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Three-Dimensional Non-Stationary Wideband Geometry-Based UAV Channel Model for A2G Communication Environments

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ABSTRACT In this paper, we propose a novel three-dimensional multiple-input multiple-output channel model to describe the air-to-ground (A2G) communication environments. The model introduces the unmanned aerial vehicle (UAV) transmitter and ground mobile receiver (MR) located at the foci points of the boundary ellipsoid, while different ellipsoids represent the propagation properties for different time delays. In light of this, we are able to investigate the propagation properties of the A2G channel model for different time delays. Furthermore, the time-varying parameters of the azimuth angle of departure, the elevation angle of departure, the azimuth angle of arrival, and elevation angle of arrival are derived to properly describe the channel non-stationarity, which is caused by the motion of the UAV transmitter, cluster, and MR. The impacts of the movement properties of the cluster in both the azimuth and elevation planes are investigated on the channel characteristics, i.e., spatial cross-correlation functions, temporal autocorrelation functions, Doppler power spectrum density, and power delay profiles.

INDEX TERMS 3D MIMO channel model, A2G communication environments, unmanned aerial vehicle, channel non-stationarity, channel characteristics.

I. INTRODUCTION

A. MOTIVATION

Unmanned aerial vehicles (UAVs) are an emerging technology that have been widely used in the public and civil domains [1]. In recent years, a variety of advanced technologies, e.g., massive multiple-input multiple-output (MIMO) [2]–[4] and cooperative spectrum sensing [5]–[7], have been introduced together with fifth generation (5G) wireless communication systems. To efficiently design communication systems and signal processing techniques for A2G communications, it is important to have reliable statistical channel model to express the propagation properties between the transmitter and receiver [8].

B. RELATED WORKS

1) GEOMETRY-BASED CHANNELS

In previous studies, geometry-based stochastic models (GBSMs), which have the advantages of low computational complexity and high accuracy, are widely utilized to reflect the propagation properties of UAV communication environments. In reality, UAV transmitters are located at a relatively high altitude compared with the ground receiver [9], [10]. Therefore, it is important to introduce a three-dimensional (3D) air-to-ground (A2G) channel model to reflect the propagation properties of UAV communications. To be specific, Gao and Hu [11] introduced a 3D MIMO channel model to describe A2G communication scenarios, which assumed that the propagation paths are single interaction and the transmitter follows a cylindrical shape. Zeng *et al.* [12] and Jin *et al.* [13] applied the 3D geometry-based MIMO channel modeling to reflect the UAV communications in A2G environments, which assumed that all effective scatterers around the ground receiver are distributed on the surface of a cylinder and a sphere, respectively. In [14], we developed a 3D geometric MIMO channel model in A2G communication environments, which adopted the elliptic-cylinder model to describe the distribution of effective scatterers around the UAV and mobile receiver (MR). Furthermore,

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Gulfam *et al.* [15] proposed a 3D geometric channel model for A2G communication scenarios, which considered the air transmitter and ground receiver located at foci points of a virtual bounding ellipsoid.

2) NON-STATIONARY CHANNELS

As demonstrated in [16], one of the main characteristics of vehicle-to-vehicle (V2V) channels is the non-stationarity, which is caused by the motion of the mobile transmitter (MT) and MR. Yuan *et al.* [17] introduced the time-varying angular parameters of azimuth angle of departure (AAoD), elevation angle of departure (EAoD), azimuth angle of arrival (AAoA), and elevation angle of arrival (EAoA) to describe the V2V channel non-stationarity. In [18], we introduced the time-varying parameters of propagation paths to reflect the channel non-stationarity. Furthermore, Jiang *et al.* [19] proposed a 3D half-sphere model to describe the distribution of scatterers in UAV MIMO channels, which introduced the update and computation methods of time-varying model parameters to describe the channel non-stationarity. Accordingly, in A2G scenarios, it is important to investigate the impacts of the movements of UAV transmitter, mobile objects, and MR on the channel characteristics. To the best of authors' knowledge, this work has not been endowed before.

3) WIDEBAND CHANNELS

In real A2G scenarios, the channel non-stationarity because of the appearance and disappearance of effective scatterers, which is caused by the fast movement of the UAV [20]. In light of this, Li and Cheng [21] developed deterministic and stochastic simulation models to reflect wideband wireless channels. Chen *et al.* [22] and Bai *et al.* [23] proposed 3D wideband stochastic multi-ellipsoid models for wireless MIMO communication channels, which assumed that interfering objects were distributed on the surface of the ellipsoids whose foci are at the center of transmitter and receiver ends. However, the models in [22] and [23] cannot be used to investigate the statistical properties for different propagation delays, which are meaningful for wideband channels, i.e., frequency-selective channels. Furthermore, Yuan *et al.* [17] developed a 3D wideband MIMO V2V channel, which introduced different cylinders represent the propagation properties for different time delays. However, the effective scatterers located on the cylinder did not have identical propagation delays and meanwhile; the complexity of the channel model increased, which negated the advantage of ellipsoid models for frequency-selective channels. However, it is worth mentioning that the interesting obstacles are randomly distributed between the UAV transmitter and ground MR in A2G scenarios, which means that the waves from the UAV experience different propagation delays to the receiver. Furthermore, Wu *et al.* [24] proposed wideband twin-cluster channel models, which defined a large number of clusters with stochastic model parameters based on the measurements and simulations, to describe A2G scenarios. Li *et al.* [25] presented a 3D cluster-based channel model to reflect V2V communication scenarios, where the azimuth and elevation angles of the cluster are assumed to follow the von Mises distribution, while the distances from the clusters to the transceivers are exponential distribution.

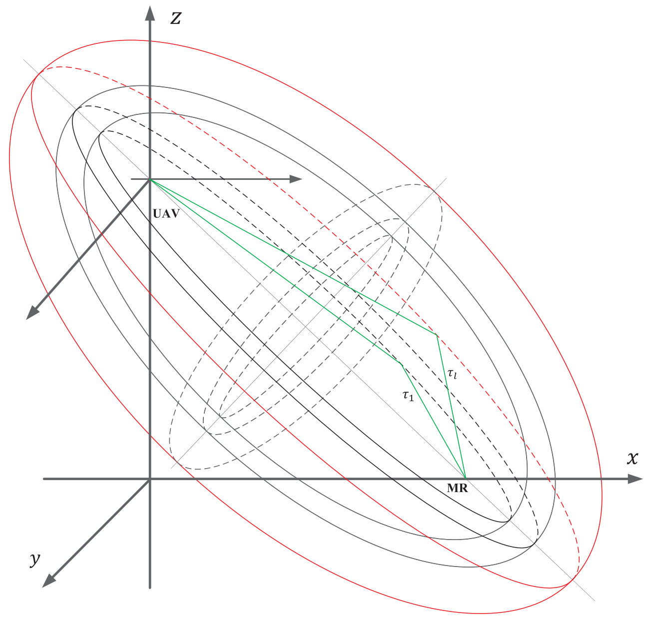

FIGURE 1. A 3D wideband ellipsoid channel model for A2G communication environments.

C. MAIN CONTRIBUTIONS

In this paper, we present a novel 3D MIMO channel model to reflect A2G communication scenarios, as illustrated in Fig. 1. The proposed model introduces the UAV transmitter and ground MR located at the foci points of the bounding ellipsoid; therefore, the propagation of waves from the UAV to MR experiences similar delays. The major contributions of this paper are outlined as follows:

(1) To the best of our knowledge, we first introduce a 3D wideband ellipsoid channel model to describe A2G communication environments, which can be used to model effective scatterers with identical delays on the same ellipsoid, while different ellipsoids represent the statistical properties for different propagation delays.

(2) The time-varying angular parameters of AAoD/EAoD and AAoA/EAoA are derived to properly describe the channel non-stationarity, which is caused by the motion of the UAV transmitter, cluster, and ground MR.

(3) In the proposed model, the impacts of the moving directions and velocities of the UAV, cluster, and MR on the channel characteristics are firstly and jointly considered, which have not been studied in existing channel models. Furthermore, the key time-varying spatial cross-correlation functions (CCFs), temporal autocorrelation functions (ACFs), Doppler power spectrum density (PSD), and power delay profiles (PDPs) for different time instants are thoroughly investigated.

The remainder of this paper is organized as follows. Section II presents the proposed 3D MIMO channel model for A2G communication scenarios. In Section III, the theoretical propagation properties of the channel model are derived and investigated. Section IV provides the numerical results and discussions. Finally, our conclusions are presented in Section V.

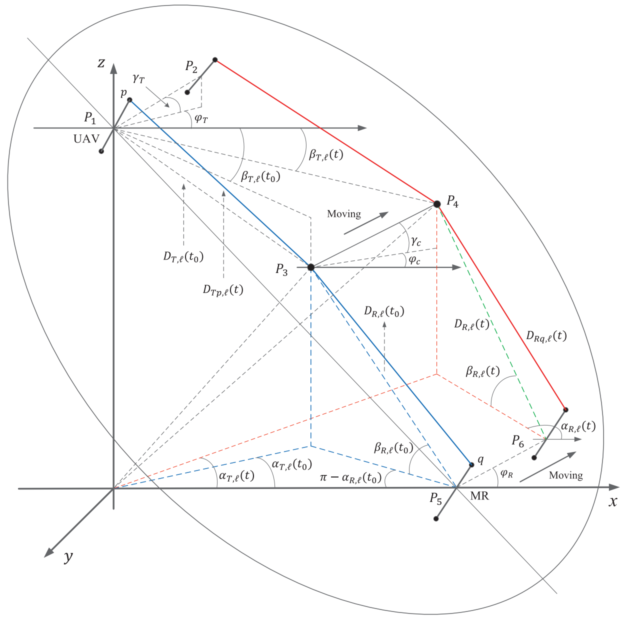

FIGURE 2. Proposed 3D MIMO channel model for A2G communication scenarios.

II. SYSTEM MODEL

A. MODEL DESCRIPTION

In real A2G communication environments, the non-LoS (NLoS) components are usually blocked by mobile birds, airship, etc.; therefore, the LoS components are very weak, while the non-LoS (NLoS) components are dominant in the signal received at the MR. Note that the MR is on the earth surface, it is improper to consider the ground reflection in the proposed model. It is worth mentioning that the UAV transmitter mainly flies at low altitude; therefore, the signals received at the MR are reflected by the interfering obstacles (clusters) in the air. However, if we consider the high altitude A2G communication environments, e.g., multiple kilometers above ground, it is important to investigate the radio wave refracts in the atmosphere since the air density changes over altitude, which will be our future work.

In this section, let us consider a novel 3D UAV MIMO geometric model to reflect A2G channels, where the UAV transmitter and ground MR are equipped with M_T and M_R uniform linear array (ULA) omnidirectional receive antennas, respectively, as illustrated in Fig. 2. In the preliminary stage, we assume that the UAV and MR are static, the line connecting the center point of the MR and the projection point of the center point of the UAV in the horizontal plane is defined as the x-axis. For the transmit and receive antenna elements, we define δ_T and δ_R as the antenna spacing elements at the UAV transmitter and ground receiver, respectively, ψ_T (ψ_R) and θ_T (θ_R) as the orientations of the transmit (receive) antenna array relative to the x-axis and to the ground plane, respectively. Note that when the UAV transmitter moves from position P_1 to P_2, cluster moves from position P_3 to P_4, and the MR moves from position P_5 to P_6, the channel model varies over time, and therefore the time-varying model parameters should be derived to describe the channel non-stationarity. It is assumed that the mobile cluster is fixed as a reference point and therefore, the equivalent channel model is shown in Fig. 3. Then, we define $v_{T/c}$ and $v_{R/c}$ as the moving velocities of the UAV and MR relative to the cluster, respectively, $\varphi_{T/c}$ ($\varphi_{R/c}$) and $\gamma_{T/c}$ ($\gamma_{R/c}$) as the moving directions of the UAV relative to the cluster in the azimuth and elevation planes, respectively. Furthermore, we define $\alpha_{T,\ell}(t)$ and $\beta_{T,\ell}(t)$ as the time-varying angular parameters of AAoD and EAoD of the ℓ-th propagation path that impinge on the cluster, $\alpha_{R,\ell}(t)$ and $\beta_{R,\ell}(t)$ as the time-varying angular parameters of AAoA and EAoA of the ℓ-th propagation path traveling from the cluster.

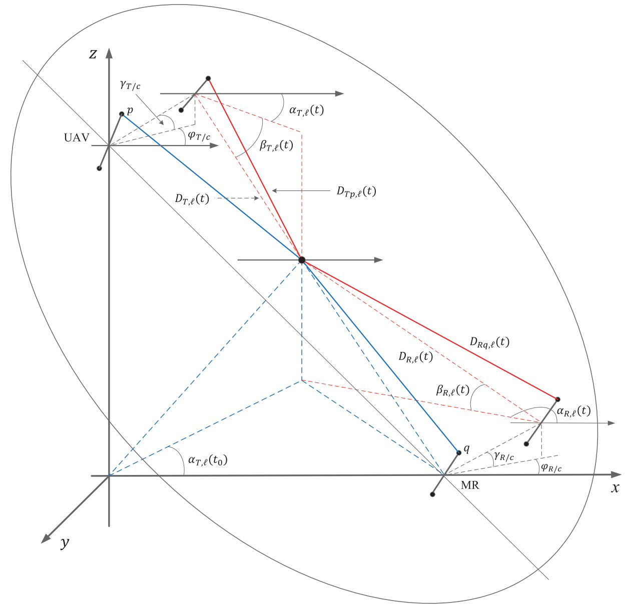

FIGURE 3. Geometric angles and propagation path lengths of the UAV transmitter and ground MR relative to the mobile cluster in the proposed model.

B. CHANNEL IMPULSE RESPONSE

In the proposed model, the waves from the UAV impinge on the large numbers of clusters (obstacles) before reaching the MR. For the proposed MIMO channel model, the physical properties can be represented by a matrix $H(t) = \left[h_{pq}(t,\tau)\right]_{M_R \times M_T}$ of size $M_R \times M_T$, where $h_{pq}(t,\tau)$ denotes the complex impulse response (CIR) between the p-th ($p = 1, 2, \ldots, M_T$) transmit antenna and q-th ($q = 1, 2, \ldots, M_R$) receive antenna, i.e.,

$$h_{pq}(t,\tau) = \sum_{n=1}^{N(t)} h_{pq,n}(t)\delta\big(\tau - \tau_n(t)\big) \tag{1}$$

In (1), $h_{pq,n}(t)$ represents a narrowband process where all the $L(t)$ sub-paths within each of the $N(t)$ clusters are irresolvable rays and have the identical propagation delay $\tau_n(t)$, P_n is the power of the n-th cluster associated with the delay $\tau_n(t)$. Here, the complex fading envelope $h_{pq,n}(t)$ can be expressed as

$$h_{pq,n}(t) = \sum_{\ell=1}^{L(t)} \sqrt{\frac{P_n}{L(t)}} e^{j\left(\varphi_0 - 2\pi f_c \left[D_{Tp,\ell}(t)+D_{Rq,\ell}(t)\right]/c\right)} \times e^{j\frac{2\pi}{\lambda} v_{T/c} t \cos\left(\alpha_{T,\ell}(t)-\varphi_{T/c}\right)\cos\left(\beta_{T,\ell}(t)-\gamma_{T/c}\right)} \times e^{j\frac{2\pi}{\lambda} v_{R/c} t \cos\left(\alpha_{R,\ell}(t)-\varphi_{R/c}\right)\cos\left(\beta_{R,\ell}(t)-\gamma_{R/c}\right)} \quad (2)$$

where f_c represents the carrier frequency, λ is the carrier wavelength, and c is the speed of light. Here, we assume that the phase φ_0 is an independent random variable, which has a uniform distribution in the interval from $-\pi$ to π, i.e., $\varphi_0 \sim [-\pi, \pi)$. It is worth mentioning that the second and third terms in formula (2) are Doppler frequency components. Furthermore, the $D_{Tp,\ell}(t)$ and $D_{Rq,\ell}(t)$ are the distances from the p-th transmit and q-th receive antenna to the cluster, respectively, which can be expressed as

$$D_{Tp,\ell}(t) = \Big[\left(D_{T,\ell}(t)\sin\beta_{T,\ell}(t) - k_p \sin\theta_T\right)^2 + \left(D_{T,\ell}(t)\cos\beta_{T,\ell}(t)\cos\alpha_{T,\ell}(t) - k_p\cos\theta_T\cos\psi_T\right)^2 + \left(D_{T,\ell}(t)\cos\beta_{T,\ell}(t)\sin\alpha_{T,\ell}(t) - k_p\cos\theta_T\sin\psi_T\right)^2\Big]^{1/2} \quad (3)$$

$$D_{Rq,\ell}(t) = \Big[\left(D_{R,\ell}(t)\sin\beta_{R,\ell}(t) - k_q \sin\theta_R\right)^2 + \left(D_{R,\ell}(t)\cos\beta_{R,\ell}(t)\cos\alpha_{R,\ell}(t) - k_q\cos\theta_R\cos\psi_R\right)^2 + \left(D_{R,\ell}(t)\cos\beta_{R,\ell}(t)\sin\alpha_{R,\ell}(t) - k_q\cos\theta_R\sin\psi_R\right)^2\Big]^{1/2} \quad (4)$$

where $k_p = (M_T - 2p + 1)\delta_T/2$ and $k_q = (M_R - 2q + 1)\delta_R/2$. Parameters $D_{T,\ell}(t)$ and $D_{R,\ell}(t)$ denote the distances from the center points of the UAV and MR to the cluster, respectively, which close-form expressions can be seen in our previous work in [18], we omit them here for brevity.

C. TIME-VARYING ANGULAR PARAMETERS AND PROPAGATION PATHS

In the proposed model, we define v_T as the moving velocity of the UAV transmitter in the 3D space, φ_T and γ_T as the moving directions of the UAV in the azimuth and elevation planes, respectively. For the mobile cluster, we define v_u as the moving velocity, while φ_u and γ_u as the moving directions in the horizontal and vertical planes, respectively. However, at the ground receiver, we define v_R and φ_R as the moving velocity and direction, respectively. Based on the principle of relative motion, the velocity of the UAV transmitter relative to the cluster can be derived as

$$v_{T/c} = \Big[\left(v_T\cos\gamma_T\cos\varphi_T - v_c\cos\gamma_c\cos\varphi_c\right)^2 + \left(v_T\cos\gamma_T\sin\varphi_T - v_c\cos\gamma_c\sin\varphi_c\right)^2 + \left(v_T\sin\gamma_T - v_c\sin\gamma_c\right)^2\Big]^{1/2} \quad (5)$$

While the azimuth and elevation moving angles $\varphi_{T/u}$ and $\gamma_{T/u}$ can be respectively derived as

$$\varphi_{T/c} = \arctan\frac{v_T\cos\gamma_T\sin\varphi_T - v_c\cos\gamma_c\sin\varphi_c}{v_R\cos\gamma_T\cos\varphi_T - v_c\cos\gamma_c\cos\varphi_c} \quad (6)$$

$$\gamma_{T/c} = \operatorname{arccot}\Big\{\frac{1}{v_T\sin\gamma_T - v_c\sin\gamma_c} \times \Big[\left(v_T\cos\gamma_T\sin\varphi_T - v_c\cos\gamma_c\sin\varphi_c\right)^2 + \left(v_R\cos\gamma_T\cos\varphi_T - v_c\cos\gamma_c\cos\varphi_c\right)^2\Big]^{1/2}\Big\} \quad (7)$$

However, at the MR, the velocity relative to the cluster can be expressed as

$$v_{R/c} = \Big[\left(v_R\cos\varphi_R - v_c\cos\gamma_c\cos\varphi_c\right)^2 + \left(v_c\sin\gamma_c\right)^2 + \left(v_R\sin\varphi_R - v_c\cos\gamma_c\sin\varphi_c\right)^2 \quad (8)$$

Then, the relative moving angles $\varphi_{R/c}$ and $\gamma_{R/c}$ can be respectively derived as

$$\varphi_{R/c} = \arctan\frac{v_R\sin\varphi_R - v_c\cos\gamma_c\sin\varphi_c}{v_R\cos\varphi_R - v_c\cos\gamma_c\cos\varphi_c} \quad (9)$$

$$\gamma_{R/c} = \operatorname{arccot}\Big\{\frac{1}{-v_c\sin\gamma_c} \times \Big[\left(v_R\sin\varphi_R - v_c\cos\gamma_c\sin\varphi_c\right)^2 + \left(v_R\cos\varphi_R - v_c\cos\gamma_c\cos\varphi_c\right)^2\Big]^{1/2}\Big\} \quad (10)$$

To capture the non-stationarity of wireless channels, many solutions have been introduced in previous literatures. To be specific, Yuan *et al.* [17] and Jiang *et al.* [18] respectively derive the time-varying angular parameters and propagation paths to describe the V2V channel non-stationarity. Here, let us define $\alpha_{\ell,R}(t_0)$, $\beta_{\ell,R}(t_0)$, $\alpha_{\ell,T}(t_0)$, and $\beta_{\ell,T}(t_0)$ as the angular parameters of AAoA, EAoA, AAoD, and EAoD at the beginning time of the movement ($t = t_0$), respectively. Then, the time-varying angular parameters $\alpha_{R,\ell}(t)$ and $\beta_{R,\ell}(t)$ can be expressed as

$$\alpha_{R,\ell}(t) = \arctan\frac{F_1\sin\alpha_{R,\ell}(t_0) - F_2\sin\varphi_{R/c}}{F_1\cos\alpha_{R,\ell}(t_0) - F_2\cos\varphi_{R/c}} \quad (11)$$

$$\beta_{R,\ell}(t) = \arctan\frac{D_{R,\ell}(t_0)\sin\beta_{R,\ell}(t_0) - v_{R/c}t\sin\gamma_{R/c}}{\sqrt{F_1^2 + F_2^2 - 2F_1F_2\cos\left(\alpha_{R,\ell}(t_0) - \varphi_{R/c}\right)}} \quad (12)$$

where $F_1 = D_{R,\ell}(t_0)\cos\beta_{R,\ell}(t_0)$ and $F_2 = v_{R/c}t\cos\gamma_{R/c}$.

Similarly, the time-varying angular parameters $\alpha_{T,\ell}(t)$ and $\beta_{T,\ell}(t)$ can be derived as

$$\alpha_{T,\ell}(t) = \arctan\frac{F_3\sin\alpha_{T,\ell}(t_0) - F_4\sin\varphi_{T/c}}{F_3\cos\alpha_{T,\ell}(t_0) - F_4\cos\varphi_{T/c}} \quad (13)$$

$$\beta_{T,\ell}(t) = \arctan\frac{D_{T,\ell}(t_0)\sin\beta_{T,\ell}(t_0) - v_c t\sin\gamma_{T/c}}{\sqrt{F_3^2 + F_4^2 - 2F_3F_4\cos\left(\alpha_{T,\ell}(t_0) - \varphi_{T/c}\right)}} \quad (14)$$

where $F_3 = D_{T,\ell}(t_0)\cos\beta_{T,\ell}(t_0)$ and $F_4 = v_{T/u}t\cos\gamma_{T/u}$.

Subsequently, the time-varying distances from the p-th transmit and q-th receive antenna to the cluster are respectively expressed as

$$D_{\ell,T,p}(t) = \Big[\big(D_{T,\ell}(t_0)\sin\beta_{T,\ell}(t_0) - v_{T/u}t\sin\gamma_{T/u}\big)^2 + F_3^2 + F_4^2 - 2F_3F_4\cos\big(\alpha_{T,\ell}(t_0) - \varphi_{T/u}\big)\Big]^{1/2} \tag{15}$$

$$D_{\ell,R,q}(t) = \Big[\big(D_{R,\ell}(t_0)\sin\beta_{R,\ell}(t_0) - v_{R/u}t\sin\gamma_{R/u}\big)^2 + F_1^2 + F_2^2 - 2F_1F_2\cos\big(\alpha_{R,\ell}(t_0) - \varphi_{R/u}\big)\Big]^{1/2} \tag{16}$$

Thus far, the time-varying angular parameters and propagation paths of the proposed model have been derived.

III. CHANNEL STATISTICS OF THE PROPOSED MODEL

For the proposed communication system, the channel properties are completely characterized by the CIRs in (1). It is worth mentioning that the spatial CCF between the two propagation links from p-th transmit antenna to q-th receive antenna and from p'-th ($p' = 1, 2, \ldots, M_T$) transmit antenna to q'-th ($q' = 1, 2, \ldots, M_R$) receive antenna is defined as the correlation between the complex fading envelope, i.e.,

$$\rho_{pq,p'q',n}(t,\tau') = \mathbb{E}\Big[h_{pq,n}(t)h^*_{p'q',n}(t-\tau')\Big] \tag{17}$$

where $\mathbb{E}[\cdot]$ denotes the expectation operation and $(\cdot)^*$ is the complex conjugate operation. In substituting (2) into (17), the spatial CCFs in the proposed model can be derived. Furthermore, the temporal ACFs, which can be used to investigate the correlation properties of $h_{pq,n}(t)$ at two different time instants, can be derived by

$$r_{pq,n}(t,\Delta t) = \mathbb{E}\Big[h_{pq,n}(t)h^*_{pq,n}(t+\Delta t)\Big] \tag{18}$$

In substituting (11)–(14) into (18), the proposed temporal ACF with respect to the different moving features of the cluster is derived. Furthermore, the Doppler PSD of the proposed channel model can be obtained by the Fourier transform of the temporal ACF $r_{pq,n}(t,\Delta t)$ with respect to the time interval Δt.

The PDP gives the intensity of a signal received through a wireless channel as a function of propagation delay, which can be measured by the spatial average of the CIR. In the proposed model, the PDP can be obtained as

$$P_{h_{pq}}(t,\tau) = \Big|h_{pq}(t,\tau)\Big|^2 \tag{19}$$

Obviously, the PDP of the proposed model is time-variant on account of the motion of the UAV transmitter, cluster, and ground MR.

IV. NUMERICAL RESULTS AND DISCUSSIONS

Fig. 4 shows the spatial CCFs of the proposed model for different receive antenna angles. It is obvious that the spatial correlation gradually decrease as the spacing between two adjacent receive antenna elements increases, which is in agreement with the measurements in [26]. Furthermore, when the receive antenna angles ψ_R and θ_R increase, the spatial correlation decreases slowly.

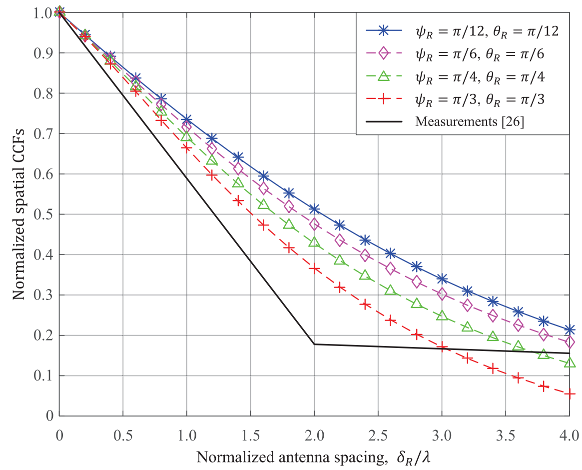

FIGURE 4. Spatial CCFs of the proposed model with respect to the different receive antenna angles when $\psi_T = \theta_T = \pi/6$ and $M_T = M_R = 8$.

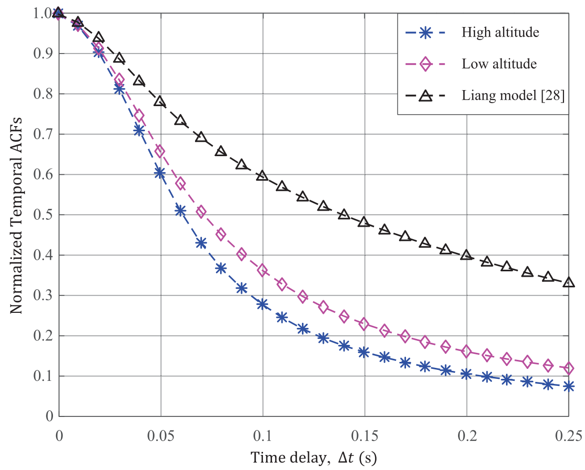

FIGURE 5. Temporal ACFs of the proposed model with respect to the different heights of the UAV when $\delta_T = \delta_R = 0.5\lambda$, $\psi_T = \psi_R = \pi/3$, $\theta_T = \theta_R = \pi/4$, and $M_T = M_R = 8$.

It was reported in [27] that the heights of the UAV transmitter have great influences on the A2G channel characteristics. In Fig. 5, we notice that the temporal correlation gradually decrease as the time delay Δt increases, which is in agreement with the results in [18]. Furthermore, when the distance from the UAV to the ground increases, the temporal correlation decreases slowly.

The impacts of the moving velocities of the UAV transmitter, cluster, and ground MR on the proposed temporal ACFs are investigated in Fig. 6. It is obvious that the temporal correlation gradually decrease when the velocities of the UAV and MR (v_T and v_R) increase. Furthermore, when the velocity of the mobile cluster v_u increases from 5 m/s to 10 m/s, the temporal correlation decreases rapidly [28].

Figure 7 illustrates the Doppler PSDs of the proposed model at different moving time instants. It can be observed

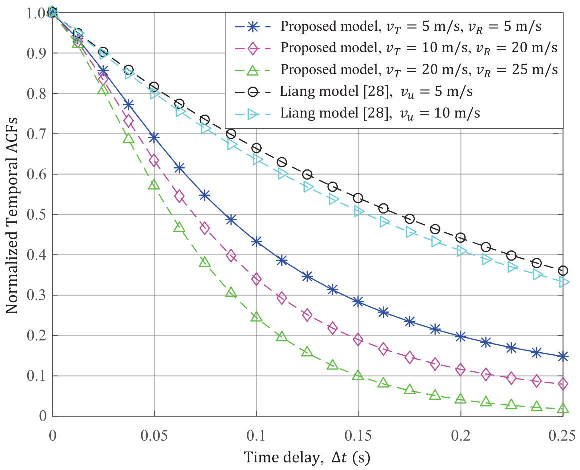

FIGURE 6. Temporal ACFs of the proposed model with respect to the different moving velocities of the UAV and MR when $\delta_T = \delta_R = 0.5\lambda$, $\psi_T = \psi_R = \pi/3$, $\theta_T = \theta_R = \pi/4$, $M_T = M_R = 8$, $\varphi_T = \gamma_T = \pi/6$, $\varphi_u = \gamma_u = \pi/6$, $\varphi_R = \pi/6$, and $v_u = 5$ m/s.

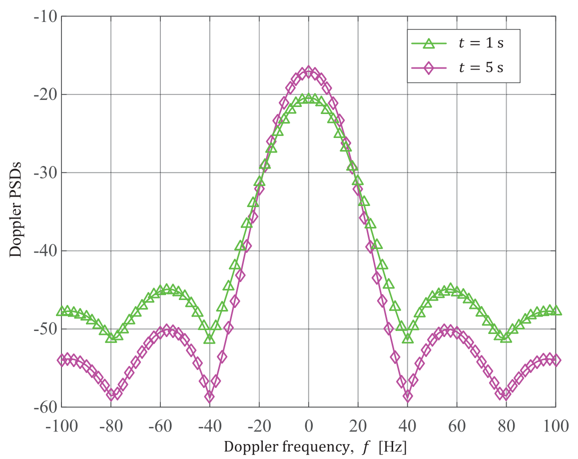

FIGURE 7. Doppler PSDs of the proposed model with respect to the moving time instants of the UAV and MR when $\delta_T = \delta_R = 0.5\lambda$, $\psi_T = \psi_R = \pi/3$, $\theta_T = \theta_R = \pi/4$, and $M_T = M_R = 8$.

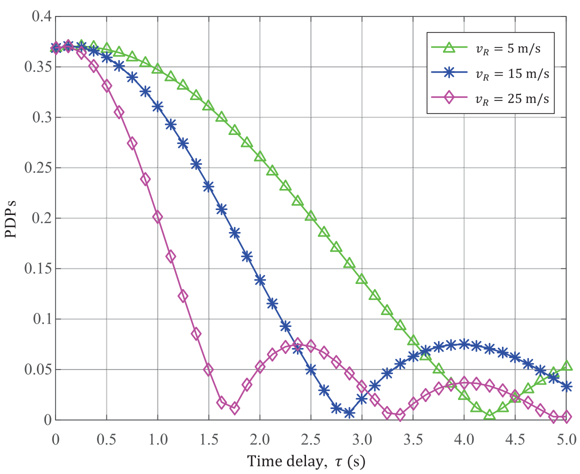

FIGURE 8. PDPs of the proposed model with respect to the different moving velocities of the MR when $v_T = 0$, $v_c = 0$, and $\varphi_R = 0$.

that the proposed Doppler spectrum fits very well with the prior results in [29], verifying the correctness of the above derivations and simulations.

In Fig. 8, we notice that when the MR moves away the origin point of the coordinate, i.e., $\varphi_R = 0$, the values of the proposed PDPs gradually decrease as the time delay τ increases. Furthermore, the PDPs of the proposed model vary more heavily as the velocity of the MR increases from 5 m/s to 25 m/s. The analysis above fits very well with the results in [30], demonstrating the accuracy of the derivations of the proposed PDPs.

V. CONCLUSION

In this paper, we have provided a novel 3D MIMO channel model to reflect A2G communication scenarios. The time-varying angular parameters of AAoD/EAoD and AAoA/EAoA are derived to properly describe the channel non-stationarity. Numerical results have demonstrated that the receive antenna angles have great influences on the theoretical propagation properties of the A2G channel model. The temporal ACFs are impacted by the moving directions and velocities of the UAV transmitter, cluster, and ground MR. Furthermore, the Doppler PSDs have different properties at different moving time instants. The above observations, overall, are able to efficiently design the system of A2G communications.

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