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Flying Ad Hoc Networks

Cooperative Networking and Resource Allocation

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Wireless Networks

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ISSN 2366-1186 ISSN 2366-1445 (electronic)
Wireless Networks
ISBN 978-981-16-8849-2 ISBN 978-981-16-8850-8 (eBook)
https://doi.org/10.1007/978-981-16-8850-8

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Preface

Reliable unmanned autonomous flight control programs and unmanned aerial vehicles (UAVs) equipped with radio communication devices have been actively developed around the world. Given their low cost, flexible maneuvering, and unmanned operation, UAVs have been widely used in both civilian operations and military missions, including environmental monitoring, emergency communications, express distribution, and even military surveillance and attacks, for example. Although UAV technologies have to some degree matured, given that a range of standards and protocols used in terrestrial wireless networks are not applicable to UAV networks, and that some practical constraints such as battery power and no-fly zone hinder the maneuverability capability of a single UAV, we need to explore advanced communication and networking theories and methods for the sake of supporting future ultra-reliable and low-latency applications. Typically, the full potential of UAV network's functionalities can be tapped with the aid of the cooperation of multiple drones relying on their ad hoc networking, in-network communications, and coordinated control. Furthermore, some swarm intelligence models and algorithms conceived for dynamic negotiation, path programming, formation flight, and task assignment of multiple cooperative drones are also beneficial in terms of extending UAV's functionalities and coverage, as well as of increasing their efficiency. Here, we call the networking and cooperation of multiple drones as the terminology 'flying ad hoc network (FANET)', and there indeed are numerous new challenges to be overcome before the widespread of so-called heterogeneous FANETs.

In this book, we examine a range of technical issues about FANETs from physical-layer channel modeling to MAC-layer resource allocation, and also introducing novel UAV aided mobile edge-computing techniques. With regard to communication channels in FANET, we commence with an introduction about UAV communication channel characteristics including its link budget, major channel fading, and channel impulse response and metrics, followed by three typical kinds of channel model. Moreover, with regard to multi-UAV-assisted seamless information coverage, we present three dynamic seamless coverage strategies for dense urban areas, quality of service (QoS)-guaranteed Internet of things (IoT) networks, as well as for minimum delay constraint. Next, we discuss cooperative resource allocation in FANETs, where we provide two near-optimal joint UAV's position/trajectory and resource allocation algorithms, while also presenting a resource allocation scheme for IoT nonorthogonal multiple access (NOMA) uplink transmission. Finally, we address the mobile edge computing for FANETs, where load balance-oriented, latency- and reliability-guaranteed, and energy-efficient secure UAV-assisted edge-computing schemes are investigated.

The aim of this book is to educate information technology engineers, computer and information scientists, applied mathematicians and statisticians, as well as systems engineers to carve out the critical role that analytical and experimental engineering play in the research and development of FANETs. This book emphasizes on multi-UAV networking technologies and applications in next-generation wireless networks.

To summarize, the key advantages of this book are listed as follows:

1. It provides an introduction to the FANET paradigm, from both physical-layer and upper-layer perspectives, which currently has attracted substantial attention from both academic and industrial areas.
2. It discusses the state of the art for the FANET and its characteristics against other mobile ad hoc networks. It also surveys the basic UAV/FANET communication channels.
3. It highlights three hot topics in FANET, i.e., seamless information coverage, cooperative resource allocation, and mobile edge computing. A range of examples are illustrated in detail so as to provide a wide scope for general readers relying on introducing their problem formulation, solution algorithms, and simulation results in a comprehensive way. These successful cases can guide us to efficiently construct a multi-UAV heterogenous network.

This book is organized as follows: Chap. 1 provides an overview of the FANET concept and discusses it against traditional mobile ad hoc networks. In Chap. 2, we introduce the UAV communication channels. In Chaps. 3–5, we provide study cases to show how to solve the key challenges in multi-UAN-aided seamless information coverage, cooperative resource allocation, and mobile edge computing in FANET, respectively.

Acknowledgments Dr. Jingjing Wang and Dr. Chunxiao Jiang would like to thank those who helped to get this book published, especially our graduate students Zhengru Fang and Zonglin Li who helped to proofread the entire book. Moreover, we would like to acknowledge the support of the National Natural Science Foundation of China and the Young Elite Scientist Sponsorship Program by CAST.

Beijing, China Jingjing Wang
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November 2021

Contents

Acronyms

A2A	Air-to-Air
A2G	Air-to-Ground
ABS	Aerial Base Stations
AI	Artificial Intelligence
AP	Access Point
AWGN	Additive White Gaussian Noise
B5G	Beyond 5G
BCD	Block Coordinate Decent
BLOS	Beyond Line-of-sight
C/N	Carrier-to-noise ratio
CAA	Civil Aviation Administration
CABR	Civil Aviation Administration
CIR	Channel Impulse Response
CNPC	Control and Nonpayload Communication
CSI	Channel State Information
D2D	Device-to-device
eMBB	Enhanced Mobile Broadband
FAA	Federal Aviation Administration
FANET	Flying Ad Hoc Networks
G2G	Ground-to-Ground
GA	Genetic Algorithm
GEO	Geosynchronous Earth Orbit
GR	Greedy Algorithm
GS	Ground Station
ICAO	International Civil Aviation Organization
IoT	Internet of Things
ITU	International Telecommunication Union
LEO	Low Earth Orbit
LMS	Least Mean Square
LOS	Line-of-sight
MANET	Mobile Ad Hoc Networks

MANETs	Mobile Ad Hoc Networks
MEC	Mobile Edge Computing
MIMO	Multiple Input and Multiple Output
mMTC	Massive Machine-type Communication
NOMA	Non-orthogonal Multiple Access
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PLS	Physical-Layer Security
QoS	Quality-of-Service
SCA	Successive Convex Optimization
SIC	Successive Interference Cancellation
SIMO	Single Input and Multiple Output
SISO	Single Input and Single Output
SWIPT	Simultaneous Wireless Information and Power Transfer
TDD	Time Division Duplexing
UAV	Unmanned Aerial Vehicles
UMENs	UAV-enabled Mobile Edge Computing Nodes
uRLLC	Ultra Reliable Low Latency Communication
VANET	Vehicular Ad Hoc Networks
VLOS	Visual Line-of-sight

Chapter 1
Introduction of Flying Ad Hoc Networks

Unmanned Aerial Vehicles (UAV) have been widely used both in military and in civilian applications. However, the cooperation of small and mini drones in a network is capable of further improving both the performance and the coverage area of UAVs. Naturally, there are numerous new challenges to be solved before the wide-spread introduction of multi-UAV based heterogeneous Flying Ad Hoc Networks (FANET), including the formulation of a stable network structure. Meanwhile, an efficient gateway selection algorithm and management mechanism are required as well. On the other hand, the stability control of the hierarchical UAV network guarantees the efficient collaboration of the drones. In this article, we commence with surveying the FANET structure and its protocol architecture. Then, a variety of distributed gateway selection algorithms and cloud-based stability control mechanisms are addressed, complemented by a range of open challenges.

This chapter is organized as follows: We first introduce the basic classification and regulations about UAVs in Sect. 1.1, and then in Sect. 1.2 we compare the differences between FANET, VANET, and MANET. Finally, we elaborate various compelling applications of FANET in Sect. 1.3.

1.1 Basic Classification and Regulation of UAVs

The networking architectures and operations of multi-UAV networks should follow the regulation and supervision of different agencies or governments.

According to the Federal Aviation Administration (FAA) of America, the small or mini unmanned aircraft must indeed remain within visual line-of-sight (VLOS) of the remote pilot in command or visual observers. Moreover, small or mini drones are only allowed daylight operations and must yield right of way to other aircrafts. The person manipulating the flight should hold a remote pilot certificate. Moreover,

J. Wang, C. Jiang, *Flying Ad Hoc Networks*, Wireless Networks,
https://doi.org/10.1007/978-981-16-8850-8_1

the maximum weight, altitude, speed, etc., are strictly regulated by a range of government rules.

As for the Civil Aviation Administration (CAA) of China, it stipulates certain illegal airspace for small and mini UAVs, such as civil airports, military bases, crowded areas, etc. In contrast to the VLOS only flight authorized by the FAA, CAA allows beyond VLOS (BVLOS) flight of small or mini drones. However, these drones must be controlled by the remote pilot, who has to be capable of stopping the flight in case of emergency. Moreover, the CAA regulates the use of the UAV cloud system.

Meanwhile, the Japanese and European authorities have promulgated a series of regulations of small and mini UAVs.

1.2 Differences Between FANET, VANET, MANET, and AANET

In contrast to classic Mobile Ad Hoc Networks (MANET) and Vehicular Ad Hoc Networks (VANET), the mobility and nimble flight attitude of UAV systems have a grave influence on their networking technologies. As a new member of the family of MANET, aeronautical Ad Hoc Network (AANET) constitutes a compelling concept for providing broadband communications above clouds by extending the coverage of Air-to-Ground (A2G) networks to oceanic and remote airspace via autonomous and self-configured wireless networking among commercial passenger airplanes [1]. More explicitly, the middle layer of objects is constituted by the aircraft of an AANET, which are capable of exchanging information with the satellite layer (top layer) and GS layer (bottom layer) via inter-layer links. Furthermore, AANETs are also beneficial for automatic node and route discovery as well as for route maintenance as aircraft fly within the communications range of each other, hence allowing data to be automatically routed between aircraft and to or from the GS. A bird's eye perspective of AANET, MANET, VANET, and FANET is illustrated in the following Table 1.1, where issues, such as the propagation channel, speed, altitude, network scale, power constraint, node density, and security are considered. Although, the MANET has initially been designed both for mobile phones and for vehicles, we have classified vehicles into VANETs, which are specifically developed for connecting vehicles. AANET distinguishes itself from MANET, VANET, and FANET in terms of its features, such as its flying speed, network coverage, and altitude, which directly result in new propagation characteristics and impose challenges both on the data link layer and network layer design. Despite this, compared with AANET, FANET is more suitable for a variety of scenarios due to its UAV system. In rescue, search, and small-scale coverage tasks, FANET has more flexible characteristics.

In [2], Zhou et al. proposed a two-layer aerial-ground cooperative networking architecture, where multiple UAVs forming an aerial subnetwork assist the

Table 1.1 Comparison between existing networks of MANET, VANET, AANET, and FANET

Networks	Objects	Channel	Speed (m/s)	Altitude (m)	Scale (km)	Power	Density	Security
MANET	Mobile phones	Rayleigh	0–1.5	1–250	0.25	Constraint	Dense	Medium
VANET	Vehicles	Rayleigh/Rician	4–36	0.5–5	1	Non-constraint	City: dense Rural:sparse	Life critical
FANET	UAVs	Rayleigh/Rician	8–128	Up to 122	80	Constraint	Mission dependent	Medium
AANET	Airplanes	Rician	245–257	9100–13,000	740	Non-constraint	Populated area: dense Unpopulated area: sparse	Life critical

terrestrial vehicular subnetwork through UAV-to-UAV and UAV-to-ground communications. The UAVs act as intermediate relays due to their flexible mobility, when for example cell-splitting occurs in the terrestrial vehicular subnetwork. The multi-UAV system was first proposed in [3] based on the concept of Flying Ad Hoc Network (FANET), where the network-centric methodology provided the UAVs with the ability to autonomously position themselves for ideal connectivity and to be able to cooperate with other UAVs for the sake of achieving the best effective coverage. Figure 1.1 illustrated a multi-UAV system, relying on ground stations, ground or airborne relay stations, and remote network monitoring stations as backhauls.

The major advantages of the multi-UAV network over its single-UAV counterpart can be summarized in terms of the networking viewpoint as well as the system viewpoint [4, 5]. Specifically, from the networking viewpoint:

- **Improves the attainable transmission efficiency:** Their information transmission capacity, processing rates, and response capability are improved. Multi-UAV

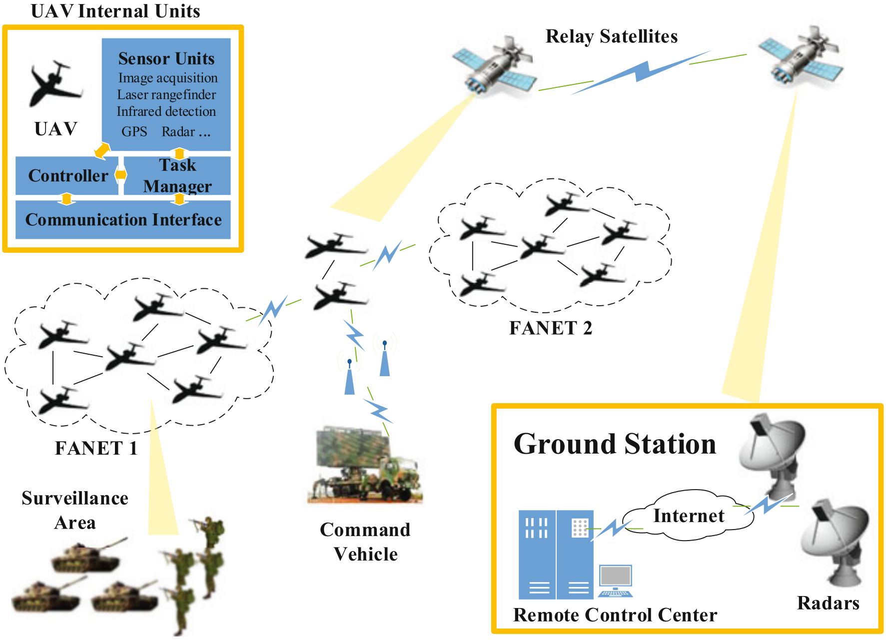

Fig. 1.1 Multi-UAV network architecture and necessary UAV internal units. Specifically, both the small and mini drones should be equipped with sensor units, control and management units, and communication units in order to fulfil certain tasks. Except for some essential sensors, such as the gyroscope, GPS, radar, etc. the drones carry specific sensors, depending on their particular missions. Moreover, the control and management units are responsible for the stable operation and the collaboration of each part. The communication units are composed of multiple modules configured by various protocols, such as IEEE 802.11, IEEE 802.15, LTE, etc. in order to support different communication scenarios [4]

systems extend the range of airborne surveillance. Meanwhile, when the relay link encounters interruptions, to ensure seamless unobstructed communication, the packets to be relayed will be forwarded to other UAVs under the control of the ground station. Additionally, due to the coordination and collaboration among multiple drones, the multi-UAV network exhibits an improved information preprocessing capability and transmission efficiency.

- **Increases survivability:** The multi-UAV network has a high reliability, and it can be constructed anytime and anywhere. Even if some UAV nodes are under attack, others can reconstruct the network and automatically choose the optimal routing to accomplish their missions. In other words, the ad hoc feature, distributed structure, and node redundancy improve the system's survivability.
- **Self-organization and adaptive:** Multi-UAV networks relying on mesh networks for example are capable of self-reorganization. This means that the multi-UAV network is resilient to node-failure, hence it is suitable for diverse circumstances.

By contrast, from a system-oriented viewpoint:

- **High energy efficiency:** The UAVs are smaller and less expensive in small and mini multi-UAV networks, which leads to a low energy consumption. Moreover, by operating in a coordinated manner, the system's power consumption can be reduced to the minimum by relying on their sleep mode as well as on sophisticated power allocation schemes.
- **Convenient scalability:** Considering the various mission requirements, the multi-UAV system is capable of changing the network architecture or adding more UAV nodes in order to achieve the required system capacity.
- **Enriches the applications:** The associated diversity aided functions broaden the application-scope of the multi-UAV network. As a benefit of the UAV-to-ground station and UAV-to-UAV communication, the multi-UAV system improves the attainable load capacity and cruising capability. Moreover, the employment of different sensors and diverse data delivery strategies result in compelling value-added functions.

Although the multi-UAV network has some significant advantages over the single-UAV mechanism, the multi-UAV network has numerous challenges, such as intermittent links, power and bandwidth constraints, etc. On one hand, due to their highly dynamic topology and nimble flight attitude, how to design a beneficial multi-hop routing schemes for UAV-to-UAV communication becomes an important issue [6]. On the other hand, in the UAV-to-ground station communication associated with a relatively long distance, only delay-tolerant services can be supported. Secure transmission and protocol compatibility should also be carefully considered. As a result, powerful spread spectrum and smart antenna aided soft hand-off methods relying on an expert system lend themselves to employment in multi-UAV networks.

1.3 Compelling Applications of FANET

Given their low cost and high-flexibility deployment, unmanned aerial vehicles (UAVs) have been widely used both in military and in civilian applications for surveillance, environmental monitoring and emergency rescue, etc. Depending on their cruising duration and action radius, UAVs may be categorized into four classes, i.e., high-altitude and long-endurance UAVs, medium-range UAVs, short-range small UAVs and mini UAVs [7]. They are usually equipped with a variety of sensors in order to fulfill different tasks. Given the maturity of the UAV industry, small and mini UAVs have also been popularized among the public and their proliferation in diverse applications has attracted a lot of research attention. Recently, UAV communications have been extensively studied for boosting the capacity and coverage of the existing wireless networks [8–14]. Specifically, UAVs can be used both as flying base stations and as relays as discussed in [9] and [12], respectively. The optimum altitudes of UAV for achieving the maximum capacity both in static and in mobile scenarios were derived in these contributions. A similar work considering the UAV's trajectory optimization at a fixed altitude was conducted by Zeng et al. in [10]. Moreover, UAVs have been introduced for Internet of Things (IoT) applications by Mozaffari et al. [11], where the UAVs are used for collecting data from IoT devices. Explicitly, the network association, the UAV placement, and the devices' transmit power were jointly optimized for achieving maximum system capacity. However, their low load-carrying capacity and modest cruising capability have substantially limited the applications of small or mini UAVs. Additionally, computationally intensive tasks impose challenges on these UAVs because of their limited processing capability and battery life [15]. Hence, novel solutions should be conceived for enhancing the UAV's computational and communications capability [16].

Considering the limitations of a single UAV, the cooperation of multiple UAVs has been developed for improving the quality of service (QoS). The UAVs relying on sophisticated sensors can be coordinated by the ground station (GS) to fulfill specific tasks. The multi-UAV system concept was first proposed in [3] based on the flying ad hoc network (FANET) philosophy, which was later expanded in [17–19]. Although multi-UAV networks have substantial benefits over their single-UAV counterparts, they also have numerous challenges. Taking air-to-ground (A2G) communications as an example, if each UAV of the FANET is allowed to set up a communication link with the GS, they would lead to low spectral efficiency and severe interference. Hence, some superior drones should be chosen as the gateways to coordinate communications between the UAVs and the GS. Gateway selection schemes have been widely investigated in the context of mobile ad hoc networks (MANETs) [20–25]. In [21], Leng et al. proposed a k-hop compound metric based clustering scheme for selecting the gateways of a MANET, where the host connectivity and host mobility were jointly considered. Their simulation results showed that the scheme was characterized by rapid convergence despite its low control overhead. A network parameter optimization based gateway selection algorithm was proposed in [22] by Bouk et al. where multiple QoS parameters, such as the path availability period, the path's load capacity, and latency were jointly optimized. Moreover, a fuzzy QoS balancing gateway selection algorithm was proposed by Zhioua et al. for vehicular networks [24], where the fuzzy logic was utilized for making decisions on the specific choice of the gateway relying on the received signal strength, on the traffic load of the cluster head, on the gateway candidates, and on the link connectivity duration. They showed that the fuzzy scheme outperformed the deterministic scheme in terms of its adaptability. As for gateway selection in FANETs, Luo et al. [26] proposed a distributed gateway selection algorithm relying on the dynamic network partitioning concept, which considered the influence of the network topology on the gateway selection process.

Mobile edge computing (MEC) and fog computing have become promising techniques for balancing and distributing the computationally intensive tasks among resource-limited devices [27–29], since the devices can offload their tasks to cloud servers that are deployed locally in their vicinity, and the cloud servers return the final computational results to the devices. In [28], Bonomi et al. defined the characteristics of mobile edge/fog computing, which make it a suitable platform for both the IoT and big data analysis. The security and resilience of edge cloud were analyzed by Shirazi et al in [29]. Relying on MEC and fog computing, both the power consumption and execution delay of the system can be substantially reduced. However, in comparison to traditional cloud computing, the computational resources in the edge cloud are typically restricted by its local configuration. Hence conceiving efficient resource allocation becomes a critical issue in MEC, which has therefore attracted much attention [30–32]. Specifically, in [30], Sardellitti et al. proposed an iterative algorithm based on successive convex approximation for jointly allocating both the radio resources and computational resources to multiple users in a multiple-input and multiple-output (MIMO) aided MEC system. Moreover, a power-vs-delay trade-off was formulated in [31] in the context of a multi-user MEC system, where the local processing capability of devices was considered and an optimal resource allocation scheme was designed with the aid of Lyapunov optimization. The power-vs-delay trade-off problems were also studied in [32, 33] with the Lyapunov optimization framework. In [34], Liu et al. studied the delay-optimal task scheduling and resource allocation problem under specific power constraints in MEC systems, where the optimal strategy was modeled by a Markov decision process. Their scheme was capable of achieving shorter average execution delay than their benchmark schemes. The computation offloading decision, the physical resource block allocation, and the MEC computational resource allocation were integrated into an amalgamated framework and were jointly optimized in [35] by Wang et al., who achieved a better integrated performance than classic resource allocation schemes. However, the existing works are focused on the interplay between the devices and edge cloud, while ignoring the interaction between the edge cloud and the powerful remote cloud.

In order to further improve the QoS performance, relying on both the flexible configuration of the edge cloud and on the more powerful computational capability of the remote cloud, a beneficial architecture combining both the edge cloud and the remote cloud has been developed in [36–42]. To elaborate a little further, Gelenbe et al. [37] studied the optimal load sharing problem between a local and a remote cloud, where an optimal scheme was proposed based on the analysis of the power consumption and the computing time in the context of diverse tasks and requirements. The fairness of resource allocation problems was investigated in [39] in the heterogenous cloud context, where a multi-resource allocation mechanism was designed for guaranteeing fairness, while maintaining service isolation among the users. Moreover, the delay-bounded task offloading problem of heterogenous cloud-based systems was highlighted by Zhao et al. [40] upon considering both the wireless transmission delay and the computational execution delay. They modeled the service arrival process by the classic M/M/1 queue. Based on this model, the success probability of the delay-bounded task execution was derived both in the context of a single-user and a multi-user scenario. Finally, a total power minimization based task scheduling problem was studied by Gai et al. [42].

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Chapter 2
Communication Channels in FANET

Unmanned aerial vehicles (UAVs) have stroked great interested both by the academic community and the industrial community due to their diverse military applications and civilian applications. Furthermore, UAVs are also envisioned to be part of future airspace traffic. The application functions delivery relies on information exchange among UAVs as well as between UAVs and ground stations (GSs), which further closely depends on aeronautical channels [1]. However, there is a paucity of comprehensive surveys on aeronautical channel modeling in line with the specific aeronautical characteristics and scenarios. To fill this gap, this chapter focuses on reviewing the air-to-ground (A2G), ground-to-ground (G2G), and air-to-air (A2A) channel measurements and modeling for UAV communications and aeronautical communications under various scenarios [2].

This chapter is organized as follows: We give some brief introductions of UAV communication channel characteristics in Sect. 2.1. In Sect. 2.2, the related UAV communication channels are modeled. Finally, the potential challenges and open issues of UAV channel modeling are discussed in Sect. 2.3.

2.1 UAV Communication Channel Characteristics

The international civil aviation organization (ICAO) decides that UAV control and nonpayload communication (CNPC) links must operate over protected spectrum. To regulate the UAV applications, international telecommunication union (ITU) has allowed the use of certain portions of the L-band: 960–977 MHz and C-band: 5030–5091 MHz for UAS CNPC link [3]. The Ku-band downlink: 10.95–12.75 GHz and uplink: 14.0–14.47 GHz, and Ka-band downlink: 19.70–20.20 GHz and uplink: 29.5–30 GHz are authorized for beyond line-of-sight (BLOS) CNPC spectrum of satellite aeronautical safety communications. The bands of 840.5–845 MHz, 1430–

J. Wang, C. Jiang, *Flying Ad Hoc Networks*, Wireless Networks,
https://doi.org/10.1007/978-981-16-8850-8_2

1444 MHz, and 2408–2440 MHz have been approved for unmanned aircraft systems relying on LOS links by China [4].

NASA has supported major UAV projects designed for terrestrial and space missions [5]. Jet Propulsion Laboratory (JPL) developed UAV communications payload for high-rate X-band links and for battlefield broadcast in the S-band [6], supporting a maximum data rate of 45 Mbps over a range up to 100 miles in the context of full duplex links. The communication capability of aircraft will be affected by the altitude, range, receiver sensitivity, transmitter power, antenna type, coax type, and length, as well as the terrain details. Lee [7] designed the UAV link budget of long-distance 200 km for Ku-band LOS wireless link at average altitude of 3 km. They calculate the system carrier-to-noise ratio (C/N) taking account of free space loss (FSL) for different geography and weather. The link between the command and control ground station and the UAV was designed in [8] at L- and C-bands for the Ecuadorian Air Force.

The rest of this section is organized as follows. In Sect. 2.1.1, we analyze the link budget and get the carrier-to-noise power radio. In Sect. 2.1.2, we consider the terrestrial shadowing attenuation in UAV air-to-ground channels. Finally, we get impulse response characteristics in LOS channels in Sect. 2.1.3.

2.1.1 UAV Link Budget

Before deployment of UAVs and ground station, we should evaluate the operating distance. Considering refractive effects of atmospheric layers, the optical horizon d_o can be verified to be $d_o = \sqrt{2k_e Rh}$. Under normal weather conditions $k_e = 4/3$ is to consider the four-third Earth effect, that is, the actual radio wave refraction behavior is described by an Earth with an extended radius of $4/3R$. This leads to a radio horizon $d_r \approx 4.12\sqrt{h_A}$ (h_A in m and d_r in km) [9], as shown in Fig. 2.1. The formula is calibrated by a statistically measured parameter by the ITU. The same distance can also be calculated using the Pythagoras' theorem without considering Fresnel and other parameters like above the sea level (ASL) [10].

The free space path-loss model is valid only when there is an unobstructed LOS path between the transmitter and the receiver and no objects in the first Fresnel zone. As shown in Fig. 2.2, the first Fresnel zone determines the minimum separation that should exist between the UAV and the highest obstacle in the path of the radio link. For a point at a given distance along the path of propagation, the radius of the first Fresnel zone is given as

$$R_m = \sqrt{\frac{\lambda d_{AO} d_{OG}}{d_{AO} + d_{OG}}}, \tag{2.1}$$

where d_{AO} is the distance in km of the point O from UAV, d_{OG} is the distance of the point O from ground station. For $d_{AO} = d_{AG}$, $R_m \approx 8.656\sqrt{d_{AG}/f}$. As the

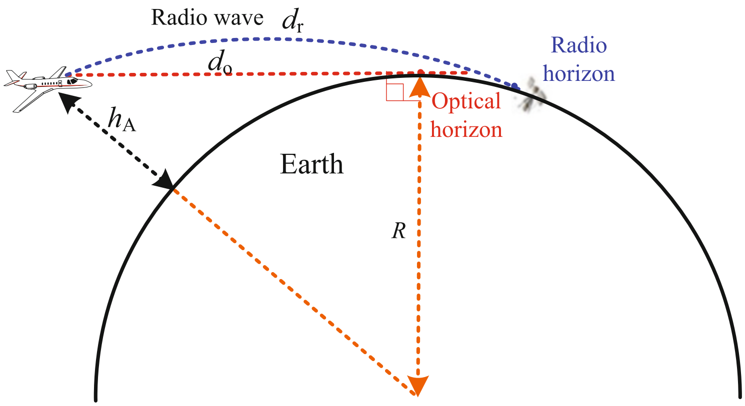

Fig. 2.1 Radio horizon distance

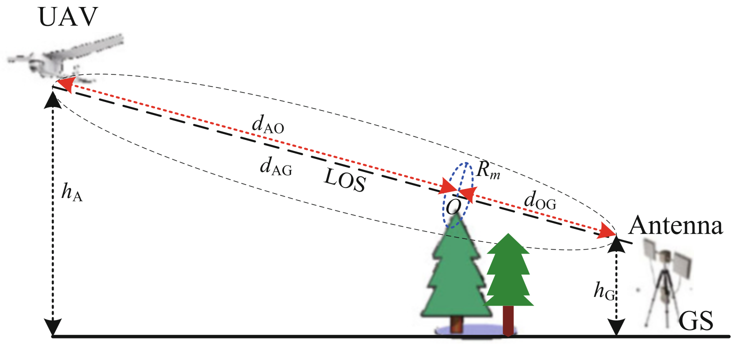

Fig. 2.2 First Fresnel zone for A2G link

obstruction moves towards tangent to the LOS path, signal losses will be as much as 6 dB or more. Best practice is to maintain at least 60% of the first Fresnel zone radius free of obstructions to avoid fading of the received signal.

Without loss of generality, we exemplify the link budget method as presented in Table 2.1. The transmitted equivalent isotropic radiated power (EIRP) equals to sum of output power of power amplifier and antenna gain: EIRP $= G_T + P_T$. Then, the received power at receiver side is computed as,

$$P_R = G_T + P_T - L_T - L_F - L_R - L_A - L_O + G_R, \tag{2.2}$$

where L_F is free space loss for LOS communication link, L_R is rain attenuation loss, L_A is gaseous atmosphere loss that consists of the effects of water vapor or dry air, and L_O is other fading loss. The total losses L_T for uplink and downlink consist of receiver feeder loss, antenna off-axis loss, polarization mismatch loss, radome loss, transmitter loss, receiver pointing loss, and receiver cable loss.

Table 2.1 Link budget table for UAV link

Parameters	Expression	Unit
Carrier frequency	f	GHz
Bandwidth	B_N	MHz
Distance	d	km
Tx power	P_T	dBm
Tx antenna gain	G_T	dBi
Tx EIRP = G_T+P_T	EIRP	dBm
Tx feeder and cable	L_{tf}	dB
Antenna off-axis	L_{oa}	dB
Radome loss	L_{rd}	dB
Polarization mismatch	L_{pm}	dB
Pointing loss	L_{pt}	dB
Rx feeder and cable	L_{rf}	dB
Implementation loss	L_{im}	dB
Total losses	L_T	dB
Free space loss	L_F	dB
Rain attenuation	L_R	dB
Atmospheric gases	L_A	dB
Other losses	L_O	dB
Rx antenna gain	G_R	dBi
Rx power	P_R	dBm
Antenna noise	T_A	K
Rx noise	T_R	K
Thermal noise $T_N = T_A + T_R$	T_N	K
Noise figure	F_N	dB
Rx noise power	P_N	dBm
$C/N = P_R - P_N$	C/N	dB
Receiver sensitivity	P_S	dBm
Excess margin $P_m = P_R - P_S$	P_m	dB

- Free space loss L_F in dB is expressed as,

$$L_F = 92.45 + 20\log f + 20\log d, \tag{2.3}$$

  where f is frequency in GHz, and d is the distance in km.
- Rain attenuation L_R can be obtained from Recommendation ITU-R P.838 [11] and procedure described in [12]. As given typically in [13], very heavy rainfall (100 mm/h) can produce 0.4 dB/km of attenuation at 5 GHz if the rain is uniformly heavy throughout the entire signal path, which is very unlikely. For L-band, rain attenuation of 30 km distance is negligible, i.e., approximately 0.3 dB (0.01 dB/km).

- Link attenuation L_A in dB due to atmospheric gases (absorption by oxygen and water vapor) is

$$L_A = \gamma_a d, \tag{2.4}$$

where γ_a is the specific attenuation in dB/km, being computed for a propagation path slightly inclined, i.e., low elevation angles, assuming a temperature of 15°C, an air pressure of 1013 hPa, and a water-vapor density of 7.5 g/m^3 for a standard atmosphere. For the two LOS bands, 1000 MHz (960–977 MHz) and 5000 MHz (5030–5091 MHz), γ_a equals to 5.4×10^{-3} dB/km and 7.4×10^{-3} dB/km, respectively.
- Losses L_O due to multipath, shadowing, beam spreading, and scintillation can be examined by using the method of small percentages of time in [12] to compute the fading depth. This kind of signal fading will be investigated together with the path loss in next subsection.

At the receiver, the antenna noise temperature and Rx noise temperature are set as T_A and T_R, respectively, resulting in equivalent noise temperature $T_N = T_A + T_R$. The noise power can be calculated as,

$$P_N = k(T_A + T_R)B_N + F_N, \tag{2.5}$$

where $k = -228.6$ dBW/K/Hz is Boltzmann's constant, and downlink noise figure is F_N.

Finally, we can get the carrier-to-noise power ratio as $C/N = P_R - P_N$, considering the signal fading margin L_O. The received power P_R can be compared to the receiver sensitivity P_S to evaluate the flight link margin P_m. Furthermore, for the case of amplify-and-forward (AF) relay typically in FANET, the linear C/N value received at the destination node, after two consecutive links of different C/N values: γ_1 and γ_2, should be calculated as

$$C/N = \gamma_1\gamma_2/(\gamma_1 + \gamma_2). \tag{2.6}$$

2.1.2 UAV Channel Fading

From the link budget above, we can roughly divide the airborne communication channel characteristics into two types:

- Large-scale fading, arising from path loss of signal as a function of distance and shadowing by large objects such as buildings and hills.
- Small-scale fading, resulting from the constructive and destructive interference of the multiple signal paths between the transmitter and receiver. Multipath fading can also arise from the aircraft itself, while these are typically weak and have a very small relative delay.

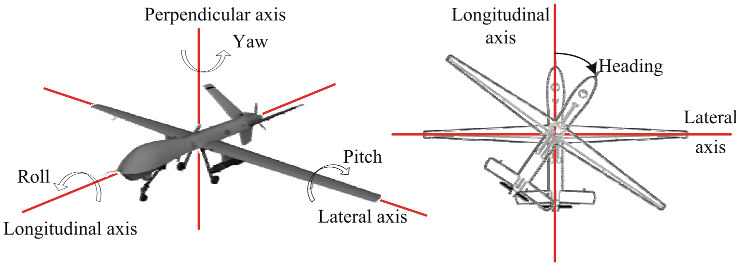

Fig. 2.3 UAV flight states of pitch, yaw, roll, and heading

Compared with mobile wireless channel, UAV air-to-ground channels will often be more dispersive, incur larger terrestrial shadowing attenuation, and change more rapidly. The channel factors include reflection, scattering, diffraction, and shadowing effects together with a direct LOS path.

- Reflection occurs when the elevation angle is low enough for the main lobe of the receiving antenna to "see" the ground.
- Scattering is known as another type of reflection and can occur in the atmosphere or in reflections from very rough objects [14].
- Shadowing may occur due to surface-based obstacles, such as buildings, terrain, or trees but can also occur from the aircraft itself during flight maneuvers.

Reliable UAV datalinks should adapt to the associated rapidly fluctuating link quality [15]. For UAVs, we express the flight states during the maneuvering: yaw, roll, pitch, and heading, as given in Fig. 2.3. Some measured results in the literature are obtained under these conditions, which critically challenge the reliability of A2G or A2A links.

2.1.3 Channel Impulse Response and Metrics

Considering the channel fading, an LOS channel with both specular and diffuse multipath is characterized by the impulse response

$$\begin{aligned} h(t) = {} & a_0\delta(t) + a_1 e^{j\Delta\theta_1} e^{j\Delta\omega_{d,1}(t-\tau_1)}\delta(t-\tau_1) \\ & + \xi(t) e^{j\Delta\omega_{d,2}(t-\tau_2)}\delta(t-\tau_2), \end{aligned} \tag{2.7}$$

where a_0 and a_1 are the amplitude of the LOS signal component and the specular reflection, respectively; $\Delta\theta_1$ is the phase shift of the specular reflection relative to the LOS component; $\Delta\omega_{d,1}$ and $\Delta\omega_{d,2}$ are the Doppler shifts of the specular reflection and diffuse multipath, respectively, relative to the LOS component; τ_1 and

τ_2 are the delays relative to the LOS component; and $\xi(t)$ is a complex zero-mean Gaussian random process.

On the other hand, the time-varying complex baseband channel impulse response (CIR) [16] can be expressed generally as follows:

$$h(t,\tau) = \sum_i a_i(t) e^{-j\phi_i(t)} \delta[t - \tau_i(t)], \tag{2.8}$$

where a_i, ϕ_i, and τ_i denote the time-varying amplitude, phase, and delay of i-th multipath component (MPC), respectively.

The power ratio between the LOS and the diffuse components, the so-called Rice factor [17], is given by

$$K = \frac{a_0^2}{c^2}, \quad \text{or} \quad K_{\mathrm{dB}} = 10 \log \left(\frac{a_0^2}{c^2} \right), \tag{2.9}$$

where a_0^2 is the power of LOS signal, c^2 is the power of the diffuse process.

Delay dispersion modeling plays an important role in channel characterization. The delay dispersion can be characterized by three parameters namely, excess delay, the mean excess delay, and root mean squared (RMS) delay spread.

- Power-delay profile (PDP) characterizes the multipath fading channel giving information about channel delay, amplitude, and power of individual path.
- Mean excess delay (MED) is the average of delay weighting each path by its contributing power relative to the overall power of all paths.
- RMS delay spread (RMS-DS) is a power-weighted standard deviation in delay. For the PDP of 3GPPs specified rural area channel model, the RMS delay spread equals to $\sigma_\tau = 100\,\mathrm{ns}$ [9].

We can quantify the delay dispersion by the RMS-DS expression as follows:

$$\sigma_\tau = \sqrt{\frac{\sum_{k=0}^{L-1} a_k^2 \tau_k^2}{\sum_{k=0}^{L-1} a_k^2} - \mu_\tau^2}, \tag{2.10}$$

where L denotes the number of MPCs. The mean excess delay is given by

$$\mu_\tau = \frac{\sum_{k=0}^{L-1} a_k^2 \tau_k}{\sum_{k=0}^{L-1} a_k^2}. \tag{2.11}$$

When either the UAV transmitter or the receiver is in high-speed motion, Doppler frequency shift is experienced by the radio signal. Doppler spread in the frequency domain is a measure of the spectral broadening caused by the time rate of change of mobile radio channel. Doppler spread is inversely proportional to the coherence time of the channel. The RMS delay spread is inversely proportional to coherence

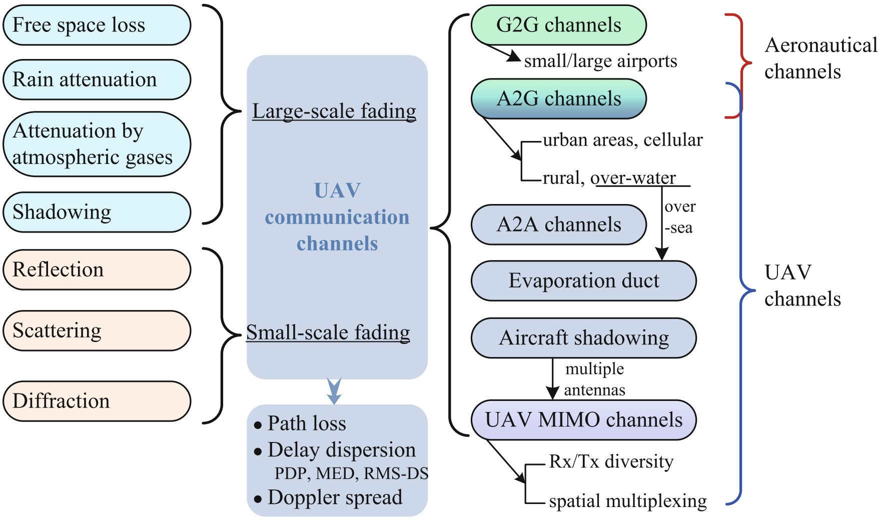

Fig. 2.4 UAV communications channel classifications of scenarios

bandwidth. The details of coherence bandwidth and coherence time are explained in [14, 18].

Considering the diverse range of categories of UAVs including the aerial platforms like aircraft, airship, balloon [19], the measured results for civil aeronautical communication would be referable for designing UAV communication, especially for large unmanned aircrafts. If it is not particularly explained, we will employ “UAV channel” for UAV communication channel modeling and “aeronautical channel” for civil aeronautical communication channel modeling in the following text. To have an intuitive understanding of the UAV channels surveyed in this chapter, we illustrate the channel classifications in Fig. 2.4 before providing detailed channel characteristics.

2.2 UAV Communication Channel Modeling

Along with the progress of embedded systems, low-power radio devices, inexpensive airframes, and the miniaturization of micro-electro-mechanical systems (MEMS), UAVs have also become affordable for hitherto unexplored scientific and commercial applications. UAVs are combined with ground control stations and data links, it forms a UAS (Unmanned Aerial System). UAS must be considered in a system context that includes the command, control, and communication (C3) system [20]. For the aerial networks of space–air–ground integrated network [4], UAVs, airships, and balloons are three primary infrastructures for constructing the hybrid aerial mobile system. Generally, large UAVs, airships, and balloons