchain technology, its characteristics, and architecture for securing UAV cellular communications. Also, current blockchain solutions for securing UAV cellular communications are also discussed.

Keywords Unmanned Aerial Vehicle (UAV) · ad hoc networks · Delay Tolerant Networks (DTN) · UAV nodes · Ground Control Station (GCS) · Distributed Ledger Technology (DLT) · Peer-to-Peer (P2P) network · Cryptography · Hashing functions · Decentralized · Immutable · Merkle tree · Consensus · Cellular communication · Hyperledger Fabric · Ethereum Blockchain · Spoofing · Swarm network

S. Suganthi (✉) · T. Poongodi
School of Computing Science and Engineering, Galgotias University, Greater Noida, Uttar Pradesh, India

G. Nagarajan
Computer Science & Engineering, School of Engineering, Presidency University, Bangalore, Karnataka, India

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9.1 Introduction

Unmanned Aerial Vehicles (UAVs) are aerial mobile nodes of the Flying Ad hoc Networks (FANETs) in which UAVs can communicate with each other and also send the collected data to the Ground Control Station (GCS). UAV is an emerging technology and can be applied vastly when combined with other technologies such as machine learning, artificial intelligence, wireless sensors, satellite systems, advanced networking systems, etc. [1]. They can be dynamically configured and easily deployed having high mobility, fast response, and having low maintenance cost [2]. Because of this UAVs are being deployed in wide application areas such as military, civilian, agricultural monitoring, remote monitoring, search and rescue, logistics, healthcare, [2] smart city, smart grids, etc. [3].

Setting up an UAV network is difficult and different from other networks due to its connectivity, routing, mobility, power constraints, services, and application areas [4]. In UAV due to mobility of the node, limited communications, dynamic interaction and rapid changes in topology it necessitates Delay Tolerant Networks (DTN), in which UAV nodes store, carry and forward the message to the next node [5]. Three dimensional spaces should be considered in path planning algorithms of UAV as it may encounter undetermined obstacles in its flying path. The communication with UAVs can be established in many ways such as through satellite systems control, radio control, cellular network, and wireless communication networks [6]. UAVs are low computing power devices in which complex procedures for securing the data cannot be run and are prone to many security risks. Hence, an efficient secure system is mandatory for the protection of data. Thus, blockchain with its robust characteristics is considered to provide required safety and privacy in FANETs.

9.2 Blockchain for Securing UAV Cellular Communications

This section covers the basics of UAV and blockchain technology and its architecture and highlights the role of blockchain in securing UAV cellular communications.

9.2.1 UAV

UAV is an aircraft which is piloted autonomously through onboard computers or remote controls. It operates without a human pilot and is initially used for military operations, but now it has been employed in many civilian applications also. It is a part of Unmanned Aircraft System (UAS), usually consisting of one or many UAVs, GCS, and a communication network. UAVs can be in varying sizes ranging from small to large and can be deployed singly or in groups forming swarms. Radio waves at specific frequencies are used and are considered to be more reliable form of drone communication which can be achieved through cellular, satellite, and wi-fi networks.

9.2.2 Blockchain Technology

Blockchain is an emanating disruptive technology that makes use of DLT (Distributed Ledger Technology), in which data is stored in a distributed way across all nodes in a Peer-to-Peer (P2P) network. It is decentralized in which there is no central server for data storage. By this way, data is secure even in the case of a node failure, and is transparent making verification and data tracking easy as it is spread across all nodes connected in the network. Basically, blockchain is a combination of several technologies such as distributed network, shared ledger, and cryptography. A transaction is said to occur in a blockchain when data is transmitted from the sender to the receiver and the group of transactions acquired over a particular period of time is grouped into a transaction block. Blockchain contains chain of blocks growing continuously which are linked together by the hash value of the previous block generated by means of mathematical procedures. Each block stores a list of public transactions which are transparent to all users of the network and are made immutable through the use of cryptographic hashing functions. The number of transactions in a block is dependent upon the size of the block and the size of the transaction.

Cryptographic functions are mathematical procedures applied to any input file which produces random compressed bit string called *hash, hash value, digest,* or *tag* which is unrelated to the input file. Thus, the transactions in a block are hashed to produce a single hash value. This makes it difficult to predict the input data with the use of the hash value. Also, it has the property of collision resistance in which no two different input files will never give the same hash value. Thus, the hash value produced for a particular input file is unique and any alterations to the input file will provide a completely different hash value. Asymmetric keys and cryptographic hashing functions are combined in the encryption mechanism of blockchains in which two asymmetric keys *private key* and *public key* are used in the encryption and decryption processes. When a user initiates a transaction, the private key is known only to the user and the public key is made open to all users in the network. This private key is combined with the hash value of the message to provide digital signatures. The user verifying the message uses the public key for decryption and verifies the hash value.

9.2.3 Blockchain Types

Depending upon the data accessibility rights and the users participating in the verification and appending of the block, blockchains can be broadly divided into *public, private,* and *consortium blockchains*.

In *public blockchain*, all nodes in the network are allowed to participate in the primary activities of the network. It is completely decentralized and transparent and follows a permissionless consensus process. It is highly immutable and has lower efficiency.

Private blockchains are owned by a single organization and follows a permissioned consent process in which the users are allowed to participate depending on the part played by the user in the organization. It possesses a centralized network controlled by a single authority and is highly efficient but less immutable.

Consortium blockchains are controlled by a group of organizations which are partially centralized and follows a permissioned consent process.

Since a secure communication in the UAVs is mandatory mostly private blockchains are employed.

9.2.4 Blockchain Characteristics

Decentralized The data stored on the blockchain database is not controlled by a central authority and anyone on the network can monitor, make changes and update data. The level of decentralization depends upon the type of blockchain and the policies used. The public blockchains are fully decentralized, however consortium blockchains are partially decentralized and private blockchains are fully centralized. But the data is present in all the nodes and no single node can take control over the network. Private blockchains are employed mostly in UAVs as secure communication is mandatory.

Immutable The data in the blockchain is validated by all other nodes and stored as blocks with cryptographic hashing functions which are irreversible. Hence, data once stored is immutable and cannot be altered or deleted. This ensures reliability and integrity of data communicated through the UAV network.

Transparency The data stored in the blockchains is timestamped and accessible to all users on the network thereby making auditing very easy and transparent. This helps in easy and efficient real time decision-making for the participating members of the blockchain which includes UAVs and control stations.

Persistence The data is stored in all nodes of the blockchain and is persistent hence it is not destroyed by any node failure. Hence the UAV network is available throughout and not susceptible to any failures.

Provenance The history of each transaction of the UAV in the blockchain can easily be tracked making it trustworthy and verifiable.

Anonymity The user is linked to a general blockchain generated address and the real identity of the person is not known. The implementation of the type of the blockchain and the policies determines the level of anonymity.

Autonomy Each UAV node on the blockchain network can act independently without the intervention of others in the network.

9.2.5 Reference Model of Blockchain Architecture

The abstract framework of the blockchain architecture is characterized by a six-layer reference model which is shown in Fig. 9.1. The key components and the techniques used in each layer is discussed as follows.

Data Layer
This layer is concerned with the manipulation of the data collected and the key techniques associated for handling the data. The data layer consists of time-stamped blocks of data and these blocks are chained together with the use of hashed and asymmetrically encrypted data structure called the Merkle trees. A block containing collection of transactions, is created by a publishing node and a new block is formed when the block reaches a predetermined number of transactions. By this way, any number of blocks can be appended to the chain of blocks. Each block consists of the *block header* and the *block body*. The block header contains meta information about the block and the later consists of the actual data which are hashed in pairs and their hash value being stored in the form of a binary Merkle tree. The block header except the first block (genesis block) contains link to the header of the previous block, which is a reference containing the hash value of the previous block The hashing process is repeated until the root node called the Merkle root is reached. Thus, any changes made in the transactions will give a different hash value at the root node. The timestamp provides the time of creation of the corresponding block and the Merkle root summarizes complete information of the transactions during specific period of time.

Network Layer
It deals with the hardware side of the blockchain containing interconnected nodes in a P2P network and also the related mechanisms such as broadcasting, forwarding and verification of the data. The nodes are connected in a decentralized, distributed manner which may be private or public and all the nodes in the network are equally privileged without being controlled by a central authority. Thus, when a transaction is created, it is broadcasted in the network to all other nodes, and the nodes acquiring the message verifies it using asymmetric cryptographic mechanism. In blockchain,

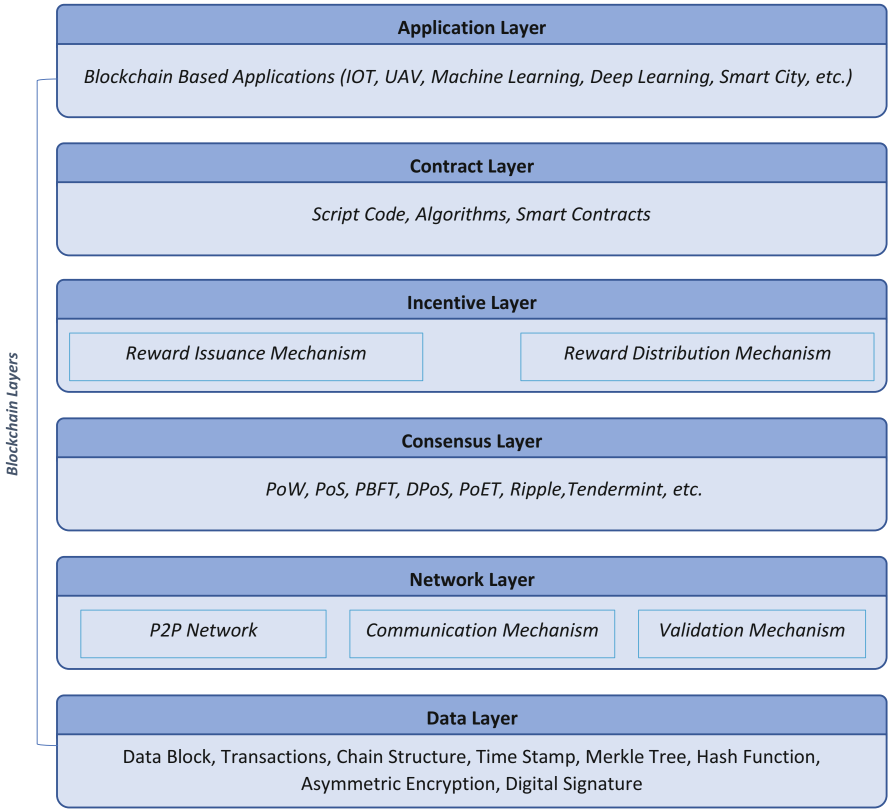

Fig. 9.1 Reference model of blockchain architecture

asymmetric cryptography and hashing functions are combined to provide digital signatures which serves as handwritten signature alternatives [7]. Once the message is verified and accepted by majority of the nodes it is appended to the chain of blocks and forwarded further, or else it is discarded.

Consensus Layer

The decentralized and distributed nature of blockchains necessitates the need for a consensus to be agreed upon by a group of unknown or untrustworthy users. The main approach is to select a node from a group of competing nodes for appending the block in the distributed ledger. This is implemented with the use of complex consensus protocols which are crucial for maintaining the data consistency and efficiency of the system. Several consensus algorithms are used of which Proof of Work (PoW), Proof of Stake (PoS), Practical Byzantine Fault Tolerance (PBFT), and Delegated Proof of Stake (DPoS) are most widely used. In PoW, a publishing node is selected if the work is done by it, by performing lots of mathematical calculations reaching a target value, which proves the legitimacy of the node. In PoS, a publishing node is selected on the basis of amount of stake that the user holds. A user having more stake or cryptocurrencies is considered to be more legitimate and selected for publishing. In PBFT a publishing node can be selected even in the case of a node failure or if the malicious nodes respond incorrectly. Two-thirds of votes from the user nodes is needed to select a publishing node and it can handle up to one-third of the malicious nodes in the group. In DPoS, the delegates are selected by the stack holders, by rewarding the nodes based on the work done. The nodes behave legitimate as they can be voted out by the stack holders if they act maliciously.

Some of the other consensus algorithms includes Round Robin Consensus model, Ripple, Proof of Authority Model, Proof of Elapsed Time Consensus Model, Tendermint, Proof of Bandwidth and many others.

Incentive Layer

Incentive layer is vital in imparting proper incentive mechanisms to provide incentives to the users for data verification and appending of the block. The data verification involves lot of computing resources, electric power and time on the part of users. In order to encourage the verifying users for maintaining the security of the network, they are rewarded based on certain mechanism in the form of virtual cryptocurrencies such as Bitcoin, Ether, Litecoin (LTC), to name a few. However, in the place of mutually trusted parties without incentives such as in private and consortium blockchain this layer is optional [8].

Contract Layer

Contract layer is most essential for activating assets and money which includes many scripts, algorithms, mechanisms and smart contracts and should be carefully designed to avoid any financial inconveniences. Smart contracts are predefined programs that are stored on the blockchain and are self-executed, when predefined conditions are met. A transaction is initiated between the agreed parties, when the participating parties agree to the rules specified in the contract by cryptographically signing the contract. Later it is broadcasted in the blockchain network to all other nodes for verification.

Application Layer

Though blockchain is in its developing stage it is utilized in various applications. The application layer is concerned with various applications that are used by the end user which are used to connect with the blockchain network and comprises of user interfaces, scripts, and API's. The applications are connected to the blockchain network through API's. Various applications of blockchain include smart cities, smart grids, machine learning, deep learning, smart healthcare, Internet of things (IOT), cloud computing, edge computing, etc.

A model is proposed by [9] in which blockchain is integrated with UAV system to provide a secure communication. It comprises of three domains in which *UAV domain* is composed of UAVs with the sensors transmitting data to the ground through wireless communication. The data may contain sensitive information which is transmitted to the next domain. The *ground control domain* acts as an intermediate in transmitting the data from UAVs to the next domain in which the data is aggregated at the ground controllers and transmitted through base stations to the next domain. The *blockchain enabled infrastructure domain* is the backend which is provisioned with blockchain framework. The miners are selected based on their PoW and they validate the data received depending on the consensus algorithm. When the miner solves the PoW puzzle the data can be appended in the blockchain. The trustworthiness of a reporting UAV node is detected by trust evaluation in which a node in more proximity to an event is considered to be more trustworthy. The distance of the UAVs from the event is also considered as a factor in determining the trust evaluation of a node. Those nodes with trust evaluation less than the predetermined threshold are considered malicious and ousted out from the network.

9.3 Current Blockchain Solutions for Securing UAV Cellular Communication

Drone operations are controlled by the energy-intensive blockchain-based infrastructure, which ensures a sense of safety for all parties involved. The security solutions for UAV cellular communication employing blockchain technology are discussed in this section.

The following are examples of existing blockchain-based technologies for securing UAV cellular communications.

- Blockchain-assisted 5G-UAV network
- Hyperledger Fabric to UAV networks
- Ethereum Blockchain to mitigate spoofing attacks in UAV

A. *Blockchain-assisted 5G-UAV Network*

Signal quality loss in cellular networks is caused by various causes, including interference, a high number of connected devices, huge buildings, and their thick metallic infrastructure [10]. In addition, certain regions, such as rural areas or areas affected by disasters, maybe outside of cellular service. Static base stations in 5G networks find it difficult to keep up with the rapidly increasing IoT traffic. Aerial vehicles (UAVs) may act as mobile switching centres (MSCs) because of their adaptability and cheap cost. It increases cellular network coverage while supporting 5G infrastructure, enabling new 5G applications. However, there is no guarantee of data security. Drones, fog, and the cloud may all be integrated using blockchain technology, ensuring data integrity and safe communication. It increases the system's dependability and trustworthiness [11]. Data security is improved across many tiers when drones are used in conjunction with blockchain technology, when a drone sprays into the incorrect hands, blockchain technology adds a layer of protection that prevents external hacking and data recovery from occurring.

Table 9.1 Comparison between BlockChain-5G UAV networks with 5G UAV network

Aspects	5G UAV network	BlockChain-5GUAV networks
Uniqueness validation	No UAV Uniqueness validation	The uniqueness of the UAV is examined to ensure that any drone may take part in the operation
Data security and privacy	Low	The information is saved in BC, which ensures its security and privacy
Resource management	5G resource management	BC is used to manage advanced 5G resources.
UAV manoeuvrability	High UAV movement range	High UAV movement range
Autonomy	High	Very Advanced

Furthermore, it verifies and secures the identities of the UAVs that are taking part in a job and completing it. The Blockchain-assisted 5G UAV network entrusts drone facilities by supplying protection, anonymity, trustworthiness, and improved appliance monitoring.

UAV-5G communication networks may benefit from blockchain technology in various ways. For example, it can offer an aerial-to-terrestrial spectrum trading platform that facilitates secure spectrum exchange among network operatives and UAV providers. This aspect built a global exchanging data medium, provides privacy and lowers the likelihood of illegal spectrum use by harmful nodes by using a distributed transferring knowledge platform.

The blockchain-assisted 5G-UAV network offers a number of benefits and increases the quality of experience for drone services users. The following are a few of the advantages of using this service:

- Improved network Quality of Service (QoS) in latency, speed, and stability are critical criteria in UAV assistance to deliver the greatest quality of experience.
- Data safety and confidentiality are ensured via the use of the BC public ledger.
- Maintain trust and secrecy; the identities of all participating drones are validated for each new transaction, preventing hostile attackers from attempting to join the UAV network.
- High-automation systems are more likely to succeed when agents trust each other, and the platform is immutable, transparent, and traceable.
- In UAV 5G-based networks, improved resource and spectrum management enables better control of interference while enhancing their adaptability, availability, and efficiency, among other benefits (Table 9.1).

A UAV network driven by blockchain technology may be more cost-effective and dependable in value and performance than a permanently fixed and overcrowded cellular network. The system delivers services either via a 5G network or in a distributed way utilizing just UAVs. UAVs are equipped with online and offline platforms, which may utilize for various applications. Furthermore, with the help of fog and cloud computational power, data and benefits are yielded quickly and efficiently.

B. *Hyperledger Fabric to UAV Swarm Environment*

UAV swarm automation is a sophisticated machinery that is presently researched and established and can be used in a variety of applications. A single drone would not be sufficient when communication and coordination among a large number of UAV participants are required. Aside from the many technical difficulties that must be overcome for such a notion to be realised, a significant problem is maintaining the security of a scheme comprised of various mobile performers against impersonation and assaults from evil objects. Blockchain technology can address a broad range of security challenges with the Hyperledger Fabric framework.

Hyperledger Fabric Overview

The Hyperledger project, sponsored by the Linux Foundation [12] started late in 2015 and is still ongoing. Aiming to enhance blockchain technology by enhancing availability and security, the project produced six distinct kinds of Hyperledger frameworks along with 6 major technologies that developers may use to build a broad range of applications [13].

Hyperledger Fabric is one of six blockchain contexts now accessible, all created as part of the Hyperledger Project. Here will discuss how the Hyperledger Fabric framework provides security solutions for UAV swarm environment. This framework, developed by the Hyperledger Project, makes it possible for designers to create their private blockchain while maintaining a high level of simplicity.

Anyone interested in joining the blockchain must do so via the MSP provider, which keeps it secret and restricted. There is a lot of flexibility in how information is stored, how the mechanism is changed, and how dissimilar MSPs are used. There is also more room for privacy because the platform lets people use different channels on the network. Every channel can possess its own distributed ledger, breaking up a network into different parts.

There are many distinct Hyperledger Fabric features, which are listed here:

- Access control,
- Anonymity and security,
- Faster functioning,
- Chaincode operability,
- Responsibility to maintain track of a project's state.

Hyperledger Application: Fabric to UAV Swarm Environment

Now, understand how Hyperledger Fabric capabilities aid secures a UAV swarm network. Consider UAV swarm network comprises GCS, Master UAV, and the Slave UAV. One of the ideas in Hyperledger Fabric is how to keep track of people's identities. It is necessary for each actor acting on a Fabric network to possess an X.509 standard digital certificate and digital identity that is encapsulated to participate in the system. These identities enable the network to distinguish itself from various actors and determine which actors have access to resources and which actors have the right to view or modify data. Swarm networks that use blockchain may determine what activities different players can do by issuing different certificates. With slave certificates, only Swarm drones would interact with each other [14]. In addition to allowing them to connect with their swarm, Master certificates would also provide them with the ability to talk with other Masters, issue instructions to Slaves inside the swarm, and communicate with GCS. Awarded GCS certifications will provide GCSs with the capability to connect to and monitor all UAVs on the network and perform some GCS-only activities.

A trustworthy Certificate Authority (CA) whose purpose is to issue credentials is required for each certificate in the network; Fabric CA, a personal root CA provider capable of preserving digital identities, is supported by Hyperledger Fabric. The Certificate Revocation List maintained by the Fabric CA may remove an untrusted actor from the swarm network. Peers hosts the ledger and the related smart contracts in a Hyperledger Fabric blockchain.

Peers in a Hyperledger Fabric blockchain are in charge of both the ledger and the blockchain-based linked to that ledger, so they are in charge of both. Each UAV shouldn't function as a peer on the network in a swarm scenario since administering the blockchain would develop challenging with so many mobile participants. As a result, only Master UAV and GCSs may operate as peers.

The endorsing peer is one of the essential peers in the Hyperledger Fabric ecosystem. The approval of this peer is necessary to authorise ledger adjustments. Other types of peers exist, including the ordered peer, which is in charge of grouping blockchain transactions into blocks and disseminating these blocks to the rest of the network for review. Moving Slaves across swarms requires acceptance from respectively Master UAV as recommending peers in a swarm. A swarm application would use approving rules to demand that the network's impacted entities endorse transactions involving UAVs or the data they transport. The implementation of orders in a swarm environment is done by non-swarm actors, such as GCSs, since they possess a more consistent network connection, allowing them to accept and handle transactions more securely.

C. *Ethereum Blockchain to Mitigate Spoofing Attacks in UAV*

Drone operations will be controlled by an energy-intensive blockchain-based platform that will provide hope and safety for all parties participating in the process. This solution aims to investigate the degree to which UAVs are vulnerable to misleading GNSS signals by creating the appropriate circumstances for UAVs to operate under the cover of a GPS (Global Positioning System) spoofing attack. It is necessary to develop a novel notion to eliminate such mistakes. Blockchains are becoming more popular, and they serve as the underlying technology for cryptocurrencies. Blockchain technology has a significant influence on UAVs applications, and the Ethereum Blockchain deployed to construct a blockchain net that will help combat spoofing threats.

Ethereum Blockchain Platform
Ethereum is an open-source, community blockchain-built computing environments decentralized system powered by smart contracts and may be used to power other applications. The Ethereum is included inside the block, including the hacking attempts made using the blockchain manual effort to view the blockchain platform.

Because of this, the Ethereum Blockchain makes use of the network that must be recorded in aeronautical pieces over register coupled with required data transfer in BC, which is accomplished via the Ethereum Blockchain. A single block provides an intruder with access to all of the data in the network; but, the data validation in the ledgers, which has been cryptographic keys assigned, prevents the intruder from wreaking harm across the whole network.

The blockchain system periodically checks the geopositioned data to find and eradicate any anomalous data as fast as possible. The data that has been confirmed is made accessible for viewing by those involved in aircraft and spacecraft operations over a dispersed network.

Figure 9.2 shows a diagrammatic depiction of the connection between an unmanned aerial vehicle and the security system. Each unmanned aerial vehicle is built with a block that contains all of the craft's information. Transmitters and receivers are declared as a transmitter and receiver combination when signals are passed from the earth control scheme to the mobile phone base station or vice versa. Because each UAV is interconnected and communicates with the others,

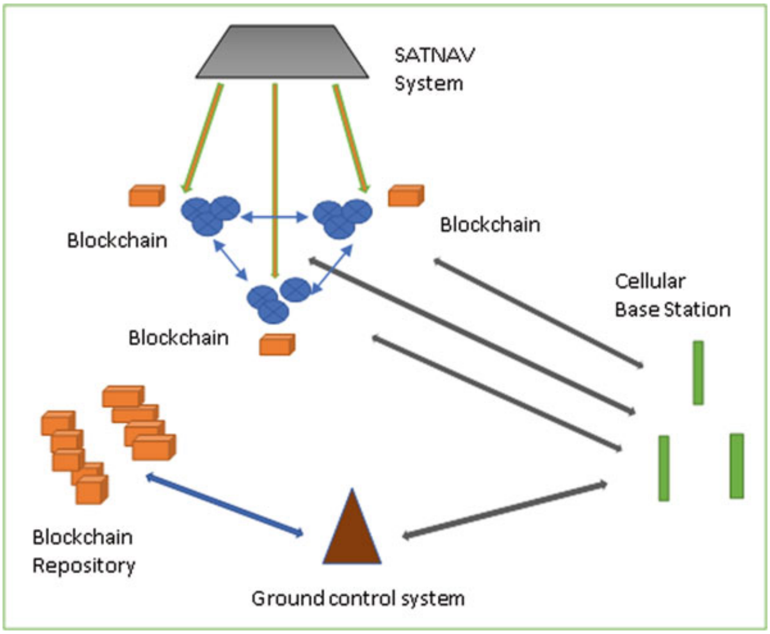

Fig. 9.2 UAV connectivity with the security system

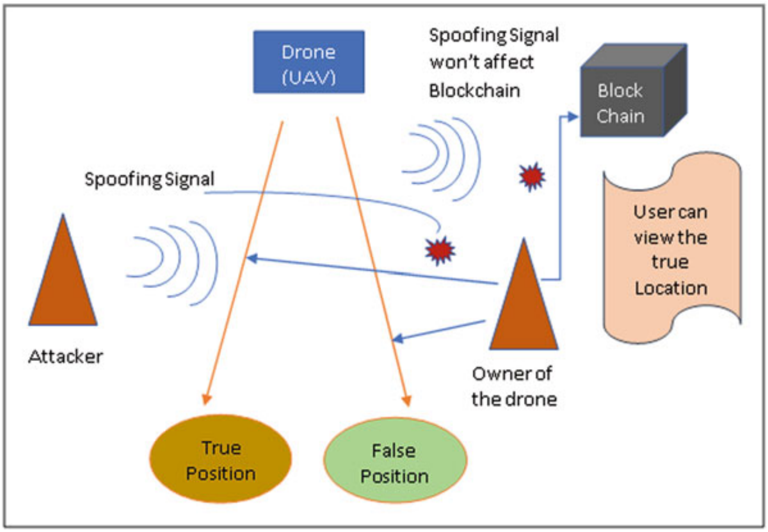

Fig. 9.3 UAV security with blockchain

the possibility of a collision between vehicles is eliminated. UAV is equipped with blockchain and can identify GPS spoofing. If third-party attempts to alter the integrity of a BC, verification will prevent this from happening, and safety is assured. In the suggested setup, an exterior storing blockchain was employed for outside use in UAV-specific blockchain repositories [15].

Figure 9.3 illustrates a blockchain network in which the data stored inside is not be changed without the agreement of all persons who are neighbours or collaborators in the network. By transferring signals for communication, the GPS positioning of UAV signals or any aerial vehicles is passed via their location. These signals are supplied with instructions from the cellular base station and handled with spacecraft prompts to get alerts first from location, as described above.

Specifically, the hacker is instructed to modify the GPS location victim device (UAV/aerial vehicles), resulting in faked geolocation of the system [16]. As a result, blockchain is being used to prevent spoofing. The blockchain stores the locations of UAVs and is impenetrable due to the hashes that are produced in each block of information. Since each block and account creation has its own unique identification number, users or clients may process or access the data contained inside the given block. Because of this, the inclusion of source code into blockchain may eliminate the need for interpretation of positional data [17]. The UAV is protected by utilizing Ethereum Blockchain technology to disguise communications.

The highlights of the Ethereum Blockchain methodology:

- Determine the degree to which unmanned aerial vehicles (UAVs) are vulnerable to misleading GNSS signals creating essential circumstances for UAVs to operate using GPS spoofing signals.

Table 9.2 Comparison between blockchain solutions in UAV cellular communication

Aspects	BlockChain-5GUAV networks	Ethereum Blockchain	Hyperledger Fabric UAV networks
Data security and privacy	The information is saved in BC, which ensures its security and privacy	The blockchain stores the locations of UAVs and is impenetrable due to hash code	Framework ensures data privacy using anonymity and security feature
Technique used	Blockchain-assisted UAV network	Ethereum Blockchain	Hyperledger Fabric Framework
QoS	Decentralized service delivery	Fast data delivery service	Membership Service Provider used for service delivery
Decentralization	Decentralized system	Decentralized Ethereum	Data stored in distributed ledger
Trust	Participants' identities are verified, and data is securely stored.	Ethereum provides trust to users by detecting GPS spoofing in UAV	Using a network, UAVs in a swarm can send control signals to all other UAVs. This report is available in concrete and can't be changed, and so the system can trust and audit it.
Swarm operations	Advanced	Based on Ethereum-based blockchain platform	Hyperledger Fabric framework based

- Ethereum Blockchain was created to establish a BC network that will help to minimize GPS spoofing.
- A blockchain-based technique connects a network registered in aeronautical parts to a ledger associated with appropriate data transmission utilizing blockchain technology (Table 9.2).

9.4 Relevance and Roles of Blockchain in Securing UAV Cellular Communication

Blockchain is effective in ensuring secure communication channels in UAVs. In this section, we discuss the major roles of blockchain in UAVs.

UAVs with Decentralized Data Storage Using Blockchain
The processing power and storage are limited for UAVs that are part of Industrial IoT networks that demand a lot of data storage. A decentralized data storage of blockchain helps in providing secure storage space for the data collected by the UAV nodes. A blockchain-enabled decentralized storage method in which UAVs operating as air sensors relay data to ground sensors, which are then rewarded for

the storage purpose and processing services via blockchain. The UAV nodes can instantly transfer data to the ground storage thereby enhancing storage, processing power, and flying time. A model is proposed in [18] in which the authors put forward employing air-ground heterogeneous IOT network with decentralized platform using blockchain technology. In this IOT-network UAVs are used to deploy sensors in air and ground sensor modules are used for storage of data by which data is exchanged mutually in a P2P network. Air sensors transmit collected cached data instantly to ground sensor modules by which data security, heterogeneous IOT transactions, and overcoming restrained memory storage in UAVs are achieved using blockchain technology with decentralized platform.

Blockchain in Swarm Networks

UAV networks are generally used for surveillance applications, and due to dynamic topological features, it faces several security issues. In urban environments it is difficult to operate due to obstructions in the urban environment that impede line of sight (LoS). To securely transfer traffic data, a blockchain-based information exchange network is being developed to manage UAV traffic. One of the frameworks of blockchain the Hyperledger Fabric which is a permissioned private blockchain model is used in networked swarms. It ensures efficient processing maintaining identity, privacy and integrity of the data. In this each UAV have to register in the system and are provided with a valid key which ensures their identity [19]. Any malicious entity trying to communicate with the system without a valid register key would be rejected and the system would be alerted. Also, the data transmitted between the drones is stored securely in the blockchain and cannot be altered providing reliability and transparency on the data stored. In [20], the author proposes a robotic swarm network using blockchain, that can be implemented in industrial applications which makes use of public key cryptography and digital signature for ensuring confidentiality and authenticity of the data, and distributed decision-making algorithms adopting blockchain for identifying data from multiple viewpoints.

Blockchain for Secure UAV Communications

The applications of UAV are going to increase in future with the risks of security attacks associated with it. UAV networks in commercial applications have the difficulty in secure data transmission, while simultaneously preserving data confidentiality. Hence a blockchain-based UAV system with asymmetric key cryptography, consensus protocols, and smart contracts will provide a robust system for securing data in UAVs. The decentralized nature of blockchain allows each UAV in the network to have a copy of the route of every other UAVs. This enables UAVs not to depend on the single GCS for its signals. Thus, UAVs are unaffected when wireless signals between GCS and UAVs get jammed. Also, collisions of UAVs in mid-air can be avoided by keeping a copy of the route in every UAV thereby maintaining distance from every other UAV. Also, an adversary can poison the original information by entering wrong data or altering the existing data thereby paving the way to hijack UAVs. This situation can be avoided by designing a consensus that can alert the system if it encounters such activity. The communication channels in UAVs are prone to many types of attacks which can be prevented through asymmetric key cryptography in blockchain which allows only valid users with proper decrypting keys.

For obtaining better security and speed, Named Data Networking (NDN) is being extensively investigated for UAV ad hoc networks. NDN, on the other hand, has features that make it extremely vulnerable to content forgery. Hence, a permissioned blockchain is used in an NDN-based UAV Network to securely validate and record the data. Services are provided in a decentralized manner by using an efficient consensus mechanism to detect inside attackers. To combat electromagnetic weapons, network jamming attacks, and other potential enemies, autonomous UAV systems are required. In [21], the author uses Ethereum-based public blockchain, where the data is stored and transmitted securely. Data integrity, authorization, and confidentiality are also ensured.

Conquering Network Issues in UAV with Blockchain

The UAV network with blockchain ensures the system works even in the case of one or more node failures making it fault-tolerant. The complete ledger is available with all miner nodes in the network and this makes the system work and later synchronizes the failure node with all other nodes when it becomes online.

Latency usually measured in milliseconds is the measure of time taken for transmission of data from the source to the destination in a network. A high-level security management scheme can be used for various IOT devices based on blockchain in which low latency and high throughput can be achieved by using efficient cryptographic algorithms.

Blockchain for Securing Privacy of Data in UAVs

Privacy or confidentiality is protecting legitimate data from unauthorized users. There are various kinds of attacks on data privacy which includes Linking attack, Sibil attack, Man in the middle attack, Eavesdropping, and attacks on anonymity and location data. By using blockchains the data is encrypted in the UAV network and is not available to anyone without a proper decryption key [22]. Also, the identity of the participating members should be proved using keys and digital signatures.

Blockchain for Securing Integrity of Data in UAVs

Integrity of the data means the correctness and consistency of the data stored in the database. Altering or modification of the data and data duplication should be avoided by any means to ensure integrity of the data. GPS spoofing is one such cyber-attack in which the legitimate GPS coordinates of the UAV are falsified. Blockchain platform with its immutable characteristic can be used in UAVs for maintaining consistency and eliminating data duplication.

Blockchain for Ensuring Availability of Data in UAVs
The data should be available and accessible at any time for the authenticated users of the UAV network. This can be achieved by blockchain which uses distributed storage of data with cryptographic hashing functions [23]. However, there are several types of attacks which affects the availability of data of which Denial of Service (DoS) and jamming are discussed here. In DoS, the server is overloaded by an attacker to prevent the users from accessing the data. In a blockchain-distributed ledger, the data is spread geographically across various nodes and any failure in a single or more nodes will have no detrimental effects. Jamming is a type of cyberattack in which the wireless communication channel is disrupted by passing interfering radio waves which obstructs the receiver to acquire the required data. For this, the smart contracts in blockchain are used by which each UAV node can act independently without the conveyance from other UAV nodes unless on meeting some conditions specified in the contract.

Although blockchain-assisted UAVs may overcome many problems associated with privacy, security, collision, decision making, coordination, signal jamming, etc., it faces challenges such as scalability, throughput, delay, and necessity of off-chain blockchain storage [24].

9.5 Blockchain-Based UAV Services

UAV in Supply Chain Automation (SCA)
The complicated procedural steps in inventory management system accomplished by the user manually are highly susceptible to errors and delays. An inventory management system using blockchain technology can be used with smart contracts, which increases trust, efficiency, transparency, and security [25]. In this, UAVs examine objects using RFID tags and communicate data to the blockchain network, which verifies the data and assures transparency. Transactions with external parties are carried out via smart contracts. A secured channel among UAVs participating multiagent system is required for commercial purposes. Due to its public and private key structure, blockchain is employed as a secure channel among UAVs.

Providing Coordinated UAV Services
UAV networks can be implemented in various applications that include network relaying, security, and disaster relief, Eventually there is a requirement for a global channel for storage and communication. UAVs may digitally sign and transmit encoded data using blockchain as a worldwide communication platform. Moreover, it promotes UAVs to make democratic decisions by accepting input from other UAVs. To categorize the areas with ultra-high user density, multiple network providers must have interservice operation capabilities. Assuring confidence amongst service providers is also significant in the market. However, UAV functions as one of the nodes in the blockchain, resulting in a blockchain-based trust

agreement among vendors in order to offer interservice operations. And the vendor's record of services kept on the blockchain in a transparent manner maintains mutual trust.

UAV Networks for Edge Computing
In Mobile Edge Computing (MEC) applications, there is a limited focus on assuring ultra-reliable communication services. An integration of blockchain and neural network-based methodologies provides more reliability [26], leveraging UAVs for caching as on-demand nodes.

9.6 Challenges in UAV Networks

Specifically, UAVs and blockchain have constraints that limit their capabilities and have a consequence on their integrated applications. We strive to present some of the significant challenges that may be stumbling blocks to their actual deployment based on our research.

Privacy UAVs can be used to surveil people's personal property without their knowledge or consent. UAVs with transceivers can be used for tracking people by taking out the unencrypted data [27]. Such UAV applications are possible, and strong regulation is required to address them. Blockchain as a technology might help UAV applications operate more efficiently, however as the number of UAVs grows, people's privacy may be jeopardized.

Limited Resources Miners require a great extent of processing power to operate blockchain consensus algorithms. It can be difficult to incorporate this in onboard UAVs. This is a typical issue that all blockchain-based UAV systems may encounter in course of time. In addition to their moving mechanism system and battery, UAVs must carry sophisticated payloads. Furthermore, if they are to act as nodes in a blockchain, their hardware will need to have significant processing power and storage capability.

Air-Traffic Violation With the growing number of UAVs in the air, a proper civil air traffic management system is required to ensure that the UAVs are coordinated. Because unknown UAVs were observed near the airport airspace, an event at Gatwick airport led to a lot of commotion and monetary damage. If adequate air space management systems for UAVs are not incorporated by civil aviation authorities, such occurrences are likely to become increasingly common. It will be a difficult challenge to expand the use of UAVs, by combining technology like blockchain, until such measures are put in place.

Machine Learning (ML) and game-theory attacks Majority attacks employing machine learning and algorithmic game theory are similarly vulnerable to blockchain-based applications. One of the major difficulties that the blockchain network must overcome in order to improve its security is this.

Quantum Attacks As quantum computers possess extremely high processing capabilities, blockchains must be protected against quantum attacks, which allows adversaries to carry out 51 percent attacks in the future. This issue could become a serious challenge in the future when it comes to protecting blockchain-based apps.

9.7 Future Research Directions in UAV

Integrating technologies such as UAVs and blockchain is a prominent topic in research presently. There has been considerable progress in this direction, but there is still much more to be done. Based on our data, we present a few potential research directions that could have a big impact.

Optimizing UAV AVs have an extremely short fly time due to their limited battery capacity. As a result, optimizing UAV operations is required to increase their fly-time. Due to the fact that blockchain-based applications necessitate higher computing power, consumption of power might be a significant issue.

Securing Private or Permissioned Systems Apart from financial markets, many of the UAV applications based on blockchain and the applications in industries require private/permissioned blockchain. Hence, they are more susceptible to attacks than public blockchains, which have a large number of members and make it impossible to carry out a majority attack. With the rise of more powerful sorts of assaults on blockchain networks, including quantum attacks, machine learning, and game theory-based attacks, the need for blockchain security is growing. To make private blockchain networks more secure and tamper-proof, more research is needed in this area.

Simulation Software Blockchain implementation in UAV systems is challenging, as integration of the system requires extensive testing before being released to the market necessitating simulation software. A dedicated platform is required, that incorporates both blockchain technology and UAVs.

9.8 Conclusion

In the future, UAVs are sure to play an important role in various systems and hence the security of those systems that depend on UAVs should be preserved. Thus, blockchain with its promising properties when incorporated with UAVs will provide reliable systems in various domains. UAVs have been found useful in many application areas when they are combined with other technologies such as machine learning, modern networking and communication systems, wireless sensors, etc. In this chapter, we assessed the role of blockchain in securing UAV cellular communication with current blockchain solutions for it. Also, blockchain-based UAV services are discussed along with challenges that are faced in implementing UAV networks. This chapter also throws light on future research directions that are to be considered for enhancing UAV applications.

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S. Suganthi is a research scholar in Computer Science and is currently pursuing PhD from Galgotias University, Delhi NCR, India. She has received her MPhil degree in computer science from Bharathidasan University, Tiruchirappalli, Tamil Nadu, India and has received master's degree in computer science from Bharathiar University, Tamil Nadu, India. Her research interests include Data Mining, Big Data, Machine Learning, Blockchain Technology, and Internet of Things. She has written several book chapters published by reputed publishers such as Springer, IET, Wiley, Elsevier, and CRC Press.

G. Nagarajan is currently working as Assistant Professor in the Department of Computer Science and Engineering in the School of Engineering at Presidency University, Bengaluru, Karnataka, India. He is pursuing PhD in Galgotias University, Greater Noida, Gautam Buddh Nagar, Uttar Pradesh, India. He received his MTech degree in Information Technology from Sathyabama University, Tamil Nadu, India. His current research interests include Cloud Computing, Big Data, Internet of Things (IoT), Cloud Security, and Computer Networks. He received the Research and Innovation award (2019) from Galgotias University. Nagarajan has published more than five research articles and has attended various conferences. He has an Indian patent. He is a member of the Association for Computing Machinery (ACM), The International Association of Engineers (IAENG), The Institute of Research Engineers and Doctors (IRED), and the International Association of Computer Science and Information Technology (IACSIT).

T. Poongodi is currently working as Professor in the School of Computing Science and Engineering at the Galgotias University, Delhi NCR, India. She received her PhD degree in Information Technology (Information and Communication Engineering) from Anna University, Tamil Nadu, India. Her current research interests include Network Security, Wireless Ad Hoc and Sensor Networks, Internet of Things (IoT), Computer Networks, and Blockchain Technology for emerging communication networks. She is CISCO, Oracle Academy certified, and handling networking and Structured Query Language courses. Dr. T. Poongodi is the author of over 40+ book chapters published by reputed publishers such as Springer, Elsevier, IET, Wiley, De-Gruyter, CRC Press, IGI global. She has published articles in 30+ international journals and attended many conferences. She has authored or coauthored 10+ books in the areas of Internet of Things, Data Analytics, Blockchain Technology, Artificial Intelligence, Machine Learning, and Healthcare Informatics, published by reputed publishers such as Springer, IET, Wiley, CRC Taylor & Francis, and Apple Academic Press. She adopts a universal and humanistic approach in her academic and research works. In her research, she has undertaken meticulous scientific studies of emerging issues in networking disciplines. She has many years of academic work experience in teaching and multidisciplinary research. She has received the Research and Innovation award (2019, 2020) and Excellence in the area of Research & Innovation/ Academic Excellence /Extension Activities (2018-19, 2019-20) from Galgotias University. Prof. Dr. T. Poongodi has also received invitations to address international conferences as a keynote speaker. She is a senior member of The Institute of Electrical and Electronics Engineers (IEEE), IEEE Women in Engineering (WIE), and member of Association for Computing Machinery (ACM), The International Association of Engineers (IAENG), The Institute of Research Engineers and Doctors (IRED), and International Association of Computer Science and Information Technology (IACSIT). She is the reviewer for several international journals and conferences, and she has four Indian patents.

Chapter 10
Unmanned Aerial Vehicle Cellular Communication Operating in Non-terrestrial Networks

Promise Elechi and Kingsley Eyiogwu Onu

Abstract The impact of the non-terrestrial network on the unmanned aerial vehicle (UAV) has been established. In this work, the channel model and the vertical height of the UAV for both ground users and base stations (BSs) were analysed. The application of NTN on UAV has also been analysed, as well as the capacity of multiple antenna systems for UAV. The results have shown that an increase in the height of the BS increases the optimal value of the BS tilt angle of the antenna. The work has also shown that different empirical models can be used to predict the signal path loss of UAVs in NTN. The work has also shown that for the BS height of 20 m and aerial height of 50 m, the optimal antenna tilt angle was 1°. However, when the height of the BS was doubled (40 m) and the aerial user height remained 50 m, the optimal antenna tilt angle increased to about 5.5°. So, an increase in the height of the BS increases the optimal value of the BS tilt angle of the antenna. Also, an increase in the distance between the BS and the user decreases the elevation angle of the UAV. This work has also shown that introducing multiple antenna arrangements either at the input for transmission or at the output for reception, or at both ends increases the capacity of the system.

Keywords Unmanned aerial vehicle · non-terrestrial network · Base station · Aerial · Antenna · SISO · MIMO · BER · Capacity

10.1 Introduction

Unmanned aerial vehicles (UAVs) are simply drones or aircrafts that are operated remotely. The remote operation of such drones or aircraft is based on already programmed systems of operation. The use of the UAV is increasingly becoming popular each day due to its promising advantages in terms of flexibility, manoeuvra-

P. Elechi (✉) · K. E. Onu
Department of Electrical and Electronic Engineering, Rivers State University, Port Harcourt, Nigeria
e-mail: elechi.promise@ust.edu.ng

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bility, and accessibility of UAVs to the ground vehicle within a cellular environment [1]. The application of UAVs is in such areas as civil and military. Successful operation of UAVs requires proper wireless connectivity. Hence wi-fi and other wireless technologies are used daily by UAVs whenever communication with the ground station is necessary [2].

Due to the difficulty encountered in using conventional wireless technologies for the wide-area and time-sensitive internet of things, non-terrestrial infrastructures like satellites or UAVs are used. Non-terrestrial Network (NTN) is empowered by MEC (mobile edge computing) since the internet of things (IoT) devices are not distributed evenly [3]. As the need for connectivity in a wireless system is continuous, terrestrial networks alone are incapable of providing the required coverage, adaptability, scalability, and flexibility. Hence NTN components have to be integrated into the system, as noted by [4].

Some key features of UAVs include its autonomous operation, high-level mobility, and the ease with which they are deployed. UAVs are already applied in such areas as agriculture, rescue mission, and gathering of scientific data for research, civil and general safety of humans.

With the introduction of NTNs, it is clear that wireless networks will grow more rapidly via satellite communication. According to [5], the spatial diversification through the small cell in multiple input multiple output (MIMO) antenna arrays enables high data throughput, improved energy efficiency, and wider coverage.

As promising as the deployment and usage of UAVs proves to be, many challenges that have to be addressed really exist. There are issues in control, communication with cellular networks, energy consumption optimization, and autonomous mobility. In [6], the problem of optimization associated with UAVs has been treated offline. The reality is that an ongoing real-time analysis ensures that the component of autonomous command and control brings about an excellent flight plan. The key contributions of this chapter are: (1) It will show that increasing the height of the base station (BS) antenna will correspondingly increase the optimal value of the BS tilt angle of the antenna. (2) It will also show that introducing multiple antenna arrangements either at the input for transmission or at the output for reception or at both ends increases the system's capacity. The organization of this chapter includes a review of related work, materials and method, signal reception in UAV, NTN models, capacity analysis of multiple antenna systems for UAV, and the analysis results.

10.2 Literature Review

10.2.1 Review of Related Work

Successful implementation of UAVs depends much on the communication effectiveness between UAVs and other cellular network devices. Many researchers have tried to predict signal strength by designing the receiver and transmitter for communication systems. In [7], received signal strength (RSS) was modelled using hybrid neuro-fuzzy networks. The focus of the modelling was on the indoor environment. A simulation of the propagation model was done using neuro-fuzzy, and the performance was compared with channels empirical models. Table 10.1 shows the summary of the literature.

This work shows the role of antenna orientation and capacity for NTNs in terms of UAV application. It will show that an increase in the height of the BS antenna increases the optimal value of the BS tilt angle of the antenna. It will also show that introducing multiple antenna arrangements either at the input for transmission or at the output for reception or at both ends increases the system's capacity. All these have not been reported in the existing literature.

10.2.2 History of Unmanned Aerial Vehicles

Sixteen years before 1917, the Wright Brothers pioneered Kitty Hawk flight; they were accredited with the invention of aircraft. In 1916, the first pilotless aircraft was created by U.S with advancement by the US Army building Kettering Bug. More so, in 1930, the US Navy experimented on radio-controlled aircraft, which resulted in the creation of the Curtiss N2C-2 Drone and during World War II, Reginald Denny created the first remote-controlled aircraft called the Radioplane OQ-2, which was the first mass-produced UAV product in the U.S and became a breakthrough in manufacturing and supply of UAV for the military [20]. Some authors [21], [22], and [23] have also reported the use of Lunokhod rovers on the moon in the 1970s deployed by the Soviet Union. Moreover, [23] also reported the use of a programmable Mars robot which was used to determine the distance between the Earth and Mars and [22] reported on the use of UAVs by the armed forces in developing countries and their challenges in terms of sensing and communication.

10.3 Materials and Method

The materials for this work were mainly a personal computer installed with MATLAB software used for analysis. The methodology adopted involved modelling, UAV parameter verification by keeping the height of aerial user (AU) constant while varying the height of the ground user (GS) and then analysing the effect of such variation of GS's height on the network outage probability. After that, the height of the GS was kept constant while the height of the AU was varied. Special attention was given to what happens to the outage probability if the height of the GS is doubled while the height of the AU is kept constant.

Table 10.1 Summary of existing literature

Author(s)	Summary of the literature
Alsamhi and Rajput (2014) [8]	Examined the performance of propagation models to ensure that handoff in HAPs is efficiently done. The authors calculated the Received Signal Strength (RSS) from the aerial platform using the model developed by Hata.
Mozaffari et al. (2018) [9]	Proposed a study on the uses of UAVs in wireless networks. The authors analysed aerial base stations and the cellular-connected users. Key challenges, applications, and fundamental open problems for each service are discussed. Finally, mathematical tools and techniques are employed to analyse UAV wireless networks.
Gupta et al., (2013) [10]	Covers routing, energy efficiency, and seamless handover pose some application scenarios where UAVs act as servers or as clients, mesh or star networking for UAV and the effect of delays and disruption in the deployment.
Bekmezei et al., (2013) [11]	Focused on ad hoc networks for UAVs connectivity. The work compared FANETs, Mobile Ad-hoc Networks (MANETs), and Vehicle Ad Hoc Networks (VANETs) and highlighted their challenges and merits.
Motlagh et al., (2016) [12]	Provided a comprehensive survey on UAVs focusing on Internet of Things (IoT) services from the sky. The work proposed an architecture for UAV and presented the key requirements and challenges of UAV.
Hayat et al., (2016) [13]	Focused on the characterization of UAV networks for communications and networking. The quality of service (QoS requirements, network-related mission parameters, data prerequisites, and the minimum data transmitted over the network for civil applications. The general networking-related requirements include adaptability, connectivity, privacy, safety, security, and scalability. Conclusively, they presented experimental results from many projects and investigated the appropriateness of the present communications technologies to support dependable aerial networks.
Hasim et al., (2018) [14]	Provided a comprehensive survey on UAV's civil applications and key research challenges, they considered challenges in charging, networking, security, swarming, and the ability to avoid a collision. They also surveyed new technology trends on the millimetre wave, free space optical, Cloud computing, Machine learning, and Image processing which enhanced wider applications of UAVs.

Harilaos et al, (2021) [6]	Studied the combination of unmanned aerial vehicles and fifth-generation cellular networks to solve the energy issues of unmanned aerial vehicles. The flight control system was offloaded at the edge of the network. This made it possible to optimize unmanned aerial vehicle energy resources as data collected was processed in real-time.
Amorosi et al, (2018) [15]	Gave attention to the optimization of autonomous management and planning of networks support by unmanned aerial vehicles.
Kourtis et al, (2020) [16]	The benefits of the fifth-generation network which supports unmanned aerial vehicles, provide the support needed for MEC, even at high speeds, and gives greater throughout and bandwidth.
Federica et al., (2021) [17]	Carried out a survey of some capabilities and features of the fifth-generation new radio. The authors studied the general architecture of the fifth-generation (5G) network and the protocols specified by the third-generation partnership (3GPP). The scalable effect numerology has on the performance of the system, and the possible challenges of the system were all considered.
Wang et al., (2019) [18]	Looked at non-terrestrial wireless technologies. Unmanned aerial vehicle for IoT and satellite. IoT were studied, with their different technologies separately reviewed for the unmanned aerial vehicle. IoT investigation of the route planning was equally carried out.
Godage, (2019) [19]	Provided an interference assessment based on unmanned aerial vehicles for fifth-generation new radio. Challenges of unmanned aerial vehicles radio scanners measurement were reviewed, and practical tools and methods for addressing the outlined challenges were also presented.

10.3.1 Channel Model

Considering an NTN for UAVs where the BSs' AUs and GSs were randomly distributed, the channel is modelled for both LoS and NLoS environments. According to [24] and [25], in a UAV application, both the line-of-sight (LOS) and non-LOS (NLOS) environments were considered as having links between a BS and a GS as well as between a BS and an AU. The probability of forming a LOS link between the BS at $x = (x_B, y_B, h_B)$ and the k_{th} user at (x_k, y_k, h_k) is given by [26]

$$P_L\left(r_{k,x}\right) = \left\{1 - \frac{\sqrt{2\pi}\xi}{|h_k - h_B|}\left|Q\left(\frac{h_k}{\xi}\right) - Q\left(\frac{h_B}{\xi}\right)\right|\right\}^{r_{k,x}\sqrt{\mu v}} \tag{10.1}$$

where $Q(x) = \int_x^{\infty} \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{t^2}{2}\right) dt$ is the Q-function and the horizontal distance between the BS and the kth user is given by $r_{k,x} = \sqrt{(x_k - x_B)^2 + (y_k - y_B)^2}$. The parameters of the environment are taken as v, ξ, *and* μ and they are assumed to be the height and densities of the obstacle. Since it has been established in other works of literature that the NLOS environment is the complementary event of the LOS environment, the NLOS probability between the BS and the kth user will be expressed as $P_N(r_{k,\,x}) = 1 - P_L(r_{k,\,x})$.

10.3.2 Requirements for Unmanned Aerial Vehicle Communication

Communication among UAVs with ground stations has certain requirements that ensure easy and successful communication. The requirements have to do with authenticating and authorizing communication, which is responsible for the operation of UAVs, the transmission of payload data to ensure HDVS (High Data Video Streaming), and interaction with different UAVs to rule out the possibility of collusion of UAVs. The command and control often referred to as C2 in UAVs, is the communications link between the ground station (GS) and the UAVs. Whether a person remotely operates an aircraft, as is the case sometimes, or it is programmed and then operates on its own autonomously. Control and command communications links are very important.

Communication links for UAVs are the data link (DL) and the control and non-payload communications link (CNPCL) [27]. The CNPCL involves communications between UAVs and control centres on the ground for the backhaul network. The functions of the control and non-payload communications link are mainly safety-related. Other functions include sending information related to the network configuration, collecting information about UAVs' flight data like the global positioning system, speed of the flight, angle of elevation, and so forth [28]. According to [29] C-bands and L-bands are the two frequency bands allocated for the CNPCL. Data Link (DL) is responsible for transmitting data between sensors, aerial BSs, mobile devices, and the gateway. By guaranteeing high-capacity requirements, millimetre wave bandwidth is adopted, especially since aerial BS to aerial BS communications are dominated mainly by LOS components [30] and [31].

The control and command links make use of diverse communications technology. For example, LOS UAVs use ultra-high frequency (UHF) or even very high frequency (VHF) as the radio frequency link, while wi-fi or Bluetooth is used by very-short-range UAVs. Satellite communications are used by UAVs that operate beyond visual LOS (BVLOS); protected spectrum, which is a portion of the radio frequency spectrum, is used by high altitude UAVs.

10.3.2.1 Authentication and Authorization in UAV Communication

Authentication and authorization can be required between UAVs and a particular ground station or between two UAVs. Certificates are first issued to the ground station and the UAV by an authorized agent. As [32] noted, the ground station verifies if an UAV like a drone has the authorization to fly. The verification is done by checking whether the certification of the drone is valid or not, thereafter, a flight session key with the UAV is generated. The flight session key is very important because it is required when the time comes for authentication of the UAV.

Before an UAV takes off, it makes an attempt to get flight approval from the ground station. In [32], it was noted that UAVs like drones and the ground station carry out mutual authentication by checking and verifying the signature contained in their certificates. The procedure for generating flight key is as outlined in [32]:

- When a UAV wants to fly, it sends a message that includes its identity (ID), its certificate, and even the plan of the flight to a particular ground station designated for that purpose.
- When the ground station receives the message from the UAV, it signs its random nonce, which it chose randomly, and also signs the UAV's own randomly chosen nonce. Such signing is done with the GS's private key. The ground station now sends, including its own certificate and all that has been signed.
- Following the sending of that message, the ground station tries to confirm if the UAV's certificate is valid or not, while the UAV does the same thing by trying to confirm the ground station's certificate. This process leads to the GS (ground station) public key extraction by the UAV from the ground station's certificate.
- The flight session key is computed, and the ground station stores the UAV ID, its flight plan, and flight session key directly to the information database. Figure 10.1 shows the communication between UAVs with BSs and GSs.

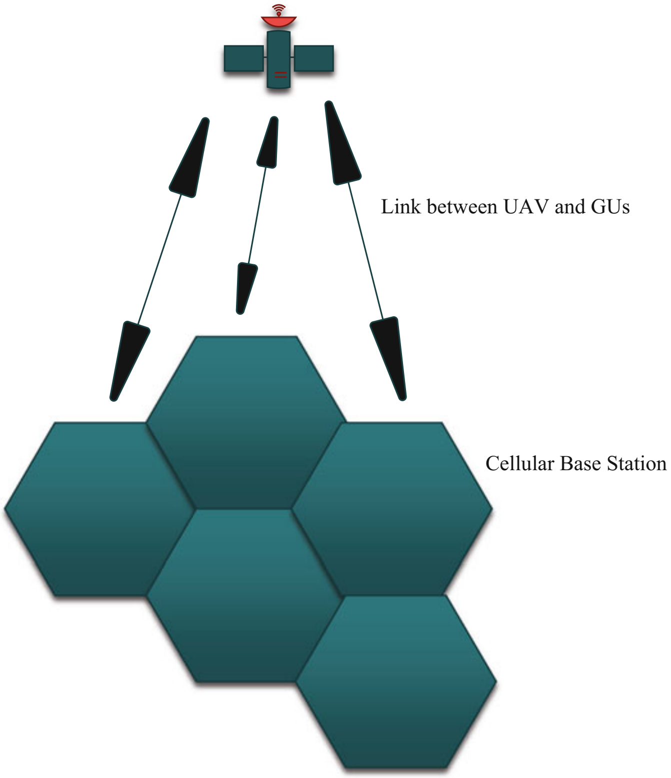

Fig. 10.1 Communication between UAV with BSs and GUs

10.3.3 Signal Reception in Unmanned Aerial Vehicles

Signal strength, even in UAVs, is a key concept that affects the performance of wireless networks. Drones, which are examples of UAVs, are controlled using signal strength [33] and [34]. Besides controlling drones, signal strength also helps maintain the drone's trajectory, detect a particular object, reach a given position with accurate precision, and signal reception from agents. However, in NTNs, some phenomena like scattering, reflection, diffraction, and shadowing adversely affect signal propagation in space. Hence, signal strength received by UAVs is weakened. Height of UAVs, distance, and path loss are some other parameters upon which RSS depends. Figure 10.2 shows the impact of scattering, diffraction, and shadowing on the propagation mechanism of UAVs in an NTN.

Different propagation models have been relied upon in the prediction of signal strength of UAVs. The models include empirical, analytical, AI, and theory, as shown in Fig. 10.3.

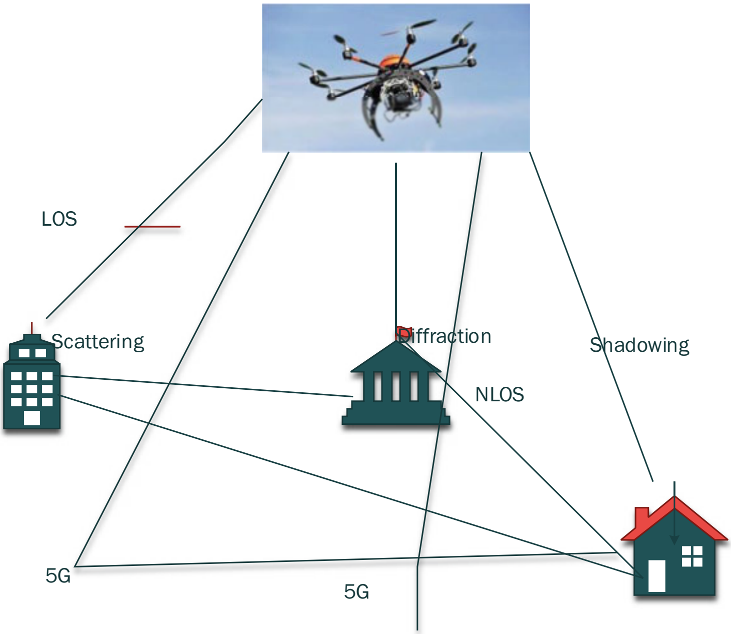

Fig. 10.2 Propagation mechanism of UAV

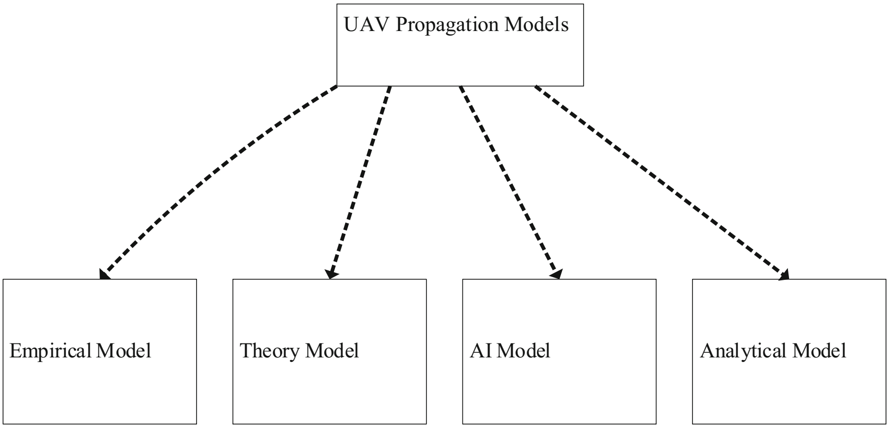

Fig. 10.3 Unmanned aerial vehicle propagation models

One example of an empirical model is the Hata model; the theory model includes the free space model and the two-ray model; analytical model includes the Ikagami model, and the artificial intelligence (AI) model includes the artificial neural network (ANN).

For LOS propagation, estimating fading requires considering Rician fading. If s represents a LOS component of field strength and I represent the Bessel function of order zero, then Rician distribution denoted by $f_{(r)}$ is given by

$$f_{(r)} = \frac{r}{\sigma^2} e^{r^2} + \frac{s^2}{2\sigma^2} I \frac{rs}{\sigma^2} \tag{10.2}$$

Introducing K-factor which is a key factor in any Rician channel, we have

$$(K) = \frac{S^2}{2\sigma^2} \tag{10.3}$$

When K tends to infinity ($k \to \infty$), the Rician probability density function is Gaussian; when K tends to zero ($K \to 0$), the Rician probability density function (pdf) is Rayleigh.

The quality of signal received by UAVs largely depends on the path loss as the signal propagates from the transmitter to the receiver. Appropriate propagation models are used to predict the average RSS from the transmitter to the receiver considering the distance between the receiver and the transmitter. As an example of the empirical model, the Hata model is often used in predicting path loss or signal attenuation. The Hata model is expressed using Eq. (10.4)

$$(P_L) = A + B \log R \tag{10.4}$$

where R is the distance between the transmitter and the receiver in a kilometre, A is a constant that depends on the frequency of operation in megahertz, the heights of the BS and mobile station in meters. The parameter A and B are given by

$$\left(A = 69.55 + 26.16 \log(f) - 13.82 \log(h_b) - a\left(h_m\right)\right. \tag{10.5}$$

$$\left(B = 44.9 - 6.55 \log\left(h_b\right)\right. \tag{10.6}$$

The value of $a(h_m)$ is obtained from Eq. (10.7)

$$a\left(h_m = \left[1.1 \log(f) - 0.7\right] h_m - \left[1.56 \log(f) - 0.8\right]\right. \tag{10.7}$$

When f, R, h_b, and h_m are known, the, the path loss can be calculated. Removing the calculated path loss from the transmitted signal strength gives the RSS as shown in Eq. (10.8).

$$\text{RSS} = S_T - P_L \tag{10.8}$$

where RSS represents the received signal strength

S_T represents transmitted signal strength
P_L represents the calculated path loss or signal attenuation

10.3.4 Non-Terrestrial Network Model

The model for an NTN that is considered here looks at a UAV system with attention given to the antenna's power gain. In UAVs with NTNs, there are at least two different ways UAVs, GSs, and BSs can be distributed. The distribution can either be random distribution or based on Mat*ĕrn* Hardcore Point Processes. The Mat*ĕrn* hardcore point processes consider the least safe horizontal separation between two AUs [25]. However, whichever method is used for performance analysis based on the distribution will still give the same result because only the density of AUs affects the performance of the system [25]. A homogeneous Poison point process (HPPP) is used to model users' location. In [35], the UAV trajectory was optimized by formulating non-convex problems and separating them into three subproblems to get the optimal solution.

Authors [36] and [37] used an inclusive-service BS positioning scheme in carrying out their respective research work on UAVs and beam-forming performance with down tilted antennas. The BSs in this scheme simultaneously serve GSs and AUs. Therefore, the design of the antenna's tilt angle must be done so that both the GSs and the AUs will be efficiently served. The modelling of BSs locations follows the HPPP having density denoted by λ [38]., used the application of AI in providing security to the integrated UAV-AV.

As [39] noted, the BS densities for ground and AUs are not different from the total BS density because there is only a single type of BS used. The inclusive service scheme is illustrated as shown in Fig. 10.4.

Another scheme is known as the exclusive service BS scheme. This scheme divides the BSs into two groups: one group serves the GSs exclusively while the other group serves AUs exclusively. The tilt angles of the antennas are differently to efficiently achieve the intended purpose. It is here assumed that the distribution of the BSs for GSs and AUs complies with the homogeneous Poisson point process with the BSs' densities for GSs and AUs denoted by λ_G and λ_A, respectively. Figure 10.5a, b show different users' BS.

10.3.5 Non-terrestrial Network Channel Model

Communication links exist between a GS and a BS. The links between an AU and a BS require that LOS environment and NLOS environment be seriously taken into account in UAVs. For a LOS link to be formed between a particular user and a BS at a distance d, the equation for the probability of forming, as given by [26] must hold.

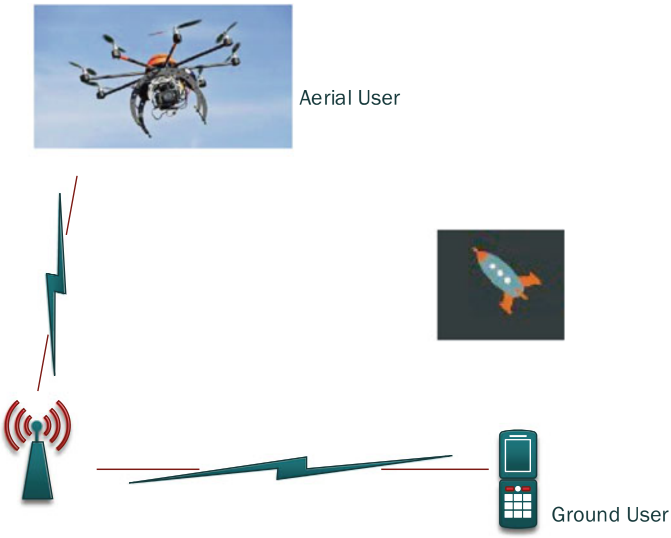

Fig. 10.4 Base station for both aerial users and ground users

$$\mathrm{P_{LoS}}= \left(1-\frac{\sqrt{2\overline{x}\varepsilon}}{|h_u-h_B|}\left|Q\left(\frac{h_U}{\varepsilon}\right)-Q\left(\frac{h_B}{\varepsilon}\right)\right|\right)^{d\sqrt{\mu v}} \tag{10.9}$$

Where μ, ε, and v are parameters due to the particular environment, h_u and h_B represent the height of a particular user and BS height, respectively. For a NLOS environment, the NLOS probability is one minus the LOS probability because NLOS environment is complementary to the LOS environment.

Hence,

$$P_{\mathrm{NLoS}} = 1 - P_{\mathrm{LoS}} \tag{10.10}$$

Channel fading based on LOS probability is modelled using Nakagami – M model for channel fading. Therefore, channel gain distribution is [31]

$$f = \frac{M_v^{m_v}}{T\ (mr)}\, x^{mv^{-1}}\, \exp^{(-mv\ x)} \tag{10.11}$$

For LOS, v in equation (10.11) is 1and for non-line of sight, v is N. Hence, the equation becomes

$$f_L = \frac{M_v^{m_L}}{T\ \ (M_L)}\, x^{ML^{-1}}\, \exp^{(-M_L\ x)} \tag{10.12}$$

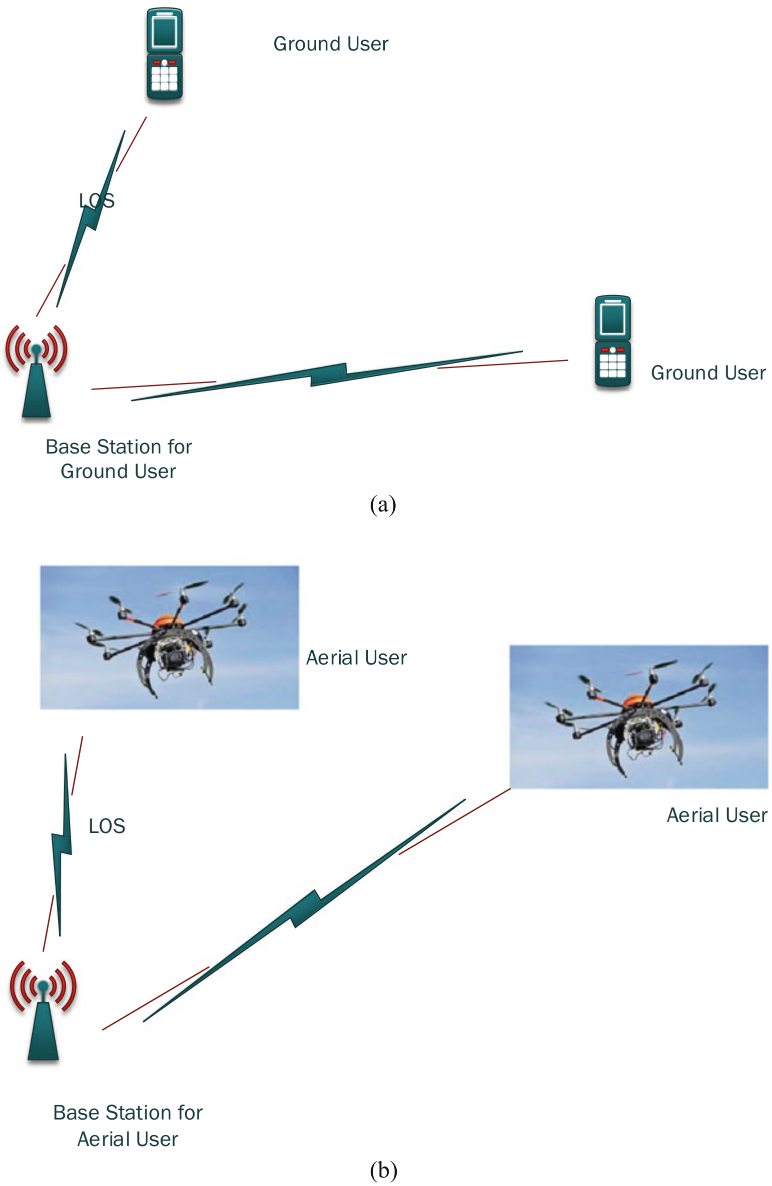

Fig. 10.5 (**a**) Base station for ground users. (**b**) Base station for aerial users

$$f_N = \frac{M_v^{Mn}}{T\ \ (M_N)}\ x^{MN^{-1}}\ \exp^{(-M_N\ x)} \tag{10.13}$$

The channel fading that occurs between the BS and a particular user is

$$C = \begin{cases} C = \text{CL, with probability of } P_{\text{L}} \\ C_{\text{N}}, \text{otherwise} \end{cases} \quad (10.14)$$

10.3.6 5G New Radio (5G NR) Support for Unmanned Aerial Vehicles

The fifth-generation (5G) network has much impact on UAVs. The 5G network provides AUs with required connectivity and improves UAVs multimedia provision while minimizing costs of power usage. An architecture that is not limited by BSs' proximity or even complex infrastructure is used by 5G networks to provide wireless services to different users, including UAVs. This architecture is termed radio access networks. Generally speaking, the 5G new radio system architecture comprises the core network and the next-generation radio access network.

The next-generation radio access network, often written as NG-RAN, combines new-generation long-time evolution enode and 5G NodeB. This combination handles radio-related functions such as connection control, admission, and management of quality-of-service flow. E-UTRA, which stands for "evolved universal terrestrial radio access", has a user or control plane protocol that the new-generation long-time evolution eNodeB (ng-eNB) uses to serve user equipment of long-term evolution (LTE). The ng-eNB and 5GC are connected via new-generation interface. While the 5G NodeB (gNB) has a central unit denoted by gNB – CU, there can be more than one single distributed unit denoted by gNB-DU. Apart from the NG interface, other logical interfaces exist. These interfaces include F_1, X_n, and X_n – C. These are illustrated in Fig. 10.6.

As shown in Fig. 10.6, 5G NodeB central units gNB-CUs are connected through the X_n – C interface. The 5G core network is denoted by 5GC. In 5GC, the control plane and the user plane are separated, and network slicing is possible. The

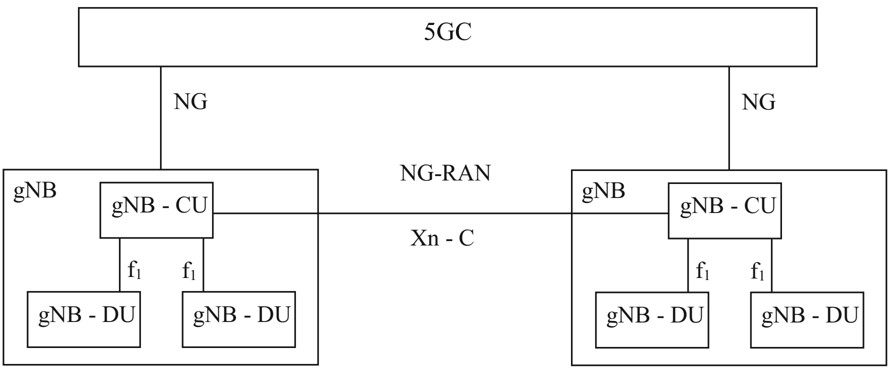

Fig. 10.6 New-generation radio access network architecture

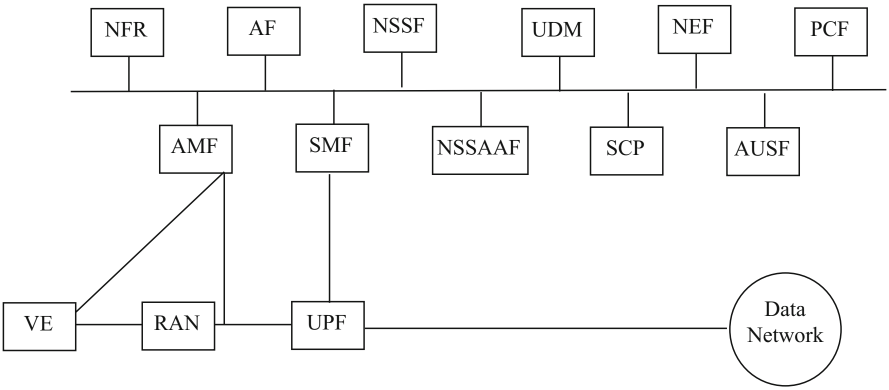

Fig. 10.7 Fifth-generation core network

following functions exist for the 5GC network and the link is illustrated as shown in Fig. 10.7.

NSSF = Network Slice Selection Function
NSSAAF = Network Slice Specific Authentication and Authorization Function
AMF = Access and Mobility Management Function
NEF = Network Exposure Function
AUSF = Authentication Server Function
PCF = Policy Control Function
NRF = Network Repository Function
AF = Application Function
SMF = Session Management Function
UDM = Unified Data Management
UPF = User Plane Function
UDSF = Unstructured Data Storage Function
UE = User Equipment
NWDAF = Network data Analysis function.

10.3.7 Multiple Antennas for Unmanned Aerial Vehicle Communication

The challenge cellular networks have as per the provision of optimal communication support to UAVs is addressed by the use of multiple antennas in both UAVs and BSs [40]. There is a smart antenna system, which is an integration of an array of antennas and digital signal processing techniques. The latter uses two algorithms: array factor (AF) and adaptive beam-forming. The AF algorithm is used for calculating the direction of arrival of all incoming signals. At the same time, adaptive beam-forming

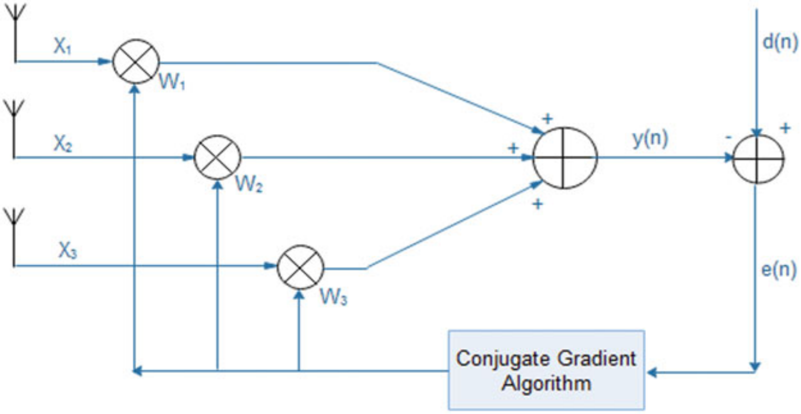

Fig. 10.8 Block diagram of adaptive beam-forming array antenna model

algorithm is used to update the weights of each element. Figure 10.8 shows the block diagram of adaptive beam-forming model.

As a result of channel interference due to nearby cells, mobility patterns of UAVs, and the direction of BS antenna tilt, which is usually downward for ground BSs, the cellular network in existence is not compatible with certain requirements for UAV communications. To overcome the shortfalls of present cellular networks, multiple antenna system is utilized in BSs.

10.3.7.1 Vertical Antenna Design

The focus here is on the design of antenna tilt angle for both GSs and AUs. The tilt angle obtains the gain of the antenna in the vertical direction $90^{\circ} > \theta_t > 90^{\circ}$ [25]. It should be noted here that antenna angle can be tilted up or down. Antenna power gain G is given by [25]

$$G = 10^{-\min\left(12\left(\frac{\theta d+\theta_t}{\theta_{3dB}}\right)2\eta/\right)10} \tag{10.15}$$

where ŋ is the least power that goes into the side lobe, and θ is the angle of elevation between user and the BS antenna, given by Eq. (10.16)

$$\theta = \frac{180}{\pi}\tan^{-1}\left(\frac{h_k - h_B}{d}\right) \tag{10.16}$$

where d is the distance between the user and the BS.

When antennas are arranged and interconnected to give a desired directional radiation pattern, they are called an antenna array. If desired, the directional radiation can be changed to any direction of interest, and this is called beamforming. The beam-forming technique is realized in at least two ways: electronic and mechanical scanning. In electronic scanning, the phase of excitation current is altered, and it is called phase arrays which find application in HF, VHF, UHF communications, radar, etc.

There are different geometrical arrangements or configurations in antenna arrays like planar, linear, and conformal arrays. An array radiation pattern is often determined by the kind of elements, the orientation, spaces between elements phases, and amplitudes of excitation. An array radiation pattern is split into the AF and the element pattern. In the AF, all the array elements radiate in all directions. Hence, the elements are referred to as isotropic radiators.

The phase difference is given by Eq. (10.17)

$$P_d = \frac{2\pi d}{\lambda} cos\theta \tag{10.17}$$

where d is the distance between the elements, λ is the wavelength, and θ is the angle of the incoming wave. Equation (10.17) is used to steer the beam electronically by simply adjusting the phases.

10.3.8 Capacity Analysis of Multiple Antenna Systems for Unmanned Aerial Vehicles

Since the use of multiple antenna systems for UAVs in BSs and UAVs is known to address the failure of the present cellular network to provide the required support to UAVs in NTNs, it is quite appropriate to analyse the performance of such multiple antenna systems based on the channel capacity. The capacity of a communications channel simply refers to the maximum number of bits that can be transmitted per symbol without any form of error in the system. A communications channel is made up of the following:

1. Transmitted signal
2. Noise
3. Channel gain and
4. Received signal

For a basic communication channel, the equation is given by

$$y = x\sqrt{g} + n \tag{10.18}$$

where y is the received signal, n is the noise, g is the channel gain, and x is the transmitted signal. The channel capacity is given by Eq. (10.19).

$$C = B\text{Log}_2 \left[1 + \frac{qg}{N_O}\right] \tag{10.19}$$

where q is the energy per symbol, given by Eq. (10.20).

$$q = \frac{P}{B} \tag{10.20}$$

where P is the power and B is the number of symbols per second. Therefore, putting Eq. (10.20) into Eq. (10.19) gives:

$$C = B\mathrm{Log}_2 \left[1 + \frac{Pg}{BN_O}\right] \tag{10.21}$$

But the expression $\frac{Pg}{BN_O}$ is equal to the signal-to-noise ratio (SNR). Hence Eq. (10.21) now becomes

$$C = B\mathrm{Log}_2 \ [1 + \mathrm{SNR}] \tag{10.22}$$

If the SNR is known, channel capacity can be determined from Eq. (10.22). Suppose the SNR is unknown, but the channel gain, the power, the noise variance, and number of symbols per second are known. In that case, system capacity can be computed using Eq. (10.21).

The antennas are arranged or combined in different ways for multiple antenna systems. There is single input single output (SISO) arrangement, single input multiple output (SIMO) arrangement, multiple input single output (MISO) arrangement, and lastly, MIMO arrangement. The SISO arrangement has been used for a very long time. Because of the need for higher capacity and coverage, multiple antenna systems began to be used at the receiver and transmitter inputs and outputs. For the various antenna arrangements, the system capacity formulas are given by [41]

$$\mathrm{SISO:} \quad C = B\mathrm{Log}_2 [1 + \mathrm{SNR}] \tag{10.23}$$

$$\mathrm{SIMO:} \quad C = N_R B\mathrm{Log}_2 [1 + \mathrm{SNR}] \tag{10.24}$$

$$\mathrm{MISO:} \quad C = N_T B\mathrm{Log}_2 [1 + \mathrm{SNR}] \tag{10.25}$$

$$\mathrm{MIMO:} \quad C = N_T N_R B\mathrm{Log}_2 [1 + \mathrm{SNR}] \tag{10.26}$$

In Eqs. (10.22), (10.23), (10.24), (10.25), and (10.26), B is the bandwidth, SNR is the SNR, N_T is the number of the transmitting antenna at the input, N_R is the number of receiving antennas at the output.

10.3.9 Bit Error Rate (BER) in Non-terrestrial Networks

During transmission and reception of signals, sometimes the receiver receives bits that the transmitter did not transmit but was introduced into the system due to noise. This results in an error being observed in the transmission and reception of data or information. The rate at which these errors occur during transmission and reception of the signal is called bit error rate. Bit error rate is obtained by comparing the transmitted bits and the received bits to determine if an error occurred and by how much. For example, if transmitted bits are 1001000110 and the received bits are 0111001110, there is an error in the first, second, third, and seventh bits: instead of 1000 in the first, second and seventh positions of transmitted bits, there are 0111 in the first, second, third, and the seventh positions of the received bits. Hence, three errors had occurred; BER is the number of errors divided by the number of transmitted bits. BER = 4/10 = 0.4. Some factors such as noise from transmission channel, system interference, signal attenuation and distortion, and multipath fading affect bit error rate, but it can be improved by applying a channel coding scheme, using slow modulation technique, and strong signal strength if it will not bring cross-talk.

10.4 Results and Discussion

The results are presented here in tabular and graphical form, and the discussions are carried out after each presentation.

Tables 10.1 and 10.2 compare SISO, SIMO, MISO, and MIMO parameters and their bit errors rate for the four different antenna arrangements, with MIMO arrangements having the lowest bit error rate for any given SNR. Therefore, MIMO antenna arrangement performs better than all the other antenna arrangements. At 10 dB SNR, SISO arrangement has the highest bit error rate, indicating its poor performance compared to the other antenna arrangements (SIMO, MISO, and MIMO) (Table 10.3).

We also present the simulation results of the BS antenna tilt angle and how it affects the outage probability of the network. Figures 10.9 and 10.10 show the plot of outage probability against BS antenna tilt angles.

Figure 10.9 shows the network outage probability for the inclusive service scheme against the BS antenna tilt angle. From the graph, the value of the antenna tilt angle for which the outage probability is minimum is equal to about 1°. This value is referred to as the optimal tilt angle. The graph also shows that for the BS height of 20 m and aerial height of 50 m, the optimal antenna tilt angle was about 1°. However, when the BS height doubled (40 m), and the AU height remained 50 m, the optimal antenna tilt angle increased to about 5.5°. So, an increase in the height of the BS increases the optimal value of the BS tilt angle of the antenna.

Table 10.2 A comparison of SISO, SIMO, MISO, and MIMO

S/N	Parameter of interest	MIMO	MISO	SIMO	SISO
1	Throughput	Best	Better than SIMO	Low	Lowest
2	BER	The use of multiple antennas at both ends optimizes BER	Few signal losses as compared to SIMO	Better than SISO	Worst
3	Data transmission	Much diversity of transmitting and receiving data	Good, but not as much as MIMO	Better than SISO	Transmission is from one single point to another
4	Received signal Quality	Best	Gain and signal quality better than in SIMO	The signal is stronger than in SISO	A weak signal is received

Table 10.3 Bit error rate of SISO, SIMO, MISO, and MIMO for various SNRs

	BER			
SNR (dB)	SISO	SIMO	MISO	MIMO
0	0.1451	0.0844	0.0811	0.0405
2	0.1123	0.0500	0.0450	0.0179
4	0.0771	0.0307	0.0253	0.00669
6	0.0631	0.0155	0.0135	0.00199
8	0.0321	0.0082	0.0062	0.00049
10	0.0223	0.0024	0.00281	0.00014

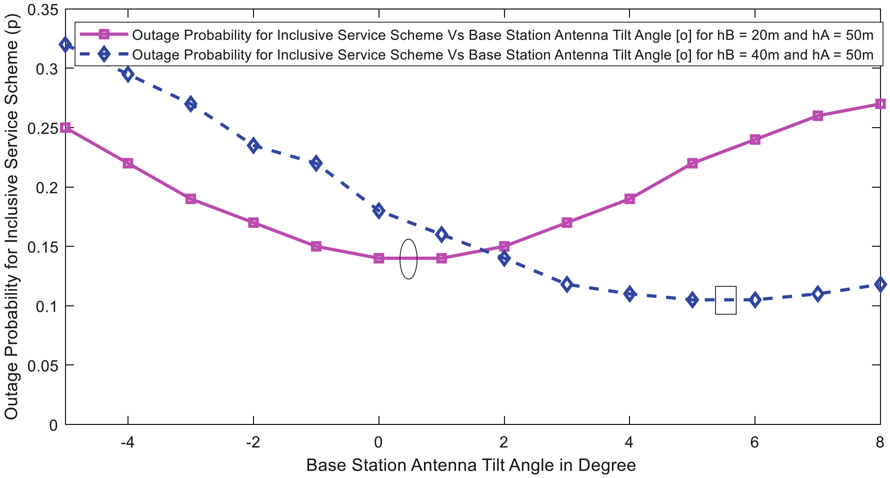

Fig. 10.9 Network outage probability against tilt angle of the antenna

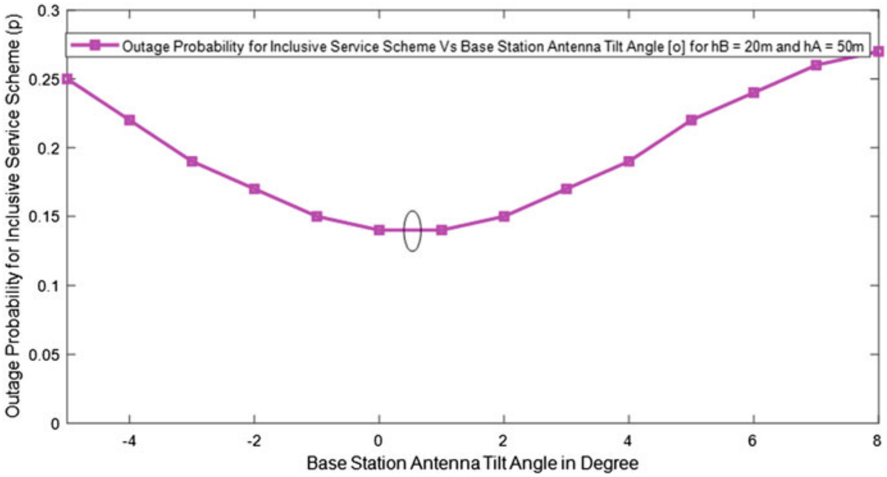

Fig. 10.10 A plot of outage probability against base station antenna tilt angle

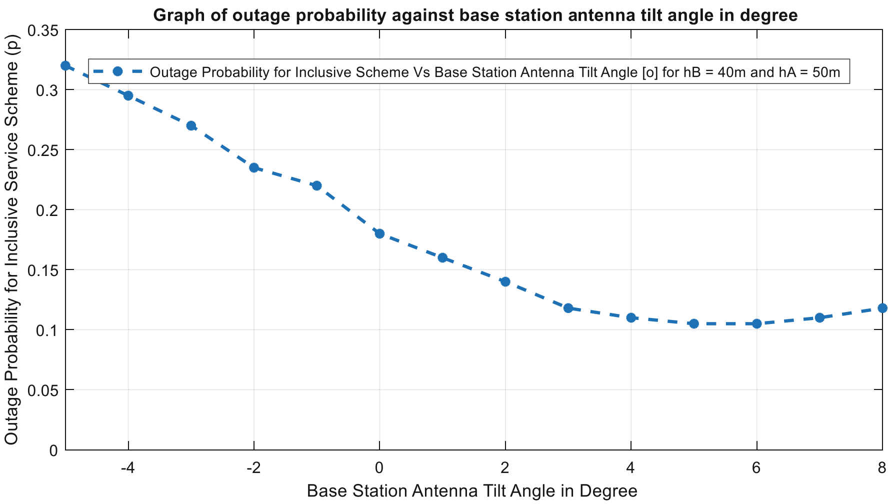

Fig. 10.11 A plot of outage probability against base station antenna tilt angle

An increase in the height of the BS for AUs increases LOS probability between AU and BS while distance path loss decreases. This is, however, different with GSs: an increase in BS height increases the probability of LOS between the BS and GSs, and the path loss also increases.

Figure 10.10 shows the minimum tilt angle for which the outage probability. That minimum tilt angle from the graph is marked with an ellipse.

Figure 10.11 shows the minimum tilt angle for which the outage probability. That minimum tilt angle from the graph is marked with a box.

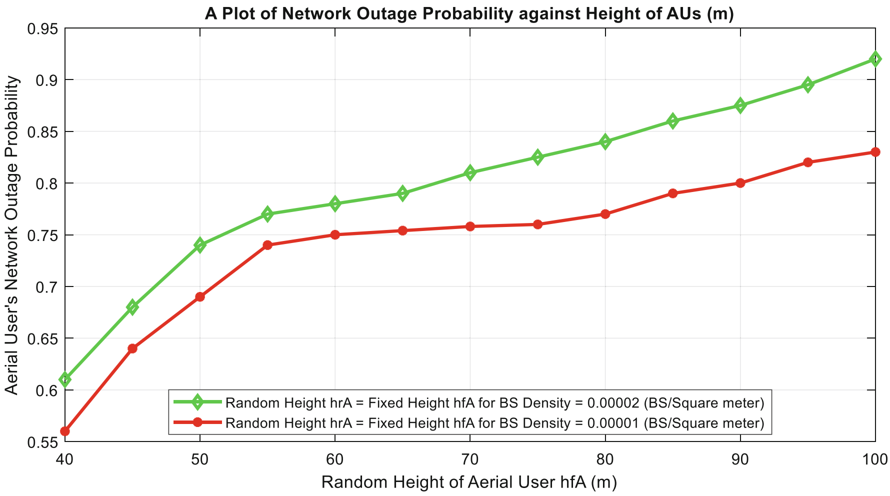

Fig. 10.12 A plot of outage probability of the network against aerial user height (m)

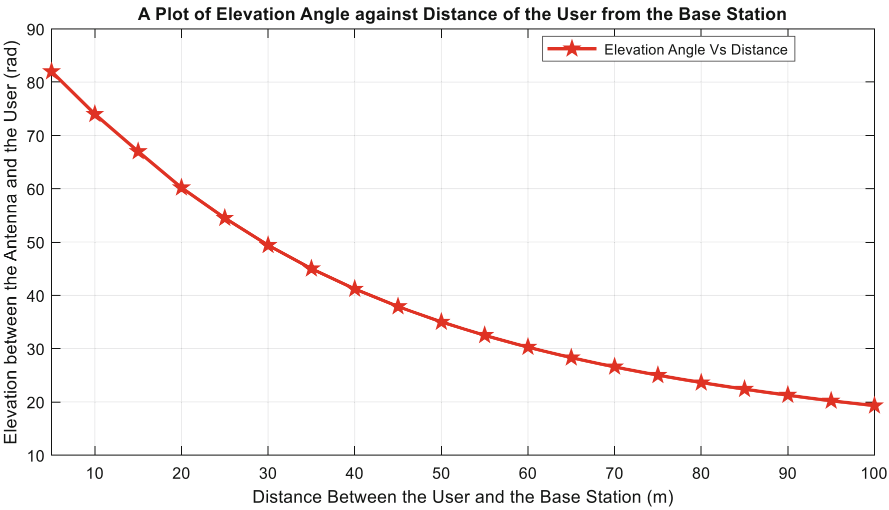

Fig. 10.13 A plot of elevation angle against distance of the user from the base station

Figure 10.12 is a presentation of the network outage probability of aerial users. The graph shows that the fixed height and the random height are different in terms of performance. But the graph shows that optimal height, which makes network outage a minimum is the same for both.

Figure 10.13 shows the angle of elevation between the BS and the user when the user moves away from the BS as the plot indicates clearly, an increase in the distance between the user and the BS decreases the elevation angle.

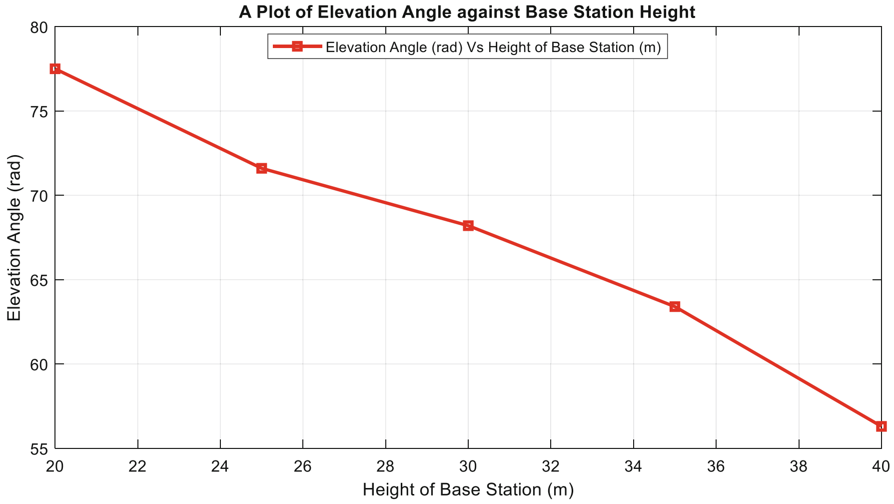

Fig. 10.14 A plot of elevation angle against base station height

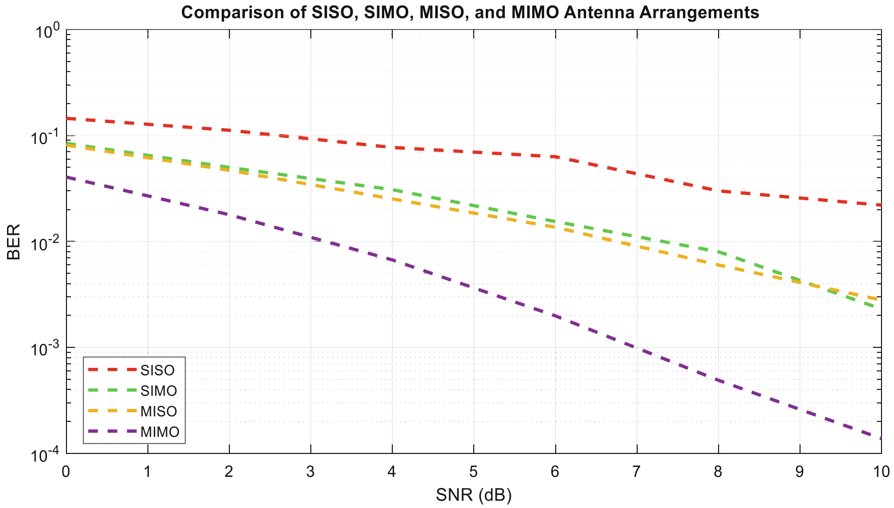

Fig. 10.15 Comparative performance of BER versus SNR of SISO, SIMO, MISO, and MIMO

Figure 10.14 is a presentation of the plot of elevation angle against the height of the BS. And as can be verified from the graph, the elevation angle decreases as the height of the BS increases.

As can be seen from Fig. 10.15, having multiple antennas arranged at the input for transmission of signals and also having multiple antennas arranged at the output for the reception of the transmitted signal reduces bit error rate far better than SISO, SIMOs, and MISO arrangements of antennas. The SISO arrangement is the least in terms of performance. MISO and SIMO arrangements have close range, though MISO performs better.

10.5 Conclusion

This research work presented models to describe the channel and vertical height of UAV in an NTN network. The results have shown that certain optimal antenna tilt angle minimizes network outage probability. It has been shown that an increase in the height of the base station increases the optimal value of the base station tilt angle of the antenna. The work has also shown that for the base station height of 20 m and aerial height of 50 m, the optimal antenna tilt angle was 1°. However, when the base station height doubled (40 m), and the aerial user height remained 50 m, the optimal antenna tilt angle increased to about 5.5°. So, an increase in the height of the base station increases the optimal value of the base station tilt angle of the antenna. This work has also shown the impact of the base station antenna height on both ground and aerial users.

As can be seen from the capacity formulas for SISO, SIMO, MISO, and MIMO (Eqs. 10.23, 10.24, 10.25, and 10.26), the introduction of multiple antenna arrangements either at the input for transmission or at the output for reception or both ends increases the capacity of the system. For example, the capacity of single input multiple outputs (SIMO) antenna arrangement is N_R, which is multiplied by the capacity of the single input single output (SISO) arrangement. For SIMO and MISO, however, if the number of receiving antennas at the output of the SIMO arrangement and the number of transmitting antennas at the input of the MISO arrangement, both will have almost the same capacity.

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Promise Elechi, received his B.Eng and M.Eng degrees in Electrical/Electronic Engineering from University of Port Harcourt, Choba, Rivers State, Nigeria in 2006 and 2011 respectively. He obtained Ph.D. in Electronic and Telecommunication Engineering from the University of Benin, Benin City, Nigeria in 2019. He is a corporate member of the Nigerian Society of Engineers (NSE), International Association of Engineers (IAEng), Institute of Engineering and Technology (IET), and Nigerian Institution of Electrical/Electronic Engineers (NIEEE). He is also a registered practicing Engineer with the Council for the Regulation of Engineering in Nigeria (COREN). His current research interest is on Radio Propagation for Mobile Communications, GSM Technology, Microwave and Millimetre wave Propagation, 5G and 6G, Signal Analysis, and Embedded System. He is currently a Senior Lecturer in the Department of Electrical and Electronic Engineering, Rivers State University, Port Harcourt, Nigeria. Elechi can be reached on: elechi.promise@ust.edu.ng, and +2348035476478.

Kingsley Eyiogwu Onu obtained his B.Tech in Electrical Engineering (Communication Option) in 2011 from the then Rivers State University of Science and Technology (RSUST), now Rivers State University (RSU). His M. Tech degree in Electrical Engineering (Communication Option) was obtained in 2020 from Rivers State University, Port Harcourt, Rivers State, Nigeria. He has published articles in reputable international journals. His research interests are in signal processing, network optimization, microwave communication and antenna design. He is currently a PhD student in Rivers State University, Port Harcourt, Rivers State. He is married with children.

Chapter 11
Design and Performance Issues in UAV Cellular Communications

Christopher Akinyemi Alabi, Oluwaseun Olayinka Tooki, and Agbotiname Lucky Imoize

Abstract The development of the 5G wireless network and its application in various Internet of Things (IoT) use cases have necessitated the exploration of new communication paradigms. With its unique advantages of high altitude and mobility, unmanned aerial vehicle (UAV) communication is one of such paradigms. Emerging IoT application that adopts UAV communication for their critical operation can quickly become casualties of the ills arising from UAV design and performance challenges. This chapter presents a comprehensive overview of UAV communication, unique attributes, and requirements in a cellular system, focusing on its associated design and performance challenges. We discussed UAV communication requirements and characteristics and reviewed key design considerations for the UAV communication system. The constraints on UAV performance due to the inherent features of cellular communication architecture were also discussed. To investigate the UAV-ground channel characteristics, we carried out a CDL-based channel simulation with ray tracing; we considered three locations with different terrains and building densities as case studies. Finally, we presented a brief review of contemporary advances in UAV communications, from the trending fifth generation to future cellular networks.

C. A. Alabi (✉)
Telecommunication Engineering Department, Faculty of Ground and Communication Engineering, Air Force Institute of Technology (AFIT), Kaduna, Nigeria
e-mail: c.alabi@afit.edu.ng

O. O. Tooki
Electrical and Electronics Engineering Department, Faculty of Ground and Communication Engineering, Air Force Institute of Technology (AFIT), Kaduna, Nigeria
e-mail: o.tooki@afit.edu.ng

A. L. Imoize
Department of Electrical and Electronics Engineering, Faculty of Engineering, University of Lagos, Lagos, Nigeria

Department of Electrical Engineering and Information Technology, Institute of Digital Communication, Ruhr University, Bochum, Germany
e-mail: aimoize@unilag.edu.ng

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Keywords Cellular communication · UAV communication · UAV design · UAV performance · Size · weight · and power (SWAP) · Control and non-payload communication (CNPC) · Payload communication (PC) · Cellular-connected UAV · UAV-assisted cellular · Line of sight (LoS) · UAV channel model · Fifth generation (5G) · Multiple input multiple output (MIMO)

11.1 Introduction

11.1.1 Background on Unmanned Aerial Vehicle (UAV)

Unmanned aerial vehicles (UAVs), also referred to as drones, are airborne objects that can be operated by a remote pilot or, in some cases, allowed to fly autonomously. At the initial stage of development, UAVs were used mainly in the military for surveillance of hostile environments and offensive attacks. Today, UAVs find application in civil operations such as environmental condition monitoring (measurement of air contamination and surveillance of forest area), safety (airspace monitoring; natural disasters, such as volcano risk assessment and situation tracking), management of extensive facilities (water bodies, power lines, and oil/gas pipelines), agriculture, and aerial shooting in film production [1]. The upsurge in the applications of UAVs is expected to generate corresponding economic benefits for various stakeholders. As projected in [2, 3], the unmanned aerial industry will produce over $13 billion in revenue for the United States' economy from 2017 and accrue to approximately $82.1 billion by 2025.

The diverse applications and use cases of UAVs have brought about corresponding variations in their design features and performance requirements. Drones can be deployed individually or (for some performance benefits) as a group. In group deployment, the set of coordinated UAVs is referred to as a swarm or a fleet. Regardless of the application, deployment, or design of UAVs, it needs to be sustained in the air and must communicate with associated terminals [4]. Endurance and communication are two core activities of the UAV that require energy, which is usually inadequate. Hence, for optimal UAV operation and effective service delivery, design and performance issues must be given due considerations

11.1.2 Wireless Technology Options for UAV Communication

Communication is an essential requirement for UAV operation and use. By reason of UAVs' mobility characteristics, only wireless communication technologies can be used practically to achieve the required connectivity. As highlighted by [7], four wireless technology candidates can be adopted individually or jointly for UAV communication. These technologies are as follows:

(i) Direct link over ISM band

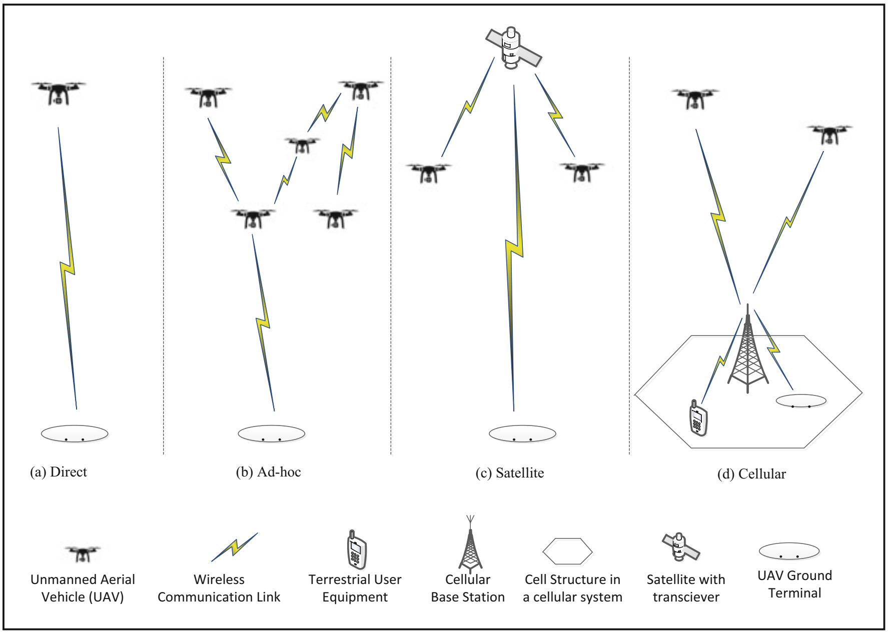

Fig. 11.1 A pictorial view of wireless communication options for UAVs

(ii) Satellite communication
(iii) Wireless ad hoc network
(iv) Cellular communication network

Figure 11.1 provides a pictorial view of the various wireless communication options available for UAV communication.

Communication can occur between the UAV and its ground pilot using the direct link over the Industrial, Scientific, and Medical (ISM) band. This communication is over the unlicensed band and is common, cheaper, and less complex. There are, however, numerous limitations. First, the UAV-ground connection is possible only when line of sight (LoS) connectivity between the UAV and ground terminals. The LoS requirement for connectivity significantly limits the operational range of the UAV. Secondly, the unlicensed spectrum is prone to interference and open to jamming attacks. Hence, direct communication over an unlicensed frequency band is not suitable for wide range, reliable, secure, and large-scale UAV deployment.

Satellite communication holds several advantages for UAV communication. First, it offers beyond LoS UAV-ground communication, supporting an extended range and diversity of UAV deployment and operation. Second, UAVs can be operated from anywhere with satellite communication, including remote areas and above the sea where terrestrial network coverage is unavailable. However, there are several challenges in using satellites for UAV communication. One is the issue of propagation delay due to the great distance associated with satellite-to-earth communication. Due to this shortfall, satellite communication is not suitable for time-critical UAV applications. In addition to the high operational cost of satellite communication, another challenge is the bulk that satellite communication equipment (such as dish antenna) potentially constitutes to the UAV. Generally, UAVs are already limited by their size, weight, and power (SWAP). Any extra bulk will require more energy.

The adoption of ad hoc networking is another viable option for UAV communication. An ad hoc network is a self-organizing network without any central control infrastructure for peer-to-peer communication among devices. It is deployed mainly among mobile devices and in scenarios or environments where conventional communication infrastructure cannot be set up easily. In an ad hoc network setup, two far apart communicating nodes require one or more relaying devices in between. This requirement constitutes end-to-end delay and is not spectrum efficient. It also increases the total amount of energy consumed for node-to-node communication.

Cellular communication technology, which presents some desirable advantages for UAV communication, is shown in the next section.

11.1.3 Brief Description of Cellular Communication System

Cellular communication is a wireless communication technology used majorly for mobile device connectivity. It involves the partitioning of large geographical areas into smaller units, called cells, for optimal spectrum utilization and effective coverage. Each cell is equipped with one or more stationary transceivers, the Base Station (BS). Mobile communicating devices, generally called User Equipment (UE), are connected to the cellular network through the BSs. Each cell is allocated several radio frequencies for UE communication with the BS. The frequency channel assignment is done to accommodate a greater number of simultaneous subscribers. The use of limited communication channels to accommodate the needs of a large number of users is achieved primarily through the reuse of allocated channels or frequencies. Frequency reuse is a major element of the cellular communication system. The frequency reuse model allows the same set of frequencies to be used repeatedly within a given coverage area [5].

Cellular technology has been evolving steadily, starting with the 1G (1st Generation) cellular network to 2G, 3G, 4G (LTE), 5G and beyond.

11.1.4 Cellular Communication Option for UAV

As presented in the preceding sections, every wireless technology option for UAV communication has inherent benefits and challenges. However, the cellular system has proven to be a more viable and readily available alternative. The UAVs can be termed cellular-enabled when connected to the cellular system for communication purposes. Cellular-enabled UAVs enjoy greater ease of deployment and cost-effective operation as they take advantage of already existing cellular network infrastructure. The ubiquitous access to the cellular network provides a wider operational range for the command and control of UAVs. There is no need to deploy additional infrastructure for coverage [6]. Cellular connectivity can also boost UAV operational safety and advance the delivery of efficient flight plans and tracking the locations of the UAV. Further description of the cellular-enabled UAV is presented in the next section.

11.1.5 Chapter Contribution and Outline

This chapter presents a comprehensive overview of the unique attributes and requirements of UAV communication in a cellular system with a focus on its associated design and performance challenges.

The subsequent parts of this chapter are outlined thus: Sect. 11.2 discussed UAV communication requirements and characteristics and reviewed vital design considerations for UAV communication systems. Section 11.3 expounded critical design and performance issues in cellular UAV communication. We also discussed some strategies for performance improvement. Section 11.4 identified applications of UAVs with practical examples and use case scenarios. We conclude the chapter in Sect. 11.5 and propose the adoption of relevant 5G and beyond 5G technology solutions for UAV communication design and performance improvement.

11.2 Literature Review

11.2.1 UAVs in Cellular Communication System

The incorporation of UAVs into the cellular communication system can be considered under two different paradigms. One paradigm is the consideration of UAVs as a new set of aerial UEs accessing the cellular network from altitudes higher than those of terrestrial UEs. As stated above, UAVs that ride on the cellular network to achieve their communication needs can be referred to as cellular-connected UAVs [7]. UAVs can be integrated into the cellular network to provide communication support as relays or aerial BSs in another paradigm. Such use of UAV can be termed UAV-assisted cellular communication.

11.2.1.1 UAV-Connected Cellular Communication

In the deployment scenario exemplified in Fig. 11.2, UAVs operate as aerial UEs alongside other terrestrial UEs in a cell based network. The UAV communication with fellow UAVs and the ground control terminal is via the cellular infrastructure.

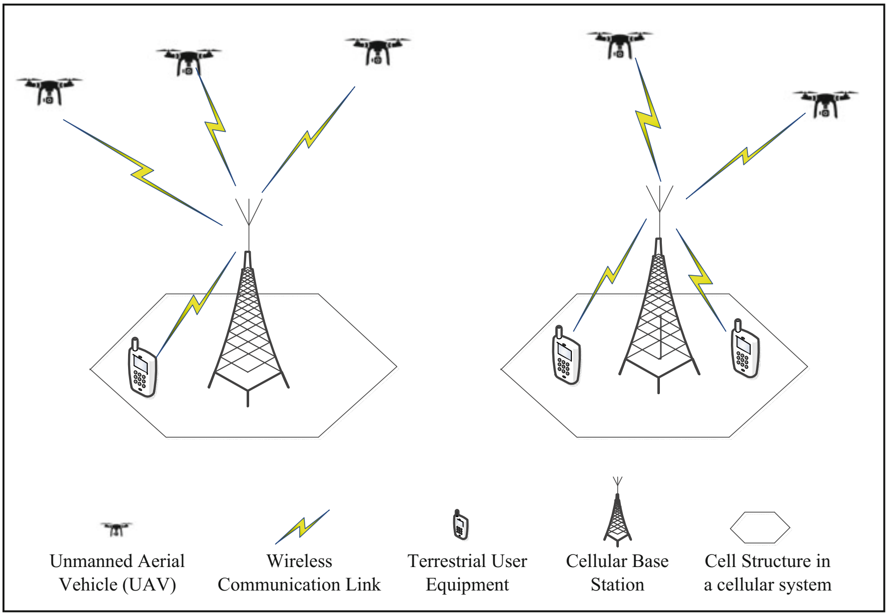

Fig. 11.2 Illustrating UAV-connected cellular communication

Cellular enabled UAVs system suffers from coverage-related issues in areas such as sea, desert, forest, and the remote regions where it is uneconomical to deploy cellular equipment. However, this limitation can be compensated for by incorporating other wireless technologies like direct links and satellite networks into future UAV communications systems [7].

11.2.1.2 UAV-Assisted Cellular Communication

A new paradigm of a UAV application is its use to support subsisting communication facilities. Such a setup can be referred to as UAV-assisted communication. Taking advantage of the favourable LoS link between the UAV and its ground station as well as the better Quality of Service (QoS) obtainable due to its 3-dimensional (3-D) mobility [8], UAVs find application as aerial BS to provide support for existing wireless communication networks. Aerial BSs are particularly useful for coverage extension, capacity enhancement, reliability improvement, and energy management in cellular networks (Fig. 11.3). Communication equipment mounted on UAVs can be deployed for quick service restoration after a complete or partial facility collapse in crowded areas such as stadiums during sporting activities or natural mishaps [6].

UAV-Assisted Communication enables operators to respond rapidly with supplementary wireless connectivity in cases of emergency, involving breakdown of existing terrestrial network, thereby offering the communication platform required

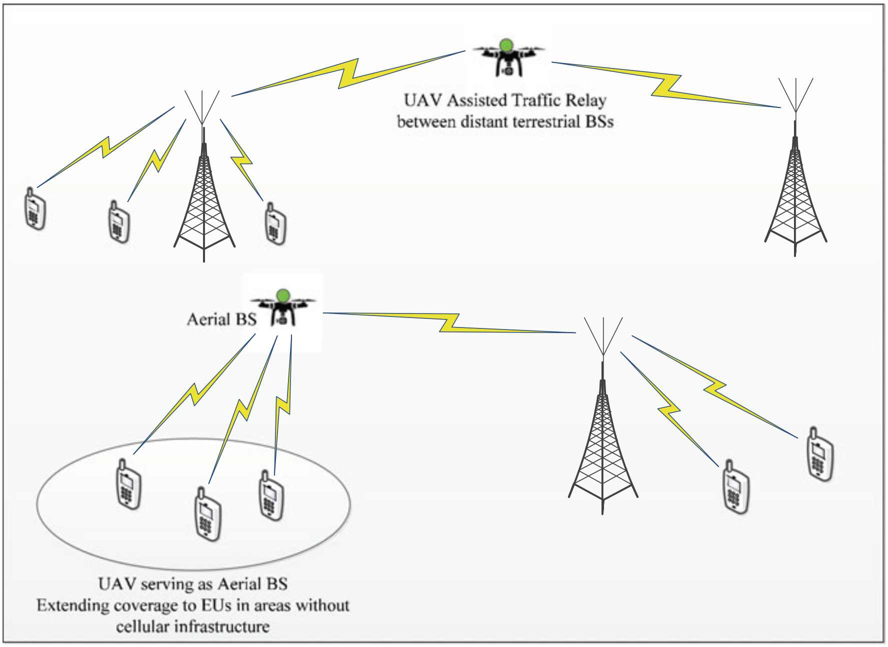

Fig. 11.3 UAV-assisted cellular communication scenario

for relief activities and support. In terms of infrastructure, UAV networks are less expensive than ground BSs because cables and towers are done away with [9].

The UAV-assisted aerial BS suffers from interference with neighbouring cells due to UAV mobility compared with terrestrial wireless networks, hence, the need to develop an advanced interference management system for UAV-assisted aerial BS.

11.2.2 UAV Communication Requirements

The successful operation of the UAV requires seamless wireless communication between the UAV and its associated system components. These include the ground terminal from which command and control are issued; the air traffic control (ATC) unit which ensures that the UAV operates safely in the air space; and other UAVs.

UAV communication can be categorized into the following:

(i) Payload communication (PC)
(ii) Control and non-payload communication (CNPC)

PC is the communication that fulfils the purpose of deploying the UAV. It is application-dependent. Its requirements, therefore, depend on the specific task or

Table 11.1 3GPP communication requirements for UAV PC and CNPC [7]

S/N	Class of communication	Data rate requirement	Reliability in packet error rate	Latency
1	CNPC	60–100 kbps (up and down link)	10^{-3} PER (up and downlink)	50 ms (DL)
2	PC	Up to 50 Mbps	Vary with application	Same as ground/terrestrial users

function the UAV is expected to undertake in the air. For instance, the transmission of aerial video to the ground station is PC for a UAV used in a video streaming application. PC usually requires a higher transmission data rate compared to CNPC.

The CNPC is comprised of all forms of communication required to ensure a secure, reliable and controlled UAV flight operation. Other functions of CNPC includes Telemetry, Command and Control (C&C), Navigation, and ATC relay for monitoring of flight altitude, update on flight command, maintaining a safe distance from obstacles and relaying of information to prevent collision with conventional aircraft [2, 7]. Although CNPC requires a lower transmission data rate, usually in the order of a few hundred kilobytes/s, its security and reliability requirements are generally higher. The communication requirements for both PC and CNPC as specified by 3GPP are summarized in Table 11.1. The International Telecommunication Union (ITU) has categorized the CNPC into three, namely:

(i) UAV Command and Control Communication
(ii) "Sense and Avoid" Support Communication
(iii) Air Traffic Control (ATC) Relay Communication

From the preceding, it is clear that the CNPC is critical to the safe operation of UAVs; hence, CNPC link failure must be avoided to avert unwanted and possibly catastrophic consequences that may arise from failed UAV coordination and control. The International Civil Aviation Authority (ICAO) has mandated that CNPC be transmitted over a protected aviation spectrum to avoid possible interference and ensure reliable communication. In line with this mandate, the International Telecommunication Union proposed the allocation of 34 MHz terrestrial and 56 MHz satellite spectrum to CNPC application. Also considered was the possibility of spectrum sharing with Long Term Evolution (LTE), and 5G was also considered, provided the interference between aerial and ground users is efficiently managed.

11.2.3 UAV Link Types and Characteristics

UAV links can be categorized based on the type and location of the terminals involved. The link types and their characteristics are presented in Table 11.2:

Table 11.2 UAV link types with their characteristics and channel model [7]

S/N	Link type	Characteristics	Channel model
1	UAV-UAV	Characterized by a clear air space relatively close range (moderate distance)	Free-space path-loss model
2	UAV-GBS	The presence of LoS components characterizes the link	Rician or Nakagami-m SsF model
3	UAV-GT	The presence of LoS components characterizes the link	Rician or Nakagami-m SsF model

(i) Ground BS-to-UAV link
(ii) UAV-to-Ground terminal link
(iii) UAV-to-UAV link

11.2.4 UAV Communication Channel Model

Channel modelling of UAV communication systems is essential for the evaluation and performance analysis of the system [7, 10]. In modelling the UAV communication channel, consideration must be given to some unique propagation conditions, including high altitude and 3-D propagation space. The high altitude provides a favourable LoS condition for the UAV-to-ground communication link.

The variation in strength of a channel, observed over time and frequency domains, can be classified into two; Small-scale Fading (SsF) and Large-scale Fading (LsF). SsF occurs when multi-path signals between transmitter and receiver experience constructive and (or) destructive interference. In contrast, LsF occurs mainly as a result of path-loss and obstructions along signal path. Since the LoS UAV-to-ground communication channel has significant LoS component, it can be modelled after the Nakagami-m or the Rician SsF model. Owing to the complex nature of LsF channel components, including those of UAV-ground link; several customized models have been developed in literature for their modelling [7]. The proposed models take parameters such as transmitter-receiver distance, UAV altitude, angle of elevation and probability of LoS condition into account. Based on the parameter of interest, we can classify the various LsF models for UAV-ground communication into three:

(i) Free space channel model (distance-dependent)
(ii) Altitude/angle-based channel models
(iii) LoS probability-based channel models

11.2.4.1 Analysis of UAV Channel Model

UAV communication channel modelling follows the Terrestrial Communications (TC) channel modelling convention but with special consideration for altitude. In UAV communications, transmitters and receivers are placed higher than TC links. UAV height is an important factor for the establishment of LoS connectivity; at higher UAV altitudes, chances of LoS connectivity are higher because the effects of shadowing and reflection are negligible. However, lower altitude have the advantage of reduced path loss.

Note As UAV altitude increases, the expected channel power first increase due to its greater chance of LoS connection; however, as the altitude increases further, the channel power decreases due to the increase in link distance and path loss. Hence, a balance between attaining LoS connectivity with increased altitude and path-loss must be given due consideration in the UAV channel modelling

In analysing the UAV channel model, we begin with the general wireless channel model which is given as

$$R = [\chi(d)h]^{\frac{1}{2}} \tag{11.1}$$

where

$\chi(d)$ is the large-scale channel fading resulting from path loss occasioned by distance and shadowing by large objects like hills and buildings.
d stands for the distance between the transmitter and the receiver.
h is the small-scale channel fading.

The model used for the path-loss calculation $\chi(d)$ at a high altitude of UAV [11] is described by the equation given below

$$\chi(d) = -P_{\mathrm{L}}(d)\,[\mathrm{dB}] \tag{11.2}$$

where

$$-P_{\mathrm{L}}(d)\,[\mathrm{dB}] = -\left[10\alpha\left(\log_{10}\right)d + \kappa_0 + \kappa_\sigma\right]\mathrm{dB} \tag{11.3}$$

P_{L} = Path-loss between a receiver and transmitter separated by a distance d (in metres).
α = exponent of the path-loss (with values ranging between 2 and 6) [7].
κ_0 = Path-loss at the point of intercept when the distance is 1 m.
κ_σ = Gaussian random variable, it accounts for the effect of shadowing.

This was modelled using normal distribution and root-mean-square variation σ.

In order to accurately model the UAV communication channel, a good knowledge of the wireless parameters involved is essential. The channel modelling of UAV-ground communications can be categorized into three based on the choice of parameters considered. The three categories are as follows:

(i) Distance-based/free-space channel model
(ii) Altitude/angle-based channel model
(iii) LoS probability-based channel model [7]

While the free-space channel modelling uses the Friis equation, the other two are briefly discussed in the next sub section.

11.2.4.2 Altitude/Angle-Dependent Channel Model

Case I: UAV at high altitude
At a high altitude of the UAV, when the effects of SsF and shadowing are absent, the free-space channel model is expressed as

$$\chi(d)^{-1} = \left(\frac{4\pi d}{\lambda}\right)^2 = \frac{1}{\overline{\chi}_0 d^2} \tag{11.4}$$

λ is the wavelength of the carrier and $\overline{\chi}_0{}^{-1} = \left(\frac{4\pi}{\lambda}\right)^2$ represents channel power with reference to a distance of 1 metre.

It is important to state that the above free-space model is more appropriate for use in rural areas where LoS link exist between UAV at high altitude and the ground station.

Case II: UAV at low altitude
At the low altitude of UAV, channel parameters are dependent on both altitude and elevation angle. These parameters are factored into (11.2).

- *Path-loss modelling*

Due to the great distance involved, the UAV-to-Ground BS communication channel is subject to path loss. The path-loss model for the distance-dependent terrestrial cellular network is adopted. The path-loss model considered three categories of links; LoS, Non-Line of Sight (NLoS), and SsF. The SsF accounts for less than 3% of the channel condition [8]. An assumption is made by ignoring the third category since the path-loss depends mostly on the first two categories. The path-loss Γ_ε due to vegetation and citified environment is given as

$$\mathrm{PL}_\varepsilon = \Gamma_\varepsilon + \mathrm{FSPL} \tag{11.5}$$

where PL_ε is the Air to Ground path-loss, Γ_ε is a constant value at various frequencies and urban environments relative to LoS and NLoS; FSPL is the Free Space Path-loss calculated using Friis equation:

$$\mathrm{FSPL} = 20\log_{10}\left(\frac{4\pi f_c D}{C}\right), \tag{11.6}$$

f_c is the frequency of the carrier in Hertz (Hz), C speed of light in free space (approximately 3×10^8m/s) and D is the distance between the UAV and the ground controller.

The chances of having LoS for device j hang-on the altitude of the UAV cell h_m, Where m is the horizontal distance between the UAV and the jth user [8], in which

$$N_j = \sqrt{\left(u_D - u_j\right)^2 + \left(v_D - v_j\right)^2} \tag{11.7}$$

The location of the jth device is given as (u_j, v_j) and UAV cell stationed at (u_D, v_D) The angle of elevation ϕ is given as

$$\phi = \mathrm{Tan}^{-1}\left(\frac{h_m}{N_j}\right) \tag{11.8}$$

11.2.4.3 LoS Probability-Based Channel Models

Case I The probability of LoS [12] is expressed as

$$P_{\mathrm{LoS}} = \frac{1}{(1 + s\,\exp(-t\,(\phi - s))}, \tag{11.9}$$

where s and t are constant, S-curve parameters, which depend on the nature of the urban environment and ϕ is the angle of elevation between the UAV and the user in degree. The values of S-curve parameters s, t and u agree with ITU-R (International Telecommunication Union-Radio-Communication Standard Sector) recommendation for urban areas. This information can be obtained from Table 11.3.

Table 11.3 ITU-R recommended S-curve parameters

Environment	S-curve parameters		
	s	t	u
Sub-urban	0.1	750	8
Urban	0.3	500	15
Dense urban	0.5	300	20
Highrise urban	0.5	300	50

Case II The probability of NLoS is defined by [8] as

$$P_{\text{NLoS}} = 1 - P_{\text{LoS}} \tag{11.10}$$

The sum of the path-loss is given by [12] as

$$\begin{aligned} P_{(\text{FSPL+LoS+NLoS})} &= \left(20\log_{10}\left(\frac{4\pi f_c D}{C}\right) + \Gamma_{\text{NLoS}}\right) + \\ ((\Gamma_{\text{LoS}} - \Gamma_{\text{NLoS}})\, P_{\text{LoS}}) &+ \left(\frac{\Gamma_{\text{LoS}} - \Gamma_{\text{NLoS}}}{\left(1 + s\exp\left(-t(\phi - s)\right)\right)}\right) \end{aligned} \tag{11.11}$$

where Γ_{LoS} and Γ_{NLoS} (measure in dB) are path-loss linked to LoS and NLoS links, respectively.

11.2.5 Traditional Versus Next-Generation Cellular UAV Deployment

Generally, all connected users in a cellular system, including UAVs, communicate on an allocated frequency and time. The dynamics of this resource (time/frequency) schedule depends on the system setup.

Traditional Cellular UAV Deployment The traditional cellular UAV deployment represents deployment approaches that have been in use over time. The infrastructure in use consists of a BS with sectorial antennas which allocates a physical resource block (PRB) to each user, thereby, exposing nearby users to substantial risk of interference.

Next-Generation Cellular UAV Deployment This exemplifies next-generation deployments in which multiple antennas, popularly called Multiple Input Multiple Output (MIMO) technique is used to enhance spectral efficiency of the wireless channel. In this deployment scenario, multiple users are served on a single PRB with the help of massive MIMO antenna array with beamforming. This approach helps to boost each user's signal power while reducing the tendencies of interference between neighbouring users.

The traditional cellular network architecture uses a three-sector bases station setup in single-user mode. This implies that each frequency-time resource is scheduled to one user at a time, which tends to generate strong interference towards nearby users. On the other hand, next-generation cellular networks use massive MIMO cellular deployment, which operates in the multi-user mode where multiple users are scheduled for every frequency-time resource. Multiple users are served on each resource block (RB) through MIMO arrays and digital beamforming, increasing the valuable signal power observable at the user end and mitigating the interference on nearby users.

The choice of cellular setup employed affects the cell selection process and the overall performance of the connected UAV. A comprehensive study by [13], which compares both traditional cellular architecture and the massive MIMO deployment showed, revealed the following:

(i) At high altitudes ($\geq$75 m), UAV Cell selection in the traditional network is predominantly driven by the secondary lobe of each BS's antenna pattern and not by the path loss difference between neighbouring BSs. UAVs, therefore, are more likely to associate with BSs that are farther away than with those located nearby.
(ii) Low flying UAVs (at 1.5 m) in a traditional network setup can attain the specified 100Kbps CNPC target rate. However, as the height increases, LoS conditions get more favourable and transmissions from more cells become accessible to the UAV. Hence, at the height of 50 m, reliability drops to 35%, while at higher altitudes, the reliability degrades considerably to 2% at 150 m and 1% at 300 m.
(iii) The massive MIMO deployment, when tested, offered better performance as it can reliably support the UAV's CNPC channel. 87% of cases, the required 100Kbps was achieved even at 300 m. When tested without pilot reuse three and contamination, reliability of 96% was achieved. This achievement can be explained by the massive MIMO antenna setup providing greater carrier signal strength, mitigating interference and offering spatial multiplexing gain.
(iv) Under the massive MIMO deployment, the GUEs' pilot signals are prone to substantial contamination from overlapping pilots produced by the UAVs. To protect the GUEs, a power policy for UAV uplink (UL) transmission is necessary.

More gains have been recorded from MIMO deployment for wireless communication. In the work of [14], three MIMO-based channel models were proposed. They are; the physical, analytical, and the standardized channel models. The MIMO technology was used to achieve some enhancement in system capacity and coverage through the simultaneous and efficient allocation of multiple users to a spatial channel. With the technology, QoS is enhanced to meet ever-increasing demand for data and high network availability.

11.2.6 Unique Considerations in UAV Communication System Design

Whether UAV operate as aerial UE or mobile BS in the cellular system, the communication challenges and corresponding design considerations are similar. The unique features and communication requirements of UAVs necessitate a shift in the design consideration in both the cellular system and the UAVs. Some design concerns are has highlighted [2]:

11.2.6.1 LoS Condition at High Altitude

UAVs are unique cellular users as they can travel high up into the sky. At high altitudes, the UAV-to-ground communication channel is not encumbered with obstructions such as trees and buildings, as with terrestrial users [5]. Hence, they enjoy a favourable LoS propagation condition with multiple BSs, including their serving BS. Due to this LoS advantage, UAVs are prone to interference. They experience interference by signals from neighbouring BSs during downlink transmission and interfere with terrestrial UEs during their UL transmission.

11.2.6.2 UAV Three-Dimensional Operational Space

UAVs operate in 3-D space, and they can move upward and downward just as they can move forward and backwards. The consideration of the 3-D motion capability of UAVs mostly concerns the design of BS antennas. Most cellular BSs have a directional antenna that propagates horizontally in two dimensions across three sectors. The antenna tilt is usually downwards to cater to the Ground UE (GUE) and avoid inter-cell interference [5]. This antenna model was not designed to favour aerial users such as UAVs particularly. Therefore, modifications to the antenna designs are required to ensure that UAVs are sufficiently accommodated in the cellular communication ecosystem.

11.2.6.3 UAV-Ground Interference

UAV-to-ground communication usually causes serious interference to the existing TC systems due to the strong LoS component in the link. The coexistence of several wireless technologies on UAVs' operating band has resulted in a shortage of radio spectrum for UAV applications. This has resulted in competition for spectrum utilization, causing spectrum want for UAV communication [10]. Some regulated bodies have proposed cognitive UAV communication techniques. This network architecture allows increased spectrum efficiency among UAV and other traditional cellular devices operating in the same band of frequencies [15].

Due to its LoS advantage at high altitude, UAV UL transmission – UAV-to-terrestrial BS – could generate interference to several neighbouring BSs [13]. As the number of airborne aerial UEs increases in a cellular system, terrestrial UEs experience degradation in their UL throughput. In the same vein, when transmitting downlink from serving BS to the aerial user, the airborne UAV experiences interference from neighbouring cell's BSs due to its LoS advantage. With downlink interference, the amount of resources such as power required to receive the BS signal also increases, increasing the cost of communication between UAV and its serving BS [16].

11.2.6.4 Asymmetric Traffic Dimension (DL/UP)

In a typical cellular system comprising terrestrial UEs and BSs, the downlink traffic is usually dominant in terms of transmission data rate and power compared with the UL. On the other hand, cellular-connected UAVs typically require a higher UL data rate depending on the application. Video streaming UAVs, for instance, require a considerably high data rate at the UL. For the UAVs, mission-specific information is transmitted from the UAV to terrestrial BS in the UL, while the downlink is mainly for UAV command and control traffic which does not require much data rate. Hence, to support UAV communication in existing LTE system, 5G and other next-generation cellular technologies must factor in the unique asymmetric traffic requirement of UAVs.

11.2.6.5 High UAV Mobility

High UAV mobility requires frequent handover from serving terrestrial BSs. The unique features of UAV mobility have stretched the conventional handover strategies in the cellular system to their limits. The handover rate and coverage probability of UAVs are affected by their displacement in space and by vertical motions. UAVs that exhibit frequent vertical movement and switch in directions have low handover rates and probability [17].

11.3 Design and Performance Issues in Cellular UAV Communication System

11.3.1 Design Standards and Regulations for UAV Communication

The ICAO has mandated that critical UAV communication, CNPC, be transmitted over a protected aviation spectrum [2]. Also, to provide ample communication spectrum to match the expected rise in UAV uses and applications, the ITU has earmarked a maximum of 34 MHz terrestrial spectrum and 56 MHz satellite spectrum to support UAV communication. To achieve this, the 5030–5091 MHz C-band spectrum was released for UAV CNPC at the World Radiocommunication Conference (WRC-12). Years later, the WRC also agreed that the spectrum originally assigned to networks served by geostationary satellites be harvested and used for CNPC in UAV operation [18].

According to 3GPP, UAVs can fly up to a maximum altitude of 122 m (400 ft), higher than buildings, for safety reasons [3].

11.3.2 UAV Design and Performance Challenges

Some of the challenges facing the performance of UAV-assisted wireless communication include LoS conditions, aerial-to-terrestrial interference, Quality of Service (QoS), SWAP constraints, and Degree of Freedom (DoF). Integrating UAVs into 5G and next-generation cellular networks is another challenge. Channel characteristics of UAV-assisted communication systems vary with UAV elevation/height. Hence, system designers in UAV communication must give special consideration to networking and interference management of the system.

11.3.3 Size, Weight, and Power (SWAP) Design Issues

UAV SWAP are key factors that contribute significantly to the performance of UAVs. An important goal in UAV design is to achieve small-sized, lightweight, and power-efficient aerial vehicles. Depending on the application, the SWAP requirements of UAVs vary. For example, a package delivery UAV is likely bigger and heavier than one built for surveillance. Monitoring may require more energy as it is expected to endure longer in the air. Regardless of the application, every UAV must be enabled to communicate control and payload information to the appropriate terminals. Hence, some communication accessories need to be attached or built into the UAVs. UAV-borne communication equipment contributes to the overall weight of the UAV system and increases the energy needed for UAV propulsion and sustenance. UAVs' SWAP constraints impede computational, endurance, and communication abilities [6].

The amount of energy storable by flying vehicles is finite and dependent on its battery capacity. Inadequate battery capacity is a major technical issue associated with contemporary UAV applications. The battery capacity of a medium-sized UAV limits its travel distance and mission duration. The mission duration of any operational UAV is limited to its energy storage capacity. The energy source and energy management strategy also play essential roles in determining the performance of the UAV. There are two viable alternatives to increasing the endurance of UAVs. Increasing the battery capacity is one option. This option comes with an attendant increase in weight for the UAV. Another option is to provide an external power bank or source from which the UAV battery can be charged; this can either be done using wired or wireless approach. UAV mobility restriction during energy replenishment is a limitation for the wired technique. On the other hand, the wireless method provides better freedom of movement; UAV gets charged wirelessly without having to travel to a fixed charge location [19]. The development of an efficient energy supply system for UAVs and the issues associated with UAV battery capacity constitute open areas for research exploration and further study.

The insufficient availability of energy hinders both the endurance and performance of the UAV system [20]. The energy required for UAV-aided communication can be grouped into energy for propulsion, the one necessary for UAV to move freely in the air, and the other needed for the communication system. Energy sources for UAV can either be batteries, fuels, or solar energy.

The limited onboard energy severely reduces a UAV system's performance and operational endurance. This problem of limited energy can be solved using two approaches; energy replenishment and energy management. These approaches aim to achieve a desirable level of UAV operation with minimum energy. A power drained UAV is scheduled to leave its operational area for energy replenishment at the source in the energy replenishment scheme. When away, a nearby UAV can be repositioned to stand in for the power drained UAV pending its returns [19]. The best time for energy replenishment in cellular coverage applications is the off-peak period (night), when there is less traffic.

11.3.4 Energy Management Techniques for UAVs

Energy management aims at reducing the UAV's energy consumption for propulsion and cellular communication. Energy consumption through propulsion can be reduced by avoiding unnecessary and energy-consuming UAV movements and manoeuvring. In the case of energy expended for communication purposes, energy management can be achieved by optimizing the signal processing and the communication circuitry for greater efficiency [6]. UAV can be connected to conventional external power supplies for charging using a cord. However, there are wireless options for charging which can be used to extend UAV's endurance. Some of these wireless techniques are discussed in this section.

11.3.4.1 Wireless Techniques for UAV Energy Replenishment

The charging of UAVs can be carried out using wireless technology. This technology can be divided into electromagnetic fields (EMF) and non-EMF. In the former, EMF is the energy source or the means of transporting energy to the UAV. Other means of energy transfer besides EMF are adopted [19].

11.3.4.2 EMF-Based Energy Replenishment

The EMF in the influence zone of the current-carrying conductors of high-voltage transmission lines has been proven to possess sufficient energy to recharge the battery of a medium-sized UAV through a technique known as wireless power transfer (WPT). This technique is divided into two types: inductive wireless power transfer (IWPT) and resonance coupled wireless power transfer (RC-WPT).

The IWPT is often used in power transformers, where two coupled coils wirelessly transfer power to one another via the magnetic core. This principle can be a viable solution for charging UAVs' batteries wirelessly. When a coil is connected to the battery of a UAV and placed at a distance, *d*, close to the high-voltage transmission lines, the EMF causes a voltage to be induced in the coil, which is then used to charge the UAV's battery [21].

Reference [22] estimated the amount of energy required to charge the UAV via high-voltage transmission lines is given as

$$\overline{H} = \frac{I}{2\pi d} \tag{11.12}$$

where $\overline{H}$, is the magnetic field intensity from the distance, d far-off the lines (conductors), and I.

The magnetic flux generated by current-carrying conductors is denoted as

$$\phi = \overline{H} A \mu \tag{11.13}$$

where μ is the magnetic permeability, and A is the cross-sectional area of the conductor coil, connected to the UAV's batteries in reference to the power transmission line's EMF.

11.3.4.3 Non-EMF Energy Replenishment

The following highlights some non-EMF wireless charging techniques for UAVs [19, 24].

(i) *Solar Energy:* Solar energy can also be used to power UAVs. PV arrays can power UAVs during the day while charging their battery for night operations when the useable solar radiation intensity is insufficient. The limitation of PV-powered UAVs is their heavy dependence on solar radiation.

(ii) *Gust Soaring:* Gust's (dynamic) soaring technique was modelled after a seabird called albatrosses. The technique is based on the principle of using wind and airflow to generate energy by altering the UAV's direction to capture uplifting airflow. In this context, UAV captures wind energy converts it to potential energy and then back to kinetic energy, as a result of which energy is obtained from the environment. The downside of this method is that it is influenced by environmental factors such as wind and airflow.

(iii) *Laser Beaming:* UAV-enabled laser beaming is another technique used for powering the airborne craft. The laser, which is powered by an external source of energy, emits a concentrated beam of light at a specific wavelength that is directed to the PV cell, which is mounted on the UAV. This PV cell converts

Table 11.4 Overview of wireless techniques for UAV energy replenishment [19, 22]

S/N	Wireless charging technique	Feature	Limitations
1	Solar energy	Powers the UAV using solar-charged photovoltaic (PV) array	It relies solely on sun radiation which may not be available at all times and in all locations
2	Gust's soaring	UAVs position to harness wind energy from the environment	It is dependent on environmental conditions, which are largely unpredictable
3	Laser beaming	UAVs are powered by PV cells which have been charged using laser beam power the charge PV cells	Laser is risky to human health

the laser beam into usable energy, which is then used to recharge the UAV battery. The military mostly uses the technique for surveillance services and intelligence gathering. The limitation of this technique is that lasers pose a risk to human health [19].

11.3.5 Performance Analysis in UAV Cellular Communication

The evaluation of UAV communication and general operational performance can be carried out through the following:

(i) Experimental field test
(ii) Computer-assisted simulations
(iii) Theoretical evaluation [23]

Theoretical methods of performance analysis hold some advantages. First, the time spent on simulation is eliminated with the theoretical techniques. Second, the theoretical analysis provides insights that are helpful in the design and optimization of UAV systems.

11.3.6 UAV Communication Performance Optimization

11.3.6.1 Interference Detection and Mitigation Strategies

In order to mitigate interference between a UAV and its ground terminal in a cellular system, it is imperative first to be able to detect the occurrence of interference. Some Interference detection possibilities were brought to bear during the study item phase of the 3GPP on enhanced LTE support for connected UAVs. Interference detection can be done either at the user end or at the network terminal.

UEs can be configured to measure some reference signals (RSs) from neighbouring cells and report to their serving eNodeB from which interference can be detected. These RS parameters include RS Received Power (RSRP), RS Received Quality (RSRQ), and RS Signal-to-Interference plus Noise Ratio (RS-SINR). The reporting of these measurements can be triggered by changing interference conditions. Network-based interference detection involves the exchange of RS configuration and transmits power information between BSs/eNodeBs. Interference estimation can be carried out using the reported data.

Interference mitigation can be enhanced by using advanced interference-mitigation capabilities on the UE side. LTE legacy versions supported interference-rejection-combination techniques, which use linear operations to suppress interference. In contrast, the later version used interference cancellation which is a more advanced and nonlinear method for network-based cancellation and reduction. The number of suppressible sources is limited by the number of antennas available on the UE side. As a result, efficiency is reduced [5, 24].

11.3.6.2 Other Performance Improvement Strategies

As discussed in Sect. 11.2.5 the use of massive MIMO offers significant performance improvement to UAV cellular communication. However, other techniques for UAV performance improvement and GUE protection in a cellular system can be explored [13]. Some of these performance optimization strategies are hereby highlighted.

- *Interference Blanking*

Since it is known that the challenges of UAV CNPC channel performance challenges arise mainly from inter-cell interference from neighbouring cells, it is reasonable to consider suppressing the most powerful interfering cells as a strategy to improve the performance of the UAV-ground link. To achieve this, the strongest interfering BSs can be configured to use nearly all blank subframes (ABSs) on the assigned time-frequency resources to the UAV CNPC channel, thereby ensuring better SINR [5, 25, 26]. Identifying the set of interfering BSs to be silenced through the use of ABSs depends on the size of the cellular cluster of the BSs as well as the UAV's height. The higher the altitude of the UAV, the more BS is exposed to interference. Hence at very high UAV altitude, the time-frequency resource that would be sacrificed to protect each UAV through interference blanking increases. This solution is therefore not spectrally efficient. It is suitable only for low-density UAV networks.

- *Opportunistic Scheduling*

This performance enhancement technique is applicable in a massive MIMO network in which UAVs are scheduled on different physical RBs. Neighbouring BSs could cooperate to adaptably schedule the downlink channel of C & C of aerial users (UAVs) dissimilar physical RBs, ensuring that UAVs though exposed to signals from nearby BSs, are not interfered with by them.

- *Fractional Pilot Reuse*

The adoption of pilot reuse 3 in a MIMO network can increase user data rates significantly. This increase can be more if BSs are fed with perfect CSI (channel state information), which can be provided by the assignment of fully orthogonal pilots across the network. The high spectrum overhead needed to provide perfect CSI makes the approach infeasible. In order to achieve better channel performance without incurring much overhead, fractional pilot reuse is considered [27]. Each BS assigns a specific set of pilots to each of the UAVs serving. That way, neighbouring BSs are relieved of pilot contamination.

- *Uplink Power Control*

To maximize the fraction of UL path-loss that can be compensated for by UL power control, we present the fractional UL power control equation as

$$P_{jk} = \min\left\{P_{\max,} P_0 . g_{jjk}^{\propto}\right\} \tag{11.14}$$

where $P_{\max}$ is the maximum limit of user power, P_0 is the cell-specific variable, $\propto$is a compensation factor for path loss and $g_{jjk}^{\propto}$ is the average channel gain measured in cell j at UE k according to the RSRP [13].

Modifying the formula for power control in (11.14), to take into account multiple cells for the RSRP; can help in achieving a better UAV-ground channel performance. The parameters in (11.14) can be altered to ensure that UAVs reduce their UL power when the RSRPs from both serving and neighbouring cells are low or equivalent.

- *Use of UAV Directional Antennas*

In a bid to improve the UAV-ground link performance, the 3GPP explored the possibility of equipping UAVs with directional antennas. While this solution looks promising, it is shown that the directional antenna must possess beam steering capabilities to yield a significant result [25]. Also, to achieve the best result from using a directional antenna at the UAV end, they must be made to point towards the adequate BS.

- *Beam Switching*

Switching at the UE end can inherently suppress the interference effect since UAVs do not depend on physical barriers to attenuate unwanted signals. This technique allows for the use of multiple antennas to increase the desired signal level while decreasing interference [5].

11.4 Case Study and Application

UAVs can be embedded into a cellular system as platforms for aerial wireless access to serve terrestrial users from a height. Three use cases are highlighted under this UAV-assisted cellular communication framework [6].

11.4.1 UAVs as Aerial Base Station

In this application, UAVs are used with space-borne BSs to increase the geographical coverage of a cellular communication system. The UAV in this case is equipped with the functionalities of a typical terrestrial BS. The unique features of the aerial BS are its height advantage and its flexible 3-D mobility. UAV positions can be changed or adjusted to the network coverage requirement. This UAV use case finds applications in (i) remote areas with little or no cellular infrastructure presence. (ii) Cellular hotspot for traffic offloading (iii) disaster management for quick recovery of communication service.

11.4.2 UAV as Aerial Relays

In this case, UAVs are employed as relays to accomplish wireless connectivity between two terrestrial user(s) that are too far apart to communicate directly in a reliable manner. UAVs as aerial relays finds application for wireless backhaul, big data transfer, coverage extension, and emergency response services.

11.4.3 UAVs as Aerial Access Points

Aerial access points (AAPs) are useful for data aggregation and dissemination. They help collect and disseminate data from a large number of terrestrial users or ground nodes, usually sensors. UAVs find applications as AAPs in UAV-assisted wireless sensor networks such as precision agriculture and Internet of Things (IoT) communication.

11.4.4 UAV for Wireless Charging of Sensors

Experimental research carried out in America and Italy has shown that remote charging of sensors used in the agricultural application can be achieved through

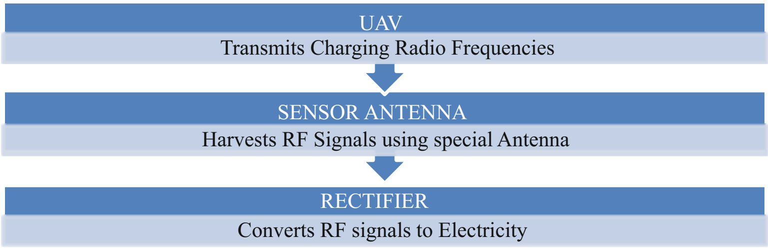

Fig. 11.4 UAV application process for wireless charging of sensors

Radio Frequency (RF) waves (RF are in the spectrum of EM waves used for wireless communication) [28]. In order to harvest energy from the RF waves, specialized antennas are built into the sensors. These antennas harvest RF signals and pass the same to a rectifier which converts the signals into electricity used for charging the sensor battery. UAVs are used to transmit the needed RF to each sensor. First, a signal is sent from the UAV to activate a particular sensor to be charged, among many others. Once the sensor is activated, the UAV draws closer to transmit the charging RF signal to the sensor antenna. Figure 11.4 shows how energy is transferred from RF waves to the sensor through the sensor antenna and the rectifier.

The current limitation of the approach is that radio waves must be close to the sensor to charge it sufficiently. The UAV activated the sensor from a distance of 27.5 m at a corresponding receiving power of −40 dBm. For charging to occur, the UAV must be at distances of 1.2 metres under a corresponding power of −18.2 dBm [27, 28].

11.5 UAV Channel Model Evaluation Using Clustered Delay Line Model with Ray-Tracing

Channel delay line (CDL) is used in channel modelling where there are multiple delay clusters in the received signal. According to 3GPP's recommendation, the CDL model is suitable for link-level channel simulation.

Technique to channel modelling can be categorized into stochastic or deterministic. Standard organizations, 3GPP and ITU-R WP-5D have adopted Ray Tracing (RT) – a hybrid channel modelling approach based on maps for analysing 5G communications technology. RT is an asymptotic technique that provides detailed angular information based on a deterministic modelling approach. It is a model for forecasting MIMO channel and time-varying characteristics for various frequency bands. RT, in contrast to stochastic communication systems, requires more computation time and is dependent on a detailed description of the environment. RT is mostly used to forecast multi-path for a specified environment model, to examine the propagation characteristics in complex scenarios, and is good for identifying fundamental propagation mechanisms [29].

The result obtained from RT analysis can be used for CDL channel model configuration. Configurations such as the 3D location of transmitter and receiver as well as geometric properties of a channel can be specified in the CDL model.

11.6 Methodology

To investigate UAV-ground channel performance, we carried out a CDL-based channel simulation using the Ray Tracing Technique (RTT). The 5G new radio channel dataset generator developed by [30] was adopted. While assuming a UAV-connected use case, three locations (Victoria Island, Lagos; Sabon-Gari (SG), Kano and Central Business District (CBD), Abuja), major cities of Nigeria, with different building densities and terrains were considered in this work. The maps of these locations were sourced from the Open Street Map (OSM) and embedded into MATLAB simulation code. Using the coordinates of each chosen location as a boundary, 10 simulation blocks were randomly created and the channel performances for 10 random BS and UAV locations were evaluated for each block. Hence, each location provided 100 UAV-ground channel instances or samples for evaluation. The simulation parameters are presented in Table 11.5.

Table 11.5 Simulation parameters

S/N	Channel parameters	Settings used
1	Locations	VI, Lagos; CBD, Abuja; SG, Kano
2	Coordinates of BS(long. and lat.)	3.41822, 3.43506; 6.43437, 6.42462 – VI, Lagos
		8.5181,8.5517;12.0293,12.0101 – SG, Kano
		7.4509,7.5183; 9.0753, 9.0366 – CBD, Abuja
3	Number of resource block (RB)	52
4	Bandwidth of subcarriers	15 kHz
5	Spacing of subcarriers	15 kHz
6	BS antenna dimension	UPA [8 × 8]
7	UE antenna dimension	UPA [2 × 2]
8	Channel centre frequency point	$f = 2.1$ GHz
9	BS height	30–40 m
10	UAV height	40–100 m

11.7 Result and Discussion

Simulation results obtained for the CDL-based RT analyses are presented in this section. Figures 11.5a, 11.6a, and 11.7a each show sample simulation blocks for VI, Lagos (high rise urban area), CBD, Abuja (urban area), and SG, Kano (dense urban area), respectively. On the sample simulation blocks, the BS is represented by the red mark while the UE is represented by the colour blue. (UAV). The two rays RT model consists of both the direct and reflected rays. Figures 11.5b, 11.6b, and 11.7b show the corresponding channel magnitude response for the subcarriers using 14 OFDM symbols.

Tables 11.6, 11.7, and 11.8 present the path loss for the direct ray and reflected ray with the corresponding UAV height and angle of elevation for 10 iterations. While direct rays occur for all simulations, it was observed in Table 11.6 that the 4th iteration has no reflected ray. The same is observable for the 1st and 9th iterations in Table 11.8. This establishes the fact that at a UAV height of 40–100 m, there is a guarantee of LoS signal between the UAV and its ground BS for the locations considered.

11.8 Conclusion with Future Research Scopes

11.8.1 Future Research Scopes

The traditional cellular network topology in which a BS serves a group of UEs within a geographical location using directional antennas has hitherto offered several gains for wireless and mobile communication [30, 31]. However, the inherent challenges of the cellular system, which include inter-cell interference, great variation in user QoS requirements, and mobile UE handover issues, constitute a major limitation to further advancement in system performance [32, 33]. Expectedly, cellular-connected UAVs and the services they enable suffer similar performance limitations as they depend on the cellular network for their communication. A viable solution to moving beyond this limitation is to eliminate the cell structure in the cellular system and adopt the use of densely distributed APs to serve EUs in a given coverage area. The APs are densely distributed so that each one renders optimal service to less number of UEs within the area [34]. This paradigm shift from the cell-based network architecture is called a cell-free massive MIMO system [31]. Cell-free massive MIMO has been highlighted as a candidate technology for enabling next-generation cellular communication systems of which UAV-based applications are potential beneficiaries [35–37].

Sixth-Generation (6G) networks have been forecasted to offer data rates around one terabit per second and latency in the range of sub-microseconds [38]. The 6G regime, therefore, promises enhanced safety and reduced collision rates of autonomous vehicles such as UAVs through very-low latency and super-fast data transfer [39, 40].

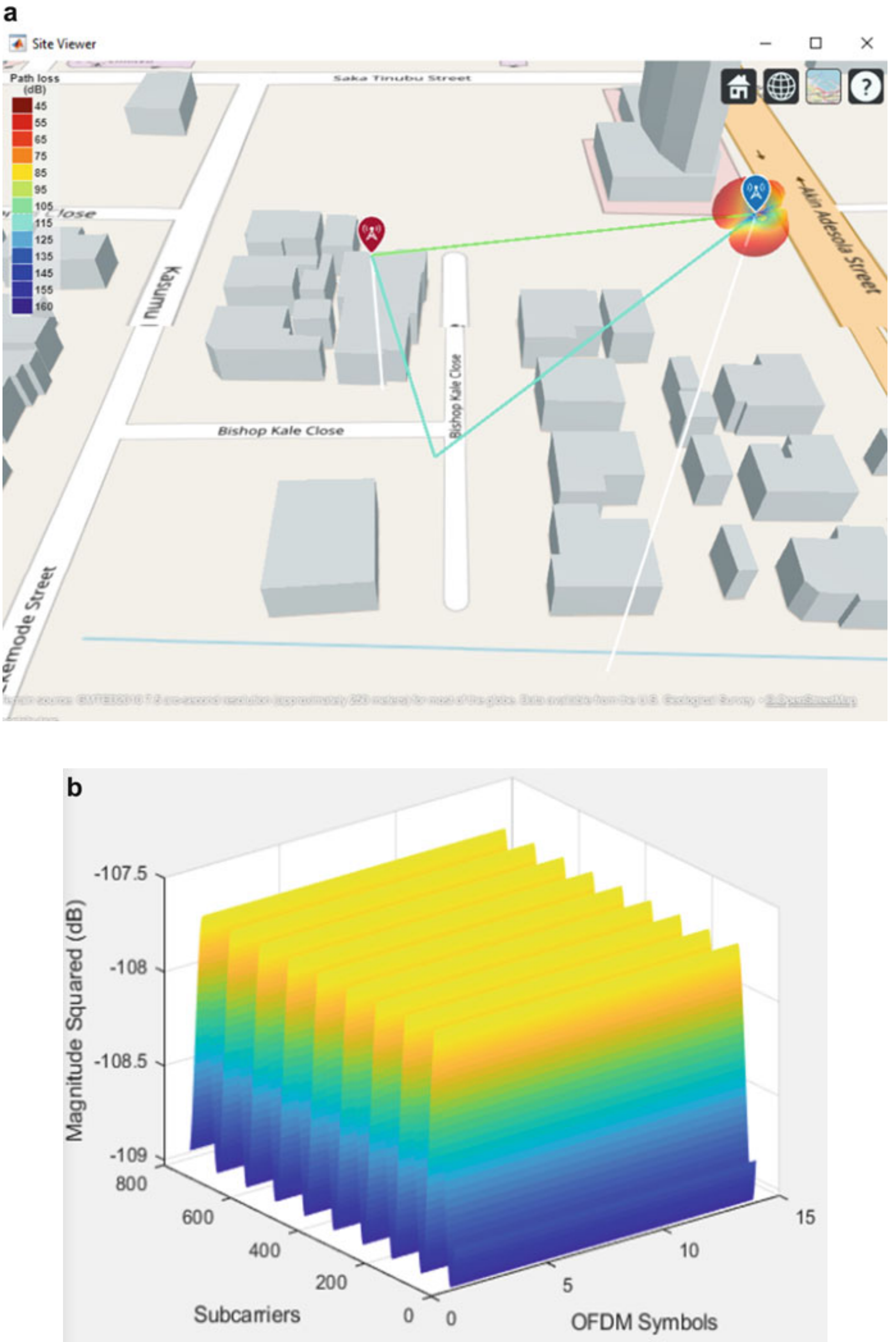

Fig. 11.5 (**a**) Sample simulation block with ray diagram – VI Lagos. (**b**) Channel magnitude response of subcarriers and OFDM symbol

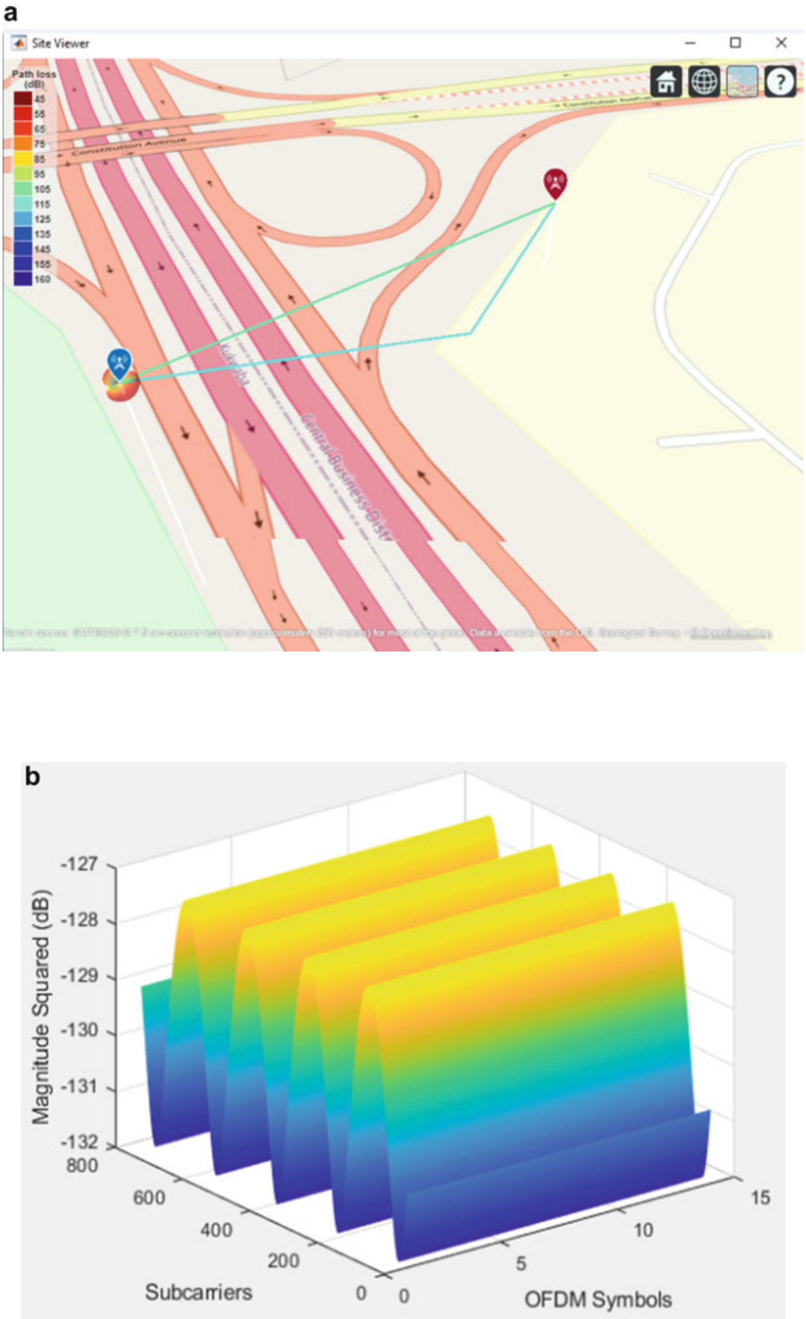

Fig. 11.6 (**a**) Sample simulation block with ray diagram – CBD Abuja. (**b**) Channel magnitude response of subcarriers and OFDM symbol

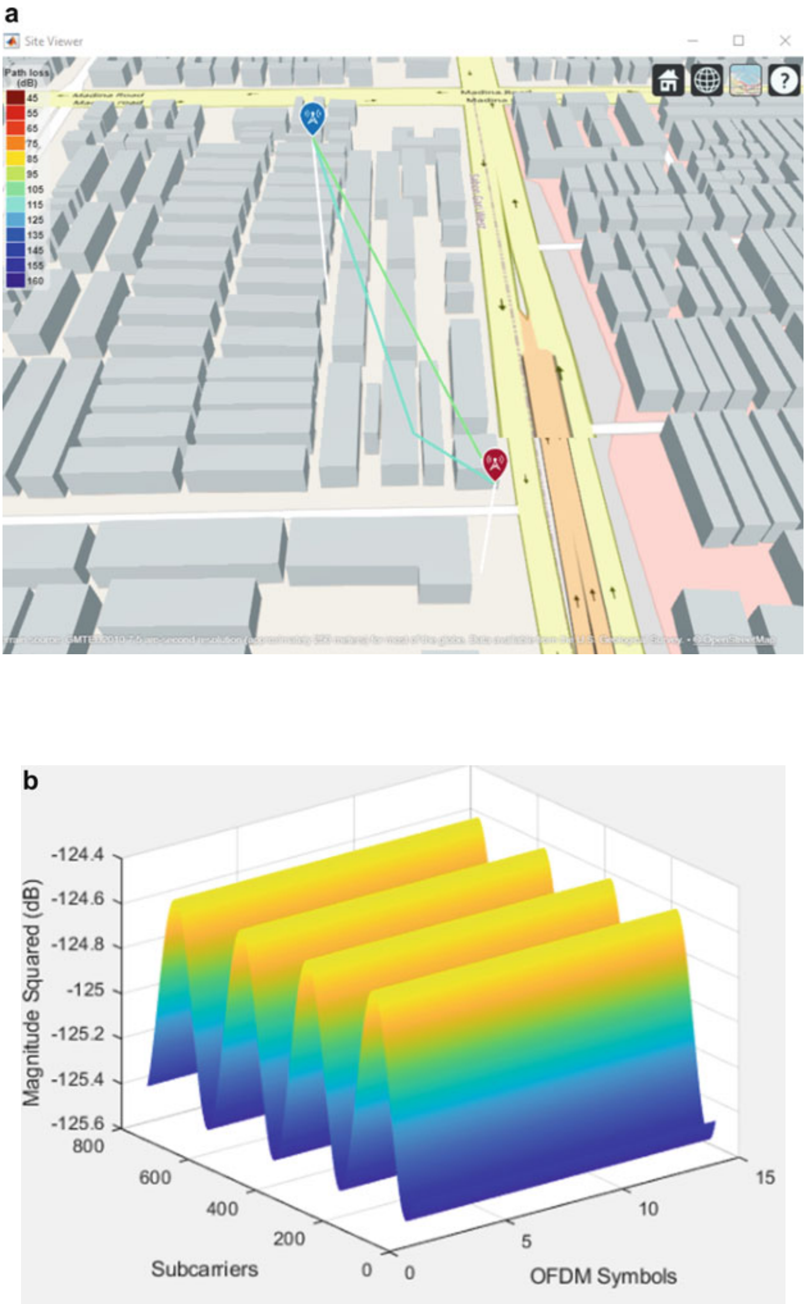

Fig. 11.7 (**a**) Sample simulation block with ray diagram – SG Kano. (**b**) Channel magnitude response of subcarriers and OFDM symbols

Table 11.6 RT simulation result showing UAV-to-ground BS pathloss, UAV height and elevation – urban location (VI Lagos, Nigeria)

Iteration no.	Pathloss (dB)		UAV height (m)	UAV elevation angle (in degree)
	Reflected ray	Direct ray		
1	115	95	54.54116429	−60.10494543
2	115	95	63.32357454	−75.99529409
3	115	95	57.68283588	−31.00161702
4	No reflected ray	105	64.05026513	−70.24676875
5	105	95	72.00425695	−60.77988592
6	115	105	76.35713709	−0.604378289
7	115	105	72.87121828	−54.19534388
8	115	95	93.76857993	−34.80940751
9	115	95	75.90260542	−82.43921197
10	115	95	97.18113123	−0.103595142

Table 11.7 RT simulation result showing UAV-to-ground BS pathloss, UAV height and elevation – urban location (CBD Abuja, Nigeria)

Iteration no.	Pathloss (dB)		UAV height (m)	UAV elevation angle (in degree)
	Reflected ray	Direct ray		
1	115	95	93.05699057	−39.8074872
2	115	105	74.24266668	−1.76198612
3	105	95	69.67281806	−29.77720922
4	115	105	83.57155698	−38.18785471
5	115	105	87.06289717	−24.32433811
6	115	105	76.00262337	−17.73484183
7	105	95	67.38563356	−73.95490665
8	115	105	57.49986269	−38.69292684
9	105	95	79.30460336	−79.89938588
10	115	95	63.10726589	−35.20646959

11.8.2 Conclusion

In this chapter, a comprehensive review of UAV communication requirements was presented. Factors affecting UAV communication systems design and performance such as channel characteristics, energy requirement, UAV size, the antenna type, and positioning were highlighted. Performance limitation due to aerial-to-ground interference in cellular-enabled UAVs was discussed extensively. Strategies for optimizing energy consumption for UAV propulsion and communication were presented in the literature. Given the Aerial UE to ground BS channel conditions obtained from simulation results, UAVs can be deployed for various applications; ranging from package delivery to communication infrastructure support in the locations considered and in other locations with similar urban characteristics. The chapter closes with the presentation of open design issues on promising technologies for performance improvement in UAV communication.

Table 11.8 RT simulation result showing UAV-to-ground BS pathloss, UAV height and elevation – urban location (SG Kano, Nigeria)

Iteration no.	Pathloss (dB)		UAV height (m)	UAV elevation angle (in degree)
	Reflected ray	Direct ray		
1	No reflected ray	105	51.88694331	−2.748685167
2	115	105	94.25840041	−66.96668343
3	115	105	95.66434138	−45.0020192
4	115	105	89.80919368	−43.1929927
5	115	95	54.93561393	−81.42500143
6	105	95	63.09355919	−54.88799836
7	105	95	66.767842	−55.58997506
8	115	105	83.98639757	−77.34980751
9	No reflected ray	105	56.82765687	−72.49404821
10	115	105	86.06137493	−51.90493641

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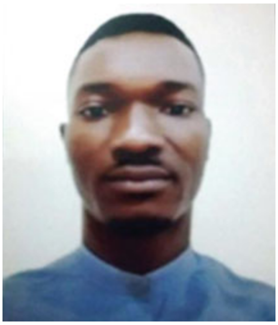

Christopher Akinyemi Alabi, is a lecturer in the Department of Telecommunication Engineering, Air Force Institute of Technology (AFIT), Kaduna. Nigeria. He received his B.Eng (Honours) in Electrical and Computer Engineering from the Federal University of Technology, Minna, Nigeria, in 2011. In 2018, he graduated from the Etisalat Telecommunication Engineering Program (ETEP), an M.Sc program hosted in Ahmadu Bello University (ABU), Zaria and supported by Etisalat Nigeria. He has over 10 years of working experience in the Information and Communication Technology (ICT) industry. He is a Registered Engineer with the Council for the Regulation of Engineering in Nigeria (COREN). His research interest is in wireless communication, focusing on spectrum management, wireless sensor network, Internet of Things, and emerging communications technologies.

Oluwaseun Olayinka Tooki, received his B.Tech., M.Tech., and Ph.D. Degrees in Electronic and Electrical Engineering in 2010, 2017, and 2022, respectively, from Ladoke Akintola University of Technology (LAUTECH), Ogbomoso, Nigeria. He is a lecturer at the Electrical/Electronic Engineering Department, Air Force Institute of Technology (AFIT), Kaduna. He is a registered member of the Council for the Regulation of Engineering in Nigeria (COREN) and a corporate member of the Nigerian Society of Engineers (NSE). He worked in the Telecommunication industry between 2014 and 2019 and is experienced in optical transmission, network operations and deployment of optical communication equipment. His research interest includes wireless, optical, and satellite communications.

Agbotiname Lucky Imoize, (Senior Member, IEEE) is a Lecturer in the Department of Electrical and Electronics Engineering, University of Lagos, Nigeria. He received B.Eng (Honours) in Electrical and Electronics Engineering from Ambrose Alli University, Nigeria, in 2008, and M.Sc in Electrical and Electronics Engineering from the University of Lagos, Nigeria, in 2012. Before joining the University of Lagos, he was a Lecturer at Bells University of Technology, Nigeria. He worked as a core network products manager at ZTE Nigeria Limited from 2011 to 2012 and as a Network Switching Subsystem Engineer at Globacom, Nigeria, from 2012 to 2017. Imoize was awarded the Fulbright Fellowship as a Visiting Research Scholar at the Wireless@VT Lab in the Bradley Department of Electrical and Computer Engineering, Virginia Tech., USA, where he worked under the supervision of Prof. R. Michael Buehrer from 2017 to 2018. He is currently a Research Scholar at Ruhr University Bochum, Germany, under the Nigerian Petroleum Technology Development Fund (PTDF) and the German Academic Exchange Service (DAAD) through the Nigerian–German Postgraduate Program. He is a Registered Engineer with the Council for the Regulation of Engineering in Nigeria (COREN) and a Nigerian Society of Engineers (NSE) member. He has co-edited one book and coauthored over 80 papers in peer-reviewed journals and conferences. His research interests are beyond 5G and 6G wireless communications, chaotic communications, and wireless security systems.

Chapter 12
Evolution and Significance of Unmanned Aerial Vehicles

S. Jayanthi, H. Shaheen, U. Balashivudu, and Meesala Shobha Rani

Abstract Unmanned aerial vehicles (UAVs) are aerial systems controlled remotely or autonomously by astronauts. Massive advancements in electronics and information technology have prompted the popularity and growth of UAVs. As a result of the huge advances made in electronics and information technology, civilian tasks can now be accomplished with UAV in a more effective, efficient, and secure way. Known as a drone, UAVs are developed and operated using a variety of technologies such as machine learning, computer vision, artificial intelligence, and collision avoidance. Having become more affordable and accessible, drone technology has become more popular among civilians. Therefore, this technology is constantly evolving and can be used across a variety of fields. The application of drones makes a huge difference in the most demanding and complex industrial environments such as those in the mining industry, maritime, oil, gas, and seaports. The usage of drones is increasing among industrialists to improve and optimize processes, as well as to enhance operational efficiency in industrial process. This chapter discusses UAVs on a wide range of topics, including evolution and historical perspectives of UAV, taxonomy of UAV, significance of UAV to society and industry, and industrial and academic perspectives on UAV.

Keywords UAV · History · Perspectives · Drone · Surveillance · Classification · Applications · IoT Drones · Blockchain-based UAV

S. Jayanthi (✉) · U. Balashivudu
Department of Information Technology, Guru Nanak Institute of Technology, Hyderabad, India

H. Shaheen · M. S. Rani
Department of Computer Science and Engineering, MVJ College of Engineering, Bangalore, India

A. L. Imoize et al. (eds.), *Unmanned Aerial Vehicle Cellular Communications*, Unmanned System Technologies, https://doi.org/10.1007/978-3-031-08395-2_12

12.1 Introduction

Increasing the resilience of wireless communication networks is crucial in emergency circumstances, in important communication missions, in freight and agricultural movements so that systems can be autonomous while maintaining high levels of energy efficiency. In response, the use of unmanned aerial vehicle (UAV) has been increasingly focused on in recent decades due to their flexibility, autonomy, and extensive range of applications [1, 2].

UAVs have been deployed for a variety of purposes and applications, including military, surveillance, observation, telecommunications, medical supply distribution, etc. The usage of UAVs is ever increasing, and report suggest that in 2023, over 35 million UAVs are expected to be in use.

It is evident that over the past decade, UAV use has steadily increased, and today it qualifies as a standard research tool for acquiring images and other data on demand. These systems have become more suitable for a variety of applications through technological advancements, from archaeological applications to smart farming to managing natural hazards. A drone can be referred to by different names, such as Remote Pilot Aircraft System (able to function without human instruction), unmanned aerial vehicle, and unmanned aerial system. In this chapter, we have used the term unmanned aerial system to represent an aircraft that can fly autonomously and be remotely controlled. This UAV is capable of collecting data, can be engineless, and employed with imaging sensors. It can fly for long time at a controlled rate of speed and height, even can fly for months without landing, and they play a part in a variety of aviation applications.

Modern UAVs and drones are a common sight and can be found in many electronics shops or an ordinary mall at an inexpensive rate. Since the drones can be accessible at lower rate also, these systems are increasingly being used even in areas where users may not have the required aeronautical expertise. These areas include archaeology, military, surveying, geospatial science, cultural heritage, and environmental applications. For example, UAV used in the military is called as military aircraft which is operated and directed by remote control system, anonymously by remote control, or both. This UAV mounted military aircraft carries suitable intelligence sensors, offensive ordinance, missiles, and onboard digital signal processing to locate, tackle, dominate and destroy enemy's targets. UAVs can be extremely efficient, offering far better range and endurance than equivalent piloted aircrafts because of their lack of pilot, assisted ventilation for saving lives, and design-safety constraints [3–5].

Following World War II, the defense forces of many countries used drones and remotely piloted vehicles (RPVs). In the early 1980s, the Israel Defense Forces fixed miniature drones mimicking big model aeroplanes equipped with infrared cameras and sensors, and trainable television, and laser-guided missiles signals, all of which were downlinked to a control centre. These vehicles were effective in monitoring the battlefield and targeting due to their small size and silent engines, which made them invisible [1, 6, 7].

Fig. 12.1 RQ-4 Global Hawk Drone [10]

Israeli success has been emulated by many other armed forces, including the United States, which has bought or licensed some of these early Israeli products. The MQ- 1 Predator is a long-endurance, multi-mission UAV, first flown in 1994 and operated out for service in 1995. It is one of the most important UAVs in the United States, and had set a trend in the development of UAVs. These UAVs have small size and quiet motors made them undetectable and proved valuable on the battlefield for battlefield surveillance and target identification. Additionally to its 8 metre length and 12.5 metre wingspan, the Predator is powered by a piston motor driving a pusher propeller. In addition to its 80-mph speed and 24-hour endurance, the aircraft can carry antitank missiles, infrared and visible television, and synthetic aperture radar. It also has passive electronic sensors. Large UAV are often employed for intelligence gathering, and reconnaissance operations [8, 9].

The RQ-4 Global Hawk, a jet-powered ship has a wingspan of 35 metres and a length of 13 metres. It is capable of flying at 640 kph for 36 hours at top speed and is equipped with a wide range of camera, radar, and electronic sensors (Fig. 12.1).

Extremely small and hand-launched UAVs allow ground combat units in battlefield to extend their line-of-sight (LOS) beyond their front lines.

The MQ-9 Reaper is a bigger, more powerful turboprop version of the Predator that has an increased payload and performance. US allies have bought the Predator and the Reaper and have used them in battle between Afghanistan and Iraq (Guilmartin et al. 2021). The Reaper is preferred for airstrikes as it is used for monitoring, surveillance, observation and exploration. Since MQ-9 reaper is equipped with infrared camera capable of detecting the survivors from 10,000 feet height, it has been ordered by the Federal Aviation Administration, an agency regulates all national aviation, passed an to employ the MQ-9 reaper in search and rescue operations (Figs. 12.2 and 12.3).

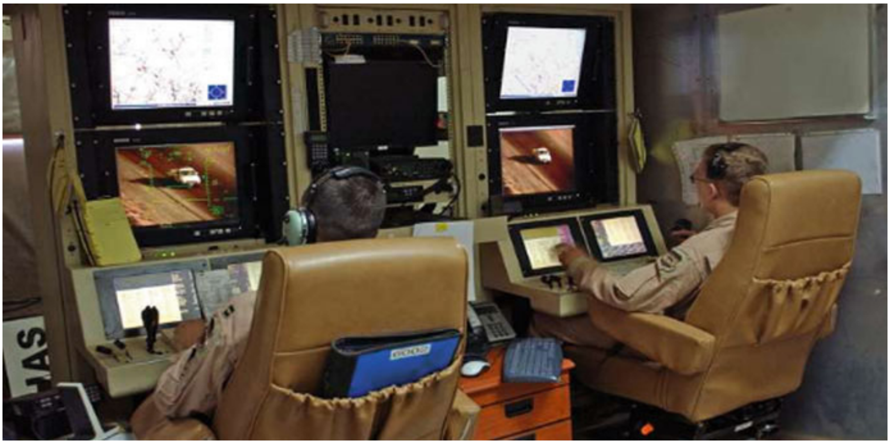

Fig. 12.2 MQ-1 Predator unmanned aerial vehicle [10]

Fig. 12.3 MQ-1 Predator [10]

As smart cities, 5G, and the Internet of Things (IoT) expand in popularity, the UAV communication is likely to become more efficient, consistent, and resilient. Recently, cellular networks, such as 5G networks, have shown an increased interest in integrating UAVs. On one hand, With enhanced cellular technologies and the ability of cellular networks to become broadly accessible, UAVs with their own missions may become as new airborne users by connecting to cellular networks. UAVs can also be used as aerial relays, access points, and base stations (BSs) to assist with 5G and other terrestrial wireless communications from the sky, establishing a new standard identified as UAV assisted communications [2, 11, 12].

In order to make systems autonomous while ensuring a great degree of energy consumption, strengthening the resilience of wireless networks is vital in emergency conditions. As a result, due to its autonomy, versatility, and diversity for applications, the usage for UAVs (drones) has become significantly the focus of research in recent decades. UAVs have now been investigated for quite a range of uses, including defense, monitoring, telephony, drug supply distribution, and firefighting. The application of UAVs has been on the rise, with several studies predicting that about 29 million UAVs drones will be in operation by 2021 [13, 14].

12.2 History

A UAV is an unmanned aircraft or balloon that can be controlled remotely using a radio control or by using onboard technology that makes it autonomous, relying just on network infrastructure. As UAVs require only a remote pilot with a radio frequency controller, they are typically used for military tasks such as surveillance, remote monitoring, armed attacks, firefighting, save and rescue, and to reduce soldier losses in a rough-and-tough territory.

The first reported usage of a UAV was at Venice in the year 1849, when Australians assaults them with helium-filled balloons laden with bombs, where each balloon contained between 11 and 14 kg of bombs. Once they had been located, the bombs were dropped from their balloon carriers over the city below to ravage it by their destructive effects. Due to a rapid change in wind direction, only one bomb actually hit the city which was fortunate for the Venetians [Alan R. Earls]. Having said that, it is fascinating to see how military technologists were considered for drones over 170 years ago. In continuation of this, UAVs were also used during World War I and II.

UAVs were also utilized for intelligence surveillance using wireless sensors in the second half of the twentieth century, thanks to advancements in onboard sensors and manufacturing technology. UAVs became less expensive and smaller in the early 2000s. They were applied to a wide range of wireless communications applications using existing network infrastructure, including package delivery in smart cities, traffic control in smart cities, and precision agriculture in Industry 4.0.

It is to be noted that UAVs are viewed as aerial user equipment (UE) in each of these scenarios, rather than as fully integrated network components. Cellular-connected UAVs are the name given to this type of wireless technology. With the continuing miniaturization of components of wireless communication apparatus such as radio frequency transceivers and hardware, UAVs can now provide consistent, cost-worthy, and ad-hoc wireless links to the users. Transceivers now weigh less than 2 KG, such as universal software radio peripheral, which is equipped with software-defined radio and can be attached on an aircraft using 3D printing [15, 16].

In light of the rapidly growing volume of cellular data traffic, the UAV-assisted wireless communications concept could be a suitable and potential technique to support this growth. As a result of increased interest of scholastic research and industry testing, ABSs are recognized as being essential for 5G and beyond [6, 7, 11, 13, 17].

Drones were initially handled manually and remotely. But, Drones nowadays increasingly include artificial intelligence (AI), which automates partial or complete functions of UAVs. Drone providers can acquire and deploy visible and ecological information using data received from sensors linked to the drone with the incorporation of AI. This information enables self-directed or guided aircraft, simplifying operations and increasing accessibility. As a result, UAVs have become an important aspect of the mobility services that are now widely used in business sector. AI-powered drones rely significantly on machine vision. This allows drones to hover and detect items, as well as assess and interpret data on the ground [18].

Computer vision technology achieves high performance, onboard image recognition with artificial neural network. To deploy machine learning techniques, an artificial neural network has a layered structure. With the help of neural networks, drones can recognize, classify, and track objects. By immediately combining this data, drones can avert mishaps and notice and locate objects. Before applying neural network models in UAVs, researchers should first develop machine learning techniques to recognize and classify images in a variety of settings. This is performed by feeding the algorithm with appropriately labelled visuals. These visualizations teach the neural network model what properties different image classes have and how to distinguish between them.

UAVs also deploy non-equilateral multi-access and wireless edge computing approaches to reach mobile users in an artificial intelligence (AI)-empowered environment (MUs). This system allows lowland MUs to discharge their computing activities concurrently, smartly, and dynamically, improving connectivity while lowering transmission delay and power consumption.

Xin Liu, 2022, has presented a multi-UAV equipped moveable broadband of Vehicles model, in which the Drones monitor to help movable fleets and provide downstream signals during journey time. Throughput is optimized in this system by optimizing vehicle navigation scheduling, power control, and UAV route all at the same time, while taking into account the anti-collision and transmission intervention constraints of UAVs. Breaking down the non-convex optimal solution into three subtasks: interaction schedule improvement, power control enhancement, and route optimization, all of which can be handled using sequential convex approximation, yields the non-convex ideal solution [19].

12.2.1 Classification of UAVs

Drones or UAVs can be classed in a variety of ways based on its size, design, and application *[Ohio University].*

12.2.1.1 Size-Based Classification of UAVs

- *Large UAVs*: UAVs of a Larger Size are employed in civilian attacks, battles, and reconnaissance. These UAVs are capable of flying for a long period and to a great height without refuelling, and are typically employed to monitor and protect a broad region.
- When these devices are utilized in battle, missiles can be installed in them that can be fired remotely if the target is detected and locked in.
- *Medium-Sized UAVs*: Typically, medium-sized UAVs are used for reconnaissance and data collection. These medium-sized UAVs are widely utilized in armed forces, industries, and smart farming sectors.
- *Small-Sized UAVs*: Small size UAVs are the most favoured and widely accessed UAVs. These small-sized units are deployed in a variety of industries, government agencies, professionals, and tinkerers.
- *Mini UAVs*: These miniaturized units are employed for very intended task, such as military, surveillance, etc.These units are so small that they can fit in the palm of your hand. During a close combat mission, military troops use it for espionage. During search-and-rescue situations, it can be utilized to look inside a surviving or wrecked building.

12.2.1.2 Design-Based Classification of UAVs

Aircraft Design UAVs in *Aircraft Design,* a propeller is located on the tail or tip of this type of UAV. Propellers are mounted on the wings of some wing design units. Large UAVs incorporate jet propulsion as well. Smaller units can be launched by hand, but bigger units will need a launchpad to get away from the land. The benefit of this design is that it consumes less energy than a UAV with a tilt-rotor design.

Tilt Rotor Design UAVs based on Tilt Rotor Design are also known as a quadcopter as they use four rotors to perform lifting and propulsion. This type of UAVs can land and take off anywhere, just like a helicopter. These UAVs are the most extensively utilized, because of their ease of take off and landing. The aircraft can be flown without the use of a landing pad or a catapult [15, 16, 18].

12.2.1.3 Application-Based Classification

- *Military*: Drones have become widespread in the military for aerial combat, attack operations, reconnaissance and observation. Cargo drones carry weapons and supplies to military troops. Drones are the technologically advanced force multiplier, helping to expand police and army's power to control violence and counter rising threats to homeland security.
- *Commercial*: Drones are used for a variety of commercial purposes. A drone with a camera is used to map the region in order to determine whether a particular

project can be built on a specific site. In the commercial sector, unmanned aerial vehicles (UAVs) are used to photograph and film buildings, construction projects, and ground areas. It's more commonly utilized in real estate firms to take photos and films to promote their construction projects.

- *Agricultural*: In the agriculture field, farmers sprinkle insecticides, fertilizers, and other chemicals with drones. In addition to this, drones are also used to detect faults in the crops, specialized sensors and cameras. Early recognition of diseased crop portions is possible with the help of drones which significantly produces greater yields from the farm. Various forms of data about the farming, plant, soil, and weather patterns can be acquired through drones which can be utilized to guarantee that the crops are healthy and that the harvest is successful.
- *Police*: Drones are used by federal investigators to deal with crime cases. They utilize it to keep an eye on a suspected candidate. Deploying police officers before knowing the actual status during active crime scenarios can be hazardous. In such cases, real-time vigilance of drones is very useful.
- *3D Mapping*: To investigate the area, advanced 3D imaging technology mounted on a drone is used. To create precise and high-definition 3D maps of a specified geographic surface, thousands of high-quality pictures are put together. It provides a complete overview of the area's topo maps.
- *Disaster Relief*: It's impossible to estimate the extent of damage right after a calamity. There is a pressing urge to obtain ground data as soon as possible. Sending search-and-rescue personnel to that location without prior learning about the ground conditions could be a waste of time. A UAV aids in determining the precise place where assistance is required.
- *Hunting Hurricane*: Typhoons and other natural calamities are ascertained using drones equipped with scientific equipment. The information gathered and evaluated during such processes is used to create forecasting analytics that aid in better predicting coming disasters.
- *Product Delivery*: Due to governmental restrictions, this form of corporate venture has yet to take off. However, numerous businesses are actively engaged in this sector. It is likely to be a lucrative segment for commodity vendors.
- *Research and Development*: Scientists use drones to collect many forms of data from the earth, ocean, and sky. They can gather relevant information without having to employ multiple teams to the specific sites. Easily and quickly acquire precise and detailed data from diverse areas.
- *Reconnaissance*: UAVs are currently extensively put in place to keep intruders out of border areas. It aids in the gathering of intelligence on the combat. The information can be used to secure the border, combat units, and surveillance systems. Military soldiers can avoid high-risk operations or accompany them with additional knowledge about the condition on the site.
- *General Users*: Amateurs operate small-scale drones for fun purposes. These devices are used to replicate the thrill of flying a plane. Many multipurpose UAVs now have a camcorder for taking photos and videos. Some of the most recent UAV types can monitor the drone pilot's movements. Drone hobbyists should be aware of stringent drone flying limitations and laws.

12.3 Issues and Challenges in UAVs

Every year thousands of small drones are manufactured. These small drones are also freely accessible both online and offline, but regulating these drones is very challenging. These small drones can be easily developed even by a complete novice from widely accessible components on the Internet. Also, pilots of unmanned aerial vehicle (UAV can lose control while operating. However, so far, there have been no major catastrophes, but there have been several reports of criminals using drones to carry illegal and restricted goods to jails. The aspects related to insurance coverage isn't entirely framed or established yet. People's privacy is jeopardized as It can be used to take a peek through windows into residences.

By implementing proper rules, policymakers have attempted to solve these challenges. There are a slew of laws and regulations controlling the possession and use of UAVs, and law enforcement authorities have already been using a variety of tactics to keep unlawful UAVs out of the sky.

Drone technology is expanding at a faster rate. Drone missile procurement is anticipated to raise $51.85 billion in 2025. UAVs are now being sold and operated widely everywhere. At the same time, the drone sector is predicted to create 100,000 employment.

The application of such innovation helps to achieving the maximum possible standard of living. UAVs have both advantages and disadvantages. Lawmakers are attempting to be vigilant by enacting appropriate rules and regulations [12, 15, 16, 18].

12.4 Swarm UAVs

A cluster of aerial robots grouped to complete unified missions is known as a swarm UAV. Each drone in the swarm is controlled by a series of air foils, which allow them to take off, and land properly. The drones can either be controlled physically by using remote controller or autonomously using processors embedded on each drone.

Drone swarms can be categorized in a variety of ways. This diagram shows the classification of drone swarms into completely autonomous and partially autonomous (semi) swarms. From the other perception, the categorization can be thought of as single layered swarms, with each drone acting itself as a chief. In case of multilayered swarm structure, chief drones available at each layer interacts to the next top level chief drones at a higher layer; ground-based data centre use to be the top most layer in this multilayered swarms structure.

In a swarm of drones, each can gather and process data, and each drone will have the computing power necessary to do so fast. Essentially, it runs on a faster server/base site, either on the cloud or in a data centre [1]. Categorization of swarm UAV is illustrated in Fig. 12.4.

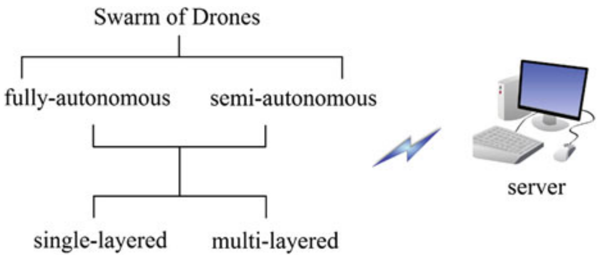

Fig. 12.4 Categorization of swarms

Swarms of UAVs have obvious advantages over single UAV systems.

- Survivability: In a single UAV, the downing of any UAV while in a mission is considered a failure. However, in a swarm of UAV, downing of a UAV is not a problem since the rest of the UAVs keep operating.
- Scalability: For unmanned aerial systems with a single drone, if an increased range of operations is needed, it can be achieved using larger UAVs. A multi-UAV system on the other hand can be easily augmented to operate over a larger area.
- Speed of mission: Studies show that the specified mission can be completed quickly using Multi-UAV systems. It can handle search and rescue jobs more efficiently since they undertake operations simultaneously, lowering the amount of time required on completing the activity.
- Autonomy: The usual way of operating in single-UAV systems is that the controller on the earth's surface need to keep continuous monitoring and control over all aircrafts. Whereas in multi-UAV systems, the controlling of the flight in line with flight schedules is achieved through online systems.
- Cost: Studies expounds that multi-UAV systems accomplishes the missions at a cheaper cost than single UAV systems.
- Communication: A constant contact to terrestrial controllers need to be maintained, in case of single-UAVs, on contrary, in a multi-UAVs, only one distinct UAV have communication with the terrestrial controllers and relays the information towards others.
- Size: The size and shape, cross-section, of UAVs in Multi-UAV systems are tiny for military uses, enhancing the secrecy and security of combat activities.
- According to research, swarm UAVs can engage in two sorts of interaction: UAV-to-UAV and UAV-to-Infrastructure communication.
- UAV-to-UAV interaction architecture: UAVs can interact directly or indirectly by establishing multi-hop communication pathways that use radars to transfer information between them efficiently.
- UAV-to-infrastructure interaction architecture: In this architecture, a stable centralized centre is used to offer direct connectivity to the UAV for real-time data exchange.

12.5 Internet of Drones

The Internet of Drones (or UAVs) has become an emerging and highly sought after technology that has the potential to be implemented across multiple sectors. UAVs in the Internet of Things can explore the infrastructure and transport products using built-in sensors.

Moreover, due to sophisticated technologies, the data collected by UAV sensors raises privacy and data security concerns. A secure data exchange can be achieved by deploying blockchain-based UAV system, which has four separate entities, namely, Uav, servers, client, and control centre. This system has two phases: authorization phase, which identifies users, portal nodes and users before granting access to information or resources, and access control phase to secure data from unauthorized UAVs. In order to improve both the phases, authorization and access control, there are several research works have been carried out to integrate big data analysis with blockchain-based UAVs.

Several drones are connected together to exchange vital information and are placed in separate flight regions in an Internet of Drones (IoD) environment. The information is then be subsequently gathered by the respective Base ground Station Server.

Before deployment in a wireless medium, all drones and ground server station are base station are recorded with the control room. As a wireless medium is highly susceptible to threats, blockchain-based UAV is deployed to secure data exchange. Initially the collected data are transformed into blocks and then an algorithm called Ripple Protocol Consensus is applied in a cloud-based computing environment [1, 8, 20].

Unmanned traffic management is a notable critical concern for tiny uavs functioning in restrained low-altitude territory outside focus. More specifically, security dangers may result in catastrophic scenarios if planned route transfers between uavs and radar systems or if control systems are not secured. A preset direction of travel, for instance, may be simply changed to allow the aircraft to carry out illicit actions. In order to provide secure data communication despite the security challenges, UTM-Chain, a compact blockchain-based crypto algorithm that matches the computing and data constraints of UAVs can be deployed.

12.6 The Societal Roles and Relevance of UAV Cellular Communications

In remote organizations, UAV-based engagement is a growing subject of study. It is used in a variety of industries, including health care, traffic monitoring, and civil defence. The enticing features of UAVs, as well as their potential on-demand capabilities, have sparked interest in both commercial and technical research. According to continuing research in the field of UAVs, it may be possible to transfer

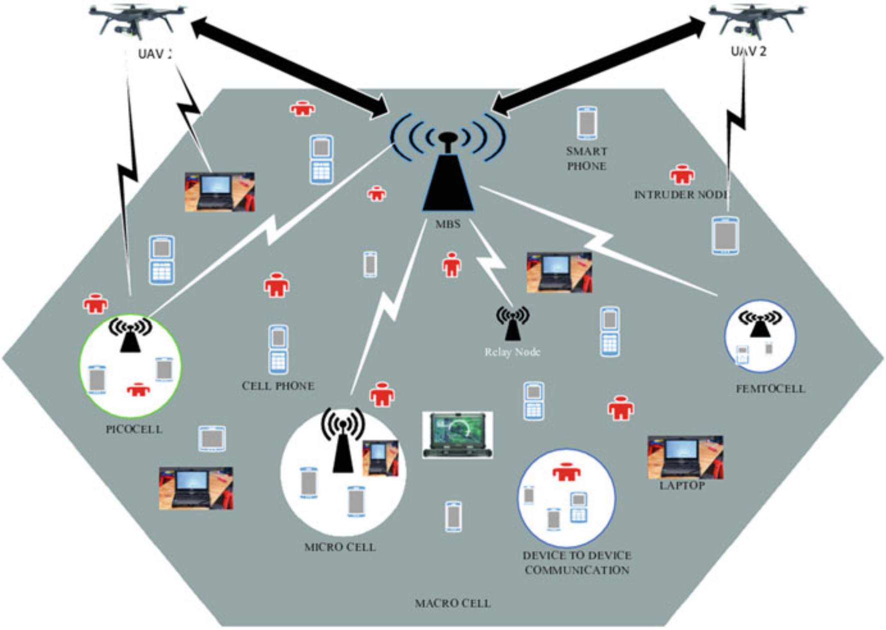

Fig. 12.5 Public safety applications of UAVs [2]

UAVs for remote public health applications, such as air inflatable boats and aircraft. When used as a base station, a UAV can increase the availability of an existing earthbound base station (TBS) by a factor of ten, allowing remote firms to improve their limitation, engagement, and production.

Uavs, in contrast to terrestrial systems, provide a more flexible and wider prospect of remote interchanges. The exceptional performances of UAVs are also important in putting the concept of unmanned drone-to-everything interchanges into action. UAVs move and collect data from various resources, including automobiles, factories, and personnel on pedestrian in the business, etc. It has the benefit of collecting vital information from areas where a desperate situation occurs, which is shown in Fig.12.5. Unmanned aerial aircraft with these powers is becoming an essential part of remote organizations.

Telecoms companies have been paying close attention to UAVs in recent years as a way to improve communication channels for earth customer by providing economical, reliable, adaptable, and energy efficient wireless networking applications, and extra capacity in case of emergencies and sudden occasion scenarios. Natural calamities have the ability to cause established terrestrial-based stations to fail [12]. Although it is impractical to create a fresh terrestrial-based stations at a time, UAVs may quickly be deployed to provide high-quality wireless access. In a proactive way, UAVs function efficiently to fulfil the needs of public security during emergency scenarios.

Because the timeframe for UAV take off and information sharing is limited, it is vital to locate a UAV in a unique environment that can accommodate the greatest number of users while consuming the least amount of electricity. Figure 12.5 depicts a tri-layered system with UAVs deployed on the outside edge to facilitate information sharing in the event of an emergency. This approach looks to be a good fit for public-sector security operations.

A variety of elements contribute to the effectiveness of UAVs. UAVs' expansion will be enhanced by high-capacity batteries, efficient engines, compactness, and weight. UAVs use batteries to power their motors during take off. So, in the coming years, UAVs with such features will become a critical component of today's remote data transport capability. UAVs have recently piqued the interest of dynamic authorities, who see them as a way to improve connection with ground clients and provide an extra limit in crisis and short-term event situations.

TBSs' operational efficiency may be impacted by natural disasters. As it may be impossible to build up new TBS immediately, UAVs can be made dependable and robust to suit the needs of public health clients while they recuperate. Because UAVs' flying and communication capabilities are limited, it is frequently important to put a UAV in a prominent location where it can serve the most number of clients with the least level of energy usage. The three-layered catastrophe-resilient system coordinates unmanned aerial aircraft positioned at the boundary to offer communication in the event of a calamity.

Unmanned aerial aircraft (UAVs), as depicted in Fig. 12.6, can provide versatile and effective monitoring in massive catastrophic disasters. Despite the numerous advantages of UAVs, a number of difficulties were uncovered throughout the design process [5, 21].

Energy efficiency is the most important issue, as it influences the entire design of unmanned drones. Environmental limitations, flight timeframe, weight, and current installation elevation are the main constraints that govern energy utilization [22, 23].

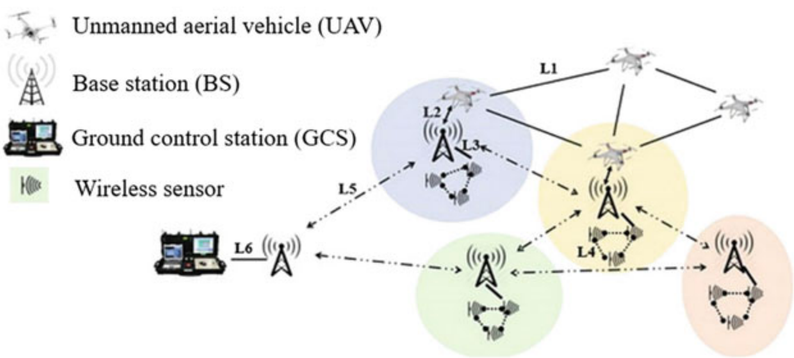

Fig. 12.6 Unmanned drones in futuristic organizations [10]

12.6.1 Societal Roles

A number of studies on UAVs, as well as questionnaires on the qualities, requirements, challenges, and limitations of UAV communication frameworks, have been conducted in recent years.

The designers introduced major challenges faced by UAVs, which are examined during its consistent and reliable correspondences. An in-depth examination defines the communication options for low-elevation UAVs. This article focuses on the state-of-the-art autonomous organization in the field of UAV streamlining.

The study looked at remote organization instructional exercises, numerical devices, and technological frameworks that are used to address the main challenges using unmanned drones. The designers provided comprehensive information on current method arrangement, practical execution, entire fundamental facts of the structure identifiable proof, and applications for small low cast unmanned aircraft. In addition, the study provided both businesses with an unmanned aerial test system. The norms and components for planning LAUs, elevated UAVs (HAUs), and coordinated private communication organizations for aerial communication were also discussed [24].

A succinct explanation of the assumptions, predictability, implementation, and important flight management instruments for crossover unmanned aerial frameworks. As a result of the research, open-source automatic pilot systems for small and micro unmanned drones have been developed. A research of catastrophic assessment was discussed, as well as the board for symbol acquisition of the use of unmanned drone vehicles system. Furthermore, with the purpose of distant detection for various types of unmanned aircraft, the developers tackled the primary challenges related to picture-based philosophy.

The characteristics of streaming site and air-to-ground signal distribution were discussed. The landscape navigability strategies and a 3D ideal organizing system were investigated. The authors suggested low-cost phases and application sectors for a perception and management method for appropriate UAVs. The limitations and potential opportunities for using UAVs in design and construction were summarized. Another comprehensive study was conducted, in which they provided comprehensive insights into the requirements, difficulties, and practical model of UAV cell correspondence framework. The designers depicted the determinants that affect an unmanned aircraft's energy usage and investigated its energy consumption models.

The research looked at ground systems, applications, and future patterns of UAV communication, as well as joint communication, reservation, and registration, with 5G developments at the practical layer [24, 25].

This research looked into a variety of remote charging methods and orders based on electromagnetic technologies that could be useful for unmanned drones. The piloting and display standards for unmanned drones were investigated. For disaster-affected areas, an energy-efficient clustering and guidance structure was devised. Simulated and real-world network security attacks were discussed. As a result, numerous UAV research has been undertaken, but there is still no overview that addresses unmanned drones from an energy efficiency aspect, specifically in open restorative settings [26–28].

Unmanned drones have a variety of uses in almost every field. Unmanned drones are divided into three types in this section: (1) elevation-based structure, (2) communication system structure, and (3) application-based clustering.

12.6.2 Aerial-Based Classification

The most difficult task in aerial communication is deciding which sort of unmanned drones would provide adequate quality of service and endurance. Unmanned drone types vary in their ability to adapt to dangerous or affected environments. A few classifications have been presented for administrative structure together TBS to improve the integration, limitation, or satisfy the wants of clients. Indeed, the fuel-efficient use of unmanned drones is coupled to the UAV categorization types, which consider flying height, speed, and time. Figure 12.7 shows the groupings of unmanned drones. In terms of height, UAVs are divided into 2 groups: HAUs and LAUs [29].

Unmanned drones are separated into two categories based on their wing types: rotatable wings and fixed wings. HAUs feature a variety of remote communication options, including moderate information exchange with the most extensive inclusion zone, less propagation latency, high transmission rate, and energy consumption. The force control-based HAU plans have been investigated. When the unmanned drone

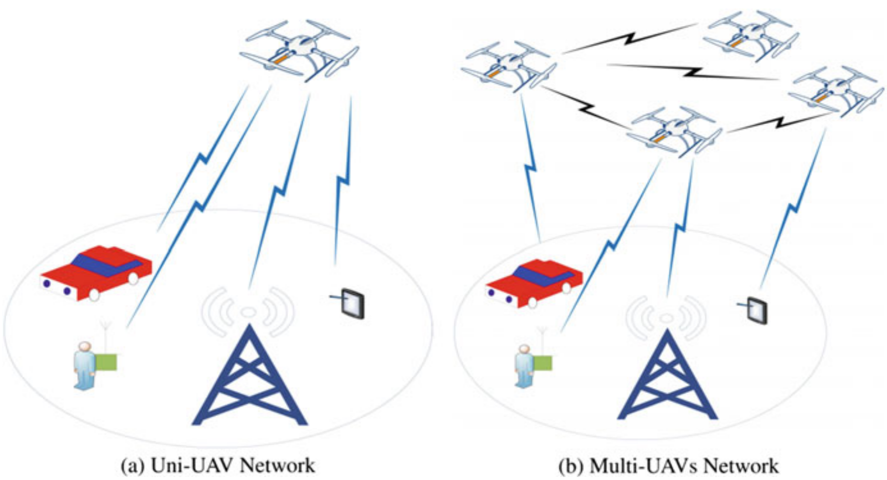

Fig. 12.7 (**a**) Uni-UAV network architecture. (**b**) Multi-UAV network architecture [29]

was flying, the controller design method was explored, and it yielded good results. HAUs have a wide range of coverage and are no longer visible everywhere.

However, HAUs are more sophisticated and extremely expensive, and they're frequently utilized as an infrastructure to provide Internet access to a large the population. Furthermore, due of the very large between-cell resistance, HAUs used in remote communication may result in increased force usage. Elevated stages are designed for endurance and long-distance activities. Moreover, HAUs handle a broader range of operations. Interruption and greater energy use are caused by resistance, shading, and dynamic routing blurring. Because of the high frequency of LOS correlation and the lower likelihood of distortion, energy consumption in HAUs is low. LAUs are beneficial for setting a remote interconnection link using remote technologies.

LAUs are especially appealing because they are easy to send and receive. LAPs can also send out fast LOS communication connections, which can increase performance while consuming less energy. The autonomous drone's path was adjusted by the designers in order to reach the most advantageous locations with the least amount of transmission capacity.

LAUs can be completely reliant on the needs of their clients. In open security application circumstances, a UAV is a truly acceptable solution for delivering a fast and ubiquitous service availability. The design of UAVs has a significant impact on energy consumption due to the large number of UAVs. All of these have their own range of opportunities, restrictions, and issues. Static wings are small unmanned drone systems with isolated particular features, disadvantages, and basic challenges. These are simple in design and provide deficit correction, strength, inexpensive, and low energy. Static-wing unmanned drone vehicles travel at a high rate and are extremely capable of doing high-energy tasks. The traditional energy utilization model was designed for energy-efficient unmanned drone transmission [30, 31].

An energy-efficient unmanned drone communication infrastructure was researched here, with the goal of extending a given flying period. An intelligent architecture for a static-wing unmanned drone, in particular, was built with low power consumption in mind. Unmanned drones with rotatory wings do the majority of today's reality connection operations. They have the ability to fly over a certain spot, allowing for vertical arrival without the need for a long voyage [32].

When ground earthbound base stations are briefly demolished in catastrophic conditions such as floods, tremors, and fires, they can quickly take flight and respond to change in order to carry out on-request adaptable connection to terrestrial customers. Under the current circumstances, it is extremely impossible to build another terrestrial station in such a short timeframe. The relationship between energy-efficient unmanned drones and spinning winged unmanned drones was investigated, and the least force-intensive notable model for curved wing unmanned drones was discovered.

Unmanned drones with rotatory or dynamic wings are tough to build. Nonetheless, they are capable of moving in a relevant area while being secure. This type of autonomous drone has poor movement and must rely on vital energy to defy gravity.

The building of rotatory-wing UAVs is complicated. They are, nevertheless, capable of drifting in a useful region while maintaining a low demeanour. Unmanned drones of this type have limited mobility and rely on vital energy to travel against gravitation [33, 34].

12.6.3 Organization-Based Classification Schemes

Constructing unmanned drone systems is highly important to better understand the benefits and drawbacks. For example, unmanned drone organization development and geographic location, how quickly geography changes, the number and type of unmanned drones required for good organizational operation, fairly reasonable technology for unmanned drone organizations, and whether an unmanned drone network consistently maintains the discharge or augmentation of a centre point There are two types of unmanned drone organizations: single-unmanned aircraft organizations and multi-unmanned aircraft organizations.

It mostly comprises of unmanned aircraft of the unmanned drone category. In both civil and military situations, UAVs have a wide range of applications. They can be utilized in war operations including surveillance, attack, monitoring, guarding, transportation, and reducing intimidation, as well as civilian operations like disaster relief, gardening, and medical care. UAVs (Uni-UAVs) are represented in a network. This design is more energy efficient, but it's only suitable for military situations with low security threats and few inclusion requirements.

At least one ground station centre and multiple aerial unmanned aircraft make up a multi-unmanned drone network. The capacity to maintain robust connectivity between unmanned drones and base stations while consuming less energy and delivering more data is the most major advantage of multi-unmanned aerial vehicular communications [32, 34].

As a result, the risk of resentment is reduced, and the most comprehensive coverage is available at a low cost. In a multi-unmanned drone network, the control framework or base station will only communicate with a few unmanned drones, and these connected unmanned drones will ensure the safety of the other UAVs in the network, as depicted.

A multi-unmanned drone network consists of at least one base station hub and more than one aerial UAV.

The most significant advantage of multi-unmanned uav networks is the ability to maintain a strong connection between the unmanned drones and the base stations while consuming less energy and transmitting more data.

12.6.4 Applications-Based Classification Schemes

According to their applications, we've divided unmanned drones into three categories: (1) commercial, (2) public safety, and (3) observation UAVs.

The focus of this study is on public health applications, with many applications being briefly addressed in the process. UAVs can be used to enable device-driven connectivity in the public health sector. That is, in unfortunate conditions, gadgets/clients can directly communicate with unmanned drones and among themselves. Unmanned aircraft are also utilized to facilitate crisis communication for railway customers during a catastrophe, since they collect data on the train's mishap-affected passengers.

12.7 Public Safety Services with a Multilayer Infrastructure

The idea of layered unmanned drone swarm engineering is useful to address the challenges of low immobility and steering obstacles in shifting unmanned drone network geography for safety communication. In this framework, no provision is included to allow for interaction in the foundation basements in the event of a disaster. To counteract it, we suggest a unique design that can provide an alternative communication path even if the first one fails [35, 36].

The multilayer framework consists of three major sections: (1) basement (storm cellar), (2) earth, and (3) air. The basement station is close by, and there is a help communication linkage. A few transceivers and help connections are also delivered to work on increased signal strength to enable intersections in the structure cellar. To avoid correspondence failure in the storm cellar, a supplementary life saver link is also transmitted to provide an alternate communication path, ensuring catastrophic site communications inclusion in any scenario, even if the TBS is lost. The unmanned drone layer can also be used to enable corner figuring correspondences to increase energy productivity by reducing idleness. As a result, the suggested technology can be used in open health exchanges.

12.8 Third-Generation Partnership Project (3GPP)

The 3GPP specified an investigation component with four critical destinations in the beginning of 2017:

- An acknowledgement of the specifications for unmanned drone traffic
- The creation of a connection model that integrates air-to-ground spread features
- Confirmation that the current LTE structure used to provide different connection for space-borne devices

- The importance of the modifications required to effectively service unmanned drone traffic based on LTE

The 3GPP defined the receiving signal that cellular modems must support for unmanned drones that operate at both the ground level and at 300 metres. According to these observations, unmanned drones are prone to downlink and uplink blocking issues. This is due to two factors: flying unmanned drones (UAVs) are projected to be in line with a significant number of such ground stations, and the vast majority of these stations are downwardly inclined.

12.9 Drones: Challenges and Opportunities

This section discusses the standing issues in drones, namely, challenges and opportunities to resolve.

12.9.1 Drones Route Optimization

Energy consumption, routing charge, operational charge, obstacle detection, transmission overhead, and trip cost all play a role in UAV route optimization. The computational optimization technique has encountered various challenges as a result of the huge rise in variable elements when resolving the routing problem for UAVs [37].

To tackle this problem, future research could use nature-inspired artificial optimization techniques. The utilization of clusters of UAVs for collaborative task performance using an environment swarm-based approach is an exciting new research area. Furthermore, reinforcement learning for UAV motion control is one of the hottest study fields in the near future. Deep learning is a promising domain for developing and optimizing UAV communication systems.

UAVs should be able to change their orientation and movement in response to terrestrial clients and flying trajectory using reinforcement deep learning. They must be able to forecast the attitude of the base station using machine learning and quickly launch UAVs in the best possible location.

12.9.2 Anonymity and Safety Challenges

Although UAVs serve consumers, users demand anonymity, security, and integrity because the service might be dangerous if data is revealed or misused. Furthermore, because modern technologies frequently need a substantial amount of processing capability and memory resources, energy consumption rises. Combining security with interconnectivity is difficult, yet there is a need to strike a balance between power consumption and reliability [19, 36, 38].

From the safety aspect, creating a system for secure and controlled descent for public security implementations is vital. As a result, a variety of techniques must be proposed that ensure a controlled descent of the aircraft in an emergency, avoiding connection network failures, crashes, and turbine breakdowns. Approaches based on artificial intelligence (AI) present exciting possibilities for UAV wireless data management.

12.9.3 Automation of Refuel Process

The most difficult difficulty in UAV communication settings is running out of fuel. It's necessary to detach the UAV from the network link on a frequent basis for refuelling and maintenance. This, on the other hand, is both costly and complicated. Macro base stations can be employed to handle battery charging and repair.

Solar energy harvesting technologies have recently been deployed, but because solar systems are dependent on the light intensity, they are less efficient than stored energy batteries. Dispersed multiple access wireless transmission mechanisms, as well as distinct energy distribution channels, can aid resource efficiency [21, 23, 29, 39].

12.9.4 Recharging Automation in UAVs

In UAV communication settings, the most difficult problem is running out of fuel. There is a significant need to disconnect the UAV from the relay network on a regular basis for charging and replacement purposes. This, however, is both costly and difficult. The authors created macro base stations in to manage battery recharge and replacement difficulties. Solar energy harvesting strategies have been developed in a recent study, but they are less efficient than fuel and preserved charge batteries because solar approaches are dependent on the intensity of light. Distributed multiple access wireless transmission systems, as well as enhanced power delivery mechanisms, can help to improve fuel efficiency [10, 24, 35].

12.9.5 Managing Swarms in UAVs

Because each UAV may give services to more than one user, controlling several UAVs at the same time is a major challenge. Consequently, controlling and processing a distributed system onboard may result in challenges with coordination, connectivity, and delays. Swarm synchronization of UAVs is also a major issue that requires special attention. Gamification, contract law, optimal transportation principle, deep learning, and optimization theory can all be used to solve these problems. As a result, efficient techniques and procedures are required to confirm and comprehend the scenario, as well as to appropriately manage it [30, 40].

12.9.6 Channel Models: High-Frequency Bands

Result of the latest development of mmWave frequencies for UAVs and other telecommunication technologies, more precise air-to-ground or air-to-air channel models for high frequency are necessary, which take into account wind, humidity, forestry, urban areas, and other areas.

As a result, there are numerous open research issues in this domain, including fast light source training and surveillance, directed and range networking, quick route adjustments, blocking, and multiuser connectivity.

For example, one of the most important challenges is transmitter light direction in order to achieve maximum antenna gain. Layered beam search techniques are effective modulation schemes training and monitoring procedures that can be applied in mmWave bands to decrease grid search complications and operational costs [32, 34].

12.9.7 Massive MIMO

Wireless gadgets now have limited range and mobility in certain settings. They also have to cope with problems with the cluster of UAVs' communications. As a result, the current system is incapable of meeting the demands of public security. MmWave is capable of meeting these standards and can thus be employed in civil protection settings.

12.10 Conclusion

UAVs can be effectively deployed for various satellite networking tasks. To effectively deploy UAVs for specific missions, a number of challenges must be solved. In this research work, we looked at contractual practices from academia, enterprises, and normalization on the vital subject of coordinating UAVs into cell frameworks. According to our research, the 3GPP has lately released new inquiry components to look into the possibilities and constraints of enabling UAVs on the latest 4G mobile networks. Initial reports show that there are a slew of serious worries about the height of UAVs, but that a large majority of them might be addressed by adding more mechanisms to current 4G frameworks. UAVs are projected to be better served by 5G and following improvements.

We looked for service providers who had built and demonstrated unmanned aerial vehicular aerial base stations as proof of their willingness to accept UAVs into interlinks. According to our findings, academics are becoming increasingly interested in this area, resulting in a rise in data and study.

In order to increase public security and individual safety, there may be a growing effort among regulatory agencies to design and invent relevant criteria for unmanned aircraft. Finally, we identified current digital legitimate security challenges, cost and economic models, and future evaluation directions for unmanned drone vehicular cell communication.

We observed that unmanned drone is still in its early phases of development, and we anticipate that interest in this interesting new exploration path will expand in the coming years. In this chaper, we analysed the importance of UAVs in civil protection information exchange from the standpoint of energy efficiency. To support the research's distinctiveness, we then summarized the current surveys in the literature. We have proposed a multilayered framework for exchanging public security information, which has the potential to make wireless routers easier to use in basements. We also looked into how Drones may be placed, interacted with, and routed in a fuel-efficient manner. In addition, we highlighted challenges and opportunities to direct future research work in the field of UAVs.

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Dr. S. Jayanthi is a Professor and Head of Department of Information Technology. She received her Ph.D. from Karpagam Academy of Higher Education, Coimbatore, India, in 2017 and Master of Engineering in Computer Science and Engineering from Anna University, India in 2009. She has 13 years of teaching and research experience. Her research interests include Data Mining, Neural Networks and Big Data analytics. She has published 2 patents and 45 research papers in various national, international conferences and journals. She has delivered invited talks in various national and international conferences and seminars. She has served as an editorial board member and reviewer committee member for many international journals. She has received the Best Faculty Award from Nehru Group of Institutions, Coimbatore, India, in 2019. She has been an active member in many professional bodies, such as the IEEE, MISSE, MISTE, among others.

Dr. H. Shaheen is presently working as an Associate Professor in the Department of Computer Science and Engineering, MVJ College of Engineering, Bangalore Affiliated to VTU, Karnataka, India. She received the B.Tech and ME degrees from Anna University, Chennai, India. She completed her PhD at Karpagam Academy of Higher Education, Coimbatore, India. Her Research interests include Artificial Intelligence, Mobile and Pervasive Computing, Blockchain Technology, Network Security and Web Services. She has published more than 26 papers in refereed international journals and 7 papers in national and international conferences as tutorial presenter. She is an active member of ISTE, IAENG and also editorial board member in IJRAST and reviewer in ASTESJ. She has published more than 15 books, 2 Book Chapters and 7 Patents. She received the IASTE Best Women Faculty – 2018 from the International Association for Science and Technical Education.

Mr. U. Balashivudu is an Assistant Professor, Department of Information Technology, Guru Nanak Institute of Technology, Hyderabad, India. He has more than 10 years of teaching and research experience. He is pursuing PhD in Computer Science and Engineering at Jawaharlal Nehru Technological University, Hyderabad, India. He is a member of IAENG and ICSES. He has published research papers in various reputed international journals. His area of interest includes machine learning, data mining, and information security.

Dr. Meesala Shobha Rani is currently working as an Assistant Professor in the Department of Computer Science and Engineering, MVJ College of Engineering, Bangalore, Karnataka, India. She received her PhD from the Department of Computer Science and Engineering, Vellore Institute of Technology, Vellore, India. She completed her M.Tech from the Karunya University, Coimbatore, India, and B.Tech from JNTU, Anantapur, India. She has published more than 13 papers in refereed international journals and conferences. Her areas of interest include social mining, opinion spam detection, intrusion detection, and sentiment analysis.

Chapter 13
An Overview of Energy Consumption for Unmanned Aerial Vehicle Cellular Communications

Vitalis Afebuame Iguoba

Abstract The emergence of unmanned aerial vehicle (UAV) technology proffers better solution to several problems bedeviling humans in a wide spectrum covering cellular communications, goods delivery, and movies production. However, this promising technology has a problem of short flight duration, due to limited battery life, and the inefficient computer program which impacts performance. In order to address these problems, further research in battery technology and computer program for drone operation becomes imperative. Ultimately, this will yield good quality improvement in cellular communication. This chapter presents an overview of energy consumption of unmanned aerial vehicles in cellular communications. Generally, a proper energy consumption model is required in selecting a UAV for any application, as this will determine the suitability of the UAV for the intended application. The overview reveals that the UAV-aided communication offers a better communication coverage and quality service than the usual terrestrial communications. Therefore, it provides an alternative access to network service in overloaded and congested areas. However, further research in cleaner energy sources and energy-efficient batteries will hold great promise for UAV applications in future wireless communication systems.

Keywords 5G wireless network · Unmanned aerial vehicle · Traffic and obstacles · UAV-aided communication · Battery efficiency · Energy consumption · Line of sight · Octa-rotor configuration · Electronic speed controller · Aerial photography · Fixed-wing drone · UAV-to-ground channel

Acronyms

LoS Line-of-sight
QoS Quality of service

V. A. Iguoba (✉)
Department of Electrical Engineering, Dangote Cement PLC, Obajana, Kogi State, Nigeria
e-mail: iguoba.vitalis@dangote.com

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NLoS	Non-line-of-sight
SBS	Small-cell base station
SNR	Signal-to-noise ratio
U2N	UAV-to-network
UAV	Unmanned aerial vehicle
4G	Fourth generation
5G	Fifth generation
A2G	Air-to-ground
AA	Air-to-air
BS	Base station
CU	Cellular unit
UAS	Unmanned aircraft system

13.1 Introduction

The word “drone” has been in use since the inception of aviation. Drones were remotely used to fly target aircraft used for practice firing warships. An example of such a drone is Fairy Queen of the 1920s and the de-Havilland Queen Bee of 1930s. Later on other special models such as the Airspeed Queen of Wasp and 1.6 km Queen Martinet became prominent. Further research in this area resulted to the invention of “GAF Jinidvik” which still finds application after many years.

An unmanned aerial vehicle (UAV) is simply an aerial vehicle that uses aerodynamic force to generate a lift in the absence of human operator after being “powered” and can either fly by itself or remotely piloted, it can carry light or heavy payload. The word unmanned means “unoccupied” or “inhibited” [20].

The acronym UAV is normally used for military applications of drones. However, UAVs are different from missiles with warhead because the vehicle itself is called munitions.

13.1.1 Categorization of Unmanned Aerial Vehicles

The unmanned aerial vehicle (UAV can simply be categorized into two; Fixed-wing and rotary-wing. Both of them have advantages and disadvantages. The fixed-wing design possesses high speed and heavy payload, a forward motion is compulsory for it to remain in air and they are not appropriate for stationary use. While the rotary-wing drone has a limited speed and payload, they have the ability to move in all directions and also stay stationary in air [7].

Wireless communication will experience a tremendous improvement as UAV performance and mobility issues are resolved [11].

The UAV-to-ground terminal has the advantage of, higher rate of data transmission and good connectivity as the speed of the UAV can adjusted to ensure a good wireless connectivity for bulk data transmission.

Their short-range line-of-sight (LoS) communication connection provides quality performance improvements over the usual method of communication. In 2005, the U.S Department of Defense and U.S Federal Aviation Administration agreed to use the unmanned aircraft system (UAS).

Apart from the software, self-operating UAV also uses a combination of new technologies which enable them to perform its mission in the absence of human interference, the new technology includes cloud computing, computer vision artificial intelligent, machines learning, deep learning, and thermal sensors [15].

In June 2019, RPAS (remotely piloted aircraft system) Canadian Government approved selectable element comprising remotely piloted aircraft, which controls station, the commander, and the required check link and any other element required during flight.

Drone "autonomously" simply means UAV operation without human intervention. That is to say it can carry out its missions by itself. Not all UAVs are necessarily termed "autonomous drones". In autonomous drone's communication management software coordinates flight and pilots the aircraft at the expense of human. Since "autonomous drones" are piloted by software instead of a human, then it is part of UAS by definition, as UAS requires a complete system to operate. The area of application surveying, mapping and transportation of goods, and inspection. Many modern drones used for civilian tax such as film making or racing technically; it can be termed as a UAS.

Percepto solution is an example of UAS comprises drones, a smart charging base, and a data management system. The Percepto base enables the sparrow drones to carry out its mission without a human pilot.

In 2018, the drone market reached $4.4billion and it is expected to hit $63.6 billion by 2025.

13.1.2 Types of UAV

The choice of any particular drone depends on the purpose of such a drone. Basically, there are four types of drones which include the following.

13.1.2.1 Multi-rotor Drones

A multi-rotor UAV as the name implies is a rotorcraft that has more than two lift–generating rotors. This helicopter has adjustable-pitch propeller whose pitch changes as the blade rotates to provide thrust force require to fly and keep the UAV in air. The multicolor has a fixed-pitch blade, this UAV movement is controlled by changing the parallel rotation of the individual rotors so as to vary the drag and torque generated.

The multi-rotor UAV is given in Fig. 13.1, and its advantage is that it provide a simpler rotor mechanics for flight control. In case of malfunction, less damage will

Fig. 13.1 Multi-rotor drones

occur due to the presence of many rotors, as this rotors will enable the drone to come down to the at ease to the ground to prevent severe accident.

The major problem with the multi-rotor drone is their short flying time (usually 15–30 Minutes) and their small payload capability.

The recent multi-rotor drone design is called Tarot T-18 Ready to fly, It is also the most expensive and rugged multi-rotor drone which can carry a payload of up to 8 kg.

Advantages of multi-rotor drones

(i) Low price
(ii) High accessibility
(iii) Great maneuverability
(iv) Ease of use
(v) Vertical takeoff & landing (VTOL)
(vi) Good camera control

Disadvantages of multi-rotor drones

(i) Short flight time
(ii) Small Payload capability
(iii) Low stability in wind

13.1.2.2 Fixed-Wing Drone

This UAV design was actualized with a wing similar to the normal aircraft to generate the lift instead of usual upward lift of rotors. It means, this type of UAV normally use its energy to move forward, not in keeping itself up in the air, this unique characteristic make them very efficient. They also have a central body, two wings with one or two propellers.

Fig. 13.2 Fixed wing drone

This type of UAV is given in Fig. 13.2. The new sense Fly eBee-X has a similar shape to that of the sense Fly and has a aerodynamic efficiency of 30% and improvement in the battery performance. This type of UAV has a longer flight endurance capability (up to 90 minutes). These characteristics make them suitable for long-distance coverage. Like usual, air plane fixed wing drones also require runway or a catapult to launch them. They do not hover in air. They find a very good application in Surveillance, Surveying & Mapping

Advantages of Fixed-wing drone

(i) Long endurance
(ii) Large area coverage
(iii) Fast flight speed
(iv) Great stability
(v) Safer recovery from motor power loss

Disadvantages of fixed-wing drone

(i) High price
(ii) Large takeoff/landing zone is required
(iii) No VTOL/hover
(iv) Challenging to fly
(v) Training is needed
(vi) Low efficient for area mapping

13.1.2.3 Single-Rotor Helicopter Drones

This UAV, as the name simply implies, possesses only one rotor and another rotor at the extreme, this additional rotor is to control the motion. These two rotors mentioned above are used for propulsion and control of the drone. The single rotor is given in Fig. 13.3 and this drone is more efficient in the lift and the battery consumption is less for similar flight operations. Due to this efficiency boost they

Fig. 13.3 Single-rotor helicopter drone

Fig. 13.4 Fixed-wing hybrid VTOL drone

readily use fuel instead of battery. They normally hover in vertical direction, Single rotor drones are used for surveyors and construction

Advantages of single-rotor helicopter drones

(i) Long endurance
(ii) VTOL and hover flight
(iii) High payload capability

Disadvantages of single-rotor helicopter drones

(i) High price
(ii) Dangerous
(iii) Difficult to fly, training is needed.

13.1.2.4 Fixed-Wing Hybrid VTOL Drones

Gradually, this UAV design are becoming more popular in the marketplace. It is simply the additions of the good features of fixed-wing UAV and the single rotor UAV. This unique characteristics makes the hybrid UAV a better choice for commercial applications. This UAV models are widely used for delivery purposes. They can fly upward vertically and later return to the horizontal position while in the air. The fixed-wing hybrid drones is given in Fig. 13.4. They have a long endurance (up to 3 hours).

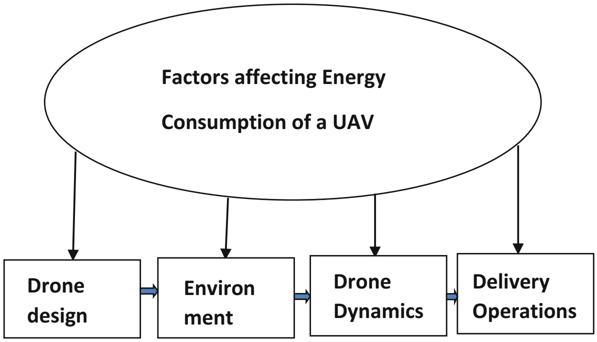


Fig. 13.5 The factors affecting UAV energy consumption

13.1.2.5 Factors Affecting UAV Energy Consumption Can Be Classified into Four Categories

The factors affecting UAV energy consumption is given in Fig. 13.5.

(i) Drone design
(ii) Environment
(iii) Drone dynamics
(iv) Delivery operations

13.1.2.5.1 Drone Design

The design model of a UAV determines the required energy to run such a vehicle. A UAV with a single rotor tends to consume less energy during a flight operation than its multi-rotor counterpart. Increasing the mass of the UAV means increasing the cost of energy to fly such a vehicle [19].

13.1.2.5.2 Environment

The nature of the environment in which a UAV is to fly directly affects its energy consumption. The air density, gravity, wind conditions and weather affect the fly of a UAV.

Without obstacles, a less dense area needs less energy to fly a vehicle than a more dense area with many obstacles such as high tower buildings or trees.

13.1.2.5.3 Drone Dynamics

The drone dynamics of UAV affects the energy consumption. This factors includes: the vehicle airspeed, motion, acceleration/deceleration and the required flight altitude. Aerial vehicles flying at a high airspeed tend to consume more energy than those flying at a lower airspeed. The required flight altitude also determines the energy consumption of a UAV. These factors listed above can affect the energy consumption of the particular vehicle.

13.1.2.5.4 Delivery Operations

The size of a payload, number of deliveries in a particular day, area of service, and empty return all affect a vehicle's energy consumption. The mass of payload to be delivered determine the required energy for such deliveries, increasing the size of payload on a UAV will produce a corresponding increase in the cost of energy. Increasing the delivery payload attributes to increase cost of delivery. The frequency of delivery and the condition of the UAV on empty return will affects the UAV energy consumption. Empty UAV will tend to run at a higher airspeed, leading to a higher energy consumption [2].

13.1.3 The Framework of UAV

The energy density and specific energy of a battery or fuel determine the range of the drone. The Lithium polymer battery technology used for commercial drones produces a short flight range compared to our usual ground vehicle delivery [22].

The drone battery performance is measured as the ratio of the strength-to-weight ratio, increasing the weight means increasing the cost of flying such drones.

The gasoline-powered drone, such as Yamaha RMAX helicopter drone, which is suitable for agricultural use, has a payload capability of 28 kg. Due to the recent advancement and wide applications of electric drones, we will focus on electric drone [3].

At the moment, UAVs are now providing a suitable way for transporting goods to consumers and it offer users the following advantages of reduced cost, low air pollution and increased speed, really major consideration for adopting drone delivery is the drone energy needed, as this will help to decide whether the drone can meet such demand (the flight time), amount of money needed and the pollution associated with it. An accurate evaluation of UAV energy consumption determines the possibility and effective application of the UAV. Such applications include surveillance, wireless communication, inspection and Agriculture [18].

The UAV-Ground offers better network coverage than the usual terrestrial communication and provides alternative network service to overloaded and congested network areas. However there exist some limitations to the application of this UAV-

Ground channel, there is no proper measurement and modeling of UAV-Ground channels as compared to the usual aviation systems.

Signal processing methods such as equalization, detection, and computational algorithm for complex Fourier transforms will improve wireless communication for 5G and beyond [8]. Going by the sudden research interest in wireless communication, the usefulness of signal processing technology cannot be overemphasized.

13.1.4 Contributions to Knowledge

Unmanned aerial vehicle technology has provided an alternative way to usual means of goods delivery, security applications, agricultural applications and performance improvement in Cellular communication. This chapter highlighted UAVs energy consumption estimation and other performance issues. It also juxtaposed the different UAV models so as to determine their suitability for any application. Unmanned aerial vehicle adaptability and suitability for improvement in cellular communication were outlined.

13.1.5 Chapter Organization

This chapter focuses clearly on (design and performance) and challenges UAV faces. Section 13.1 comprises the introduction. Section 13.2 outlines the evolution and different generations of UAV. Section 13.3 presents related works. Section 13.4 provides case study. Section 13.5 provides future trend and conclusion of UAV technology.

13.2 The Evolution of UAV

Signal processing, equalization, detection, and computational for complex fourier transforms has helped us to improve the quality of communications for 5G and beyond. Going by the current research and interests in wireless communications, the usefulness of signal processing cannot be overemphasized [17].

Several research has been carried in UAV technology, the major gap in the available is the lack of accurate energy estimation model which can tell the user the energy required to cover a particular kilometer when all other conditions are met. Apart from the several applications the UAV technology can now provide, its also very essential for wireless communications. They now serve as mobile base station (BS) in some locality where there are no communication signal, over the years this technology has be a game changer for the wireless communication [16].

The applications of UAVs are now meant for different purposes. For example, its now possible to delivers rescue items with UAVs or for agricultural applications At the moment, the allowable operation time of a UAV is quite short, this seems to be a limitation to the use of UAV. Generally, small UAVs have short flight endurance ranges from 5 to 15 minutes. Some big drones can now fly for several hours [4].

13.2.1 Generations of UAV

In the first generation, Basic remote control application a good example is De Havilland DH. 82B Queen Bee aircraft was a low-cost radio-operated drone designed for aerial target practice.

The second generation possesses fixed design, mounted with camera, video recording and photos, and manually piloted. They find a good application for indoor inspections. A good example is FLAYABILITY Elios-2.

In the third generation, they use two-axis gimbal, static design, HD video, assisted piloting, and implemented basic safety models. A good example of in DJ/Mavic 2 which area of application was mainly aerial photography and videography, their flight endurance time was 34 minutes at a speed of 42 mph (67 kph) in sport mode.

There was a transformative design in the fourth generation, with three-axis gimbals, HD video, and availability of intelligent piloting.

A good example is the FREELY AILTA 8 which possess a high-end airmatography. It is a commercial drone. The key difference between the fourth and third generations is that the fourth generation is ideal for movies whereas the third generation is not but only for non-professional movies.

In the fifth generation, it also used transformative designs, 360° gimbals, availability of intelligent piloting and HD video. A good example is DJ/AGRAS MG-1 AGRICULTURE. It was designed for agricultural applications. It helps farmers to gather quality data, offer them the opportunity to remote spray insecticides and fertilizers.

In the sixth generation, there was a good commercial suitability, intelligent piloting models and complete autonomous, good safety and regulation in the designed, pay load adaptability, and automated safety models. A good example is the PARROT ANAFI USA-PUBLIC SAFETY.

In the seventh generation, full commercial compatibility, adhered to safety and regulation in the model, and payload simultaneously, enhanced intelligent piloting models, automated safety modes, full air space awareness, and auto action.

A good example is SENSEFLY EBEE CLASSIC. It has a good capability for mapping and surveying.

13.2.2 Applications of UAV

Over the years, there have been tremendous success in the application of autonomous drones. It is now possible to fly them beyond human sight level while increasing their production, minimizing costs, risks, improving safety, and making drone operation autonomous.

UAVs application includes:

13.2.2.1 General Application

These categories of UAVs find application for general purposes. This is used for activities such as; recreation, disaster relief, law enforcement, terrorism, etc.

13.2.2.2 Commercial

The commercial drones are basically designed for surveillance. Their design consideration is mainly the time of flight required and camera definition needed for such application. The user procured such drones for business application. The aim of any business entity is solely for profit making. These UAVs find applications for the following areas: filmmaking, surveillance scientific, journalism, forestry, solar farming, energy, agriculture, ports, mining, cargo transport, and manufacturing.

13.2.2.3 Warfare

Due to the advancement in UAV technology, the military personnel worldwide, now find this technology very useful to them in tasks such as surveillance, transportation, attack/ combat, and communications purposes [10].

Recently, UAV designs in various capacities are now available for military applications around the globe. Today, more than 100 nations of the world find good UAV applications at various levels. Globally, Military UAV is controlled by the USA, Israel, and China. The U.S military-market shares exceed every other country. Some of the high-profile UAV manufacturers in U.S includes General Atomics, Boeing, Lockheed Martin, and Northrop Grumman, directly following CASC a Chinese company.

13.2.2.4 Aerial Photography

UAVs are very suitable for taking aerial shots, photographs, and filmmaking. In a small-sized UAV, one person can perform the task of piloting and cameraman. Precisely, the big size UAV has a cine camera and such one person cannot perform both operation of piloting and recording. The camera operator who control the recording is different from the pilot. A good example of such drone is AERIGON cinema drone commonly used for movie productions [12].

13.2.2.5 Agriculture and Forestry

The demand for food supply worldwide increases numerically; hence, the manpower needed to meet this demand is reducing daily, The traditional methods of farming are no longer effective, and there is a need to develop new smart agricultural solutions. More progress is expected from the agricultural drones and robotics industry [21]. Today, in Africa, agricultural drones are now used for various agricultural purposes including the detection and fighting of wide fire [14].

13.2.2.6 Law Enforcement

Nowadays, security agencies such as police can now employ UAV technology for search, rescue mission, and traffic monitoring. This particular application of UAV has been implemented by many countries, as it enhances the efficiency of the security networks across various locations.

13.2.2.7 Cellular Communication

A. UAV-Ground channel

   The UAV-assisted communication is given in Fig. 13.6. The usual air-ground channels used by aeronautics for piloted aircraft are well known, whereas the proper evaluation and modeling of UAV-Ground channel are not. While the usual aviation systems have ground site with tall antenna towers, the UAV-Ground channels for UASs are more complex in nature. Obstacles such as buildings and topography block the LoS link in most cases.

B. UAV-UAV channel

   The LoS component mainly controls the UAV-UAV channel. The effect of multipath fading as a result of ground reflection is negligible when compared to UAV-Ground channels. Higher Doppler frequencies may exist in UAV-UAV than UAV-Ground, because of the large comparable velocity between UAVs.

   However, the supremacy of LoS links may be an indication that the new mmWaves communications will be used to achieve high-capacity UAV-UAV wireless communication [10].

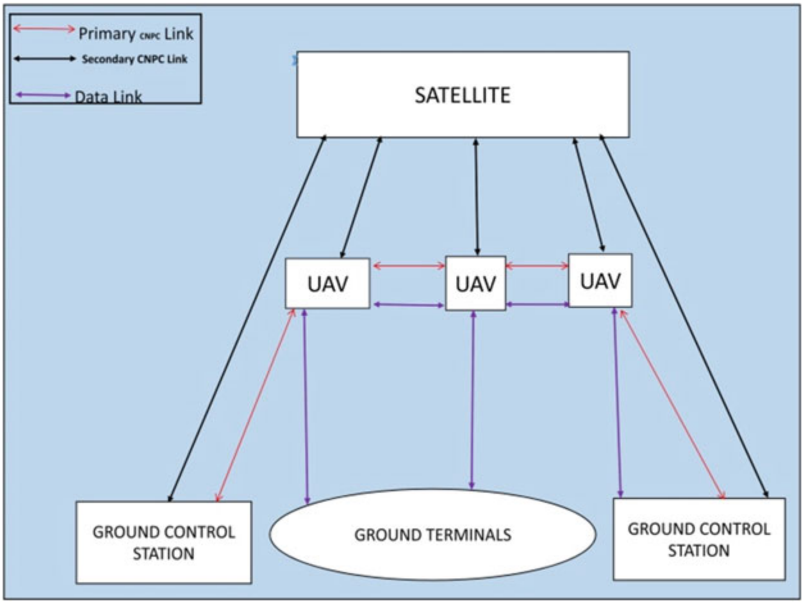


Fig. 13.6 The basic network architecture of a UAV

13.2.3 Parts of a UAV Design

13.2.3.1 The UAV Frame

A UAV's frame determines its shape and holds all the components together.

The UAV frame is the housing that accommodates or carries the entire components. Anything made of carbon, wood, metal, plastic, or fiberglass is called the frame. The frame is simply anything that holds your Drone together. Without which the drone cannot fly. The two main materials used for drone frames are (i) carbon fiber-reinforced composite (CRFCs) and (ii) thermoplastics such as polyester and nylon. Thermoplastics are commonly used for big size industrial UAV due to their availability, cheapness, and can readily be processed into complex parts by using the injection molding process [6].

The weight determines the selection of any particular material for a drone design to strength ratio of the material. Any drone designer aims to choose materials that will help minimize the drone mass, for every gram of material used to produce a drone require a corresponding cost of energy to lift it, reducing the mass of drones enhances the performance in the following ways (i) increased the payload (ii) increased flying time and (iii) reduced inertia and improved maneuverability. Selecting materials with low density enable us to achieve this drone mass minimization.

13.2.3.2 Motors and Propellers

A thrust is the lifting force for a UAV, providing the adequate thrust is necessary without which the UAV cannot be lifted off the ground.

Drones are either driven by electric motors or fuel engine. Our focus in this chapter electric- driven UAV. The electric motor has a permanent magnet and windings-copper laminations. The casing of this motor can either be made of thermoplastics or aluminum alloys to reduce the weight and good strength-to-weight ratio.

The rotor has blades that are required to turn at a high speed, as mechanical wear-and-tear will occur during operation. The rotor blades are either made of carbon fiber-reinforced composite or thermoplastics. There are two types of motors used in drones: brushed and brushless motors. The brushless motor is more powerful for their weight advantage than the equivalent brushed motors, bigger drone design uses the brushless motors whereas small drone design use brush motors.

13.2.3.3 Battery

This can simply be termed as the power to fly a UAV. The battery serves as the source of energy for a UAV operation. The battery performance is directly proportional to the overall performance of the drone. Improvement in battery technology will produce a corresponding increase in the fly time duration of a UAV, as this can be termed as its performance [5].

The battery performance can be measured from the strength-to-weight ratio. Battery ability to produce energy in terms of mass is measured by The specific energy (J/Kg), the joule per unit kilogram, and specific power (W/Kg), which is the watts per unit kilogram.

The traditional lead-acid and Ni-Cd batteries does not find a good application for UAV operations due to their excessive weight [9].

At the moment, Lithium ion batteries produce sufficient energy at the and a light weight, making them more suitable for UAV applications.

13.2.3.4 Electronic Speed Controller (ESC)

The electronic speed controller (ESC) is given in Fig. 13.9. It is an essential part of electric propulsion system's hardware. It acts like the brain of the system by telling the motor how fast to go based on data signals it receives from the throttle controller.

For smaller applications like drones and RC vehicles, this controller has the name "ESC", whereas for larger manufacturing applications it may be called an electronic control unit, inverter, or motor controller. The mechanism within the ESC as well as its interaction with the battery and motor are quite fascinating. In this article, we will cover the fundamentals on how ESCs work, the protocols they use, and how they are used to control brushless motors and drones. The role of the ESC is to act

Fig. 13.7 The controller communicates with the drone's onboard throttle receiver

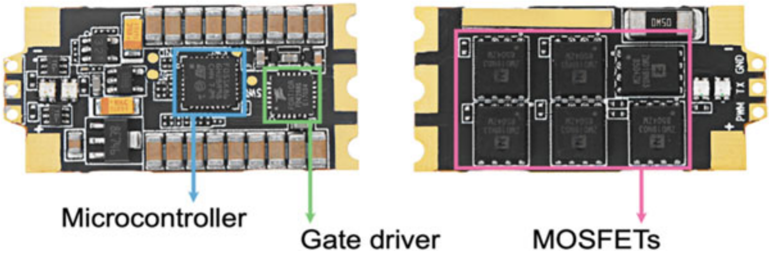


Fig. 13.8 Key component of an ESC

as the regulating middleman between the battery and the electric motor. It controls the rotation of the motor by supplying timed electric signals that are converted into speed variation. It uses the direct current from the battery coupled with a switch system to achieve an alternating three-phase current that is sent to the motor.

The vehicle's throttle controller is used to change the rotation of the motor, whether it be an electric car, plane, or drone. Increasing the throttle increases the output power, which modifies the frequency at which the switches open and close in the ESC's system (Fig. 13.7).

There are several signal delivery protocols that are used to convey throttle information from the remote controller to the ESC. The protocol performance is not uniform; the readily available ones being PWM, Oneshot, Multishot, and Dshot. Their significant difference is the frequency of signals they deliver. Lower frequencies allow a faster signal and a quicker drone response time. Furthermore, the Dshot protocol sends digital signal while others send analog signals. Due to the aforementioned reason, Dshot signals are more reliable less affected by electrical noise and with a higher resolution (Fig. 13.8).

13.2.3.5 Microcontroller (MCU)

The microcontroller plays three key roles in the Esc's operation: (1) housing the firmware that interprets the signal from the controller and feeds it in a control loop, (2) keeping track of the motor's position in order to ensure smooth acceleration, (3) sending pulses to the gate driver to achieve a desired command [1].

The firmware used in ESCs is often preinstalled by the manufacturer but an open source version can also be obtained from third party sources. In hobby drones, the preinstalled firmware is generally a variation of BLHeli (either BLHeli_S or BLHeli_32), though other software such as SimonK and KISS are also available. The chosen firmware is most compatible with the hardware as it will determine the ESCs performance and what protocols can be used.

The microcontroller also determines the motor's position through a sensored or sensorless systems that use electronic sensors in the motor to track the rotor's position, which is great for low speed and high torque applications such as ground vehicles.

13.2.3.6 Gate Driver

The gate driver's job is to act as the middle man between the controller and the gate of the MOSFETs. Upon receiving a low-voltage signal from the microcontroller, the gate driver amplifies the signal and delivers a high-voltage signal to the MOSFETs. The driver has lower resistance than the microcontrollers so can deliver higher current, which also amplifies the speed of the signal. This allows for faster switching and lower heat production. Some ESCs have insulation optical chips between the low voltage microcontroller and the high voltage transistors (Fig. 13.9).

13.2.4 The Octa-rotor UAV Configuration

Multi-rotor UAVs have various arrangements. They have a unique characteristics of high lifting and mass reduction, also have 4 arms and 2 rotors attached to all the

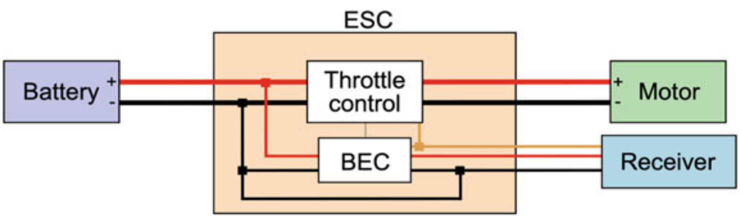
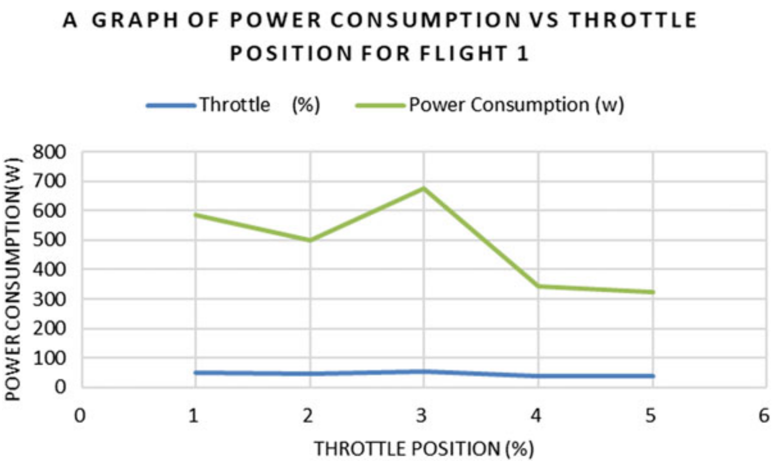


Fig. 13.9 Electric propulsion system wiring including an ESC and BEC



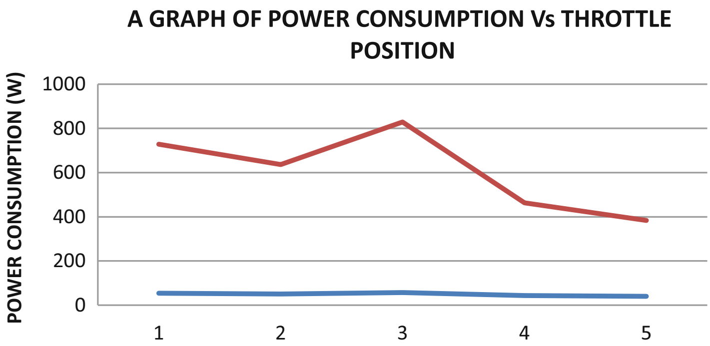


Fig. 13.10 (**a**) A graph of power consumption versus throttle position for flight 1. (**b**) A graph of power consumption versus throttle position for flight 2

arms, however, they have a disadvantage of 22% motor thrust loss at lower level [5]. The performance analysis for flight missions 1 and 2 are given in Fig. 13.10a, b, and the parameters are presented in Table 13.1.

13.2.4.1 Blade Element Momentum Theory

Momentum theory considers the propeller as a simple actuator disk. It can speed up the flow of air in the axial direction, and this air is used to pressurize the propeller plane. The propeller is then seen as a continuous circular disk with infinite blades. This theory assumed the inflow and outflow of air through it, as air flows through a tube.

Table 13.1 UAV power consumption

UAV power consumption in flight test								
	Flight test 1				Flight test 2			
	UAV total weight: 30 kg				UAV total weight: 35 kg			
Movement	Throttle (%)	Rotation speed (RPM)	Power consumption (w)	No. of motor operation	Throttle (%)	Rotation speed (RPM)	Power consumption (W)	No. of motor operation
Lifting up	50	2250	586.4	8	54	2392	673.9	8
Hover	47	2150	501	8	50	2250	586.4	8
Tilted flight high	54	2392	673.9	4	57	2525	771.9	4
Tilted flight low	40	1950	343.4	4	43	1980	419.6	4
Landing	37	1790	324.4	8	40	1824	343.4	8

13.2.4.2 Power Analysis of Propulsion System

A mechanical device for driving a boat or aircraft has a rotating shaft with more than 2 wide-angled blades connected to it. The propeller rotates at a high rate of speed, and the relative speed provides a push which is called thrust. The manner in which they are made makes them to provide thrust efficiently. It can be described as a spinning wing due to its special shape it can direct flow of air.

13.2.4.3 PWM Value and Throttle Percentage

Pulse width modulation (PWM) is the first ESC protocol and it is still in use. PWM control motor speed by using timed power pulse to determine how fast to turn the motor, it is a function of the input from the throttle controller which sends a signal to the ESC's microcontroller which tells it how much voltage to draw from the battery and deliver to then rotor.

The signal is delivered as pulses, whose width determines for how long voltage is drawn. Voltage pulses ('on') are separated by "off" periods where no voltage is delivered. The greater the ratio of "on" time to "off" time, the more power is delivered and the faster the rotor will turn. The ratio of "on" to "off" time is called the duty cycle. The gate driver takes the voltage from the microcontroller and delivers it to the MOSFETs, where it drives them to switch between its three phases. The higher the incoming voltage to the MOSFETs, the faster they switch phases, and the faster the rotor turns. The energy consumption for flight missions 1 and 2 during lifting up, hover, tilted flight, and landing are given in Figs. 13.11 and 13.12, and their parameters are presented in Tables 13.2 and 13.3, respectively, and the governing energy equation for the rotor is given by Eq. (13.1)

The battery efficiency is the actual amount of energy gotten from a battery compared to the energy put into the battery. The energy from a battery is always

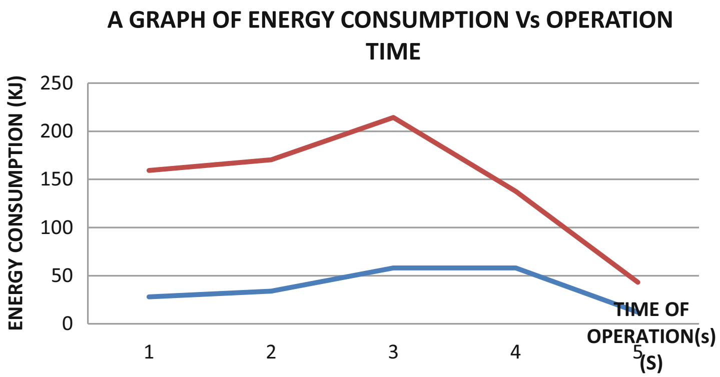


Fig. 13.11 A graph of energy consumption versus time of operation for flight 1

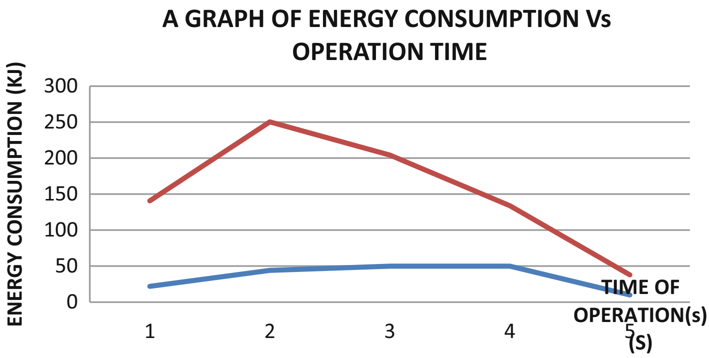


Fig. 13.12 A graph of energy consumption versus time of operation for flight mission 2

Table 13.2 UAV energy consumption

Flight mission		
Movement	Operation time (S)	Energy consumption (KJ)
Lifting up	28	131.3
Hover	34	136.3
Tilted flight high	58	156.3
Tilted flight low	58	79.7
Landing	12	31.1

Table 13.3 Flight mission 2

Flight mission 2		
Movement	Operation time (S)	Energy consumption (KJ)
Lifting up	22	118.6
Hover	44	206.4
Tilted flight high	50	154.4
Tilted flight low	50	83.9
Landing	10	27.9

less than the energy stored in such a battery [13]. Some specific factors give rise to this difference in the battery output power. It is simply the ratio of energy delivered by a battery to the total stored energy in that battery.

Power capacity of a battery is the amount of energy stored in such a battery, and It is usually in watt-hours (Wh). A Wh of battery is the product of the battery's voltage (V) by and the quantity of current (AMPS) and the time duration (hours) which the battery provided the current.

$$\text{Voltage} * \text{Amps} * \text{hours} = \text{Wh} \tag{13.1}$$

13.3 The Future of Drone Technology

At the moment, the drone technology is in between the fifth and the sixth generation, and there exist a gap between the present and the future of drone technology. It will be a game-changing career. Many sectors such as military innovation, exciting hobby, commercial industries transformation, and wireless communication are yet to utilize drone technology fully. The future opportunities in the field are limitless.

13.4 Challenges of UAV Design Technology

The main design challenges for drone technology include the following:

1. The big-size batteries used by drones are heavy and easily get used up.
2. Inability of a UAV to detect Traffic and obstacles.
3. Navigation problems encountered by UAV.
4. UAV-aided communication does not have proper evaluation and modeling of UAV-to-Ground channels. Further research on this will provide a quality improvement in the performance of wireless communications.
5. The computer engineer needs to develop a better computer program for UAV to reduce the wasteful energy during hover condition is not doing any work.

13.5 Conclusion

The summation of the power consumptions of the vital elemental parts has been used to evaluate the total energy consumption of this UAV design, for different flight missions. The mass of a drone determines its energy consumption. It is also a criteria for battery and motor selection [5]. The airspeed and payload of a UAV determine the power consumption for such a mission. The throttle position is proportional to the RPM and the energy of a UAV.

Much energy is wasted during the hover condition, as indicated by the graph energy consumption and time if operation. UAV applications hold a better future for cellular communication than our present terrestrial communication.

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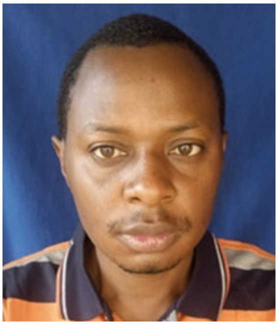

Vitalis Afebuame Iguoba is a Senior Engineer in the Electrical Department at Dangote Cement PLC, Nigeria. He holds a bachelor's degree (Honours) in Electrical and Electronics Engineering from Ambrose Alli University, Ekpoma, Nigeria, in 2012, and an M.Sc. in Electrical and Electronics Engineering from the University of Benin, Benin City, Nigeria, in 2017. In 2014, he joined Interglobal Procurement and Engineering Services (IGPES) at the Amukpe Epic Gas Compressor project (SPDC) as an E&I Engineer. He has worked as an O&M Engineer at Obu Cement Power Plant, Okpella, Nigeria, from 2015 to 2021. He then joined Dangote Cement PLC, Nigeria, as a Senior Engineer in 2021.

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