Towards Connected Unmanned Aerial System: A Channel Modeling Perspective

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Abstract—Unmanned aerial vehicles (UAVs) have attracted increasing interest in integrating them in next-generation wireless communication. It has reached a consensus that unmanned aerial system (UAS) plays an intensely crucial role in the emerging aerial networks. Concerning connected UAV, a multitude of communication scenarios are involved, such as intercommunications between UAVs and interactions with the ground user equipment (UE), the cellular base station (BS), and the ground station (GS), etc. In this article, we pour attention into the essentials of corresponding air-to-air (A2A) and air-to-ground (A2G) links in the above scenarios from the perspective of channel modeling. We first extract new characteristics related to UAV channel modeling, compared with traditional cellular and vehicular channels. We then provide a brief review of A2A and A2G channel statistics and models based on existing works. Following that, we show the impacts of the environment and frequency on A2G channel characterizations with the aid of measurements. Besides, we employ a realistic channel model to show how it influences communication performance. Finally, potential directions are discussed for paving the way to more accurate and effective UAV channel modeling.

Index Terms—Air-to-air, air-to-ground, channel modeling, connected aerial network, unmanned aerial vehicle.

I. BACKGROUND

Many promising directions are excavated for applying unmanned aerial vehicles (UAVs) into wireless communications in recent years. As an example, a UAV serving as an aerial base station (ABS) could assist or substitute a terrestrial base station (TBS) in specific situations [1]. It is confirmed that the UAV is playing an important role in a slice of arising communication systems [2]. It is simultaneously expected that the connected unmanned aerial network is a significant promoter to approach the ultimate goal of global coverage. Worth emphasizing that UAV represents a wide-sense concept where typical unmanned aerial platforms include drone, airship, air balloon, and other aircrafts [3]. In this article, we focus on the connected unmanned aerial system (UAS), in which typical communication scenarios mainly consist of three categories: UAV-to-UAV, UAV-to-base station (BS), and UAV-to-ground station (GS) or user equipment (UE) [1], as shown in Fig. 1. The characteristics of corresponding communication links are summarized as follows.

- **UAV-to-GS/UE**: The link previously refers to the controlling link between UAV and GS, operating at unlicensed bands, i.e., 2.4 GHz and 5 GHz. Subsequently, the UAV is regarded as an auxiliary or alternative of terrestrial BS (TBS), serving ground UEs as aerial BS (ABS). Therefore, the operating frequency bands on this link range from hundreds of MHz to millimeter-wave (mmWave) bands, in which L-band for non-payload and C-band for payload communications are recommended by International Telecommunication Union Radiocommunication Sector (ITU-R).
- **UAV-to-BS**: To guarantee reliable communication in long-distance flights, UAVs are expected to connect almost ubiquitous TBSs, which is known as cellular-connected UAV communications. The unique characteristics of TBS include a downtilt sectorized antenna, fixed position, and few heights, which differ from the GS. Thus, we category them as distinct communication scenarios.
- **UAV-to-UAV**: For many use cases such as aerial relay and flying ad hoc network, UAVs are conceived to be interconnected. Compared with conventional vehicle-to-vehicle communication, UAV-to-UAV communications exhibit more challenges since drones can fly with highly variable heights in a three-dimensional (3D) space, comparably, vehicles generally travel along with linear trajectory on the ground level.

As far as propagation channels are concerned, air-to-air (A2A) and air-to-ground (A2G) channels are involved in the wireless links mentioned above. Note that A2G channels include UAV-to-GS/UE and UAV-to-BS scenarios. As we know, an accurate channel model is paramount for effectuating reliable communication links. Thus, the article aims at investigating the state-of-the-art channel modeling and illustrating important factors that can affect UAV-related propagation channels, which are crucial for exploiting the full potential of the integration between UAV and wireless.

It is acknowledged that the prevailing methods of channel modeling are composed of statistical, deterministic, and stochastic ways. Each modeling approach has its pros and cons. For example, the effectiveness of the ray-tracing-based deterministic modeling is highly dependent on the accuracy of the 3D reconstructed environment and corresponding electromagnetic properties of scatterers in the environment. For better generality, geometry-based stochastic channel models (GB-SCMs) are under extensive studies, however, the predefined geometry may deviate the reality and thus reduce the accu-
racy. Due to specific measured frequencies and environments, measurements may lack favorable expansibility. However, numerous measurements have been conducted for a plenty of frequencies, environments, communication links, and UAV altitudes, which are supportive of providing a comprehensive investigation. Thereby we study UAV-related propagation channels mainly based on channel measurements conducted in the literature and our previous work. More specifically, in the article, we are mainly committed to answering the following questions:

- What are the new characteristics in UAV-related channel modeling, compared with traditional cellular or vehicular channels?
- How do the carrier frequency and propagation environment influence the A2G channel characterization?
- How does a realistic channel model of UAV influence communication performance?
- What is the state-of-the-art A2G and A2A channel modeling, meanwhile, what are the potential directions for future work?

These heuristic questions mainly constitute the structure of the article, and the corresponding answers we will provide are favorable for highlighting our main contributions.

II. NEW CHARACTERISTICS CONCERNING UAV CHANNEL MODELING

The special features of UAV and its flight directly induce some new characteristics in pertinent communication systems, compared with traditional cellular or vehicular communications. These characteristics can accordingly influence UAV channel modeling. Thus, we highlight them in detail in this section, where new characteristics are composed of variable altitude, high maneuverability, jittering/shadowing, various environments, and multiple bands.

**Variable altitude:** An evident feature of a UAV is its variable altitude. The distinct property transformatively enables that wireless communications have vertically evolved into the air level from traditional ground level. For a UAS, the aerial platform can be divided into the high-altitude platform (HAP) with altitudes ranging between 17 and 32 km, and low-altitude platform (LAP) with altitudes below 5 km. Moreover, the divergence of channel characterization is quite obvious for UAV heights, thereby it is meaningful to pay more attention to height-dependent channel modeling [2].

**High maneuverability:** One of the advantages in UAV communications relies on the high maneuverability, that allows drone rapidly being deployed in emergencies such as disaster when ground infrastructures are damaged. However, the high mobility or velocity is adverse to reliable signal transmission, since propagation channels are more vulnerable to suffer from frequency-selective fading, i.e., non-stationarity. In this condition, the birth-and-death processes of multipath components (MPCs) should be considered in non-stationary channel modeling.

**Jittering and shadowing:** As we know, UAVs can be roughly divided into the fixed-wing (FW) and rotor-wing (RW) kinds. The main difference lies in that RW-UAVs can hover in the air \(v \geq 0\) while FW-UAVs need to maintain certain aerodynamic lift by keeping mobile \(v > 0\). However, extremely stable flights are impractical for both kinds of UAVs. Thus, the impacts of UAV jittering on propagation channels ought to be carefully considered. Besides, since the shadow fading caused by the large-size fuselage of UAV is generally not negligible, analyzing fuselage shadowing is beneficial to proposing an accurate large-scale channel model.

**Various environments:** In addition to representative environments such as urban and suburban environments, UAVs expect to provide communication services for users in various non-typical environments, such as over-water, forest, mountain, and other remote or harsh environments. Thus, considering the diversity of propagation environments is of significance for channel modeling.

**Multiple bands:** Since the trend that UAVs deeply melt in wireless communications is becoming unequivocal, the frequency bands used in UAV communications range from hundreds of MHz to mmWave bands. As an example, several Long-Term Evolution (LTE) bands, e.g., 850 MHz and 1900 MHz, are confirmed to serve aerial users in cellular-connected UAV communications. However, multiple frequency bands bring more challenges to channel modeling, which requires more effort to characterize the impact of diverse frequency bands and model frequency-dependent channel parameters.

III. STATE OF THE ART

In this section, we first enumerate the recent progress of A2A and A2G channel modeling in terms of large-scale and small-scale statistics. Then, we comprehensively review channel models that were proposed in the literature. The state of the art not only provides a better understanding of propagation channels in UAV communications but also inspires some potential directions for improving the deficiencies and filling the gaps in existing works.

A. Large-Scale Statistics

Large-scale channel statistics such as path loss and shadow fading, are undeniably important for the system design and performance evaluation. For the sake of a detailed description,
we summarize the representative A2A and A2G channel measurements in Table I, where important settings and corresponding channel statistics are included. For the setting of frequency, we found that most measurements regardless of A2A or A2G channels focus on sub-6 GHz, where L-band, C-band, LTE band, and IEEE 802.11n band constitute the majority. Altitudes of aircraft range from several meters to hundreds of meters for A2G channels with GS terminal, while UAV heights are lower than 120 m considering the signal strength of TBS for cellular-connected UAV communications. For A2A channels, two UAVs generally fly at low altitudes in dozens of meters in the literature we investigated. As aforementioned, UAVs can be used in various environments that were considered in measurement campaigns.

Since various path loss models are based on path loss exponent (PLE) and shadowing factor (SF), we focus on the two key parameters, where PLE and SF are denoted as \( n \) and \( \sigma_s \), respectively. It is found that as the altitude of UAV arises, the PLE becomes smaller for both A2A and A2G channels. As an example, in [5], \( n \) ranges from 2.5 to 3.0 for altitudes between 4 m and 16 m. Moreover, measurements in [3], [4] show that the values of \( n \) are smaller than 2.2, which indicates that the A2G channel is close to free-space propagation for high altitudes. For cellular-connected UAV communications, the PLEs vary in a large range as the height. For instance, the measurement in [7] at the LTE band, shows that \( n \) can be up to 3.7 for the near-ground height, which is similar to the result of cellular channels. Notably, A2A channels present analogous results, indicating that \( n \) gradually varies from 2.7 to 2.3 for 0-50 m in [8].

The shadow fading is familiarly modeled as a Gaussian random variable (RV) with zero mean and standard deviation of \( \sigma_s \). Table I shows that the typical values of SF for A2G channels range from 2.6-7.7 dB that is less than the typical values of 4-8.2 dB for cellular channels in outdoor environments suggested by the third generation partnership project (3GPP). Besides, measurement in [8] shows the typical values of SF for A2A channels range from 1.9-5.5 dB, which are slightly less than that in A2G channels since few scatters distribute in the vicinity of both UAVs. According to measurements in [5], one can find that the shadowing is highly related to the selected environment. The result shows that \( \sigma_s \) is between 3.1 and 4.0 dB in an open-filed area, however, it becomes significant, ranging from 4.3 to 5.3 dB in a suburban environment.

### B. Small-Scale Statistics

Small-scale channel parameters are important for relevant system design. For example, the root-mean-square delay spread (RMS-DS) is useful in the design of the transmit symbols. Besides, the RMS-DS and Rician \( K \)-factor (KF) are generally used to characterize the multipath propagation. Thus, we focus on the two representative parameters with analysis from the perspective of multipath effects.

In an over-sea environment, average Rician KFs were reported to be 12.5 dB and 31.3 dB for L-band and C-band, respectively [3]. Similar results were found for a suburban measurement in [4], where the mean values of Rician KF were 12 dB and 27.4 dB for L-band and C-band, respectively. The similarity can be well explained by the high altitude of the aircraft. Note that UAV flew above 504 m in both environments, which results in that the power of some of the multipath components (MPCs) caused by ground scatterers such as buildings become negligible, and thus these MPCs make a very limited contribution to the none-line-of-sight (NLOS) power.\(^1\) For low-altitude heights, the average Rician KF was 7.6 dB for 30-100 m reported in [6], which illustrates the strong impact of terrestrial scatterers on the NLOS power.

The investigations of RMS-DS are as follows. In [3], the median values of RMS-DS were 9.6-9.8 ns for multiple over-water measurements, whereas they concentrated around 9.6-11 ns for suburban and near-urban environments. A manifest difference lies in the largest RMS-DS, which generally occurs when large buildings provide strong MPC reflections. For instance, the result indicates that the largest RMS-DS was 364.7 ns for an over-water environment, however, it reaches 4.24 \( \mu \)s in the suburban environment [4].

### C. Channel Models

Channel models provide formulated expressions that can be straightly applied in the system design and evaluation. Accordingly, we herein focus on discussing essential channel models including the path loss model, small-scale fading model (SSFM), and MPC model for UAV communications. A thorough summary is given in Table II, where concrete representations are provided. Path loss models are mainly composed of log-distance, modified free-space (FS), close-in (CI), floating intercept (FI), excess loss (EL), and 3GPP models. Among these, the log-distance model is the most

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\(^1\)Rician \( K \)-factor represents the ratio of the power of the line-of-sight (LOS) path and the aggregated power of NLOS paths.
TABLE II
A SUMMARY OF UAV CHANNEL MODELS.

| Model       | Ref.     | Representation       |
|-------------|----------|----------------------|
| Path loss   | [3], [4], [6] | Log-distance         |
|             | [7]      | Modified free-space  |
|             | [8]      | Close-in             |
|             | [9]      | Floating intercept   |
|             | [10]     | Excess loss          |
|             | [11]     | 5GPP                 |
| SSFM        | [5], [6] | Nakagami-m           |
|             | [7], [8] | Rician               |
|             | [9]      | Rayleigh             |
| MPC model   | [10]     | Two-ray              |
|             | [11]     | Three-ray            |
|             | [12]     | Over-three-ray       |

popular in the literature for both A2A and A2G channels. Note that the EL model can be merely exploited in A2G channels since it separates the total loss into terrestrial and aerial parts. Moreover, the 3GPP model is tailored for cellular-connect UAV communications, aiming to enable the LTE network to provide communication services to aerial platforms.

The SSFM mainly indicates the probability distribution of the envelope of small-scale fading and can be used to describe both narrowband fading channels and individual MPCs in wideband channels. Popular probability distributions consist of Rician, Rayleigh, and Nakagami-m distributions. Abundant measurements have revealed that A2A and A2G channels are more likely to experience Rician fading because of the presence of strong LOS path in most cases. Whereas Nakagami-m can be a more general representation with the increasing multipaths, such as in [5]. Rayleigh fading is rare in existing works, nonetheless, research in [12] shows that A2G channels may exhibit Rayleigh fading under NLOS condition in low altitudes.

Wideband simulations or measurements make it easier to detect MPCs and characterize their properties, which facilitate the reconstruction of the channel impulse response (CIR). An intuitive representation of UAV-related channel resides in two-ray propagation, that was verified in [13] where the ray-tracing simulation was conducted for mmWave A2G channels. However, more MPCs were observed in measurements [3], where a three-ray model was found to model A2G channels well for over-water environments, even though the third ray is intermittent and needs to be expressed in a probabilistic way. Besides, over-three-ray models were found to model both A2A and A2G channels in built-up environments where wave impinging with buildings resulted in more MPCs. It was found that MPCs for A2G channels can reach nine in a suburban environment [4]. Moreover, A2A channel measurements and ray-tracing simulations in the reconstructed suburban environment have shown that the number of MPCs is up to seven, composed of the LOS, the ground reflection, four single-bounce wall reflections, and one double-bounce wall reflection.

IV. IMPACTS OF FREQUENCY AND ENVIRONMENT ON A2G CHANNEL CHARACTERIZATION

In this section, we utilize two examples to illustrate how operating frequency and propagation environment influence A2G channels, with the aid of our prior work. We will first briefly introduce previous narrowband and wideband measurements. Then, the results of path loss and power delay profile (PDP) intuitively reveal the effects.

A. Narrowband and Wideband Measurements

For showing the impact of the frequency band, narrowband measurements were carried out at 4 GHz and 24 GHz. Both frequencies play vital roles in the payload communications of UAVs. More specifically, the quasi-mmWave and C-band are regarded as candidate bands for realizing high-data-rate transmission. Multi-frequency A2G channel measurements were performed in a campus, where UAV flew vertically from 0 to 24 m, and GS was placed on the 25-meter rooftop of the building, with a horizontal distance of around 350 m between UAV and GS. More details can be found in [14].

Wideband measurements were conducted with two identical commercial DWM1001 modules. Each module includes an ultra-wideband (UWB) antenna, radio frequency circuitry, and a motion sensor. One module used as a transmitter was mounted on the bottom of the six-rotor DJI drone, and the other was used as a receiver, placed at 0.5 m above the ground. UWB antennas for both ends are vertically polarised and approximately omnidirectional with 0 dBi gain. Moreover, the center frequency was at 6.5 GHz with a bandwidth of 500 MHz, providing a high delay resolution (2 ns) that is supportive of possibly capturing the most of MPCs. Note that due to the limited transmit power, the UAV flew at low altitudes (≤30 m). Measurement campaigns were performed in two different scenarios, including over-lake and suburban environments. More details can be found in [15].

B. Impact of Frequency

Path loss results with narrowband measurements are depicted in Fig. 2. Results show that path losses for both frequencies have similar slopes, indicating that they have close PLEs. It can intuitively observe that the fluctuations of the curve at 24 GHz are more apparent in both LOS and NLOS cases than those at 4 GHz. Such fluctuations are mainly
caused by small-scale fading, and thus can be quantitatively characterized by the fading depth\(^2\) (FD) that is useful for the design of link fading margin. It can be found that FDs at 4 GHz and 24 GHz are 6.8 dB and 4.8 dB for the NLOS case, respectively, whereas for the LOS condition, FDs are 4.6 dB and 1.2 dB. The results show that A2G channels at high frequency are vulnerable to suffering from deep fading.

\(\text{FD} = \text{Power at 50\% level of small-scale fading} - \text{Power at 1\% level of small-scale fading}\)

C. Impact of Environment

A great number of PDPs can be obtained with wideband measurements, which prompts us to compare the discrepancy in terms of MPCs and corresponding channel parameters in different propagation environments. For the post-processing of raw PDPs, the dynamic range remains as 30 dB, which implies that the MPC with its power lower than 30 dB than the LOS power would be abandoned. Fig. 3 depicts processed PDPs for both environments. Notably, protruding peaks in the figure generally suggest potential MPCs. We can find that there are more intermittent MPCs in the suburban environment than that in the over-lake environment. Reflections from buildings can favorably interpret the difference. Besides, a quantitative analysis was performed concerning key small-scale channel parameters. We first extracted potential MPCs from PDPs using a high-resolution estimation algorithm, i.e., space-alternating generalized expectation-maximization (SAGE) algorithm. With extracted MPCs, we then calculated Rician KF and RMS-DS according to their definitions. As shown in Fig. 3, the mean KFs are 13.10 dB and 6.93 dB for over-lake and suburban environments, respectively. For the RMS-DS, the mean values are 16.05 ns and 25.87 ns for over-lake and suburban environments, respectively. The large Rician KF together with small RMS-DS illustrates the sparsity of MPC in an over-lake environment, which follows the result in [3] where a three-ray model was found. By contrast, MPCs present a more dense distribution in the suburban environment. By means of SAGE, we found that the typical number of MPCs ranges from 7 to 12 in the suburban environment. The findings are beneficial for providing a more practical channel model.

V. IMPACT OF REALISTIC 3GPP CHANNEL MODEL ON COVERAGE PROBABILITY

In this section, we utilize a practical channel model for cellular-connected UAVs to illustrate how the realistic channel model influences communication performance. We first introduce 3GPP models and the system model. Afterward, we conduct the coverage probability\(^3\) analysis for different UAV heights through signal-to-interference-plus-noise ratio (SINR) that is calculated according to channel models.

A. Practical 3GPP Antenna and Channel Model

The channel models released by 3GPP Technical Report 36.777 aim to support LTE network to serve aerial vehicles [11], which is dedicated for cellular-connected UAV communications. In the evaluation, we use a homogeneous Poisson point process (HPPP) to designate the distribution of TBS. The scheme of the strongest average receive power is used for TBS associations. A sectorized antenna with 15° downtilt setting is used for the TBS, meanwhile, aerial and ground UEs are equipped with omnidirectional antennas. Since the LOS probability and path loss models are available, we can calculate the SINR for UEs in diverse heights. Notably, the highest supportive altitude stipulated by the 3GPP is 300 m for aerial vehicles, due to the limited power transmitted from downtilt TBS.

B. Influence on Coverage Probability

To assess the impact of UE heights on the coverage probability, four separated heights for ground UE at 1.5 m and aerial UE at 50 m, 100 m, and 250 m were selected in numerical simulations. Fig. 4 shows the coverage probabilities versus the SINR threshold for different UE heights. We found that the aerial UE at 50 m receives a better coverage probability than any three heights. It clearly shows that although the antenna of TBS is down tilted, the coverage can be compensated by high LOS probability for the aerial UE. Nonetheless, aerial UEs at 100 m and 250 m obtain smaller coverage probabilities than the ground UE, since aerial UEs typically receive the

\(\text{coverage probability} = \frac{\text{number of successful connections}}{\text{total number of connections}}\)

\(^2\)The fading depth is defined as the difference in power values between the 50\% and 1\% level of small-scale fading.

\(^3\)The coverage probability represents that the probability that the SINR of UE is larger than the given SINR threshold.
signal from the side lobe of the TBS antenna. Because the LOS probability is treated as 100% for altitudes higher than 100 m in the 3GPP report, aerial UEs higher than 100 m is free of compensation of higher LOS probability, which elucidates the smaller coverage probability at 250 m. Fortunately, the simulation result provides an insight into UAV operation, since it implies that UAV can achieve the same considerable performance with ground UE if it can find the optimal height between 50 m and 100 m.

VI. POTENTIAL DIRECTIONS

In the former sections, we have proposed new characteristics concerning UAV channel modeling, reviewed recent progress, and illustrated the impacts of essential factors with measurements and simulations. In this section, we point out some potential directions in terms of A2A and A2G channel modeling, which aims to provide a reference to future researches.

A. Multi-Frequency, Multi-Environment, and Multi-Antenna Channel Measurements

Although numerous measurements have been performed for multitudinous environments and frequencies, most of the existing works concentrate on typical environments at sub-6 GHz, i.e., L-band and C-band. Thus, it leaves many vacancies in terms of high-frequency bands and non-typical environments, particularly for A2A channels. For instance, UAV incorporating mmWave band is regarded as a potential to achieve high data transmission rates. Moreover, the nature of the very short wavelength in the mmWave band enables the multi-input multi-output (MIMO) antenna to mount on the UAV, which brings a new issue related to the UAV MIMO channel measurement, characterization, and modeling. Besides, since UAVs can be operated in 3D space, typical environments are difficult to involve all environments where UAVs would fly. Thus, non-typical environments should be taken into consideration. Notably, non-typical environments can be indoor and forest environments, etc. To conclude, the study on multi-frequency, multi-environment, and multi-antenna (3M) channel measurements has progressively developed as one of the promising directions in future UAV channel modeling.

B. Learning-based Channel Modeling Methods

The effectiveness and accuracy are the most critical metrics regardless of any modeling methods. In addition to the aforementioned three conventional methods, novel methods need to be explored and developed to remedy existent flaws. Learning-based methods have attracted much attention in the field of channel modeling, in which deep learning and reinforcement learning are the most prevalent. However, the forthputting of learning-based methods is currently in the initial stage. For example, deep learning can predict the signal strength with considerable accuracy after the large-scale training with measured receive power data. Thereby it is meaningful to develop more effective and accurate learning-based predictors to characterize various channel parameters involving large-scale and small-scale kinds.

C. Meticulous Channel Characterizations

In traditional A2A and A2G channel modeling, the terminals are generally assumed as non-physical nodes without premeditating their sizes. However, the experiences from vehicular channel modeling remind us that the physical size of the vehicle has a significant impact on channel properties. Thus the shadowing and small-scale fading caused by the fuselage of UAV is worth considering. Moreover, the jittering or fluctuation produced during the flight of UAV is being initially investigated for their impacts on A2A and A2G channels. These examples show that meticulous channel characterization is becoming increasingly popular with full considerations of the physical size of UAV, the jittering of flight, and other exhaustive details.

D. Emerging UAV-related Channels

With the evolution of wireless communication, the fifth generation (5G) communication system has begun to be commercialized, at the meantime, the next-generation communication is under boundless envisions. Under this circumstance, the UAV is considered to play an essential role in next-generation communication. One is that UAV can be used in the aerial layer in the space-air-ground integrated network, where this network is expected to realize the global coverage. However, the emerging network pours many challenges to UAV channel modeling since lots of communication nodes such as satellites are comprised in this network. Another example concerns the technology of reconfigurable intelligence surface (RIS) that can be used for RIS-assisted UAV communications. Thereby, it requires an accurate channel model between UAV and RIS. In a summary, UAV communication is going through unprecedented development, which leads to many connections between UAV and other emerging nodes. Thus, it is necessary to model sundry UAV-related channels when UAV is incorporated in arising communication scenarios.

VII. CONCLUSION

In this article, we focus on A2A and A2G propagation channels for connected UAV communications. We summarized new characteristics for UAV channel modeling in terms of
altitudes, frequencies, environments, maneuverability, shadowing, and jittering. Afterward, a comprehensive investigation of recent progress illustrates the large-scale and small-scale statistics. We found that the typical PLEs and standard deviations of shadowing for A2G channels are 1.3-3.7 and 2.6-7.7 dB, respectively. We also provided a summary of UAV-related channel models such as path loss, small-scale fading model, and multipath model. The log-distance path loss model and Rician fading are the most commonly used in both A2A and A2G channels to describe the large-scale and small-scale fading, respectively. We subsequently gave two illustrative examples to show the impacts of frequency and environment on A2G channel characterization. We found that the frequency has a strong effect on fading depth and the environment mainly influences the distribution of MPCs. The system-level simulations can provide a direct view of how a practical channel model affects communication performance, therefore we evaluated coverage probability by employing a realistic 3GPP path loss model. The results show that an aerial UE can achieve considerable performance as a ground UE by adjusting its height in a certain range. Finally, potential directions are extracted with focuses on the 3M channel measurements, learning-based modeling methods, meticulous channel characterizations, and emerging UAV-related channels such as satellite-to-UAV and UAV-to-RIS channels.

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REFERENCES

[1] L. Zhou, H. Ma, Z. Yang, S. Zhou and W. Zhang, “Unmanned aerial vehicle communications: path-loss modeling and evaluation,” IEEE Veh. Technol. Mag., vol. 15, no. 2, pp. 121-128, Jun. 2020.
[2] W. Khawaja, I. Güvenç, D. W. Matolak, U. Fiebig and N. Schneckenburger, “A survey of air-to-ground propagation channel modeling for unmanned aerial vehicles,” IEEE Commun. Surveys Tuts., vol. 21, no. 3, pp. 2361-2391, thirdquarter 2019.
[3] D. W. Matolak and R. Sun, “Air-ground channel characterization for unmanned aircraft systems part i: methods, measurements, and models for over-water settings,” IEEE Trans. Veh. Technol., vol. 66, no. 1, pp. 26-44, Jan. 2017.
[4] D. W. Matolak and R. Sun, “Air-ground channel characterization for unmanned aircraft systems part iii: the suburban and near-urban environments,” IEEE Trans. Veh. Technol., vol. 66, no. 8, pp. 6607-6618, Aug. 2017.
[5] W. Khawaja, I. Güvenç and D. Matolak, “UWB channel sounding and modeling for UAV air-to-ground propagation channels,” Proc. 2016 IEEE Global Communications Conference (GLOBECOM), Washington, DC, Dec. 2016, pp. 1-7.
[6] X. Cui et al., “An empirical air-to-ground channel model based on passive measurements in LTE,” IEEE Trans. Veh. Technol., vol. 68, no. 2, pp. 1140-1154, Feb. 2019.
[7] R. Amorim, H. Nguyen, P. Mogensen, I. Z. Kovács, J. Wigard and T. B. Sørensen, “Radio channel modeling for UAV communication over cellular networks,” IEEE Wireless Commun. Lett., vol. 6, no. 4, pp. 514-517, Aug. 2017.
[8] T. Liu et al., “Measurement-based characterization and modeling for low-altitude UAV air-to-air channels,” IEEE Access, vol. 7, pp. 98832-98840, Jul. 2019.
[9] D. Becker, U. Fiebig and L. Schalk, “Wideband channel measurements and first findings for low altitude drone-to-drone links in an urban scenario,” Proc. 2020 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, 2020, pp. 1-5.
[10] A. Al-Hourani and K. Gomez, “Modeling cellular-to-UAV path-loss for suburban environments,” IEEE Wireless Commun. Lett., vol. 7, no. 1, pp. 82-85, Feb. 2018.
[11] 3GPP, “Study on enhanced LTE support for aerial vehicles (Release 15),” 3rd Generation Partnership Project (3GPP), Tech. Rep. 36.777, V15.0.0, Dec. 2017.
[12] J. H. Bae, Y. S. Kim, N. Hur and H. M. Kim, “Study on air-to-ground multipath channel and mobility influences in UAV based broadcasting,” in Proc. 2018 International Conference on Information and Communication Technology Convergence (ICTC), Jeju, 2018, pp. 1534-1538.
[13] W. Khawaja, O. Ozdemir and I. Güvenç, “UAV air-to-ground channel characterization for mmWave systems,” in Proc. 2017 IEEE 86th Vehicular Technology Conference (VTC-Fall), Toronto, ON, 2017, pp. 1-5.
[14] C. Briso, C. Calvo, Z. Cui, L. Zhang and Y. Xu, “Propagation measurements and modeling for low altitude UAVs from 1 to 24 GHz,” IEEE Trans. Veh. Technol., vol. 69, no. 3, pp. 3439-3443, Mar. 2020.
[15] Z. Cui, C. Briso-Rodríguez, K. Guan, I. Güvenç and Z. Zhong, “Wideband air-to-ground channel characterization for multiple propagation environments,” IEEE Antennas Wirel. Propag. Lett., vol. 19, no. 9, pp. 1634-1638, Sept. 2020.