Performance Analysis of a Visible Light Vehicle-To-Vehicle Wireless Communication System

Vima Gupta
Department of Electrical and Electronics Engineering,
Birla Institute of Technology and Science, Pilani-Campus,
Pilani – 333031, India
f2014246@pilani.bits-pilani.ac.in

Rahul Singhal
Department of Electrical and Electronics Engineering,
Birla Institute of Technology and Science, Pilani-Campus,
Pilani – 333031, India
rahulsinghal@pilani.bits-pilani.ac.in

***Abstract* - Analysis of an optical wireless communication (OWC) system based on visible light communication (VLC) applied for vehicle-to-vehicle (V2V) communication is presented here. The theoretical investigation assumes arrays of light emitting diodes (LEDs) and photodiodes (PDs) for full duplex communication with spatial diversity between head- and tail-lights of vehicles in visible spectrum. The transmission spectrum from both sides i.e. 400 – 550 nm for headlight, 560 – 700 nm for taillight, falls on opposite sides of visible spectrum and no interference from source to detector in tandem is assumed. A signal received at detector in tandem with headlights suggests communication between vehicles moving towards each other. Two lights in front as well as back of vehicle develop an opportunity to explore and analyze a multiple input and multiple output (MIMO) possibility. A 2 × 2 MIMO configuration is assumed along with transmit and receive diversity to maintain communication in particular instances such as at T-junctions between two vehicles. Performance analysis of an OWC system suggests that a high bit rate transmission may be achieved depending on distance between vehicles.**

Keywords—Optical wireless, visible light communication, vehicle-to-vehicle communication, MIMO

I. Introduction

Free space optical (FSO) or OWC systems are getting popular due to development of economical optical sources and detectors [1]. Intelligent transportation systems (ITS) [2] involves V2V communication [3] and affordable VLC based OWC [4] seems to be need of present times towards road safety employing ITS. Developments in such systems are meant for intelligent traffic management, congestion control, improve safety and lower travel times. Simpler VLC systems employ Intensity modulated direct detected (IM/DD) systems those commonly exploit fundamental on-off keying (OOK) to transport data from source LED to destination PD detector. LEDs are robust and exhibit potential for high speed intensity variations against rapid changes in drive current. LEDs and photodiodes may be fabricated on a single substrate in tandem configuration [5] and thus, vehicles with headlights and taillights made up of arrays of LEDs and PDs having capability of emission and detection of wavelengths together at same time are assumed here for duplex communication.

To confine light for transmission and detection purposes, suitable optics including aperture lenses and reflectors while typical parameter values for LEDs and PDs are assumed for analysis. Large-element arrays of LEDs and PDs together provide spatial diversity [1] that helps during bad weather condition. Since each vehicle has two headlights in front and two taillights in back, a 2 × 2 MIMO configuration based communication may be easily established with transmit and receive diversity. Till two vehicles are in Line-of-sight (LOS), communication is prone to atmospheric turbulences and pointing errors due to traffic motion in a clear air scenario. Transmit and receive diversity due to two source-detector pair may overcome the turbulence and misalignment fading if distance between them is in tens of meters. During non-line-of-sight (NLOS) scenario, possibly during bad weather or 90 degree turn at T-junction on road, selection transmit and combining diversity assumption saves possibility of data transfer.

II. System Model

Practically employed IM/DD system with OOK modulation is assumed here. A source headlamp transmits 400 – 550 nm and is detected by PD detector array in the tail lamp of a vehicle ahead. Similarly if tail lamps emit 560 – 700 nm, optical power is received by PD detector array in headlamp of the following vehicle. If interference from other sources emitting visible spectrum is considered to be present in form of solar noise or ambient light sources, they can be rejected for being a common and constant source. The received signal is proportional to responsivity of PDs employed. The signal energy changes due to turbulence, misalignment, noise, etc. Thus, the signal is integrated at receiver within a bit period while background noise is identified as constant bias and is eliminated.

The received signal, R is modeled as, $R = HrX + N$ where, r is Responsivity of PDs, $R = r_{ij}; i = 1:2; j = 1:2$ is received signal vector, $H = h_{ij}; i = 1:2; j = 1:2$ is channel response vector where, $h_{ij} = [h_{ij}^{IRR} h_{ij}^{TUR} h_{ij}^{MIS}]$ where h_{ij}^{IRR} denotes irradiance losses; h_{ij}^{TUR} indicates fading due to atmospheric turbulences, and h_{ij}^{MIS} corresponds to misalignment fading.

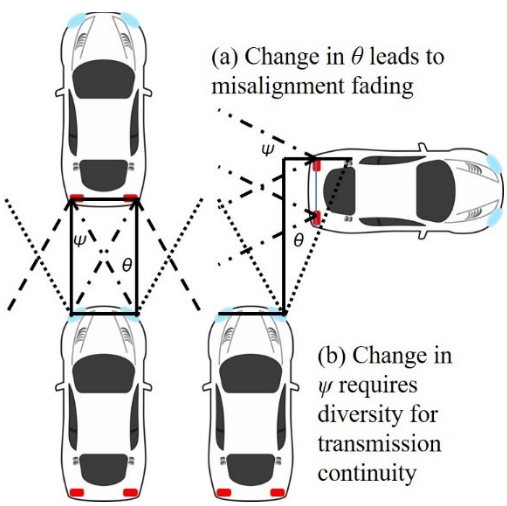

Fig. 1. Misalignment Fading and Diversity requirement in V2V applications

Noise Vector, $N = n_{ij}; i = 1:2; j = 1:2$ is additive with variance, σ_N^2 that is a sum of shot noise variance σ_{shot}^2 and thermal noise variance $\sigma_{thermal}^2$ [4]. The input vector X is signal radiated from LEDs with average power of value, P_T. The channel response includes deterministic lamp irradiance effects with random atmospheric turbulences and misalignment fading. Signal to Noise Ratio (SNR), ρ at detector for OOK scheme can be expressed as, $\rho = (P_T rH)^2 / I + \sigma_N^2$ where, P_T is transmitted optical power and I represent interference power.

Communication between two vehicles is established within LOS when field of view (FOV) of receiver PD falls within the beam waist projected by angle of irradiance of transmitter LEDs. The irradiance path loss [3], h_{ij}^{IRR} is defined as,

$$h_{ij}^{IRR} = \begin{cases} \frac{(m+1)A}{2\pi D_{ij}^{2}} \cos^m(\theta_{ij})\cos(\psi_{ij}) & \text{if } 0 \le \psi_{ij} \le \Psi \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where, A is area of PD detector, θ_{ij} is angle at transmitter while ψ_{ij} is incidence angle, Ψ is half-width of FOV, m represents order of emission[6], D_{ij} is distance between LED and PD.

Fading due to atmospheric turbulences h_{ij}^{TUR} is modeled by a gamma-gamma distribution [7],

$$f_{h^{TUR}}(h^{TUR}) = \frac{2(\alpha\beta)^{\frac{\alpha+\beta}{2}}}{\Gamma(\alpha)\Gamma(\beta)} \left(h^{TUR}\right)^{\frac{\alpha+\beta}{2}-1} K_{\alpha-\beta}(2\sqrt{\alpha\beta h^{TUR}}) \quad (2)$$

where, $\Gamma(.)$ and $K(.)$ are Euler's gamma function and modified Bessel function of second kind. The fading parameters α and β denote effective number of large and small scale turbulent cells respectively [8] and are related to each other with following relation, $\alpha > \beta$ and are individually expressed as follows:

$$\alpha = \frac{1}{e^{\left(\frac{0.49\sigma_r^2}{(1+1.11\sigma_r^{12/5})^{7/6}}\right)} - 1}; \beta = \frac{1}{e^{\left(\frac{0.51\sigma_r^2}{(1+0.69\sigma_r^{12/5})^{5/6}}\right)} - 1},$$

where, $\sigma_r^2 = 1.23 C_n^2 k^{7/6} D_{ij}^{11/6}$ is Rytov variance [9], d is detector aperture diameter, k is wave number and C_n^2 is refractive index parameter. Refractive index parameter depends on various other factors like location coordinates, time of day, weather, etc.

Factor h_{ij}^{MIS} corresponds to misalignment fading within the channel response and factor h_{ij}^{IRR} take cares of irradiance effects in link. If a Gaussian beam with a waist radius, ω_d falls on back of vehicle ahead with tail light detection aperture radius, γ at a distance D_{ij} and the distance between two vehicles, D is assumed enough so that the both detectors with taillights of the vehicle are illuminated by any one of the headlamps of the following vehicle, then the probability density function (PDF) including fading due to irradiance and misalignment together is given by [10],

$$f_{h^{MIS}}(h^{MIS}) = \frac{\xi^2}{A_0^{\xi^2}} \left(h^{MIS}\right)^{\xi^2-1}, \; 0 \le h^{MIS} < A_0 \quad (3)$$

where, $\xi = \omega_{deq} / 2\sigma_p$ is ratio between equivalent beam radius and standard deviation in pointing error at detector, and from [11],

$$\omega_{d_{eq}}^2 = \omega_z^2 \frac{\sqrt{\pi}\, erf(\nu)}{2\nu e^{-\nu^2}}; \quad \nu = \frac{\sqrt{\pi}\gamma}{\sqrt{2}\omega_z}; \quad A_0 = [erf(\nu)]^2,$$

where, $erf(.)$ is error function.

Considering gamma-gamma fading as a consequence of atmospheric turbulence with misalignment fading, the distribution of h_{ij} is expressed as,

$$f_{h_{ij}}(h_{ij}) = \frac{\alpha\beta\xi^2}{A_0\Gamma(\alpha)\Gamma(\beta)} G_{1,3}^{3,0}\left(\frac{\alpha\beta h_{ij}}{A_0} \middle| \begin{matrix} \xi^2 \\ \xi^2-1, \alpha-1, \beta-1 \end{matrix}\right) \quad (4)$$

where, $G_{p,q}^{m,n}\left(\cdot \middle| \begin{matrix} \cdots \\ \cdots \end{matrix}\right)$ is Meijer-G function[12].

III. BER Performance

System performance is observed by evaluating probability that the SNR, ρ falls below a threshold SNR, ρ_{th}. Here, a 2 × 2 MIMO system with selective transmit and receive diversity is used to ensure signal transfer even in turbulent and misalignment fading. A signal SNR if is greater than ρ_{th}, it is quite likely that signal is detected by PDs at taillight of vehicle. Selective transmission through LEDS is possible through identification of receiving PDs in a duplex communication.

The bit error rate (BER) of an OOK based IM-DD system is given by expressions as follows;

$$P_b(e \mid h) = Q\left(\frac{\sqrt{2} P_T h_{ij}}{\sigma_N}\right) \quad (5)$$

where, Q(.) is Gaussian Q-function. The average BER, $P_b(e)$ is obtained when $P_b(e|h_{ij})$ is averaged over pdf of h_{ij} i.e.,

$$P_b(e) = \int_0^\infty f_{h_{ij}}(h_{ij}) P_b(e \mid h_{ij}) dh_{ij} \quad (6)$$

Substituting $f_{h_{ij}}(h_{ij})$ in equation of $P_b(e)$, solution of BER is derived. The integral can be evaluated using Meijer's G-Functions to express integrands of modified Bessel and error functions [13]. Single input and single output (SISO) performs poorly in turbulent channels with pointing errors [14]. A closed form solution for for BER of SISO is expressed as follows,

$$P_{SISO}(e) = \frac{2^{\alpha-2}}{\sqrt{\pi^3}\,\Gamma(\alpha)} G_{5,2}^{2,4}\left[\frac{4\mu}{\alpha^2} \middle| \begin{matrix} \frac{1-\alpha}{2}, \frac{2-\alpha}{2}, 0, \frac{1}{2}, 1 \\ 0, \frac{1}{2} \end{matrix}\right] \quad (7)$$

where, μ is j-th order moment expressed by $\mu_{h_{ij}}(j) = \int_0^\infty h_{ij}^j f_{h_{ij}}(h_{ij}) dh_{ij} = \frac{\Gamma(j+1)\Gamma(j+\alpha)}{\alpha^n \Gamma(\alpha)}$, knowledge of that can define scintillation index (SI) [14]. Spatial Diversity may be implemented either as MISO or SIMO or MIMO. Since 2 × 2 MIMO is quite suitable for V2V communication, the received SNR with equal gain combining (EGC) and the average BER for a MIMO FSO communication may be expressed as follows,

$$\rho_{EGC} = \frac{r^2 P_T \left(\sum_{i=1}^{2}\sum_{j=1}^{2} h_{ij}\right)^2}{N} \quad (8)$$

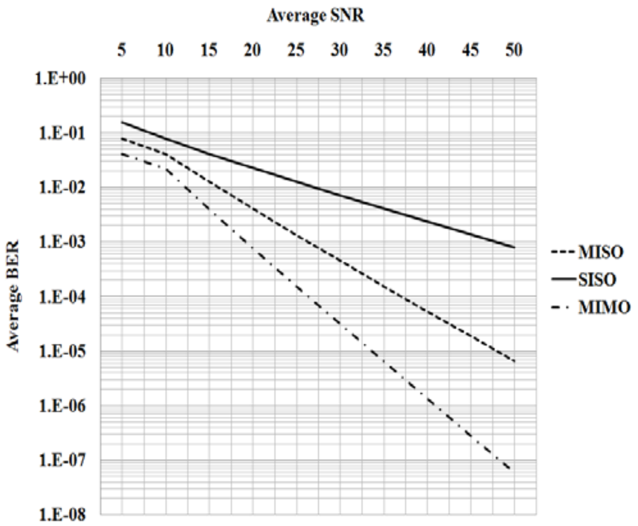

Fig. 2. Average BER vs. Average SNR for a OOK based V2V FSO communication system.

$$P_{MIMO}(e) = \int_{h_{ij}} f_{h_{ij}}(h_{ij}) \times Q\left(\frac{r}{4\sigma_N}\sqrt{\sum_{1}^{2}\left(\sum_{1}^{2} h_{ij}\right)^2}\right) dh_{ij} \qquad (9)$$

where, interference and noise variances are represented together through noise power, N. EGC is quite effective than other forms of combining in spatial diversity based FSO schemes [15].

Expression for average BER of multiple inputs and multiple outputs (MIMO) [16] is presented here in (10) and numerical results are plotted for comparison purpose.

$$BER = \mathrm{A} G_{5,2}^{2,4}\left(\mathrm{B}\left|\begin{matrix}\frac{1-\alpha_1}{2}, & \frac{1-\alpha_1}{2}, & \frac{1-\alpha_1}{2}, & \frac{1-\alpha_1}{2}, & 1\\ & & 0, \ \frac{1}{2} & & \end{matrix}\right.\right) \qquad (10)$$

where, $\alpha_1 = MN\alpha$; $\beta_1 = MN\beta$; and,

$$\mathrm{A} = \frac{2^{\alpha_1+\beta_1}}{8\pi^{3/2}\Gamma(\alpha_1)\Gamma(\beta_1)} \; ; \; \mathrm{B} = \frac{8\rho\left(h_{ij}MN\right)^2}{\left(\alpha_1\beta_1\right)^2}$$

For numerical example, typical values for LEDs and PDs are used here and distance between two vehicles is restricted to a value of positive SNR. Values for numerical analysis such as $C^2_n = 20 \times 10^{-14}\,m^{-2/3}$, SI = 1, $\alpha = 4$, $\omega_d/\gamma = 5$, and $\sigma_p/\gamma = 1$ are assumed here.

IV. Conclusion

An OWC system based on VLC is studied and analyzed for a possible V2V communication in this work. The analysis assumes LED and PD arrays for full duplex communication with spatial diversity between head- and tail-lights of vehicles in visible spectrum. Two lights in front as well as back of vehicle develop an opportunity to explore and analyze a multiple input and multiple output (MIMO) possibility. A 2 × 2 MIMO configuration is assumed along with transmit and receive diversity to maintain communication in particular instances such as at T-junctions between two vehicles. Performance analysis of an OWC system suggests that communication is possible but a SNR ≥ 20 dB is to achieved in a MIMO configuration to stay connected. Spatial diversity at transmitter as well as receiver improves the system performance compared to SISO configuration.

References

[1] S. Li, B. Huang and Z. Xu, "Experimental MIMO VLC Systems Using Tricolor LED Transmitters and Receivers," 2017 IEEE Globecom Workshops (GC Wkshps), Singapore, 2017, pp. 1-6.

[2] P. Papadimitratos, A. D. La Fortelle, K. Evenssen, R. Brignolo and S. Cosenza, "Vehicular communication systems: Enabling technologies, applications, and future outlook on intelligent transportation," in IEEE Communications Magazine, vol. 47, no. 11, pp. 84-95, November 2009.

[3] B. M. Masini, A. Bazzi and A. Zanella, "Vehicular visible light networks with full duplex communications," 2017 5th IEEE International Conference on Models and Technologies for Intelligent Transportation Systems (MT-ITS), Naples, 2017, pp. 98-103.

[4] Pengfei Luo, Zabih Ghassemlooy, Hoa Le Minh, Edward Bentley, Andrew Burton, and Xuan Tang, "Performance analysis of a car-to-car visible light communication system," Applied Optics Vol. 54, Issue 7, pp. 1696-1706 (2015).

[5] D. Threm, J. L. Gugat, A. Pradana, M. Radler, J. Mikat and M. Gerken, "Self-Aligned Integration of Spin-Coated Organic Light-Emitting Diodes and Photodetectors on a Single Substrate," in IEEE Photonics Technology Letters, vol. 24, no. 11, pp. 912-914, June1, 2012.

[6] S. Lin, J. Wang, X. Bao and Y. Li, "Outage performance analysis for outdoor vehicular visible light communications," 2017 9th International Conference on Wireless Communications and Signal Processing (WCSP), Nanjing, 2017, pp. 1-5.

[7] M. A. Al-Habash, L. C. Andrews, and R. L. Philips, Mathematical model for the irradiance probability density function of a laser propagating through turbulent media," Opt. Eng., vol. 40, no. 8, pp. 1554–1562, Aug. 2001.

[8] H. Kazemi, Z. Mostaani, M. Uysal and Z. Ghassemlooy, "Outage performance of MIMO free-space optical systems in gamma-gamma fading channels," Proceedings of the 2013 18th European Conference on Network and Optical Communications & 2013 8th Conference on Optical Cabling and Infrastructure (NOC-OC&I), Graz, 2013, pp. 275-280.

[9] Mohammad Taghi Dabiri, Seyed Mohammad Sajad Sadough, Performance analysis of EM-based blind detection for ON–OFF keying modulation over atmospheric optical channels, Optics Communications, Volume 413, 2018, Pages 299-303, ISSN 0030-4018.

[10] Antonio García-Zambrana, Carmen Castillo-Vázquez, and Beatriz Castillo-Vázquez, "Outage performance of MIMO FSO links over strong turbulence and misalignment fading channels," Optics Express Vol. 19, Issue 14, pp. 13480-13496 (2011).

[11] A. A. Farid and S. Hranilovic, "Outage Capacity Optimization for Free-Space Optical Links With Pointing Errors," in Journal of Lightwave Technology, vol. 25, no. 7, pp. 1702-1710, July 2007.

[12] M. R. Bhatnagar and Z. Ghassemlooy, "Performance Analysis of Gamma–Gamma Fading FSO MIMO Links With Pointing Errors," in Journal of Lightwave Technology, vol. 34, no. 9, pp. 2158-2169, 1 May1, 2016.

[13] H. G. Sandalidis, T. A. Tsiftsis, G. K. Karagiannidis and M. Uysal, "BER Performance of FSO Links over Strong Atmospheric Turbulence Channels with Pointing Errors," in IEEE Communications Letters, vol. 12, no. 1, pp. 44-46, January 2008.

[14] T. A. Tsiftsis, H. G. Sandalidis, G. K. Karagiannidis and M. Uysal, "FSO Links with Spatial Diversity over Strong Atmospheric Turbulence Channels," 2008 IEEE International Conference on Communications, Beijing, 2008, pp. 5379-5384.

[15] Li Chen, Weidong Wang, "Effective capacity of MIMO free-space optical systems over gamma–gamma turbulence channels," Optics Communications,Volume 382,2017,Pages 450-454,ISSN 0030-4018.

[16] P. Kaur, V. K. Jain, S. Kar, "Performance analysis of free space optcal links using multi-input multi-output and aperture averaging in presence of turbulence and various weather conditions," IET Communications, 2015, Vol. 9, Iss. 8, pp. 1104 – 1109.