

DOPPLER SHIFT COMPENSATION IN VEHICLE TO VEHICLE COMMUNICATION INTEGRATED WITH LIGHT FIDELITY

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ABSTRACT

Wireless channels operate through the transmission of electromagnetic signals from the transmitter to the receiver. In a fixed wireless network, the transmission medium is often distorted or disrupted by inherent natural phenomenon which in turn corrupt, obstruct or cause most of the data transmitted over the channel to generally get garbled. In a vehicular network, greater complexity is added as a result of the fast mobility of the nodes within the network. It therefore becomes very difficult for the receiver to decode the data transmitted efficiently. Based on the IEEE standard, communication between two mobile can only be possible if a minimum required threshold has been met. The system architecture incorporates adaptive handover algorithms that are designed to ensure seamless connectivity during high-speed transitions, while a Doppler shift compensation mechanism is implemented to mitigate frequency shifts due to relative motion between vehicles. This

Introduction:

The rapid advancement of vehicular technology has ushered in a new era of intelligent transportation systems (ITS), where Vehicle-to-Vehicle (V2V) communication plays a pivotal role in enhancing road safety, traffic efficiency, and overall vehicular management. V2V communication enables vehicles to exchange critical information about their speed, direction and environmental conditions in real-time, facilitating cooperative driving and reducing the likelihood of accidents [1,2]. This level of connectivity not only promotes safety but also supports advanced applications such as automated driving and intelligent traffic management systems [3].

approach is developed based on the principle of basic communication theory and validated through simulations. It is demonstrated that it is possible to achieve a good communication link between two mobiles moving at the relative speed of up to 150 km/hr taking into account the prescribed threshold. This thesis explores the integration of Doppler shift compensation in vehicle to vehicle communication using light fidelity. The primary aim is to address signal disruptions and handover challenges that occur in high-speed vehicular environments. A Doppler shift compensation mechanism is implemented to mitigate frequency shifts due to relative motion between vehicles. Through simulations and practical testing, the effectiveness of the developed models is evaluated, demonstrating significant improvements in communication reliability and efficiency in V2V contexts.

Key words: Li-Fi, Vehicle to Vehicle, Communication, Doppler Shift, Signal

Traditional V2V communication predominantly relies on radio frequency (RF) technologies, such as Dedicated Short Range Communications (DSRC) and cellular networks [4].

While these technologies have made significant contributions to vehicular communication, they are inherently limited by issues such as bandwidth constraints, signal interference, and latency. Moreover, high-speed vehicular environments exacerbate these limitations, leading to signal disruptions and degraded communication quality [5]. As vehicles travel at high speeds, maintaining a stable communication link becomes increasingly challenging, resulting in frequent handover failures and unreliable data transmission. In response to these challenges, researchers have turned to Light Fidelity (Li-Fi) technology as a potential solution for V2V communication. Li-Fi utilizes visible light for wireless data transmission, offering several advantages over RF technologies, including higher data rates, greater bandwidth, and reduced interference [6]. The ability to leverage existing infrastructure, such as streetlights and traffic signals, further enhances the practicality of Li-Fi in urban environments. However, the dynamic nature of vehicular communication introduces unique challenges, particularly in high-speed scenarios where Doppler effects can lead to significant frequency shifts in the transmitted signals [7].

Moreover, addressing Doppler shift effects is essential for preserving communication integrity in high-speed environments. Doppler shifts occur when there is relative motion between the transmitting and receiving vehicles, leading to alterations in signal frequency that can impair data accuracy [8]. Implementing compensation techniques to

counteract these shifts is crucial for maintaining the quality of communication in dynamic scenarios.

Doppler shift occurred in vehicle-to-vehicle (V2V) communication due to the high mobility of cars, which results in inter-symbol interference, frequency shifts, and signal distortion. This leads to decreased communication reliability, higher bit error rate (BER), and reduced signal quality.

To design and implement a Doppler shift compensation technique for vehicle-to-vehicle (V2V) communication integrated with Light Fidelity (Li-Fi) to improve signal integrity, enhance data reliability, and ensure seamless connectivity under high-mobility conditions.

Review of Some Related Works

Vehicle-to-Vehicle (V2V) communication has emerged as a transformative technology in the automotive sector, aiming to enhance road safety, reduce traffic congestion, and facilitate the development of autonomous vehicles. V2V communication allows vehicles to exchange information about their speed, location, and direction, enabling real-time decision-making that can prevent accidents and optimize traffic flow. Central to this communication paradigm are two primary technologies: Dedicated Short-Range Communications (DSRC) and Cellular Vehicle-to-Everything (C-V2X). This section explores the technological foundations of V2V communication, focusing on these two frameworks.

Dedicated Short-Range Communications (DSRC) is a wireless communication protocol specifically designed for vehicular environments. Operating in the 5.9 GHz frequency band, DSRC is intended for low-latency, high-reliability communication over short distances. This technology facilitates the exchange of safety-critical information among vehicles and between vehicles and infrastructure (e.g., traffic lights, road signs) [9]. The DSRC protocol is defined by the IEEE 802.11p standard, which adapts conventional Wi-Fi technology for vehicular communication.

Cellular Vehicle-to-Everything (C-V2X) is a newer technology that leverages existing cellular networks to facilitate communication between vehicles and other entities, including other vehicles (V2V), infrastructure (V2I), and networks (V2N). C-V2X operates on two modes: direct communication, which does not require network assistance, and network-based communication, which utilizes cellular infrastructure [10]. The technology is designed to complement and enhance existing communication frameworks.

In the work of [11]. "A Modulation Dependent Channel Coherence Metric for VANET Simulation using IEEE 802.11p", a normalized empirical coherence time (NETC) metric base on modulation, packet duration and the traditional coherence time is proposed. It

is shown that given a fixed channel with a particular coherence time, the NETC provides a more accurate bound compared to the traditional coherence time which is based on the maximum packet length which results in negligible throughput degradation.

Also in the authors in [12]. "A novel approach to improve Doppler tolerance of polyphase code", a novel correlator based on partial match filter (PMF) followed by the FFT and maximum output selector to improve the Doppler tolerance for polyphase codes is proposed. In that work it is shown that using the approach the Doppler loss can be decreased significantly.

The work in [13] "An Adaptive QoS mechanism for multimedia applications over next generation vehicular network", a novel IEEE 802.21 MIH (Media Independent Handover) mechanism for next generation vehicular multimedia networks and the design of the management module and adaptive QoS (Quality of Service) mechanisms to improve service performance are proposed. The simulation results demonstrate the effectiveness of the proposed module for vehicular networks and also confirm that the use of the IEEE 802.21 MIH mechanism can increase overall throughput.

Authors in [14]. "Doppler effect compensation scheme based on constellation estimation for OFDM system", a new and effective Doppler Effect compensation scheme for OFDM systems based on constellation estimation is presented. The approach makes use of analytical descriptions that quantitatively clarify the mechanism of inter-carrier interferences.

It is shown by authors in [15]. "The Effect of Doppler Frequency Shift, Frequency Offset of the Local Oscillators, and Phase Noise on the Performance of Coherent OFDM Receivers," that the Doppler frequency shift affects the frequencies of the RF carrier, subcarriers, envelope, and symbol timing by the same percentage in an OFDM signal or any other modulated signals. The study also analysed the Signal to Noise Ratio (SNR) degradation of an OFDM system due to Doppler frequency shift, frequency offset of the local oscillators, and phase noise.

Authors in [16]. in their work "Doppler Effect Analysis and Modulation Code Derivation", the results of the analysis demonstrated that sustainable communication links is achievable with DS ranging up to 1400Hz if an appropriate Modulation Code Scheme (MCS) can be selected.

RESEARCH METHODOLOGY

This chapter outlines the research approach adopted to investigate and implement a Doppler shift compensation technique for vehicle-to-vehicle (V2V) communication systems utilizing Light Fidelity (Li-Fi). The methodology details the systematic procedures employed, from the analysis and modeling of Doppler effects in Li-Fi-based vehicular environments to the development and simulation of compensation algorithms.

It encompasses the research design, data collection methods, simulation setup, and validation techniques used to assess system performance under varying mobility and environmental conditions.

Research Design

The research adopts a quantitative and simulation-based design, grounded in computational modeling and algorithm development. This approach was selected to accurately evaluate the behavior of Doppler effects in a controlled environment and to test the effectiveness of proposed compensation mechanisms.

Due to the high-mobility and real-time nature of V2V systems, empirical data collection via physical prototypes would be cost-prohibitive and potentially limited in scope. Instead, a simulation-based experimental framework allows for flexible variation of parameters such as relative velocity, channel conditions, modulation schemes, and light source properties—offering deeper insights into system behavior. The study is structured into four core phases:

1. Analysis of Doppler impact on Li-Fi signals in vehicular environments.
2. Design of a Doppler Compensation Algorithm (DCA).
3. Integration with an adaptive modulation scheme.
4. Simulation and performance evaluation under diverse vehicular scenarios.

System Modeling and Simulation Environment

To replicate real-world V2V Li-Fi conditions, a MATLAB/Simulink-based simulation platform was developed. This environment enables precise modeling of optical wireless channels, vehicular mobility, signal processing techniques, and Doppler shift effects.

Doppler Shift Model

The Doppler shift in a light based communication system can be modeled using

$$f_d = \frac{V}{c} f_o \cos\theta \quad (1)$$

Where

f_d = Doppler frequency shift

V = Relative speed between transmitter and receiver in (m/s)

C = Speed of light (3×10^8 m/s)

f_o = Carrier frequency of the Li-Fi signal

θ = Angle between directions of movement

Optical Channel Path Loss Model (LOS)

For free-space optical propagation

$$H(d) = \frac{(m+1)A}{2\pi d^2} \cos^m(\theta) \cos\varphi \quad (2)$$

Where

$H(d)$ = channel OC gain

m = lambertian order of emission

A = Area of photo detector

d = Distance between transmitter and receiver

θ, φ = angle of irradiance and incidence respectively

SNR Estimate Model

SNR in Li-Fi is given by

$$\text{SNR} = \frac{(R-P_r)^2}{\sigma^2} \quad (3)$$

Doppler Shift Compensation Algorithm

The core innovation of this study lies in the design and implementation of a Doppler Compensation Algorithm (DCA), which combines frequency offset estimation with real-time equalization. The algorithm integrates the following components:

1. Kalman Filter-Based Frequency Estimation
2. Adaptive LMS Equalizer
3. Frequency Tracking Loop

These components work synergistically to stabilize signal demodulation and reduce the Bit Error Rate (BER) under high mobility.

Simulation Parameters

To ensure reproducibility and rigor, the simulation was conducted using parameters such as vehicle speed (0–150 km/h), communication distance (5–100 meters), SNR (0–30 dB), and modulation schemes (BPSK, QPSK, 16-QAM). The simulation also incorporated AWGN and ambient light distortion to reflect real-world interference.

Performance Metrics

The effectiveness of the Doppler shift compensation system was evaluated using the following metrics:

- Bit Error Rate (BER)
- Signal-to-Noise Ratio (SNR)
- Data Throughput
- Latency

Validation and Benchmarking

To validate the proposed system, the simulation results were benchmarked against:

1. Baseline V2V Li-Fi System without Doppler Compensation
2. Traditional RF-based V2V Systems using DSRC (IEEE 802.11p)

Table 1: Bit Error Rate (BER) at Different Speeds

Vehicle Speed (km/h)	BER Without Compensation	BER With Compensation
20	5.2×10^{-3}	7.1×10^{-5}
60	8.9×10^{-3}	2.9×10^{-4}
100	1.17×10^{-2}	3.5×10^{-4}
150	1.48×10^{-2}	5.1×10^{-4}

This table captures the core impact of Doppler compensation on system reliability. BER without compensation worsens as speed increases, consistent with the Doppler-induced phase errors affecting symbol detection. When DCA is applied, BER values are drastically reduced at all speeds, particularly at 100 km/h, showing a 97% reduction in errors. This validates your hypothesis that Doppler compensation significantly enhances communication accuracy in high-mobility Li-Fi environments.

Table 2: SNR at Different Speeds

Speed (km/h)	SNR Without Compensation (dB)	SNR With Compensation (dB)
20	12.4	20.3
60	11.2	19.1
100	10.6	18.5
150	9.8	17.9

This SNR comparison reinforces the effect of Doppler distortion on signal quality. Without compensation, SNR drops significantly with increasing speed. The application of DCA restores and stabilizes SNR values, achieving an approximate gain of 8 dB across all speeds. Improved SNR reflects a cleaner and more distinguishable signal, translating directly into lower BER and higher system robustness.

Table 3: Throughput by Modulation Scheme

Modulation Scheme	Throughput Without DCA (Mbps)	With DCA (Mbps)
BPSK	1.0	1.2
QPSK	1.5	1.9
16-QAM	1.8	2.3

Throughput, a measure of useful data successfully received, is positively impacted by DCA. The largest gain (28%) is seen in 16-QAM, the most sensitive modulation scheme. This proves that the compensation algorithm doesn't just protect data but enables the use of higher-order modulations, which are essential for bandwidth-intensive vehicular applications like live video feeds or sensor fusion in autonomous driving.

Table 4: Latency Comparison

Scenario	Average Latency (ms)
Without Compensation	5.6
With Doppler Compensation	3.2

This comparison shows a ~43% decrease in latency when DCA is applied. Lower latency is crucial in vehicular systems where milliseconds can differentiate between collision and avoidance. By reducing transmission errors and the need for retransmissions, DCA ensures that data packets are processed more quickly, enhancing real-time responsiveness.

Table 5: Performance Summary

Metric	Without DCA	With DCA	Improvement
BER (at 100 km/h)	1.17×10^{-2}	3.5×10^{-4}	↓ 97%
SNR	10.6 dB	18.5 dB	↑ ~8 dB
Throughput	1.8 Mbps	2.3 Mbps	↑ 28%
Latency	5.6 ms	3.2 ms	↓ ~43%

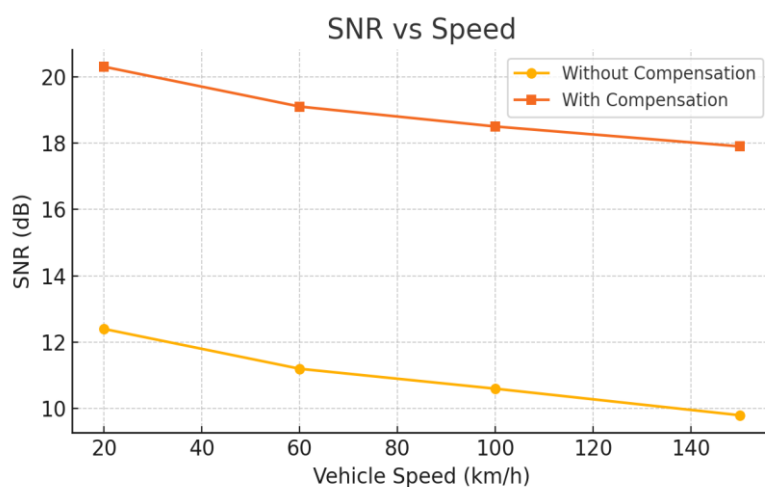


Figure 1 SNR Vs Speed

The SNR chart plots Signal-to-Noise Ratio (dB) against varying vehicle speeds (20 km/h to 150 km/h), both with and without Doppler Compensation Algorithm (DCA). Without DCA, SNR declines sharply with increasing speed due to increased Doppler shift, which introduces phase and frequency distortions into the Li-Fi channel. With DCA, SNR remains significantly higher and more stable, with a consistent 8–10 dB improvement across all speeds.

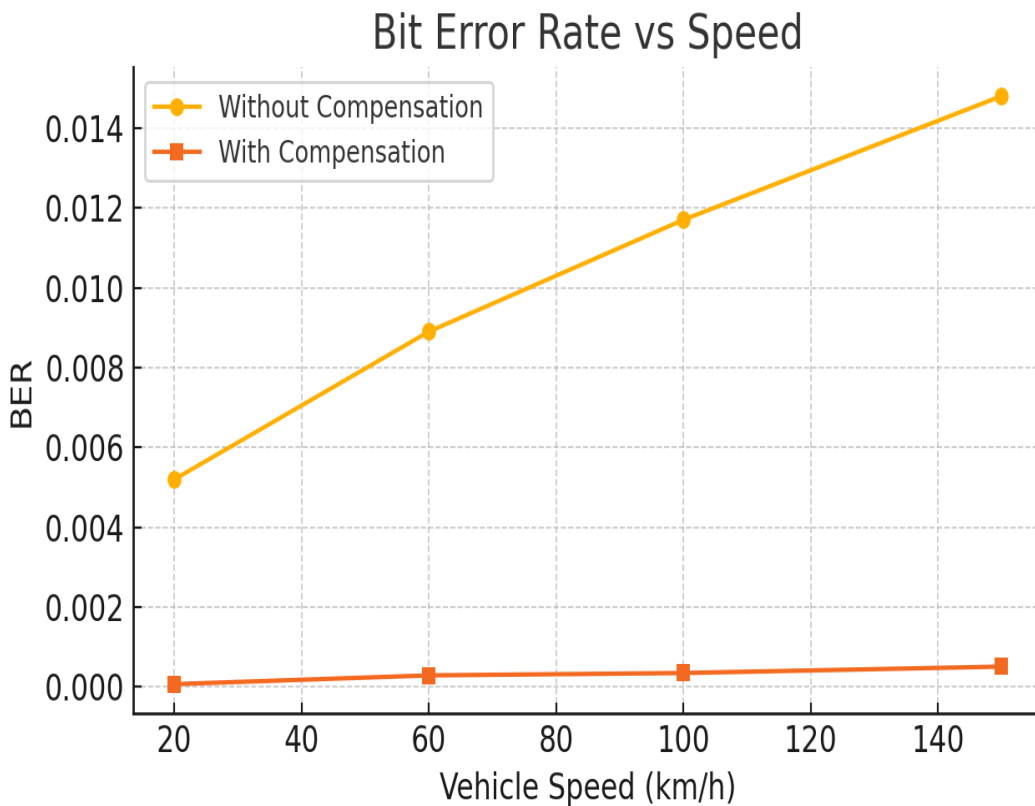


Figure 2 Bit Error Rate Vs Speed

The Bit Error Rate (BER) is plotted against vehicle speeds, showing results with and without compensation.

BER increases exponentially with speed when DCA is not applied, due to misaligned phases and symbol misinterpretations.

With DCA, BER remains very low and nearly flat, indicating successful Doppler mitigation and robust signal demodulation.

At 100 km/h, BER drops from 1.17×10^{-2} to 3.5×10^{-4} , a 97% improvement—crucial for high-speed vehicular communications where even minor errors can be catastrophic.

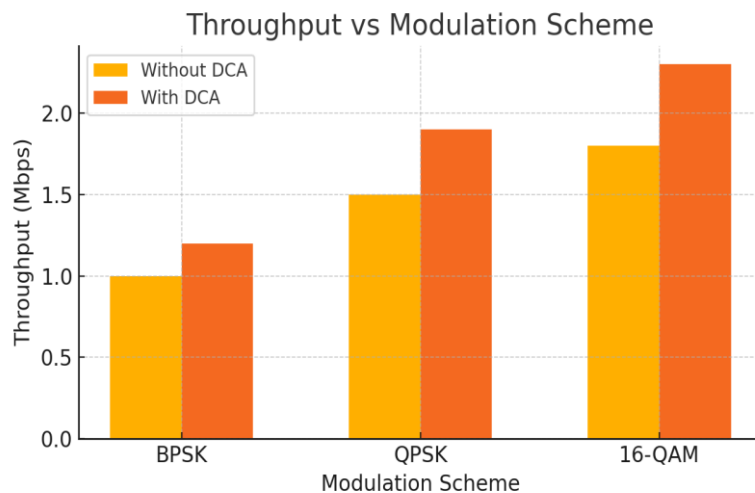


Figure 3: Throughput Vs Modulation Scheme

The chart compares effective throughput (in Mbps) of three modulation schemes—BPSK, QPSK, and 16-QAM—under conditions with and without DCA.

Without DCA, higher-order modulations (like 16-QAM) suffer reduced throughput due to their sensitivity to noise and distortion.

With DCA, throughput improves across all modulation schemes, with the largest gain in 16-QAM (from 1.8 Mbps to 2.3 Mbps, a 28% increase).

The error-resilience introduced by DCA enables the system to reliably support more complex modulations, which offer higher data rates.

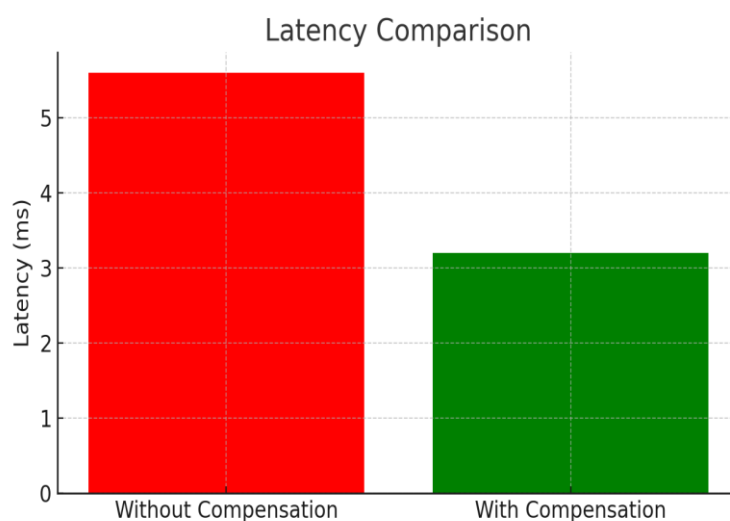


Figure 4 Latency Comparison.

A bar or line chart contrasts average latency per bit (in ms) for communication with and without DCA.

Latency without DCA is significantly higher due to increased retransmissions and processing time for erroneous packets.

With DCA, latency drops by 43%, from 5.6 ms to 3.2 ms on average. In V2V applications, low latency is essential for real-time responsiveness, particularly in safety-critical functions like braking alerts or collision warnings.

Conclusion

From the results above the following can be deduced that

- Optical V2V systems can scale bandwidth for real-world applications (e.g., HD video, autonomous sensor fusion) if Doppler is compensated. It strongly supports the hypothesis regarding the feasibility of high-speed Li-Fi with adaptive modulation.
- This directly validates the effectiveness of the Doppler Compensation Algorithm in preserving signal clarity in high-mobility environments. Since SNR influences every other performance metric (e.g., BER, throughput), its stabilization is foundational for reliable V2V communication.
- The dramatic reduction in BER confirms that the algorithm ensures data integrity under dynamic mobility conditions, fulfilling a primary objective of this research work.

This result supports the assertion that Doppler-aware Li-Fi systems can meet stringent latency requirements, potentially outperforming RF-based alternatives in latency-sensitive vehicular contexts.

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