Chapter 1
Introduction to UAV Communications

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Abstract Unmanned Aerial Vehicles (UAVs), also known as drones, have experienced a remarkable surge in popularity across diverse sectors, including military, civilian, and commercial domains. Their expansive array of applications promises transformative benefits, but to harness this potential, UAVs rely critically on reliable, efficient communication systems that enable real-time functionality. However, UAV communication systems face several challenges, including limited bandwidth, unreliable connectivity, and susceptibility to interference. In response to these challenges, researchers have diligently explored innovative techniques. Concepts like cognitive radio (CR), cooperative communication, and multiple-input multiple-output (MIMO) systems have emerged as promising strategies to overcome these hurdles, ensuring UAVs can fulfill their missions effectively. Here, we will provide a comprehensive overview of UAV communication systems, delving into the realm of UAV communication systems, exploring their diverse applications, the hurdles they confront, and the cutting-edge solutions proposed to conquer them. Additionally, we spotlight the latest advancements in UAV communications, encompassing the integration of 5G technologies and the emergence of satellite-based communication systems. These cutting-edge technologies hold the potential to redefine the capabilities and reach of UAVs, promising to elevate the landscape of unmanned aerial vehicle technology.

1.1 Development of UAV Communications

Unmanned Aerial Vehicles (UAVs), more commonly referred to as drones, have rapidly gained popularity in recent years. These autonomous aircraft operate without a human pilot on board, offering exceptional versatility and the capability to tackle tasks that are often too perilous or technically demanding for manned flight. UAVs find applications in a wide range of fields, including military reconnaissance, com-

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mercial photography and videography, environmental monitoring, package delivery, agricultural surveys, and search and rescue operations. The proliferation of UAVs continues to transform industries and redefine what is achievable in various domains. Yet, beneath the surface of their impressive capabilities lies a pivotal factor essential to their functionality and success UAV communications. This vital aspect allows these unmanned systems to seamlessly interact with operators, enabling real-time control, data transmission, and situational awareness.

UAV communications encompass two vital categories: control link communications and data link communications, each serving distinct but interconnected purposes.

- **Control Link Communications**: These communications primarily involve transmitting commands from the Control Station (CS) to the UAV. Through the control link, operators provide instructions, adjust flight paths, and ensure safe and precise maneuvering. This real-time connection is essential for maintaining control over the UAV's movements and actions.
- **Data Link Communications**: In contrast, data link communications focus on the exchange of information, data, and feedback between the UAV and the CS. This two-way data flow enables the transmission of critical data, such as telemetry information, payload data (such as images and sensor readings), and situational awareness updates. These data links provide operators with a comprehensive view of the UAV's status and the environment in which it operates.

Collectively, UAV communications empower operators and autonomous systems to remotely control UAVs, continuously monitor their operational status, and receive real-time data updates. This comprehensive approach fosters precise control, efficient data transmission, and effective coordination among UAVs and their associated communication systems.

As UAVs are inherently mobile and can operate in various environments, including remote or hard-to-reach locations, UAV communications harness wireless communication technologies to establish and sustain connectivity, facilitating seamless interactions between UAVs and various devices, such as ground terminals, satellites, and even other UAVs. The methods utilized within UAV communications encompass a range of communication technologies, including radio frequency (RF) communication, such as Wi-Fi, Bluetooth, and dedicated RF links, as well as satellite communication for beyond-line-of-sight (BLOS) operations. Additionally, UAV communication systems may employ networking protocols and technologies like mesh or ad-hoc networks to establish robust and resilient communication links, particularly in scenarios involving multiple UAVs or challenging and remote environments.

While UAVs have transformed numerous applications with their capabilities, they also bring forth a set of security challenges, particularly in the realm of wireless communications. As UAVs become increasingly integrated into everyday operations, ensuring the security of these communication systems is paramount. Here are some key security concerns:

(1) Frequency Interference: UAVs rely on wireless communication systems that operate in specific frequency bands. Frequency interference from other devices or communication systems can disrupt or degrade UAV communication signals, leading to loss of control or compromised data transmission. Proper frequency allocation, spectrum management, and interference mitigation techniques are essential to address this safety problem. The contribution of [1] is to explore the vulnerability of UAVs to deceptive Global Positioning System (GPS) signals. It investigate the potential risks and impacts of spoofing or jamming GPS signals on UAV navigation and operation.
(2) Signal Loss and Link Failure: UAVs may experience signal loss or link failures due to obstructions, radio signal propagation limitations, or technical issues. Loss of communication links can result in losing control over the UAV. Implementing robust communication protocols, redundancy mechanisms, and fail-safe procedures is crucial to ensure UAVs can safely return to a pre-defined state or execute contingency plans during communication loss. Ref. [2] provided path loss exponents for an open field and a campus scenario. Path loss exponent is a parameter used to model the attenuation of wireless signals as they propagate through a medium. This paper is likely to contain empirical measurements and signal propagation analysis specific to these environments.
(3) Cybersecurity Vulnerabilities: UAV communication systems are susceptible to cybersecurity threats, including unauthorized access, data breaches, and cyber-attacks. Malicious actors may attempt to intercept or manipulate UAV communication, leading to unauthorized control, tampering with data transmission, or disrupting the UAV's operation. Strong encryption, authentication protocols, intrusion detection systems, and secure communication standards are necessary to mitigate cybersecurity risks and safeguard UAV communication.
(4) Spectrum Congestion: As the number of UAVs in operation increases, airspace congestion, and spectrum overcrowding can occur, especially in densely populated areas or during large-scale events. Spectrum congestion can lead to communication delays, decreased reliability, and compromised UAV operations. Implementing effective spectrum management strategies, dynamic spectrum allocation techniques and traffic control mechanisms can help alleviate this safety problem [3, 4].
(5) Human Error and Operator Training: UAV communications' safety also depends on the proficiency and training of the UAV operators. Human errors in managing communication systems, misinterpretation of data, or failure to respond to communication issues can impact the safety of UAV operations. Proper training, certification, and adherence to standard operating procedures are crucial to minimize human-related safety risks.
(6) Environmental Factors: UAV communication is not immune to environmental factors, which can include weather disturbances, electromagnetic interference, or geographical obstacles. These external conditions, such as high winds, severe

weather events, or signal reflection, have the potential to disrupt communication links or lead to signal degradation [5]. Recognizing and addressing these environmental limitations is crucial for maintaining the safety and reliability of UAV communications [6]. Implementing robust communication systems that can withstand such challenges ensures that UAV operations remain secure and effective, even in adverse conditions. By proactively considering environmental factors and engineering solutions to mitigate their impact, UAV operators can enhance the resilience and overall performance of their communication systems.

Addressing these safety problems requires a holistic approach that combines technical solutions, regulatory frameworks, operator training, and industry collaboration. Ongoing research, development of standardized protocols, and adherence to safety guidelines are essential to enhance UAV communications' safety and foster the safe integration of UAVs into airspace systems [7, 8].

These innovative solutions not only bolster security but also significantly expand the capabilities of UAVs across a diverse range of applications. Below, we highlight a selection of remarkable UAV-based communication systems that have gained prominence in recent years. In the realm of relay networks, UAVs assume a pivotal role as intermediate nodes, facilitating signal transmission between source and destination nodes. Reference [9], the authors focus on a UAV relay network where UAVs serve as amplify-and-forward relays. This pioneering approach capitalizes on UAVs' exceptional mobility, which offers an enticing opportunity to enhance the performance of wireless communication systems. Within the context of data collection, UAVs play a transformative role. In [10] delves into a UAV-enabled data collection framework, where UAVs are dispatched to acquire specific data volumes from fixed ground terminals. The paper navigates critical facets such as data scheduling, energy efficiency, and data quality, crucial considerations in optimizing UAV-enabled data collection scenarios. The concept of non-orthogonal multiple access (NOMA) takes center stage in Ref. [11], presenting a novel framework for UAV networks with massive access capabilities. This paper explores the application of NOMA techniques in UAV networks, with the primary objective of enhancing spectral efficiency and accommodating an extensive array of connected devices. These cutting-edge UAV-based communication systems exemplify the ongoing commitment to advancing UAV capabilities while simultaneously addressing the challenges posed by security and performance. By harnessing UAVs' unique attributes and integrating state-of-the-art technologies, these systems pave the way for more robust, versatile, and efficient UAV operations across numerous domains, ranging from telecommunications to data collection and beyond. As research in this field continues to evolve, so too will the possibilities for enhancing the potential of unmanned aerial vehicles.

1.2 Basic Concept and Features

1.2.1 Composition of UAV Communications

UAV communications can be broadly categorized into different types based on the communication links involved. Here are the four categories you mentioned:

(1) Satellite to UAV Communications: This refers to the communication link between a satellite and a UAV, as shown in Fig. 1.1. Satellites can provide BLOS communication capabilities, enabling UAVs to operate over long distances and in remote areas where direct ground-based communication is limited. Satellite-to-UAV communications typically utilize satellite links for data transmission, control commands, and real-time telemetry, enabling UAVs to access global communication coverage.

(2) UAV to UAV Communications: UAV to UAV communications involve communication links established between multiple UAVs, as shown in Fig. 1.2. This type of communication is essential for tasks such as collaborative missions, swarm operations, coordinated surveillance, or distributed sensing. UAV-to-UAV communications allow for the exchange of information, coordination of actions, and sharing of data among the UAVs, enabling them to work together efficiently and achieve common objectives.

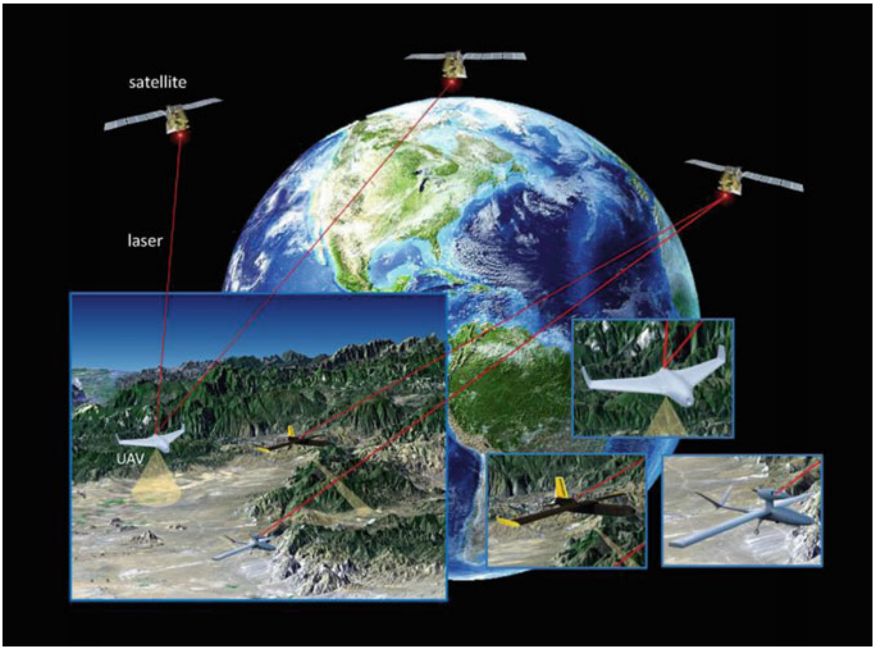

Fig. 1.1 Satellite to UAV communications

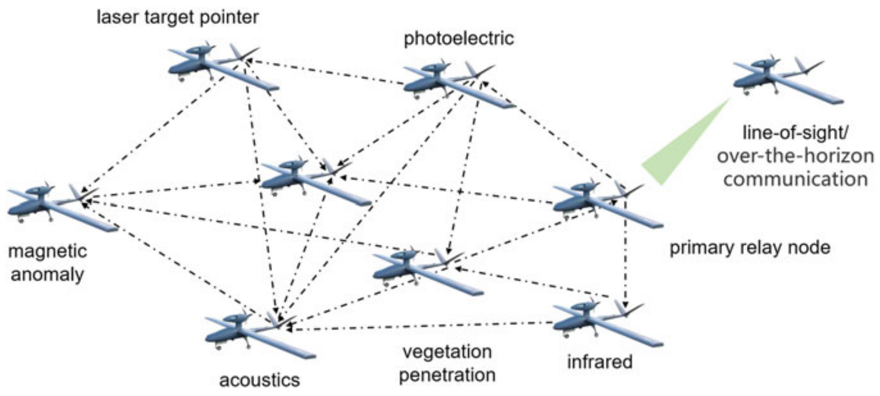

Fig. 1.2 UAV to UAV communications

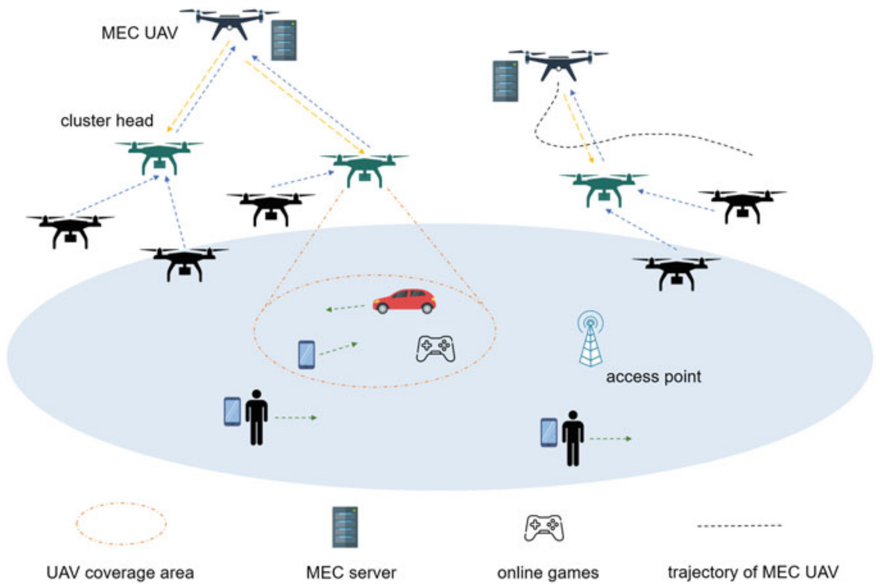

Fig. 1.3 UAV to ground communications

(3) UAV to Ground Communications: UAV-to-ground communications refer to the communication link between a UAV and a ground station or control center, as shown in Fig. 1.3. This link is vital for real-time control, command and control functions, data transmission, and mission monitoring. UAV-to-ground communication allows operators or ground-based systems to control the UAV remotely, receive telemetry data, and exchange commands, ensuring seamless operation and monitoring of the UAV.

(4) Hybrid Communications: Hybrid communications represent an integration of the above-mentioned three communication types, as illustrated in Fig. 1.4. This innovative approach creates a comprehensive communication network, facilitating the seamless exchange of data and control commands between satellites, UAVs, and ground stations. The result is a robust infrastructure that empowers BLOS operations, long-range communication, and uninterrupted connectivity across various platforms. This, in turn, significantly augments the range, versatility, and overall capabilities of UAV communication systems, marking a significant advancement in the field.

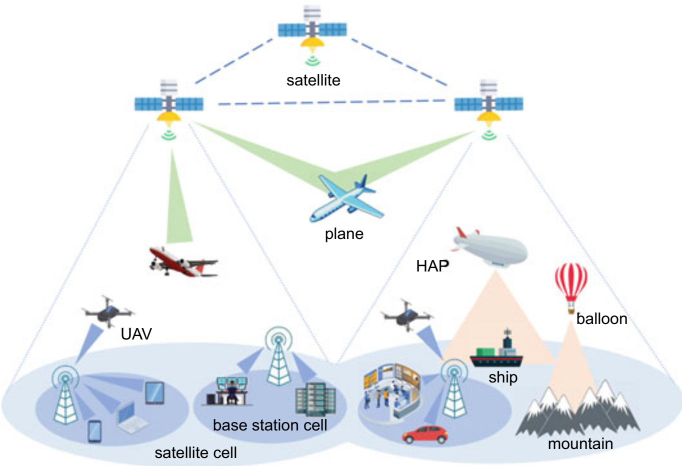

Fig. 1.4 Satellite-UAV-ground communications

These different types of UAV communications serve specific purposes and have their own challenges and requirements. Advancements in technology, such as satellite communication systems, networking protocols, and ground-based infrastructure, improve the efficiency, reliability, and safety of UAV communications across these different linkages.

1.2.2 Features of UAV Communications

UAV communication possesses several distinct characteristics that differentiate it from traditional communication systems. Here are some critical attributes of UAV communication:

(1) Wireless and Remote: UAV communications rely on wireless communication technologies to establish and maintain links between the UAV and the ground

station or other communication nodes. This wireless nature enables UAVs to operate in remote areas, over challenging terrains, and in environments that may be inaccessible or hazardous for humans. Moreover, UAVs can operate on various communication frequencies, including radio frequencies (RF) and satellite communication. The choice of frequency affects factors like data transmission speed, range, and susceptibility to interference.

(2) LOS and BLOS communication: In the realm of UAV communication, two distinct modes exist, LOS and NLOS, each with its own unique characteristics and implications. LOS communication is a fundamental concept in UAV operations, where a direct, unobstructed LOS between the UAV and its control station is required. This type of communication is widely used for remote piloting and real-time data transmission. In LOS scenarios, UAVs typically operate within the visual LOS of their ground stations or operators. This requirement is driven by the nature of RF communication, which relies on a direct path between the UAV and receiver. Any physical obstacles or interference in the LOS can disrupt the RF signals, affecting communication reliability. Consequently, LOS constraints naturally limit the range and operational capabilities of UAVs. In contrast, Beyond-Line-of-Sight (BLOS) communication represents a significant advancement that empowers UAVs to operate beyond the visual line of sight of their operators. BLOS communication harnesses a range of technologies, including satellite communication and long-range radio links, to overcome the limitations of LOS. These technologies enable UAVs to establish communication over extended distances and across obstacles, making them essential for applications requiring long-range surveillance and autonomous package delivery.

(3) Bandwidth Limitations: UAVs often have limited bandwidth available for communication due to frequency spectrum allocation, RF hardware limitations, or the need to conserve power. Therefore, communication protocols and data transmission techniques for UAVs are designed to optimize the utilization of available bandwidth while meeting the specific requirements of the mission or application.

(4) Reliability and Resilience: UAV communication systems must be reliable and resilient to ensure consistent connectivity between the UAV and the ground station. Since UAVs may operate in dynamic and challenging environments, communication systems must handle interference, signal degradation, and other obstacles while maintaining a reliable and stable link. Encryption ensures that the data transmitted between the UAV and the ground control station remains secure and cannot be intercepted by unauthorized parties. This is crucial for maintaining the privacy and integrity of sensitive information. To enhance reliability, some UAVs incorporate redundant communication systems. If one communication link fails, the UAV can seamlessly switch to a backup link to maintain control and data transmission.

(5) Low Latency Requirements: Some UAV applications, such as real-time surveillance or autonomous operations, require low-latency communication. The ability to transmit and receive data with minimal delay is crucial for timely decision-making and responsiveness of UAV systems.

(6) Multi-hop and Mesh Networks: UAVs can form multi-hop or mesh networks, where data is relayed from one UAV to another until it reaches the destination. This enables UAVs to extend their communication range and overcome LOS limitations by leveraging intermediate UAVs as relays. Multi-hop and mesh networking also enhance the resilience and fault tolerance of the communication system.

These characteristics highlight the unique aspects of UAV communications and the challenges involved in establishing reliable, efficient, and secure communication links for UAVs.

1.2.3 Basic Aspects of UAV Communications

1.2.3.1 UAV Communication Channels

In UAV communication, the establishment of connectivity between two devices generally relies on wireless methods, primarily due to the mobility of UAV terminals. Consequently, an in-depth examination of the wireless propagation channel assumes paramount significance as it significantly influences the overall system performance. Numerous existing resources comprehensively encompass the characteristics, ongoing research advancements, as well as the persisting challenges within UAV communication channel modeling. For a more detailed exploration, readers are encouraged to consult [12, 13]. In this section, we will provide an overview of the prevalent channel models widely adopted in the existing literature.

Finding a unified channel model that can accurately represent the propagation characteristics of various UAV communication applications is a challenging task. The end-to-end channel experience for the transmitted signals is contingent upon several factors, such as the selected frequency bands, the scattering properties within the propagation environments, antenna configurations, and the Doppler effects induced by UAV movements. To effectively characterize propagation behavior while operating under specific assumptions and parameters, two primary modeling approaches are commonly embraced: deterministic modeling, stochastic modeling, and geometry-based stochastic modeling.

- **Deterministic Model** This approach operates under the premise that environmental obstructions are arranged in specific layouts, making it particularly suitable for situations where the size of environmental objects greatly exceeds the wavelength. It can accurately depict the realistic behavior of electromagnetic wave propagation but is heavily reliant on the availability of environment-specific databases. In other words, the accuracy of deterministic models hinges on the quality of information pertaining to the environment, including details about terrain topography, electrical properties of buildings, and other obstructive materials. Typically, this type of model is implemented using 3D ray-tracing software. For example, in [14, 15], analytical aerial-ground propagation models are proposed for urban environments, covering frequencies ranging from 200 MHz to 5 GHz and altitudes ranging from 100 to 2000 m. Additionally, a generic path loss model is introduced in [16] using statistical parameters recommended by the International Telecommunication Union at 700, 2000, and 5800 MHz. However, it's important to note that these models may not be readily applicable to different environments and often overlook fading effects caused by small-scale variations.

- **Stochastic Model** These models are constructed on the premise that wireless channel behavior is inherently uncertain, shaped by a multitude of influencing factors that include both large-scale fading and small-scale fading as critical components. Large-scale fading encompasses factors like path loss, which quantifies how signal strength diminishes with distance, and shadowing, which accounts for the effects of obstacles and terrain by introducing random variations in signal strength. The primary contributors to large-scale fading in UAV communication are the dynamics of the UAV itself, including variables such as altitude, distance, and elevation angle, as indicated in [13]. Small-scale fading, on the other hand, refers to rapid and short-term signal strength fluctuations caused by the constructive and destructive interference of multipath components. This phenomenon is typically represented as a complex stochastic process. Small-scale fading is more localized and changes rapidly, often occurring over a limited spatial or temporal scale. In UAV communications, small-scale fading can follow various statistical distributions such as the Loo model, Rayleigh, Rician, or Nakagami, contingent on the specific characteristics of the wireless channel. Stochastic models are valuable for analyzing the time-varying attributes of the UAV channel. However, many existing results primarily offer numerical analyses and often lack validation through measured data. Developing effective stochastic frameworks tailored to the unique characteristics of UAV channels is crucial to advancing our understanding of these systems.

It is worthy to mention that the integration of both deterministic and stochastic models can yield more comprehensive and versatile UAV propagation models. Given the popularity of stochastic models in the performance analysis and system optimization of UAV communications, we will provide a more in-depth introduction to this approach, covering both its widely utilized large-scale and small-scale components.

(1) Large-Scall Fading Models: The large-scall fading occurs when the Line-of-Sight (LOS) path between UAV communication terminals is obstructed by an object that is significantly large relative to the wavelength. In situations where the LOS path remains unobstructed, the only other substantial large-scale effect is the two-ray variation stemming from multipath components. Numerous measurement campaigns have been conducted in the existing literature to study this. One of the most well-known models for this behavior is the log-distance free space path loss model, which can be expressed as:

$$PL(d) = PL_0 + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + X, \tag{1.1}$$

where, PL_0 represents the path loss at the reference distance d_0 in free space and is given by $10 \log \left[\left(\frac{4\pi d_0}{\lambda}\right)\right]$, λ is the wavelength, γ denotes the path loss exponential, which is determined through minimum mean square error best fit and typically falls within the range of 1.5–4. The aerial-aerial channel is generally better than aerial-ground channel in terms of path loss exponent. The variable X accounts for random effects, such as shadowing, or, in the case of LOS channels, variations around the linear fit. The reference distance in the free space path loss model mentioned above can be eliminated and represented by two additional parameters, the slope (α) and the intercept (β). This yields the following expression:

$$PL(d) = 10\alpha \log_{10}(d) + \beta + X. \tag{1.2}$$

This modified model is commonly referred to as the "floating intercept model." In this model, the path loss is determined without the need for a reference distance, and linear least square error regression is employed to fit the data. It's worth noting that while the floating intercept model offers increased flexibility, it may not be as accurate as the free space path loss model at both short and long distances. To improve accuracy, further evaluation of the slope parameter may be required, particularly for different distance ranges. Furthermore, various models take into account shadowing for NLOS paths, as well as additional losses incurred due to other obstacles, as described in [17]. Additionally, modified free-space path loss models that factor in the altitude of UAVs are developed to account for the three-dimensional motion of UAVs, as discussed in [18, 19]. These models offer a more comprehensive understanding of the path loss characteristics in UAV communication systems by considering various environmental factors and UAV dynamics.

Another commonly used model for path loss in UAV communication systems is one that averages the path loss over the probabilities of LOS and NLOS conditions, as presented in [20]. It can be expressed as:

$$PL = \Pr(LOS) \times PL_{LOS} + (1 - \Pr(LOS)) \times PL_{NLOS}, \tag{1.3}$$

where PL_{LOS} and PL_{NLOS} represent the path loss in LOS and NLOS conditions, respectively, while $\Pr(LOS)$ denotes the probability of having a LOS link between the communication terminals. This mixture path loss model calculates an average path loss over a large number of potential LOS and NLOS link possibilities. It's important to exercise caution when using this model in system-level analysis, especially when calculating end metrics such as throughput and outage. The accuracy of this approach relies on the appropriate estimation of LOS probabilities and path loss values in both LOS and NLOS conditions, which can be influenced by the specific characteristics of the environment and the UAV communication system.

In summary, the free space path loss model is the most widely used due to its simplicity and its ability to provide a standard platform for comparing measurements in various environments using a reference distance. However, in scenarios where the reference free space path loss model is not applicable, alternative forms of large-scale models may be employed. The choice of an appropriate path loss model for a given

UAV propagation scenario is of paramount importance, as it significantly impacts the accuracy of system performance predictions and analysis. Careful consideration of the specific environmental and operational conditions is essential in selecting the most suitable model for the task at hand.

(2) Small-Scale Fading Models: Small-scale fading models are typically applied to narrow-band channels or to individual multipath components, often referred to as “taps” in tapped delay line wide-band models, within a certain bandwidth. These stochastic fading models can be derived through various means, including theoretical analysis, empirical data collection, or geometric analysis and simulation. In the following section, we will explore several commonly used models for small-scale fading in the context of UAV communication. These models are crucial for understanding how signal strength fluctuates rapidly over short distances due to factors like multipath propagation, interference, and scattering.

Rayleigh Fading Model: Rayleigh fading is a widely used fading model that assumes a purely scattered propagation environment without a dominant LOS component. It occurs when multiple uncorrelated paths exist between the transmitter and receiver, resulting in a random and fluctuating signal strength. Rayleigh fading is typically observed in urban and dense environments with significant multipath reflections [21, 22]. The samples for the Rayleigh flat-fading samples are drawn in Fig. 1.5 from the following random variable $\mathbf{h} = \|X + jY\|$ where $X \sim N\left(0, \sigma^2/2\right)$ and $Y \sim N\left(0, \sigma^2/2\right)$. The average power in the distribution is $P_a v = \sigma^2$. Therefore to model a channel with $P_a v = 1$, the normal random variables X and Y should have the standard deviation $\sigma = 1/\sqrt{(2)}$. Rayleigh models was theoretically proved to be accurate for cooperative relay based UAV systems, multiple-access ground-aerial channels, and channels for the field measurements with large elevation angles in a mixed-urban environment.

Rician Fading Model: Rayleigh distribution is well suited for the absence of a dominant LOS path between the transmitter and the receiver. However when a LOS path does exist, Rician is more preferred to approximate the fluctuations in the fading channels. Rician fading is a multipath fading model that accounts for a dominant LOS component and scattered or reflected paths. It assumes the received signal combines a dominant signal and multiple weaker scattered signals. Rician fading is applicable in scenarios with a strong LOS path, such as in open areas with limited obstacles [23–25]. Specifically, the fading process can be represented as the sum of a complex exponential and a narrowband complex Gaussian process $g(t)$. If the LOS component arrives at the receiver at an Angle of Arrival (AoA) θ, phase ϕ and with the maximum Doppler frequency f_D, the fading process in baseband can be represented as

$$h(t) = \underbrace{\sqrt{\frac{K\Omega}{K+1}}}_{\text{A:=}} e^{(j2\pi f_D \cos(\theta)t+\phi)} + \underbrace{\sqrt{\frac{\Omega}{K+1}}}_{\text{S:=}} g(t), \tag{1.4}$$

where K represents the Rician K factor given as the ratio of power of LOS component $\left(A^2\right)$ to the power of scattered components $\left(S^2\right)$ marked in the equation above, that is, $K = \frac{A^2}{S^2}$. The received signal power Ω is the sum of power in the LOS component and the power in scattered components, given as $\Omega = A^2 + S^2$. In fact, the severity of the multipath fading in a Rician channel is quantified using the Rician K factor. In Rician fading, the best-case scenario occurs when $K = \infty$, representing a channel with a strong LOS path where the signal behaves like a Gaussian channel. On the other hand, the worst-case Rician fading channel corresponds to $K = 0$, indicating a Rayleigh channel with no LOS path. In practical terms, a high K value signifies a more dominant LOS component, while a low K value implies that the signal is primarily affected by scattered components and lacks a strong LOS path.

Nakagami-*m* Fading Model: Nakagami-*m* fading is a statistical fading model that characterizes the wireless channel as a gamma distribution, which are appropriate for characterizing teh UAV fading channels intended for high altitude applications. It represents a generalization of the Rayleigh fading model, accounting for different levels of severity or fading depth. The parameter m determines the severity of fading, with higher values indicating less severe fading and approaching a non-fading channel [26, 27].

Loo Model: The Loo model is a composite channel model that combines elements of both Rician and Log-Normal distributions. Specifically, it uses a Log-Normal distribution to model the LOS component and typically employs the Rician model for the multipath components. This model is designed to provide a more accurate representation of fading statistics in wireless communication channels. The results given in [28] show that Loo model is effective in capturing the statistical behavior of the channel, particularly in urban settings where multipath and LOS components play crucial roles in signal propagation.

As summarized in [13], fading channel statistics for most UAV communication cases reported in the literature are analyzed with the Nakagami-m and Rician distributions. These fading models are essential for analyzing the performance of UAV communication systems, as shown in Fig. 1.5. They help in designing efficient modulation and coding schemes, evaluating link quality, estimating channel capacity, and optimizing communication strategies to compensate for the variations in signal strength caused by fading effects.

When undertaking theoretical analyses of UAV communication systems, the choice of communication channel model is a critical decision that should align with various factors. These factors include the operational range, data transfer needs, regulatory stipulations, and the existing communication infrastructure specific to the scenarios under consideration. Ensuring this alignment is essential for constructing accurate theoretical models and predictions. Furthermore, strict adherence to local regulations is imperative. This includes securing the requisite licenses or permissions for utilizing particular frequency bands or communication channels in UAV operations. Compliance with these regulations not only fosters legality but also promotes responsible and interference-free UAV communication practices, contributing to the overall safety and reliability of unmanned aerial vehicle operations.

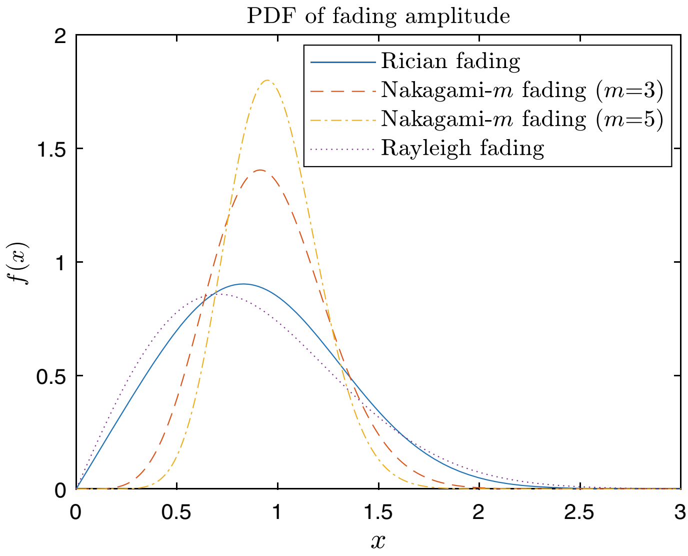

Fig. 1.5 PDF for different fading channels

1.2.3.2 Performance Metrics

Several metrics are commonly used when assessing the performance of UAV communication systems. Here are three key performance indicators:

- **Outage Probability (OP)**: OP measures the probability that the UAV communication system fails to meet a specified quality of service (QoS) threshold, as shown in Fig. 1.6. It is typically defined as a desired data rate or signal-to-noise ratio (SNR) level. A lower OP indicates better system performance, implying a higher likelihood of meeting the desired QoS target.
- **Ergodic Capacity (EC)**: EC represents a UAV communication system's average achievable data rate over a long-term duration, considering fading channel conditions as shown in Fig. 1.7. It captures the channel's statistical behavior and estimates the system's capacity for data transmission. Higher EC implies better overall performance in terms of achievable data rates.
- **Packet Error Rate (PER) or Bit Error Rate (BER)**: PER or BER measures the ratio of erroneous packets or bits to the total transmitted packets or bits, respectively, as shown in Fig. 1.8. These metrics quantify the quality of the received data and assess the impact of errors in the communication system. Lower PER or BER values indicate better system performance and higher reliability in terms of data transmission.

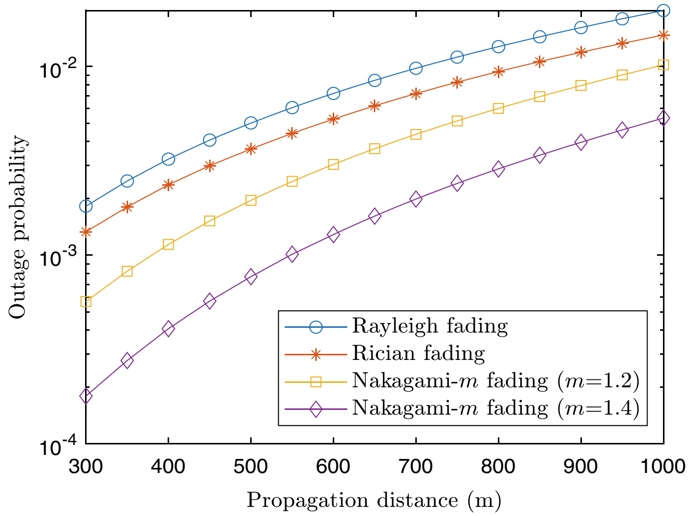

Fig. 1.6 OP for different fading channels

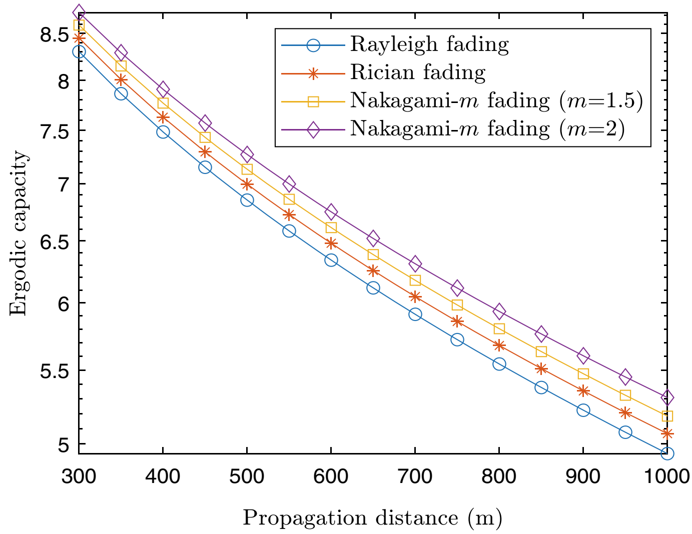

Fig. 1.7 EC for different fading channels

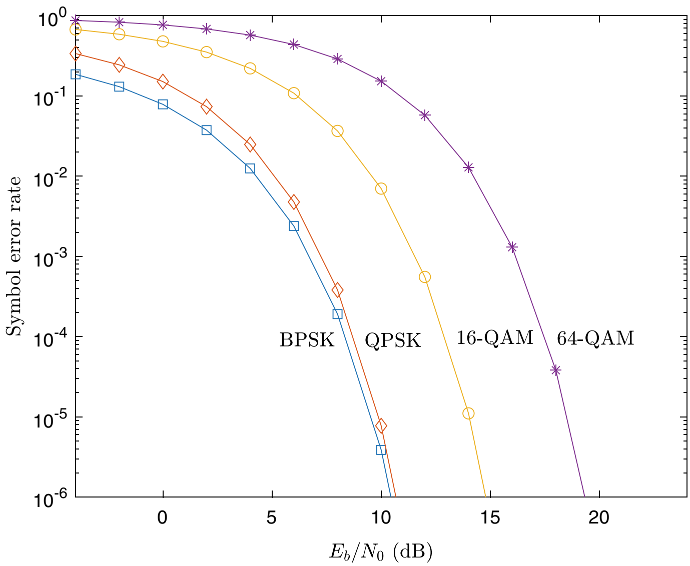

Fig. 1.8 Symbol error rate for different fading channels

These performance metrics are commonly used to evaluate and optimize the performance of UAV communication systems. By analyzing OP, EC, and PER/BER, system designers can make informed decisions about communication protocols, modulation schemes, coding techniques, transmit power control, and other system parameters to ensure reliable and efficient communication between the UAV and the ground station or other communication devices.

The transmission of data in UAV communications unfolds within the expansive three-dimensional aerial space, presenting acute concerns regarding information security. Within this context, the concept of PLS takes center stage, serving as a linchpin for safeguarding the confidentiality and integrity of data as it traverses the physical layer of communication. It utilizes the properties of the wireless channel, such as channel fading, noise, and interference, to provide secure and confidential communication. Through techniques such as beamforming, artificial noise injection, cooperative communication, and the implementation of secure coding schemes, PLS not only enhances the security of UAV communications but also effectively thwarts unauthorized access and eavesdropping attempts. Here, we delve into two pivotal components integral to the domain of PLS:

- **Secrecy Outage Probability (SOP)**: SOP is a metric used to evaluate the level of secrecy or confidentiality achieved in a communication system, as shown in Fig. 1.9. It represents the probability that an eavesdropper can decode the transmitted information above a certain threshold. A lower SOP indicates better protection against eavesdropping and higher confidentiality.

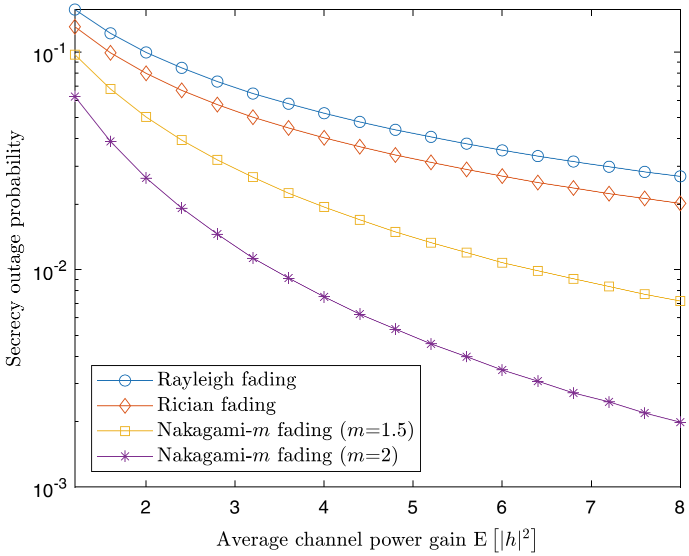

Fig. 1.9 SOP for different fading channels

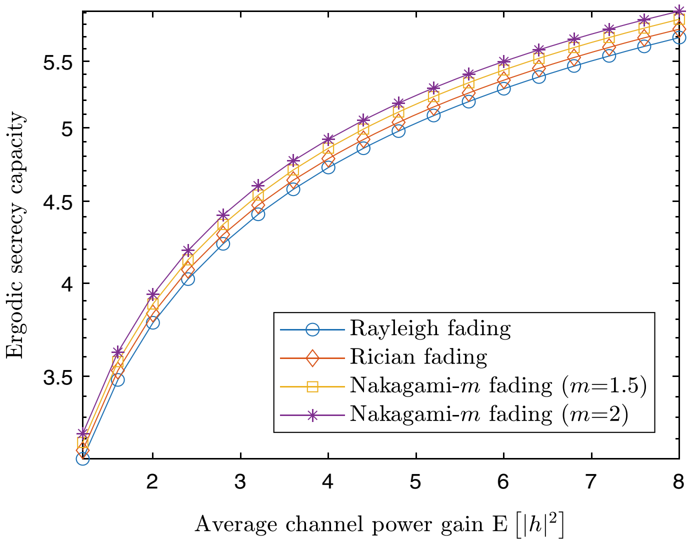

Fig. 1.10 ASC for different fading channels

- **Average Secrecy Capacity (ASC)**: ASC measures a communication system's maximum achievable secrecy rate or information-theoretic security over a long-term average, as shown in Fig. 1.10. It considers both the legitimate receiver's quality of service and the secrecy requirement against eavesdroppers. ASC quantifies the maximum secure communication rate sustained over time, considering the channel conditions and system constraints.

By considering SOP and ASC and leveraging PLS techniques, UAV communication systems can achieve improved confidentiality, integrity, and protection against eavesdropping attacks. These measures safeguard sensitive information transmitted between the UAV, ground station, or other communication devices.

1.2.3.3 A Useful Tool of Modeling the Randomness of Nodes

Stochastic geometry serves as a robust mathematical framework employed to analyze and model the random or probabilistic spatial distribution and behavior of objects. In the context of UAV communication, stochastic geometry plays a pivotal role in both the study and optimization of UAV networks. This branch of mathematics specializes in elucidating spatial patterns and structures that emerge from random geometric processes, encompassing the examination of random point patterns, random tessellations, and various related objects. To provide a deeper understanding of this mathematical discipline, we delve into fundamental formulas and concepts commonly applied in stochastic geometry:

(1) Point process intensity: A point process represents a random collection of points in a given space within stochastic geometry. The intensity of a point process refers to the average number of points per unit area or volume. This parameter serves as a foundational measure for quantifying the spatial distribution of objects within a stochastic framework.
(2) Pair correlation function: The pair correlation function, denoted as $g(r)$, stands as a critical tool for measuring the relative density of points at a distance r from a reference point compared to a random distribution. This function offers valuable insights into the spatial clustering or repulsion characteristics present within a point process.
(3) K-function: Another pivotal measure of spatial clustering or dispersion in a point process is the K-function, denoted as $K(r)$. This function quantifies the expected number of points located within a distance r of a typical point in the process, relative to a random distribution. It provides a complementary perspective on spatial arrangement patterns.
(4) Void probability: The void probability, symbolized as $V(r)$, represents the probability that a randomly chosen point in a point process lies at a distance greater than r from the nearest neighboring point. This measure characterizes the degree of clustering present in a point pattern.
(5) Second-order characteristics: Stochastic geometry often centers on exploring the second-order characteristics of point processes, including the pair correla-

tion function ($g(r)$), the K-function ($K(r)$), and other related measures. These characteristics offer invaluable insights into the spatial organization of points within a given context. They find application in modeling and analyzing diverse phenomena, encompassing the distribution of objects, network connectivity, and coverage within wireless communication systems.

Stochastic geometry provides indispensable tools and techniques for modeling the locations and movements of UAVs, the distribution of ground users or devices, and the intricate characteristics of the communication environment. It enables the consideration of random spatial distributions, movement patterns, and environmental factors, thereby enhancing the understanding and performance of UAV networks. Here are some key applications:

(1) Coverage Analysis: Stochastic geometry is harnessed to assess the coverage probability of UAVs within a designated area. By modeling the spatial arrangements of UAVs, ground users, and potential obstacles, engineers can estimate the likelihood that a ground user will establish a reliable communication link with a nearby UAV. This analysis proves invaluable in optimizing network coverage, particularly in applications such as remote sensing or disaster response.
(2) Interference Modelling: In the complex landscape of UAV networks, interference is a significant concern. Stochastic geometry allows for the in-depth analysis of interference patterns, taking into account the spatial distribution of UAVs and their respective transmit powers. By evaluating interference levels experienced by different users, engineers can strategize optimal deployment approaches to mitigate interference and enhance network reliability.
(3) Path Loss Modeling: Stochastic geometry excels in modeling path loss and signal propagation dynamics, even in intricate and unpredictable environments. This modeling accounts for factors such as terrain, obstacles, and atmospheric conditions, thereby enabling precise predictions of signal strength and the optimization of communication range. Path loss modeling is instrumental in ensuring reliable communication across varying landscapes.
(4) Capacity Analysis: The estimation of network capacity is a crucial aspect of UAV communication systems. Stochastic geometry allows for the modeling of the spatial distribution of UAVs, ground users, communication requirements, and constraints. This comprehensive analysis yields valuable insights into the maximum achievable data rates and overall network capacity, guiding network dimensioning efforts.
(5) Trajectory Planning: Stochastic geometry plays a pivotal role in planning UAV trajectories to optimize various tasks, including data collection, surveillance, and communication. It accounts for diverse factors such as terrain characteristics, obstacles, communication range constraints, and the spatial distribution of targets or points of interest. Through trajectory planning, engineers ensure efficient UAV paths, minimize travel time, and conserve energy resources.

In summary, stochastic geometry provides a powerful mathematical foundation for designing, analyzing, and optimizing UAV communication systems. It is essential to note that the specific mathematical formulations within stochastic geometry vary according to the unique problem or model under consideration. Advanced topics within this discipline delve into models such as Poisson point processes, random tessellations (e.g., Voronoi tessellations), and more intricate spatial structures. Stochastic geometry's versatility and ability to address the spatial challenges inherent in UAV operations make it an invaluable tool for ensuring the reliability, efficiency, and effectiveness of UAV communication networks across diverse real-world scenarios.

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