Chapter 7

Vehicular Visible Light Communications

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Additional information is available at the end of the chapter

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Abstract

Vehicular communications are foreseen to play a key role to increase road safety and realize autonomous driving. In addition to the radio frequency (RF)-based dedicated short range communication (DSRC) and long-term evolution (LTE) communication technologies, vehicular visible light communication (V2LC) is proposed as a complementary solution, utilizing readily deployed vehicle light emitting diode (LED) lights as transmitter with image sensors such as photodetector (PD) and camera as the receivers. V2LC fundamentals including transmitter and receiver characteristics with dimming capabilities are reviewed in this chapter. Depending on the field measurements using off-the-shelf automotive LED light, communication constraints are demonstrated. Moreover, considering the line-of-sight (LoS) characteristics, security aspects of V2LC is compared with the DSRC for a practical vehicle-to-vehicle (V2V) communication scenario. Finally, superiority of V2LC in terms of communication security with the proposed SecVLC method is demonstrated through simulation results.

Keywords: vehicular visible light communications, V2V, VLC dimming, V2LC security

1. Introduction

Next-generation mobility trends such as autonomous driving and ride sharing necessitate various vehicular connectivity schemes. On the other hand, intelligent transportation systems (ITS) harmonized with vehicular communications aim to reduce traffic congestion, accidents, air pollution, energy, and time wastage. Upto date, vehicular communications are expected to provide timely and efficient data dissemination regarding accidents, traffic jams, and road conditions beyond the drivers' knowledge.

Currently, RF-based IEEE 802.11p (DSRC) and LTE are the strongest candidates for V2V and vehicle to everything communications (V2X). However, regarding limited bandwidth and security vulnerabilities of RF-based communications, optical wireless communication is proposed as a complementary technology for vehicular connectivity. Utilizing redundant communication schemes for vehicular communications is expected to increase road safety while supporting safer automated driving applications.

LEDs enable flexible vehicle headlight/taillight design, while providing better illumination, low energy consumption, and longer durability. Hence, LED lights are started to be widely deployed with new production vehicles. Moreover, vehicle LED lights enable creation of various illumination patterns to prevent glare from other road users and illuminate the blind areas better [1]. LED lights illumination requirements and design guidelines are also included in the automotive light regulations [2], which paves the way for more manufacturers to utilize LED in their vehicles. Dimming capability of LED lights is another favorable feature for automotive industry, providing energy efficient vehicular lighting.

Modern vehicles are also equipped with image sensors such as PDs and cameras. PDs are utilized to detect ambient light levels and rain to automatically activate headlights or wiper blades, while the cameras are used for driver assistance systems such as lane keeping assistant, traffic sign recognition, pedestrian detection, and forward collision warning. Hence, usage of the existing vehicle LED lights and image sensors is foreseen to allow low vehicular visible light communication (V2LC) system implementation costs.

Visible light communication (VLC) systems with intensity modulation and direct detection (IM/DD) utilize signal intensity instead of signal phase information. As phase information is prone to distortions for mobility scenarios, sole dependence on signal intensity of IM/DD scheme also makes VLC a promising technology for vehicular communications.

Currently, V2V aims to transmit vehicle position and state information to enhance the road awareness of nearby vehicles. However, with the upcoming autonomous driving features, high-definition real time road maps, vehicle radar data, high-resolution image, and video data from on-board cameras are expected to be exchanged between nearby vehicles. These events driven large size data is required to be conveyed with minimum latency. Furthermore, high mobility requires higher message update rates resulting with dense message generation. In order to provide high data rates with minimum latency, hybrid schemes, utilizing various communication technologies simultaneously, are provisioned to be favorable. It has already been demonstrated that, communication degradation sourced by packet collisions and contention with the usage of single scheme such as DSRC can be avoided with a hybrid scheme employing DSRC and V2LC [3].

Upto date, VLC is reported to achieve multi-Gbit/s data rates for a few meter distances. Compared to DSRC maximum data rate support with 27 Mbps upto 1000 m distances [4], Gbit/s data rates make VLC attractive for high data rate vehicular communications. In addition to higher data rate advantages, with its immunity to malicious jamming with LoS characteristics, VLC is also foreseen to off-load RF networks while providing secure communications for safety critical applications.

In the literature, various studies investigated V2LC applications. In Ref. [5], LEDs are utilized as vehicle ambient lights and dome lights are foreseen to act as VLC transmitters. Authors in

Ref. [6] implemented IEEE 802.15.7 standard to convey information using vehicle LED lights. In Ref. [7], V2LC system that is based on image sensor and high-speed camera receivers is demonstrated.

2. V2LC transmitters

LEDs are used in vehicle headlights, turn signals, taillights, and stop lights. LED arrays with high power form the headlights, fog lights, stop lights, and taillights, whereas single low- or mid-power LED usage is preferred for turn-signals. High-power automotive LEDs draw upto 700 mA current with a typical luminous flux of 200 lm. Low/mid-power off-the-shelf vehicle LEDs turn on with the currents between 60 and 300 mA. Higher current requirements are known to limit the switching capability of LEDs. Furthermore, white LEDs used in the vehicle lighting are usually phosphor-based and have a 3-dB modulation bandwidth in the order of a few megahertz. Phosphor-based white LEDs consist of a blue LED component coated by a phosphor layer. Even though the blue component of LEDs provides upto 20 MHz modulation bandwidth, slow phosphor relaxation time is known as another limitation for the modulation bandwidth of the vehicle LEDs. Thus, higher modulation frequencies of LEDs for V2LC are not considered to be feasible.

Light intensity of an LED source, modulated at an angular frequency of $\boldsymbol{\omega}$ is calculated by, [8]

$$I(\boldsymbol{\omega}) = \frac{I(0)}{\sqrt{1 + (\omega\tau_{eff})^2}} \tag{1}$$

where $\mathbf{I(0)}$ is the light intensity at zero modulation frequency and $\boldsymbol{\tau_{eff}}$ is the effective carrier lifetime. It can be inferred that, $\boldsymbol{\omega}$ is also upper bounded with the minimum road illumination requirements as the intensity decreases with the increasing $\boldsymbol{\omega}$. Hence, it is also important to avoid modulation frequencies higher than the 3-dB modulation bandwidth of an automotive LED.

LED light output is linearly proportional to the forward bias current at the linear working region. Driving LEDs at the linear working region is crucial for generating light levels, proportional to the modulation signals. Linear working region of mid-power LED is depicted in **Figure 1a** whereas high-power automotive LED linear working range is shown in **Figure 1b**. **Figure 2** demonstrates the linear working region variation of an automotive LED aimed to be used in headlights with respect to temperature. Even though the illumination degradations linked to nonlinearity of LEDs may not be perceptible with human eye, optical power fluctuations substantially limit the communication performance. Thus, LED nonlinearity should be considered with the selection of modulation and waveforms for V2LC.

V2LC is foreseen to provide high data rates through the usage of multicarrier modulation schemes such as orthogonal frequency-division multiplexing (OFDM). However, high peak-to-average power ratio (PAPR) of OFDM signals necessitates LEDs to work in nonlinear region, resulting optical power efficiency degradation. Hence, PAPR reduction techniques are investigated in Refs. [9, 10] to obtain noticeable bit error rate (BER) performance gain for VLC.

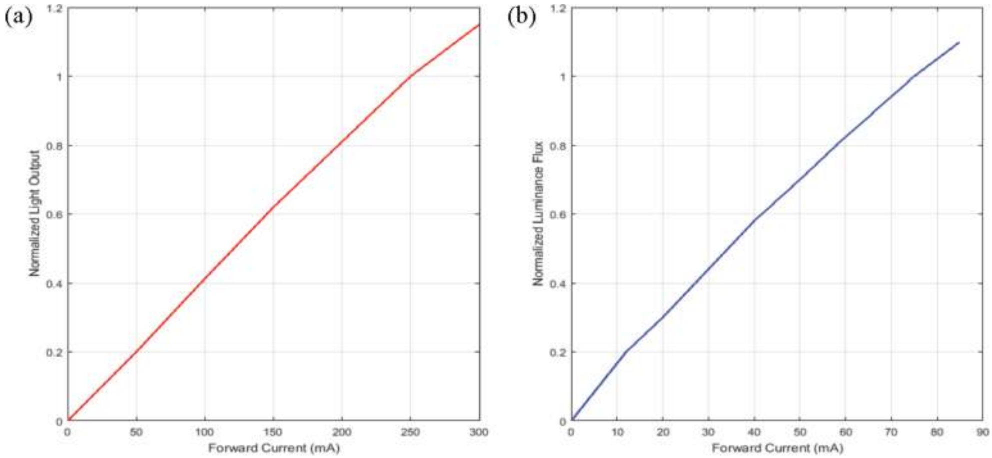

Figure 1. (a) High-power automotive LED bulb; (b) mid power automotive LED bulb linear region.

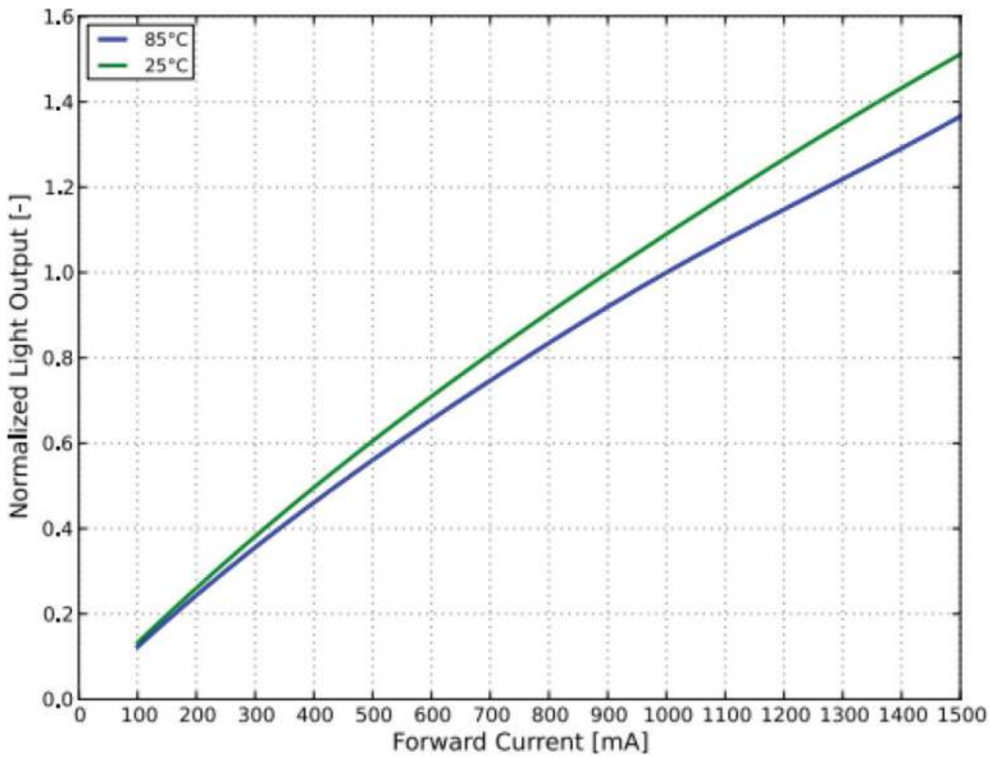

Figure 2. Automotive LED linear working region variation with temperature.

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LED radiation patterns define the relative optical power strength from the light source. Almost every single LED chip is designed to emit Lambertian pattern. However, refractions and internal reflections inside the encapsulating housing describe the final radiation pattern of LEDs. As vehicle LEDs are encapsulated into housing with reflectors and lenses, pure Lambertian radiation pattern assumption is not practical for V2LC applications employing LED arrays such as headlights and taillights. However, certain vehicle lights, utilizing single LED, can be approximated to Lambertian radiation model as detailed in Section 2.2.

2.1. Lambertian model

Single LED sources are generally designed to have Lambertian beam distribution where the spatial luminous intensity distribution is a cosine function of Lambertian order and half-intensity beam angle.

Optical channel gain of the Lambertian radiation pattern is defined by,

$$H(0) = \begin{cases} \frac{(m+1)A_{pd}}{2\pi d^{\gamma}} cos^{m}(\varphi) T_s(\theta) g(\theta) \cos(\theta), & 0 \leq \theta \leq \theta_c \\ 0, & elsewhere \end{cases} \tag{2}$$

where d is the inter-vehicular distance, $\boldsymbol{\varphi}$ is the irradiance angle, $\boldsymbol{\theta}$ is the incidence angle, $\boldsymbol{\theta_c}$ is the PD field of view (FOV), $\mathbf{A_{pd}}$ is the active receiver area of PD, γ is the path loss exponent, $\mathbf{T_s}(\boldsymbol{\theta})$ is the filter gain, $\mathbf{g}(\boldsymbol{\theta})$ is the gain of an optical concentrator calculated by,

$$g(\theta) = \begin{cases} \frac{n^2}{sin^2(\theta)}, & if |\theta| \leq \theta_c \\ 0, & if \ |\theta| \geq \theta_c \end{cases} \tag{3}$$

in which n is the internal refractive index of PD and m is the order of Lambertian model specifying transmitter directivity and obtained by,

$$m = -\frac{\ln 2}{\ln(\cos \varnothing)} \tag{4}$$

where $\varnothing$ is the half-intensity beam angle of an LED. The coverage range and radiation pattern of single LED light is affected by the half-intensity beam angle $\varnothing$ such that narrower $\varnothing$ increases the illumination range. The average received optical power $\mathbf{P_r}$ is computed by;

$$P_r = H(0) P_t \tag{5}$$

Half-intensity beam angle of a single LED light can be accessed through data sheets provided by manufacturer. Moreover, PD and optical receiver-related parameters such as $\mathbf{A_{pd}}$, $\mathbf{T_s}(\boldsymbol{\theta})$, $\mathbf{g}(\boldsymbol{\theta})$are also accessible through product specifications. Irradiance ($\boldsymbol{\varphi}$) and incidence angle ($\boldsymbol{\theta}$) values can be calculated through the relative locations of the transmitter and receivers on the vehicle.

2.2. Approximated Lambertian model

LEDs are encapsulated in automotive light housing with collimating and diffusing optics including lenses and reflectors. Thus, headlight, taillight, or stop light can be considered as a single radiation source. Furthermore, the half-intensity beam angle of a single LED is no longer applicable to Eq. (1) in order to obtain the optical channel gain. Additionally, for mobile scenarios, path loss component (γ) is directly related to half-intensity beam angle due to rapid irradiance and incidence angle variations. Single LED light without a lens, emits optical power within a smaller angle. Thus, path loss exponent is more prone to fluctuations with vehicle mobility. On the other hand, vehicle LED lights employing either a lens or reflector, provide increased irradiance angle when compared to a single LED and experience less fluctuations sourced by the mobility.

Half-intensity beam angle of a vehicle light is not specified by manufacturers and can be estimated through measurements. In order to model the VLC channel practically, path loss exponent also needs to be estimated through received optical power measurements for various light conditions.

Linear least squares algorithm is used in Ref. [11] to estimate the half-intensity beam angle and path loss exponent. In **Figure 3a**, optically received power comparison between ideal Lambertian radiation pattern and the measured power levels from an automotive LED fog light is demonstrated. **Figure 3b** depicts the estimated Lambertian radiation pattern whereas the measured radiation pattern is shown in **Figure 3c**. Half-intensity beam angle is estimated to be 50.66° while the path loss exponent is calculated as 1.8139 according to the nighttime static measurements. It can be observed that, decremented patterns for both the estimated Lambertian model and the actual measured fog light are consistent. However, the actual measurements indicate the increased intensity due to vehicle light optics.

Vehicle light irradiance angle upper limits are defined with the automotive lights regulation [12]. According to the regulation, vehicle fog lights are expected to illuminate upto 26° . viewing angle. In **Figure 4**, regulation compliant measurement resulted from an off-the-shelf automotive fog light is depicted. It can be concluded that, received power decreases with both the increasing distance and angles. Power degradation depending on the incidence angle should be highlighted, when compared to RF-based vehicular communications. However,

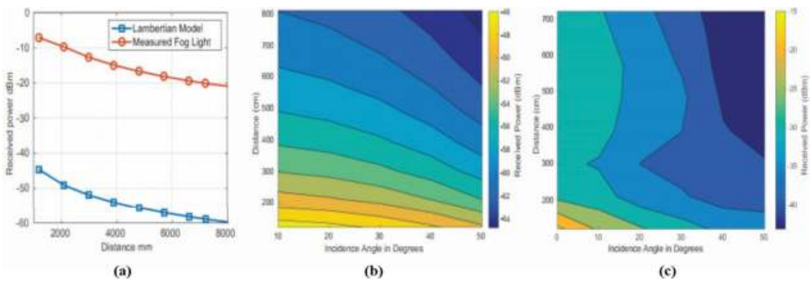

Figure 3. (a) Ideal Lambertian vs. measured model radiation pattern; (b) estimated Lambertian radiation pattern; and (c) measured radiation pattern.

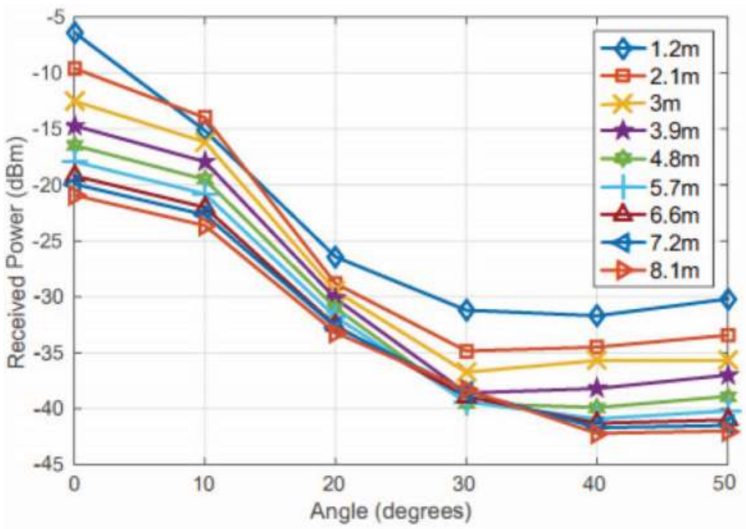

Figure 4. Off-the-shelf automotive fog light received power measurements.

apart from the traditional vehicle lights, newly developed custom pattern generating LED lights such as matrix LED automotive lights are foreseen to provide a flat illumination and stable optical power, similar to RF radiation [13].

3. V2LC receivers

PDs, PD arrays, or cameras can be employed as V2LC receivers. Depending on the sensors FOV, location and lens selection plays a key role to realize practical V2LC applications. Sunlight and artificial background lights are also supposed to be considered at the receiver side. Direct exposure to sun light causes either saturation or excess shot noise at the image sensors resulting with inability to detect intensity-modulated signals. In Ref. [14], direct current (DC), suppressing front-end circuit usage, is proposed to suppress noise sourced by sunlight. Artificial light sources such as advertising boards and traffic signals are usually operated at the 60 Hz AC voltage and its harmonics. Hence, modulating V2LC LEDs in the order of at least a few hundred kHz to a few MHz is beneficial to minimize artificial light noise effects.

PDs target high-rate VLC, whereas cameras are foreseen to support low-rate VLC with positioning capabilities. Current vehicles with automatic headlight and rain sensors are already equipped with PDs. On the other hand, the number of vehicles with cameras is increasing to enable features such as forward collision warning, pedestrian detection, traffic sign detection, and lane keeping. Both camera and PD sensors are located in the middle of the windshield above the rear-view mirror. Even though the already deployed image sensors can be utilized for V2LC, experiments in Ref. [15] located the sensors, around the headlights and taillights to evaluate the performance dependence to the multipath reflections from the road.

Responsivity of PDs is a measure of the sensitivity of PD to the light input. It is defined as the photocurrent ratio (**I_p**) to the incident light power (P) at a given wavelength by;

$$R_p = \frac{I_p}{P} \tag{6}$$

Figure 5 depicts typical spectral responsivity of a low-cost silicon PD, which can be employed in vehicles as a V2LC receiver.

Fraction of the incident photons contributing to photocurrent is defined as the quantum efficiency (QE) of a PD, given as,

$$QE = \frac{R_{p\ observed}}{R_{p\ ideal}} \tag{7}$$

QE is known as the capability of a PD to convert light energy to electrical energy. In **Figure 6**, QE variations sourced by operating temperature are demonstrated.

White LED's spectral response (**Figure 7a**) depicts that the blue component is dominant, whereas for the tail and stop lights, red component in the wavelength interval of 600–640 nm is dominant (**Figure 7b**). Hence, it can be concluded that different PDs should be employed for the front and rear of the vehicles as the front PDs are expected to capture red LED taillights whereas the rear PDs are foreseen to capture white LED headlights.

V2LC systems can also utilize readily deployed vehicle on-board cameras. Camera usage effectiveness heavily depends on image processing or computer vision techniques for emitter

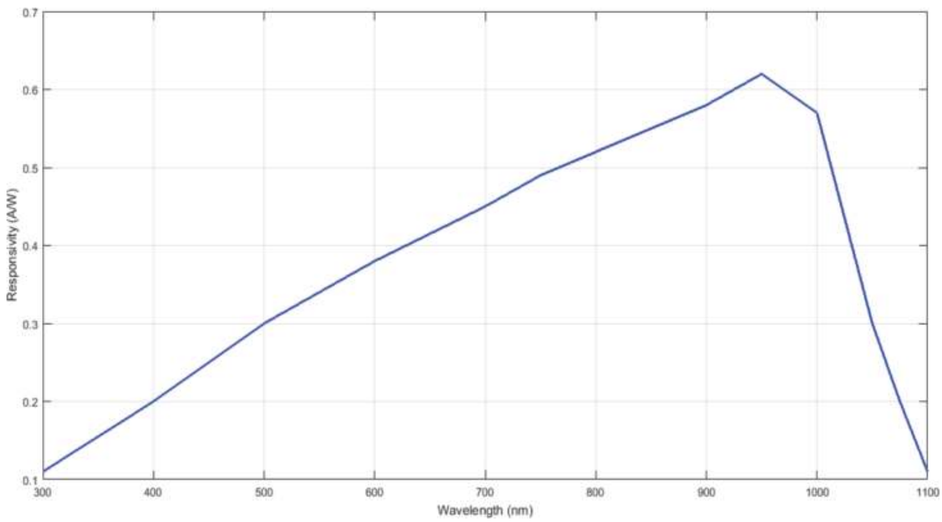

Figure 5. Typical spectral responsivity of Si-PD (Thorlabs PDA100A).

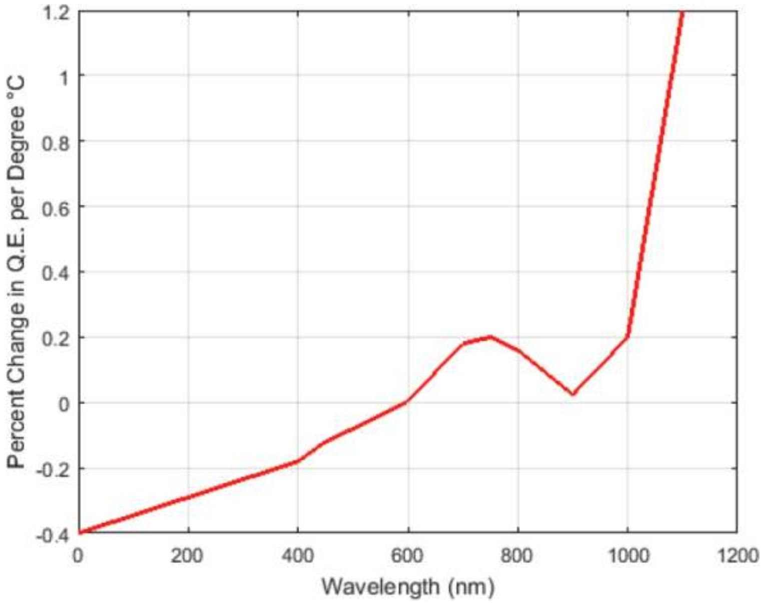

Figure 6. Temperature dependence of quantum efficiency.

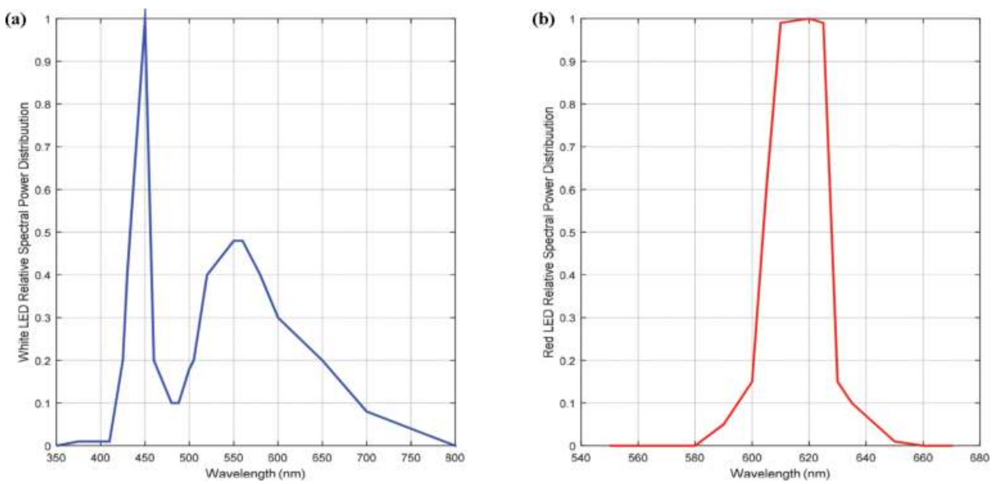

Figure 7. (a) White automotive LED spectral response; (b) red automotive LED spectral response.

finding and tracking. On-off-keying (OOK) and rolling shutter effect-based modulation schemes are proposed to be applicable for V2LC applications.

High speed camera with 1000 frames/s (fps) is shown to provide road to vehicle VLC upto 60 m distance at 4 kbps rate with a BER of. 10^{-3} [16].

Photodetector	Wavelength (nm)	Responsivity (A/W)
Silicon PN	550–850	0.41–0.7
Silicon PIN	850–950	0.6–0.8
InGaAs PIN	1310–1550	0.85
InGaAs APD	1310–1550	0.8

Table 1. Typical photodetector characteristics.

Using camera with customized image sensor, 10 Mbps data rate is achieved in Ref. [17], whereas 45 Mbps without bit errors is achieved in Ref. [18].

Currently, off-the-shelf image sensors utilized in the vehicles have extended dynamic ranges upto 120 dB with approximately 30 fps capture rates. Therefore, off-the-shelf automotive cameras provide superior detection capabilities for various light conditions but the data rate is limited to 15 bit/s (bps) or less to satisfy the Nyquist frequency requirement. Furthermore, additional time needed for image processing to detect and track the LED transmitter, should carefully be considered to fulfill communication latency requirements (**Table 1**).

4. V2LC channel

4.1. V2LC dimming support

It is possible to dim LEDs to an arbitrary level depending on the application requirement in order to save energy. Dimming capability of LEDs makes them also favorable for vehicle lighting. Depending on day light conditions, vehicle lights are expected to change their brightness to prevent glare and increase road safety while providing energy efficiency with the dimmed LEDs. Furthermore, dimming capability of vehicle LED lights gains attention in terms of life span, as dimmed LEDs require less current; hence produce less heat, which extends lifetime of an LED bulb. Dimming is provided via changing the forward bias current through the LED. In terms of communication, dimming has crucial effect on signal-to-noise ratio (SNR), with the achievable data rate and BER. Thus, detailed analysis of dimming effects on V2LC and proper dimming methods or protocols should be developed to provide the right trade-off between illumination and communication. Analysis of dimming functionality and efficient dimming techniques in V2LC systems will contribute to the safety and allow the vehicular system to have full control over the lighting output.

V2LC systems are foreseen to be designed in a fashion where data transfer is maintained while the LEDs are dimmed. Two different dimming schemes are proposed at the IEEE 802.15.7 standard [19]. Using OOK modulation, additional time slots for the on and off times are considered, where these time slots decrease the transfer data rate and keep the maximum communication distance constant. Furthermore, on and off level light intensities can be redefined to achieve dimming with OOK modulation where the data rate is kept constant with dimming. Adding compensation symbols to match target dim level is classified as the time

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domain approach whereas changing intensity levels or frequencies of message symbol occurrences is regarded as intensity domain approach [20] in the VLC dimming literature.

Intensity domain approach is utilized with the DC bias scaling. In DC bias scaling, to decrease brightness up to 25%, OFF symbol DC bias level is increased and ON symbol DC bias level remains constant. For further dimming upto 75% of the regular illumination, ON symbol bias level decreases while keeping OFF symbol DC bias level constant.

Compensation symbol adding decreases bandwidth usage, hence limits high data rate communications. Therefore, intensity domain approach provides more advantage in terms of high data rates.

Figure 8a depicts the received power with dimming support and **Figure 8b** denotes the DPDR performance for four dimming levels of a VLC hardware adapted for V2LC using off-the-shelf automotive LED fog light. Intensity domain approach is utilized where dimming level 0 denotes the minimum intensity and the dimming level 9 denotes the regular brightness level. Outdoor measurements, emulating platoon distances upto 5 m are conducted at static scenarios where the transmitter and receiver units are aligned at 36 cm height. 100 packets are conveyed to evaluate the data packet delivery ratio (DPDR) with respect to dimming levels. Dim level is shown to have crucial effect on communications, as 100% DPDR is achieved with normal brightness at 10 m distance while no packet delivery is possible at 5 m distance with dimming. It is eminent to note that, with the intensity domain dimming, even though the target data rates are preserved, communication reliability decreases as the decreased ON signal intensity levels lower the detectability of ON-OFF signal differences. However, utilizing time domain dimming approaches, increased reliability can be expected as the optical power levels of the message signal remains constant and the power differences between ON and OFF signals stay more detectable at the receiver.

Experiment results indicated that, knowing the distance from the receiver, vehicle LED dim levels could be adjusted to ensure reliable data dissemination while preventing sudden glare for safety reasons. High mobility of vehicles requires adaptive dimming schemes to guarantee communication reliability with road safety and energy efficiency.

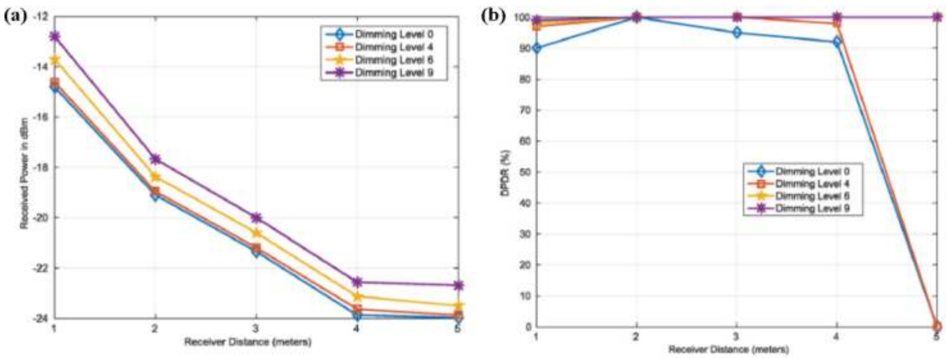

Figure 8. (a) Received power with dimming support; (b) DPDR for four dimming levels.

Considering the variable pulse-position modulation (VPPM), pulse width is varied to control dimming. However, changing pulse width, data transfer rate remains constant whereas the maximum communication range decreases. Vehicle LED lights are already employing pulse-width modulation (PWM) scheme to prolong the life cycle of LEDs and obtain energy efficiency. Hence, combining pulse-position modulation (PPM) with PWM, VPPM can be deemed as a favorable modulation technique to utilize dimming property of LEDs. Moreover, for the applications targeting constant following distances such as platoons, as the maximum communication distance is already limited, keeping transfer rate constant becomes more favorable. Dimming support for OOK and PPM are well defined and can effectively be utilized. However, inter-symbol interference with the OOK and PPM limits the achievable spectral efficiency and Gbit/s data rates.

LEDs dynamic range is crucial to prevent nonlinear distortion sourced by the clipping of OFDM signals. Hence, linear working region of vehicle LEDs plays a key role for efficient dimming support of V2LC devices.

5. Secure vehicular communications through V2LC

One promising application area of V2LC is vehicular platoon where a group of cooperative adaptive cruise control (CACC) vehicles kept in close proximity through DSRC. In the vehicular platoon, inter-vehicular space gap is less than 15 m at vehicle speeds less than 100 km/h [21]. On the other hand, VLC communication range has been demonstrated to be 100 m for headlights and 30 m for taillights [15]. Moreover, the light directivity and impermeability of the optical signal through vehicles and obstacles provide more secure communication than DSRC by limiting the transmission area. This limited transmission area restricts the availability of the data to the attackers, while still allowing communication in the vehicular setting. However, utilizing only VLC in vehicle platoon may degrade communication, since VLC is sensitive to environmental effects, i.e., fog, and might have short-term unreachability due to the increase in the inter-vehicle distance and/or LoS on a curvy road. Thus, IEEE 802.11p and VLC hybrid architectures are proposed to provide redundancy for better reliability in vehicular platoons [21–24].

Recently, many researchers are aggressively investigating V2LC for different purposes such as channel characteristics [25, 26], requirements [9, 27–29]. Proposed V2LC schemes were studied either experimentally [5, 9, 15, 27] or via computer-based simulations using the Lambertian property of LEDs [26, 28]. Most of the academic research on V2LC has targeted achievement of high data rates by using advanced modulation schemes [20, 30, 31]. Since the history likes to repeat itself, a common mistake in novel applications was to underestimate the security issues [24]. Currently, the V2LC industry is on the same path again where the V2LC applications have directed researchers focus away from the security issues. However, one of the features that make the V2LC alternative to the DSRC is security.

In this section, we outline the security implications of V2LC and present the possible approaches to secure the vehicular communication. Finally, a case study where a secure V2LC protocol is presented to enable efficient and secure data sharing among vehicles via the usage of VLC directionality property.

5.1. Securing vehicular visible light communication

Vehicular network security attacks can be categorized into three parts as demonstrated in **Figure 9**. In system level attack, vehicle hardware/software or security certificate is targeted by either malicious insider in manufacturing level or by an outsider. Via altering critical vehicle parts such as sensors, a malfunctioning system is intended. Even though the vehicular communication channel is secure, vehicle generates faulty information that has a catastrophic effect on safety. Furthermore, application and network layer attacks targeting vehicular communication may have substantial effects on vehicular communications security. Application layer attacks can be summarized as; spoofing, where an adversary imitates another vehicle within the transmission range and injects wrong information into the network; replay attack, where the disseminated packet is stored by adversary and replayed at a later time to ruin vehicular security, and eavesdropping, where adversary secretly collects the transmitted packet within its transmission range and processes the packet information. Compared to application layer, network layer attacks aim multiuser applications where in denial-of-service (DoS) and distributed DoS communication medium is congested via redundant transmissions. In RF radio jamming, particular geographical locations are attacked via DoS and vehicles in the area are disturbed. Research findings on various types of attacks using the actual vehicle have been presented in the past 5 years [32–35].

In real-world V2LC deployment, the communication needs to be protected against predefined security attacks. Moreover, to ensure the security in V2LC, three requirements; authentication,

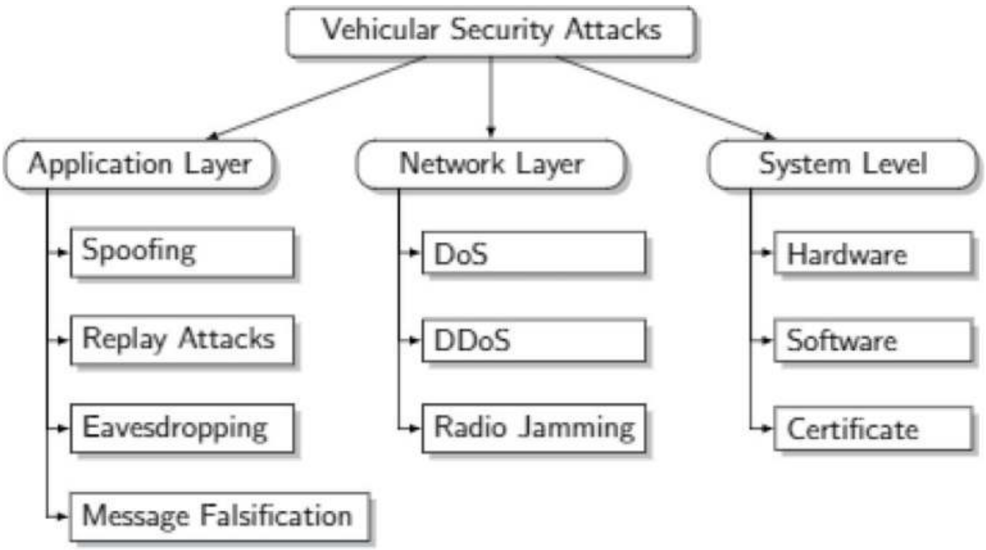

Figure 9. Categorization of vehicular network security attacks.

confidentiality, and integrity must be satisfied. Authentication confirms the identity of the vehicle and gives permission to authorized vehicles to access the communication medium. Confidentiality ensures only the participating vehicles decode the content of messages. Integrity, on the other hand, confirms that the transmitted data is not modified during over the air transmission. To enable the authentication, confidentiality and integrity for V2LC networks, physical layer protection, stenographic protection, and cryptographic key generation/management security methodologies are foreseen to be exploited.

5.1.1. Stenographic protection

Steganography relies on keeping a secret data within the transmitted message. It can be combined with VLC where a secret message can be placed in existing communication. In V2LC, two endpoints share a secret that defines the camouflage of the message within the communication. Despite the steganography ensures the confidentiality, it suffers from the lack of authentication and integrity. However, hiding a secret light beam in V2LC is worth investigation for devices that do not have resources to run complex operations.

5.1.2. Cryptographic key generation and management

In cryptographic key generation/management, vehicles use secret keys to secure the VLC based on either asymmetric cryptography [36] or symmetric cryptography [37, 38]. In asymmetric cryptography, sender and receiver establish a secret key by using pairs of keys. The public key can be disseminated publicly, while the private key is only known to the owner. Sender and receivers agree upon a secret key using a key establishment protocol periodically. On the other hand, in symmetric cryptography, a shared key between two or more vehicles is used to maintain a private information link. These secret or shared keys are then used in the encryption and decryption of the message at the sender and receiver, respectively.

Allowing access to the secret key by two or more vehicles makes symmetric key encryption vulnerable to security attacks. As an alternative, asymmetric cryptography has been recently proposed for vehicles where group key is cooperatively established via RF communication [33]. The shared group key is then used to secure the communication among vehicles.

Unlike steganography, cryptography ensures the confidentiality via encryption/decryption, integrity with hashing, and authentication by using message authentication codes. The resilience of VLC against jamming attack makes it possible to propose a hybrid architecture where VLC is used for key generation and the generated key is used for securing the both VLC and RF communications.

5.2. Case study

In the case study, a secure light communication protocol, namely SecVLC, is proposed. The unique features of SecVLC are as follows:

1. It uses the directionality property of VLC to ensure only target vehicles participate in the communication.

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2. It utilizes the full-duplex communication where infrared (IR) is the outgoing link to share a secret key and VLC is the incoming link to receive encrypted vehicle data.

3. It operates with keys generation and share mechanism that is used for the data encryption and decryption where data packets cannot be decrypted without generated keys.

SecVLC stands for cryptographic key generation/management where vehicles use IR to share a secret key. After receiving the secret key from the destination, the source encrypts the data packet based on Advanced Encryption Standard (AES) and transmits the encrypted packet via light beams in VLC.

SecVLC is implemented in Java on top of Li-1st transceiver software [39] that is integrated in Keyczar [40] key generation toolkit. Li-1st is the first commercial product of VLC that is manufactured by pureLifi Ltd [41]. It provides an opportunity to rapidly develop and test VLC applications that utilize commercial LED infrastructures. Li-1st consists of transmitter unit (Tx) and PD-based receiver unit (Rx). Tx is attached to two symmetrical LED fog lights [42] where automotive fog lights are preferred due to their wide and flat illumination pattern to minimize reflection by fog. On the other hand, Keyczar is an open source toolkit developed by Google for key generation. Experimental setup parameters are depicted in **Table 2**.

Two Vishay [43] high-speed infrared emitting diodes are utilized as IR transmitter and IR receiver for sharing the secret key between source and destination. Both Tx and Rx are connected to computers for evaluating communication performance. In order to compare the security vulnerabilities of communication medium, scenarios, where vehicles use DSRC and visible light data transmission, namely VLC, are evaluated. The DSRC communication scenario is simulated with the convoy driving implemented simulator, VEhicular NeTwork Open Simulator (VENTOS) [44]. On the other hand, VLC and SecVLC experiments are performed in an outdoor environment as shown in **Figure 10** to take into account the reflections from vehicles and road. Nighttime outdoor measurements are executed to compensate shot noise, sourced by diurnal variations. Our experiment emulates the scenarios that are the front of following vehicle-disseminating commands (i.e., mission orders, mission plan, etc.) with LED

Parameters	Value
LED fog lights ground height	36 cm
LED fog lights separation distance	150 cm
Inter-vehicular distance	2–6 m
Data packet size	100 bytes
Li-first modulation	Pulse-amplitude modulation
Li-1st error correction	Reed–Solomon
Li-1st data rate	5 Mbps
Secret key packet rate	4 bytes
Vishay IR half intensity	18°

Table 2. Experimental setup parameters.

Figure 10. V2LC experimental setup.

fog lights to the rear of leading vehicle proceeding on a curved path. **Table 2** lists the experimental system parameters.

Performance evaluation of SecVLC focuses on the security analysis of SecVLC where the system with a malicious insider is investigated. The malicious insider is a vehicle that is positioned on the road with constant mobility. For each experiment, 100 data packets are sent over the network and malicious insider tries to extract the data content. In security analysis of SecVLC, malicious vehicle's data decoding ratio is analyzed. Data decoding ratio is defined as the ratio of the number of successfully plain text converted data packets to the total number of transmitted data

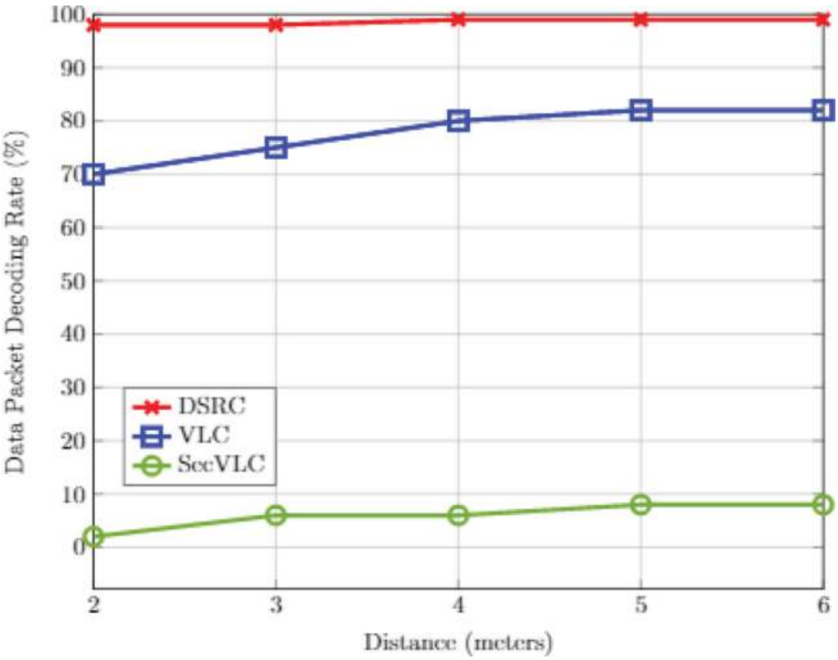

Figure 11. Data packet decoding rate comparison.

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packets. In this scenario, the malicious vehicle receives the data packets and tries to decode the data for subsequent processes such as stealing the vehicle identity information.

Figure 11 demonstrates that adversary vehicle can receive the data packet in both DSRC and VLC scenarios with minimum 70% data packet decoding ratio. In the DSRC, adversary vehicle overhears the channel if it is located in the transmission range (300 m) of transmitting vehicle. On the other hand, VLC limits the adversary data reception due to its directional transmission. However, adversary vehicle still receives the data if it is positioned in headlight coverage. Compared to DSRC and VLC, SecVLC encrypts the data packet and data content can only be decrypted with the secret key. Even if the adversary vehicle overhears the channel, it can only receive plain text control packets transmitted in the initialization phase of the protocol.

Experimental evaluation of SecVLC demonstrates its suitability for securing light-based vehicular communication. In the security analysis of SecVLC, it is observed that despite VLC limits the data reception due to its directional transmission, it is still possible to receive and decode the data packet if the adversary is located inside the light coverage. Furthermore, secret key enabled SecVLC prevents data packet decoding of adversary vehicle even though it is captured successfully.

6. Conclusion

In this chapter, V2LC key features such as automotive LED characteristics, PD features, dimming functionality application to vehicle LEDs, and vehicular communication security enhancement through complementary usage of V2LC are discussed. Apart from indoor VLC, V2LC requires high power LEDs with collimation and diffuse optics to fulfill long-range road illumination for all weather and ambient light conditions. High power LEDs limited switching capability, white LED usage and minimum illumination requirements for road safety upper bound the modulation frequencies.

PD or image sensor selection also plays a key role to realize V2LC practical applications. Receivers located in front of the vehicle are expected to capture taillights in red color, whereas the rear optical receiver sensors are foreseen to capture communication signals transmitted through white LEDs. Furthermore, image sensor or high-speed camera usage is also practiced with various experiments, and data rates above RF-based DSRC communications are achieved. Image sensor usage is also deemed favorable due to positioning capabilities of optical image sensors.

LEDs dimming capability enables energy savings prolong LED life and adaptive illumination for safer traffic. However, considering power and illumination limitations of outdoor environment, time domain dimming schemes providing more SNR at the receiver are regarded to be practical, despite the data rate limitations.

Hybrid usage of V2LC and RF-based DSRC enables enhanced security for vehicular communications. As both technologies can complement each other in terms of data rates, directional communications and range extension, exploiting both technologies for vehicular networks, are demonstrated to be practical in terms of security.

All in all, following advantages of V2LC are believed to make VLC a strong candidate and as a complementary solution for vehicular communications.

- Low complexity and cost: Due to the much smaller multipath effect, and IM/DD scheme, V2LC transmitter design is easier when compared to heterodyne communication systems. Moreover, already deployed LED lights are demonstrated to be capable of supporting V2LC.
- Scalability: V2LC is foreseen to be utilized as a complementary solution for LoS vehicular communications. Hence, the vehicle density increase in crowded traffic scenarios is not expected to cause interference, contention, or packet collision issues, which may degrade the communication performance.
- Security: Malicious attacks and intentional jamming should be made in LoS distances for V2LC networks. Thus, attacker will be exposed with high possibility.
- Compatibility: Electromagnetic compatibility problem is expected to be minimized with V2LC as RF and visible light occupy different parts of the spectrum.

Spectrum availability: Recently, growing interest to use DSRC allocated spectrum for Wi-Fi is declared due to the scarcity of the RF spectrum. However, with VLC, 10,000 times larger license free spectrum availability is favorable to support multiple V2LC channels simultaneously.

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