Vehicular Li-Fi performance across diverse geographical regions employing spatial multiplexing

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This paper presents a novel vehicular light fidelity (Li-Fi) based multiple-input-multiple-output (MIMO) free space optical (FSO) communication system, addressing the impact of rain across diverse geographical regions (China, USA, Japan, India) identified based on road accident rates. Real-time rain data analysis enables the prediction of quality of received signal in terms of signal-to-noise ratio (SNR), path loss, and throughput with respect to vehicle speed and distance between vehicles by employing quadrature phase shift keying (QPSK) modulation. The study reveals that 8×8 MIMO configuration outperforms other MIMO systems in terms of superior signal strength, reduced path loss and lower SNR value under adverse rain weather conditions.

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1. Introduction

With the development of technology, the problem of spectral overloading, and the requirement for faster data transfer, researchers are exploring options beyond wireless fidelity (Wi-Fi) for transmission of signals between distant locations [1]. Light Fidelity (Li-Fi) is an emerging technology with a concept of wireless data transmission from every light and spans over a visible light spectrum which is 10,000 times larger than the radio wave spectrum and can theoretically transmit up to 100 Gbit/s [2].

Air suffers a variety of losses during the laser beam propagation process including geometric loss due to misalignment between transmitter and receiver, and atmospheric loss due to fog, rain, haze, snow, storms, and other atmospheric conditions. The meteorological and geographical features of the area might act as external factors affecting the performance of the link. Rain is one of the crucial factors and thus, has been considered for the analysis. In the present study, we analyzed the performance of Li-Fi system for vehicular communication under the effect of rain weather conditions [3-5].

In order to create a safer and more comfortable intelligent transportation system (ITS), a great deal of information including traffic congestion, status of traffic on the road, navigation data, and accident updates is required to be exchanged among vehicles [6]. The sharing of information is one of the research challenges associated with the use of visible light communication (VLC) in vehicular communication. Channel fading, Shadowing, ambient noise, multi-path reflections [7, 8], alignment, mobility, and non-line-of-sight (NLOS) communication between vehicles [9] are some of research challenges in terms of accuracy and throughput in vehicular communication [10].

Meanwhile, most automobiles have headlamps thanks to light emitting diodes (LEDs), and LED-based traffic signals and streetlights allow for the use of VLC for high-speed vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. A current method for vehicular communication under the IEEE 802.11p standard is called dedicated short-range communication (DSRC) and is feasible in transferring real-time data at a high data rate in a dependable and cost-effective manner. As a result of relative motion between vehicles, the doppler shift may lead to changes in signal frequency during propagation. To account for fading and doppler shift effects multiple-input multiple-output (MIMO) additive white gaussian noise (AWGN) channel model has been employed based on channel frequency response [11].

Among various MIMO techniques, spatial multiplexing stands out, wherein each transmitting antenna can independently transmit a distinct data stream, thus offering increased data rate and enhanced bandwidth utilization [12]. Different methods have been explored by researchers for the integration of MIMO technology with the DSRC standard, establishing it as a communication paradigm between RSUs (Roadside Units) and OBUs (On Board Units) in ITS employing SDR (Software Defined Radio) technology. Authors in the past have employed different MIMO techniques such as SDR technology and cooperative and space time block codes (STBC) MIMO, to achieve an efficient, reliable, and high data rate communication respectively. Optimization-based centralized lane change technique has also been investigated for reducing the disturbance caused by lane change maneuvers [13].

In this work, real-time rain analysis has been performed for the diverse geographical regions namely China, USA, Japan, and India during the monsoon months (June, July, and August) for years from 2018 to 2023. The average rain attenuation of the regions has been determined, considering the Marshal and Palmer model as well as the Carbonneau model. Further, we propose a physical layer model for the proposed vehicular Li-Fi-based MIMO-FSO system specifically addressing the impact of rain weather conditions. The proposed system performance has been evaluated by employing spatial multiplexing and quadrature phase shift keying (QPSK) modulation for varying values of different vehicular internal system parameters mainly vehicle speed and distance between vehicles. In addition, the findings have been achieved with respect to signal-to-noise ratio (SNR), path loss, and throughput, considering different internal parameters of the vehicle system.

The remaining portions of the paper are arranged as follows: We explain our rain attenuation models in Section 2. Section 3 presents a system model for the proposed PHY layer along with the mathematical modelling employed in the study. Section 4 demonstrates the results and its corresponding discussions. Finally, Section 5 provides the conclusion, summarizing the key findings and implications of the research.

2. Rain attenuation model

The rain rate data in (mm) has been collected from year 2018 to 2023 in case of diverse geographical regions namely China, USA, Japan, and India for 6 consecutive years from 2018–2023 selected based on road accidental data in the past few decades as per the reports of ministry of roadways and highways [14, 15].

The coefficient of rain attenuation is computed as:

$$\gamma\left(\frac{dB}{km}\right)rain = 4.343\int_0^{\infty} Q(D,\lambda,m)N(D)dD \qquad (1)$$

where 'λ' is the wavelength, 'D' is the raindrop diameter, and 'Q' is the cross-section of a raindrop. The symbol for the refractive index of water is 'm'. The size distribution function of the drop is denoted by 'N(D)'.

In Marshal and Palmer's model, 'a' and 'b' have respective values of 0.365 and 0.63 [3]. In the context of the Carbonneau Model, 'a' and 'b' have defined values of 1.076 and 0.67. Equation (2) depicts the general rain attenuation formula. Meanwhile, the $'\gamma_{mp}'$ and $'\gamma_c'$ represents the specific rain attenuation value for Marshal and Palmer, and Carbonneau models that have been depicted in equations (3) and (4) respectively.

$$\gamma\left(\frac{dB}{km}\right) = a.R^b \qquad (2)$$

$$\gamma_{mp} = 0.365R^{0.63} \qquad (3)$$

$$\gamma_c = 1.076R^{0.67} \qquad (4)$$

where 'R' is the rain rate (mm/hrs) and 'a' and 'b' are power-law parameters.

The Carbonneau model's 'a' and 'b' parameters are larger than those of the Marshal and Palmer models. The Carbonneau model predicts that the average rain attenuation is maximum for the year 2022 and is lowest for the year 2018. The graphical representation of rain attenuation for diverse geographical regions using Carbonneau and Marshal and Palmer model is shown in Fig. 1.

Among the four diverse regions, the Indian region stands out with maximum average rain attenuation values of 0.17 dB/km and 0.45 dB/km in case of Marshal and Palmer, and Carbonneau model. Further, it has been observed that the Carbonneau model exhibits high rain attenuation values compared to the other model under consideration. Consequently, the obtained attenuation value of 0.45 dB/km and Indian region have been selected for further analysis to analyze the effect of rain on the proposed system performance.

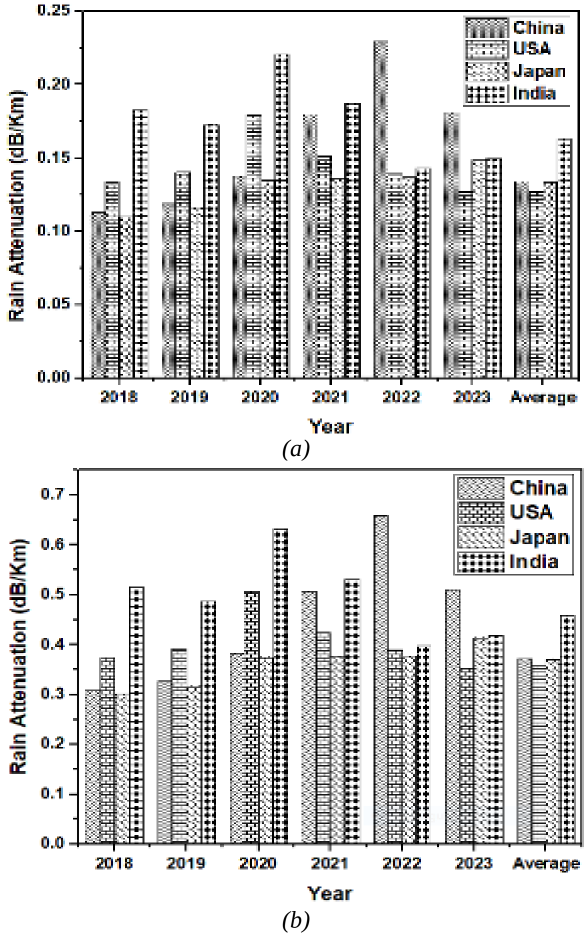
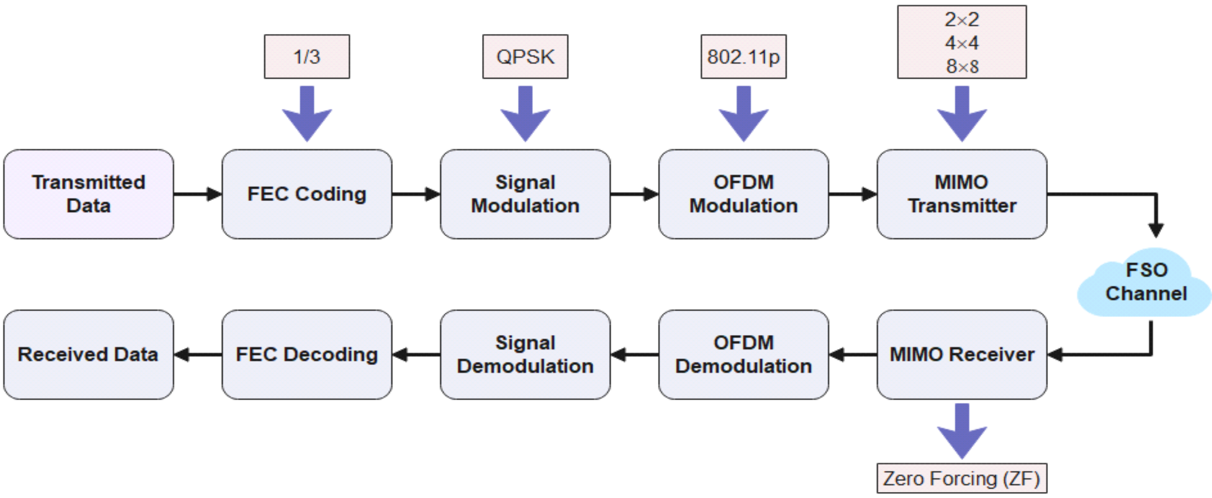


Fig. 1. Average rain attenuation (dB/Km) for rain attenuation model (a) Marshal and Palmer (b) Carbonneau

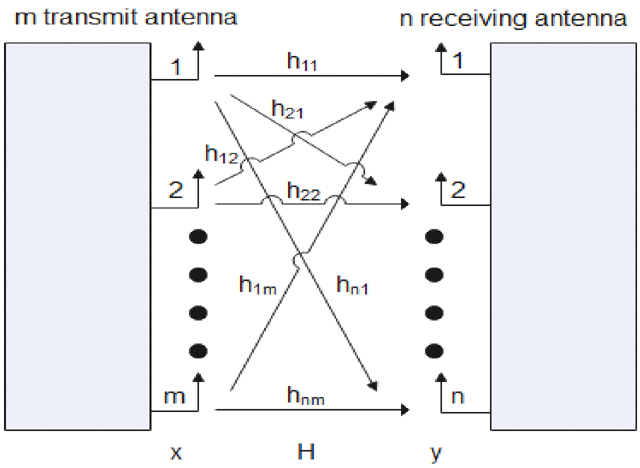
3. System model

In this section, we proposed a model that involves the integration of MIMO into DSRC's PHY layer according to the IEEE 802.11p standard. We utilize orthogonal frequency division multiplexing (OFDM) with a 10 MHz channel and include forward error correction (FEC), signal modulation, and MIMO technology to enhance throughput, enabling efficient real-time data transfer. The FEC block employs convolutional coding for error correction, while the Viterbi algorithm has been utilized for efficient decoding of transmitted data under noisy conditions. Additionally, the zero forcing (ZF) equalizer mitigates inter-symbol interference by inverting the channel's transfer function, thereby restoring the original signal. The components enhance reliability and signal clarity in the PHY layer of the DSRC system.

For our suggested model, Fig. 2 (a) and (b) depicts the modified conventional block diagram of PHY layer of the DSRC system employing ZF equalizer and MIMO configuration setup respectively.



(a)



(b)

Fig. 2. Schematic block diagram of (a) modified conventional block of the PHY layer of the DSRC system (b) MIMO configurations setup (colour online)

In Fig. 2(b), the scenario involves 'm' transmitting antennas and 'n' receiving antennas, represented as column matrices, with the channel depicted as a multidimensional matrix (16).

$$y_{n\times 1} = h_{n\times m} \times x_{m\times 1} + n_{n\times 1} \qquad (5)$$

The transmit antenna matrix in equation (5) is denoted by $x_{m\times 1}$, the channel matrix by $h_{n\times m}$, the receive antenna matrix by $y_{n\times 1}$, and the noise matrix in the channel by $n_{n\times 1}$.

In mitigating channel noise, we investigated 2x2, 4x4, and 8x8 MIMO setups with ZF equalizers for compensation, employing 1/3 coding rate for FEC error detection and correction in MATLAB simulations, validated using three metrics [17, 18].

1) **SNR:** The strength of the received signal in relation to the background noise is measured by SNR. It is computed as the ratio of the noise power $'P_{noise}'$ to the received signal power $'P_{signal}'$, and is commonly expressed in decibels (dB).

$$SNR\ (dB) = 10\ log_{10}(\frac{P_{signal}}{P_{noise}}) \qquad (6)$$

2) **Path Loss:** It occurs due to distance and obstacles between transmitter and receiver. It's crucial in describing power loss during transmission, with formulas like the free space path loss (FSPL) varying depending on the model employed as [19]:

$$FSPL = (\frac{4\pi d}{\lambda})^2 \quad (7)$$

where, 'd' is the distance between transmitter and receiver, and 'λ' is the wavelength of the signal.

3) **Throughput:** Throughput, measured in bps, reflects successful data transfer rate influenced by channel bandwidth, modulation, coding rate, and conditions. Shannon capacity formula provides the theoretical maximum throughput bound for a communication channel [20].

$$C = B\, log_2(1 + SNR) \quad (8)$$

where, 'B' is the channel's bandwidth in hertz (Hz), 'C' is the channel capacity in bits per second (bps), and 'SNR' is the signal to noise ratio.

4. Results and discussion

This section presents findings from modeling a vehicular Li-Fi system using MIMO spatial multiplexing. The system performance has been analyzed in terms of SNR, path loss and throughput considering vehicle speed and distance between vehicles. MATLAB R2023b software has been used for the simulation and the system parameters have been listed in Table 1. Further, a doppler shift of 30 Hz and ZF equalizer has been considered for 2x2, 4x4, 8x8 MIMO configurations.

Table 1. Simulation parameters of proposed system

Specifications	Parameter	Values
Transmitter	Type	High beam headlamp
	Wavelength of Light	700 nm
Receiver	Field of View (FOV)	180^0
	Responsivity	0.28 A/W
	Noise Density	10^{-22}
Vehicle	Length	4.673 m
	Width	1.846 m
	Height	1.371 m
Weather	Type	Rain Weather
	Attenuation	0.45 dB/Km

Fig. 3 represents the SNR with respect to transmission range (10 to 60 m) between vehicles for 2x2, 4x4, and 8x8 MIMO configurations. At a distance of 30 m, the maximum value of SNR (23.5 dB) is obtained with 8x8 MIMO, surpassing the 4x4 MIMO (20 dB) and 2x2 MIMO (17 dB) configurations.

Fig. 4 (a) and (b), shows the path loss values with respect to distance between vehicles and vehicle speed respectively. It can be observed from the figures that minimum path loss of 164 dB to 184 dB and 44 dB to 64 dB has been observed in case of 8×8 MIMO as a function of distance between vehicles and vehicle speed respectively.

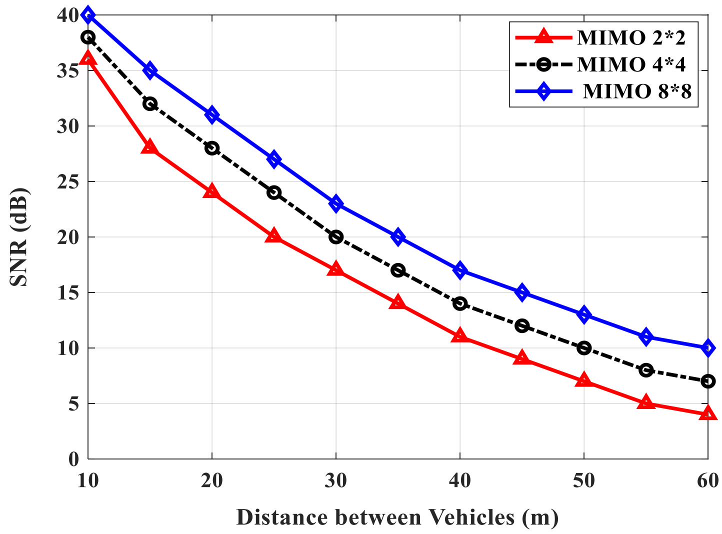
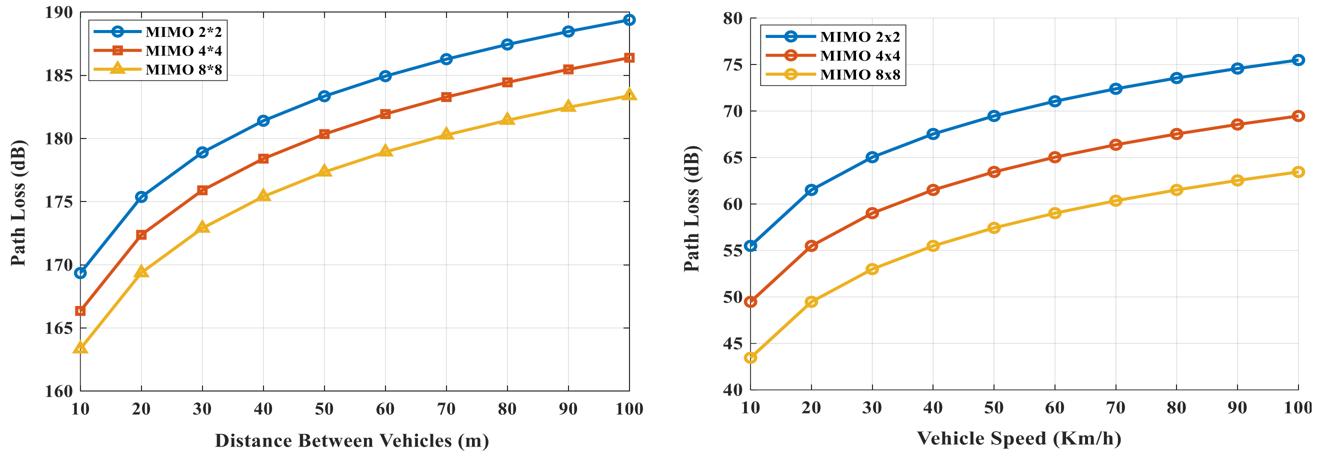


Fig. 3. SNR as a function of distance between vehicles (colour online)



(a) *(b)*

Fig. 4. Path loss as a function of (a) distance between vehicles (b) vehicle speed (colour online)

Fig. 5 depicts the average throughput with respect to SNR for 2x2, 4x4, and 8x8 MIMO configurations. An increase in SNR from 0 to 30 dB generally enhances data throughput, especially noticeable in high order MIMO configurations like MIMO 8x8, enabling more effective data exchange among vehicles for optimal data transmission.

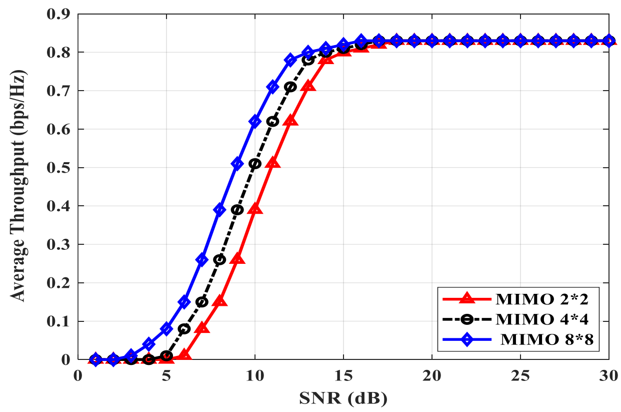


Fig. 5. Average throughput as a function of SNR (colour online)

5. Conclusion

The real-time rain rate attenuation for the diverse geographical regions has been estimated to predict the performance of vehicular Li-Fi system under the impact of rain employing QPSK modulation. The received signal quality has been examined in terms of signal-to-noise ratio (SNR), path loss, and throughput with respect to vehicle speed and distance between vehicles. Maximum value of SNR and minimum path loss have been observed in case of MIMO 8×8 system with SNR and path loss values observed at 30 m as 23.5 dB and 173.3 dB. Further the research work can be extended by incorporating Artificial Intelligence (AI) in vehicular communication system for accuracy prediction and estimation.

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