Deterministic and Stochastic Simulators for Non-Isotropic V2V-MIMO Wideband Channels

Yiran Li¹, Xiang Cheng¹,*, Nan Zhang²

¹ State Key Laboratory of Advanced Optical Communication Systems and Networks, School of Electronics Engineering and Computer Science, Peking University, Beijing 100876, China
² Wireless Algorithm Department, Product Research and Development System, ZTE Corporation, Shanghai 201203, China
* The corresponding author, email:xiangcheng@pku.edu.cn

Abstract: In this paper, we consider a novel two-dimensional (2D) geometry-based stochastic model (GBSM) for multiple-input multiple-output (MIMO) vehicle-to-vehicle (V2V) wideband fading channels. The proposed model employs the combination of a two-ring model and a multiple confocal ellipses model, where the signal is sum of the line-of-sight (LoS) component, single-bounced (SB) rays, and double-bounced (DB) rays. Based on the reference model, we derive some expressions of channel statistical properties, including space-time correlation function (STCF), Doppler spectral power density (DPSD), envelope level crossing rate (LCR) and average fade duration (AFD). In addition, corresponding deterministic and stochastic simulation models are developed based on the reference model. Moreover, we compare the statistical properties of the reference model and the two simulation models in different scenarios and investigate the impact of different vehicular traffic densities (VTDs) on the channel statistical properties of the proposed model. Finally, the great agreement between simulation models and the reference model demonstrates not only the utility of simulation models, but also the correctness of theoretical derivations and simulations.

Keywords: vehicle-to-vehicle; wideband channels; simulation model; statistical properties

I. INTRODUCTION

Nowadays, since the intelligent transportation system and vehicle self-organizing network have achieved rapid growth, the research on vehicle communication channel is increasing day by day [1], [2]. Because of the characteristics of vehicle traveling at high speed and limited moving area, the vehicle-to-vehicle (V2V) communication system has a significant difference from the traditional cellular system. The biggest difference between the V2V communication systems and the cellular network in the transmission environment is both the transmitter (Tx) and receiver (Rx) are moving. In addition, there are a lot of scatterers around the Tx and Rx. Therefore, in order to facilitate our understanding of the unique V2V channel characteristics and design of the vehicle communication systems, it is desirable to conduct in-depth and detailed research on different scenarios of V2V multiple-input multiple-output (MIMO) channels, and develop accurate yet easy-to-use channel models.

Based on our research [3], the V2V chan-
nel models can be divided into two categories generally, such as deterministic models [4] and stochastic models, and the latter can be further classified as non-geometrical stochastic models (NGSMs) and geometry-based stochastic models (GBSMs). The GBSM uses simplified ray tracing principles and equivalent scatterer concepts to simulate propagation environments. What’s more, the GBSMs can be classified as two parts, including irregular shaped GBSMs (IS-GBSMs) [5] and regular-shaped GBSMs (RS-GBSMs). Since V2V communication scenarios are in general time variant due to the movement of the Tx and Rx, the GBSM method is more suitable as this method directly deals with propagation environments. Therefore, the use of the GBSM method for modeling V2V propagation channels has attracted more and more attention.

In [6], in order to model the isotropic single-input single-output (SISO) V2V Rayleigh fading channel, a 2D two-ring RS-GBSM was proposed. In [7] and [8], the authors proposed a general two-ring GBSM, which is suitable for the non-isotropic V2V-MIMO Ricean channels. In addition, a RS-GBSM was proposed which is the combination of an ellipse and two-ring model for non-isotropic V2V-MIMO channels in [9] and [10]. The paper [11] proposed a generic three-dimensional (3D) twocylinder model for narrowband V2V channels. Furthermore, the paper [12] proposed some research on the vehicular traffic density (VTD), which can demonstrate the VTD have some effect on the channel statistical characteristics of V2V channels.

Moreover, all the above mentioned RS-GBSMs were proposed for the narrowband V2V channels. An important characteristic of the narrowband channel is that its propagation delay is far less than the data symbol duration Ts, the delay differences caused by different effective scatterers can be neglected. However, since the propagation delay is larger than the data transmission rate Ts and can not be ignored in the wideband systems. Therefore, it is important to develop the corresponding wideband V2V channel models. Paper [13], [14] proposed a two-concentric-cylinder model for wideband channels, which can be considered as an extension of the twocylinder narrowband model. In [15], a 2D two-ring and ellipse model for V2V narrowband channel has been extended to wideband channel by using confocal multiple ellipses model to represent the tapped delay line (TDL) structure, and the effect of Doppler spectral power density (DPSD) on the model was also investigated. However, it did not derive the expression of the corresponding statistical properties of space-time correlation function (STCF), envelope level crossing rate (LCR) and average fade duration (AFD). Note that these aforementioned GBSMs [13]–[15] are the so-called reference model since these models assume an infinite number of effective scatterers, i.e., has an infinite complexity, and thus cannot be directly implemented in practice. Unlike the reference model, a simulation model has a finite complexity and thus is realisable in practice. Therefore, accurate simulation models play an important role in the practical simulation and performance evaluation of any wireless communication systems. It is worth noting that the 2D GBSM modeling and investigation of V2V-MIMO wideband channels are surprisingly missing in the current literature.

To fill up the aforementioned gaps of V2V-MIMO GBSMs, this paper proposes a new generic 2D GBSM for V2V-MIMO wideband channels. The proposed 2D wideband GBSM mainly investigates on the basis of a two-ring and a multiple confocal ellipse model for V2V-MIMO wideband channel proposed in [15], which combines line-of-sight (LoS) components, single-bounced (SB) and double-bounced (DB) components. This paper’s main contributions and novelties can be summarized as follows.

1) Based on a proposed reference model for V2V-MIMO wideband channels, the expressions of STCF, DPSD, envelope LCR and AFD are derived.
2) Corresponding deterministic and stochastic simulation models are developed based on the reference model. The great agreement
between the reference model and simulation models demonstrates the correctness of derivations and the utility of the proposed simulation models.

3) Based on the derived expressions of the V2V-MIMO wideband channel statistical properties, we investigate the impact of different VTDs on the channel statistical properties, and present some interesting observations and useful conclusions.

The structure of this paper can be summarized as follows. Section II introduces the reference model of V2V-MIMO wideband channel briefly. In Section III, from the reference model, the expressions of channel statistical characteristics are derived, including STCF, DPSD, envelope LCR and AFD. Based on the proposed reference model, corresponding deterministic and stochastic simulation models are proposed in Section IV. Section V presents some comparison and analysis of the statistical characteristics between proposed simulation models and the reference model. Finally, we draw some conclusions in Section VI.

II. A WIDEBAND V2V-MIMO CHANNEL REFERENCE MODEL

In this section, we propose a 2D GBSM for a wideband V2V-MIMO communication channel based on [15]. It is assumed that both the Tx and the Rx that equipped with \( n_{Tx} \) and \( n_{Rx} \) receive low elevation antenna elements are moving, where \( I \leq p \leq p' \leq n_{Tx} \) and \( I \leq q \leq q' \leq n_{Rx} \), respectively.

It is assumed that the scatterers are distributed over the tworing model and the confocal multi-ellipsoidal model randomly. The two-ring model is used to represent moving scatterers, such as the moving vehicles, and the multiple confocal ellipse models are used to represent the static scatterers, such as the static roadside environment. For a two-ring model, it is assumed that \( N_{s} \) effective scatterers are distributed around the ring of radius \( R_s \) at Rx, and the \( n_{1,2} \)th \((n_{1,2} = 1, 2, ..., N_{1,2})\) effective scatterer is defined by \( s^{(n_{1,2})} \). In addition, for the elliptical model, the multiple confocal ellipses model is used here to represent the TDL structure, where their focal points are located at Tx and Rx. It can be seen that the distance between the transmitter and receiver can be expressed as \( D = 2f \), which the parameter \( f \) represents the half length of the two foci connection of the ellipse. Assuming that the the \( l \)th ellipse’s semi-major axis (i.e., the \( l \)th tap) is \( a_{l} \), and there are \( N_{l,s} \) effective scatterers distributed over it, \((l = 1, 2, ..., L)\), where \( L \) is the total number of confocal ellipses. Note that the \( n_{2,l} \)th \((n_{2,l} = 1, 2, ..., N_{2,l})\) effective scatterer can be described as \( s^{(n_{2,l})} \).

Fig.1 shows the basic 2×2 V2V-MIMO wideband channel model \((n_{Tx} = n_{Rx} = 2)\), that is, the transmitter and receiver set up two uniform linear antenna components. In addition, the velocities of the Tx and Rx are denoted as \( v_T \) and \( v_R \), and the movement direction angles are \( g_T \) and \( g_R \), respectively. By considering the real V2V communication scenario, it is assumed that the moving scatterers distributed around Tx and Rx move at speed \( v_T \) and \( v_R \), respectively, and their movement directions are along the x-axis. The angle of departure (AoD) \( \alpha_T^{(n_{Tx})} \((i = 1,2,3)\) characterizes the relative position of scatterer \( S^{(n_{2,i})} \) to Tx. Similarly, the angle of arrival (AoA) \( \alpha_R^{(n_{Rx})} \) characterizes the relative position of scatterer \( S^{(n_{2,i})} \) to Rx. The AoD and AoA of the LoS path are denoted by \( \alpha_T^{LoS} \) and \( \alpha_R^{LoS} \).

Because the different rays have different contributions in a real V2V communication environments, we need to design different taps of our model to express the V2V channel statistics. For the first tap, the corresponding single- and double-bounced components can be considered as produced by the scatterers located on the first ellipse or one of the two rings, and the scatterers located on both two-rings, respectively. In addition, considering other taps, we design that only the scatterers on the confocal ellipses can generate the
single-bounced rays, while the double-bounced rays come from the corresponding ellipse and one of the two rings.

Here, we use an \( n \times n \) matrix \( H(t, \tau) = [h_{pq}(t, \tau)]_{p,q=1}^n \) to describe the V2V-MIMO wideband channel. The channel impulse response between the \( p \)th Tx and the \( q \)th Rx antenna elements can be expressed as \( h_{pq}(t, \tau) = \sum_{l=1}^{L} c_l h_{pq}(t) \delta(\tau - \tau_l) \), where \( c_l \) represents the gain of the \( l \)th tap, and the complex time-variant tap coefficient and the discrete propagation delay of the \( l \)th tap are denoted as \( h_{pq}(t) \) and \( \tau_l \) respectively. For the first tap, the complex tap coefficient of the Tap-Rq link can be expressed as [16]

\[
h_{1,pq}(t) = h_{1,pq}(t) + \sum_{l=2}^{L} h_{lpq}(t) + h_{SPq}(t) \tag{1}
\]

with

\[
h_{1,pq}(t) = \frac{\sqrt{K \Omega}}{K+1} e^{[2\pi f_{R_q} \cos(q \pi) - 2\pi f_{R_q} \cos(q \pi) - \gamma_3]}
\]

\[
h_{lpq}(t) = \frac{\eta_{S_{R_q}}}{K+1} \lim_{N_1 \to \infty} \frac{1}{\sqrt{N_1}} \sum_{n=1}^{N_1} e^{[2\pi f_{R_q} \cos(q \pi) - 2\pi f_{R_q} \cos(q \pi) - \gamma_3]}
\]

\[
h_{SPq}(t) = \frac{\eta_{S_{R_q}}}{K+1} \lim_{N_1 \to \infty} \frac{1}{\sqrt{N_1}} \sum_{n=1}^{N_1} e^{[2\pi f_{R_q} \cos(q \pi) - 2\pi f_{R_q} \cos(q \pi) - \gamma_3]}
\]

\[
\sum_{n=1}^{N_1} e^{[2\pi f_{R_q} \cos(q \pi) - 2\pi f_{R_q} \cos(q \pi) - \gamma_3]}
\]

where \( I_i = 3 \), the symbols \( W_{pq} \) and \( K \) denote the total power of the Tap-Rq link and the Ricean factor, respectively. The scattering-caused phases \( \psi_n^\alpha \) and \( \psi_n^\beta \) are random variables with uniform distributions over \([\pi, \pi] \). \( \tau_{pq} = \tau_{pq} / c, \tau_{pq,1} = (\varepsilon_{pq,1} + \varepsilon_{pq,2}) / c, \) and \( \tau_{pq,1,2} = (\varepsilon_{pq,1} + \varepsilon_{pq,2}) / c \) are the waves’ travel times through the link \( Tp - Rq, Tp - S_{pq}^{\alpha,1} - Rq, \) and \( Tp - S_{pq}^{\alpha,2} - Rq, \) respectively, and \( c \) is the speed of light.

For other taps \( (I_i > 1) \), the complex tap coefficient \( h_{I,lpq}(t) \) can be expressed as

\[
h_{I,lpq}(t) = h_{I,lpq}(t) + \sum_{l=2}^{L} h_{lpq}(t) \tag{3}
\]

with

\[
h_{I,lpq}(t) = \frac{\eta_{S_{R_q}}}{K+1} \lim_{N_1 \to \infty} \frac{1}{\sqrt{N_1}} \sum_{n=1}^{N_1} e^{[2\pi f_{R_q} \cos(q \pi) - 2\pi f_{R_q} \cos(q \pi) - \gamma_3]}
\]

\[
\sum_{n=1}^{N_1} e^{[2\pi f_{R_q} \cos(q \pi) - 2\pi f_{R_q} \cos(q \pi) - \gamma_3]}
\]

\[
\sum_{n=1}^{N_1} e^{[2\pi f_{R_q} \cos(q \pi) - 2\pi f_{R_q} \cos(q \pi) - \gamma_3]}
\]

Fig. 1. A RS-GBSM combining a two-ring model and a multiple confocal ellipses model with LoS components, single- and double-bounced rays for wideband V2V-MIMO channels (\( n_r = n_B = 2 \)).
For the multiple confocal ellipses produced from the combination of one-ring energy than the double-bounced components from ellipse models are allocated less under a high VTD, the single-bounced components. For two rings model, converted by the following widely used approx expressions of distance can follow the paper [9]. As we know, since the scatterers distributed over the theoretical reference model are usually assumed to be infinity, we can use the the continuous expressions of AoD $\alpha^{(n)}_r$ and AoA $\alpha^{(n)}_\theta$ to replace the discrete expressions $\alpha^{(n)}_r$ and $\alpha^{(n)}_\theta$, respectively. Based on our research, the distribution of azimuth angles for scatterers $\alpha^{(n)}_r$ and $\alpha^{(n)}_\theta$ has been described using several probability density functions, including uniform [17], Gaussian, Laplacian [18], and of Mises [19]. But the most commonly used is the von Mises PDF because it approximates many of the previously mentioned distributions and leads to closed-form solutions for many useful situations [11]. It is defined as $f(\alpha) = \exp[k \cos(\alpha - \alpha_0)]/2\pi I_0(k)$, where $\alpha \in [-\pi, \pi)$, $I_0(\cdot)$ is the zeroth-order modified Bessel function of the first kind, $\alpha_0$ accounts for the mean value of the angle $\alpha$, and the real-valued parameter $k(k > 0)$ is designed to control the distribution of the angle $\alpha_0$.

### III. Statistical Properties of the Proposed Wideband V2V-MIMO Channel Model

In this section, based on the research of literature on the statistical properties of narrowband V2V-MIMO reference models [7] – [11], some important channel statistical characteristics of the V2V-MIMO wideband channel model for non-isotropic scattering environment will be derived, including the STCF, Doppler PSD, envelope LCR and AFD.

#### 3.1 Space-time correction function

The normalized space-time CF [20] between two arbitrary complex tap coefficients $h_{\mu}(t)$ and $h_{\nu}(t)$ can be defined as

$$R_{\mu,\nu}(\delta_\tau, \delta_\theta, \tau) = \frac{E[h^*_{\mu}(t)h_{\nu}(t + \tau)]}{\sqrt{E[|h_{\mu}(t)|^2]E[|h_{\nu}(t + \tau)|^2]}}$$

$E[\cdot]$ and $(\cdot)^*$ denote the statistical expectation operator and complex conjugate operation, respectively. It can be written as the superposition of the LoS, single- and double-bounced components. For the first tap,
\[ R_{p,q,r}^{L_{D}}(\delta, \delta, r, \tau) = R_{p,q,r}^{L_{D}}(\delta, \delta, \tau) \]
\[ + \sum_{\gamma=1}^{L} R_{p,q,r}^{\text{SR}}(\delta, \delta, r, \tau) + R_{p,q,r}^{\text{DB}}(\delta, \delta, r, \tau) \]
\[ (5) \]
with
\[ R_{p,q,r}^{L_{D}}(\delta, \delta, r, \tau) = \frac{K e^{-2\pi f_{0} r}}{K + 1} \]
\[ e^{i2\pi f_{0} \cos(\delta_{1} - \delta_{1}) - \tau} \]
\[ (6a) \]
\[ R_{p,q,r}^{\text{SR}}(\delta, \delta, r, \tau) = \frac{\eta_{\text{SR}}}{K + 1} \sum_{i=1}^{r} f(\alpha_{i}) \]
\[ e^{-\frac{2\pi f_{0}}{K} \cos(\delta_{1} - \delta_{1}) \tau} \]
\[ (6b) \]
\[ R_{p,q,r}^{\text{DB}}(\delta, \delta, r, \tau) = \frac{\eta_{\text{DB}}}{K + 1} \sum_{i=1}^{r} f(\alpha_{i}) \]
\[ e^{-\frac{2\pi f_{0}}{K} \cos(\delta_{1} - \delta_{1}) \tau} \]
\[ (6c) \]

For other taps,
\[ R_{p,q,r}^{L_{D}}(\delta, \delta, r, \tau) = R_{p,q,r}^{\text{SR}}(\delta, \delta, r, \tau) \]
\[ + \sum_{\gamma=1}^{L} R_{p,q,r}^{\text{DB}}(\delta, \delta, r, \tau) \]
\[ (7) \]

\[ R_{p,q,r}^{\text{SR}}(\delta, \delta, r, \tau) = \eta_{\text{SR}} \sum_{i=1}^{r} f(\alpha_{i}) \]
\[ e^{-\frac{2\pi f_{0}}{K} \cos(\delta_{1} - \delta_{1}) \tau} \]
\[ e^{i2\pi f_{0} \cos(\delta_{1} - \delta_{1}) \tau} \]
\[ (8a) \]
\[ R_{p,q,r}^{\text{DB}}(\delta, \delta, r, \tau) = \eta_{\text{DB}} \sum_{i=1}^{r} f(\alpha_{i}) \]
\[ e^{-\frac{2\pi f_{0}}{K} \cos(\delta_{1} - \delta_{1}) \tau} \]
\[ e^{i2\pi f_{0} \cos(\delta_{1} - \delta_{1}) \tau} \]
\[ (8b) \]
\[ R_{p,q,r}^{\text{DB}}(\delta, \delta, r, \tau) = \eta_{\text{DB}} \sum_{i=1}^{r} f(\alpha_{i}) \]
\[ e^{-\frac{2\pi f_{0}}{K} \cos(\delta_{1} - \delta_{1}) \tau} \]
\[ e^{i2\pi f_{0} \cos(\delta_{1} - \delta_{1}) \tau} \]
\[ (8c) \]

### 3.2 Doppler power spectral density

In order to study the corresponding Doppler PSD of the proposed V2V wideband model, we can use the Fourier Transform to the STCF, which can be expressed as
\[ S_{p,q,r}(f_{\nu}) = \int_{-\infty}^{\infty} R_{p,q,r}(\tau)e^{-j2\pi f_{\nu} \tau}d\tau, \]
where \( f_{\nu} \) is the Doppler frequency.

### 3.3 Envelope LCR

Here, based on the research [21], we can define the LCR \( L(r) \) using the rate at which the signal envelope crosses a specified level \( r \) with a positive or negative direction. The LCR for V2V channels can be written as
\[ L(r) = \frac{2\sqrt{K + 1}}{\pi^{\frac{1}{2}}} \left( \frac{b_{2}}{b_{0}} \right) e^{-K(K+1)r^{2}} \]
\[ \int_{0}^{\infty} \cos(2\sqrt{K(K+1)}\cdot r \cos \theta) \]
\[ \left[ e^{-\left(\chi \sin \theta \right)^{2}} + \sqrt{\pi} \chi \sin \theta \cdot \text{erf}(\chi \sin \theta) \right] d\theta \]
(9)

where \( \cos(\cdot) \) and \( \text{erf}(\cdot) \) can be described as the hyperbolic cosine function and error function, and \( \chi = \sqrt{Kh_{0}^{2}} / \left( b_{1}b_{2} - b_{0}^{2} \right) \). Based on the [10], we first discuss the parameters \( b_{0} \) of the first tap of the proposed model, which can be expressed as
\[ b_{0} = b_{0}^{\text{SR}} + b_{0}^{\text{DB}} = \frac{1}{2(K + 1)}. \]
(10)

Similarly, we can express parameters \( b_{1} \) and \( b_{2} \) as
\[ b_{m} = b_{m}^{\text{SR}} + b_{m}^{\text{DB}} = \frac{1}{2(K + 1)}. \]
(m = 1, 2)
(11)

with
\[ b_{m}^{\text{SR}} = \frac{\eta_{\text{SR}}}{2(K + 1)} \int_{0}^{\pi} f(\alpha_{i}) \]
\[ \left[ f_{m}^{\text{SR}}(\alpha_{i}) \cos(\alpha_{i} - \gamma_{1}) \right. \]
\[ + f_{m}^{\text{SR}}(\alpha_{i}) \cos(\alpha_{i} - \gamma_{2}) \]
\[ \int_{0}^{\pi} f(\alpha_{i}) \]
\[ \left. \int_{0}^{\pi} f(\alpha_{i}) \right] d\alpha_{i} \]
\[ (12a) \]
\[ b_{m}^{\text{DB}} = \frac{\eta_{\text{DB}}}{2(K + 1)} \int_{0}^{\pi} f(\alpha_{i}) \]
\[ \left[ f_{m}^{\text{DB}}(\alpha_{i}) \cos(\alpha_{i} - \gamma_{1}) \right. \]
\[ + f_{m}^{\text{DB}}(\alpha_{i}) \cos(\alpha_{i} - \gamma_{2}) \]
\[ \int_{0}^{\pi} f(\alpha_{i}) \]
\[ \left. \int_{0}^{\pi} f(\alpha_{i}) \right] d\alpha_{i} \]
\[ (12b) \]

For other taps, we can obtain parameter \( b_{0} \) as
\[ b_{0} = b_{0}^{\text{SR}} + b_{0}^{\text{DB}} = \frac{1}{2(K + 1)}. \]
(13)

The parameters \( b_{1} \) and \( b_{2} \) can be expressed as
\[ b_{m} = b_{m}^{\text{SR}} + b_{m}^{\text{DB}} = \frac{1}{2(K + 1)}. \]
(14)

with
\[ b_{m}^{\text{SR}} = \frac{\eta_{\text{SR}}}{2(K + 1)} \int_{0}^{\pi} f(\alpha_{i}) \]
\[ \left[ f_{m}^{\text{SR}}(\alpha_{i}) \cos(\alpha_{i} - \gamma_{1}) \right. \]
\[ + f_{m}^{\text{SR}}(\alpha_{i}) \cos(\alpha_{i} - \gamma_{2}) \]
\[ \int_{0}^{\pi} f(\alpha_{i}) \]
\[ \left. \int_{0}^{\pi} f(\alpha_{i}) \right] d\alpha_{i} \]
\[ (15a) \]
\[ b_m^{(D)} = \frac{\eta_{m,1}}{2(K+1)} (2\pi)^n \int_{-\alpha}^{\alpha} \int_{-\alpha}^{\alpha} f(\alpha_T^1) f(\alpha_T^3) \]
\[ \left[ f_{m,1} \cos(\alpha_T^3 - \gamma_T^1) + f_{m,3} \cos(\alpha_R^3 - \gamma_R^1) \right] (15b) \]
\[ b_m^{(D)} = \frac{\eta_{m,2}}{2(K+1)} (2\pi)^n \int_{-\alpha}^{\alpha} \int_{-\alpha}^{\alpha} f(\alpha_T^1) f(\alpha_T^2) \]
\[ \left[ f_{m,2} \cos(\alpha_T^3 - \gamma_T^1) + f_{m,3} \cos(\alpha_R^3 - \gamma_R^1) \right] (15c) \]

We can bring the \( b_0, b_1, \) and \( b_2 \) into the (9) to get the LCR of the proposed model.

### 3.4 Envelope AFD

The average time when the signal envelope \( |h_m(t)| \) stays below a certain level \( r \) is used to represent the signal envelope AFD \( T(r) \). In the proposed model, the AFD can be written as [10]
\[ T(r) = \frac{1 - Q(\sqrt{2K}, \sqrt{2(K+1)r^2})}{L(r)} \] (16)
where \( Q(\cdot) \) is the Marcum Q function.

### IV. NEW 2D WIDEBAND V2V-MIMO CHANNEL SIMULATION MODELS

The reference model considers an infinite number of scatterers, but an infinite number of sinusoidal curves cannot be realized in reality. Thus, we need to design a corresponding simulation model with limited complexity and capable of being implemented in practice. Therefore, a limited number of scatterers are considered in the simulation model, and this model is intended for system performance evaluation for reasonable complexity [22], [23].

Based on the above discussion, the approximation of the channel statistical characteristics between the simulation model and the reference model depends on the sampling mode of the scatterers. When the scatterer's sample approaches the probability density function of the scatterer distribution in the reference model, the practicality of the simulation model will become stronger. In other words, it is important to find a way to design the sets of AoDs \( \alpha_T^{(n)} \) and AoAs \( \alpha_R^{(n)} \) of the simulation model to represent the desired channel statistical characteristics. Next, we will propose the corresponding deterministic and stochastic simulation models, respectively.

### 4.1 Deterministic simulation model

First, a deterministic simulation model is proposed, which requires constant parameters during simulation. In other words, based on our proposed model, the AoDs \( \alpha_T^{(n)} \) and AoAs \( \alpha_R^{(n)} \) have definite values for different simulation experiments. Based on [24], the AoDs and AoAs are designed as the follows.

1) We first define a new parameter \( \alpha_T^{(n)} \) which has the same environment parameters as \( \alpha_T^{(n)} \) on a von Mises distribution.

2) Then, we use the following method to get the set of \( \alpha_T^{(n)} \) as
\[ \tilde{\alpha}_T^{(n)} = F^{-1}_{T(i)} \left( \frac{n_i - 1/4}{N_{T(i)}} \right), (n_i = 1, 2, ..., N_{T(i)}) \] (17)
where \( F^{-1}_{T(i)} \) denotes the inverse function of the von Mises CDF for \( \alpha_T^{(n)} \).

3) In order to ensure that the simulation model’s AoDs and AoAs are in the range \([\pi, \pi]\), we use the following mapping, that is
\[ \alpha_T^{(n)} = \begin{cases} \alpha_T^{(n)} + 2\pi, & \alpha_T^{(n)} < -\pi \\ \alpha_T^{(n)} - 2\pi, & \alpha_T^{(n)} > \pi \\ \alpha_T^{(n)}, & \text{else} \end{cases} \] (18)

### 4.2 Stochastic simulation model

The deterministic simulation model is easy to implement and has a short simulation time. However, in an actual communication channel, the scatterers are not placed in a certain place like the proposed deterministic model. Therefore, this model can be transformed into a stochastic simulation model if we allow the phases or frequencies to be random variables. Since the addition of random variables, the channel characteristics of the stochastic simulation model change with each simulation trial, but will converge to the expectations of the model in a sufficient number of simulation trials. Similarly, the AoAs and AoDs designed by the stochastic simulation model can be ex-
pressed as follows.

1) We first propose a new random variable \( \tilde{\alpha}_{T(R)}^{(n)} \), which has the same environment parameters as \( \alpha_{T(R)} \) on a von Mises distribution.

2) Then, we use the following method to get the set of \( \tilde{\alpha}_{T(R)}^{(n)} \) as

\[
\tilde{\alpha}_{T(R)}^{(n)} = F_{T(R)}^{-1}\left(\frac{\overline{n}_{j} + \theta - 1/4}{N_{i,j}}\right), (n_{j} = 1, 2, ..., N_{i,j}).
\]

(19)

The parameters \( \theta \) is independent random variable uniformly distributed on the interval \([-1/2, 1/2)\). Due to the introduction of random variable, the set of AoDs and AoAs varies with different simulation trial.

3) In order to ensure that the simulation model’s AoDs and AoAs in the range of \([-\pi, \pi)\), we use the following mapping, that is

\[
\tilde{\alpha}_{T(R)}^{(n)} = \begin{cases} 
\tilde{\alpha}_{T(R)}^{(n)} + 2\pi, & \tilde{\alpha}_{T(R)}^{(n)} < -\pi \\
\tilde{\alpha}_{T(R)}^{(n)} - 2\pi, & \tilde{\alpha}_{T(R)}^{(n)} > \pi \\
\tilde{\alpha}_{T(R)}^{(n)}, & \text{else}
\end{cases}
\]

(20)

Based on our proposed way, we can get discrete expressions of the parameters the AoAs and AoDs of 2D V2V MIMO simulation model and bring them into (1)–(4) to get the corresponding statistical properties. Because of page constraints, the corresponding statistical properties’ derivation of the simulation models can refer to Section III.

V. NUMERICAL SIMULATION AND ANALYSIS

In this section, we will compare the channel statistical characteristics between the proposed simulation models and reference model, and validate the usefulness of the two simulation models. The values of the parameters used for our numerical analysis are

\( D=2\text{m}=300\text{m}, R_T=R_R=10\text{m}, \varphi=\psi=0, f_c=5.9\text{GHz}, f_{f_{r_{1}}} = f_{f_{t_{1}}}=360\text{Hz}, f_{f_{r_{2}}} = f_{f_{t_{2}}}=570\text{Hz}. \)

Due to page constraints, we only consider a three-tap model, which the semi-major axis of the confocal multi-ellipse is assumed to be \( a_c = [160,170,180] \). Suppose the environment-parameters are \( K = 3.8, k_e = 6.6, \mu_f = 12.8, k_e = 8.3, \mu_e = 178.7, k_e = 7.7, \mu_e = 31.3 \) for low VTD, and \( K = 0.856, k_f = 0.6, \mu_f = 12.8, k_e = 1.3, \mu_e = 178.7, k_e = 8.5, \mu_e = 20.6 \) for high VTD. In the case of low VTD, for the first tap, it is assumed that the corresponding energy-parameters are \( \eta_{SR_1} = 0.203, \eta_{SR_2} = 0.335, \eta_{SR_3} = 0.411, \) and \( \eta_{DB} = 0.051 \). For the \( l \)’th taps (\( l > 1 \)), assume that the corresponding energy parameters are \( \eta_{SR_1} = 0.762, \eta_{DB_1} = 0.119, \) and \( \eta_{DB_2} = 0.119 \). In the case of high VTD, for the first tap, we use energy-parameters \( \eta_{SR_1} = 0.126, \eta_{SR_2} = 0.126, \eta_{SR_3} = 0.063, \) and \( \eta_{DB} = 0.685 \) to describe the first tap. For the \( l \)’th taps (\( l > 1 \)), assume that the corresponding energy parameters are \( \eta_{SR_1} = 0.088, \eta_{DB_1} = 0.456, \) and \( \eta_{DB_2} = 0.456 \). Both deterministic and stochastic simulation models assume that the number of effective scatterers is \( N_{1,1} = N_{1,2} = N_{1,3} = N_{2,3} = N_{3,3} = 20 \) and the

![Fig. 2. Doppler PSDs of the reference model and the two simulation models with different VTDs for the same direction of movement of the Tx and Rx under two different tap scenarios: (a) first tap and (b) second tap.](image)
number of simulation experiments for stochastic simulation model is $N_{\text{stat}} = 50$.

Figs. 2 and 3 compare that when the Tx and Rx are moving in the same and opposite directions, the Doppler PSDs between the proposed reference and simulation models with different VTDs, where the images (a) and (b) denote the first and second tap. It can be seen that the proposed simulation model can match well with the reference model, which further proves the usefulness and practicality of our proposed deterministic and stochastic simulation models. At the same time, the VTDs also have some effect on the DPSD for V2V channels. It can be observed that the Doppler PSD distribution is more flatly under high VTD scenarios, while the DPSD tends to be steeply with low VTDs. It is because that in a low VTD scenario, the received power mainly concentrates on several directions, e.g., the static scatterers on the roadside environment and/or the directions of LoS components, which results in the received power tending to concentrate at certain Doppler frequencies. In contrast, in the case of high VTDs, the received power mainly comes from the moving cars around the Tx and Rx from all directions, which means the distribution of DPSD is more uniform.

Similarly, Figs. 4 and 5 show the LCR between the reference and simulation models with different VTDs when the moving direction of Tx and Rx is same or opposite, where the images (a) and (b) present the first and second tap, respectively. We can see that the value of LCR is small when the VTD is low. This phenomenon can be explained that in a high VTD, the received power mainly comes from moving scatterers distributed in all directions, and the rate of change of the signal envelope is high, resulting in the value of the corresponding LCR is large. Unlike the high VTD scenarios, the received power comes from several specific directions with low VTDs. Therefore, the temporal stability of V2V channels is higher, and the value of LCR shown in the image is low.

Fig. 6 shows the STCF of the proposed models with different VTDs when the moving direction of Tx and Rx is same and opposite. It can be seen that the VTD affects the STCF of the model. The space-time correlation de-
creases as the VTD increases. This phenomenon can be interpreted as the spatial diversity of the channel increases as the VTD increases, and the correlation decreases. At the same time, it shows that both deterministic and stochastic simulation models can have a reasonable agreement with the reference model. In addition, we can observe that the stochastic simulation model can obtain better agreement with the reference model compared with the deterministic simulation model. Therefore, although the deterministic simulation model is easy to be implemented and can be achieved with a short simulation time, it is more suitable to choose the stochastic simulation model for the system performance evaluation when the computational complexity is similar.

VI. CONCLUSION

In this paper, based on the study of a reference model for non-isotropic V2V-MIMO wideband channels which is the combination of a two-ring and a multiple confocal ellipses model, we have derived the expressions of channel statistical characteristics, i.e., STCF, DPSD, LCR and AFD. Moreover, corresponding deterministic and stochastic simulation models have been proposed based on the reference model. Based on numerical results, we have found out that different VTDs have a significant impact on channel statistical properties, and the great agreement between the reference model and simulation models has demonstrated the correctness of derivations and the utility of proposed simulation models. Finally, the simulation results have shown that the stochastic simulation model is more suitable for the system performance evaluation when the computational complexity is similar.

ACKNOWLEDGEMENTS

This work was supported in part by the project from the ZTE, the National Natural Science Foundation of China under Grant 61622101 and Grant 61571020, and National Science and Technology Major Project under Grant 2018ZX03001031.
References


Yiran Li, graduate student with the School of Software and Microelectronics, Peking University. Her current research interests include channel modeling and vehicular communications. Email: yiran.li@pku.edu.cn

Xiang Cheng, professor with the School of Electronics Engineering and Computing Science, Peking University. His current research interests include channel modeling, wireless communications (vehicular communications and 5G), and data analytics. Email: xiangcheng@pku.edu.cn

Nan Zhang, received the bachelor degree in communication engineering and the Master degree in integrated circuit engineering from Tongji University, Shanghai, China, in July 2012 and March 2015, respectively. He is now a Senior Engineer at the Department of Algorithms, ZTE Corporation. His current research interests are in the field of 5G channel modeling, new air-interface and MIMO techniques. Email: zhang.nan152@zte.com.cn