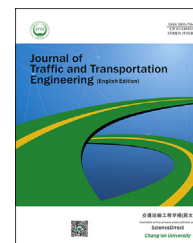


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Review Article

Visible light communication for intelligent transportation systems: A review of the latest technologies

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HIGHLIGHTS

- Recent developments in visible light communication (VLC) technology and its potential use in ITS applications are reviewed.
- Light-emitting diodes (LEDs) and laser diodes (LDs) can be used as transmitters in VLC systems.
- The overall performance of LDs is superior to that of the LEDs.
- LDs can transmit more data over longer distances due to their high quantum efficiency and modulation bandwidth.
- It is recommended to focus more on LD-based illumination in V2V and V2I communications.

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ABSTRACT

In seeking to improve traffic congestion and safety on roads and highways, there has been an increased interest in intelligent transportation systems (ITS). The emerging visible light communication (VLC) technology is a new candidate to enable wireless access in ITS. The purpose of this study is to present a comprehensive review of the current studies related to VLC. Since VLC facilitates illumination and data communication simultaneously, it reduces energy consumption significantly. Additionally, VLC is immune to electromagnetic interference, provides high data security, and utilizes unregulated visible light spectrum, showing promise as a potentially cheaper alternative to existing radio frequency (RF) based technology. Moreover, recent advances in semiconductor materials and solid-state technologies have enabled the development of efficient light-emitting diodes (LEDs) and laser diodes (LDs) which are used as transmitters in a VLC system. Although 10 s of Gbits/s data rate has been demonstrated in indoor VLC links, successful implementation of it in outdoor environments requires further research to overcome the challenges presented by environmental factors, unwanted lights, non-line of sight communication, directional radiation pattern, frequent fragmentation, and so on. Besides, in recent years, semiconductor LDs have been garnering more attention since they can transmit more data over longer distances due to their high quantum efficiency and modulation bandwidth compared to LEDs.

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As a result, urban planners, policy-makers, transportation engineers, and vehicle manufacturers are considering LD-based VLC to facilitate vehicle-to-vehicle and vehicle-to-infrastructure communication. Thus, this paper reviews and compares the most recent developments in VLC technologies, identifies their benefits and potential use in ITS applications, discusses the probable barriers for their implementation in our existing transportation infrastructure, and suggests future research directions and recommendations to overcome these challenges.

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1. Introduction

Internet of things (IoT) through which people and machines are always connected are no longer concepts of the distant future (Huang et al., 2020; Porru et al., 2020; Shirowzhan et al., 2020). This technology is expected to make our lives easier; however, reaping the benefits of such comforts comes at the cost of processing huge data traffic which our present infrastructures are not yet capable of handling. Although we have a high-speed optical fiber internet backbone under our oceans, low-speed internet at the consumer end due to the limitations of radio frequency (RF) technology is posing a challenge. Thus, high data rates at the subscriber level are required to step into the future, and visible light communication (VLC) has been identified as a promising solution. VLC is an optical wireless communication (OWC) that uses the visible spectrum of electromagnetic waves instead of radio frequencies.

Besides, the internet of vehicles combined with other roadside infrastructures (RSIs) is one of the key components of intelligent transportation systems (ITS) which demand newer means of wireless connectivity other than RF and OWC. Existing OWC systems typically use the infrared band of the optical spectrum as a result of the immediately available transceiver technologies which were originally developed for fiber optic systems. However, in recent years, there has been a growing interest in the potential development of the visible light band for vehicular communication. This is due to the recent advances in semiconductor materials and solid-state technologies that have enabled the development of highly efficient light-emitting diodes (LEDs) and laser diodes (LDs). VLC is more advantageous over the RF network systems in many ways such as the utilization of unregulated visible spectrum, absence of electromagnetic interference, superior data security, higher data rate, and so on. In addition, the VLC platform reduces energy consumption to a great extent by facilitating illumination and data communication simultaneously.

Also, in recent times, the requirement for electricity has been skyrocketing with the exponential rise in the use of various technologies in our daily lives. Around 19% of the total electricity produced in the world is utilized for illumination (AlShunaifi, 2014). Consequently, to reduce electricity consumption, energy-efficient lighting in the form of semiconductor LEDs is now being implemented everywhere. Due to its low energy consumption, pleasant light, higher efficiency, and longer life span compared to incandescent

bulbs, LEDs have already established their position as reasonable lighting technology. Moreover, newer generations of LEDs have other attractive features such as high tolerance to humidity, lower power consumption, and reduced heat dissipation. Thus, governments worldwide are planning to phase out incandescent bulbs and fluorescent lights in favor of adopting more energy-efficient LED technologies.

Moreover, LEDs are widely being used in headlights/tail-lights of vehicles and RSIs such as advertising displays, dynamic/variable traffic signs, traffic signals, street lightings, etc. Such an arrangement presents a great opportunity for creating a connected VLC network that facilitates communication between vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I). For instance, Fig. 1 shows a sketch of V2V and V2I communication, illustrating how all these units are connected in a network. In this scenario, vehicles with front and back LED-based light sources can communicate with each other, with other units, and with the main network at high speeds which offers a great many benefits to the end-users. This is also true for LD-based light sources.

However, the use of LEDs in visibility limiting environmental conditions (such as fog and vehicular exhaust) and street heat, which can cause scintillation effect (depending on the distance), warrants further research. In addition, the performance of LEDs suffers from limited modulation bandwidth (Ghione, 2009) and output-power non-linearity (Khalid et al., 2012) (low quantum efficiency at elevated current injections). As a result, extensive work is being carried out to improve these fundamental performance parameters. Alternatively, semiconductor LDs have been garnering attention in recent years, and soon they are expected to

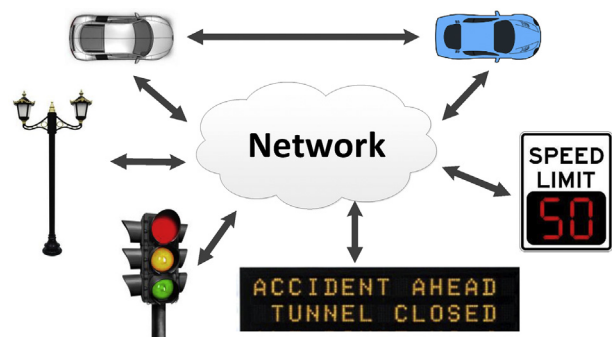


Fig. 1 – Different elements in a VLC vehicular network.

replace LEDs. In other words, the possibility of acquiring high quantum efficiency, smaller footprint, and modulation bandwidth offered by these devices, compared to their LED counterparts, has shifted the current research paradigm towards visible LD-based lighting and VLC.

2. Research method

The articles used in this study were collected from well-respected academic databases such as Web of Science, Scopus, ScienceDirect, Sage, and Emerald. Several keywords such as “VLC”, “ITS”, “smart city”, “V2V”, “V2I”, “vehicle-to-everything (V2X)”, “RF”, “LED”, “LD”, “transportation network”, and “vehicular network”, were used to identify related articles. The period under review was from 2007 to 2020, which led to the identification of more than 200 articles. To select specific articles, a two-round selection technique was utilized. In the first round, titles, abstracts, and keywords of the selected articles were checked to identify work that is related to the scope of the current review. In the second round, detailed reading and analysis were conducted to ensure that the selected articles were related to the objectives of the review. Lastly, more than 80 articles were selected and utilized in this review study.

3. VLC architecture

VLC addresses the visible region of the electromagnetic spectrum as a means of communication. The visible spectrum of the electromagnetic wave is ranged between 380 and 780 nm (400–800 THz). In general, application (APP), media access control (MAC), and physical (PHY) layers build up the architecture of a VLC system (comprising of transmitter and receiver) as illustrated in Fig. 2 (Khan, 2017). The Institute of Electrical and Electronics Engineers (IEEE) has defined and standardized the PHY and MAC layers as IEEE 802.15.7 to simplify the discussion of the VLC system architecture (Ley-Bosch et al., 2016). Accordingly, the following sub-sections present a discussion of these two layers.

3.1. Physical layer

The essential physical elements of a VLC system are illustrated as a block diagram in Fig. 3. In this system, the desired information is first converted to a digital binary sequence which is then modulated in an encoder. Next, LED/LD works as a transmitter that converts the modulated electrical signal to an optical signal. At the receiver end, an optical filter is placed before the lens to filter out any unwanted

signals. The lens then focuses the light beam to send it to the photodetector. The photodetector then converts the optical signal to an electrical signal and sends it to an amplifier. The amplified reconstructed signal is finally decoded to extract the transmitted information.

Besides, the data rate in a VLC link largely depends on how the transmitter (LEDs/LDs) is modulated. On-off-keying (OOK), a single carrier modulation format, is the most common of all formats. It is simply turning on and off the transmitter in a megahertz to gigahertz frequency range to send a data bit of either 1 or 0. This direct modulation technique has been used extensively to demonstrate high-speed communication (Liu et al., 2017; Oubei et al., 2015; Shamim et al., 2019).

Other single carrier modulation formats like pulse amplitude modulation (PAM) (Li et al., 2015; Lu et al., 2016a) and pulse position modulation (PPM) (Kong et al., 2015; Yoo et al., 2016) have also been employed to demonstrate high data rate VLC link. High order PPM is advantageous because of its higher power efficiency; however, the spectral efficiency is compromised in PPM. PAM solves the problem of spectral efficiency by trading off power efficiency. A compromise between the advantages and disadvantages of PAM and PPM is OOK, making it more popular in comparison (Béchadargue et al., 2019).

In recent years, however, multi-carrier modulation format like orthogonal frequency division multiplexing (OFDM) has been a quite popular way to enhance the data rate in a VLC link. In this modulation format, data are sent parallelly through orthogonal sub-carriers which can be modulated by its phase and amplitude, namely phase-shift keying (PSK) and quadrature amplitude modulation (QAM). Depending on the number of sub-carriers used and the order of QAM, the data rate can be increased significantly.

3.2. Media access control layer

The MAC layer in a VLC system controls the access of various users to the network. In the case of ITS applications, the users could be vehicles, RSI, traffic lights, traffic signs, etc. Thus, various forms of vehicular VLC, such as V2V, V2I, V2X, etc., are formed. To allow synchronization and priority of seamless data flow among these units, various network topologies are considered in the IEEE 802.15.7 standard, namely peer-to-peer, star, and broadcast, as depicted in Fig. 4.

Peer-to-peer topology can be applied in the presence of line-of-sight between units such as two vehicles. Whereas, in the star topology, the communication between the units is coordinated in a small cluster. Several of these clusters can then form a bigger network—an essential feature of the MAC layer that allows a citywide network of the vehicles. However, having multiple units/nodes in a cluster reduces the

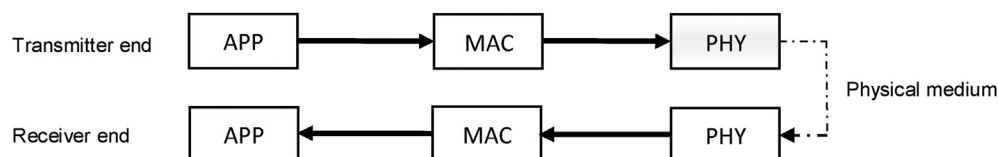


Fig. 2 – Layers in the VLC architecture.

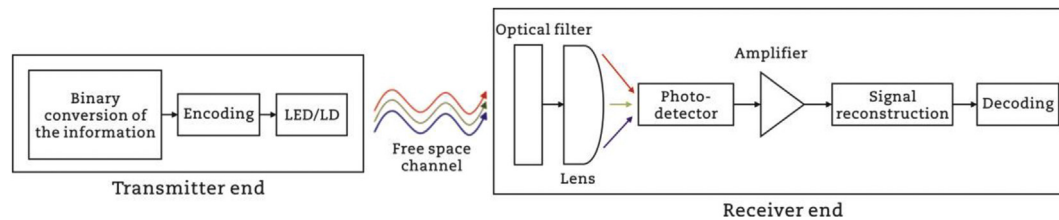


Fig. 3 – Block diagram of a VLC system.

percentage of successful transmission by reducing the throughput of the network (Makvandi and Kavian, 2019). Furthermore, in broadcast topology, a particular unit has the right of single direction communication with the other units in its coverage area. This feature can be used when a traffic control sign communicates with vehicles in a vehicular VLC network.

Besides, the performance of these topologies has been discussed in various reports. For instance, Dang and Mai (2019) used the star topology as the MAC layer and assessed the impact of the physical layer error on its performance. In addition, an experimental implementation of the I2V2 V architecture was proposed in Nawaz et al. (2019) which shows a very low latency of 10 ms—a desirable safety feature for ITS applications—for a distance of 50 m.

On the other hand, the MAC layer also performs other tasks in the vehicular network such as ensuring mobility, dimming, visibility, security, flickering mitigation support, etc (Khan, 2017). Nevertheless, providing a reliable link between peer MAC entities is a challenge and requires further research as they include not only vehicles but also other mobile devices equipped with different wireless modules (Arenas and Pau, 2019).

4. General VLC applications

VLC comes with interesting features in communication that would otherwise be either impossible or very hard to come by. For instance, VLC makes localization of positioning of an object possible which can complement or supplement the use of GPS in various situations (Alam et al., 2019). In any case, VLC localization is low latency and a more accurate alternative to

the GPS. Besides, applications like smart parking systems have been proposed using VLC technology where parking information and direction guidance can be provided to the drivers by using illuminating devices such as LEDs and LDs (Kim et al., 2014). Similarly, another interesting application of VLC is the communication of the information displayed on signboards to other devices, providing real-time useful information through faster wireless local area networks. VLC can also be implemented in hospitals, airplanes, big halls, and other confined places where high data rate communication is required.

Moreover, due to the exponential growth of artificial intelligence, IoT devices are becoming part and parcel of our daily lives. We are living in an era where machines can communicate with other machines, easing our tasks significantly. However, such a lifestyle needs to be backed by huge data traffic which our current technologies are unable to solve and handle. Here again, VLC, due to its high bit-rate communication capabilities, presents itself as a great solution. At the same time, VLC also provides the best solution for data security by physical means. Since visible light cannot penetrate solid objects, the data in a closed room is safe physically. This feature can be of special interest to data centers that are always vulnerable to outside threats.

Besides, VLC is a free-space-based communication link, making it very suitable for ITS applications. To this date, most of the VLC demonstrations have been exhibited in indoor environments except for a few sporadically presented works on outdoor VLC channel modeling such as Lee et al. (2012, 2019). Specifically, in Lee et al. (2009), the effect of solar irradiance is modeled using the SPCTRAL2 simulation tool (Bird, 1984). The effect of artificial light sources is further incorporated in the VLC channel model based on either

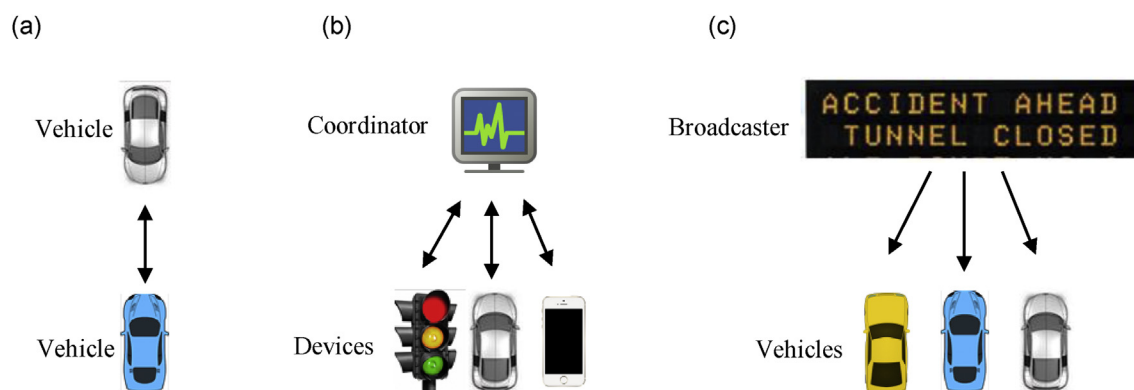


Fig. 4 – Topology of MAC layer in IEEE 802.15.7 standard. (a) Peer-to-peer. (b) Star. (c) Broadcast.

some measured data or simulation results. While these initial works point out the differences between indoor and outdoor VLC channels, systematic channel modeling, and characterization of outdoor VLC channels still demand a rigorous investigation, particularly considering the ITS environments and scenarios.

Outdoor VLC is particularly challenging due to various natural elements such as fog, solar irradiance, temperature, dust, wind, etc. Accordingly, [Kim et al. \(2015\)](#) studied VLC link in a foggy environment and found that the signal to noise ratio (SNR), a parameter that determines the quality of the data transmission, drops significantly (at least by 12 dB) when the visibility reduces from a clear to extremely foggy weather ([Kim et al., 2015](#)). Similar investigations were conducted using near infra-red LDs in the desert ([Esmail et al., 2017](#)) and coastal ([Alheadary et al., 2017](#)) environments.

On the other hand, the application of the VLC is not only restricted to our local surroundings, rather its horizons span even under the water and into space. Recently, [Amanor et al. \(2018\)](#) proposed a communication link among the satellites that are being used in the earth's orbit, so they can communicate with each other. Likewise, NASA has already started projects to incorporate VLC in international space stations. This will provide low latency and highly reliable communication links from the earth to space and vice versa ([Granath, 2015](#)).

Similarly, underwater optical wireless communication using visible LDs ([Shen et al., 2016a](#)) and LEDs ([Wang et al., 2016](#)) has recently gained much popularity due to its potential applications in undersea communication and exploration. Since visible light performs better than sonar and RF communication under the water, it is of particular interest to underwater researchers who explore the mysteries of the ocean using submarines and underwater vehicles. As a result, a rigorous study on the effects of the temperature gradient, wave, scintillation, and other parameters has been done by [Kang et al. \(2019\)](#). Hence, VLC in an underwater environment shows promise to fulfill the growing data rate requirement in underwater networks, facilitating ocean studies, seismic monitoring, seafloor surveys, oil explorations, and so on.

5. VLC in vehicular communication

Lately, there has been a growing interest in the implementation of VLC technology to improve traffic congestion and safety on roads and highways. Accordingly, many vehicles already use LED lamps; at the same time, the number of vehicles using LDs is increasing ([Audi Technology Portal, 2015](#); [Photonics Media, 2020](#); [Ulrich, 2013](#)). Traffic lights and signage along with streetlamps are also implementing LED technology, creating massive opportunities for various vehicular communications. Vehicles with LED/LD front and backlights can communicate with each other at higher speeds and lower latency compared to RF-based technologies. Furthermore, VLCs offer some inherent advantages such as a high degree of spatial confinement, allowing a high reuse factor. Besides, a vehicular VLC

network consists of vehicles, also referred to as onboard units (OBUs), and roadside units (RSUs) such as traffic lights and streetlamps where both the OBUs and the RSUs can be used as simultaneous transceivers. In this system, the RSI network helps connect the RSUs to the backbone network.

However, research on VLC-based vehicular communication is sparse. Early studies on the use of LEDs for V2I communication (optically transmitting data from traffic signals to vehicles) were based on a 1997 US patent ([Hochstein, 1996](#)). An evaluation of such a traffic information system based on the performance of basic parameters like the power received and the SNR has been outlined in [Akanegawa et al. \(2001\)](#). Another performance evaluation study, which considers the communication between a street light and a vehicle, has been reported in [Kitano et al. \(2003\)](#), and the received SNR has been obtained for two common types of road surfaces, namely asphalt and concrete. In [Nagura et al. \(2010\)](#), V2I and VLC by means of using a camera (as a receiver) have been investigated, which is rather costly for widespread usage.

Nonetheless, [Wang et al. \(2015\)](#) performed an outdoor experiment in 2015 in which they were able to transmit an aggregated data rate of 1.8 Gb/s in a free-space channel of 50 m. Later, [Cailean et al. \(2018\)](#) successfully demonstrated a VLC link covering 130 m between a traffic light and a vehicle by employing phototransistor-based VLC sensors, noise mitigation techniques, and advanced signal processing techniques. Whereas, a comprehensive analysis of line of sight communication link under the influence of solar radiation and artificial light sources were characterized by [Cui et al. \(2011\)](#). Their investigation shows that a modulation bandwidth of 3–5 MHz is achievable from the commercial LED traffic lights used in the streets. Also, in this study, they demonstrated a 1 Mbit/s communication using the traffic LED as a transmitter covering a distance of 75 m. Soon after, [Liu et al. \(2018\)](#) demonstrated the potential of the vehicle headlamp by achieving a data rate of 315 Mbps in a channel of 3 m length in a laboratory environment.

In addition, various modulation techniques have been investigated to identify a suitable scheme for outdoor VLC, especially in V2V and V2I scenarios. For example, [Dahri et al. \(2019\)](#) demonstrated 3.5 Mbps of data rate over a distance of 0.5 m and 500 kbps over 15 m in an outdoor environment employing frequency, amplitude, and phase shift keying schemes. Later, [Béchedergue et al. \(2019\)](#) investigated the OOK and OFDM scheme for V2V-VLC communication and found that the OOK link becomes totally jammed, whereas the OFDM scheme is able to handle the narrowband interferences produced by outdoor lighting such as the LED signs. They also concluded that OFDM is more robust than OOK in real-life multipath propagation of light scenarios by demonstrating more than 90% packet reception rate—the ratio between the total number of error-free packets received over transmitted packets—for longer distance in the case of the former scheme. On the other hand, [Kim et al. \(2015\)](#) investigated the performance of SNR in a scenario where the VLC link was established between V2I. In this study, they considered two types of weather conditions, sunny and cloudy, and attained an SNR as large as 16–26 dB depending upon the time of the day.

6. Evolution of LED and LD

When light fidelity (Li-Fi), also known as VLC technology was first introduced by Tanaka et al. (2003), LED was the primary technology behind it due to its widespread availability. Simultaneous illumination and communication are the most attractive features of VLC technology. To serve this purpose, white light generated from concurrent red, green, and blue (RGB) LEDs has been used in the wave-division multiplexing (WDM) VLC system (Lu et al., 2017b). In this system, three LEDs can be modulated and used as the transmitter at the same time, increasing the data rate almost three times. However, collimating the LEDs perfectly to produce white light is an engineering challenge and requires bulky optical components. Instead, a more compact solution is to use phosphor in a blue LED-based transmission system which can convert the blue light to white using an appropriate formula. Although high-quality lighting is achievable by this technique, the spectral efficiency is somewhat compromised which limits the data transmission capacity of the LED.

As a result, to improve the spectral efficiency, μ LED has been introduced in which the active region is small compared to the commercial LEDs, allowing lower spontaneous emission lifetime and higher modulation bandwidth. Although this technology facilitates Gb/s data rate, it suffers from efficiency droop—a phenomenon where the efficiency of the LED drops as soon as the injection current is scaled up. As a solution to this problem, a superluminescent diode (SLD) that ensures high optical output power, broad spectral width, and lower coherency was developed. The light emitted from this kind of source is not only efficient for VLC but also soothing to the eyes. Recently, using a blue SLD, Shen et al. (2019) reported 3.4 Gb/s data transmission employing 16-QAM DMT modulation format.

Although Gb/s data rate is achievable in an indoor environment using μ LEDs (Tsai et al., 2019) and SLDs (Shen et al., 2019), they are hardly efficient in the outdoor environment. LDs come as a solution since it has important features like high optical output power, high coherency, and enhanced modulation bandwidth which are essential for a high bit rate communication. Due to the higher modulation bandwidth of LDs, a very efficient communication link can be established. Similar to LEDs, multi-color LDs have been used in a WDM configuration to demonstrate a 35 Gb/s data rate in an indoor environment of 39 m² area (Chun et al., 2019). To reduce the footprint of the optical setup, an integrated modulator in LD was demonstrated showing 1 Gb/s data

transmission (Shen et al., 2016b). Diffused light communication using a phosphor-coated blue LD has also been investigated where the efficiency of the LD surpasses that of the LEDs. Besides the modulation format, other assisting technique such as optical and optoelectronic injection locking has been demonstrated to further increase the data rate (Li et al., 2017). These assisting techniques are capable of enhancing the modulation bandwidth of the LD significantly, which is the key factor behind higher data rates (Shamim et al., 2018). Such an assisting technique was successfully demonstrated with an achievement of 56 Gb/s by Lu et al. (2017a).

Table 1 summarizes the fundamental differences between LEDs and LDs. As technology is progressing, the LDs are slowly replacing the LEDs owing to their superior performance in both illumination and communication. Higher modulation bandwidth (>1 GHz), enhanced coherency, smaller footprint, and increased efficiency of the LDs is garnering the attention of researchers in this field.

Besides, Fig. 5 depicts the trend of the VLC data rates from 2010 to 2019. From the inception of the VLC-based networking, both LEDs and LDs have been tested. Over the years and especially in the last decade, the data rates of the VLC link have been increasing, owing to advanced modulation format and progress in device technology. Clearly, the data rate has increased from sub-Gb/s to tens of Gb/s. In recent years, the majority of the VLC demonstrations have been based on LDs which appear to be far ahead of LED-based systems in terms of data rate and transmission distance. For ITS applications, long-distance and high bit-rate data transmission are essential, and LDs have been proven to be a suitable candidate.

Moreover, there has also been a shift towards OFDM from OOK over the years. The former is becoming more popular as it allows higher data transmission rates. On the other hand, the transmission distance has increased from 0.23 m in 2010 to longer distances of up to 16 m in 2017. In short, LDs (OFDM) are faring better than LEDs in terms of higher transmission rates and long-distance free-space communications. The transmission distance in meters (m) is indicated within the parentheses, and BtB refers to back-to-back communication in Fig. 5.

7. Barriers to implementation and future research directions

There are several barriers to the successful and effective implementation of VLC in terms of general applications and

Table 1 – Difference between LED and LD.

Item	LED	LD
Footprint (Cantore et al., 2016)	11 mm ² for 60 W incandescent bulb equivalent	0.3 mm ² for 60 W incandescent bulb equivalent
Efficiency droop (Pourhashemi et al., 2013)	Efficiency droop is observed at a higher current density	LD is free of efficiency droop
Modulation bandwidth (Shen et al., 2015)	<100 MHz	>1 GHz
Emission	Spontaneous (broadband)	Stimulated (narrowband)
Lifetime (Wierer et al., 2013)	30,000–50,000 h	About 30,000 h

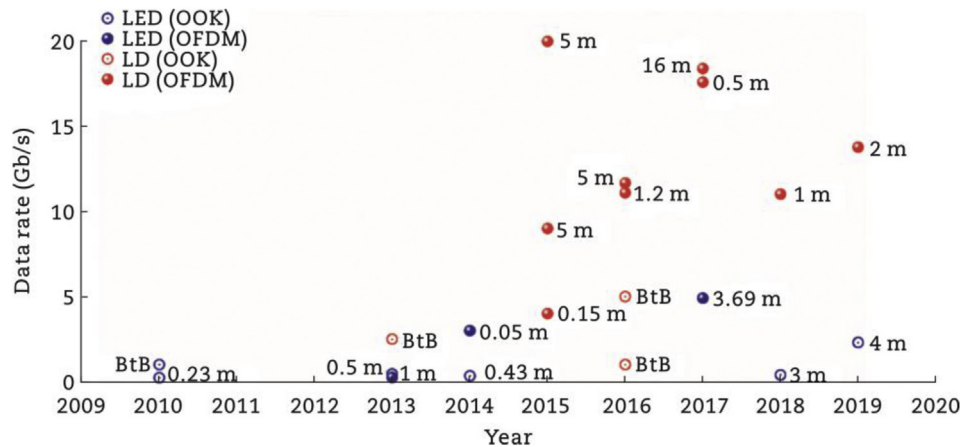


Fig. 5 – Evolution of data rate and transmission distance from 2010 to 2019 using LED and LD as the transmitter and OOK and OFDM as the modulation format (Azhar et al., 2013; Binh et al., 2013; Chi et al., 2015; Fujimoto and Mochizuki, 2013; Huang et al., 2017a, b; Islim et al., 2017; Lee et al., 2015; Lu et al., 2016b; McKendry et al., 2010; Tsonev et al., 2014; Vucić et al., 2010; Watson et al., 2013; Wei et al., 2018, 2019; Yeh and Lu, 2016; Yeh et al., 2018, 2019; Ying et al., 2015).

vehicular communication. Although many of these issues have been investigated over the years, they are still at an introductory stage and require further research focus. The first of these barriers is the influence of environmental conditions such as fog, vehicular exhaust, dust storms, etc., on the performance of VLC systems (Elamassie et al., 2018). Likewise, excessive light from the sun and other sources make it difficult for receivers to register signals transmitting from LEDs/LDs, reducing the signal-to-noise ratio significantly and lowering the efficiency of communication. Hence, the impact of weather and unwanted light in a VLC system needs to be studied further.

Another barrier to successfully transmitting data in a VLC system is that visible light cannot pass through solid objects like walls which limits the transmission range of a VLC link significantly. Although a line of sight channel is required between the sender and the receiver, it is not always attainable in indoor and outdoor environments. However, a recent study by Sun et al. (2017) achieved a data rate of 71 Mbit/s in a misaligned (an angle of 12° between the transmitter and the receiver) free-space VLC link. In addition, they investigated the possibility of non-line of sight communication in an underwater environment (Sun et al., 2018). Nonetheless, non-line of sight communication, which is typically the case in real-life scenarios, needs further improvement.

In addition, the use of VLC in establishing a vehicular network, a crucial component of ITS, has its own challenges (Pina, 2020). For example, VLC transmitters have a directional radiation pattern in contrast to RF sources that typically have an isotropic pattern. Due to isotropic radiation, identifying neighbors and initiating handovers are relatively easier in RF systems. Nevertheless, to benefit from a VLC system's high data transmission rate and to also have weather-resistant access offered by an RF system, a hybrid VLC-RF system could be promising (Chowdhury et al., 2019). Such a hybrid system, comprising of VLC and RF links functioning as complementary technologies, would allow harnessing the

benefits of both technologies while overcoming the limitations of each. However, merging these two technologies could raise more research questions about the compatibility and the efficiency of the resulting hybrid system which is a topic worth investigating further.

Moreover, fast-moving vehicles create a highly dynamic topology in a vehicular network making it difficult for vehicles and RSUs to establish communication links with each other (Pina, 2020). This in turn causes frequent fragmentation during data transmissions such as disruption of an ongoing communication or file transfer between two units of the network. As a solution, cooperative content distribution by which contents of a file are distributed through cooperation between the nodes in a network could be investigated.

It is evident from the evolution of LDs and LEDs since the last decade that the overall performance of LDs is superior to that of LEDs. Accordingly, LDs are likely to dominate VLC applications in the near future. Hence, urban planners, policy-makers, transportation engineers, and vehicle manufacturers are recommended to focus on LD-based illumination rather than LED in vehicles and transportation infrastructures. As a result, the fundamental building block of a VLC system will become widespread, launching numerous ITS-related business opportunities for public organizations, transportation agencies, and telecommunication companies. In other words, the implementation of this technology will highly contribute to building ITS eco-systems and delivering a set of relevant services and applications.

8. Conclusions

Diode-based VLC technology is emerging as a strong candidate to enable wireless access in ITS. Although the technology is in its initial phase, it still offers a wide range of potential applications being a low-cost, license-free, and high bandwidth system. Consequently, in this review, the evolution of two primary

transmitters of a diode-based VLC system, i.e., LED and LD, over the last decade has been discussed. While the data rate of an LD-based VLC system reached 20 Gbits/s in a laboratory environment, it was limited to under 5 Gbits/s in the case of LED. However, various issues such as unwanted light, visibility limiting environmental conditions, scintillation effect, non-line of sight communication, identifying neighbors, initiating handovers, frequent fragmentation of data due to highly dynamic topology, etc., arise when a VLC link is established in an outdoor environment the impacts of which warrant further investigation. Nevertheless, in adverse weather conditions, LDs are expected to perform better than LEDs in terms of providing energy-efficient, cost-effective, and high-speed VLC. As a result, adopting LDs in various ITS applications could be the first step towards addressing some of these challenges. Hence, it is recommended that the present illumination devices in vehicles and transportation systems be changed from LEDs to LDs so that an already established infrastructure is utilized to build a functioning vehicular VLC network.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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