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A Review of Visible Light Communications in Automotive Applications

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ABSTRACT: This paper presents the concept of an intelligent transportation network based on Visible Light Communications (VLC) applications by enabling wireless communication among vehicles and the traffic infrastructure, safety, efficiency, and the Environment and reducing fuel waste. Intelligent Transport Systems resulted in the safer, more efficient, and eco-friendlier movement of vehicles. Considering the numerous advantages of the VLC technology encouraged the survey in automotive applications as an alternative to traditional radio frequency-based communications.

KEYWORDS: Visible Light Communication (VLC), Intelligent Transport System (ITS), Vehicle to Vehicle (V2V) Communication

1. INTRODUCTION

In recent years, modern society has presented an increasing interest in wireless communication technologies, and the demand for wireless data transfer is expected to increase exponentially in the next five years [1]. In most cases, radio frequency (RF) type communications satisfied the solution for this unprecedented demand. Due to the maturity level and wide acceptance, RF communications are now the best solution for wireless communications. However, this technology has its drawbacks, such as limited bandwidth. Besides this, there are some cases or scenarios where RF can cause interferences, such as in aircraft, airports, or hospitals. Meanwhile, the development of Solid-State Lighting (SSL) devices, especially of Light-Emitting-Diodes (LEDs), had tremendous growth. Nowadays, LEDs are highly reliable, energy-efficient, and have a lifetime far exceeding classical light sources. Considering the numerous advantages, LEDs began to be used in more and more lighting applications, and it is considered that, shortly, they will completely replace traditional lighting sources [2] - [5]. Besides these remarkable characteristics, LEDs can rapidly switch, enabling them to be used for lighting and communication.

Visible Light Communication (VLC) represents a new communication technology that uses energy-efficient solid-state LEDs for lighting and wireless data transmission. VLC uses visible light (380-780 THz) as a communication medium, which offers enormous bandwidths free of charge; no law limits it, and it is safe for the human body, allowing for high-power transmissions. VLC has the potential to provide low-price, high-speed wireless data communication. Even if VLC is a new technology, it developed quickly, proving its vast potential. In just six years, the maximum data rate reported for VLC systems evolved from 80 Mb/s in 2008 [6] to 3000 Mb/s in 2014 [6].

Visible Light Communication uses light to transmit information. In addition, the idea behind VLC applications is to provide lighting and communication simultaneously. Thus, VLC systems will always have components to transmit and receive light. In the vast majority of work available in the literature, LEDs are used as transmitters. These LEDs are used to modulate the intensity of light to send data. On the receiver side, photo sensors capture this light directly (Direct Detection), converting it into a data stream [7]. In VLC, lighting illumination brightness mustn't be affected by manipulating light while transmitting the information. Hence, the type of LED impacts the performance of a VLC system.

Figure 1 gives an overview of the architecture of a VLC system. LEDs transmit data through Intensity Modulation. The receiver must be in the line of sight of the LED so that it receives the light beams containing the information. In fact, during light transmission, there will be a loss in light signal quality due to particle diffusion and the inherent interference of ambient light. Filters may be used to reduce interference. At the receiver node, light is incident on the photosensor, directly altering the current. Amplifiers make the signals less prone to interference and noise [8]. Finally, the signal is demodulated to retrieve the original information.

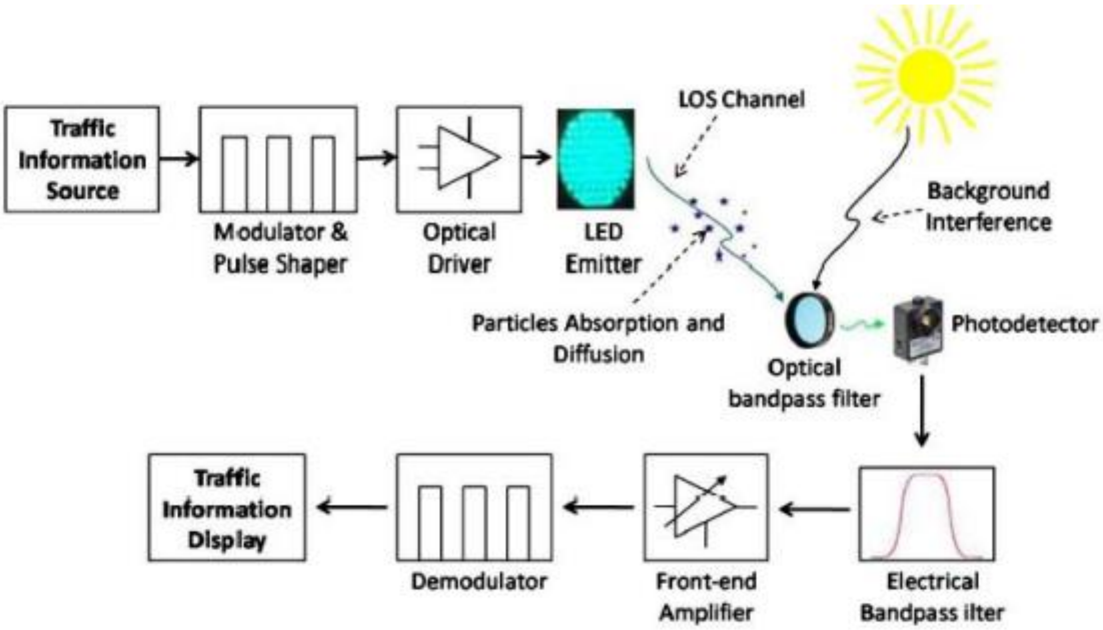

Figure 1. VLC System Architecture, adapted from [9].

Transmitters:

In general, LEDs are used as transmitters in VLC systems. Most commercially available light bulbs contain several LEDs. These light bulbs contain a driver responsible for controlling the current passing through the LEDs, directly influencing the intensity of the illumination. In other words, the current arriving at the LED is controlled by transistors, which manipulate the light signals that the LED emits at high frequency, thus making the communication imperceptible to human eyes [10].

Receivers:

Receivers are responsible for capturing light and converting it into electrical current. Normally, photodiodes are used as receivers in Visible Light Communication systems [11]. However, photodiodes are extremely sensitive and capture waves beyond the visible light spectrum, such as ultraviolet and infrared [12]. They also saturate quickly in an external environment and are exposed to sunlight; for example, the photodiode would fail to receive data due to high interference. For this reason, other components can be used to capture light. The smartphone camera lets any cell phone receive data from a VLC transmitter. In addition to these devices, LEDs themselves can be used as receivers because they feature photo-sensing characteristics [13]

2. INTELLIGENT TRANSPORTATION SYSTEM

Transportation is an essential component of the growing society, so it needs to be more efficient, secure, reliable, cost-effective, and environmentally friendly. The above can be done in one structure known as Intelligent Transportation System (ITS). The number of vehicles that use the transportation infrastructure increases every year. For this reason, it is mandatory to improve the safety and efficiency of the transportation system continuously. Even if the automobile industry has progressed a lot and cars are safer today than ever, road accidents kill more people yearly. More than 1.3 million people die yearly because of car accidents, while 0ver 50 million are injured [14]. Road accidents are the leading cause of death among young people aged between 15 and 29 years due to the slow response and inability of automobile drivers to take the right action at the right time [15]. Furthermore, the forecasts are even worse: it is estimated that 2020 road accidents will be the sixth cause of death, with 1.9 million victims yearly [16] and [17]. In this work, the concern for reducing the number of road accidents and the associated victims is increasing. The United Nations has declared 2010 a Decade of Action for Road Safety to improve the safety of vehicles and roads.

The increasing number of road fatalities is a paradox because today's cars integrate high-quality safety equipment and advanced driver assistance systems. Electronic Stability Control (ESP), Anti-lock Braking System (ABS), or electronic brake-force distribution are some of the most popular active driver assistance systems meant to increase the safety of the transportation system and reduce the number of road fatalities. Each system proved its efficiency on individual vehicles, but the number of crashes increased. Awareness of different vehicles sharing information is needed for the next generation of car safety systems to improve safety. To be able to create a highly efficient road accident prevention system, there is the need to enable cooperation among vehicle-vehicle(V2V) and infrastructure-to-vehicle (I2V) communication to ensure the safety of people, traffic flow, and comfort of drivers, as shown in Figure 2 to increase the safety and the efficiency of the transportation system [18]. ITS relies on reliable, robust, secure communication among vehicles and infrastructure (traffic lights, billboards). ITS integrates advanced wired and wireless communication technologies for data gathering and distribution. ITS has the potential to change the point of view regarding road accidents. If, until now, the problem was how to help people survive accidents, ITS's future objective will be to help people avoid accidents. Enabling wireless communications among vehicles and between vehicles and infrastructure can substantially improve the safety and efficiency of road traffic. Inter-Vehicle Communication (IVC) or Vehicle-to-Vehicle Communication (V2V) systems, as shown in Figure 2, allow modern vehicles to communicate with each other and to share information regarding their mechanical state (position, velocity, acceleration, engine state, etc.) or information about the traffic. At the same time, IVC systems can potentially improve passengers’ comfort.

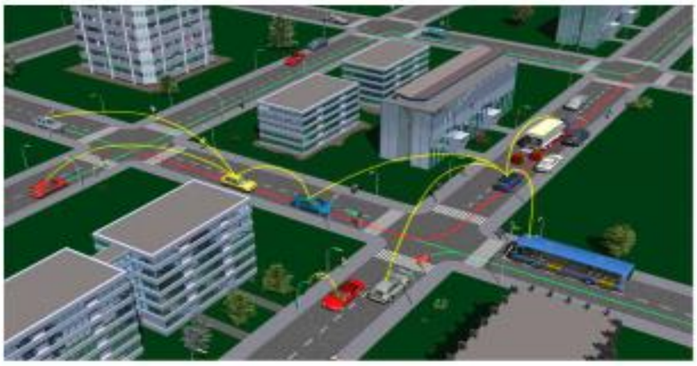

Figure 2: Vehicle to Vehicle communication

ITS adds value to the transportation system by offering real-time access to traffic information. ITS continuously gathers, analyzes, and distributes information to increase efficiency. The collected data automatically adapts the transportation system to different traffic situations. From this consideration, an essential requirement for the ITS is its widespread distribution. For the system to be operative, it needs as many intelligent vehicles as possible to achieve interoperability. Large geographical distribution of the intelligent infrastructure is also required so that the system can gather more data and distribute it efficiently. At the same time, a significant challenge for the ITS is to keep the implementation cost as low as possible without affecting its reliability. ITS is concerned with three significant issues: safety, congestion, and environment. The safety of the transportation system can be improved by increasing vehicle awareness. Studies show that combining V2V and V2I communication has the potential to reduce 81 percent of all-vehicle target crashes annually [19]. Enabling V2I communication can help the transportation system by providing real-time data regarding traffic, data that can help manage transportation to increase efficiency and reduce traffic jams, which can help reduce gas consumption and CO_2 emissions. The benefits of adding intelligence to the transportation system are the efficient monitoring and management of the traffic, which will help reduce congestion and provide optimized alternative routes depending on the traffic situation. Increasing the transportation system’s efficiency will help save time and money and reduce pollution. However, the most crucial benefit of the ITS will be the millions of lives saved. The primary beneficiaries of the ITS are the travelers who will travel safely and will use optimized travel routes, as well as the transportation companies and the industry.

Figure 3: ITS architecture, including the three major components

ITS has three significant components connected by wireless and wired communication technologies. The three components are:

- the intelligent vehicles;
- the intelligent infrastructure;
- the traffic centers.

The interconnectivity of the ITS components is illustrated in Figure 3. Intelligent vehicles equipped with onboard equipment for wireless communication are connected to the intelligent infrastructure, forming a vehicular ad hoc network (VANET) [20]. This is the data-gathering component. Vehicles transmit data to the traffic infrastructure data that is analyzed and redistributed. Intelligent infrastructure also uses wireless communication technologies to communicate with intelligent vehicles and wired communications to connect with the traffic center and for interconnections. The intelligent infrastructure is the connection between intelligent vehicles and the traffic center. This way, the infrastructure has the role of fixed gateways for the communication network while the cars are the mobile nodes. The intelligent infrastructure has two primary functions: data distribution and data collection. It gathers information from the vehicles and sends it to the traffic center. The traffic center analyzes the data, decides the required measures, and distributes the results geographically to vehicles through intelligent infrastructure. The distributed information can be either safety-related information, like accident warnings or traffic sign warnings, information regarding the weather, or messages containing alternative routes. IVC and vehicle-to-infrastructure communication (I2V/V2I) are the two major research preoccupations in developing the intelligent transportation system (ITS). Vehicular communications enable intelligent vehicles that use wireless short-range communications to connect and form the VANETs. V2V communications can address 79% of all vehicle crashes [17]. I2V communications link the vehicles with the road infrastructure through wireless short-range communication technologies. I2V communications can target 26% of all vehicle crashes [17]. An essential component of I2V communications is broadcasting traffic safety information from the traffic infrastructure to vehicles. This way, the presence of stop signs, signal status, speed limit, surface condition, and pedestrian crosswalks is transmitted, helping the drivers/vehicles to take the necessary safety measurements. The other component of the I2V/V2I is the data gathering component. Vehicles transmit data to the traffic infrastructure data that is analyzed and redistributed.

3. RF COMMUNICATIONS

Several technologies were proposed and investigated for communication between vehicles and infrastructures, such as infrared [21], Bluetooth [22], 3G [23], [24], LTE [25], or even combinations of these technologies [26]. However, the strongest focus is radio frequency Dedicated Short Range Communication (DSRC). DSRC is regulated by the IEEE 802.11p standard for Wireless Access in Vehicular Environments (WAVE) [27]. The IEEE 802.11p standard was developed based on the IEEE 802.11a standard but with the improvement of the PHY and MAC layers. The enhancements performed on the standard aim to provide higher robustness and to adapt to the fast movement conditions imposed by vehicular applications. The DSRC channel is divided into 7 channels of 10 MHz for different applications, where each channel is divided into 52 subchannels with a bandwidth of 156.25 kHz. All the safety-related messages are broadcast using the control and center channels. Depending on their criticalities, the messages are categorized into four priority categories to reduce the latency of the high-importance messages. The IEEE 802.11p standard uses the well-known Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) as a collision-preventing mechanism. DSRC involves half-duplex communication with data rates from 3 to 27 Mbps. It uses orthogonal frequency division multiplex (OFDM) as a modulation technique to ensure data multiplex. DSRC aims to achieve communication ranges of up to 1000 meters. Even if the standard were developed considering the difficult conditions of the vehicular application, numerous studies would report issues related to its ability to support vehicular communications. Channel congestion affects communication performances and represents the major impediment to reliable communication [28]. Channel congestion is determined mainly by vehicle density, message generation rate, and transmission range. Since communication-based vehicular safety applications aim to exchange a large amount of real-time dynamic data, it is obvious that this will generate serious issues. In the case of VANETs, the different nodes will increase the channel congestion, causing mutual interference and the phenomenon called a "broadcasting storm" [29]. VANETs are considered extremely dynamic topologies with strict constraints concerning delays and packet delivery. The quality of the channel modifies randomly in time and is difficult to predict since it depends on the behavior of each communication link. Furthermore, each node (vehicle) creates interference that covers an area wider than the covered communication area. Another significant problem in high-traffic densities is the CSMA/CA. Recent studies showed that when such conditions are fulfilled, the behavior of the CSMA/CA is approaching the one of ALOHA, meaning that the nodes transmit their message after a random time without sensing other transmissions [30], [31]. This phenomenon generates packet decoding failure even for communication between nearby vehicles. The failure of the CSMA mechanism in high traffic densities was also observed in [32]-[34]. These aspects are significant, especially in traffic safety applications requiring latencies as low as 20 ms [35]. Under these circumstances, in high traffic densities, such as on highways or in crowded cities, the reliability of communications is rather questionable [36]. Ensuring proper message delivery in high traffic, not even for high-priority messages, was also demonstrated in [37]. This paper concluded that DSRC cannot ensure time-critical message distribution. Analysis of the DSRC in a highway scenario also points out that even if the latency requirements could be satisfied, the reliability requirements are difficult to meet, mainly due to external collisions [38]. The same study points out that the hidden node is a stringent problem in the highway scenario, significantly affecting the packet delivery ratio. In addition to channel congestion, the Doppler spread is another disturbing phenomenon affecting the DSRC. The Doppler spread causes signal spread, leading to a broader spectrum than the transmitted signal. The channel variations cause sub-carrier interference, which degrades the performance. The Doppler spread negatively affects BER and throughput performances [39]. The effect of the Doppler spread is proportional to the velocity of the vehicles and the distance separating the vehicles [40]. The multipath effect is also a perturbing phenomenon for DSRC. The multipath distortions are mainly caused by different length paths resulting from unwanted reflections. Due to the highly dynamic nature of VANETs, this application area is characterized as a rich multipath environment. The multipath components also widen the Doppler spectrum. The no line of sight (NLoS) condition represents a stringent problem for VLC and the case of 802.11p. Buildings situated at crossroads pose a major problem for communication [41]. The roadside vegetation blocks communication in the case of tight curves [32]. In the case of the steep crest, the NLoS condition makes communication impossible [42]. Also, vehicles interposed between the emitter and receiver lead to packet losses or communication breakdown [43]. In all these instances, the connectivity is lost almost immediately after the LOS is altered. To conclude, it can be observed that DSRC is mainly affected by high traffic densities, NLoS, and high velocities. These factors reduce the communication range, cause numerous packet collisions, increase delays, and reduce reliability. Considering the mentioned analytical and experimental results, it can be observed that DSRC systems are fully reliable, just in ideal conditions. However, in real situations, the aforementioned perturbing factors will cumulate in plenty of cases (e.g., high speed with NLoS), leading to even poorer performances than the ones described above. Moreover, it is also observed that communication breakdowns occur mostly in the situations they were meant for. At high speed, in tight curves, is the moment when these systems are required the most. Considering that [23]- [43] represents just a narrow segment of studies that question the DRSC's capability to face all problems related to vehicular communications, the competition for the winning communication technology in vehicular networks remains open.

4. THE APPLICATIONS VLC IN ITS

Whereas IVC has been in the attention of academic society for more than 20 years, due to its early stage, only recently was VLC considered a possible solution to enable IVC. The low complexity, reduced implementation cost, and ubiquitous character represent the main advantages of VLC usage in automotive applications. All these characteristics can facilitate rapid and broad market penetration, representing a solid consideration (argument) in favor of VLC. LEDs are highly reliable and energy-efficient and have a lifetime that far exceeds classical light sources. These unique features made the car manufacturers consider replacing the classical halogen lamps with LED lighting systems. At this moment, as illustrated in Figure 2, vehicle lighting systems based on LEDs are standard. The efficiency of the LEDs made them used also for LED-based traffic lights. This new generation of traffic lights is becoming increasingly popular and is beginning to be used on an extended scale. The main advantages of these traffic lights are low maintenance cost, long life, and low energy consumption but also better visibility [44]. These advantages had already convinced some of the city's authorities to replace the classical traffic lights with new-generation LED-based traffic lights. Meanwhile, other cities are progressively following in their footsteps. The standard sizes for the traffic lights are 200 and 300 mm in diameter [45]. The LED-based traffic light consists of a large number (100-200) of HB-LEDs that offer data communication besides the signaling function. Enhancing the LED traffic light with communication capabilities does not affect compliance with the standards [45]. Considering the trends in the lighting industry, it is expected that street lighting is expected, so road illumination will also be able to provide communication support [46], [47]. In this case, the constant short distance between the street light and the vehicle and the high power implied allows for high data rates and increased communication stability. Under these circumstances, this particular case of I2V VLC has vast developing potential. Moreover, due to the low cost and high reliability, LEDs began to be integrated into traffic signs to improve visibility. This type of traffic sign is used mainly on road segments with increased accident risk.

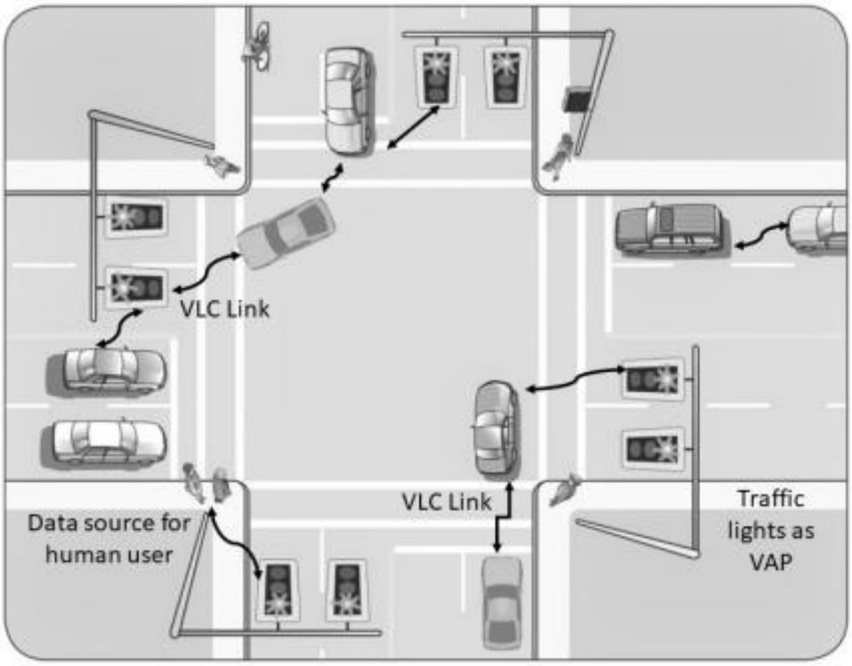

Figure 4. An intelligent transport system using visible light communication (VLC).

In this context, one can see that LED-based lighting will be part of the transportation system, integrated into vehicles and the infrastructure. The large geographical area in which LED lighting will be used, combined with VLC technology, will allow ITS to gather data from a widespread area and enable the distribution of high-quality communications. These additional functions will be possible without affecting the primary goal in any way, which is signaling or lighting. The success of ITS largely depends on its penetration [48]. Insufficient penetration means insufficient data collection and distribution. Suppose it is to think of RF solutions for the ITS. In that case, this will only be possible for a short time ahead because all intersections and streets must be equipped with RF units for the system to be effective, which implies substantial implementation costs. One of the most significant advantages of VLC compared with DRSC is its low complexity and reduced implementation cost. Being already half integrated into the existing transportation infrastructure and in-vehicle lighting systems makes VLC a ubiquitous technology and ensures its fast market penetration. In the case of RF, the problem of market penetration is considered a severe issue that can block deployment. It is estimated that for such a system to begin to be effective, it requires at least a 10% market penetration [49]. However, achieving this would require a few years in which the systems bring little or no benefits, meaning that the early buyers mainly support the deployment cost. Even with that, most consumers replaced their cars in this period without benefiting from the purchased system. The safety vehicles proceed on the damaged cars and transmit the information in the neighborhood of this area. The neighboring cars receive the data using light sensors and send them further to the nearest neighbors using their head/back lights. Data are thus propagated throughout the highway. The traffic infrastructure contributes to the information broadcast as well. Furthermore, the cars can also communicate with each other regarding their mechanical state or other issues needed to enhance traffic safety and security. The fact that VLC can satisfy the requirements imposed in vehicular networks in actual working conditions has been confirmed. Furthermore, VLC was also found compatible with platooning [50]

5. VLC RESEARCH DIRECTION AND FUTURE CHALLENGES

Concerning the VLC receivers, it has been observed that there are two primary directions in their development. One considers using camera systems as a receiver, and the other one considers the usage of photoelements, generally photodiodes. Embedded cameras have the main advantage of a wider angle, which increases mobility. Such systems can achieve communication ranges up to 100 meters but at a high BER (as high as 10-2 – 10-1). In the best cases, decent BER results can be obtained for distances up to a few tens of meters. As for the data rate, VLC links that can achieve a few Mb/s have been reported. However, the communication performances are strictly related to the camera, meaning that the camera has to be a high-speed model, which is still too expensive for broad distribution in the automotive industry. Under these circumstances, high-speed cameras seem to be reserved for laboratory prototypes. On the other hand, photo-sensing elements like photodetectors are quite efficient regarding noise performance and can be used over long distances. Their fast response time enables them to be used for high data rates at considerably lower prices. Such systems can achieve communication ranges of 40 - 50 meters at data rates of a few tens of kb/s. It was seen that the performances of such systems could be enhanced with optical systems that focus the light on the photo element and improve the SNR. Active control of the position of the sensing element was also found to enhance the performance. In the case of photosensors, the main challenge is to minimize the interference of the ambient light, which significantly affects the SNR, especially as the emitter-receiver distance increases. A central problem in this area is the design of a suitable receiver that can enhance the conditioning of the signal and avoid disturbances due to environmental conditions. Even if VLC is a relatively new communication technology, its fast evolution indicates enormous potential. The development of VLC is impressive, but there is still a long way ahead. To be suitable for automotive applications, VLC still needs to enhance the communication range and the robustness to noise. This could be achieved by using an adaptive gain circuit that will significantly improve the communication range in low and medium light conditions without affecting the robustness of the communication in bright conditions. Higher complexity filters and optical filtering can also improve the SNR and increase the communication range. As for the stringent Los condition, the problem can be solved in vehicular networks by using multi-hop networking. Vehicles can retransmit the original message for vehicles that are outside the LOS of the initial transmitter. This way, high-priority messages can be propagated through the VANET and reach vehicles outside the LOS. Multi-hop networking can substantially increase the communication range.

6. CONCLUSIONS

This paper has introduced the concept of ITS, presenting its objectives, key components, and strategies. The potential usage and the role of VLC in the ITS have been discussed. VLC is the solution in ITS, especially for urban high-traffic densities. When such conditions are fulfilled, RF-based communication technologies are affected by severe collisions, leading to decreased packet delivery ratio (PDR) and increased latencies, making RF communications unsuitable for traffic safety applications. In transportation-related applications, VLC also has the advantage that next-generation vehicles and next-generation traffic infrastructures will be LED-based, which will facilitate the implementation.

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