Chapter 11
Design and Performance Issues in UAV Cellular Communications

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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.

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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

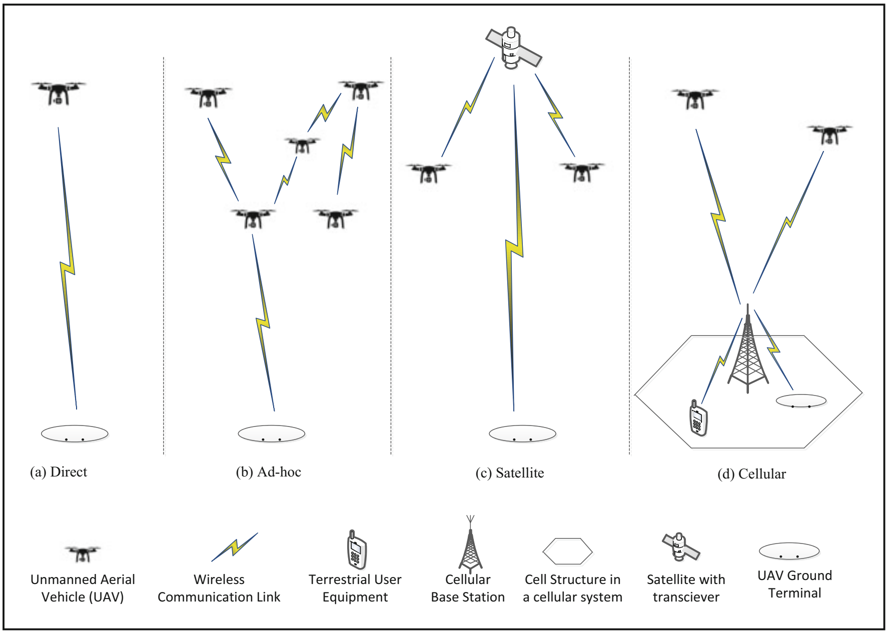

Fig. 11.1 A pictorial view of wireless communication options for UAVs

(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-toearth 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.

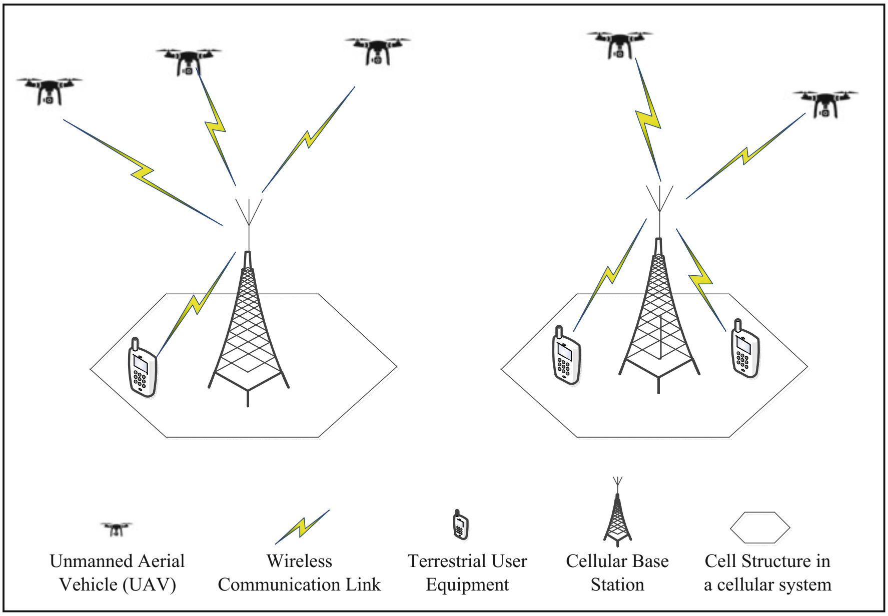

Fig. 11.2 Illustrating UAV-connected cellular communication

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

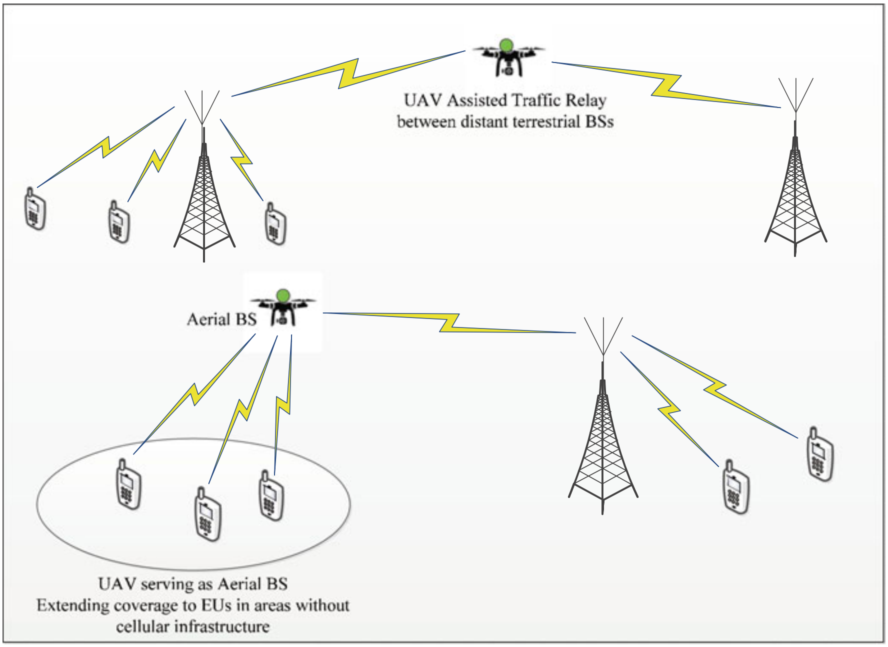

Fig. 11.3 UAV-assisted cellular communication scenario

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 $\mathrm{PL}_{\varepsilon}$ 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:

$$\mathrm{FSPL} = 20\log_{10}\left(\frac{4\pi f_{\mathrm{c}} D}{C}\right), \tag{11.6}$$

f_{c} is the frequency of the carrier in Hertz (Hz), C speed of light in free space (approximately 3×10^{8}m/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

	S-curve parameters		
Environment	*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

$$P_{\mathrm{NLoS}} = 1 - P_{\mathrm{LoS}} \tag{11.10}$$

The sum of the path-loss is given by [12] as

$$\begin{aligned} P_{(\mathrm{FSPL+LoS+NLoS})} &= \left(20\log_{10}\left(\frac{4\pi f_c D}{C}\right) + \Gamma_{\mathrm{NLoS}}\right) + \\ &\left(\left(\Gamma_{\mathrm{LoS}} - \Gamma_{\mathrm{NLoS}}\right) P_{\mathrm{LoS}}\right) + \left(\frac{\Gamma_{\mathrm{LoS}} - \Gamma_{\mathrm{NLoS}}}{\left(1 + s\exp\left(-t(\phi - s)\right)\right)}\right) \end{aligned} \tag{11.11}$$

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

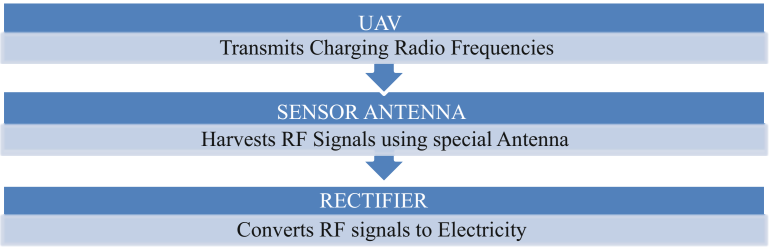

Fig. 11.4 UAV application process for wireless charging of sensors

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].

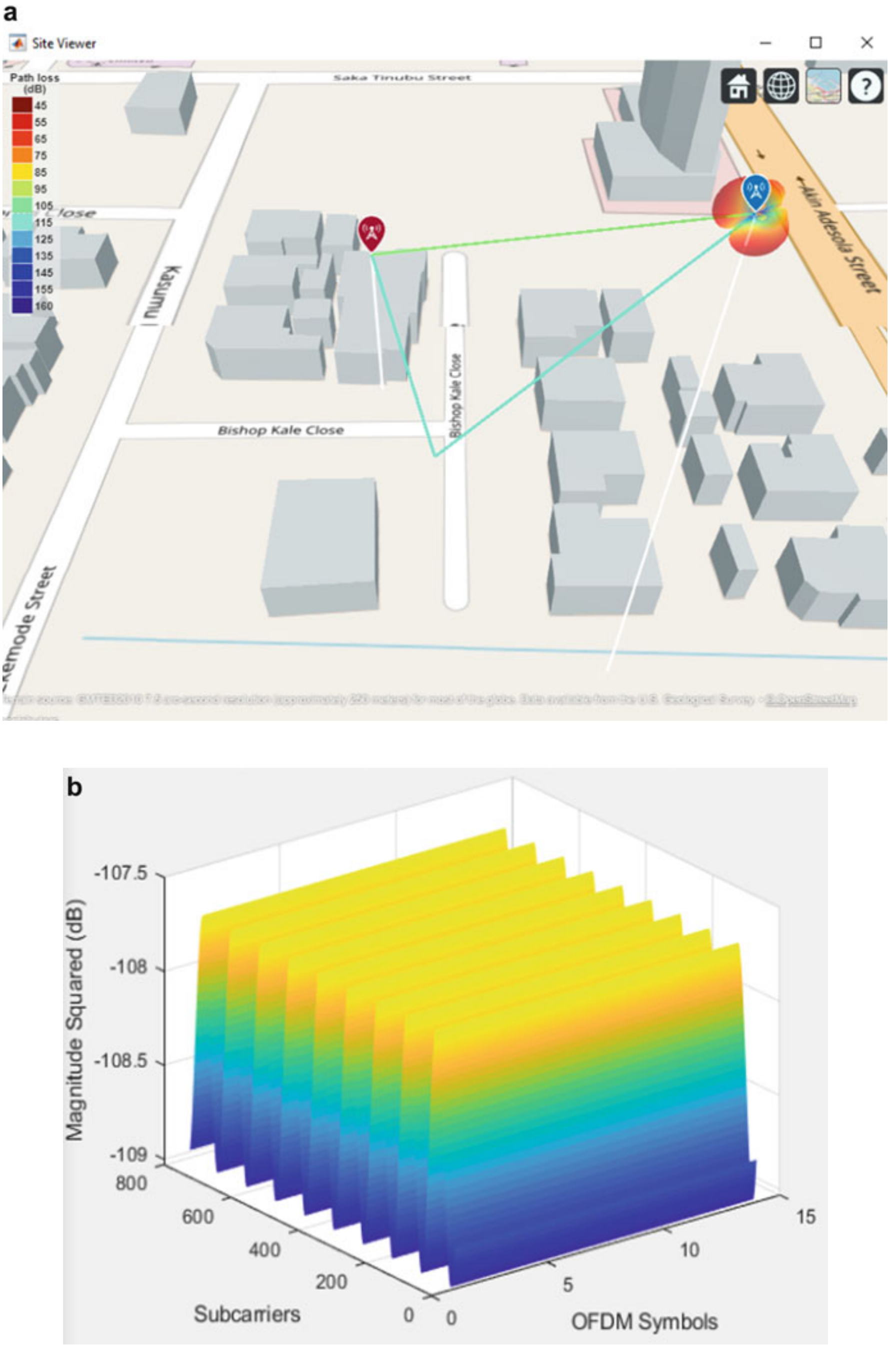

Fig. 11.5 (**a**) Sample simulation block with ray diagram – VI Lagos. (**b**) Channel magnitude response of subcarriers and OFDM symbol

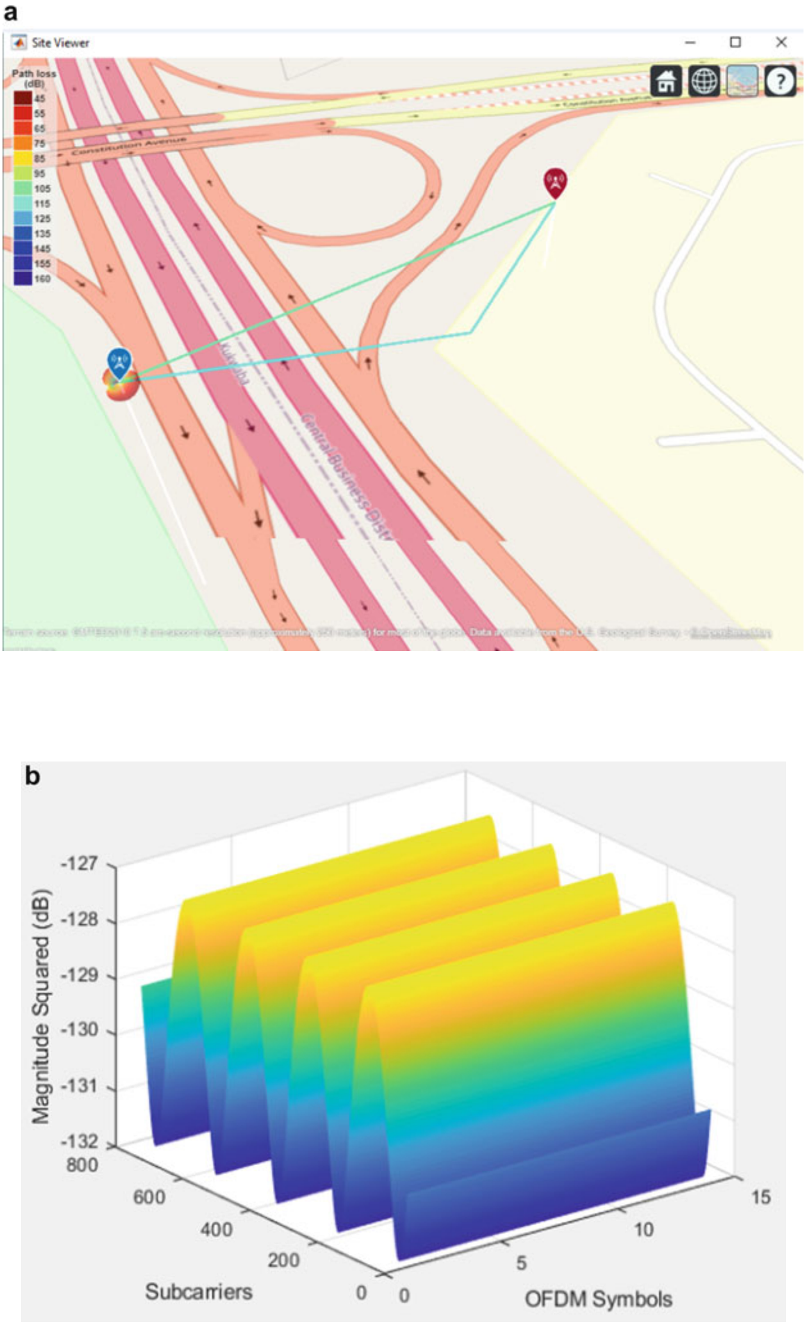

Fig. 11.6 (**a**) Sample simulation block with ray diagram – CBD Abuja. (**b**) Channel magnitude response of subcarriers and OFDM symbol

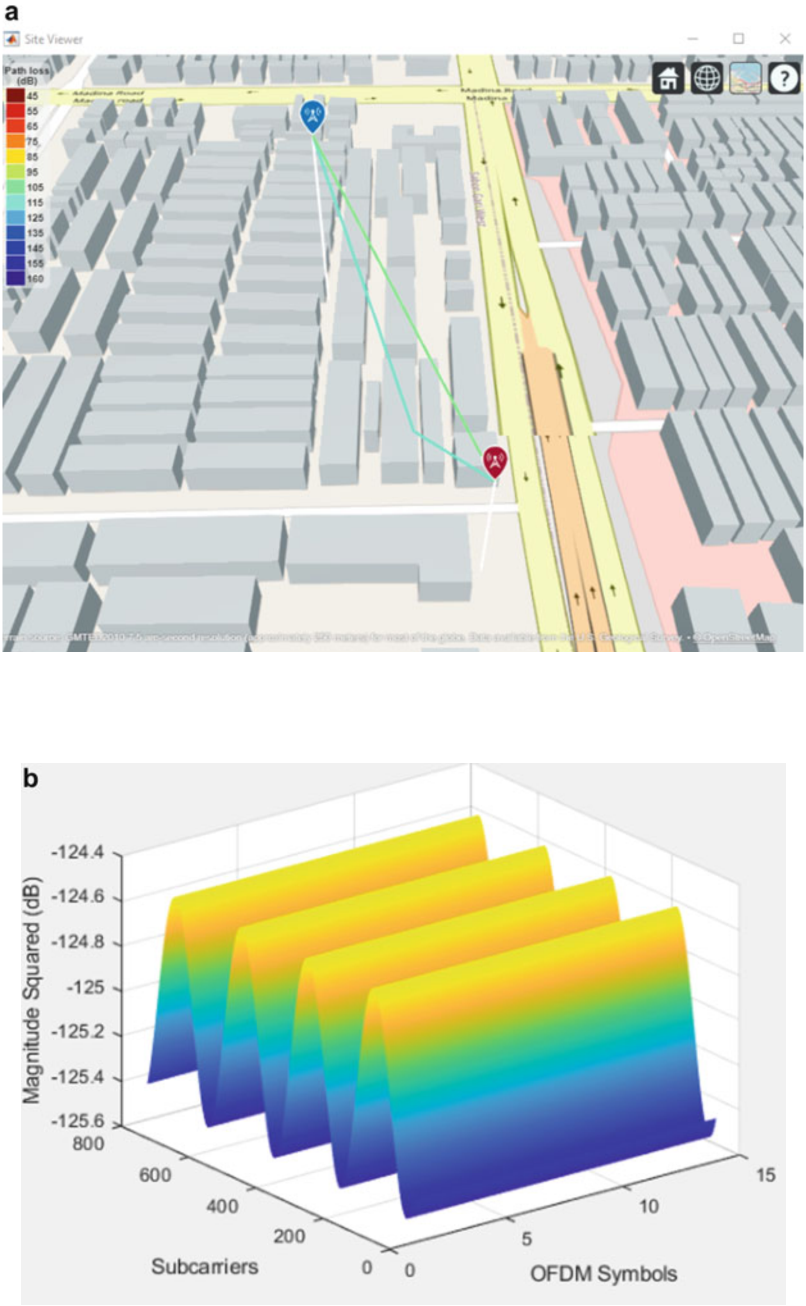

Fig. 11.7 (**a**) Sample simulation block with ray diagram – SG Kano. (**b**) Channel magnitude response of subcarriers and OFDM symbols

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) Reflected ray	Direct ray	UAV height (m)	UAV elevation angle (in degree)
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) Reflected ray	Direct ray	UAV height (m)	UAV elevation angle (in degree)
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)

	Pathloss (dB)			
Iteration no.	Reflected ray	Direct ray	UAV height (m)	UAV elevation angle (in degree)
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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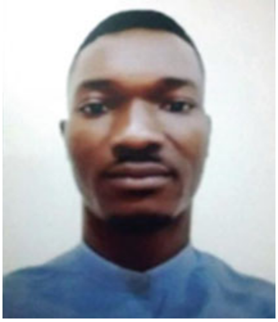

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