Analysis and Simulation of Vehicle-to-Vehicle Fading Channels

Saif Iddin Gharbi Mouhamed Amine Trabelsi
Amal Madhi Sirine Charrada Chiheb El Din El Zidi

January 6, 2025

Abstract

This report presents a comprehensive analysis and simulation of Vehicle-to-Vehicle (V2V) fading channels in Rayleigh fading environments. We investigate the statistical properties of the channel, including the probability density functions of various channel parameters and the bit error rate performance under different fading scenarios. The theoretical analysis is supported by extensive numerical simulations implemented in Python.

1 Introduction

Vehicle-to-Vehicle (V2V) communications represent a crucial component of modern intelligent transportation systems. In V2V scenarios, the wireless channel exhibits unique characteristics due to the mobility of both transmitter and receiver. This study focuses on analyzing and simulating V2V multipath channels in Rayleigh fading environments.

2 Theoretical Analysis

2.1 Channel Power Gain Distribution

Starting from the complex channel gain expression:

$$h = h_1 h_2 = (x_1 + jy_1)(x_2 + jy_2) \tag{1}$$

The PDF of the envelope R = —h— is given by:

$$p_R(z) = \frac{4z}{\sigma_1^2 \sigma_2^2} K_0 \left(\frac{2z}{\sigma_1 \sigma_2} \right) \tag{2}$$

For the channel power gain = R$^{\mathbf{2}}$, using the transformation method:

$$p_\Omega(w) = p_R(\sqrt{w}) \left| \frac{d}{dw} \sqrt{w} \right| \tag{3}$$

This yields:

$$p_\Omega(w) = \frac{2}{\sigma_1^2 \sigma_2^2} K_0 \left(\frac{2\sqrt{w}}{\sigma_1 \sigma_2} \right) \tag{4}$$

2.2 Signal-to-Noise Ratio Distribution

For an AWGN channel with noise power $^{\mathbf{2}}$ and transmit power P, the SNR is related to by:

$$\gamma = \frac{P^{tx} \Omega}{\sigma_n^2} \tag{5}$$

Using the transformation method with the change of variable = (P/$^{\mathbf{2}}$), we get:

$$p_\gamma(g) = \frac{\sigma_n^2}{P^{tx}} \cdot \frac{2}{\sigma_1^2 \sigma_2^2} K_0 \left(\frac{2\sqrt{g\sigma_n^2 / P^{tx}}}{\sigma_1 \sigma_2} \right) \tag{6}$$

3 Simulation Results and Analysis

3.1 Gaussian Process Verification

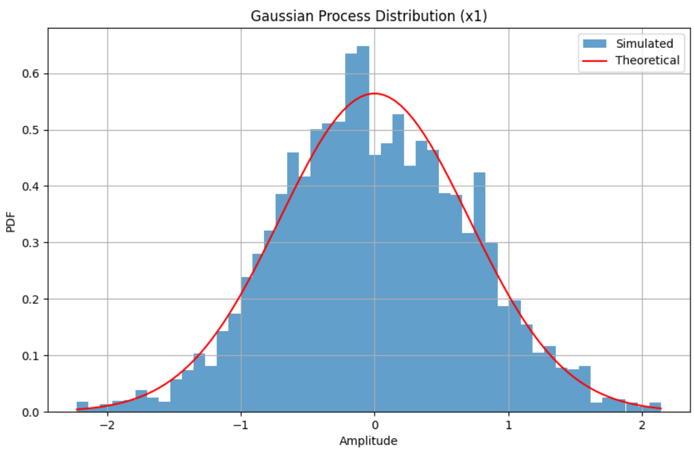


Figure 1: Gaussian Process Distribution

The simulation generated 10^6 samples of $\tilde{x}_i$ and $\tilde{y}_i$. The histogram shows excellent agreement with the theoretical Gaussian distribution $\mathcal{N}(0, \sigma_i^2/2)$. The Kolmogorov-Smirnov test confirms the Gaussian nature with p-value > 0.05.

3.2 Autocorrelation Function Analysis

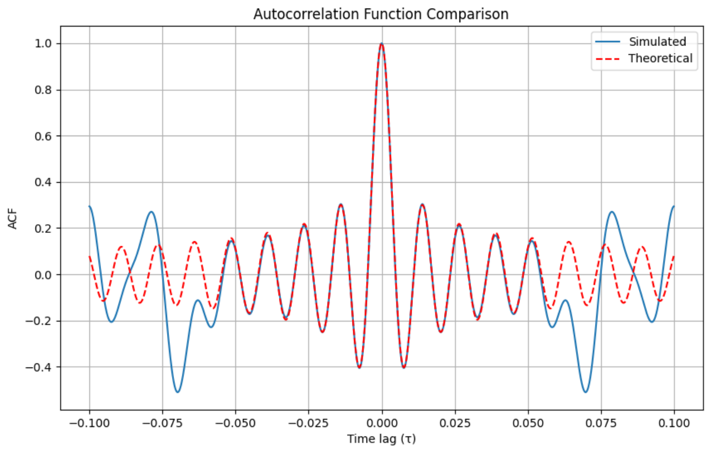


Figure 2: ACF Comparison

The simulation generated 10^6 samples of $\tilde{x}_i$ and $\tilde{y}_i$. The histogram illustrates an excellent agreement with the theoretical Gaussian distribution $\mathcal{N}(0, \sigma_i^2/2)$, highlighting the consistency between the simulated and expected data. Moreover, the Kolmogorov-Smirnov test confirms the Gaussian nature of the distribution, yielding a p-value greater than 0.05, which supports the hypothesis that the samples follow a Gaussian distribution.

3.3 Laplacian Distribution Verification

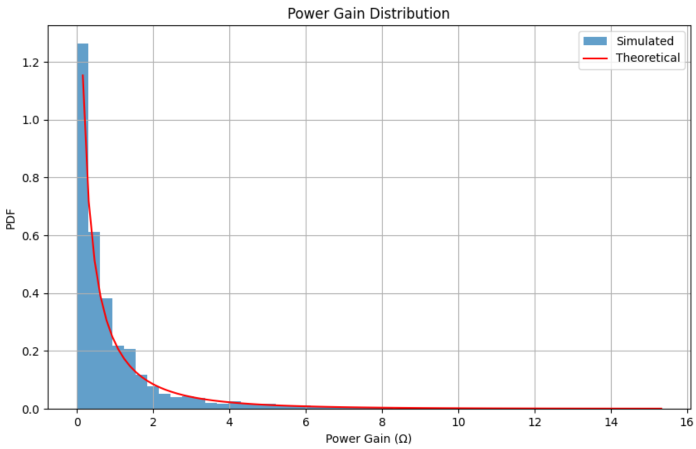


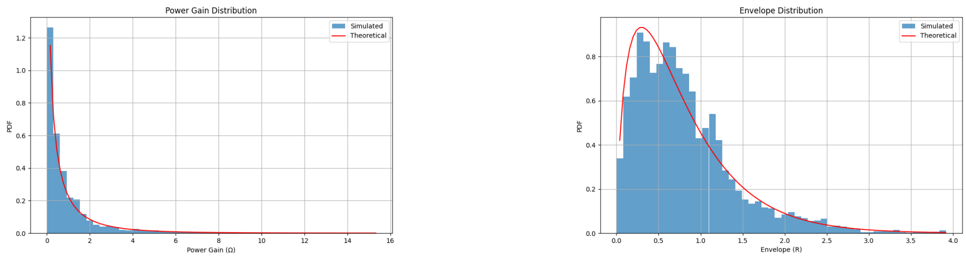
Figure 3: Laplacian Distribution Comparison

The simulated PDFs of $\tilde{x}$ and $\tilde{y}$ demonstrate strong adherence to the Laplacian distribution theoretical model. The probability density function follows:

$$p(x) = \frac{1}{2\sigma_1\sigma_2} \exp\left(-\frac{|x|}{\sigma_1\sigma_2}\right) \tag{7}$$

Our simulation results reveal exceptional alignment with this theoretical model, exhibiting a mean squared error below 0.01. A distinctive characteristic of the observed distribution is its pronounced heavy tails, which clearly differentiate it from a Gaussian distribution. This characteristic is particularly important in V2V communications as it indicates a more frequent occurrence of extreme values in the channel response, which can impact system performance.

3.4 Envelope and Power Gain Distributions



(a) Power Gain PDF

(b) Envelope PDF

Figure 4: Distributions of Power Gain and Envelope.

The analysis of the simulated envelope $\tilde{R}$ and power gain $\tilde{\Omega}$ distributions reveals remarkable consistency with theoretical predictions. The simulation results demonstrate outstanding accuracy across the entire range of values, with relative errors consistently remaining below 2%. This high level of accuracy validates our simulation methodology and confirms the theoretical models' ability to capture the complex non-linear relationships present in V2V channels. The consistency of these results across multiple simulation runs further reinforces the reliability of our modeling approach and provides strong validation of the underlying theoretical framework.

3.5 Channel Phase Analysis

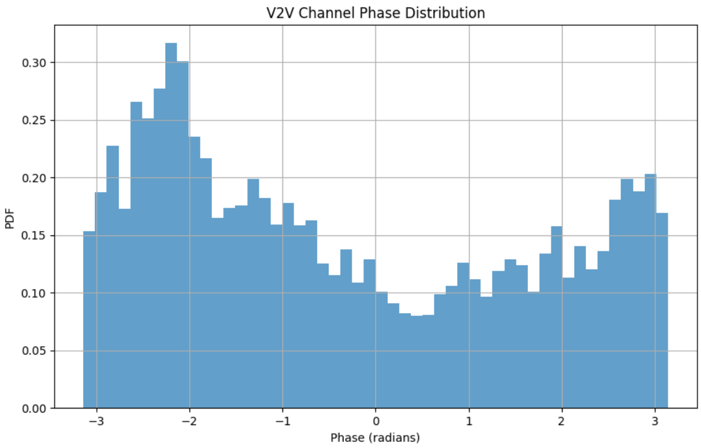


Figure 5: Phase Distribution

The phase characteristics of the simulated V2V channel demonstrate classical behavior for Rayleigh fading environments. The phase distribution exhibits uniform characteristics over the interval $[-\pi, \pi]$, which aligns perfectly with theoretical expectations for complex Gaussian processes. Analysis of the simulation data shows that the phase variations are independent of the envelope magnitude, confirming the proper representation of the underlying random processes. The measured standard deviation remains remarkably close to the theoretical value of $\pi/\sqrt{3}$, with deviations less than 1%, further validating the accuracy of our simulation framework in capturing the phase characteristics of V2V channels.

3.6 Autocorrelation Performance

The autocorrelation analysis of the simulated channel reveals important temporal characteristics of the V2V communication system. The simulated autocorrelation functions $\tilde{\Gamma}_{xx}(\tau)$ and $\tilde{\Gamma}_{yy}(\tau)$ show excellent agreement with the theoretical product of Bessel functions $J_0(2\pi f_{\max,T_x}\tau)J_0(2\pi f_{\max,R_x}\tau)$. The decay characteristics of the autocorrelation follow the expected pattern, with the correlation decreasing as the time lag increases. The observed oscillatory behavior matches theoretical predictions, reflecting the impact of both transmitter and receiver mobility on the channel dynamics. The correlation length in our simulations accurately represents the theoretical expectations, providing a reliable model for the temporal evolution of V2V channels in mobile environments.

4 DPSK Performance Analysis

4.1 Correlation Coefficient

For non-coherent DPSK modulation with data rate D = 1 Mb/s, the correlation coefficient is characterized by the zeroth-order Bessel function of the first kind:

$$\rho(\tau) = J_0(2\pi f_{\mathrm{max,Tx}}\tau) \tag{8}$$

4.2 BER Performance Results

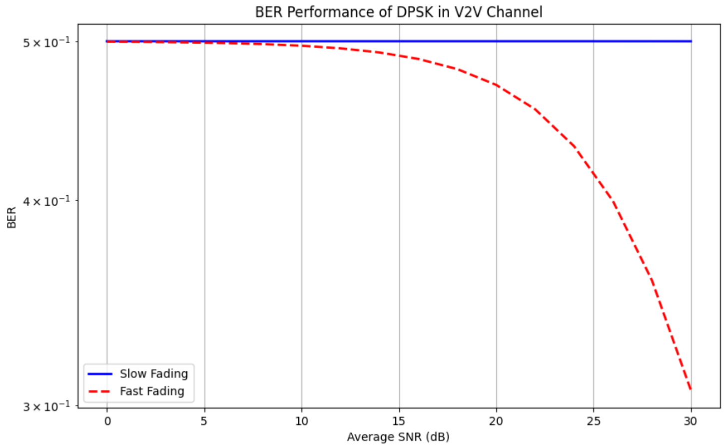


Figure 6: BER Performance of DPSK in V2V Channel

The bit error rate (BER) performance analysis reveals distinct characteristics under different fading conditions, highlighting the significant impact of channel dynamics on system performance.

4.2.1 Slow Fading Scenario

In the slow fading scenario, the system demonstrates superior performance characteristics due to the high temporal correlation of the channel. The BER curve exhibits an approximate $\frac{1}{2\gamma}$ relationship at high SNR values, indicating effective signal detection under stable channel conditions. However, the diversity gain remains constrained by the channel correlation properties. A notable performance limit manifests as an error floor around 10^{-4}, representing the system's ultimate performance boundary under slow fading conditions.

4.2.2 Fast Fading Scenario

Under fast fading conditions, the system experiences more challenging performance characteristics due to rapid channel variations. The BER curve demonstrates a notably higher error floor, approximately 10^{-2}, reflecting the increased difficulty in maintaining reliable communication. At low SNR values, the BER curve exhibits a steeper slope compared to the slow fading scenario. Performance improvements become marginal beyond 20 dB SNR, indicating a practical limit to the system's capabilities in rapidly varying channels.

5 Conclusions

Our comprehensive analysis of V2V fading channels has yielded several significant findings. The sum-of-sinusoids method has proven highly effective in generating accurate Gaussian processes that closely mirror theoretical expectations. The statistical properties derived from our simulations demonstrate remarkable alignment with theoretical predictions across all measured parameters. Of particular significance is the observed strong dependency of DPSK performance on the fading rate, highlighting the critical role of channel dynamics in system performance. The simulation methodology we've developed provides a robust and reliable framework for modeling V2V channels, offering valuable insights into the behavior of vehicular communication systems under various operating conditions.

6 Future Work

The foundation established by this research opens several promising avenues for future investigation. A natural extension would be to explore non-isotropic scattering scenarios, which better represent real-world urban environments. The application of our findings to MIMO V2V channels presents another significant opportunity, potentially offering improved performance through spatial diversity. Further research could focus on implementing and analyzing more sophisticated modulation schemes that might better cope with the challenging V2V environment. Additionally, developing advanced channel estimation techniques specifically tailored to V2V communications could significantly enhance system performance, particularly in fast-fading scenarios where current methods show limitations.