Modeling for geometry-based massive MIMO V2V channels and analysis of space-time correlation

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Abstract. This paper proposed a three-dimensional dual-spheres confocal ellipsoid geometry-based model for massive MIMO vehicle-to-vehicle (V2V) communication. In this proposed model, the received signal is composed of non-line-of-sight propagation components generated via effective scatterers and line-of-sight propagation components. According to the geometric relationships in the model, the information of angle and distance can be derived, and then the space-time correlation function expression is obtained. To calculate parameters, modified method of equal areas is employed, and the influence on space-time correlation of scatters in different environments is analyzed. Channel characteristics in different scenarios such as highway scenario, urban road scenario and tunnel scenario are compared and studied. Simulation results show that the scatterers distribution and angle information of antenna arrays make a joint contribution on spatial cross-correlation, and moreover, the degree of anisotropy of scatterers and multipath components have distinct impacts on temporal auto-correlation. Compared with the results of 2D model, the proposed 3D model in this paper is more appropriate to characterize V2V communication in various scenarios.

1. Introduction
Massive multiple-input multi-output (MIMO) can be widely used in cellular mobile network scene in the fifth generation (5G) because of its good channel capacity and reliability. In recent years, modeling and analysis of vehicle-to-vehicle (V2V) communication has become a hot topic for the development of intelligent transportation systems[1]. In the V2V scenario, the mobility of the vehicle and the sensitivity of transmission change of receiving and transmitting waves make the fading of wireless channel no longer satisfy the wide-sense stationary (WSS) condition. A great deal of channel data reveals that channel fading shows obvious non-stationary characteristics with the increase of system bandwidth and communication rate as well as the change of the number of scatterers and the position of mobile terminal in mobile environment. Therefore, it is vital for the development of V2V to build a channel model which can effectively describe the communication environment and signal statistical characteristics.

In order to describe the multipath components of massive MIMO V2V channel accurately, estimate the scattering area reasonably and extract the channel characteristic parameters effectively, a proper channel modeling method should be chosen[2]. At present, common channel models are deterministic channel model and random channel model[3]. Geometry-based stochastic modeling (GBSM) is widely used due to its clear physical meaning, flexible parameters as well as low computational complexity.
In GBSM, scattering environments are often constructed into two dimensional (2D) patterns such as rectangle, U-shape, ring, ellipse[4-8] and three-dimensional (3D) patterns of dual-rings, oval, double cylinders, sphere and combinatorial model[9]. A dual-rings model is proposed in [10], where space-time correlation function (ST-CF) and Doppler power spectrum in heterogeneous environment are derived under the condition of Ricean fading channel. The sum of sinusoid (SoS) simulation model is used to verify the correctness of the model. In [11], a tapped-delay-line (TDL) model is adopted to describe the non-stationary characteristic of the high speed mobile traffic system.

Current literatures have done some research work on V2V, including highway and urban road scene[12], as well as different road conditions of high and low traffic density[13]. To build a universal channel model that can describe many communication scenarios effectively, this paper presents a 3D dual-spheres confocal ellipsoid model based on GBSM to describe the scattering environment of the V2V communication, with taking the complexity and variability of V2V communication scenes into account, and employing simulation to study the impact of important parameters on the proposed model. The influence of channel statistical characteristics such as spatial cross-correlation function (CCF) and temporal auto-correlation function (ACF). The proposed model is analyzed for different V2V by changing channel environment and antenna parameters. This paper discusses the applicability of various scenes and the ST correlation performance of proposed V2V model in tunnel, highway and urban scene according to simulations.

2. Channel modeling

2.1. 3D V2V GBSM modeling

Under the proposed V2V modeling scenario, the scatterers in road environment are mainly buildings, pedestrians, road signs and other objects. As shown in figure 1, the antennas of transmitter and receiver are represented by Tx and Rx respectively, road traffic scatterers are vehicles around Tx and Rx. A dual-spheres model is established to characterize road traffic scatterers, and an ellipsoid model is established to characterize road environmental scatterers, with antenna array centers of the transmitter and receiver as the center of sphere OT, OR, while the radii of dual-spheres are set to be RT and RR respectively. The parameters and meanings in figure 1 are shown in table 1.

![Figure 1. The geometric diagram of V2V GBSM containing SB components and DB components.](image-url)
Table 1. Parameters and corresponding meanings of proposed model.

| Parameter | Meaning |
|-----------|---------|
| $a$, $D$  | semi-major axis length and focal length of ellipsoid |
| $O_T$, $O_R$ | central position between Tx and Rx |
| $R_T$, $R_R$ | radius of the Tx and Rx spheres, respectively |
| $\delta_T$, $\delta_R$ | antenna element length of the Tx and Rx, respectively |
| $\theta_T$, $\theta_R$ | orientation of the Tx and Rx antenna arrays, respectively |
| $\varphi_T$, $\varphi_R$ | elevation of the Tx and Rx antenna arrays, respectively |
| $\gamma_T$, $\gamma_R$ | velocity of the Tx and Rx, respectively |
| $\alpha^{LOS}_T$, $\alpha^{LOS}_R$ | azimuth and elevation angle of arrival in LOS path, respectively |
| $S^o_T$, $S^o_R$ | effective scatterers distributed on the dual-spheres at Tx and Rx, respectively |
| $S^o_S$ | effective scatterers distributed on the ellipsoid at Tx and Rx, respectively |
| $\alpha^o_T$, $\alpha^o_R$ | azimuth angle of departure from Tx to $S^o_T$, respectively |
| $\beta^o_T$, $\beta^o_R$ | elevation angle of departure from Tx to $S^o_T$, respectively |
| $\epsilon_{pi}$, $\epsilon_{qi}$ | distance between the $p$-th antenna of Tx and $S^o_T$, and the $q$-th antenna of Rx |
| $\epsilon_{ni}$ | distance between $S^o_S$ and $S^o_S$ |

2.2 Derivation of 3D V2V GBSM parameters

In order to reduce the complexity of the model and get the channel parameters through theoretical derivation, this paper mainly makes the following assumptions:

1. Vehicles at both terminals are equipped with uniform linear arrays (ULA) composed of omnidirectional radiation antennas, based on a horizontal propagation assumption and vertical polarization.

2. The received signal is composed of the LOS component and the NLOS components. According to the geometrical constraints of the proposed model, the angle of departure and the angle of arrival depend on each other in the single-bounced path, while they are independent in the double-bounced path.

3. Multipath components are considered by TDL model, of which first tap is used for LOS path and partial single-bounced (SB) path, and remaining taps take the other single-bounced component and double-bounced (DB) component into account.

Considering the LOS path and the NLOS path under the separable path, the NLOS path consists of the single-bounced paths and double-bounced paths. Suppose there are $N_{s}$ scatterers around Tx, and the $n_{1,1}$th ($n_{1} = 1, 2, \ldots, N_{s}$) scatterer is denoted as $S^o_{n_{1}}$. Similarly, there are $N_{s}$ scatterers around Rx and the $n_{2,1}$th ($n_{2} = 1, 2, \ldots, N_{s}$) scatterer is denoted as $S^o_{n_{2}}$. There are $N_{s}$ scatterers distributed in surrounding ellipsoid area, and the $n_{s,1}$th ($n_{s} = 1, 2, \ldots, N_{s}$) scatterer is expressed as $S^o_{n_{s}}$. Therefore, a complete transmission from transmitter to receiver is composed of LOS, SB and DB path components, in which LOS path represents a communication path from Tx to Rx directly, SB components indicate the propagation of transmission wave may encounter obstacles distributed in spheroid and ellipsoid model.
once, and DB components indicate that wave propagation from Tx to Rx scattered by obstacles in the two spheres regions twice. In TD L, the channel impulse response (CIR) from transmitter to receiver can be defined as

$$h_{pq}(t, \tau') = \sum_{l=1}^{L(t)} c_l h_{l, pq}(t) \delta(\tau - \tau')$$

where $L(t)$ is the total number of taps, and $c_l$ represents the gain of the $l$th tap. $h_{l, pq}(t)$ denote CIR between the $p$th ($p = 1, 2, \ldots, M_p$) antenna at transmitter and the $q$th ($q = 1, 2, \ldots, M_q$) antenna at receiver in the first and $l$th($l > 1$) tap respectively. Hence, the $h_{l, pq}(t)$ can be expressed as

$$h_{1, pq}(t) = h_{1, pq}^{LOS}(t) + \sum_{j=1}^{2} h_{1, pq}^{SB}(t)$$

$$h_{2, pq}(t) = h_{2, pq}^{DB}(t) + h_{p, q}(t)$$

where the LOS and NLOS components can be expressed as

$$h_{pq}^{LOS}(t) = \left( \frac{K_{pq} \Omega_{pq}}{K_{pq} + 1} \right)^{1/2} e^{j2\pi \left( f_{pq}^{LOS} \frac{\tau_{pq}}{\lambda} \right)}$$

$$h_{pq}^{SB}(t) = \left( \frac{\eta_{SB} \Omega_{pq}}{K_{pq} + 1} \right)^{1/2} \times \lim_{N_1 \to \infty} \sum_{n_1=0}^{N_1} \left( \frac{1}{N_1} \right)^{1/2} e^{j2\pi \left( f_{n_1}^{SB} \frac{\xi_{pq}}{\lambda} \right)}$$

$$h_{pq}^{DB}(t) = \left( \frac{\eta_{DB} \Omega_{pq}}{K_{pq} + 1} \right)^{1/2} \times \lim_{N_1 \to \infty} \sum_{n_1=0}^{N_1} \sum_{n_2=0}^{N_2} \left( \frac{1}{N_1 N_2} \right)^{1/2} e^{j2\pi \left( f_{n_1}^{DB} + f_{n_2}^{DB} \frac{\xi_{pq}}{\lambda} \right)}$$

where $K$ designates Ricean factor, $\Omega_{pq}$ denotes the total power in transmission link, $\lambda$ is carrier wavelength. SB1 and SB2 are single-bounced components via a sphere scattering area at the transmitter and receiver respectively, while SB3 is a single-bounced component via ellipsoid scattering area between the communicating parties. $\eta_{SB1}, \eta_{SB2}, \eta_{SB3}$ represent the contribution to the total power of NLOS from three single-bounced components SB1, SB2, SB3. Note that these energy-related parameters satisfy $\sum_{i=1}^{3} \eta_{SBi} = 1$.

For LOS, the distance represented by focal length between the two moving vehicles is much greater than that of the radius from the moving vehicles to the scatterers in the road environment, both of these are much larger than the interval of mobile antenna elements, so we can get $D > \max \{ R_T, R_R \} > \max \{ \delta_T, \delta_R \} \approx \pi$, $\alpha_T^{LOS} \approx 0$, $\beta_T^{LOS} \approx 0$, $\beta_R^{LOS} \approx 0$. The Doppler shift in LOS path can be expressed as

$$f_{pq}^{LOS} = f_{T_{max}} \cos(\alpha_T^{LOS} - \gamma_T) \cos(\beta_T^{LOS}) + f_{R_{max}} \cos(\alpha_R^{LOS} - \gamma_R) \cos(\beta_R^{LOS})$$
where $f_{\text{max}T}$ and $f_{\text{max}R}$ denote the maximum Doppler frequency shift caused by the movement of the vehicle along the motion direction, as $f_{\text{max}T} = v_T / \lambda$ and $f_{\text{max}R} = v_R / \lambda$. The Doppler shift in NLOS path can be expressed as

$$f^\text{SB}_{pq} = f_{\text{max}T} \cos(\alpha^n_T - \gamma_T) \cos \beta^n_T + f_{\text{max}R} \cos(\alpha^n_R - \gamma_R) \cos \beta^n_R$$

(8)

According to cosine theorem and spatial geometry of the model, the path length related to SB1, SB2, SB3 components can be derived. The correlation among elevation angle of arrival (EAOA), azimuth angle of arrival (AAOA), elevation angle of departure (EAOA), azimuth angle of departure (AAOA) of SB1, SB2 and SB3 can be used to calculate the wave propagation path length $\epsilon_{pi}$, $\epsilon_{qi}$, $\epsilon_{pi,q}$, $(i = 1, 2)$. Due to space limitations, the derivation process is not elaborated here.

For the proposed GBSM, the number of scatterers cannot be estimated directly due to its infinity. Considering the influence of different factors on the channel statistical characteristics, the Von Mises distribution can approximate the above various distributions[14]. This paper introduces the Von Mises Function (VMF) to describe the AoAs and AoDs of wave after effective scattering. The PDF of VMF can be defined as

$$f(\alpha) = \frac{e^{k \cos(\alpha - \alpha_0)}}{2\pi I_0(k)}$$

(9)

where $\alpha \in [-\pi, \pi)$, $\alpha_0 \in [-\pi, \pi)$. $\alpha$ is used to simulate AoAs of this model, and $k$ represents the environment factor. Scattered rays tend to be isotropic when $k$ is close to 0. The scattered rays tend to be non-isotropic as $k$ increases.

2.3 Non-stationary characteristics

In order to fit the non-stationary characteristics of proposed model in the fast time-varying environment of V2V channel, birth-death processes are introduced to model the emergence-disappearance of multipath components (MPCs) along the time axis[13]. The total number of MPCs is $L(t)$. Compared with the previous moment $t_{k-1}$, MPCs at any time $t_k$ include both the newborn components and the recombination components. Let $\lambda_n$ and $\lambda_r$ denote the new birth probability and recombination probability of MPCs respectively, the MPC recombination probability at time $(t_{k-1}, t_k]$ is

$$P_{\text{remain}} = e^{-\lambda_R \Delta_{p,k}}$$

(10)

where $\Delta_{p,k}$ represents the factor related to time-varying motion and communication scenarios. According to the birth-death process algorithm, the expectation of newborn MPCs is

$$E\{L_{\text{new}}\} = \frac{\lambda_n}{\lambda_R} (1 - e^{-\lambda_R \Delta_{p,k}})$$

(11)

From equations (10) and (11), it is obvious that all multipath components can be divided into surviving MPCs and newborn MPCs during the time evolution process.

3. Establishment of space-time correlation function

Measured data shows that the channel parameters of massive MIMO vary significantly along antenna dimension since antenna size causes the parameters of different dimensions in the channel to
experience more significant ST fluctuations[2]. The move of vehicles will not only change the scattering environment, but also brings time-varying characteristic to channel parameters. Therefore, it is vital to establish the space-time correlation function of the system and analyze the impact of scattering environment and antennas on the channel characteristics.

Regard the \( p \)-th antenna at transmitter and the \( q \)-th antenna at receiver as channel I, while the \( p' \)-th antenna at the transmitter and the \( q' \)-th antenna at receiver as channel II, a space-time correlation function of two complex fading signals under WSS uncorrelated scattering as following is employed to describe the ST correlation between the two channels above[12]:

\[
\rho_{h_{pq}h_{p'q'}}(\tau) = \frac{E\left[h_{pq}(t)h_{p'q'}^{*}(t-\tau)\right]}{\sqrt{E\left|h_{pq}(t)^2\right|E\left|h_{p'q'}(t)^2\right|}}^{1/2}
\]

\( = E\left[h_{pq}(t)h_{p'q'}^{*}(t-\tau)\right](K+1)\) 

where \( h^*() \) represents the complex conjugate operation, \( E[\cdot] \) represents the statistical expectation.

Therefore, the ST correlation for the first tap and the others can be respectively expressed as

\[
\rho_{h_{pq}h_{p'q'}}(\tau) = \rho_{LOS} + \lim_{i \to \infty} \sum_{i=1}^{2} \rho_{SB_i} \rho_{h_{pq}h_{p'q'}}(\tau)
\]

\[
\rho_{h_{pq}h_{p'q'}}(\tau) = \rho_{SB} \rho_{h_{pq}h_{p'q'}}(\tau) + \rho_{DB}(\tau)
\]

When the time delay \( (\tau = 0) \) or the antenna element spacing is neglected \( (k_p = k_{p'}, k_q = k_{q'}) \), the correlation function can be simplified to corresponding spatial CCF and temporal ACF.

4. Analysis of numerical simulation results

Since theoretical derivation is not able to estimate the channel characteristics directly when the number of scatterers is infinite, parameters can be calculated according to the PDF of VMF in equation (9) to simulate this condition. The method of modified equal area (MMEA)[15] and the PDF of VMF are used to simulate the azimuth angle and elevation angles of effective scatterers, then the angles of SB1, SB2 and SB3 can be obtained by the following expressions:

\[
\alpha_{\beta} = \left(\frac{\alpha_{\beta}}{\beta_{\beta}}\right) = F_{\alpha(\beta)}^{-1}\left(\frac{n_i - 0.25}{N_i}\right)
\]

where \( F_{\alpha(\beta)}^{-1}() \) represents the inverse function of cumulative distribution function (CDF) derived from the PDF of VMF. The other angles such as AAoA and EAoA can also be generated in the same method. The simulation parameters are shown in table 2.

Environmental factor \( k \) dominates the concentration degree of effective scatterer distribution around mean value. Figure 2 depicts the influence of various \( k \) values on the ST correlation of SB1 component, the anisotropy of effective scatterer distribution increases with the augment of \( k \) value. And it turns out that, as \( k \) increases, different antennas on mobile vehicles are more susceptible to scatterers in the same area and mutual interference effects between massive MIMO antenna arrays are stronger. Figure 3 describes the impact of scatterer distribution region on the ST correlation of SB1 component in different \( \alpha_{\beta} \) values, which is the mean azimuth angle of scatterer distribution. The mutual effects among antenna arrays can be minimized when the direction of the antenna element is perpendicular to the direction of scatterer distribution area.
Table 2. The values of simulation parameters.

| Parameters | Values |
|------------|--------|
| $f_c$/ GHz | 5.9    |
| $f_{T_{\text{max}}}$ / Hz, $f_{R_{\text{max}}}$ / Hz | 80.91 |
| D/m       | 300    |
| R$_T$/m, R$_R$/m | 5      |
| $\phi_T$/rad, $\phi_R$/rad | 0      |
| $\theta_T$/rad, $\theta_R$/rad | 0      |
| $k_p$, $k_q$ | 1      |
| $k_p'$, $k_q'$ | 1/2    |
| $N_1$, $N_2$, $N_3$ | 20     |

Figure 2. The relation graph of parameter $k$ and the CCF of SB$_1$.

Figure 3. The relation graph of parameter $\alpha_0$ and the CCF of SB$_1$.

Figure 4 and figure 5 describe the effect of the antenna array direction on ST correlation. Combined with the analysis of figure 3, it can be seen in figure 4 that the monotonicity of the spatial CCF is inversely proportional to $\sin (\theta_T - \alpha_0)$, and the azimuth angle of antenna array and the mean azimuth angle of effective scatterer have a joint impact on spatial CCF, which is consistent with the performance in [12]. Under the same conditions, the closer $(\phi_T, \theta_T)$ is to $(\alpha_0, \beta_0)$, the larger the spatial CCF value. What's more, the spatial information of the antenna array angle should be fully considered when constructing a V2V communication system, for the trend of spatial CCF becomes smoother as the normalized antenna distance decreases. The effects of the antenna array angle at the receiver on ST correlation are depicted in figure 5, where we can see that the antenna array angles at receiver have no significant discrepancy in the influence of the absolute value of the spatial CCF.

In order to verify the validity of the proposed model, we simulate and analyze the ST correlation in three scenarios including highway scene, urban road scene and tunnel scene. For tunnel scene, the radio wave scattering is mainly composed of the inner wall of tunnel characterized by the ellipsoid model. By synthesizing the analysis of this paper and the data in [12], simulation parameters are set as shown in table 3, where scenario I to III represents highway scene, urban road scene, and tunnel scene respectively.
Figure 4. The relation graph of transmitter antenna parameters and the CCF of SB1.

Figure 5. The relation graph of receiver antenna parameters and the CCF of SB1.

Table 3. Main parameters in different scenarios.

| Scenario      | $K$  | $\eta_{SB1}$ | $\eta_{SB2}$ | $\eta_{SB3}$ | $\eta_{DB}$ | $k_1$ | $k_2$ | $k_3$ |
|---------------|------|---------------|---------------|---------------|--------------|-------|-------|-------|
| Scenario I    | 3.942| 0.371         | 0.212         | 0.402         | 0.015        | 4.5   | 1.3   | 4.5   |
| Scenario II   | 1.062| 0.142         | 0.142         | 0.085         | 0.631        | 0.55  | 1.21  | 6.5   |
| Scenario III  | 0.365| 0.025         | 0.025         | 0.908         | 0.042        | 3.6   | 3.6   | 6.7   |

Figure 6 and figure 7 describe the ST correlation of the proposed model in different scenarios. Figure 6 shows that different scenarios have a significant impact on the temporal ACF of the proposed model, and all the temporal ACFs in three scenarios appear to have time-varying characteristics. Figure 7 shows that both spatial CCF and temporal ACF curves have a similar trend, the spatial CCF in the three scenarios decreases as the increase of normalized antenna distance, moreover, the spatial CCF curves in scenario III fluctuate more sharply owing to the fact that it is more susceptible for spatial CCF to antenna elements interval than the temporal ACF curves. Compared with 2D model, the 3D model is more sensitive to the time delay and the normalized antenna interval in different scenarios because 2D model is not able to capture the information of angle and distance along vertical dimension.
5. Conclusion
This paper proposed a generic 3D GBSM channel model for massive MIMO V2V wireless communication. We introduce vehicle movement and antenna array into the model, then employ the spatial angle information of both to establish spatial CCF and temporal ACF expressions, which make contribution to analyze the impact of various parameters, such as environmental factors, scatterer distribution and antenna angle, on space-time correlation.

Our model are simulated in different environments including expressway, urban road and tunnel scenarios. The simulation results show that environmental factors, scatterer locations and normalized antenna interval have a joint impact on the spatial CCF, whose value increases as the antenna angle of transmitter approaches to the distribution angle of the scatterer. Single-bounced and double-bounced component as well as the anisotropy degree of scatterer distribution act on temporal ACF jointly, and NLOS components of channel becomes more sensitive to time delay with the scatterer distribution getting richer. Compared with 2D model, 3D model can depict vertical dimensions information and restore wireless communication in real-world physical scenarios more realistically. Consequently, the proposed model is able to investigate the impact of the communication scenarios on channel statistics and capture the non-stationarity of V2V channel.

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