

Postprint: Channel Modeling and Capacity Analysis for V2V Communications in Street Environments

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Abstract

The performance of Vehicle-to-Vehicle (V2V) communication systems depends on the characteristics of wireless channels; therefore, it is particularly important to adopt an appropriate model to characterize the communication channel. For vehicular communication channels in a 3D scattering street environment, considering scatterers such as tall buildings and trees on both sides of the road, with both transmitter and receiver ends in motion and employing multiple antenna technology, an elliptical cylinder scattering model is established. Using geometric analysis methods, the temporal autocorrelation function (ACF) and spatial cross-correlation function (CCF) are derived, the differences in ACF and CCF under Line-of-Sight (LOS) and Non-Line-of-Sight (NLOS) conditions are compared, and the feasibility of the simulation method is verified; the differences in channel capacity under different antenna arrays and scattering environments are investigated, highlighting the superior accuracy of the 3D model. The consistency between measurement results and theoretical analysis demonstrates the usability of the 3D model proposed in this paper, thereby broadening research on vehicular communication systems.

Full Text

Preamble

Street Environment V2V Communication Channel Modeling and Capacity Analysis

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Abstract: The performance of vehicle-to-vehicle (V2V) communication systems depends on the characteristics of wireless channels, making it crucial to employ appropriate models for channel characterization. This paper investigates vehicular communication channels in three-dimensional (3D) street scattering environments. Considering scatterers such as tall buildings and trees along roadsides, and accounting for mobility at both transmitter and receiver, we establish an elliptical cylinder scattering model using multi-antenna technology. Through geometric analysis, we derive the time auto-correlation function (ACF) and spatial cross-correlation function (CCF), comparing ACF and CCF differences between line-of-sight (LOS) and non-line-of-sight (NLOS) scenarios to verify the feasibility of our simulation approach. We examine channel capacity variations across different antenna arrays and scattering environments, demonstrating the superior accuracy of the 3D model. The consistency between measurement results and theoretical analysis confirms the applicability of our proposed 3D model, thereby expanding research horizons for vehicular communication systems.

Keywords: V2V communication; channel model; correlation functions; channel capacity

0 Introduction

The era of big data, 5G, and autonomous driving is approaching, where rapid transmission of traffic information can improve transportation efficiency and reduce accident rates. Consequently, research on vehicle-to-vehicle (V2V) communications has gained increasing attention. Compared with conventional channels, V2V communication channels exhibit greater dynamic behavior and more severe fading due to complex driving environments. Therefore, establishing accurate models tailored to specific scattering environments and enhancing channel transmission efficiency are particularly important for V2V communications [1]. Multiple-input multiple-output (MIMO) technology can improve communication system performance, and its application to V2V communications represents a current research focus [2].

Channel models vary depending on the geometric scattering environment. Common models include the single-ring model [1], double-ring model [2], and elliptical model [3], with further distinctions between two-dimensional (2D) [1-3] and three-dimensional (3D) [4-7] variants. Real-world scattering environments contain nearly infinite scatterers, which can be categorized as isotropic or non-isotropic. Isotropic environments typically employ uniform distributions [6], while non-isotropic environments may use Von Mises, Gaussian, or Laplacian distributions [5], with the appropriate distribution selected based on actual environmental conditions. V2V communication environments typically include street scenarios [8], highways [9,10], and tunnels [11,12], making the study of signal scattering properties in these contexts highly significant.

When the elevation angle of signal propagation can be neglected in scattering environments, a 2D channel model should be established for computational simplicity. However, when scatterer heights cannot be ignored, a 3D model becomes necessary for accurate channel characterization [7]. Reference [3] only considered correlation functions and channel capacity for elliptical channels in 2D mode, neglecting elevation angle effects. This paper addresses the significant impact of roadside building and tree heights on signal propagation direction in street environments by incorporating elevation angles and establishing a sophisticated 3D model.

Focusing on low-traffic street environments, we ignore mobile scatterers and consider only static scatterers, employing a 3D elliptical cylinder scattering model to characterize V2V channels. Channel ACF, CCF, and capacity are critical metrics for communication system performance. Based on MIMO technology, this paper investigates differences in MIMO channel ACF and CCF between LOS and NLOS scenarios, verifies simulation method feasibility, and explores how factors such as antenna array configuration and scattering environment affect channel capacity through simulation analysis. Finally, we validate our theoretical framework with measured data.

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1 Elliptical Cylinder Scattering Model

The complex gain of the MIMO channel reference model in this paper can be described as a matrix $\mathbf{H}(t) = [h_{lk}(t)]_{L \times K}$. At carrier frequency f_C , the complex channel gain from the l -th transmit antenna element to the k -th receive antenna element is $h_{lk}(t)$. In LOS conditions, this consists of a line-of-sight component and a single-scattering component. The channel follows a Rice distribution under LOS conditions and a Rayleigh distribution under NLOS conditions.

Figure 1 [Figure 1: see original paper] illustrates the 3D street elliptical cylinder model considered in this paper. The ellipse on the ground plane has semi-major axis a and semi-minor axis b , with focal length f . The transmitter (TX) and receiver (RX) represent mobile terminals located at the ellipse's foci, separated by distance D (where $D = 2f$). The TX velocity and direction are \mathbf{v}_T and α_{v_T} , respectively, while the RX velocity and direction are \mathbf{v}_R and α_{v_R} . Both TX and RX are equipped with uniform linear antenna arrays comprising L and K antenna elements, respectively. The array orientations relative to the x-axis are θ_T and θ_R , with element spacings d_T and d_R .

The elliptical cylinder surface contains infinitely many scatterers. S_n denotes the n -th static scatterer (typically buildings, trees, or signs; $0 < n \leq N$, with

$N \rightarrow \infty$). Signals transmitted from TX scatter off S_n and are received at RX. The azimuth angle of departure (AAOD) is α_n^T and the elevation angle of departure (EAOD) is β_n^T . Similarly, the azimuth angle of arrival (AAOA) is α_n^R and the elevation angle of arrival (EAOA) is β_n^R . The distance between the l -th transmit antenna element A_l and S_n is d_{ln} , while the distance between S_n and the k -th receive antenna element A_k is d_{nk} . The vertical height of S_n above the horizontal plane is h_n , with l_{tn} and l_{nr} representing the horizontal distances from TX to S_n and from S_n to RX, respectively. The coordinate system uses TX as the origin, RX on the positive x-axis, and the x-y plane as the horizontal plane.

In this model, the departure and arrival angles are correlated: once the arrival azimuth α_n^R and elevation β_n^R are determined, the departure azimuth α_n^T (dependent only on α_n^R) and departure elevation β_n^T (dependent on both α_n^R and β_n^R) can be obtained.

Since scatterer distributions in real environments are not perfectly uniform, we employ the von Mises distribution [3] for azimuth angles and cosine distribution [6] for elevation angles:

$$p(\alpha_n^R) = \frac{\exp[\kappa \cos(\alpha_n^R - \mu)]}{2\pi I_0(\kappa)}, \quad \alpha_n^R \in [0, 2\pi)$$

$$p(\beta_n^R) = \begin{cases} \frac{\pi}{4\beta_m} \cos\left(\frac{\pi\beta_n^R}{2\beta_m}\right), & |\beta_n^R| \leq \beta_m \\ 0, & \text{otherwise} \end{cases}$$

where β_m represents the maximum elevation angle, μ denotes the mean azimuth angle, and κ controls the concentration around the mean. Larger κ values indicate stronger concentration. When $\kappa = 0$ and $\beta_m = 0$, the environment represents isotropic scattering.

3 Numerical Simulation and Analysis of Correlation Functions

Based on the derived correlation function formulas, this section presents simulation analysis for both NLOS and LOS channel correlations. We employ the Modified Method of Equal Areas (MMEA) to simulate signal azimuth and elevation angles [14], solving the following equations to obtain the required simulation angles:

$$\int_{-\pi}^{\alpha_n} p(\alpha) d\alpha = \frac{2n-1}{2N}, \quad n = 1, 2, \dots, N$$

The space-time correlation function (ST-CF) of the channel complex gain can be obtained through:

$$r_{lk,l'k'}(\tau, d_T, d_R) = E\{h_{lk}(t) \cdot h_{l'k'}^*(t + \tau)\}$$

which decomposes into LOS and scattering components:

$$r_{lk,l'k'}(\tau, d_T, d_R) = r_{lk,l'k'}^{LOS}(\tau, d_T, d_R) + r_{lk,l'k'}^S(\tau, d_R)$$

The time auto-correlation function (ACF) is obtained by setting the antenna spacing $d_T = d_R = 0$ in the time-space correlation function formulas, while the spatial cross-correlation function (CCF) is obtained by setting the time interval $\tau = 0$.

Simulation parameters are: Rice factor $C_r = 3$, carrier frequency $f_0 = 5.9 \times 10^9$ Hz, $a = 100$ m, $b = 80$ m; θ_T and θ_R are both 45° , both vehicles travel in the 0° direction with $v_T = v_R = 5$ m/s (maximum Doppler frequency $f_{max} = 100$ Hz); $\kappa = 10$, AOA mean $\mu_R = 45^\circ$, maximum elevation angle $\beta_m = 20^\circ$ [15] (unless otherwise specified, all subsequent simulations use these parameters).

Figure 2 [Figure 2: see original paper] shows the channel temporal correlation function under NLOS conditions. The correlation exhibits oscillatory behavior for small normalized time intervals, gradually approaching zero as the time interval increases.

Figure 3 [Figure 3: see original paper] presents the channel temporal correlation function under LOS conditions with identical parameters and Rice factor $C_r = 0$. The oscillatory pattern resembles Figure 2, but the final value is not zero. Reference [6] similarly shows LOS ACF final values around 0.7, consistent with Figure 3. This demonstrates that with LOS propagation, the channel maintains temporal correlation even for large time intervals.

Figures 4 [Figure 4: see original paper] and 5 [Figure 5: see original paper] show the spatial correlation functions between channels 11 and 22 for reference models under NLOS and LOS conditions, respectively. Similar to the ACF, spatial correlation between two channels under LOS does not approach zero with increasing antenna spacing, indicating that significant correlation persists even for large antenna separations in LOS scenarios, unlike NLOS cases.

To verify simulation method feasibility, we present the CCF simulation function and error between reference and simulation models under NLOS conditions (Figures 6 [Figure 6: see original paper] and 7 [Figure 7: see original paper]). Figure 7 reveals that the maximum error remains below 0.06, an acceptable tolerance, confirming that the MMEA method is suitable for simulating this model and will be used in subsequent sections.

4 Channel Capacity Analysis

Channel capacity of MIMO communication systems, measured in bits/s/Hz, reflects data transmission capability. To maximize capacity, power is typically allocated equally across antenna elements. The capacity is calculated as:

$$C = \log_2 \det \left(\mathbf{I}_K + \frac{\rho}{L} \mathbf{H}(t) \mathbf{H}^H(t) \right)$$

where L and K are the numbers of transmit and receive antennas, \mathbf{I}_K is the K -dimensional identity matrix, ρ represents signal-to-noise ratio (SNR), and \mathbf{H} is the channel gain matrix ($L \times K$) using Equation (3) for NLOS scenarios. Numerous factors affect channel capacity, including antenna element spacing, array orientation, antenna count, SNR, and Rice factor. We investigate these influences to maximize capacity in practical systems.

Reference [16] conducted capacity measurement experiments in urban low-traffic scenarios (similar to our setting) using 2×2 antenna arrays with 0.5 m spacing and 20 dB SNR. Table 1 and Table 2 present measured capacity values from [16] for campus and shopping street scenarios, respectively, in bps/Hz.

Table 1: Measured Channel Capacity in Campus Scenario

Vehicle Distance	10 m	15 m
Capacity (bps/Hz)	8.7	8.67

Table 2: Measured Channel Capacity in Shopping Street Scenario

Vehicle Distance	10 m	15 m
Capacity (bps/Hz)	8.7	8.67

Figure 8 [Figure 8: see original paper] illustrates the impact of antenna element spacing on capacity for a 2×2 array with 17 dB SNR. As spacing d_T and d_R increase from zero, capacity grows, but beyond a certain value, further spacing yields negligible improvement. This matches the 2D elliptical model behavior in [3] and aligns with practical expectations.

Figure 9 [Figure 9: see original paper] shows the effect of antenna element count on capacity with 0.2 m spacing. Capacity increases with both SNR and antenna quantity. Under NLOS conditions from Table 1, measured capacities are 8.7 and 8.67 bps/Hz for 10 m and 15 m vehicle distances, respectively. Our simulation under equivalent conditions yields approximately 10 bps/Hz, with the discrepancy arising from more complex real scattering environments and larger inter-vehicle distances in our simulation compared to [16].

Figure 10 [Figure 10: see original paper] demonstrates the impact of antenna array orientation for a 2×2 array with 17 dB SNR and 0.2 m spacing. Using uniform linear arrays, we investigate orientation effects. Capacity is minimized when the receive array orientation $\theta_R = 45^\circ$. The transmit array orientation $\theta_T = 5^\circ$ shows slightly lower capacity than other orientations. When $\theta_R = 45^\circ$, we obtain $\theta_R - \mu_R = 0$ (where μ_R is the AAOA mean relative to the receiver, previously set to 45°). When $\theta_T = 5^\circ$, $\theta_T - \mu_T \approx 0$ (the AAOA mean relative to the transmitter μ_T is approximately 5°). This analysis indicates that capacity decreases as array orientation aligns more closely with the scatterer center direction.

Beyond antenna effects, environmental characteristics significantly impact capacity. Figure 11 [Figure 11: see original paper] shows the Rice factor C_r influence using a 1×1 array with 17 dB SNR. Capacity with $C_r = 0$ (NLOS) is slightly lower than with $C_r = 2$ or 5. The measured data in Tables 1 and 2 consistently show marginally higher capacity in LOS versus NLOS scenarios, confirming our simulation analysis and indicating that LOS conditions favor capacity maximization.

Figure 12 [Figure 12: see original paper] presents the maximum elevation angle β_m effect. Elevation angle introduction represents the key feature distinguishing elliptical cylinder channels from 2D elliptical channels and provides greater realism. For $\beta_m = 1^\circ, 10^\circ$, and 20° , larger β_m yields higher capacity, though the increase is modest compared to antenna array modifications. The $\beta_m = 1^\circ$ case approximates 2D elliptical scattering, demonstrating that 2D channel models underestimate capacity. This conclusion aligns with [17], where 3D double-ring models also show higher capacity than 2D models.

5 Conclusion

This paper employs a 3D elliptical cylinder scattering model to characterize V2V channels in low-traffic street environments. Using geometric analysis, we derive relationships between departure and arrival angles. MMEA-based simulations show close agreement between simulated and reference model ACF/CCF, validating the method's applicability. The analysis reveals that LOS channels maintain certain temporal and spatial correlations. V2V channel capacity is influenced by antenna spacing, antenna count, SNR, and array orientation, which must be considered in system optimization. Combined with measured data, our analysis shows greater capacity under LOS conditions. Finally, comparing 2D and 3D model capacities demonstrates that 2D elliptical scattering models underestimate capacity, confirming the validity of our 3D approach. The accurate characterization of elliptical cylinder scattering channels and analysis of ACF, CCF, and capacity provide a foundation for V2V communication channel research and transmission performance evaluation.

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