MAC Layer Performance of Multi-Hop Vehicular VLC Networks with CSMA/CA

Hossien B. Eldeeb, Evsen Yanmaz, and Murat Uysal
Department of Electrical and Electronics Engineering, Özyeğin University, Istanbul, Turkey, 34794.
Email: hossien.eldeeb@ozyegin.edu.tr

***Abstract*—Majority of works in the field of vehicular visible light communication (VLC) networks are based on some ideal assumptions. Particularly, the ideal Lambertian pattern is assumed for channel modeling and only a simple point-to-point transmission link is considered in the network analysis. In this paper, we investigate the performance of multi-hop vehicular VLC networks based on the recent reference channel models and upcoming standards like IEEE 802.15.7r1 and 802.11bb. The impact of the asymmetrical radiation pattern of car headlamps, as well as the road reflectance are considered. In MAC layer, we deploy carrier-sense-multiple-access with collision-avoidance (CSMA/CA) as the medium-access protocol.**

***Index Terms*—Vehicular visible light communication networks, channel modelling, vehicle-to-vehicle communication, ray tracing.**

I. Introduction

Intelligent transportation systems aim to improve road safety and traffic flow through the use of advanced sensing, control and communication technologies. A key enabler in the design of such systems is vehicle-to-vehicle and vehicle-to-infrastructure communications [1], [2]. Radio-frequency (RF) technologies such as IEEE 802.11p [3] and LTE-V [4] have been already standardized and are used for vehicular connectivity in the current automotive market [5], [6]. While the current market penetration of connected vehicles is limited, the predictions show significant growth in the near future [3], [7]. With the widespread adoption of connected vehicles, limited allocated RF bands can suffer from high interference levels particularly in heavy traffic and urban areas. Traffic congestion of such networks will result in longer delays and lower packet rates [8], [9].

Such limitations with RF technologies motivated the introduction of vehicular visible light communication (VLC) [10]. VLC was originally proposed in the context of indoor wireless networks where LED luminaries act as access points [11]. Increasing adoption of LEDs in current automotive lighting (e.g., brake lights, headlamps, taillights and turn signals) has further made possible the use of VLC as a vehicular connectivity solution [12].

The work of Hossien B. Eldeeb was supported by the European Horizon 2020 MSC ITN (VISION) under Grant 764461. The work of Murat Uysal was supported by the Turkish Scientific and Research Council (TUBITAK) under Grant 215E311.

In comparison to indoor applications, vehicular VLC imposes additional challenges such as the effect of adverse weather conditions, exposure to sunlight etc. This requires the development of dedicated channel models for outdoor environments addressed in [13]–[19]. Physical layer design for vehicular VLC was further studied in [20]–[23]. A key enabler for connectivity in vehicular VLC is multi-hop transmission where the transmitted signal from the source car can reach the destination car through a number of intermediate cars termed relays [18], [24], [25]. Elamassie et.al. in [18] developed a path loss channel model for vehicular VLC and used this expression to determine the maximum achievable distance to ensure a given bit error rate (BER). They further investigated the deployment of relay-assisted systems to extend transmission ranges. In [24], Abualhoul et.al. considered a VLC-based platoon with longitudinal and lateral control to maintain a constant inter-distance between cars and analyzed the BER performance of this multi-hop system. In [25], Cailean et.al. presented experimental results for a dual-hop vehicular VLC system to connect a distant car to road side access point through a closer car.

As the above literature survey highlights, most of the works on vehicular VLC, including multi-hop systems, are mainly limited to physical layer design issues. There are also some sporadic efforts on medium access control (MAC) layer [26]–[34]. There are essentially two main approaches on how users can access the channel. In the first approach, system resources (frequency, time, etc.) are partitioned and users are scheduled on an orthogonal basis [26]–[29]. For example, in [26], a vehicular VLC network based on orthogonal frequency division multiple access (OFDMA) was presented where an ID was assigned for each VLC transmitter in a way to trigger suitable handover mechanism and hence improve the system capacity. Same in [27] where a dynamic soft handover algorithm based on coordinated multipoint (CoMP) transmission was proposed. In [28], a protocol based on time division multiple access (TDMA) scheme combined with adaptive power control system was presented for vehicular platoons. In [29], a MAC protocol based on the combination of optical code division multiple access (CDMA) and TDMA schemes was proposed for vehicular VLC networks in an effort to reduce the average access delay and enhance the throughput by encoding the data using orthogonal codes.

The second approach is contention-based schemes such as collision avoidance time allocation (CATA) protocol and

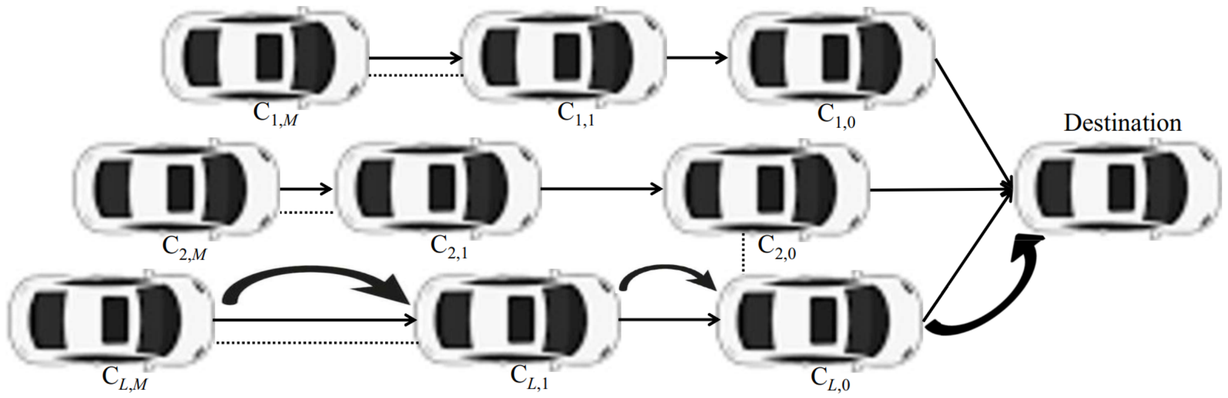


Fig. 1. Vehicular VLC system under consideration.

carrier sense multiple access (CSMA) protocols. In [30], a congestion adaptive algorithm was proposed to improve the packet delay ratio, while the packets of the hybrid VLC and RF networks are jointly handled. In [31], the 802.11p MAC protocol (used for WiFi network) was utilized for vehicular VLC networks in an urban scenario. In [32], CSMA with collision detection was proposed for a vehicular VLC network and improvements in packet delivery were reported. A simulation comparison between DSRC and VLC was provided in [33] to evaluate the quality of videos delivered in a platooning scenario.

Most of previous works on the MAC layer performance of vehicular VLC systems are built on some simplified channel models. For example, Lambertian source models are used in [28]–[32] which can not capture the asymmetrical distribution of headlamps or effect of weather conditions are not considered [26], [28]–[34].

In this paper, we consider a multi-hop vehicular VLC network whose physical layer builds upon PHY I defined in IEEE 802.15.7 standard with OOK modulation scheme [35]. For a precise channel modeling, we use a vehicular VLC path loss model obtained through ray tracing [17] where different weather conditions and road reflectance are taken into account. As MAC protocol, we consider non-beacon enabled random access of CSMA with collision avoidance (CSMA/CA). In this protocol, unlike CSMA/CD which waits after a collision occurs, it works to prevent collisions before they can occur. When a node has a packet to be transmit, it investigates the channel before the transmission to be assured that it is idle (clear). Otherwise, it has to wait for a randomly selected period of time. If the channel is found to be clear, the node send a Request-to-Send (RTS) message and then waits until receiving a Clear-to-Send (CTS) message. We analyze the MAC performance of vehicular VLC network under consideration through a simulation study and present throughput and packet-error-ratio (PER) under different channel conditions.

The remainder of this paper is organized as follows. In Section II, we describe the system model. In Section III, we present the performance analysis of vehicular VLC network.

Fig. 2. Location of transmitters and receivers on the car.

Section VI presents the obtained numerical and simulation results. Finally, we conclude our paper in Section V.

II. System Model

We consider a multi-hop multi-path vehicular VLC system in a dense network as shown in Fig. 1. The number of parallel paths is denoted by L and the number of relays in each path is denoted by M. All paths communicate with one destination car and the total number of cars in each path is given by $M+1$. The location of any car in the network is described by $C_{l,m}$, where $l = 1, 2, ..., L$ denotes the path's index and $m = 0, 1, ..., M$ represents the car's index in the path. The car $C_{l,0}$, $\forall l \in L$ can send its information directly to the Destination car. Since this is not possible for the other (M) cars, we assume that the m^{th} car in the l^{th} path, $C_{l,m}$, where $m = 0, 1, ..., M-1$, acts as a relay which can decode and forward (DF) the information from $C_{l,m+1}$ car to $C_{l,m-1}$ one and so on until reach to the destination car.

The cars are equipped with VLC transmitter/receiver front-ends. As shown in Fig. 2, each of cars has two headlamps (Tx 1 and Tx 2) and two taillights (Tx 3 and Tx 4) acting as transmitters to send the data in front and back directions, respectively. Each car is also equipped with two photodetectors (PDs). The first one (PD 1) is located at the center of the front of the car while the next (PD 2) is installed at the middle of the back of the car (see Fig. 2).

In this work, we follow IEEE 802.15.7 standard [35] and consider non-beacon enabled random access with CSMA/CA. The reason for non-beacon enabled is that it does not require a coordinator which is more convenient with vehicular networks. At the destination car/node, there will be L number of cars/nodes compete to access the channel. In CSMA/CA protocol, the l^{th} node listens to the channel for an interval time called distributed inter-frame space (DIFS) before the transmission. Then, if the channel is found to be idle, it generates a random back-off time, b_l, for $l = 1, \ldots, L$ where L is the number of competing nodes/cars. The value of b_l is uniformly chosen between 0 and w, where w represents the contention window size. The node with the lowest b_l is prior to transmit. Therefore, it sends the RTS frame before $L-1$ other sender nodes. If the RTS frame is received successfully by the destination node, it replies after a short inter-frame space (SIFS) with a CTS frame. Therefore, only the l^{th} node starts to transmit the data frame after a time interval of SIFS if it receives the CTS frame. After that, an acknowledgement (ACK) is transmitted after a period of SIFS by the receiver node to notify the successful packet reception. At the same time, this receiver node transmits channel busy (CB) tone. All sender nodes that can hear the CB tone will hold their back-off counter. The back-off counter will be re-activated when the channel is sensed idle again after a period of DIFS. If CB is not sent, the nodes who cannot hear the current sender node will start to send RTS frame after waiting for the second back-off period.

III. Performance Analysis

As performance metrics, we adopt system throughput and PER. In CSMA/CA protocol, there is a number of nodes L which compete on the channel, each with a probability of transmission of P_o. The probability of at least one transmission can happen in a time slot, τ_{slot} is given by

$$P_{tx} = 1 - (1 - P_o)^L \quad (1)$$

The probability of a successful transmission that can take place in τ_{slot} is given by

$$P_{suc} = \frac{L P_o (1 - P_o)^{L-1}}{P_{tx}} \quad (2)$$

Let $\mathbb{E}\left[\tau_D\right]$ denote the average transmission time of data packet. Similarly, define $\mathbb{E}\left[\tau_s\right]$ as the average time of a successful transmission. We assume that each node notices the channel to be busy for a time of τ_c. The normalized throughput of the network (i.e., the portion of time that the channel is used to successfully send payload bits) can be calculated by [36]

$$\mathrm{T}_n = \frac{P_{tx} P_{suc} \mathbb{E}\left[\tau_D\right]}{(1 - P_{tx})\,\tau_d + P_{tx} P_{suc} \mathbb{E}\left[\tau_s\right] + P_{tx}(1 - P_{suc})\tau_c} \quad (3)$$

where τ_d is the propagation time of the signal and $\tau_c = \tau_{\mathrm{RTS}} +$ DIFS $+ \tau_d$. Here, τ_{RTS} is the time of RTS massage. Under the assumption that all data packets contain the same length, we have $\mathbb{E}\left[\tau_s\right] = \tau_s$ which can be calculated as

$$\begin{aligned} \mathbb{E}[\tau_s] = {} & \tau_{\mathrm{RTS}} + \mathrm{SIFS} + \tau_d + \tau_{\mathrm{CTS}} + \mathrm{SIFS} + \tau_d + \tau_H \\ & + \tau_D + \mathrm{SIFS} + \tau_d + \tau_{\mathrm{ACK}} + \mathrm{DIFS} + \tau_d \end{aligned} \quad (4)$$

where τ_H, τ_{ACK}, and τ_{CTS} are the total packet header time, the time taken to send the ACK message and time of CTS

TABLE I
Channel and Network Parameters.

	Channel Parameters	Network Parameters	
Transmitter	Brand: Philips	Payload length:	2000B
	Power: 0.1 Watt	Physical header:	128b
	Pattern: Asymmetrical	MAC header:	272b
Receiver	Area: 1 cm^2	RTS packet size:	288b
	FOV: 90°	CTS packet size:	240b
	N_0: 10^{-21}	ACK packet size:	240b
Road	Material: Asphalt	SIFS duration:	16μs
	Lane width: 3.75 m	DIFS duration:	32μs
Car	Length: 4.7 m	Back-off duration:	8μs
	Width: 1.85 m	Contention window:	8,16
	Height: 1.38 m		

TABLE II
Weather Parameters

Type:	Clear	Rainy	Foggy
Size (μm):	10^{-4}	100	10
Density (cm^{-3}):	10^{19}	0.1	124.5
Particle index:	1.0003	1.33	1.33
c (m^{-1}) :	1×10^{-5}	0.92×10^{-3}	0.077

message. Further details about the calculation of the previous parameters are provided in [36].

The average throughput at destination vehicle is written as $T_D = (1/L)\sum_{l=1}^{L} T_{lD}$, where T_{lD} is throughput at the destination from the l^{th} node which can be calculated by

$$T_{lD} = \frac{T_n B_W}{L} \log_2\left(1 + \gamma_l\right) \quad (5)$$

where γ_l is the signal-to-noise-ratio (SNR) for the link between the l^{th} node and the Destination one. B_W is the bandwidth. γ_l in (5) can be calculated for OOK by

$$\gamma_l = \frac{(R P_t h_l)^2}{N_0 B_W} \quad (6)$$

where N_0 is the noise spectral power density, R is the photodetector responsitivity, and P_t is the transmitted optical power. In (6), h_l represents the channel gain associated for the link between the l^{th} node and Destination one. In [17], a vehicular VLC channel model was developed taking into account asymmetrical pattern of car headlamp as well as the effect of weather conditions. According to [17], h_l is given by

$$h_l = A d_l^{-2B} \exp(-c d_l) \quad (7)$$

where c is the extinction coefficient, A represents the geometrical loss value at a reference distance, B is the decaying factor, and d_l is the distance between the l^{th} node and Destination node. In [17], the value of B is defined through the

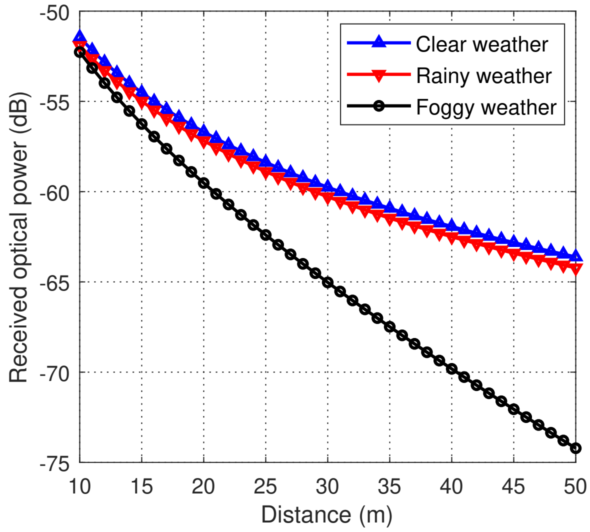


Fig. 3. Received optical power versus distance for clear, rainy, and foggy weathers [17].

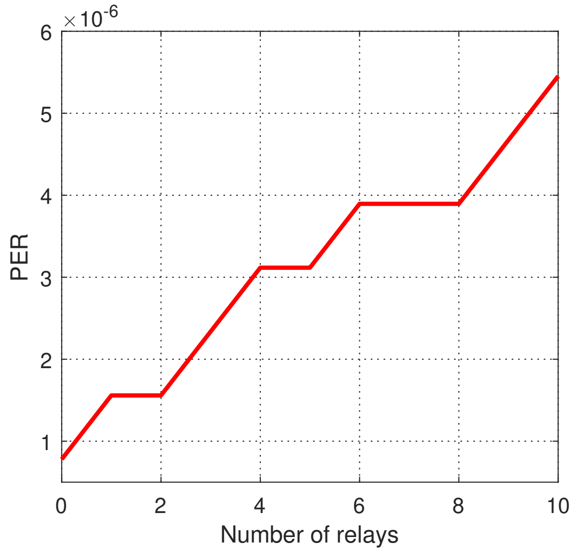


Fig. 4. PER assuming different inter-distance values between the cars (general case) and clear weather.

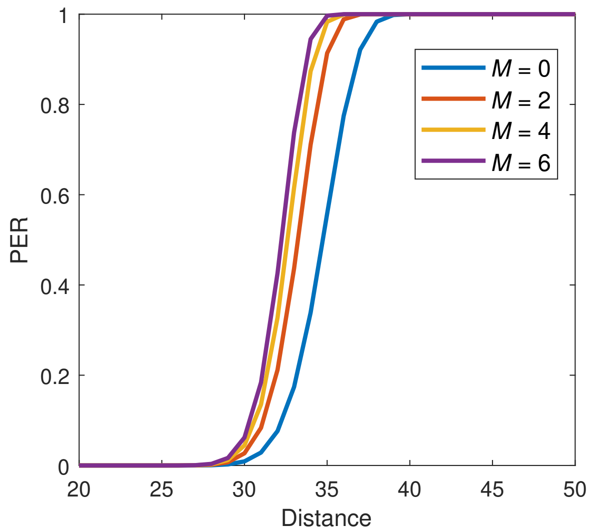


Fig. 5. PER versus distance at clear weather condition for different number of relays.

simulation to be 0.7 for foggy weather while in case of clear and rainy conditions, it is determined to be 0.87. Under the assumption of the same noise condition and assuming different longitudinal distances between the cars in each path, the bit-error-rate (BER) due to data transmission from m^{th} car to the Destination can be given by

$$BER^{m,D} = \sum_{m=1}^{M} BER_m, \tag{8}$$

where, BER_m is the BER of the data transmitted from the $(m-1)^{th}$ car to m^{th} one. As an special case when the intermediate distances between the cars are identical, (8) can be written as $BER^{m,D} = MBER_{hop}$. Thus M is the number of relays between the m^{th} car and the destination one and BER_{hop} is the BER between any two neighboring cars.

IV. Numerical Results

In this section, we present numerical results for vehicular network scenarios under consideration. We assume a photodetector with an area of 1 cm^2, FOV of 90°, and responsivity of $R = 0.28$ A/W. First, we consider the general case in terms of inter-distance between the cars. In [37], the distances between two cars in real scenario was measured using a sounding system technique. The minimum distance between the cars was found to be 10 m while the maximum was depending on the traffic conditions. Since we consider vehicular network in dense traffic scenario, we choose random distance values between 10 m and 50 m and provide the network performance in terms of PER. Then, we assume special case scenario where the distances between the cars in the same path are identical and present the effect of increasing such distance on the network performance for all weather conditions under consideration. All channel and network simulation parameters are summarized in Table I and Table II.

In Fig. 3, we present the received optical power versus distance for different weather conditions using (7). It can be observed that the rainy weather has a negligible impact on received power while fog introduces severe degradation.

In Fig. 4, we assume the general case scenario in clear weather condition and present the PER versus number of relays. It can be shown that in DF relaying technique, the larger relays number the higher PER value in the network.

In Fig. 5, we assume the case of identical inter-distance between the cars and present the effect of increasing such distance on the PER value considering different relay numbers. It is observed that the PER worsens with increasing either the distance or relays number (M). For example, consider a distance of 32 m. The PER for direct link $M = 0$ is 7%.

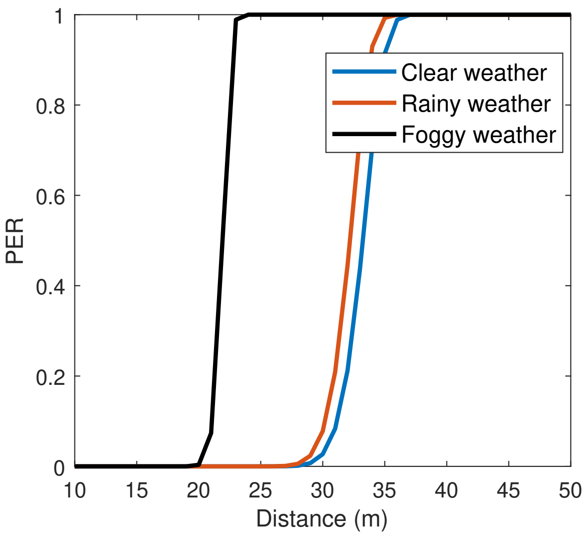


Fig. 6. PER versus distance assuming $M = 2$ for clear, rainy, and foggy weathers.

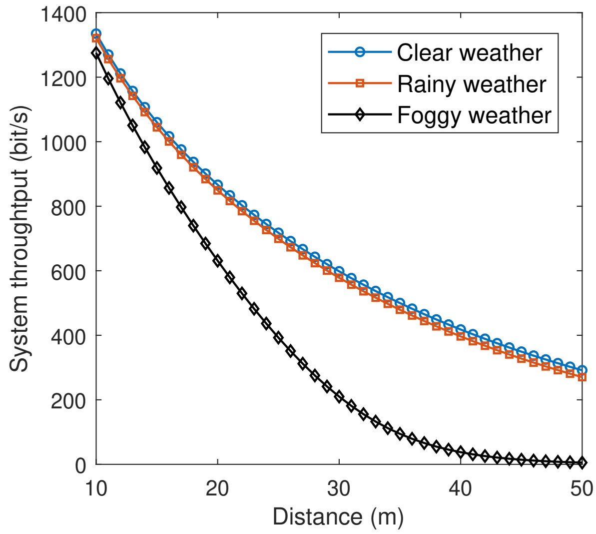
This reduces to 20%, 30%, and 40% respectively for $M = 2$, $M = 4$, and $M = 6$.

In Fig. 6, we present the PER over distance and investigate the effect of weather conditions. It is observed that up to 30 m, the vehicular VLC network under consideration can deliver the packets with a value of PER lower than 0.1 in clear and rainy weathers. This distance reduces to 21 m in case of foggy weather.

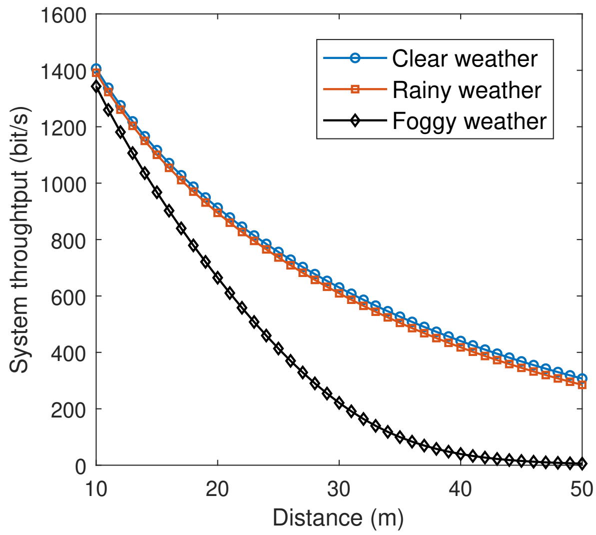
In Fig. 7, we present the system throughput based on (5) assuming $M = 2$ and $L = 3$. We consider two values of contention window size; (a) $w = 8$ and (b) $w = 16$. It is observed that increasing the contention window size can reduce the collision through the network and hence increase the system throughput. However, for low traffic networks, this will result in unnecessary delays.

V. Conclusions

In this paper, we have investigated the performance of vehicular VLC networks based on CSMA/CA as medium access protocol and by considering a realistic channel model obtained by a professional ray tracing approach of Zemax®. Results indicated that a reliable packet delivery in vehicular VLC network can be achieved when CSMA/CA protocol is adopted. Such vehicular networks are highly sensitive to the considered contention window size as well as the foggy weather.



(a)



(b)

Fig. 7. Overall system Throughput at all weather conditions under consideration for (a) W = 8 (b) W = 16.

References

[1] K. Zheng, Q. Zheng, P. Chatzimisios, W. Xiang, and Y. Zhou, "Heterogeneous vehicular networking: A survey on architecture, challenges, and solutions," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2377–2396, 2015.

[2] M. Amadeo, C. Campolo, and A. Molinaro, "Information-centric networking for connected vehicles: a survey and future perspectives," *IEEE Commun. Mag.*, vol. 54, no. 2, pp. 98–104, 2016.

[3] H. Zhou, N. Cheng, Q. Yu, X. S. Shen, D. Shan, and F. Bai, "Toward multi-radio vehicular data piping for dynamic dsrc/tvws spectrum sharing," *IEEE J. Sel. Areas Commun.*, vol. 34, no. 10, pp. 2575–2588, 2016.

[4] R. Molina-Masegosa and J. Gozalvez, "Lte-v for sidelink 5g v2x vehicular communications: A new 5g technology for short-range vehicle-to-everything communications," *IEEE Veh. Technol. Mag.*, vol. 12, no. 4, pp. 30–39, 2017.

[5] "Cellular v2x: Continental successfully conducts field trials in china," https://www.continental-corporation.com/en/press/press-releases/2017-12-18-cellular-v2x-116994, [Accessed: May 26, 2020].

[6] "Toyota commits big to DSRC," https://www.adandp.media/blog/post/toyota-commits-big-to-dsrc, [Accessed: May 26, 2020].

[7] A. Yastrebova, R. Kirichek, Y. Koucheryavy, A. Borodin, and A. Koucheryavy, "Future networks 2030: Architecture & requirements," in *2018 10th International Congress on Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT)*. IEEE, 2018, pp. 1–8.

[8] P. H. Pathak, X. Feng, P. Hu, and P. Mohapatra, "Visible light communication, networking, and sensing: A survey, potential and challenges," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 4, pp. 2047–2077, 2015.

[9] L. E. M. Matheus, A. B. Vieira, L. F. Vieira, M. A. Vieira, and O. Gnawali, "Visible light communication: Concepts, applications and challenges," *IEEE Commun. Surveys Tuts.*, 2019.

[10] A.-M. Cailean and M. Dimian, "Impact of ieee 802.15. 7 standard on visible light communications usage in automotive applications," *IEEE Commun. Mag.*, 2017.

[11] H. Burchardt, N. Serafimovski, D. Tsonev, S. Videv, and H. Haas, "Vlc: Beyond point-to-point communication," *IEEE Commun. Mag.*, vol. 52, no. 7, pp. 98–105, 2014.

[12] M. Uysal, Z. Ghassemlooy, A. Bekkali, A. Kadri, and H. Menouar, "Visible light communication for vehicular networking: performance study of a v2v system using a measured headlamp beam pattern model," *IEEE Veh. Technol. Mag.*, vol. 10, no. 4, pp. 45–53, 2015.

[13] M. Akanegawa, Y. Tanaka, and M. Nakagawa, "Basic study on traffic information system using led traffic lights," *IEEE Trans. Intell. Transp. Syst*, vol. 2, no. 4, pp. 197–203, 2001.

[14] S. Lee, J. K. Kwon, S.-Y. Jung, and Y.-H. Kwon, "Evaluation of visible light communication channel delay profiles for automotive applications," *EURASIP j. Wireless Commun. Netw.*, vol. 2012, no. 1, p. 370, 2012.

[15] H. B. Eldeeb and M. Uysal, "Vehicle-to-vehicle visible light communication: How to select receiver locations for optimal performance?" in *11th International Conference on Electrical and Electronics Engineering (ELECO)*. IEEE, 2019, pp. 402–405.

[16] Y. H. Kim, W. A. Cahyadi, and Y. H. Chung, "Experimental demonstration of vlc-based vehicle-to-vehicle communications under fog conditions," *IEEE Photon. J*, vol. 7, no. 6, pp. 1–9, 2015.

[17] H. B. Eldeeb, F. Miramirkhani, and M. Uysal, "A path loss model for vehicle-to-vehicle visible light communications," in *2019 15th International Conference on Telecommunications (ConTEL)*. IEEE, 2019, pp. 1–5.

[18] M. Elamassie, M. Karbalayghareh, F. Miramirkhani, R. C. Kizilirmak, and M. Uysal, "Effect of fog and rain on the performance of vehicular visible light communications," in *2018 IEEE 87th Vehicular Technology Conference (VTC Spring)*. IEEE, 2018, pp. 1–6.

[19] M. Karbalayghareh, F. Miramirkhani, H. B. Eldeeb, R. C. Kizilirmak, S. M. Sait, and M. Uysal, "Channel modelling and performance limits of vehicular visible light communication systems," *IEEE Trans. Veh. Technol.*, pp. 1–1, 2020.

[20] S. Arai, S. Mase, T. Yamazato, T. Endo, T. Fujii, M. Tanimoto, K. Kidono, Y. Kimura, and Y. Ninomiya, "Experimental on hierarchical transmission scheme for visible light communication using led traffic light and high-speed camera," in *2007 IEEE 66th Vehicular Technology Conference*. IEEE, 2007, pp. 2174–2178.

[21] J. Liu, P. W. C. Chan, D. W. K. Ng, E. S. Lo, and S. Shimamoto, "Hybrid visible light communications in intelligent transportation systems with position based services," in *2012 IEEE Globecom Workshops*. IEEE, 2012, pp. 1254–1259.

[22] A. Cailean, B. Cagneau, L. Chassagne, S. Topsu, Y. Alayli, and J.-M. Blosseville, "Visible light communications: Application to cooperation between vehicles and road infrastructures," in *2012 IEEE Intelligent Vehicles Symposium*. IEEE, 2012, pp. 1055–1059.

[23] M. Anand and N. Kumar, "New, effective and efficient dimming and modulation technique for visible light communication," in *2014 IEEE 79th Vehicular Technology Conference (VTC Spring)*. IEEE, 2014, pp. 1–4.

[24] M. Y. Abualhoul, M. Marouf, O. Shagdar, and F. Nashashibi, "Platooning control using visible light communications: A feasibility study," in *16th International IEEE Conference on Intelligent Transportation Systems (ITSC 2013)*. IEEE, 2013, pp. 1535–1540.

[25] A.-M. Cailean, B. Cagneau, L. Chassagne, S. Topsu, Y. Alayli, and M. Dimian, "Visible light communications cooperative architecture for the intelligent transportation system," in *2013 IEEE 20th Symposium on Communications and Vehicular Technology in the Benelux (SCVT)*. IEEE, 2013, pp. 1–5.

[26] X. Bao, X. Zhu, T. Song, and Y. Ou, "Protocol design and capacity analysis in hybrid network of visible light communication and ofdma systems," *IEEE trans. veh. technol.*, vol. 63, no. 4, pp. 1770–1778, 2013.

[27] M. S. Demir, H. B. Eldeeb, and M. Uysal, "Comp-based dynamic handover for vehicular vlc networks," *IEEE Commun. Lett.*, 2020.

[28] M. Segata, R. L. Cigno, H.-M. M. Tsai, and F. Dressler, "On platooning control using ieee 802.11 p in conjunction with visible light communications," in *2016 12th Annual Conference on Wireless On-demand Network Systems and Services (WONS)*. IEEE, 2016, pp. 1–4.

[29] Q. Mao, P. Yue, M. Xu, Y. Ji, and Z. Cui, "Octmac: A vlc based mac protocol combining optical cdma with tdma for vanets," in *2017 International Conference on Computer, Information and Telecommunication Systems (CITS)*. IEEE, 2017, pp. 234–238.

[30] A. Bazzi, B. M. Masini, A. Zanella, and A. Calisti, "Visible light communications as a complementary technology for the internet of vehicles," *Computer Commun.*, vol. 93, pp. 39–51, 2016.

[31] B. Masini, A. Bazzi, and A. Zanella, "Vehicular visible light networks for urban mobile crowd sensing," *Sensors*, vol. 18, no. 4, p. 1177, 2018.

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

[33] W. L. Junior, J. Costa, D. Rosario, E. Cerqueira, and L. A. Villas, "A comparative analysis of dsrc and vlc for video dissemination in platoon of vehicles," in *2018 IEEE 10th Latin-American Conference on Communications (LATINCOM)*. IEEE, 2018, pp. 1–6.

[34] C. B. Liu, B. Sadeghi, and E. W. Knightly, "Enabling vehicular visible light communication (v2lc) networks," in *Proceedings of the Eighth ACM international workshop on Vehicular inter-networking*. ACM, 2011, pp. 41–50.

[35] S. Rajagopal, R. D. Roberts, and S.-K. Lim, "Ieee 802.15. 7 visible light communication: modulation schemes and dimming support," *IEEE Commun. Mag.*, vol. 50, no. 3, pp. 72–82, 2012.

[36] G. Bianchi, "Performance analysis of the ieee 802.11 distributed coordination function," *IEEE J. sel. areas in commun.*, vol. 18, no. 3, pp. 535–547, 2000.

[37] Y. Yang, J. Xu, G. Shi, and C.-X. Wang, *5G wireless systems*. Springer, 2018.