Air-to-Ground Channel Measurement and Modeling for Low-Altitude UAVs: A Survey

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Abstract: As important infrastructure for airborne communication platforms, unmanned aerial vehicles (UAVs) are expected to become a key part of 6G wireless networks. Thus, modeling low- and medium-altitude propagation channels has attracted much attention. Air-to-ground (A2G) propagation channel models vary in different scenarios, requiring accurate models for designing and evaluating UAV communication links. Unlike terrestrial models, A2G channel models lack detailed investigation. Therefore, this paper provides an overview of existing A2G channel measurement campaigns, different types of A2G channel models for various environments, and future research directions for UAV air-land channel modeling. This study focuses on the potential of millimeter-wave technology for UAV A2G channel modeling and highlights non-suburban scenarios requiring consideration in future modeling efforts.

Keywords: unmanned aerial vehicle (UAV); air-to-ground (A2G); channel measurement; channel modeling; small-scale and large-scale fading

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1 Introduction

Drones were developed more than a century ago and initially served military purposes. At present, unmanned aerial vehicles (UAVs) are also widely used in civil applications in many countries, including power line inspection, pesticide spraying, aerial surveying and mapping, wildlife protection, meteorological monitoring, special weather tracking, disaster rescue, and search and rescue of stranded people. These applications demonstrate remarkable effectiveness compared with traditional manpower, particularly in high-risk and time-critical operations[1]. All these are enabled by UAV-based wireless communication systems with low cost, simple operation, and flexible configuration[2–4].

In the 5G era, artificial intelligence (AI) and other emerging technologies are providing strong impetus to the drone industry. These technology combinations are creating secondary markets for drone applications. Examples include the emergence of advanced military drones such as the Predator and the Global Hawk. Wireless connectivity to drones is key for enabling the integration of drones into national airspace and expanding the scenarios in which drones can be used.

In contrast to conventional terrestrial communication systems such as cellular and vehicular networks, UAV communication systems exhibit unique three-dimensional (3D) characteristics, including 3D scattering environments, 3D flight trajectories, and 3D antenna arrays. These features significantly influence the propagation characteristics of UAV communication systems. UAVs can operate at various flight altitudes, causing the signal propagation to transition from a simple line of sight (LoS) path to more complex paths involving ground reflections and scatterings from obstacles. This results in strong randomness of the received signal and rapid changes in the received signal envelope. Additionally, UAVs can maneuver freely in real environments, where obstacles are inevitable. Unlike traditional air-to-ground (A2G) systems that assume aircraft can avoid ground obstacles, UAVs often face challenges in obstacle avoidance, further complicating the propagation environment. The mobility of both the transmitter and receiver also impacts the fading characteristics of the signals. In particular, the high flight speeds of UAVs can lead to significant Doppler shifts in bands with large carrier frequencies. To address these complexities and enhance modeling accuracy, researchers have proposed advanced channel models.

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For instance, Ref. [5] introduced a non-stationary ray-tracing (RT) channel model that incorporates 3D scattering environments, 3D flight trajectories, and 3D antenna arrays. This model combines deterministic methods for computing inter-path parameters based on geometric configurations with stochastic approaches for generating intra-path parameters, thereby improving computational efficiency and reducing complexity. Furthermore, Ref. [6] developed a 3D non-stationary geometry-based stochastic model (GBSM) that accounts for UAV body orientations. By introducing time-varying 3D attitude matrices, this model characterizes UAV attitude dynamics and analyzes their effects on channel statistical properties, such as temporal autocorrelation functions and spatial cross-correlation functions. These studies collectively highlight that UAV attitude variations are critical factors influencing channel characteristics and must be explicitly incorporated into channel modeling frameworks.

UAV operating environments and scenarios pose technical challenges for communication between the control point and the UAV, and these technical issues have attracted many researchers to investigate them. For instance, Ericsson researchers have shown that mobile networks can provide wide-area, high-speed, and secure wireless connectivity to enhance the control and safety of UAV operations[7], and Nokia Bell Labs researchers have proposed that UAVs connected to cellular network path loss and shadowing parameters must follow highly correlated models[8]. Typically, A2G channels are considered free-space channels or two-ray channels, which add reflections from the Earth's surface to the LoS parameter. Traditionally, A2G channel measurements and modeling have been carried out at high altitude with large aircraft[9].

For public safety reasons, however, some countries including Japan, Ireland and the Philippines limit the application of UAVs to low-altitude flight (below 150 m) under LoS[10] conditions. However, the A2G propagation channel model used for high-altitude aerial communications is usually not directly applicable to low-altitude UAV communications, as low-altitude communications are strongly influenced by a variety of factors, such as the vehicle, terrain, and weather. For example, in terms of vehicle selection, small UAVs of different manufacturers and models do not have uniform and fixed structures or flight characteristics. In terms of the environment, it is technically challenging to provide continuous coverage for low-altitude communications in obstructed environments such as hilly terrains, mountain forests, rivers, and high buildings.

Compared with terrestrial propagation channels, UAV A2G propagation channels have not yet attracted widespread attention. There are few studies on the characteristics of A2G propagation channels, with Ref. [11] being an exception. To encourage more research on UAV A2G propagation channels, this paper summarizes the basics and characteristics of UAV A2G propagation channels, presents an overview of UAV A2G channel measurement methodologies, and outlines future research directions in this field.

The rest of the paper is organized as follows. Section 2 describes the basics and characteristics of UAV A2G channels based on the literature. Section 3 overviews important UAV A2G channel measurement campaigns. Section 4 classifies UAV A2G channel models for diversified scenarios. Section 5 presents future research directions for UAV A2G channel measurement and modeling, and Section 6 concludes the paper.

2 Basic Information and Characteristics of Air-to-Ground Channels

2.1 Introduction to Air-to-Ground Communication

A2G communication generally refers to the communication between ground command institutions and aerial vehicles. Such systems use aerial platforms to carry communication payloads via air-based relaying or mobile switching, and integrate with multiple ground platforms (stations) to achieve information interaction of wireless communication systems. A2G communication essentially aims to increase the height of ground-based communication equipment, converting over-the-horizon communication into LoS communication. This enables long communication distances, large coverage areas, wide transmission bandwidths, and easy network deployment. Additionally, it is highly mobile and flexible[12].

According to the lifting altitude of the air platform, the coverage radius of wireless communication can range from tens to hundreds of kilometers. Current propagation models for fading in A2G wireless channels can be divided into three main categories: free-space transmission, shadow fading, and propagation models for multipath fading. Among them, free-space transmission and shadow fading are generally classified as large-scale fading, because they primarily cause changes in received power over long distances with their impact on wireless signals unfolding relatively slow (also termed slow fading). In contrast, multipath fading is often referred to as small-scale fading or fast fading. This is because the signals from the mobile station near scattering bodies (such as terrain, features, and moving objects) undergo multipath propagation. As a result, the received signal experiences rapid rises and falls due to the superposition of multiple paths at the receiving point.

2.2 Large-Scale Decay

Statistical models of A2G communication channels are divided into large-scale and small-scale models. Large-scale models typically include path loss and shadow fading models. Large-scale fading mainly includes path loss (PL) and shadow fading (SF). PL refers to the signal fading over long distances, while SF occurs when the signal encounters obstacles or uneven terrain. SF is characterized by its dependence on the topography of the radio propagation and the distribution and heights of obstacles. In most of the literature, the well-known ground-based logarithmic distance PL model is used as:

$$\mathrm{PL}(d) = \mathrm{PL}(d_0) + 10\gamma\log_{10}\frac{d}{d_0} + X_\sigma \quad (1),$$

where $\mathrm{PL}(d)$ denotes the path loss in dB when the spacing between transceiver devices is d; $\mathrm{PL}(d_0)$ represents the reference path loss measured at a reference distance d_0 (typically 1 m, derived from actual measurement); γ is the path loss exponent (PLE) obtained through a best-fit minimum mean square error method, which quantifies the rate at which the path loss increases with distance. Theoretically, γ should equal 2 in free space. However, Table 1 shows that the measured PLE γ is approximately 1.5 – 4[13 – 20]. In Eq. (1), X_σ is a normal random variable with a standard deviation of sigma, which is used to account for the variations in shadowing or in the linear fit in the LoS channel. A large body of literature shows that shadow fading obeys a zero-mean lognormal distribution[21]:

$$f(m) = \frac{1}{\sqrt{2\pi\sigma^2}}e^{\frac{-(\ln m - \mu)^2}{2\sigma^2}} \quad (2),$$

where μ is the mean value, and σ is the standard deviation. UAV A2G channels tend to be more dispersed than mobile radio channels, producing greater ground shadow attenuation and faster variations. Channel factors typically include reflection, scattering, diffraction, and shading effects in the direct view path. However, in most LoS A2G channels, large-scale fading occurs only when the LoS path between the UAV and the ground station (GS) is obstructed by an object with a large relative wavelength. Several models have been developed for this fading condition (e.g., terrain diffraction and tree shading). Many large-scale fading models for UAV A2G channels in the literature cover both PL and SF. For example, Ref. [13] conducted comprehensive measurements of path loss in the L-band and C-band in different propagation scenarios, and two primary conclusions were obtained. 1) The PLE varied slightly but was usually close to the free space value for urban, suburban, hilly, and water scenarios; 2) the standard deviation of the linear fit was usually less than 3 dB. Table 1 summarizes the literature on large-scale A2G propagation and its path loss parameters, with the log-distance PL model being the most common model. The PL estimates are given via the logarithmic model[15, 17, 22 – 23]. Other PL models consider the shadowing of non-line of sight (NLoS) paths, as well as additional losses due to other obstacles[9, 19]. In Ref. [19], shadowing losses are considered in the modeling and evaluated as a function of the elevation angle of the NLoS path.

Table 1. Research on large-scale A2G propagation and its path loss parameters in existing literature

Ref.	Scenario	Propagation Path	Model	PLE γ
[13]	Urban/ suburban	LoS	Log-distance path loss model, two-ray model	L-band: 1.7, C-band: 1.5 – 2
[14]	Urban/ open field	LoS	Free space path loss model	
[15]	Urban/ rural	LoS	Log-distance path loss model	4.1
[16]	Open field	LoS	Log-distance path loss model	2.01
[17]	Aerial	LoS	Log-distance path loss model	2.32
[18]	Water	LoS	Log-distance path loss model	1.9
[19]	Urban/ suburban	LoS, NLoS	Free space path loss model	
[20]	Urban	LoS, NLoS	Free space path loss model	

A2G: air-to-ground LoS: line of sight NLoS: non-line of sight PLE: path loss exponent

2.3 Small-Scale Decay

Small-scale modeling of the UAV A2G channel relies on the multipath fading characteristics of the channel and the Doppler power spectrum. Small-scale fading models are applicable to narrowband channels or individual multipath components (MPCs). Stochastic fading models are usually obtained from empirical data or geometric analysis and simulation[24 – 29]. PL, including shadowing, was reported in Refs. [15, 30 – 32], where we note that in the case of LoS without real obstacles in the first Fresnel zone, it is not actually shadowing that causes the PL to change, but rather small-scale effects.

Ref. [31] noted that the PL and its associated shadows are attributed to buildings only when the UAV is flying near the ground, whereas when the UAV is flying higher, actual shadows do not exist, but changes in small-scale fading still occur. Table 2 summarizes the fading characteristics of small-scale A2G propagation channels in the literature[15, 30 – 34].

Table 2. Fading characteristics of small-scale air-to-ground propagation channels in the literature

Ref.	Frequency/ GHz	Fading Distribution	K-factor/dB	Scenario
[33]	3.1 – 5.3	Nakagami		Suburban/ open field
[15]	2	Rayleigh, Ricean		Urban/suburban
[30]	5.75	Ricean	−5 – 10	Urban/suburban
[32]	0.968 – 2.06	Ricean	12 – 27.4	Urban/suburban
[34]	8 – 18	Ricean, Nakagami	2 – 5	Forest
[31]	2	Ricean		Urban/suburban

2.3.1 Multipath Components

Small-scale multipath fading refers to rapid fluctuations in the amplitude, phase, or multipath delay of a wireless signal over short time intervals or distances (typically within half a wavelength). This fading results from the mutual interference of multipath components originating from the same transmitted signal, which propagate through different paths and arrive at the receiver with varying time delays. HUANG et al.[35] considered a time-varying approach to model the propagation between a GS and a UAV. They proposed a method based on MPC distances to track the evolution of MPC during UAV flight to obtain MPC trajectories that were modeled with straight-line segments. To describe the evolutionary trend of the MPC, several properties (including survival length, initial position spacing, initial relative delay, and relative slope) were also defined and statistically characterized for each flight trajectory. The model serves as a basis for modeling time-varying radio propagation channels between a low-altitude UAV and a ground base station.

Notably, in UAV A2G channel modeling, multipath fading can also come from the UAV itself, albeit usually weak and with minimal relative delays. The main propagation paths for A2G communications include the direct propagation path between the UAV and GS and a cluster of reflected, delayed propagation paths; thus, for statistical analysis, the channel model usually includes the LoS component and a cluster of NLoS components that comprise multiple reflected paths with varying delays.

2.3.2 Doppler Shift

The Doppler effect is caused by the mutual motion between the mobile station and the base station or by the motion of other objects in the propagation environment. In UAV communications, this effect is influenced by the UAV's speed, geometry, and operational wavelength. If the UAV flies too rapidly, it may generate a large Doppler shift, potentially causing issues due to higher Doppler frequencies. In addition, since the frequency and wavelength of electromagnetic waves are inversely proportional, the lower the operating frequency band, the smaller the Doppler shift for high-speed UAVs. However, the spectrum resources in the lower frequency bands are very tight, so the Doppler shift caused by high-speed movement of UAVs is a major challenge for the UAV data chain. Doppler shift introduces a carrier frequency shift and inter-carrier interference. Doppler shift modeling in A2G scenarios has long been studied[30, 36 – 39]. Ref. [30] investigated the Doppler shift and its impact on channel performance in different flight phases (parking and taxiing, in-flight, take-off, and landing) through simulation. The Doppler shift for the realization of orthogonal frequency division multiplexing (OFDM) systems in multipath environments was considered in Ref. [39], where different frequency offsets were observed for the arriving multiple components.

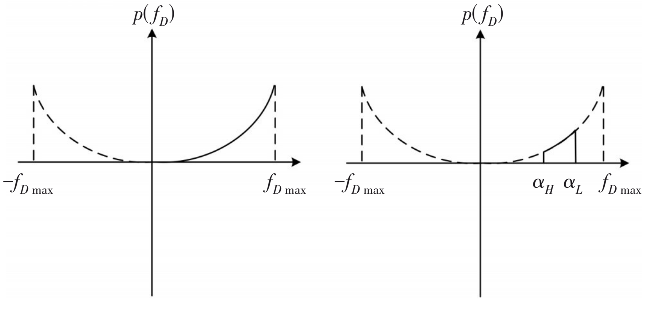
In Ref. [40], the Doppler frequency profile (DFP) of a vehicle in different states was analyzed, as shown in Fig. 1, and the Doppler shift equation was given:

$$f_D = f_{D_{\max}} \cos\left[\alpha_L + \mu(\alpha_H - \alpha_L)\right] \quad (3),$$

where $\mu \in [0, 1]$ is a uniformly distributed random variable, and α_H and α_L are the maximum and minimum angles of arrival under navigation, respectively. The statistical model proposed by ELNOUBI et al. [41] characterizes UAV-to-ground propagation based on transmission coefficients and performs a Doppler spectral analysis of the scattered MPCs. ZAMAN et al.[42] proposed a model with both LoS and NLoS components, describing the Doppler shift as a random process and using an unmodulated 118 MHz carrier as the input to the channel. They observed that the output signal's amplitude spectrum deviated from the carrier frequency. LI et al.[43] presented a simulation model for high-altitude UAV communication scenarios, in which statistics such as temporal correlation and Doppler spectrum were investigated. CHENG et al.[44] proposed a 3D nonstationary geometric model for wideband UAV channels. The Doppler shift induced by the UAV's high-speed motion is determined by the analyzed correlation and Doppler properties. However, the scenarios considered in previous studies typically exclude the presence of nearby scatterers. This limitation restricts the applicability of these studies to broader multi-antenna UAV scenarios that may involve various altitudes.

2.4 Typical Scenario of UAV Air-to-Ground Channel Propagation

The first step in UAV communication research is modeling the communication channel. However, A2G propagation channel models developed for both traditional terrestrial and high-altitude aerial communication systems are not directly applicable to low-altitude UAV communications. UAV communication systems operate in more complex and variable environments, often influenced by terrain, obstacles, and self-



(a) Doppler shifts for the arrival and takeoff scenarios
(b) Doppler shifts for the en-route scenario

Figure 1. Doppler shifts in different states of the aircraft

occlusion caused by the UAV itself. These factors make LoS connections infeasible in all scenarios, which needs to be considered in UAV communication research. Fig. 2 illustrates a common A2G propagation scenario with ground obstacles, often referred to as scatterers.

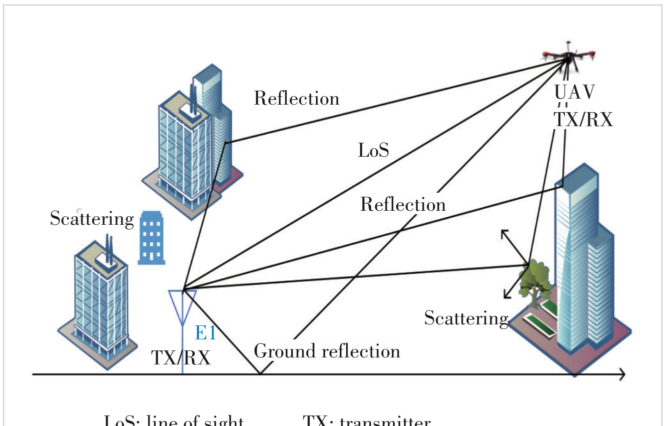


Figure 2. A typical scenario of UAV air-to-ground channel propagation

3 UAV Air-to-Ground Channel Model

3.1 Channel Modeling Based on Measured Data

UAV channel measurements have received increasing attention over the past decade. Table 3 summarizes the literature on channel measurements via small rotor UAVs[8, 10, 16 – 17, 22, 33, 35, 45 – 56]. In Ref. [45], the channel measurement system consists of a six-rotor UAV, a cylindrical antenna, a Universal Software Radio Peripheral (USRP), and a

Table 3. Summary of important A2G channel measurement research in the literature

Ref.	Frequency	Bandwidth/MHz	UAV	Maximum Flight Altitude/m	Scenario	Antenna	Characteristics
[33]	3.1 – 5.3 GHz	2 200	Quadcopter	16	Open field, suburban	Dipole SISO	PL, SF, TOA, PDP, CDF, RMS, BC
[45]	2.585 GHz	18	Hexacopter	100	Suburban, campus	Quasi-omnidirectional-discone, SISO	PL, SF, K-factor, DPP
[46]	2.585 GHz	18	Hexacopter	300	Suburban, campus	Omni-directional, SISO	PDP, RMS, CDF, K-factor
[47]	1 – 24 GHz	—	Hexacopter	24	Semi Urban	Monopole, SISO	PL, SF
[48]	1.2 – 4.2 GHz	—	Hexacopter	100	Semi Urban	MIMO	PL, K-factor
[8]	800 MHz	—	Hexacopter	120	Suburban	Dipole, SISO	PL, SF
[49]	5.8 GHz	20	Octocopter	165	Uptown, montane	MIMO	RMS, DC, CDF
[35]	2.5 GHz	9	Hexacopter	105	Suburban	Omni-directional, SISO	MPC
[50]	2.5 GHz	15.36	Hexacopter	105	Suburban	SISO	PL, SF, DPP
[22]	2.4 GHz	—	Quadcopter	120	Open field, campus	SISO	PL, AO
[16]	5.24 GHz	—	Quadcopter	110	Open field	Dipole MIMO	PL, PAS, UDP, CDF
[51]	0.915 GHz	—	Quadcopter	—	Urban, open field	Omni-directional, SISO	PL, RSSI
[17]	2.4 GHz	—	Hexacopter	20	—	Inverted-FSISO	RSSI
[52]	5.76 GHz, 1.817 GHz	13.5	Hexacopter	50	Suburban	Three-leaf antenna, SISO	PL, SF, PDP, K-factor, RMS, CDF
[53]	2.4 GHz	—	Fixed wing	75	—	Omni-directional, MIMO	AC
[54]	2.4 GHz	—	Hexacopter	40	Laboratory, outdoors	Omni-directional, MIMO	PL, PAS, K-factor, PDF
[55]	900 MHz	—	Fixed wing	—	Rural	SISO	Pr
[56]	850 MHz	—	Quadcopter	120	Suburban	SISO	PL, SF
[10]	909 MHz	—	Quadcopter	100	Open field	Dipole, SISO	PL

A2G: air-to-ground
AC: antenna correlation
AO: antenna orientation
BC: bandwidth-coherence
CDF: cumulative distribution function
DC: direct current
DPP: Doppler power profile
FSISO: full-duplex single input single output
MIMO: multiple-input multiple-output
MPC: multipath component
PAS: power angle spectrum
PDP: power delay profile
PL: path loss
Pr: power-received
RMS: root mean square -delay spread
RSSI: received signal strength indicator
SF: shadow fading
SISO: signal input signal output
TOA: time-of-arrival
UAV: unmanned aerial vehicle
UDP: user datagram protocol

laptop for controlling the USRP and connecting the laptop to a router. Measurements of five horizontal flights at different altitudes and five ascending flights at different horizontal distances to the base station were carried out in the 2.585 GHz band, as shown in Fig. 2. This is a common experiment for UAV air-to-ground channel measurements.

In Ref. [46], a new channel modeling method was proposed based on a feature selection algorithm, an effective and fundamental method for big data analysis. The measurement was conducted via a USRP-based channel sounder by transmitting a frequency modulated (FM) continuous wave with a center frequency of 5 760 MHz and a bandwidth of 16 MHz. Refs. [17, 22, 33] also provided propagation measurement examples performed by a rotorcraft during both flight and hovering. These A2G propagation measurements were conducted at different UAV altitudes ranging from 16 m to 120 m.

However, the effect of UAV hovering on the received signal was not considered in these measurements. Ref. [47] investigated the multi-frequency A2G propagation channel of a low-altitude UAV flying vertically. The basic parameters of large-scale and small-scale channels, including path loss, autocorrelation, shadowing and small-scale fading characteristics, were comprehensively analyzed and modeled. Moreover, Ref. [48] studied the variation in the propagation channel over the flight range of a small- to medium-sized UAV.

Measurements of different routes in a semi-urban complex environment have been carried out to obtain data at different locations. Analysis of the measurement results reveals that small-scale fading is more strongly influenced by the flight altitude than by the elevation angle or distance. In Refs. [35, 50], a height-dependent model was proposed for path loss and shadowing parameters. Measurements in Ref. [51] were conducted in open terrain to explore the feasibility of fixed cellular networks for UAV telemetry and control, focusing on radio propagation, which is shorter in the air than on the ground. In addition to conventional A2G channel detection, such measurements can also leverage fixed cellular networks using the IEEE 802.11 standards with different protocol versions for indirect UAV A2G channel measurements[13, 17, 22]. Specifically, Ref. [13] used a tracking algorithm based on multipath component distances and proposed a dynamic model that could describe the time-varying radio propagation channel between a low-altitude UAV and a ground base station from identified time-varying trajectories.

Ref. [7] proposed a flyby communication scenario using an airborne UAV connected to a cellular network. The study tested several scenarios with different altitudes, orientations, and distances, and analyzed the performance of LTE networks in dynamic 3D environments. Simple extensions to the communication system are proposed to achieve quasi-isotropic radiation to provide uniform 3D connectivity.

Antennas are also key components that cannot be ignored in A2G communications. The number, type and orientation of antennas are all factors that affect the performance of an A2G link. Most A2G channel measurements use a standalone (single) antenna, and a multiple-input multiple-output (MIMO) antenna configuration is available in the literature for A2G propagation measurements[48, 53–54]. Antennas can be classified into two types based on their directionality: directional antennas and omnidirectional antennas. Directional antennas, which provide significant gain in a specific direction, are suitable for long-distance communication. However, their performance is poor during movement due to their limited angular coverage. In contrast, omnidirectional antennas offer superior performance during movement because of their wide coverage area. This makes them particularly popular in vehicle communications.

The omnidirectional or directional orientation of the antenna affects the received signal strength and system throughput. Ref. [12] reported that the PLE of IEEE 802.11 communication varies during UAV hovering and moving due to the different orientations of vehicle-mounted antennas. Compared with the vertical-vertical orientation, the horizontal-horizontal orientation exhibits better throughput performance in Ref. [57]. In Ref. [58], the horizontal antenna orientation helps overcome the difference in yaw; similarly, the vertical orientation performs better during UAV tilting. Therefore, antenna orientation maps may affect the true channel path loss characteristics, but eliminating their effects is not always easy.

Ref. [25] suggested the use of MIMO systems to improve the channel capacity of A2G propagation channels. Different values of MIMO channel capacity are obtained by varying the circular antenna array diameter and UAV flight altitude[59]. Omnidirectional antennas are usually more suitable for UAVs than directional antennas due to the high maneuverability of UAVs during flight. In addition, the generated PL model is still useful for the particular UAV configuration used. However, owing to arbitrary mobility patterns and different types of communication applications[60], UAV A2G communications face many other challenges.

3.2 Geometry-Based Random Channel Model

In recent years, geometry-based stochastic channel models have been widely used. They offer higher accuracy than statistical models and better integration with MIMO techniques, while requiring less computational effort than deterministic models. Any geometry-based model is determined by the position of the scatterer. In deterministic geometric methods (e.g., RT), the position of the scatterer is set in a database. In contrast, the geometry-based stochastic channel model (GBSCM) generates the scatterer positions randomly according to a specific probability distribution. The GBSCM can be further classified into a regular-shaped GBSCM and an irregular-shaped GBSCM. For the former, the scatterer distribution, such as an ellipsoid, a cylinder, or a sphere, is ideal.

Overall, the main difference among regular-shaped GB-

SCMs is the locations and statistical distributions of scatterers, which leads to variability in the calculation results of 2D angular parameters. Table 4 presents the Angle-of-Arrival (AOA) distributions of common GBSCMs and compares different shape models[27, 44, 57, 61 – 65]. Among them, cylindrical and spherical channel models are currently the primary methods for UAV-based geometrically stochastic A2G channel modeling. With the application of MIMO technology, an increasing number of stochastic channel models have incorporated MIMO capabilities. For example, Ref. [61] proposed a 3D hemispherical GBSM for UAV MIMO channels, which takes into account the non-smooth propagation environment due to the fast movement of UAVs and scattering clusters.

Ref. [66] modeled UAV rotation as a sinusoidal process and investigated the effect of UAV rotation on the MIMO channel characteristics of air-to-ground communication systems by considering the effective scatterers within the main flap of the directional antenna. Ref. [67] introduced a Gauss-Markov mobility model to describe the 3D arbitrary trajectories of UAVs and proposed a 3D cylindrical GBSM for UAVs with broadband unsteady channels. Considering a uniform and two different propagation scenarios with variable speeds, the numerical results reveal that under the uniform speed condition, the vertical motion of the UAV has a greater effect on the time correlation function than does the horizontal motion. In contrast, when the UAV moves at a variable speed, the effect of the UAV on the correlation function at a constant speed disappears due to the randomness of maneuvering.

Ref. [64], with the same assumption as Ref. [24], proposed a 3D columned GBSM for UAV-MIMO Rayleigh channels, as shown in Fig. 3, and investigated the effects of several UAV-related parameters on the GBSM. The numerical results reveal that both the UAV's direction of motion and its position strongly influence the obtained correlations. They indicate that to maintain a stable UAV link, the UAV should move toward the ground mobile users, whereas for reliable MIMO performance, the UAV should move horizontally. Ref. [68] proposed a stochastic model for A2G channels based on 3D geometry. Moreover, a Gauss-Markov mobility model was used to generate dynamic trajectories. According to different scattering environments, a reference model and a statistical simulation model of the A2G channel were developed. The dynamic motion scenarios generated by the Gauss-Markov process were analyzed, along with their effects on the correlation of the A2G channel. Notably, the authors developed a statistical simulation model

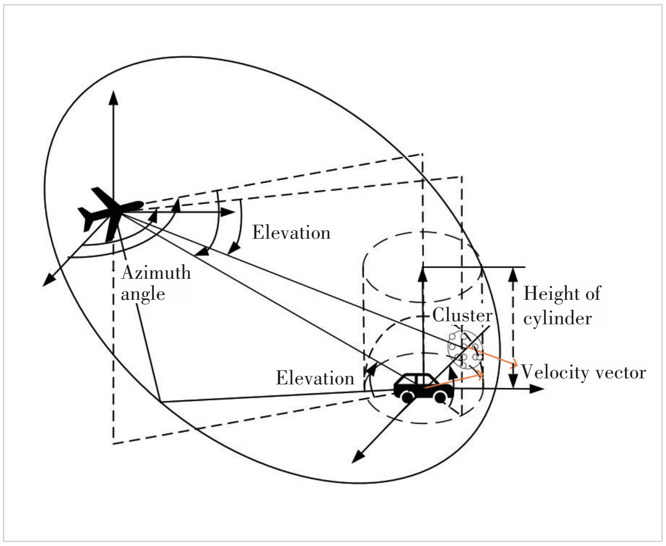


Figure 3. MIMO air-to-ground channel model of a UAV

Table 4. Comparison of geometry-based stochastic channel models

Model	Ref.	Angle Distribution Function	Scenario
Cylindroid	[27, 62]	AOA: $f_{\alpha^{-s}_{\mathrm{rx},n,m}}(\alpha) = \frac{e^{k\cos(\alpha - \alpha^{-s}_{\mathrm{rx},n})}}{2\pi I_0(k)}$ EOA: $f_{\beta^{-S}_{\mathrm{tx},n,m}}(\beta) = \frac{\pi}{4\left\|\beta_{R_m}\right\|}\cos\left(\frac{\pi}{2}\frac{\beta - \beta^{-S}_{\mathrm{tx},n,m}}{\beta_{R_m}}\right)$	Highly accurate, but relies on geographic information and high computational complexity
Sphere	[61 – 63]	AOA: $P^{-S}_{\alpha_{\mathrm{rx},n,m},\beta_{\mathrm{rx},n,m}}(\alpha,\beta) = \frac{e^{k\left(\cos\beta\cos\beta^{-S}_{\mathrm{rx},n}\cos\left(\alpha - \alpha^{-S}_{\mathrm{rx},n}\right) + \sin\beta\sin\beta^{-S}_{\mathrm{rx},n}\right)}}{\left(k^{-\frac{1}{2}}\right)(2\pi)^{\frac{3}{2}} I_{\frac{1}{2}}(k)}$	Angular parameters can be abstracted to specific mathematical distributions, which can greatly simplify calculations
Cylinder	[57] (R=3 km, H_C =300 m); [64] (R=100 m); [44] (R=500 m); [65] (R=50 m, H_C=700 m)	AOA: $f_{\alpha^{-s}_{\mathrm{rx},n,m}}(\alpha) = \frac{e^{k\cos(\alpha - \alpha^{s}_{\mathrm{rx},n})}}{2\pi I_0(k)}$ EOA: $f_{\beta^{-s}_{\mathrm{tx},n,m}}(\beta) = \frac{\pi}{4\|\beta_{R_m}\|}\cos\left(\frac{\pi}{2}\frac{\beta - \beta^{-s}_{\mathrm{tx},n,m}}{\beta_{R_m}}\right)$	

AOA: Angle of Arrival EOA: Elevation over Angle to reduce computational complexity. This is relatively rare.

3.3 UAV Channel Modeling Across Different Frequency Bands and Bandwidths

UAV communication systems are being explored across diverse frequency bands and bandwidths to meet varied application requirements.

1) Sub-6 GHz frequency band

At sub-6 GHz frequencies, UAV channels exhibit characteristics similar to terrestrial channels, but feature enhanced 3D scattering and multipath effects due to the aerial nature of UAVs. Path loss and shadowing are significant, and the impact of terrain and urban structures on signal propagation must be carefully modeled. For instance, in urban environments, signal reflections from buildings and the ground create complex multipath scenarios. Studies including Ref. [69] show that traditional PL models need adaptation for the higher elevation angles typical in UAV communications.

2) Millimeter-wave (mmWave) frequency band

The mmWave frequency band offers large bandwidths for high data rate communications but suffers from higher path loss and sensitivity to blockage. UAV channels in this band are highly dependent on LoS conditions. The narrow beamforming used in mmWave communications requires precise alignment between the UAV and GS, which is challenging due to the mobility of UAVs. Research in Ref. [70] indicates that unique 3D flight trajectories of UAVs necessitate advanced beam management and tracking algorithms to maintain reliable connections.

3) Terahertz (THz) frequency band

The THz band promises ultra-high data rates and ultra-low latency, making it attractive for future 6G applications. However, signal propagation in this band is severely affected by atmospheric absorption and scattering, leading to significant path loss. UAV channel modeling in the THz band must incorporate the effects of weather conditions and molecular absorption. As highlighted in Ref. [71], the integration of ultra-massive MIMO techniques is crucial to compensate for propagation losses in this band.

4) Impact of bandwidth on channel modeling

The increasing use of large bandwidths in higher frequency bands poses new challenges for channel modeling. Frequency-selective fading and Doppler spread become more pronounced, requiring more sophisticated models to capture the dynamic nature of UAV channels. For example, in mmWave and THz bands, the channel model must account for the rapid changes in channel characteristics due to the high mobility of UAVs and the narrow beam widths used.

3.4 RT-Based Channel Model

In the A2G propagation channel of a UAV, MPCs appear due to reflections from the Earth's surface, from ground objects, and sometimes from the body of the UAV itself. The characteristics of the channel depend on the material, shape and size of the scattering object. In A2G propagation scenarios, the strongest MPCs other than the LoS component are usually single reflections from the Earth's surface. This gives rise to the well-known two-ray model shown in Fig. 4. Table 5 summarizes the two-ray model for selected A2G channels[13, 15, 17, 23, 32–33, 59, 72–74]. In two-ray PL modeling, there is a clear peak in the PL variation with distance due to the superposition of the dominant and surface-reflected components. In most of the PL models, PL variation is approximated as a log-normal random variable. This variation may be due to shadows from the UAV airframe or MPC from ground scatterers such as buildings[13, 19, 27, 72]. Ref. [73] presented path loss and shadow

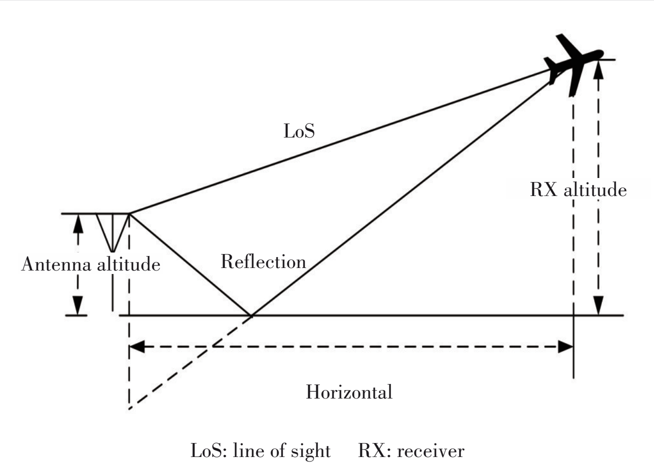


Figure 4. Two-ray model

Table 5. Two-ray model for selected A2G channels

Ref.	Frequency	Bandwidth	Transmit Power/dBm	Channel Characteristics
[13, 23, 32, 72]	0.968 GHz, 5.06 GHz	5 MHz, 50 MHz	40	PL, K-factor
[15]	2.05 GHz	—	—	MPC, K-factor, PL
[33]	3.1–5.3 GHz	2.2 GHz	−14.5	PL, MPC
[17]	2.4 GHz	—	0	RSSI
[59]	5.7 GHz	—	40	PL
[73–74]	200 MHz–5 GHz	—	—	PL, SF

A2G: air-to-ground MPC: multipath component PL: path loss RSSI: received signal strength indicator SF: shadow fading statistics functions related to elevation and height with PL expressions through 3D RT experiments.

Ref. [73] modeled the LoS transmission probability based on the shape of the cell building and knife-edge diffraction theory. The model takes into account key statistical parameters such as the building height, building size, building coverage, and street width. In Ref. [74], 3D RT experiments were conducted to characterize the height-dependent attenuation of A2G transmission in suburban environments. Al-HOURANI et al.[75 – 77] implemented environmental terrain based on simulations of statistical parameters recommended by the ITU.

In Ref. [76], a generic PL model was proposed for low-altitude platforms in which the channel model parameters were estimated via 3D RT at 700 MHz, 2 000 MHz and 5 800 MHz. The simulation results show that the elevation angle has a significant effect on multipath path loss.

In the work of DANIEL et al.[74] and FENG et al.[73], channel models are limited to urban and suburban environments and are not generalizable for migration to other environments. In the work of Al-HOURANI et al.[75 – 76], the propagation conditions depend on the height and coverage radius of the UAV. The above three models are applied to different scenarios and have their own advantages and disadvantages, which are summarized in Table 6.

Although the statistical model based on the measured data has low computational complexity, random parameter-based modeling cannot meet the accuracy requirements of actual signal transmission, and the application range is limited to a large extent. The RT-based deterministic model requires precise channel scene parameters to accurately restore the signal propagation process, but the computational effort is too large. The geometry-based stochastic model matches the actual channel scene, but it is difficult to reduce the computational complexity.

3.5 Technical Challenges and Solutions in UAV Channel Measurement

UAV channel measurement requires addressing a series of technical challenges, including low-power consumption and miniaturization, large-bandwidth high-frequency operations, transceiver synchronization, airframe shadowing and dynamic scenarios, as well as the integration of measurement hardware, protocols, and synchronization mechanisms.

1) Low power consumption and miniaturization

Table 6. Comparison of the models proposed in Refs. [73 – 76]

Model	Advantage	Disadvantage
Measurement-based model	Matching actual channel scenarios	Single application scenario
Ray-tracing-based model	Discriminating multipath in the channel	High computational volume and complexity
Geometric random channel model	Matching actual channel scenarios	More complex calculations

Channel measurement systems for UAVs must achieve stringent low-power operation and compact form factors to accommodate deployment on small aerial platforms. Ref. [78] demonstrated that integrating efficient signal processing algorithms and lightweight hardware architectures can substantially reduce both power consumption and physical dimensions. For instance, practical implementations utilize low-power RF front-ends and miniaturized antenna arrays to enable high-precision channel characterization. Such designs adhere to UAV payload constraints while ensuring extended operational durations under limited power budgets.

2) Large bandwidth and high-frequency bands

UAV communications predominantly operate in high-frequency bands such as mmWave spectra, which offer large bandwidth but impose stringent requirements on measurement systems. Ref. [79] addressed these challenges by deploying advanced signal processing techniques to mitigate high-frequency signal attenuation and noise interference. Key strategies include high-sampling-rate analog-to-digital converters (ADCs) and adaptive filtering algorithms to maintain signal integrity across wide bandwidths. Furthermore, Ref. [80] presented empirical results from low-altitude A2G channel measurements in the 915 MHz band, revealing significant spatial diversity even in sparse multipath environments. These insights highlight the potential for high-capacity UAV communication links in practical deployments.

3) Transceiver synchronization

Accurate time and frequency synchronization between transceivers is critical for reliable UAV channel measurements. Ref. [16] emphasized the necessity of GPS-based timing alignment and high-precision frequency references to minimize synchronization errors. For example, GPS synchronization during measurement campaigns reduces timing discrepancies by over 80%, enhancing data reliability. Complementary work in Ref. [81] validated the use of GPS time-stamping to ensure temporal coherence in multi-device measurement systems.

4) Airframe shadowing and dynamic scenarios

UAV airframes and wings introduce signal shadowing and reflection effects, while environmental obstacles and rapid terrain variations further degrade channel stability. Ref. [82] proposed optimized measurement protocols, including multi-antenna configurations and angular diversity techniques, to mitigate shadowing and environmental interference. For instance, deploying omnidirectional antennas reduces polarization mismatch-induced path loss by 35% in scenarios with large roll angles. Additionally, Ref. [83] quantified the impact of UAV attitude dynamics on channel statistics, demonstrating that real-time attitude-aware data correction is essential for accurate measurements in dynamic flight conditions.

5) Integrated measurement systems

The complexity of UAV channel measurements demands holistic solutions integrating hardware innovation, protocol optimization, and synchronization frameworks. Ref. [16] introduced an FPGA-based real-time processing algorithm for extracting channel impulse responses (CIRs), compensating for system response distortions, recovering power loss, and adaptively identifying MPCs. This approach reduces data storage requirements by 60% while improving processing efficiency. Parallel work in Ref. [81] developed a dedicated channel-sounding system for low-altitude A2G measurements, achieving sub-nanosecond timing resolution through optimized antenna configurations and adaptive measurement protocols. These integrated methodologies not only capture the time-varying and spatially diverse nature of UAV channels, but also provide robust datasets for next-generation channel modeling.

4 UAV Air-to-Ground Channel Measurements in Different Scenarios

As with terrestrial cellular channels, the classification of the various A2G channel types[84] exhibits ambiguity and overlap. The measurement activities of different A2G propagation channels can be broadly categorized based on terrain, terrain coverage, and sounding signal characteristics. The representative environments include deserts, rural areas (plains), forests, suburban areas, and urban neighborhoods. However, these classifications are not always disjoint or exhaustive. In this chapter, we provide a brief overview and comparison of measurement activities in different environments.

4.1 Urban and Semi-Urban Environments

In urban and semi-urban environments, A2G channels are significantly affected by the dense network of buildings and infrastructure. Signals often encounter multiple reflections and scatterings from these structures, leading to complex multipath effects and shadowing. Ref. [85] performed a model-based fading statistical analysis of a narrowband UAV propagation channel in an urban area, with the UAV flying at low elevation angles (1° to 6°) and altitudes of 100 m to 170 m. The study used a 2 GHz continuous wave signal in an urban area with an average building height of 22 m. These data represent the received signal distribution through second-order statistics, power spectral density, and an autocorrelation function with a strong coherent component plus a diffuse reflection contribution under Ricean assumptions. This work is unique because second-order channel fading statistics for A2G propagation via UAVs are rarely available in the literature. The authors of Ref. [85] concluded that the partial shadowing model is best suited for characterizing the dynamics of low-altitude links located between pure terrestrial and land mobile satellite channels. Using the partial shadowing model as a starting point, they developed a narrowband time series generator capable of reproducing the observed signal dynamics, which consists of two main modules: one generating the diffuse reflectance component and the other generating the direct/coherent signal. They also proposed a narrowband channel estimator capable of reproducing the dynamic characteristics of the signal.

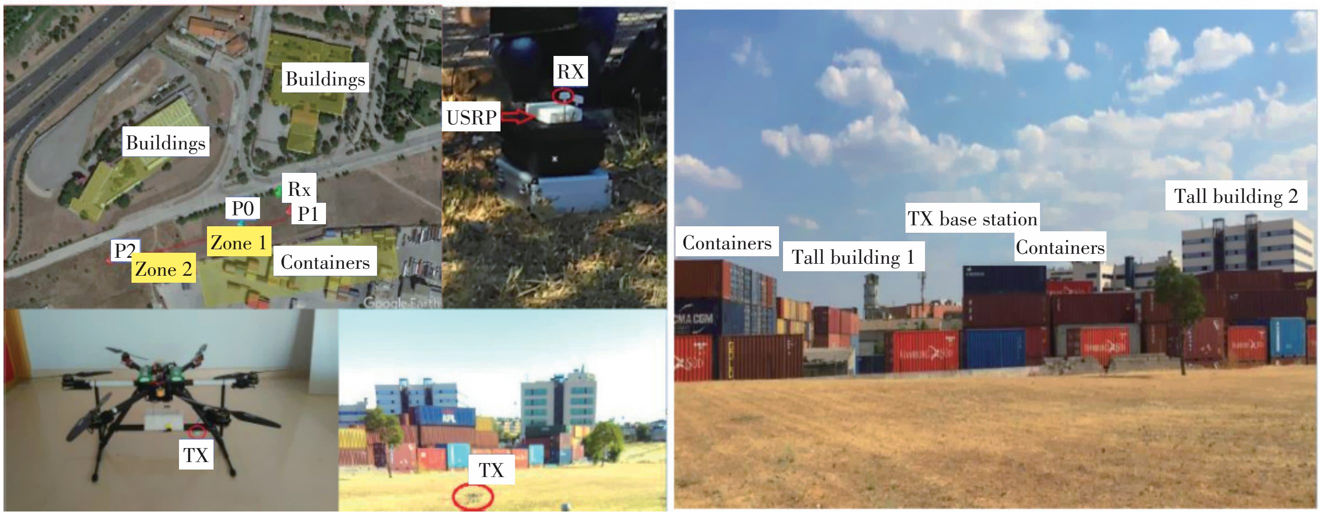
The authors of Ref. [20] conducted some related measurement campaigns using a similar device to simulate urban area path loss models for flight altitudes between 150 m and 300 m. They used a new methodology to simulate urban area path loss models. In addition, they obtained measurements in urban and forested areas[31, 85] for the research of spatial diversity techniques and concluded that heavily wooded areas achieved greater diversity gains than open sites. However, at lower elevation angles, the open sites presented significant gains in diversity. Compared with the diversity gain in the urban areas studied in Ref. [85], this gain is approximately 4% lower.

Ref. [13] reported broadband A2G propagation channel measurements in L-band and C-band urban areas. It is observed that the reflection-guided root mean square (RMS) delay extension increases in high-rise buildings. Ref. [86] performed channel measurements using continuous waves with a center frequency of 2 GHz. Received power was measured in different propagation environments, including woods, and significant differences were observed between shadowing effects in the woods and uban buildings.

Studies have shown that the PLE in urban environments typically ranges from 2.5 to 3.5, which is higher than that in other scenarios. For example, measurements in urban areas at 2.4 GHz reveal a PLE of 3.2, indicating increased signal attenuation compared to free space. These conditions necessitate robust channel models that can capture the dynamic changes in signal propagation, making them essential for reliable communication system design.

4.2 Suburban Environment

In the suburban environment, A2G channels exhibit a blend of LoS and NLoS signal paths due to the mix of open spaces and scattered obstacles like trees and low-rise buildings. Measured PLE values here are moderate, typically between 2.0 and 2.5. CAI et al.[52] investigated the scenario of a low-altitude A2G UAV wireless channel on the outskirts of Madrid, Spain. Field experiments of UAVs flying above a cluster of containers with a carrier frequency of 5.76 GHz were conducted, and both narrowband and broadband measurements were performed, as shown in Fig. 5. In the vertical flight test, the UAV flew up and down from 0 to 50 m in altitude, while the UAV performed the horizontal test at a distance of 210 m. The authors investigated the large-scale fading effect in the UAV propagation channel and proposed an improved PL model and power delay profile (PDP). They also computed the PLE in the horizontal and vertical directions using the logarithmic distance path and the double-slope loss model, as shown in Eq. (4). They reported that for a UAV's performance in a particular environment, the delay dispersion increased with height as the UAV rised above the metal structure.



(a) Narrow band measurement scenario (b) Broadband measurement scenario

RX: receiver TX: transmitter USRP: Universal Software Radio Peripheral

Figure 5. Measurement scenarios and equipment

$$PL(d) = \begin{cases} \alpha_{d_1} 10\log_{10}(d) + \beta_{d_1} + X_\sigma, \ d \le d_1 \\ \alpha_{d_1} 10\log_{10}(d) + \beta_{d_1} + \alpha_{d_1} 10\log_{10}\left(\frac{d}{d_1}\right) + X_\sigma, \ d > d_1 \end{cases} \tag{4}$$

where d_1 is the fitted slope of the distance range between the two links separated by the threshold, α_{d_1} is the slope of the fit for the two link distance ranges separated by the threshold, β_{d_1} is the intercept, and X_σ is the random variable representing the variation in the fit. CHU et al.[79] conducted RT simulations in a simplified environment at ultralow altitudes (0 – 100 m) to analyze A2G channels with path loss, K-factors, multipaths, and delay extensions at 1.2 GHz and 4.2 GHz. The K factor denotes the power ratio of the LoS path to that of the other paths, as shown in Eq. (5).

$$K = \frac{P_{\mathrm{LoS}}}{P_{\mathrm{NLoS}}} \tag{5}$$

The RMS delay spread is calculated using Eq. (6):

$$\sigma_\tau = \sqrt{\bar{\tau} - \overline{\tau^2}} \tag{6}$$

Experiments show that the multipath component decreases with increasing altitude and eventually stabilizes at high altitude, which can be used to design wireless communication systems for mainstream small UAVs that are restricted to flying at specific altitudes. Ref. [58] presented a detailed measurement analysis of the A2GMIMO propagation channel. It was observed that the spatial decorrelation of the received signals at the GS is quite high due to the interaction of the non-planar wavefront resulting from the near-field effects of the measurement vehicles fitted with the GS antennas. More significant near-field effects are expected from more conventional aerial platforms. Interestingly, the authors suggested that at higher elevation angles, the placement of scatterers near the GS could produce greater spatial diversity.

In Ref. [86], MIMO system performance was tested in different scenarios in outdoor environments, including urban, rural, open field, and forest environments. The effect of terrain coverage on the received power was analyzed for these different scenarios. The results revealed that ground reflections play a central role in affecting the propagation channel model, whereas in forested areas, tree reflections and shadows are the primary factors influencing the propagation channel characteristics. Although there are differences between rural and urban environments, reflections from the walls and surfaces of buildings play an important role. In Ref. [87], a flight measurement campaign was described for an L-band A2G channel with a center frequency of 970 MHz, and the aerial measurements considered a rural environment similar to an airport, featuring a mix of large and small buildings and open grassy areas.

5 Research Directions for Future UAV Air-to-Ground Channel Modeling

In this chapter, we discuss possible future research directions for currently available A2G channel measurements and models. Our goal is to promote more comprehensive propagation channel models for future UAV communication applications.

5.1 UAV Millimeter-Wave Channel Modeling

UAV mmWave communication, as a promising future communication technology, has received increasing attention in fields such as air base stations, wireless relays, emergency communications, and battlefield communications. UAVs often have LoS paths in the communication process due to their higher flight altitude, while the mmWave frequency band exhibits higher path loss and lower scattering characteristics, leading to higher requirements on LoS propagation conditions for mmWave communication systems. Therefore, UAVs can be an excellent platform for mmWave communication technology. However, there are currently few actual measurement campaigns for UAV A2G channels in the mmWave band. Ref. [69] presented a path loss model for mmWave channels based on measured data in the 28 GHz frequency band, but it did not consider the characteristics of small-scale fading. In UAV communication scenarios, the changes of channel characteristics are extremely sensitive to the variations in narrow beam pointing, and the cluster fading phenomenon is also more obvious, which significantly increases the difficulty and complexity of UAV channel modeling.

Ref. [70] discussed the delay power spectrum and signal angle distribution of UAV mmWave channels by reconstructing city, hill, forest, and ocean scenarios with the RT method. Compared with other types of channel models, the RT-based model has the advantages of high flexibility in scene construction and lower cost of data acquisition, but it faces challenges in analyzing small-scale fading.

Obtaining channel parameters for actual propagation scenarios is one of the key techniques for the accurate operation of UAV mmWave channel models. Although the RT-based prediction of mmWave propagation parameters is accurate, it is difficult to reflect the randomness and non-stationarity of the fast time-varying environment of UAVs. For UAV mmWave channels, the changes in channel characteristics caused by new scenarios are currently unknown. In the future, a large number of channel data can be generated using actual measurements or simulations, and the analysis of large-scale channel data using machine learning methods should be able to make better use of the spatial and angular information of the MPCs and the intrinsic correlation between the model parameters to discover new characteristics.

Combining the analysis with machine learning methods may be an effective means of investigating the stochastic and non-stationary nature of UAV channels. In conclusion, it is certain that the future development of UAV communication will be characterized by multi-scene applications, high mobility, high frequency, and multi-antenna technologies. Therefore, the establishment of suitable UAV mmWave channel modes plays an important role in the scheme design, performance optimization and evaluation verification of future UAV mmWave communication systems. Moreover, Ref. [88] upgraded the existing UAV channel model to an ultra-large-scale MIMO mmWave-terahertz oriented channel model, which is an important research direction in the future. The mmWave-terahertz communication can utilize the huge communication bandwidth to meet the application requirements of high-rate transmission and ultra-low latency.

However, the signal wavelength in the mmWave-terahertz band is extremely short. To mitigate this, Ref. [89] used beamforming to achieve high gain and combined it with massive MIMO technology to compensate for the high propagation loss of terahertz signals in practical applications. Currently, a 3D mmWave-terahertz channel model to support hyperscale MIMO wireless communication systems has been initially proposed in Ref. [90], in which the evolution of clusters in the spatial domain and the actual discrete phase shifts were taken into account.

5.2 Ultra-Wideband Technology

In addition to mmWave, ultra-wideband (UWB) technology is a research priority for future UAV A2G communication systems. The ability of UWB signals to capture MPC with good temporal resolution makes UWB an attractive technology for developing broadband propagation models. The large bandwidth of UWB also promotes high data rates, better penetration through materials, and coexistence with narrowband networks for UAV A2G communications. Although the UAV propagation channel has been studied in the literature, most of the existing work focuses on the path loss characteristics of the A2G channel, and there are almost no comprehensive and dedicated UWB channel models for UAV A2G propagation channels. KHAWAJA et al. developed random path loss and multipath channel models to characterize the A2G UWB propagation channel based on measured data[33]. However, the maximum altitude of UAV flight is only 16 m, and the communication range is short.

Meanwhile, current UWB propagation channel models developed for other scenarios[85, 91] cannot be applied to UAV A2G channels due to different propagation environments. Therefore, establishing a suitable UAV UWB channel model requires prior A2G channel measurements.

5.3 Advanced Modeling and Integration Strategies

Beyond mmWave and terahertz channel modeling, several other promising directions deserve attention. AI and machine learning can enhance the accuracy and efficiency of channel modeling by analyzing large datasets from measurement campaigns. This can help discover new characteristics of UAV channels and improve the predictive capabilities of channel models. Additionally, the integration of advanced antenna technologies like ultra-massive MIMO and intelligent reflecting surfaces (IRS) can significantly improve communication performance and optimize UAV communication systems. Dynamic and adaptive channel models that incorporate the mobility of UAVs and the time-varying nature of the propagation environment are also crucial for providing more accurate predictions. Furthermore, exploring the integration of UAV communication systems with other technologies such as satellite communications and IoT networks can enhance the overall communication infrastructure and enable more diverse applications.

6 Conclusions

This paper comprehensively reviews the fundamentals and characteristics of UAV A2G channels, emphasizing their unique aspects compared to terrestrial channels, such as fully 3D scattering environments, flight trajectories, and body shadowing effects. We discuss the challenges of UAV channel measurement, including low-power and miniaturized environments, high-frequency bands with large bandwidths, transceiver synchronization, airframe shadowing, and dynamic scenarios. Additionally, we overview UAV channel measurements across different frequency bands and bandwidths and classify UAV A2G channel models based on various environments. Finally, we explore future research directions, including the potential of mmWave and terahertz technologies, ultra-wideband technologies, and the integration of advanced modeling strategies with machine learning to improve UAV channel modeling accuracy.

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