A General 3D Non-Stationary Wideband Twin-Cluster Channel Model for 5G V2V Tunnel Communication Environments

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ABSTRACT

In this paper, we propose a general three-dimensional (3D) non-stationary wideband two-cluster channel model for fifth-generation (5G) vehicle-to-vehicle (V2V) tunnel communication environments. In the proposed model, the received signal is constructed as a sum of the components with line-of-sight (LoS) propagations and the components via the two-cluster model, i.e., non-line-of-sight (NLoS) propagations; therefore, the model has the ability to sufficiently describe a variety of 5G wireless communication scenarios. In order to investigate the non-stationary properties of clusters, we introduce a birth-death algorithm to model the appearance and disappearance of clusters on both the array and time axes. The impacts of the non-stationary properties of clusters on the multiple-input and multiple-output (MIMO) channels are investigated via statistical properties, including spatial cross-correlation functions (CCFs), temporal spatial auto-correlation functions (ACFs), and Doppler power spectrum densities (PSDs). Numerical results of the proposed propagation properties fit the simulation results and prior measured results very well, which demonstrate that the proposed 3D model is able to describe the real 5G V2V communications in tunnel environments.

INDEX TERMS

Two-cluster channel model, 5G V2V tunnel communication environments, birth-death process, non-stationary properties.

I. INTRODUCTION

In recent years, thorough investigation of the statistical propagation properties of fifth generation (5G) vehicle-to-vehicle (V2V) scattering environments has attracted a great deal of research attention in order to develop wireless intelligent transportation systems [1][2]. It is considered to be very beneficial to employ multiple-input and multiple-output (MIMO) technologies in 5G V2V communication systems as they are able to satisfy the increasing traffic demands for vehicular communications in the 5G wireless networks [3][4]. Therefore, a fundamental understanding of statistical propagation properties of MIMO V2V channels is critical in both theoretical and practical aspects [5].

In wireless MIMO communication environments, the waves from the transmitter impinge on the scatterers in the roadside environments before reaching at the receiver [6]; therefore, the existing literatures adopt Ricean fading channels to characterize the propagation characteristics in 5G V2V communications [7]. Numerical studies have demonstrated that the computational complexities of the solution of the geometry-based stochastic channel modeling are extremely low while their accuracies are very high; therefore,
the researchers are more likely to introduce geometric models to study the statistical propagation properties of V2V channels in 5G communication scenarios. Thus far, a variety of geometric channel models have been introduced to depict the distribution region of interfering objects in wireless communication scenarios. In light of this, the propagation path lengths and angular parameters in different scenarios can be derived according to specific geometric relations among the transmitter, receiver, and interfering objects. To be specific, Refs. [8] and [9] proposed multi-bounced scattering models to study the statistical characteristics in V2V channels, which adopted an ellipse model to depict the distribution region of interfering objects in mobile radio communication environments. R. S. He et al. [10] studied the time-varying statistical characteristics of M2M channels in a two-ring reference model, which assumed that the movement directions and velocities are fixed. Measurements in [11] demonstrated that when the propagation of the waves from a transmitter to a receiver is in a two-dimensional (2D) model, the evaluation of the performance of wireless communication system is not accurate. Therefore, it is of vital importance to adopt three-dimensional (3D) channel models, i.e., including azimuth angles and elevation angular parameters, to study the statistical propagation properties [12]. The authors in [13] presented a 3D MIMO channel model to mimic the communication scenarios between the transmitter in the air and the receiver on the ground, which assumed that the high altitude transmitter and ground receiver located at the foci points of the 3D tilt ellipsoid model. Furthermore, the authors in [14] presented a 3D massive MIMO channel model for 5G high-speed train wireless communications, which studied the cluster evolutions to model channel non-stationary properties in space, time, and frequency domains.

It is worth mentioning that the communications between a transmitter and a receiver in 5G V2V channels have different geometric distribution of interfering objects, i.e., rectangular, horseshoe, oval, circular, and semi-circular shapes. Modeling of V2V channels in tunnel environments, especially for many roads are passing through tunnels, is of importance for the development of 5G communication systems. The authors in [15] proposed a theoretical channel model in tunnels with vehicular traffic flow, which demonstrated that the propagation properties in tunnel channels were influenced by the number, size, and position of the vehicles, the size of the tunnel, and the vehicular traffic load. The authors in [16] proposed a 3D wideband MIMO channel model for vehicle-to-vehicle (V2V) communications in tunnel scenarios. In [16], we introduced a variety of confocal semi-ellipsoid models to investigate the statistical characteristics in V2V channels for different propagation delays. The authors in [17] proposed a wideband MIMO scattering channel model for car-to-car (C2C) communications, which assumed that an infinite number of scatterers were randomly distributed on the semi-circular tunnel wall. Furthermore, in [18], Y. Liu et al. proposed a 3D non-stationary theoretical geometric model for high-speed train tunnel communication environments by adopting the distributed antenna system.

It was reported in [19] and [20] that in high mobility communication scenarios, the channel statistical characteristics would vary over the movement time while the transmitter and receiver are not static. Therefore, it is of importance to introduce non-stationary channel models to investigate the propagation properties, i.e., the time-varying number of clusters, power, propagation delays, and angular parameters [21]. The authors in [22] and [23], respectively, proposed a 3D wideband twin-cluster channel model and a 2D multi-confocal ellipse channel model for massive MIMO communication scenarios, which studied the birth-death process to model non-stationary properties of clusters such as cluster appearance and disappearance on both the array and time axes. In [24], the authors improved the algorithm in [22] by including mean power evolution and updates of rays within clusters for the unified 5G communication framework.

In this article, we propose a general 3D non-stationary wideband two-cluster channel model for 5G V2V communications in tunnel environments, as shown in Fig. 1. Overall, the main contributions and innovations of this paper are outlined as follows:

1. In the model, we study the analytical and simulation results of the statistical propagation characteristics for different moving directions and time instants of the mobile transmitter (MT) and mobile receiver (MR) in 5G V2V tunnel Ricean fading channels.

2. Important statistical channel propagation properties, such as the proposed spatial cross-correlation functions (CCFs), temporal auto-correlation functions (ACFs), and Doppler power spectrum densities (PSDs), are derived and thoroughly investigated.

3. The proposed model is validated by comparing the statistical propagation properties of the analytical and simulation results in different moving time instants, which validates that our model can be adopted to diverse 5G V2V communication scenarios by changing the angular and model variables.

![FIGURE 1: Proposed 3D wideband two-cluster channel model for 5G V2V tunnel communication scenarios.](image-url)

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(4) We introduce the birth-death process to model the appearance and disappearance of clusters (i.e., cluster evolution) on both the array and time axes, which make the channel model essentially non-stationary.

The rest of this article is summarized as follows. Section II provides the system channel model for 5G V2V communication scenarios. The propagation scenarios and geometric relationships are provided in detail. In Section III, statistical propagation properties in 5G V2V tunnel channels such as spatial CCFs and temporal ACFs are derived and investigated based on the proposed model. Section IV discusses the numerical analytical and simulation results of the proposed V2V channel model. Finally, our conclusions are shown in Section V.

II. SYSTEM CHANNEL MODEL

In this section, we first discuss the complex channel impulse response (CIR) of the channel model. Then, we introduce the birth-death process to model the channel non-stationary properties.

A. COMPLEX CHANNEL IMPULSE RESPONSE

In this section, let us consider a wideband MIMO system for V2V communications in tunnel environments, as shown in Fig. 1. For a twin-cluster channel model, we define Cluster\(T\) as the cluster at the MT side modeling first bounce; Cluster\(R\) as the cluster at the MR side modeling last bounce. It is worth mentioning that the propagation environment between the Cluster\(T\) and Cluster\(R\) is abstracted as a virtual link [25]. The proposed geometric model describes the scattering environment inside a tunnel with a length of \(D\). Assume that the cross-section of the tunnel is a semi-circle with radius \(R\). The MT and MR are equipped with a uniform linear antenna arrays consisting of of \(M\) and \(N\) antenna elements, and the inter-element spacings between the elements are denoted by \(\delta_T\) at the MT and \(\delta_R\) at the MR. The orientations of the MT and MR antenna arrays relative to the positive direction of the \(x\)-axis are denoted as \(\psi_T\) and \(\psi_R\), respectively. The positions of the center points of the MT and MR antenna arrays are determined by \((x_T, y_T, z_T)\) and \((x_R, y_R, z_R)\), respectively. It is assumed that there exist \(N_1\) effective s-scatterers in the Cluster\(T\), and the \(n_1\)-th \((n_1 = 1, 2, ..., N_1)\) scatterer is defined as \(s^{(n_1)}\); there are \(N_2\) effective scatterers in the Cluster\(R\), and the \(n_2\)-th \((n_2 = 1, 2, ..., N_2)\) scatterer is defined as \(s^{(n_2)}\). The positions of the scatterer \(s^{(n_1)}\) of the Cluster\(T\) and the \(s^{(n_2)}\) of the Cluster\(R\) are determined by \((x_{n_1}, y_{n_1}, \sqrt{R^2 - y_{n_1}^2})\) and \((x_{n_2}, y_{n_2}, \sqrt{R^2 - y_{n_2}^2})\), respectively, where \(x_{n_1}, y_{n_1}, x_{n_2}, y_{n_2}\) are random variables.

The complex CIR between the \(p\)-th \((p = 1, 2, ..., M\) element of the MT and the \(q\)-th \((q = 1, 2, ..., M\) element of the MR can be expressed as

\[
h_{pq}(t, \tau) = h_{pq}^{t\,\text{LoS}}(t)\delta(\tau - t) + h_{pq}^{N\,\text{LoS}}(t)\delta(\tau - t)\quad (1)
\]

where \(t\) denotes the propagation delay of the LoS components from the center point of the MT antenna array to that of the MR antenna array, \(\tau\) is the mean propagation delay of the NLoS components from the center of the MT antenna array to that of the MR antenna array via the twin-cluster model.

In (1), the complex CIR of the components of the LoS propagations can be expressed as

\[
h_{pq}^{t\,\text{LoS}}(t) = \sqrt{\frac{K}{K + 1}}e^{j\left(\varphi_0 - 2\pi f_t\xi_{pq}(t)/c\right)}
\]

\[
\times e^{j2\pi v_T t\cos\left(\alpha_T^{\text{LoS}}(t) - \gamma_T\right)\cos\beta_T^{\text{LoS}}(t)}
\]

\[
\times e^{j2\pi v_R t\cos\left(\alpha_R^{\text{LoS}}(t) - \gamma_R\right)\cos\beta_R^{\text{LoS}}(t)}
\]

where \(\varphi_0\) denotes the initial phase of the LoS components, which is assumed to be an independent random variable with an uniform distribution from \(-\pi\) to \(\pi\), i.e., \(\varphi_0 \sim [-\pi, \pi]\). Here, \(K\) designates the Rice factor, \(\lambda\) is the wavelength. The \(\alpha_T^{\text{LoS}}(t)\) and \(\alpha_R^{\text{LoS}}(t)\) are the time-varying mean azimuth angle of departure (AAoD) and azimuth angle of arrival (AAoA) of the components of the LoS propagations, respectively; \(\beta_T^{\text{LoS}}(t)\) and \(\beta_R^{\text{LoS}}(t)\) are the time-varying mean elevation angle of departure (E AoD) and elevation angle of arrival (E AoA) of the LoS path, respectively.

However, when the waves propagate from the MT to the MR via the two-cluster model, i.e., NLoS propagations, the complex CIR can be expressed as [26]

\[
h_{pq}^{N\,\text{LoS}}(t) = \sqrt{\frac{1}{K + 1}}\lim_{N_1 \to \infty} \lim_{N_2 \to \infty} \sum_{n_1=1}^{N_1} \sum_{n_2=1}^{N_2} \frac{1}{\sqrt{N_1N_2}}
\]

\[
\times e^{j\left(\varphi_{n_1} - 2\pi f_t\xi_{pq,n_1,n_2}(t)/c\right)}
\]

\[
\times e^{j2\pi v_T t\cos\left(\alpha_T^{(n_1)}(t) - \gamma_T\right)\cos\beta_T^{(n_1)}(t)}
\]

\[
\times e^{j2\pi v_R t\cos\left(\alpha_R^{(n_2)}(t) - \gamma_R\right)\cos\beta_R^{(n_2)}(t)}
\]

(2)

where \(\varphi_{n_1}\) denotes the initial phase of the NLoS components, which is assumed to be an independent random variable with an uniform distribution from \(-\pi\) to \(\pi\), i.e., \(\varphi_{n_1} \sim [-\pi, \pi]\). The \(\alpha_T^{(n_1)}(t)\) and \(\beta_T^{(n_1)}(t)\) are, respectively, the time-varying mean AAoD and EAoD of the propagation path that impinge on the scatterer \(s^{(n_1)}\) of the Cluster\(T\); while \(\alpha_R^{(n_2)}(t)\) and \(\beta_R^{(n_2)}(t)\) are, respectively, the time-varying mean AAoA and EAoA of the propagation path that reflected by the scatterer \(s^{(n_2)}\) of the Cluster\(R\).

Furthermore, \(\xi_{pq,n_1,n_2}(t)\) denotes the propagation distance of the waves from the \(p\)-th MT antenna to the \(q\)-th MR antenna via the scatterer \(s^{(n_1)}\) of the Cluster\(T\) and the scatterer \(s^{(n_2)}\) of the Cluster\(R\), which can be calculated as

\[
\xi_{pq,n_1,n_2}(t) = \xi_{pq,n_1}(t) + \xi_{pq,n_2}(t) + \sigma_{n_1,n_2}
\]

(4)

where \(\sigma_{n_1,n_2}\) is assumed to follow an exponential distribution. The
\[ \alpha^{(n_1)}_T(t) = \arctan \frac{D^{(n_1)}_T \sin \alpha^{(n_1)}_T(t_0) \cos \beta^{(n_1)}_T(t_0) - \nu_T t \sin \phi_T}{D^{(n_1)}_T \cos \alpha^{(n_1)}_T(t_0) \cos \beta^{(n_1)}_T(t_0) - \nu_T t \cos \phi_T} \]  

\[ \beta^{(n_1)}_T(t) = \arccot \left\{ \frac{1}{D^{(n_1)}_T \sin \beta^{(n_1)}_T(t_0)} \times \sqrt{\left(D^{(n_1)}_T \sin \alpha^{(n_1)}_T(t_0) \cos \beta^{(n_1)}_T(t_0) - \nu_T t \sin \phi_T\right)^2 + \left(D^{(n_1)}_T \cos \alpha^{(n_1)}_T(t_0) \cos \beta^{(n_1)}_T(t_0) - \nu_T t \cos \phi_T\right)^2} \right\} \]  

\( \xi_{pn_1} \) is the distance from the \( p \)-th antenna of the MT array to the scatterer \( s^{(n_1)} \) of the Cluster\( T \); while \( \xi_{qn_2} \) is the distance from the \( q \)-th antenna of the MR array to the scatterer \( s^{(n_2)} \) of the Cluster\( R \). They are calculated as:

\[ \xi_{T,n_1} = \xi_{T,n_1} - \frac{M_T - 2p + 1}{2} \delta_T \times \cos \beta^{(n_1)}_T \cos (\alpha^{(n_1)}_T - \psi_T) \]  

(5)

\[ \xi_{R,n_2} = \xi_{R,n_2} - \frac{M_R - 2q + 1}{2} \delta_R \times \cos \beta^{(n_2)}_T \cos (\alpha^{(n_2)}_R - \psi_R) \]  

(6)

where \( \xi_{T,n_1} \) denotes the distance from the center point of the MT antenna array to the scatterer \( s^{(n_1)} \) of the Cluster\( T \); while \( \xi_{R,n_2} \) is the distance from the center of the MR antenna array to the scatterer \( s^{(n_2)} \) of the Cluster\( R \). The closed-form expressions of the \( \xi_{T,n_1} \) and \( \xi_{R,n_2} \) are expressed as:

\[ \xi_{T,n_1} = \left[ \left( x_{n_1} - x_T \right)^2 + \left( y_{n_1} - y_T \right)^2 \right]^{1/2} \]  

(7)

\[ \xi_{R,n_2} = \left[ \left( x_{n_2} - x_R \right)^2 + \left( y_{n_2} - y_R \right)^2 \right]^{1/2} \]  

(8)

Note that the existing literature \[27\] derived the time-varying angular parameters to characterize the non-stationary properties of wireless V2V channels. Here, let us define \( \alpha^{(n_1)}_T(t_0), \beta^{(n_1)}_T(t_0), \alpha^{(n_2)}_R(t_0), \) and \( \beta^{(n_2)}_R(t_0) \) as the AAoD, EAoD, AAoA, and EAoA at the beginning time of the movement \( t = t_0 \), respectively. Then, the time-varying \( \alpha^{(n_1)}_T(t), \beta^{(n_1)}_T(t) \) can be derived in (9) and (10), respectively. It is worth mentioning that the closed-form expressions of the time-varying \( \alpha^{(n_1)}_T(t) \) and \( \beta^{(n_1)}_T(t) \) can be derived in a similar method.

Furthermore, we should mention that when the numbers of effective scatterers of the Cluster\( T \) and Cluster\( R \) are approaching to infinite, the discrete AAoD \( \alpha^{(n_1)}_T \), EAoD \( \beta^{(n_1)}_T \), AAoA \( \alpha^{(n_2)}_R \), and EAoA \( \beta^{(n_2)}_R \) can be replaced by continuous random variables \( \alpha^{(1)}_T, \beta^{(1)}_T, \alpha^{(2)}_R, \) and \( \beta^{(2)}_R \), respectively. Here, the distributions of azimuth and elevation angles at the MT and MR are assumed to follow von Mises distributions, and both of which are mutually independent. Therefore, the PDF of arrivals of the corresponding cluster can be expressed as:

\[ f(\alpha^{(i)}_{T/R}, \beta^{(i)}_{T/R}) = \frac{1}{4\pi^2 I_0(k_1)I_0(k_2)} \times e^{k_1 \cos (\alpha^{(i)}_{T/R} - \alpha^{(0)}_{T/R})} \]  

(11)

where \( \alpha^{(0)}_{T/R} \) and \( \beta^{(0)}_{T/R} \) designate the mean values of azimuth angles \( \alpha^{(i)}_{T/R} \) and elevation angles \( \beta^{(i)}_{T/R} \), respectively.

### B. NON-STATIONARY PROPERTIES

To characterize the non-stationary properties of the proposed V2V channel in tunnel environments, we in this subsection introduce the birth-death algorithm to model the appearance and disappearance of clusters on both the array and time axes \[22\]. The array-time cluster evolution for the proposed 5G V2V tunnel communication system can be described as follow.

Step 1: To describe the algorithm of the array-time cluster evolution, we assume that the initial cluster \( C_{T,1} = \{ c_{T,x} : x = 1, 2, ..., N \} \) and \( C_{R,1} = \{ c_{R,x} : x = 1, 2, ..., N \} \) at the initial time instant \( t \) are given, where \( N \) denotes the initial number of the clusters, \( c_{T,x} \) and \( c_{R,x} \) are two representations of Cluster\( x \). Then, these clusters in cluster sets \( C_{T,1} \) and \( C_{R,1} \) evolve according to birth-death process on the array axis to recursively generate the cluster sets at the rest of antennas at the receiver and transmitter at the initial time instant \( t \), which can be expressed as:

\[ C_{T,p-1}(t) \xrightarrow{E} C_{T,p}(t) \quad (p = 2, 3, ..., M_T) \]  

(12)

\[ C_{R,q-1}(t) \xrightarrow{E} C_{R,q}(t) \quad (q = 2, 3, ..., M_R) \]  

(13)

where \( E \) denotes the cluster evolution on either the array or time axis. The \( C_{T,p}(t) \) and \( C_{R,q}(t) \) are the cluster sets
generated for each antenna based on the birth and death processes on the time and array axes. Furthermore, the survival probabilities of the clusters inside the cluster set the on array axis at the transmitter $P_{T,\text{survival}}$ and the receiver $P_{R,\text{survival}}$ can be modeled as exponential functions, i.e.,

$$P_{T,\text{survival}} = e^{-\lambda_G \frac{(t+\Delta t)}{\tau_T}}$$

(14)

$$P_{R,\text{survival}} = e^{-\lambda_R \frac{(t+\Delta t)}{\tau_R}}$$

(15)

where $\lambda_G$ and $\lambda_R$ denote the cluster generation rate and recombination rate, respectively, $D_c$ is the scenario-dependent correlation factor on the array axis. According to the birth-death process, the average number of newly generated clusters $N_{T,\text{new}}$ and $N_{R,\text{new}}$ on the array axis can be calculated as

$$\mathbb{E}[N_{T,\text{new}}] = \frac{\lambda_G}{\lambda_T} (1 - e^{-\frac{\Delta t}{\tau_T}})$$

(16)

$$\mathbb{E}[N_{R,\text{new}}] = \frac{\lambda_G}{\lambda_R} (1 - e^{-\frac{\Delta t}{\tau_R}})$$

(17)

where $\mathbb{E}(\cdot)$ denotes the expectation operation. After the time interval $\Delta t$, the survival probability $P_{\text{survival}}(\Delta t)$ of the cluster can be expressed as

$$P_{\text{survival}}(\Delta t) = e^{-\lambda_R \frac{P_T(\Delta v_T + \Delta v_R)}{\tau_c}}$$

(18)

where $P_T$ designates the percentage of movement clusters, $\Delta v_T$ and $\Delta v_R$ are the average relative movement velocities of the MT and MR, respectively. The random number at the instant $t + \Delta t$ is generated according to a Poisson distribution with mean

$$\mathbb{E}[N_{\text{new}}(t + \Delta t)] = \frac{\lambda_G}{\lambda_T} (1 - P_{\text{survival}}(\Delta t))$$

(19)

After the time evolution process as (12)-(19) show, all clusters can be categorized as survived clusters or newly generated clusters.

### III. STATISTICAL PROPERTIES OF THE PROPOSED MODEL

In this section, we will derive the statistical propagation properties of the proposed channel model. It is worth mentioning that the complex CIRs $h_{pq}(t, \tau)$ in (2) and (3) have the ability to characterize the physical properties of the components of the LoS propagations and the components of the NLoS propagations via the two-cluster model; therefore, the spatial CCFs of the proposed V2V tunnel channel model can be expressed as [28]

$$\rho_{h_{pq},h_{pq}^*}(t, \delta_T, \delta_R, \Delta t) = \mathbb{E}[h_{pq}(t)h_{pq}^*(t + \Delta t)]$$

(20)

where $*$ denote the complex conjugate operation. Assume that the LoS and NLoS propagation components are independent to each other; therefore, the spatial CCF of the propagation components in the proposed model can be expressed as

$$\rho_{h_{pq},h_{pq}^*}(t, \delta_T, \delta_R, \Delta t) = \rho_{h_{pq}^*,h_{pq}^*}(t, \delta_T, \delta_R, \Delta t)$$

(21)

In substituting (2) into (21), the spatial CCF of the rays with LoS propagations can be calculated as

$$\rho_{h_{pq}^*,h_{pq}^*}(t, \delta_T, \delta_R, \Delta t) = \frac{K}{K + 1} \times e^{j2\pi f_0 \xi_{pq}^*(t+\Delta t) - \xi_{pq}(t)} / c$$

$$\times e^{j2\pi \nu_T \Delta \cos(\alpha_{T,\text{LoS}}(t) - \gamma_T)} \cos(\beta_T^\text{LoS}(t))$$

$$\times e^{j2\pi \nu_R \Delta \cos(\alpha_{R,\text{LoS}}(t) - \gamma_R)} \cos(\beta_R^\text{LoS}(t))$$

(22)

It is worth mentioning that in the NLoS propagation components via the via the two-cluster model, when a cluster evolves from $h_{pq}(t)$ to $h_{pq}^*(t)$, the survival probability is $e^{-\lambda_R |p'-q'|/\gamma_R + |q'-q'|/\gamma_R}$. In light of this, when we substitute (2) into (21), the spatial CCF of the NLoS propagation components can be calculated as

$$\rho_{h_{pq}^*,h_{pq}^*}(t, \delta_T, \delta_R, \Delta t) = \frac{1}{(K + 1)N_1N_2} \times$$

$$\times \int \int \int \int e^{j2\pi \xi_{pq,n_1,n_2}^*(t+\Delta t) - \xi_{pq,n_1,n_2}(t)} \times$$

$$\times e^{j2\pi \nu_T \Delta \cos(\alpha_{T,\text{NLoS}}(t) - \gamma_T)} \cos(\beta_T^\text{NLoS}(t))$$

$$\times e^{-\lambda_R |p'-q'|/\gamma_R + |q'-q'|/\gamma_R} \times$$

$$\times f(\alpha_{T,\text{NLoS}}^0, \beta_T^0) d(\alpha_{T,\text{NLoS}}^0, \beta_T^0)$$

(23)

In substituting (11) into (23), the closed-form expression of the proposed spatial CCFs for two different NLoS propagation components via the two-cluster model can be obtained. Furthermore, we should mention that when we impose $\delta_T = 0$ and $\delta_R = 0$, the expression of the temporal ACF of the propagation paths in the proposed model can be obtained.

### IV. NUMERICAL RESULTS AND DISCUSSIONS

In this following, we will investigate the statistical propagation properties of the proposed channel model, including the spatial CCFs and temporal ACF. The following variables are adopted for our simulation analysis: $(x_T, y_T, z_T) = (20 \text{ m}, 2 \text{ m}, 1 \text{ m})$, $(x_R, y_R, z_R) = (40 \text{ m}, 2 \text{ m}, 1 \text{ m})$, $R = 5 \text{ m}$, $M_T = M_R = 32$, $N_1 = N_2 = 40$, $f_c = 5.99 \text{ GHz}$, $K = 1$, $\nu_T = 10 \text{ m/s}$, $\nu_R = 20 \text{ m/s}$, $\gamma_T = \gamma_R = \pi/4$, $\psi_T = \psi_R = \pi/4$, $\gamma_T = \gamma_R = \pi/3$, $\lambda = 0.15 \text{ m}$, $\lambda_T = 4 \text{ m}$, and $D_c = 30 \text{ m}$.

Figure 2 shows the spatial CCFs of the proposed spatial CCFs for different $k_1$ and $k_2$ in different time instants. The figure shows that when the movement time of the MT and MR rises from 0 s to 10 s, the spatial correlation increases slowly. It is worth mentioning that the parameters $k_1$ and $k_2$ control the width of the von Mises distribution and influence the values of AAoD/EAoD and AAOA/EAOA, the
angular parameters of the channel model will also affect the NLoS propagation components, which further influence the distribution of statistical propagation properties. Here, we can notice that for isotropic case, the value of the spatial correlation is 1 as the antenna spacing is zero; however, the value of the spatial correlation is not equal to 1 for the case where the antenna spacing is zero. Furthermore, we notice that the analytical and simulation results of the proposed spatial CCFs match with each other at different time instants, which ensure the correctness of the above simulations and derivations.

As mentioned in Section III, the temporal ACFs of the proposed V2V tunnel channel model can be derived by imposing $p = p', q = q'$, and $\delta_T = \delta_R = 0$ in (23). Fig. 3 studies the analytical and simulation results of the proposed temporal ACFs for different $k_1$ and $k_2$ at different time instants $t$. It is obvious that the proposed temporal ACFs present different behaviors as movement time $t$ varies from 0 s to 10 s, which is similar to the distribution of the results of the spatial CCFs in Fig. 2. Furthermore, we notice that when the parameters $k_1$ and $k_2$ vary from 0 to 5, the temporal correlation increases slowly. The analytical results of the temporal correlation fit the simulation results very well, which demonstrates the correctness of the above analysis.

Figure 4 shows the analytical results of the proposed temporal ACFs with/without the LoS propagation component at different time instants. Figure 5 shows the analytical results of the Doppler PSDs of the proposed V2V tunnel channel model for different $k_1$ and $k_2$ at different time instants. It can be seen that the temporal correlation increases as the time $t$ increases from 0 to 10 s. Furthermore, when we do not consider the LoS component in the proposed model, the temporal correlation is much lower than that in the Ricean channels.

FIGURE 2: Analytical and simulation results of the spatial CCFs of the proposed V2V tunnel channel model for different $k_1$ and $k_2$ in different time instants.

FIGURE 3: Analytical and simulation results of the temporal ACFs of the proposed V2V tunnel channel model for different $k_1$ and $k_2$ at different time instants.

FIGURE 4: Analytical results of the temporal ACFs of the proposed V2V tunnel channel model with/without the LoS component at different time instants.

FIGURE 5: Analytical results of the Doppler PSDs of the proposed tunnel channel model for different $k_1$ and $k_2$ at different time instants.
Doppler PSDs for different $k_1$ and $k_2$ in different time instants. It can be seen that the distribution curves of the proposed Doppler spectrums drift over the time $t$, which is resulted from the movements of the MT and MR. Note that when the time $t$ varies from 0 s to 10 s, the Doppler PSDs increase slightly. Furthermore, we notice that when the parameters $k_1$ and $k_2$ vary from 0 to 5, the Doppler PSDs of the proposed V2V tunnel channel model increase.

V. CONCLUSION

In this paper, we have provided a general 3D non-stationary wideband two-cluster channel model for 5G V2V communications in tunnel environments. In the model, we have introduced the birth-death algorithm to model the appearance and disappearance of clusters on both the array and time axes. The closed-form expressions of the spatial CCFs and temporal ACFs considering the birth-death algorithm are derived and investigated. It has been demonstrated that the spatial CCFs of the proposed channel model behave different curves as the movement time instant $t$ varies. It has also been demonstrated that the distribution curves of the proposed Doppler PSDs drift over the movement time, which is resulted from the movements of the MT and MR. The analytical results of the propagation properties are in agreement with the simulation results, which demonstrate that the proposed model is able to describe the real 5G V2V communications in tunnel environments.

REFERENCES


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