Research Article

A Novel 3D Nonstationary Channel Model Based on the von Mises-Fisher Scattering Distribution

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In the last decade, the nonstationary properties of channel models have attracted more and more attention for many scenarios, that is, vehicle-to-vehicle (V2V), mobile-to-mobile (M2M), and high-speed train (HST). However, little research has been done on the real-physical channel model. In this paper, we propose a generalized three-dimensional (3D) nonstationary channel model, in which the scatterers are assumed to be distributed around the transmitter (Tx) and receiver (Rx) on a two-sphere model. By employing the von Mises-Fisher distribution, the mean values of the azimuth angle of departure (AAoD) and elevation angle of departure (EAoD) and the azimuth angle of arrival (AAoA) and elevation angle of arrival (EAoA) are tracked by time-variant (TV) Brownian Markov (BM) motion paths, which ensure the nonstationarity of the proposed channel model. Moreover, the TV autocorrelation function (ACF) and Doppler power spectrum density (DPSD) of the proposed nonstationary channel model are calculated by using signal processing tools, for example, fast Fourier transform (FFT) and short-time Fourier transform (STFT). In addition, the simulation results show that the TV scatterer distribution results in a nonstationary nonisotropic channel model, and the proposed model can be employed to simulate the 3D nonstationary channel model.

1. Introduction

The transmission channel is one of the most crucial parts in mobile communication systems, while the generation of an accurate and effective channel model for testing of communication systems represents a particular challenge. The majority of existing channel models in the literature rely on the assumption of wide-sense stationary (WSS) and uncorrelated scattering (US) [1, 2]. Under such an assumption, different transmission delays stay uncorrelated and the second-order channel moments are stationary. However, the physical channel in the real world is nonstationary [2–4]. Furthermore, plenty of empirical and analytical reports reveal that the WSSUS assumption is valid only for a short travelling distance. Therefore, in order to develop a more accurate and suitable channel model for the real-physical channel, it is essential to study nonstationarity channel modeling, which is a newly explored research field.

The channel modeling can be classified into three categories, that is, deterministic, geometry, and correlation statistics

[4]. In terms of deterministic channel modeling, Ai and He have applied their measurement data to V2V and HST scenarios employing the nonstationary channel modeling. In [2, 3], the stationary region especially has been extracted according to the correlated matrix distance. This is beneficial to elicit the extent of the channel variation if one could reconstruct the nonstationary channel simulators to approximate the real-physical channel. For geometry methods, [5] proposed a two-dimensional (2D) evolutionary spectrum approach to model nonstationary broadband mobile fading channels. In [6, 7], the nonstationary properties of massive MIMO channels have been characterized by cluster evolution (birth-death process) on both the array and time axes. Besides, in [8, 9], Pätzold suggested a nonstationary one-ring scattering channel model by utilizing Brownian random movement paths of the mobile station and deriving the angle of arrival (AoAs) and angle of departure (AoDs). In addition, [10] provided a generic method to find the MIMO correlation channel matrices under nonstationary interferences. However, on the one hand, all methods mentioned above only took into account

FIGURE 1: The proposed 3D two-sphere channel model.

the nonstationarity of the vertical plane while they ignored the impact of elevation plane; on the other hand, their modeling process required a high computational complexity and lacked flexibility. Therefore, it is essential to develop a simple and feasible 3D channel model for nonstationary research and to extend the 3D nonstationary channel model to capture the real-physical channel characteristics.

In this paper, we propose a more general 3D geometric situation where the scatterers are assumed to be distributed around the user in a sphere area. By employing the von Mises-Fisher scattering distributions, the centers of the AoDs and AoAs scattering distribution are tracked by TV Brownian motion paths [11, 12], which could effectively reflect the movement process of the MS. Furthermore, the ACF of the complex channel gain and local PSD of the Doppler frequencies are calculated by nonstationary signal processing tools, for example, STFT and FFT [13, 14]. In addition, the results show that the time-variation of the scatterer distribution results in a nonstationary nonisotropic channel model and that the proposed model has the outstanding ability to describe vital statistical characteristics of nonstationary channel, such as the envelope distribution and the TV ACF and PSD [15]. Moreover, it also offers the advantages of low computational complexity and easy realization [8].

The remainder of this paper is organized as follows: Section 2 discusses a novel 3D channel model based on the geometrical two-sphere model. In Section 3, the von Mises-Fisher (VMF) distribution is employed to describe the 3D scatter distribution. A time-variant Brownian motion process is provided in Section 4. And then Section 5 proposes a novel 3D nonstationary channel model. The related simulation and numerical analysis are presented in Section 6. At last, the conclusion is drawn in Section 7.

2. A Novel 3D Channel Model

Let us consider a narrowband V2V communication channel with omnidirectional antennas. The radio propagation

environment around the transmitter and the receiver is characterized by 3D nonisotropic scattering under line-of-sight (LoS) and none line-of-sight (NLoS) conditions. Figure 1 illustrates the novel 3D geometrical channel model, in which the local scatterers are modeled on the surface of two spheres of radii R_T and R_R [16]. In order to limit the computational complexity of this model, both local scatterers around the Tx and Rx are considered. Therefore we assume that there are N_1 scatterers on the sphere (around the Tx) of radius R_T and the n_1 th ($n_1 = 1, 2, \dots, N_1$) scatterer is denoted by S_{n_1} . Similarly, around the Rx, N_2 scatterers lie on a surface of sphere of radius R_R , and the n_2 th scatterer is denoted by S_{n_2} . The geometric symbols in Figure 1 have the following meaning: $\alpha_R^{(n_i)}$ and $\beta_R^{(n_i)}$ denote the main AAoA and main EAoA of the n_i th scatterer, respectively. In the same way, $\alpha_T^{(n_i)}$ and $\beta_T^{(n_i)}$ denote the main AAoD and main EAoD of the n_i th scatterer, respectively, and D is the distance between the Tx and Rx. It is worth noting that the distance D is assumed to be much larger than the radius R_R or R_T (i.e., R_T or $R_R \ll D$). Therefore, the channel impulse response (CIR) of the two-sphere model at the carrier frequency f_c can be expressed as [17]

$$h(t) = h^{\text{LOS}}(t) + h^{\text{NLOS}}(t), \quad (1)$$

where

$$\begin{aligned} h^{\text{LOS}}(t) = & \sqrt{\frac{K}{K+1}} e^{-j2\pi f_c \tau_1} \\ & \times e^{j2\pi f_{T\max} t \cos(\alpha_T^{\text{LOS}} - \gamma_T) \cos \beta_T^{\text{LOS}}} \\ & \times e^{j2\pi f_{R\max} t \cos(\alpha_R^{\text{LOS}} - \gamma_R) \cos \beta_R^{\text{LOS}}}. \end{aligned} \quad (2)$$

The CIR especially of two-sphere model under NLoS conditions is constructed as a sum of the single- and double-bounced rays with different energies. So it can be rewritten as

$$\begin{aligned}
 h^{\text{NLOS}}(t) &= \sum_{i=1}^2 h^{\text{SB}_i}(t) + h^{\text{DB}}(t) \\
 h^{\text{SB}_i}(t) &= \sqrt{\frac{\eta_{\text{SB}_i}}{K+1}} \lim_{N_i \rightarrow \infty} \sum_{n_i=1}^{N_i} \frac{1}{\sqrt{N_i}} e^{j(\varphi_{n_i} - 2\pi f_c \tau_2)} \\
 &\quad \times e^{j2\pi f_{T\max} t \cos(\alpha_T^{(n_i)} - \gamma_T) \cdot \cos \beta_T^{(n_i)}} \\
 &\quad \times e^{j2\pi f_{R\max} t \cos(\alpha_R^{(n_i)} - \gamma_R) \cdot \cos \beta_R^{(n_i)}}, \\
 h^{\text{DB}}(t) &= \sqrt{\frac{\eta_{\text{DB}}}{K+1}} \lim_{N_1, N_2 \rightarrow \infty} \sum_{n_1, n_2=1}^{N_1, N_2} \frac{1}{\sqrt{N_1 N_2}} e^{j(\varphi_{n_1, n_2} - 2\pi f_c \tau_3)} \\
 &\quad \times e^{j2\pi f_{T\max} t \cos(\alpha_T^{(n_1)} - \gamma_T) \cdot \cos \beta_T^{(n_1)}} \\
 &\quad \times e^{j2\pi f_{R\max} t \cos(\alpha_R^{(n_2)} - \gamma_R) \cdot \cos \beta_R^{(n_2)}}
 \end{aligned} \tag{3}$$

with

$$\begin{aligned}
 \alpha_T^{\text{LOS}} &\approx \beta_T^{\text{LOS}} \approx \beta_R^{\text{LOS}} \approx 0, \\
 \alpha_R^{\text{LOS}} &\approx \pi, \\
 \tau_1 &\approx \frac{D}{c}, \\
 \tau_2 &\approx \frac{(\xi_{n_i} + R_{T/R})}{c}, \\
 \tau_3 &\approx \frac{(\xi_{n_1, n_2} + R_T + R_R)}{c},
 \end{aligned} \tag{4}$$

where SB_1 and SB_2 stand for the subcomponents of single-bounced rays from the Tx sphere and Rx sphere, respectively. DB means the double-bounced rays. η_{SB_i} and η_{DB} are the factors of normalized power, which specify the amount powers of single- and double-bounced rays contribute to the total normalized power. Herein, K is the Rician factor and c denotes the speed of light, and φ_{n_i} and φ_{n_1, n_2} are independent and identically distributed (i.i.d.) random variables with uniform distribution over $[-\pi, \pi]$ [17]. In addition, $f_{T\max}$ and $f_{R\max}$ represent the maximum Doppler frequencies of the transmitter and the receiver, respectively. γ_T and γ_R stand for moving direction of the Tx and Rx, respectively. The statistical properties and performances of the proposed 3D V2V channel model will be analyzed as follows.

2.1. Envelope and Phase. Multiple uncorrelated fading processes bring the complex envelope, which can be written as

$$h(t) = h_i(t) + jh_q(t). \tag{5}$$

Considering the distribution of the channel envelope $\xi(t) = |h(t)|$ and phase $\phi(t) = \arg\{h(t)\}$, their corresponding probability density functions (PDF) can be written as [6]

$$p_\xi(z) = \frac{z}{\delta_0^2} e^{-(z^2 + k_0^2)/2\delta_0^2} \cdot I_0\left(\frac{zk_0}{\delta_0^2}\right), \tag{6}$$

$$\begin{aligned}
 p_\phi(\phi) &= \frac{e^{-k_0^2/2\delta_0^2}}{2\pi} \\
 &\quad \cdot \left\{ 1 + \frac{k_0}{\delta_0} \cdot \sqrt{\frac{\pi}{2}} \cos(\phi - \arg\{h^{\text{LOS}}(t)\}) \right\},
 \end{aligned} \tag{7}$$

where z represents the amplitude variable, the symbol k_0 is defined as $k_0 = \sqrt{K/(K+1)}$, and $I_0(\cdot)$ is the zeroth-order modified Bessel function of the first kind, while δ_0^2 stands for the mean power of the channel.

2.2. ACF and PSD. The normalized ACF between any two complex fading envelopes is defined as

$$r_{hh}(\tau) = \frac{E[h(t) \cdot h^*(t - \tau)]}{\sqrt{E[|h(t)|]^2 \cdot E[|h(t - \tau)|]^2}}, \tag{8}$$

where $(\cdot)^*$ is the complex conjugate operation and $E[\cdot]$ represents the statistical expectation operator. Then, we obtain the ACF of the proposed channel model. Taking the LoS and NLoS components into account, the equation of the ACF can be written as

$$r_{hh} = r_{hh}^{\text{LOS}}(\tau) + \sum_{i=1}^2 r_{\text{SB}_i}^{\text{NLOS}}(\tau) + r_{\text{DB}}^{\text{NLOS}}(\tau), \tag{9}$$

where

$$\begin{aligned}
 r_{hh}^{\text{LOS}}(\tau) &= \frac{K}{K+1} e^{j(2\pi/\lambda) \cdot 2D} \\
 &\quad \cdot e^{j2\pi\tau(f_{T\max} \cos \gamma_T - f_{R\max} \cos \gamma_R)}, \\
 r_{\text{SB}_i}^{\text{NLOS}}(\tau) &= \frac{\eta_{\text{SB}_i}}{K+1} \iint_{-\pi}^{\pi} \left[e^{j2\pi\tau(f_{T\max} U^{(i)} + f_{R\max} V^{(i)})} \right] \\
 &\quad \cdot f(\alpha_{T/R}^{(n_i)}, \beta_{T/R}^{(n_i)}) d(\alpha_{T/R}^{(n_i)}, \beta_{T/R}^{(n_i)}), \\
 r_{\text{DB}}^{\text{NLOS}}(\tau) &= \frac{\eta_{\text{DB}}}{K+1} \iiint_{-\pi}^{\pi} \left[e^{j2\pi\tau(f_{T\max} U^{\text{DB}} + f_{R\max} V^{\text{DB}})} \right] \\
 &\quad \cdot f(\alpha_T^{(n_1)}, \beta_T^{(n_1)}) \\
 &\quad \cdot f(\alpha_R^{(n_2)}, \beta_R^{(n_2)}) d(\alpha_T^{(n_1)}, \beta_T^{(n_1)}) d(\alpha_R^{(n_2)}, \beta_R^{(n_2)}),
 \end{aligned} \tag{10}$$

where i means there are two subcomponents for single-bounced rays. For example, $i = 1$ means the single-bounced rays from the Tx sphere. Similarly, $i = 2$ means the single-bounced rays from the Rx sphere. And $f(\alpha_{T/R}^{(n_i)}, \beta_{T/R}^{(n_i)})$ stands for the joint azimuth and elevation angle distribution function of the n_i th scatterers on Tx or Rx. According to

the mathematical law of triangle functions, the geometric relationships between each parameter are defined as

$$\begin{aligned} U^{(1)} &= \cos(\alpha_T^{(n_1)} - \gamma_T) \cdot \cos(\beta_T^{(n_1)}), \\ V^{(1)} &= \cos(\alpha_R^{(n_1)} - \gamma_R) \cdot \cos(\beta_R^{(n_1)}), \\ \alpha_R^{(n_1)} &\approx \pi - \frac{R_T \cdot \cos \beta_T^{(n_1)}}{D} \cdot \sin(\alpha_T^{(n_1)}), \\ \beta_R^{(n_1)} &= \arccos\left(\frac{D - R_T \cos \beta_T^{(n_1)} \cdot \cos \alpha_T^{(n_1)}}{\xi_{n_1}}\right), \end{aligned} \quad (11)$$

$$\begin{aligned} \xi_{n_1} &= \sqrt{Q_{n_1}^2 + R_T^2 \sin^2 \beta_T^{(n_1)}}, \\ Q_{n_1} &= D + R \cdot \cos(\beta_R^{(n_1)}) \cos(\alpha_R^{(n_1)}), \\ U^{(2)} &= \cos(\alpha_T^{(n_2)}) \cdot \cos(\beta_T^{(n_2)}), \\ V^{(2)} &= \cos(\alpha_R^{(n_2)}) \cdot \cos(\beta_R^{(n_2)}), \\ \alpha_T^{(n_2)} &\approx \frac{R_R \cdot \cos \beta_R^{(n_2)}}{D} \cdot \sin(\alpha_R^{(n_2)}), \end{aligned} \quad (12)$$

$$\beta_T^{(n_2)} = \arccos\left(\frac{D + R_R \cos \beta_R^{(n_2)} \cdot \cos \alpha_R^{(n_2)}}{\xi_{n_2}}\right), \quad (13)$$

$$\xi_{n_2} = \sqrt{Q_{n_2}^2 + R_R^2 \sin^2 \beta_R^{(n_2)}}, \quad (14)$$

$$Q_{n_2} \approx D + R_R \cos \beta_R^{(n_2)} \cos \alpha_R^{(n_2)}, \quad (15)$$

$$U^{DB} = \cos(\alpha_T^{(n_1)}) \cdot \cos(\beta_T^{(n_1)}), \quad (16)$$

$$V^{DB} = \cos(\alpha_R^{(n_2)}) \cdot \cos(\beta_R^{(n_2)}). \quad (17)$$

The DPSD has been used for nonisotropic scattering channels and the theoretical expression DPSD is

$$S_{hh}(f) = \int_{-\infty}^{\infty} r_{hh}(\tau) e^{-j2\pi f\tau} d\tau. \quad (18)$$

3. von Mises-Fisher Distribution

The VMF distribution [18, 19] is a close model for directional data distributed uniformly with rotational symmetry on the unit hypersphere S^{p-1} . When p is 3, the ordinary sphere usually corresponds to the set of all points embedded in the Euclidean space R^3 . The vector Ω stands for any direction of scatterers on the unit sphere surface and it can be described in Cartesian coordinates as

$$\Omega = [\cos \beta \cos \alpha, \cos \beta \sin \alpha, \sin \beta]^T, \quad (19)$$

where $[\cdot]^T$ represents the transpose operation. It is obvious that β and α denote the coelevation and azimuth angles of vector Ω , respectively. Then, the general form of the VMF distribution can be written as

$$f_p(\Omega; \mu, k) = \frac{(k/2)^d}{\Gamma(d+1) \cdot I_d(k)} \exp(k\mu^T \Omega), \quad (20)$$

where k controls the concentration of the distribution about the mean direction vector. In particular, when $k = 0$, the distribution is isotropic, and when $k \rightarrow \infty$, the scattering becomes a point source on the surface. Furthermore, parameter $d = p/2 - 1$. From a physical point of view, the direction spread represents the degree of direction from the arrival subpaths of a cluster to the mean center of the AoA. Therefore, the mean center value of the AoA indicates the mean direction vector from the MS to the cluster and a subpath shows a multiple within a cluster of scatterers. For the ordinary sphere, the VMF PDF to characterize the distribution of effective scatterers can be defined as

$$\begin{aligned} f(\alpha, \beta) &= \frac{k}{4\pi \sinh(k)} \\ &\cdot \exp\{k[\cos \beta_0 \cos \beta \cos(\alpha - \alpha_0) + \sin \beta_0 \sin \beta]\}, \end{aligned} \quad (21)$$

where α_0 and β_0 represent the mean values of the azimuth and elevation angle, respectively, $-\pi \leq \alpha_0 \leq \pi$, $0 \leq \beta_0 \leq \pi$.

4. TV Brownian Random Process

In this section, we will bring the temporal Brownian random process [17] to simulate a nonstationary TV 3D channel model. A standard BM process $\{B(t) : t \in [0, T]\}$ is a Wiener process, in which the increments satisfy a normal and independent distribution. Besides, it needs to satisfy the following conditions:

- (1) $B(0) = 0$.
- (2) When $0 \leq i \leq j \leq T$, the increment $B(j) - B(i)$ obeys the normal distribution with zero mean and variance $j - i$; that is, $B(j) - B(i) \sim N(0, j - i)$.
- (3) When $0 \leq m \leq n \leq i \leq j \leq T$, the increments $B(m) - B(n)$ and $B(j) - B(i)$ are statistically independent.

Due to the fact that the same statistical properties impact the receiver between the AoA distribution motion and the MS random movement, this paper proposes that the variation of the AoA distribution can be used for simulating a 3D nonstationary channel. To model the motion process of the AoA distribution in the 3D plane, we provide a path model with BM movement components along the elevation and azimuth plane. The fluctuations of the motion path especially are modeled by two independent temporal BM processes: $B_t^{(\alpha)}$ and $B_t^{(\beta)}$. Therefore, the motion path can be modeled as

$$P(\alpha_t, \beta_t) = \begin{cases} \alpha_t(t) = \alpha_s + wt \cdot \Delta t + \Delta t^2 \cdot B_t^{(\alpha)} \\ \beta_t(t) = \beta_s + wt \cdot \Delta t + \Delta t^2 \cdot B_t^{(\beta)}, \end{cases} \quad (22)$$

where w stands for the random drift parameter used to control the behavior of the deterministic drift degrees along each axis and Δt represents the degree of randomness of the path. Meanwhile, $\Delta t = 1/w$; α_s and β_s are the start points of the process along each axis. According to the proof of the

BM paths model in [17], it is not difficult to find that the mean value of each angle always depends on time t and the ACF is also determined by a function of the time difference τ . Consequently, we can conclude that the BM path model is a nonstationary process. More details about Brownian random process can be found in [17].

5. The Nonstationary Properties of the Proposed Model

In this section, we consider the TV CIRs, ACF, and DPSD of the nonstationary process. At first, we introduce the BM process to the VMF scatterer distribution, and the TV-VMF PDF can be rewritten as

$$f(\alpha_{T/R}^{(n_i)}(t), \beta_{T/R}^{(n_i)}(t)) = \frac{k}{4\pi \sinh(k)} \cdot \exp \left\{ k \right. \\ \cdot \left[\cos \beta_{T/R0}^{(n_i)}(t) \cdot \cos \beta_{T/R}^{(n_i)} \cos(\alpha_{T/R}^{(n_i)} - \alpha_{T/R0}^{(n_i)}(t)) \right. \\ \left. \left. + \sin \beta_{T/R0}^{(n_i)}(t) \cdot \sin \beta_{T/R}^{(n_i)} \right] \right\}. \quad (23)$$

Then the TV CIRs of the proposed model in (1)–(3) are obtained when the AoA and AoD become TV variables due to the random motion of the scatterers. Furthermore, the envelope PDF of the modified simulation model is the same as that in (6) and the phase PDF is also presented by (7) because both of them are unrelated with TV frequencies. We consider the TV ACF and DPSD of the nonstationary process [20] as

$$r_{\bar{h}\bar{h}}(t, \tau) = r_{\bar{h}\bar{h}}^{\text{LOS}}(t, \tau) + \sum_{i=1}^2 r_{\text{SB}_i}^{\text{NLOS}}(t, \tau) + r_{\text{DB}}^{\text{NLOS}}(t, \tau), \quad (24)$$

where

$$r_{\bar{h}\bar{h}}^{\text{LOS}}(t, \tau) = \frac{K}{K+1} e^{j(2\pi/\lambda) \cdot 2D} \\ \cdot e^{j2\pi\tau(f_{T\max} \cos \gamma_T - f_{R\max} \cos \gamma_R)}, \\ r_{\text{SB}_i}^{\text{NLOS}}(t, \tau) = \frac{\eta_{\text{SB}_i}}{K+1} \iint_{-\pi}^{\pi} \left[e^{j2\pi\tau(f_{T\max} U^{(i)} + f_{R\max} V^{(i)})} \right] \\ \cdot f(\alpha_{T/R}^{(n_i)}(t), \beta_{T/R}^{(n_i)}(t)) d(\alpha_{T/R}^{(n_i)}(t), \beta_{T/R}^{(n_i)}(t)), \\ r_{\text{DB}}^{\text{NLOS}}(t, \tau) = \frac{\eta_{\text{DB}}}{K+1} \iiint_{-\pi}^{\pi} \left[e^{j2\pi\tau(f_{T\max} U^{\text{DB}} + f_{R\max} V^{\text{DB}})} \right] \\ \cdot f(\alpha_T^{(n_1)}(t), \beta_T^{(n_1)}(t)) f(\alpha_R^{(n_2)}(t), \beta_R^{(n_2)}(t)) d(\alpha_T^{(n_1)}(t), \beta_T^{(n_1)}(t)) d(\alpha_R^{(n_2)}(t), \beta_R^{(n_2)}(t)). \quad (25)$$

In particular, the parameters in (24)–(25) are given in Section 2. Note that the AoAs $(\alpha_R(t), \beta_R(t))$ and AoDs $(\alpha_T(t), \beta_T(t))$ are applied together with the TV variables [18].

It is noteworthy that the definition of the TV ACF keeps the symmetrical delay characteristic τ , $r_{\bar{h}\bar{h}}(t, \tau) = r_{\bar{h}\bar{h}}(t - \tau)$, and $r_{\bar{h}\bar{h}}(t, \tau)$ is the real function if $\tilde{h}(t)$ is a real process, which

FIGURE 2: 2D VM PDF.

results in the Fourier transform having the symmetrical and real characteristics. Beyond the TV DPSD, the short-time DPSD is widely used to analyze the nonstationary process [17], which is the amplitude's square of the signal's STFT [21, 22]:

$$\text{ST}_{\bar{h}\bar{h}}(f, t) = \int_{-\infty}^{\infty} r_{\bar{h}\bar{h}}(t, \tau) e^{-j2\pi f\tau} \cdot w(t - \tau) d\tau, \quad (26)$$

where $(t - \tau)$ is the analytic window slipping with time. The nonstationary process can be viewed as stationary within the analysis window.

6. Simulation Results and Numerical Analysis

In this section, simulations are carried out to illustrate the nonstationary properties of our proposed 3D TV channel model based on the VMF scatterer distribution. The impact of the model parameters on the VMF scatterer distribution is investigated first. Then, the nonstationary properties of the proposed two-sphere channel model are evaluated and analyzed in terms of the AoAs and AoDs motion path at the Tx and Rx, the TV ACF of the complex channel gain, and the TV DPSD.

Firstly, we consider the performance of the VMF scatterers distribution. From Figure 2, it is not difficult to find that the parameter k controls the shape of the distribution. Meanwhile, Figure 4 shows the VMF PDF in 3D coordinates by setting the mean angles $\alpha_0 = 90^\circ$ and $\beta_0 = 45^\circ$. It is clear that the two-dimensional (2D) von Mises (VM) PDF is derived from the 3D VMF PDF for azimuth angle α with $\beta = 0^\circ$. Furthermore, the scatterer distribution based on the VMF PDF has been shown in Figure 3. Assuming scatterer distribution is dependent on the axis of symmetry specified by the z -axis, it can be seen that the larger the value of k , the higher the density near the z -axis. Especially when $k = 0$, the distribution is isotropic.

Secondly, Figure 5 illustrates a realization of the temporal BM motion path where $k = 1$, $w = 10$, and $\Delta t = 0.01$. As seen from this figure, the trajectories of $\alpha_0^{(i)}(t)$ and $\beta_0^{(i)}(t)$ are varying with time, respectively. The properties of

FIGURE 3: Effect of the concentration parameter.

FIGURE 4: 3D VMF PDF.

FIGURE 5: The simulation of Brownian paths.

the BM process prove that the proposed path results in a nonstationary nonisotropic channel model.

Thirdly, Figures 6–8 show the proposed TV 3D models in detail for each statistical value. The simulation settings are as follows: $f_c = 5.9$ GHz, $D = 300$ m, $f_{T\max} = f_{R\max} = 570$ Hz, $R = 25$ m, $\gamma_T = \gamma_R = 0^\circ$, $\alpha_{T0}^{(n1)} = 147.8^\circ$, $\beta_{R0}^{(n1)} = 17.2^\circ$, $\alpha_{T0}^{(n2)} = 31.6^\circ$, and $\beta_{T0}^{(n2)} = 171.6^\circ$. Considering the vehicular traffic density (VTD) based on [4], we have $K = 3.876$, $k = 3.6$, $\eta_{SB1} = 0.625$, $\eta_{SB2} = 0.225$, and $\eta_{DB} = 0.15$ for low and $K = 0.156$, $k = 0.6$, $\eta_{SB1} = 0.15$, $\eta_{SB2} = 0.225$, and $\eta_{DB} = 0.625$ for high VTD scenarios because both parameters K and k are related to the distribution of scatterers (normally, larger values of k corresponding to less dense moving vehicles.).

Figure 6 validates the absolute values of the temporal ACF for the proposed 3D channel model in both low and high VTD scenarios. It can be observed that the temporal ACF is affected by the VTD; namely, the temporal ACF in low VTD scenarios is always higher than that in high VTD scenario. Additionally, Figures 7 and 8 depict the envelope and the phase PDF of 3D channel model determined by the parameters K and k , respectively.

Finally, we assume that the mean elevation and azimuth angles are moving along the TV-BM motion paths shown in Figure 5 and we set the maximum Doppler frequency of the transmitter and receiver as 570 Hz. Meanwhile, the effect of the proposed TV-BM motion path on the scattering model is the same as the one in which the vehicle moves randomly in different directions on the AoAs and AoDs. Therefore, as shown in Figures 9 and 12, the absolute value of the resulting local ACF ((24) and (25)) is illustrated. According to these figures, it is manifest that the shapes of the ACF change with different values of time which is due to the nonstationarity of the TV AoAs and AoDs motion processes. It has been proven that the AoAs and AoDs motion processes based on

FIGURE 6: The absolute values of the temporal ACF for the proposed 3D TV channel model.

FIGURE 7: The PDF of amplitude.

the TV-BM path model are first-order nonstationary in [17]. For the same reason, the TV PSD, which is derived from the local ACF by utilizing the FFT with respect to time delay τ , is illustrated in Figures 10 and 13 for low and high VTD scenarios, respectively. Both of them show that the similar U-shape of the PSD varies with time t . And this is another way to display the nonstationary properties of the proposed channel model. In addition, the short-time (ST) DPSD $ST_{\tilde{h}\tilde{h}}(f, t)$ (see (26)) is shown in Figures 11 and 14. Compared with the FFT DPSD and ST DPSD, we can conclude that the nonstationary properties of them are very similar to each other. This means the STFT has the ability to process the nonstationary channel model. In addition, by comparing the nonstationary properties of the channel model in the low and high VTD scenarios, it can be found that the DPSD derived from the low VTD scenarios is closer to the ideal Jakes DPSD (U-shape spectrum). That is because the effect of nonstationary properties of channel model is more obvious in the high VTD assumption scenarios.

7. Conclusion

In this paper, a novel 3D nonstationary channel model for V2V is proposed. By employing the proposed temporal

FIGURE 8: The PDF of phase.

FIGURE 9: Time-variant ACF.

FIGURE 10: Time-variant DPSD (FFT for high VTD).

FIGURE 11: Time-variant DPSD (STFT for high VTD).

FIGURE 14: Time-variant DPSD (STFT for low VTD).

FIGURE 12: Time-variant ACF (low VTD).

FIGURE 13: Time-variant DPSD (FFT for low VTD).

BM process with the VMF PDF scatterer distribution, we derive a nonstationary nonisotropic channel model which can be applied to simulate the 3D channels in real time. Moreover, the dynamic changes of the local ACF and PSD have been provided. Lastly, the nonstationary properties of the proposed channel model are verified by simulation. In particular, we have proven that the STFT is also valid for analyzing nonstationary channel models.

Competing Interests

The authors declare that they have no competing interests.

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