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Current Challenges for Visible Light Communications Usage in Vehicle Applications: A Survey

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***Abstract*—In the context of an increasing interest toward reducing the number of traffic accidents and of associated victims, communication-based vehicle safety applications have emerged as one of the best solutions to enhance road safety. In this area, visible light communications (VLC) have a great potential for applications due to their relatively simple design for basic functioning, efficiency and large geographical distribution. This article addresses the issues related to the VLC usage in vehicular communication applications, being the first extensive survey dedicated to this topic. Although VLC has been the focus of an intensive research during the last few years, the technology is still in its infancy and requires continuous efforts to overcome the current challenges, especially in outdoor applications, such as the automotive communications. This article is aimed at providing an overview of several research directions that could transform VLC into a reliable component of the transportation infrastructure. The main challenges are identified and the status of the accomplishments in each direction is presented, helping one to understand what has been done, where the technology stands and what is still missing. The challenges for VLC usage in vehicle applications addressed by this survey are: 1) increasing the robustness to noise; 2) increasing the communication range; 3) enhancing mobility; 4) performing distance measurements and visible light positioning; 5) increasing data rate; 6) developing parallel VLC and 7) developing heterogeneous dedicated short range communications (DSRC) and VLC networks. Addressing and solving these challenges lead to the perspective of fully demonstrating the high potential of VLC and therefore to enable the VLC usage in road safety applications. This article also proposes several future research directions for the automotive VLC applications and offers a brief review on the associated standardization activities.**

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***Index Terms*— IEEE 802.15.7 standard; inter-vehicle communications; optical communications; visible light communications; vehicle safety.**

I. INTRODUCTION

IN THE recent years, the modern society shows an increasing interest towards wireless communication technologies. Furthermore, this demand is expected to increase exponentially in the next years [1]. Facing this unprecedented request represents a major challenge for the next years. However, in spite of all efforts, due to the limited available bandwidth, the current networks are not able to fully satisfy this traffic demand. Therefore, a new wireless communications technology is strongly required to fill-in the existing gap.

An alternative to the existing radio frequency (RF) based wireless communications is represented by the visible light communications (VLC) technology. VLC uses the visible light (380 – 780 nm) as a carrier for the data, and thus it offers a 1000 times greater bandwidth compared to the RF communications. Furthermore, the visible light spectrum is not regulated and therefore the cost of the technology is significantly reduced. The huge available spectrum enables VLC to achieve very high data rates that can currently go up to few tens of Gb/s [2], [3]. Moreover, since this data rate has been achieved in less than a decade after the beginning of VLC systems development, it is obvious that the technology’s potential is even greater. Furthermore, higher data rates could be achieved by using multiple input multiple output (MIMO) communication techniques. These characteristics offer VLC the premise to be part of future 5G technologies [4] - [7]. The VLC technology is also fully compatible to RF communications, so the two can complement each other, forming hybrid or heterogeneous networks and further enhancing the communication performances [7], [8].

Another important advantage of VLC is that unlike other wireless communication technologies, VLC is safe for the human health. In comparison, the radio waves are currently classified as a *potential cause of cancer in humans* [9] - [12], whereas the infrared (IR) light can cause irreversible thermal damage to the cornea. Furthermore, VLC systems do not affect the functionality of the highly sensitive electronic systems and thus, they can be used in RF restricted places (e.g.

airplanes, hospitals, chemical or nuclear plants). Moreover, in the context of a growing interest to reduce greenhouse emissions, VLC is also energy efficient, since it uses no extra energy for data transmission. In its case, the same light is used for both illumination and as a carrier for the data.

A major difference between VLC and RF communications comes from the inherent properties of the exploited electromagnetic waves. The RF waves have the ability to penetrate through most nonmetallic materials, whereas the visible light can only penetrate through transparent materials. Even though in some cases, the limited penetration capability acts as a disadvantage by limiting the mobility or the coverage area, it could also represent a major benefit, since it limits the interferences between the non-Line-of-Sight (nLoS) systems and prevents eavesdropping.

In addition to the upper mentioned benefits, one of the greatest advantages of VLC is the ubiquitous character. In VLC, the data transmission capacity is enabled by fast switching light emitting diodes (LEDs), as an additional function besides lighting. Thus, the data is transmitted onto the instantaneous power of the light, at speeds unperceivable by the human eye. Since it is mainly based on the already existing lighting infrastructure, VLC has the potential to provide high-speed wireless communications wherever there is artificial lighting, indoor and outdoor. Currently, the main application area envisioned for the VLC technology is in providing high data rate indoor links for fast internet connections or for fast data broadcast. Significant efforts were made by the researchers in the area, allowing VLC to obtain impressive results in a relatively short period. Another challenging application domain for VLC is represented by the communication between vehicles and/or between traffic infrastructures and vehicles. Even though right from the early stage VLC has been found suitable for traffic applications [13] - [15], this domain has been rather neglected by the scientific community, compared to the indoor VLC applications. In indoor applications, the challenge was to provide high data rate links with communication ranges of few meters. On the other hand, in automotive applications, the challenge is to achieve long range robust communications, but at the cost of lowering the data rate.

This survey addresses the usage of the VLC technology in vehicular communication applications, as a possible way to increase the safety and efficiency of road transportation. Although this domain is almost 20 years old, as far as we know, there are no conclusive reviews on this topic. Indeed, there are several reviews on the VLC usage [16] - [19], but neither of them strictly addresses the usage of VLC in automotive applications. Thus, in [16], after addressing the aspects related to free space optical (FSO) communications, smart lighting and VLC, the authors conclude that the problem of wireless networking and of energy efficient lighting should be treated together, rather than as complementary technologies. Hence, the solid state lighting (SSL) emitters should be developed considering the requirement for both lighting and networking, and thus a tradeoff should be sought. In [17], the problem of outdoor long range FSO communication is addressed but unlike in this work, the paper only considers the near IR band. A well detailed survey on VLC can be found in [18]. Here, the authors justify the transition toward VLC, list the VLC benefits, describe the system structure, and approach the issues regarding hybrid VLC schemes, modulation techniques and light dimming. Although this survey mentions the Intelligent Transportation System (ITS) as a related application, the paper is clearly focused on the indoor scenario. The authors of [19] also provide a comprehensive survey on indoor VLC and detail the aspects regarding VLC systems and their physical layer characteristics, including channel modeling and modulation methods, or medium access techniques. The fact that this article also mentions vehicular communication as a highly promising use case clearly points out the importance of the domain and emphasizes the necessity of a survey presenting a detailed state of the art in this area. Furthermore, none of the existing surveys highlights the extra challenges involved by the outdoor environment or by the requirements imposed to the inter-vehicle communications domain.

The VLC usage in outdoor environments assumes significantly different conditions and thus, there are dissimilar premises and expectancies. In this context, this article addresses the challenges imposed by the usage of VLC in automotive applications. These challenges are at the same time: i) old as VLC, ii) quite current as the VLC developers are still working on addressing them, and iii) still forthcoming as the technology will have to be continuously improved. In the existing VLC literature, there are several other papers that address the challenges that could further enhance the VLC technology and pave its way towards the market [19] - [22]. However, this is the first article that strictly refers to the automotive-related VLC applications. Furthermore, unlike other papers, this one offers an up to date review on how these challenges are addressed by the scientific community, providing a summary of the existing solutions for each challenge.

The rest of the survey is structured as follows. It begins by providing a view of the general structure of the VLC systems in Section II. Section III emphasizes the motivations of using VLC in vehicular communication applications, underling its advantages, and points out the similarities and the differences compared to the indoor VLC scenario. Section IV highlights the technology shortcomings and points out the challenges in the field. The scientific community response to these challenges is reviewed, pointing out the main solutions found for their overtaking. Section V contains a discussion about the road ahead, proposes several future research directions that could be addressed and resumes the activities related to the VLC standardization, whereas Section VI presents the conclusions of this survey.

II. General Architecture of a Visible Light Communications System

A VLC system mainly consists of a VLC transmitter that modulates the LED produced light and a VLC receiver based on a photosensitive element (generally a positive-intrinsic-negative (PIN) photodiode or an image sensor) that is used to extract the data signal from the modulated light beam. The transmitter and the receiver are physically separated from each other, but connected through the VLC channel. For VLC systems, the line-of-sight (LoS) is a mandatory condition. A schematic of a VLC system is illustrated in Fig. 1. As the VLC system's structure is detailed in [18], this section will provide only the information necessary for a proper understanding of the rest of the article, without approaching all the aspects related to the hardware development and implementation of the VLC systems.

A. VLC emitter

The VLC emitter transforms information into messages that can be transmitted over the FSO medium by using visible light. The purpose of the VLC emitter is to simultaneously provide illumination and to transmit data. However, the data transmission must not affect in either way the lighting or signaling functions. From this reason, the VLC emitter must use the same optical power or if the application requires it, to allow for light dimming. Furthermore, the VLC emitter must not induce any noticeable flickering.

A central component of the VLC emitter is the encoder which converts the data into a modulated message. The encoder commands the switching of the LEDs according to the binary information and the required data rate. The binary data are thus converted into a modulated light beam. In the simplest case, the data is modulated using On-Off Keying (OOK), but more complex modulation techniques might be used as well. Detailed information regarding other modulation techniques used in VLC applications can be found in [17]-[19]. A cost effective solution for the encoder is represented by the usage of microcontrollers. In most cases, their quality is high enough to ensure relatively good performances. However, in more complex applications, the microcontroller must be substituted by a Field Programmable Gate Array (FPGA) which will be able to provide improved performances.

The parameters of the VLC emitter are mainly limited by the characteristics of the LEDs. The data rate (i.e. transmission frequency) depends on the switching abilities of the LEDs, while the emitter's service area depends on the transmission power and on the illumination pattern (i.e. emission angle). Currently, the SSL industry is able to produce general purpose LEDs that can offer switching frequencies of few tens of megahertz. However, as VLC is rapidly advancing toward multi-Gb/s data rates, the LEDs "*slow*" switching capacity is the one limiting the system's performances [23].

An argument in favor of VLC development comes from the simplicity of transforming any LED light source into a VLC emitter. Simply by adding an encoder module consisting of a microcontroller and a digital power switch, the LED light source is able to become a broadcast station unit. A second argument comes from the advantages of using LED lighting sources and their envisioned omnipresent distribution. As a matter of fact, LED lighting sources are expected to totally replace incandescent, fluorescent and halogen lighting [24]-[26]. Accordingly, VLC has the potential of becoming a ubiquitous wireless communication technology.

B. VLC receiver

The VLC receiver is used to extract the data from the modulated light beam. It transforms the light into an electrical signal that will be demodulated and decoded by the embedded decoder module. Depending on the required performances and on the cost constraints, the decoder can be based on a microcontroller or a FPGA. The careful design of the VLC receiver represents a serious issue because in most applications, the VLC receiver's performances have the greatest influence on the performances of the VLC system, determining the communication range and the resilience against interferences.

1) Photodiode based VLC receivers

Generally, the VLC receivers are based on photosensitive elements which have high bandwidth and offer the possibility of high-speed communications. However, as the incident light might contain parasitic light coming from other light sources (i.e. artificial or natural), the receiver is subject to significant interferences. The performances of the VLC receiver can be

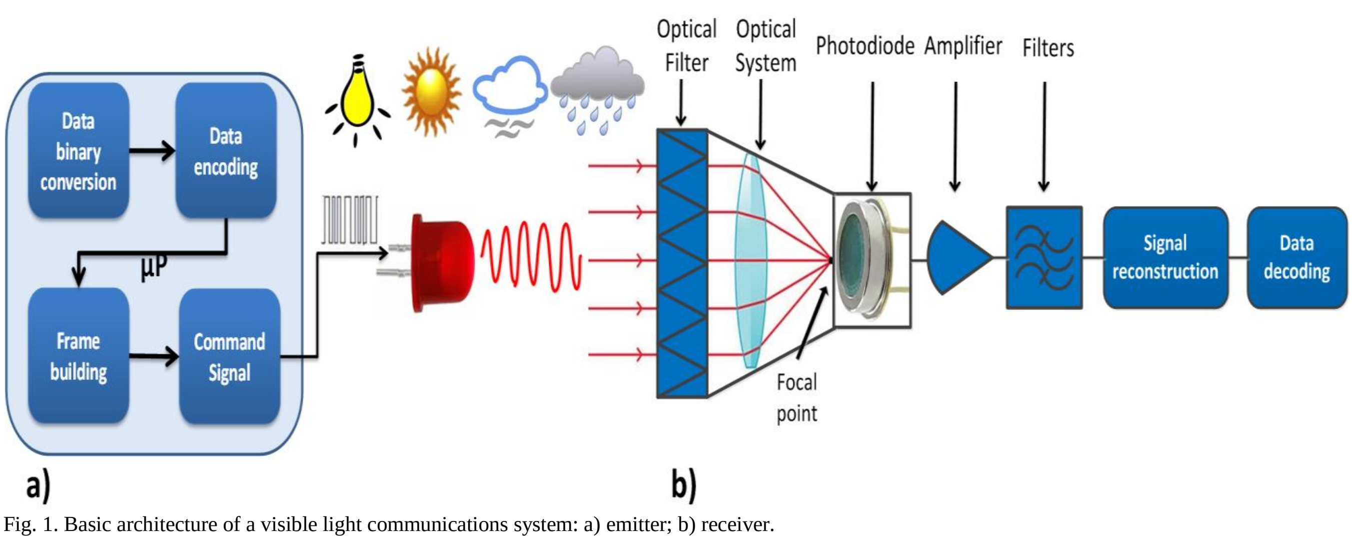

Fig. 1. Basic architecture of a visible light communications system: a) emitter; b) receiver.

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enhanced by using an optical filter that rejects the unwanted spectrum components, such as the IR component. Moreover, in high speed applications using white light, the optical filter allows only the passage of a narrowband radiation, corresponding to the blue color. The reason for this choice is that the white light is obtained from blue LEDs and yellow phosphor, and in this case, only the blue component of the white light is used for the signal processing [27], [28].

The effect of the interferences can also be reduced by narrowing the receiver field of view (FOV), which in consequence influences the service area. A wider FOV enables a wider service area but comes with the disadvantage of capturing more noise, leading to signal to noise ratio (SNR) degradation. However, indoor short-range applications require increased mobility and the possibility of narrowing the FOV is not considered in most of the cases. On the other hand, for outdoor long-range applications, where the range induces small angles, the narrow FOV is an effective solution. The receiver's FOV is determined by the FOV of the optical system, which also concentrates the light on the photodetector by using a lens. The photodetector is usually based on a reverse biased silicon photodiode operating in photoconductive mode that generates a current proportional to the incident light. The value of the photocurrent also depends on the photodiode's spectral sensitivity. From this reason, increasing the area of the photodetector can enhance the performances of the system. However, the area of the photodetector strongly influences its capacitance, which in turn influences the achievable bandwidth. In these circumstances, choosing the photodetector's area represents a compromise between SNR and bandwidth. Next, due to the small values of the generated photocurrent, a transimpedance circuit is used to transform the small current into a voltage. The transimpedance solution offers a fair trade-off between gain-bandwidth product (GBP) and noise. The voltage provided by the transimpedance circuit is amplified and filtered to remove high and low frequency noise, and also the DC component. After all these operations, the signal should correspond to the emitted signal containing the data. Then, the data processing unit decodes the information from the reconstructed signal obtaining the original message.

2) Camera based VLC receivers

Considering the multitude of devices that are already equipped with cameras (e.g. smartphones, tablets, laptops or automobiles), image sensors are also being used in VLC applications for the light reception. As an extended survey regarding optical communications based on image sensors can be found in [29], this subsection will only point out some relevant characteristics of the image sensors receivers.

The image sensor consists of a high number of photodetectors arranged in a matrix or on an integrated circuit. Although widely spread, such devices have several drawbacks considering the VLC usage. A first problem comes from their noise performances which are lower than the ones of independent photoelements. However, the main limitations come from the camera's limited number of frames per second (fps), which limit the communication performances. Most of the low cost cameras have up to 50 fps, which means that such devices can only achieve very low data rates. The data rate can be enhanced up to several kb/s by using the rolling shutter property of the camera [30], [31]. The rolling shutter is a procedure which uses a row by row reading of the pixels instead of reading the entire matrix at once. Yet, the results are only suitable for static low data rate applications. An attempt to develop vehicle VLC systems using low-cost image sensor is found in [32]. However, the communication distance is below 1 meter, and therefore its usage in automotive application can be only limited.

Significantly improved results are obtained when high speed cameras are used. In their case, the number of fps is about 1000, and therefore higher data rates of up to several Mb/s and long distance communications are enabled. The main advantage of image sensor VLC receivers is the enhanced FOV which allows a wide area data reception. All these characteristics make image sensor VLC receivers to be a strong candidate for mobile long distance applications, as in the automotive domain. Nevertheless, it must be pointed out that the high performances come at a very high cost, limiting their extended use applicability.

Before ending this section another major difference between photodiode and image sensor VLC receivers must be pointed out. In the case of photodiode-based receivers, the background noise is received and processed simultaneously with the data signal, whereas the camera-based receivers are able to spatially isolate the noise sources. Further on, in photodiode based receivers the data is recovered by using different types of analog and/or digital signal processing techniques, whereas in the second case, the information is obtained based on high complexity image processing techniques. In some cases, the increased complexity of these procedures does not allow real time data decoding or, when it does, it requires a powerful and thus expensive data processing unit. As this article addresses the VLC usage in automotive applications, where the cost control is an essential aspect, it can be considered that at least for the near future, camera-based VLC systems are mainly reserved for laboratory prototypes and not for the general usage.

III. Considerations On The VLC Usage In Vehicular Applications

The following section addresses the opportunity of using VLC for inter-vehicle communications, presenting some of the characteristics of the technology, its advantages considering the use in automotive applications and the main characteristics that differentiate vehicular VLC applications from the indoor VLC ones.

A. General Context

The number of automobiles that use the transportation infrastructure is constantly increasing. Within this context, the number of victims resulting from traffic accidents is also increasing, making road accidents one of the leading causes of death [33] - [35]. Furthermore, for young people aged between 15 and 29 years, traffic accidents represent the leading cause

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of mortality [34], [35]. On these grounds, the scientific community, the automotive industry and the governmental agencies are joining their efforts to increase the safety of vehicles and roads. These joint efforts have led to a new paradigm in vehicle safety. If in the past, the research efforts were directed on *how to help people survive accidents*, currently, the research efforts are focused on *how to help people avoid accidents.* Within this context, it is considered that the safety and the efficiency of the transportation system can be substantially increased by using wireless communications to enable real-time data exchange between vehicles and traffic infrastructures. By combining vehicle to vehicle (V2V) and infrastructure to vehicle (I2V/V2I) communications, up to 81% of all vehicle crashes could be prevented [36]. However, supporting inter-vehicle communications is rather problematic because of the channel characteristics and of the strict limits for quality of service. The VLC technology has the potential to significantly enhance the performances of vehicular networks, especially in high traffic densities [37], as it is not affected by the broadcasting storm phenomenon [38], [39].

The Intelligent Transportation System (ITS) [40] considers using state-of-the-art cooperative technologies in order to reduce the number of accidents and of associated fatalities. Furthermore, the ITS aims to improve the efficiency of the transportation system and therefore, to reduce the CO_2 emissions. ITS adds value to the transportation system by providing real-time access to relevant traffic information. By using I2V/V2I and V2V communications, ITS continuously collects traffic data, analyzes it and distributes it, in order to increase the vehicle awareness. Moreover, this information enables an efficient management of the transportation system, increasing efficiency and reducing traffic jams. The assembled data is used to automatically adjust the transportation system to different traffic situations. Therefore, a crucial aspect for the ITS is the widespread distribution. However, in order to ensure its effectiveness, the system requires a large geographical distribution of the intelligent vehicles and of the intelligent infrastructures, enabling it to gather more data and to efficiently distribute it. Withal, a major challenge for the ITS is to maintain the implementation cost as low as possible, but without affecting its reliability.

The benefits of adding intelligence to the transportation system are the efficient monitoring and management of the traffic, which in turn can help reduce congestion and provide optimized alternative routes, depending on the traffic situation. Increasing the efficiency of the transportation system will help save time, money and will reduce pollution.

B. Advantages of VLC usage in vehicular applications

LEDs are highly reliable, energy efficient, whereas their life-time exceeds the one of classical light sources. These unique characteristics made the car manufacturers consider replacing the classical halogen lamps by LED lighting systems [41]. Currently, LED-based vehicle lighting systems are commonly used on production vehicles (see Fig. 2).

Fig. 2. Integration of LEDs lighting systems in series vehicles.

Fig. 3. Examples of LEDs usage as part of the transportation infrastructure.

The efficiency of the LEDs made them being used for LED-based traffic lights as well. This new generation of LED-based traffic lights is rapidly gaining popularity and its usage on extended scale is only straightforward. These traffic lights have as advantages a low maintenance cost, long life and low energy consumption and also offer a better visibility. While some of the cities authorities have already replaced the classical traffic lights with LED-based traffic lights, other cities are progressively following this trend. The standard sizes for the traffic lights are 200 and 300 mm in diameter [42]. The LED-based traffic light consists of a large number (100 - 200) of LEDs that offer besides the signaling function, the possibility to provide data communication. The enhancement of the LED traffic light with communication capabilities does not affect its compliance to the traffic regulation standards.

Considering the trends in the lighting industry, it is expected that in the near future, street lighting will be LED based as well. Therefore, with the help of the VLC technology, the road illumination will also be able to provide communication support as in [43], [44]. In such a case, the constant short distance between the street light and vehicles, along with the high power implied, enables high data rates and

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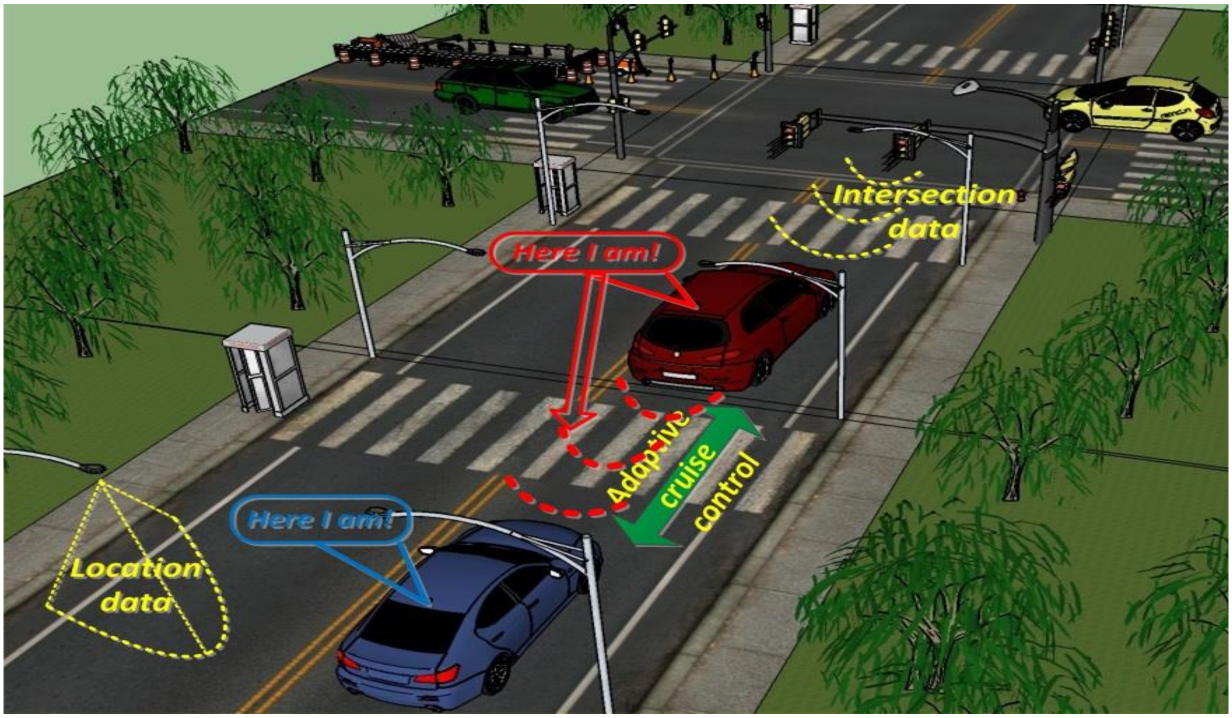

Fig. 4. VLC usage scenario: road safety data is transmitted using the vehicle lighting systems, the street lighting system and the traffic lights.

increased communication stability. Under these circumstances, this particular case of I2V VLC has a huge developing potential. Moreover, due to the low-cost and high reliability, LEDs begun to be integrated in traffic signs as well, in order to improve the visibility. Currently, this type of traffic signs are used mainly on the road segments which are considered with a high accident risk. Several examples of LED usage as part of the transportation infrastructure are illustrated in Fig. 3.

Considering the upper mentioned context, one can see that LED-based lighting will be part of the transportation system, being integrated in vehicles and also in the infrastructure. The large geographical area in which LEDs lighting will be used, combined with VLC technology will allow ITS to gather data from a widespread area and thus, the VLC technology can enable widespread distribution of high quality communications. The success of the ITS is largely dependent on its penetration. Insufficient penetration means insufficient data collection and distribution. If it is to think of RF solutions for the ITS, this will not be possible for a long time ahead because, in order the system to be effective, it is needed that all intersection and streets to be equipped with RF units, which implies a huge implementation cost. Hence, one of the strongest advantages of VLC is its low complexity and the reduced implementation cost. Being already half integrated in the existing transportation infrastructure, as well as in vehicle lighting systems, makes VLC a ubiquitous technology and ensures it a fast market penetration. A scenario that illustrates the usage of VLC in communication based vehicle safety applications is presented in Fig. 4. Here, road safety data (e.g. location data, phase of the traffic light and time before next change, maintenance work and speed limits) is broadcasted towards the approaching vehicles with the help of intelligent traffic lights and of the street lighting system. Additionally, the vehicles are able to exchange data concerning their state (e.g. location, velocity, acceleration, engine state, etc.). In the case of RF, the problem of market penetration is considered a serious issue that can block the deployment. It is estimated that in order for such a system to begin being effective it requires at least a 10% market penetration [45]. However, to achieve this, it would require a few years in which the system brings little or no benefits, meaning that the deployment cost is mostly supported by the early buyers. Notwithstanding that a significant part of the consumers replace the car in this period without having any benefit from the purchased system.

C. Differences between the indoor and the outdoor scenarios

Before moving toward the challenges which slow down the advancements in vehicular VLC applications, this section briefly emphasizes the issues that differentiate the outdoor from the indoor scenarios, highlighting the similarities and the differences.

1) Considerations on the communication premises, associated expectancies and on the communication channel

Although we are talking about a single technology and thus a similar operating principle, the VLC usage in outdoor applications assumes different expectations, dissimilar channel conditions and therefore rather different challenges. First of all, indoor applications are expected to provide very high data rates (multi Gb/s) for distances that are usually below 2 or 3 meters (i.e. the distance between the celling and the workspace). On the other hand, outdoor applications in general and automotive applications in particular, are expected to provide significantly larger communication distances (i.e. currently up to 100 meters) and in consequence, lower data

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rates can be achieved. Furthermore, if we strictly refer to communication-based vehicle safety applications, this use case requires very high packet delivery ratio (PDR) and latencies as low as 20 ms [37], meaning that a higher robustness to disturbances is expected.

Besides the significantly different expectancies for vehicular VLC versus indoor VLC, another major difference between them comes from the totally dissimilar channel conditions. In indoor applications, the influence of the ambient light interferences is negligible, as the light of the VLC emitter is usually the main source of light. Compared to the indoor channel, the outdoor one is significantly more problematic, as it is strongly influenced by the background solar radiation. In this case, the power of the incident parasitic light can be up to 10 mW/cm^2, compared to the power of the light containing the information which can be as low as few μW/cm^2, Furthermore, the outdoor VLC channel also involves the presence of other light sources, disturbances caused by the weather, whereas the dynamics of the vehicular environment make the channel highly unpredictable. Hence, achieving the mandatory robustness becomes much more problematic in this case.

In conclusion, indoor applications have as main challenge to find enhanced designs and improved modulations techniques with the purpose of increasing the data rate, whereas in vehicular communication, the main goal is to mitigate the effects of the intense ambient interferences and to ensure a reliable long range link.

2) Bidirectional communications - very problematic in indoor applications quite simple in vehicular applications:

A challenging issue regarding indoor VLC applications is represented by the bidirectional communications. Establishing VLC bidirectional communications represents a major issue in the case of indoor applications. Besides the technical difficulties caused by the mobile conditions, the most important problem is represented by the fact that the majority of the indoor devices do not have a lighting function that could be used for data transmission. To solve this problem, indoor applications consider the usage of a second communication technology (i.e. generally RF or IR) for the data upload. This approach is quite efficient in terms of achievable data rate, but it has the disadvantage of a more complex design and therefore, a higher cost.

In automotive applications, the usage of the VLC technology is very straightforward, as all the involved devices (i.e. vehicles and traffic infrastructures) have a lighting function, which can be used to transmit the data. Furthermore, in this case, the power of the light is relatively high, favoring relatively long communication distances.

3) Outdoor applications are less stringent to the lighting requirements:

Unlike in other wireless communication technologies, in VLC, the light wave carrier is perceivable by the human eye. Thus, another advantage concerning the VLC usage in vehicular communication applications comes from the fact that this domain is less stringent concerning the lighting requirements. In indoor applications, VLC have to be maintained while providing high resolution diming (i.e. as low as 0.1%). Supporting communication in these circumstances implies the usage of specially designed modulation techniques. The IEEE 802.15.7 standard [46] for optical communications using visible light proposes two solutions for high resolution diming based on OOK and variable pulse position modulation (VPPM), but in their case the diming is achieved by reducing the data rate, respectively by reducing the communication distance.

Concerning V2V applications, in their case no dimming is implied whatsoever, as the vehicle lighting systems have a constant light intensity. The same statement can be true for I2V applications as well. Here, the traffic lights or the traffic signs do not change the lighting intensity. On the other hand, I2V communications based on the street lighting systems might involve diming for energy saving applications based on light intensity control. However, in such applications, the diming resolution is less essential, allowing for diming resolution as high as 10%.

Another VLC specific problem is related to light intensity flickering. The IEEE 802.15.7 standard is again very strict in this problem and it proposes only the usage of run length limited (RLL) coding (e.g. Manchester, 4B6B, or 8B10B). Such codes prevent flickering by having an equal number of *1s* and *0s*. However, as demonstrated in [47], the Manchester code for example is very bandwidth consuming, whereas 4B6B or 8B10B codes are less throughput efficient. In vehicular applications the flickering mitigation can be less rigorous, as the exposure to the modulated light is rather short and also less direct. Furthermore, due to the high modulation frequencies, the flickering effect is only limited. This fact can enable the usage of other codes, besides the RLL ones. Being able to use other codes is quite important, as different codes can ensure higher performances in different situations. Thus, the Miller code was found to be suitable for future MIMO applications [47], [48], spread spectrum codes were found to increase the robustness to noise [49], [50], overlay coding enables hierarchical coding ensuring the reliability of the high priority data [51], whereas multi-tone codes offer the premises for higher data rates.

IV. Current Challenges Regarding VLC Usage In Vehicular Communication Applications

In the upper-mentioned context, the following section addresses the main challenges for the future development of the VLC technology, in order to make it fully compatible to the requirements imposed for communication-based vehicle safety applications. Besides introducing the challenges and pointing out their importance, this section presents a review of the existing solutions and perspectives to address each challenge.

A. Challenge 1 – Increasing the robustness to noise

The strongest problem for outdoor VLC is triggered by the numerous sources of parasitic light, which perturb the communication. As demonstrated in [52] - [54], the vehicular VLC channel is extremely noisy, being affected by various types of light, each of them with its specific characteristic. Therefore, we have incandescent lamps which produce a 100 Hz interfering signal and its harmonics that can go up to 2 kHz, the fluorescent lamps with a spectrum extending up to 20 kHz, and the fluorescent lamps geared by electronic ballasts which generally produce band interfering signals between 20 - 40 kHz. Moreover, in this last case, lower amplitude interferences can extend up to more than 1 MHz [54]. Hence, all these light sources are at the same time important sources of degradation in the optical wireless channel. From this reason, the IEEE 802.15.7 standard [46] moves the communication to an upper band, where the influence of the artificial light sources is less significant. More precise, for the outdoor VLC applications, the standard specifies the usage of optical clocks of 200 kHz for OOK and of 400 kHz for VPPM.

In addition to the artificial light sources, the sunlight represents the most powerful source of noise. Thus, the power of the background light fluctuates in one day with approximately 20 dB [55]. In this case, the unmodulated parasitic light incident on the photodetector introduces a very strong DC component. Although the DC component can be easily removed using capacitive filters, the generated current also produces a shot noise component. In the presence of background light, the shot noise is the dominant noise source. Moreover, if directly facing the receiver, the strong sunlight can saturate the photoelement, making it blind and thus, obstructing the communication. An accurate and highly appreciated model of the optical wireless channel can be found in [56]. Furthermore, the dynamic nature of the vehicular environment and the diverse weather conditions make the VLC channel very unpredictable. Besides sunlight, VLC can also be affected by snow or by heavy dust, which can obstruct the communication path, and therefore, influence the power of the received signal. Moreover, the water particles from fog or from rain drops, affect the light passage through a combination of absorption, reflection, and scattering [57], [58], further increasing the channel unpredictability.

In addition to the above mentioned factors, automotive VLC applications imply long distance communications (currently up to 80 - 100 meters [59], [60]), which are significantly affected by distance dependent path loss. Consequently, the SNR of such applications is quite low. For all these reasons, *increasing the robustness to noise is the strongest challenge for automotive VLC applications*.

The existing literature on VLC admits the multitude of perturbing elements and struggles to find efficient solutions to mitigate them. As previously mentioned, the sunlight is the strongest source of noise for outdoor VLC systems and so, the most difficult to counteract. In general, the power of the received noise is strictly dependent of the receiver FOV. Therefore, the simplest and probably the most efficient solution to diminish its effect is by narrowing the FOV [56], [61]. In most cases, the VLC receivers are equipped with an optical collecting system that reduces the FOV, and in consequence, the environmental light coming from the sides. The optical collecting system usually englobes an optical concentrator or lens, that focuses the incoming light on the photosensitive element. The concentrator provides an additional gain whose value is given by eq. 1 [56]:

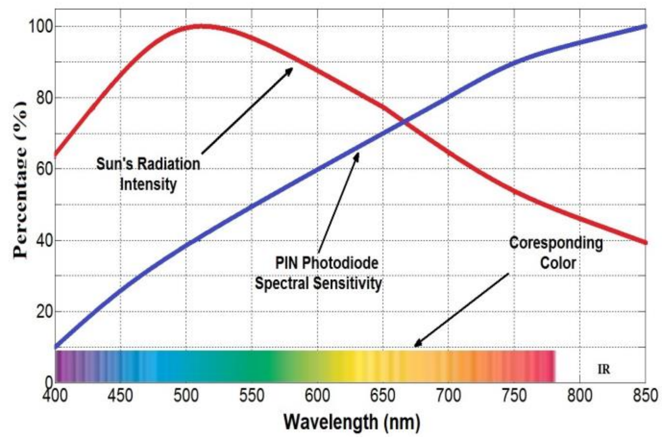

Fig. 5. Sun radiation intensity and PIN photodiode sensitivity over the visible light spectrum.

$$g(\psi) = \begin{cases} \dfrac{n^2}{sin^2\ FOV}, & 0 \le \psi \le FOV \\ 0, & \psi > FOV \end{cases}, \qquad (1)$$

where n is the optical concentrator refractive index and ψ is the angle of incidence with respect to the receiver axis.

Such a solution is experimentally confirmed in [62]. Here, by using a focal lens with a FOV of ± 10°, a communication distance of up to 50 meters is achieved, whereas the bit error rate (BER) is maintained lower than 10^{-7}, even in outdoor sunny conditions. Although this solution significantly enhances the SNR, it has as disadvantage the fact that it proportionally reduces the mobility. Similar approaches based on narrow FOV and optical filters can also be found in [63], [64]. Besides conventional lenses, Fresnel lenses have been found to be very effective in the SNR enhancement [65], whereas in [66], their usage has been confirmed experimentally to enhance communication performances under fog conditions.

Another solution to significantly enhance the SNR in daytime conditions is suggested in [55]. Here, the authors use a VLC receiver containing two front-ends, each of them equipped with a narrow band optical filter (40 nm) dedicated to a specific spectrum component (color). The front-ends are connected to a selective combining circuit, which selects the signal to use based on the highest SNR. This method considerably enhances the robustness to noise, enabling a reliable, low BER communication, even in daytime conditions.

A rather similar, but more complex, approach to address the problem of intense background light in vehicular applications is based on the usage of spectrum sensor arrays [67]. This method involves wavelength division followed by signal reconstruction based on individual weightings for each specific spectrum component [68]. This approach enables a precise noise rejection allowing for an optimized signal reconstruction, and therefore it maximizes the SNR. Even if this proposal is more complex than the previously mentioned examples, it is probably one of the most advanced solutions in the field. Furthermore, although the authors did not emphasize this aspect, their technique can also compensate for the color specific atmospheric attenuation and for the variable sensitivity of the PIN photodiodes. As illustrated in Fig. 5, the sun radiation has different intensities over the light spectrum, whereas PIN photodiodes have different spectral sensitivities throughout the spectrum. This fact makes the green and the blue color signals to be more vulnerable to noise compared to the red color signals. This aspect has been experimentally observed in [62], where the receiver had a significant (approx. 30%) communication distance difference between the red color of the traffic light and the green color.

One can observe that all the upper-mentioned SNR enhancement solutions are more or less, based on optical filtering techniques. However, there are also other solutions to enhance the resilience to noise. A different approach to mitigate the effect of parasitic light, without affecting the receiver mobility is proposed in [69]. In this case, the gain of the pre-amplification stage was calculated in order to prevent photodiode saturation and to enable communication even under direct sunlight exposure. The solution is efficient in terms of robustness to noise. However, because of the limited gain, it has the disadvantage of a relatively short communication distance (10-14 meters). On the other hand, in [70], [71], the robustness to noise is improved by using spread spectrum coding. More exact, they use a modulation technique based on Direct Sequence Spread Spectrum (DSSS) using sequence inverse keying [72], which enables the system to achieve a steady communication range of more than 40 m. Even though the resilience to noise is considerably enhanced, the raw data rate drops by 10 times (20 kb/s) due to the large bandwidth required by the modulation. The high potential of the digital filters has led to the development of fully digital signal processing VLC architectures. Such structural designs enable superior filtering results and therefore enhance the robustness to noise [73], [74]. Furthermore, such systems are more flexible, enabling parameter adjustments and thus, the usage in variable situations (e.g. mobile multi-channel communications [73]).

From a software point of view, the communication resilience to noise can also be enhanced by lowering the data rate and by using punctured codes based on different puncturing ratios. Although this solution is quite efficient, it has the disadvantage of significantly affecting the throughput and therefore the data rate performances [75], [76].

Although this article approaches several challenges that have the potential to enhance VLC vehicular communications, enhancing the robustness to noise is the crucial challenge. Thus, progresses made in this area will determine the approach for the rest of the challenges, whereas problems in this area will negatively affect all the other aspects.

B. Challenge 2 - Increasing the communication range

The second main challenge to enable the usage of the VLC technology in automotive applications is increasing the communication distance. As long-distance communications involve very low power signals at the receiver side, and therefore low SNR levels, this challenge is closely related to the upper-mentioned noise mitigation problem.

Financially supported by the U. S. Department of Transportation National Highway Traffic Safety Administration, the Vehicle Safety Communications Consortium (VSCC) consisting of BMW, Daimler Chrysler, Ford, GM, Nissan, Toyota, and VW has concluded that the safety and the efficiency of the transportation system can be substantially increased by using wireless communications to enable real-time data exchange between the vehicles and the traffic infrastructures. Furthermore, VSCC has published a report [77], where it has defined the preliminary vehicular communication requirements. Referring to the communication distance, the report specifies ranges of up to 1000 meters. These specifications stood at the base of the development of the IEEE 802.11p standard for wireless access in vehicular environment (WAVE) [78], also known as dedicated short range communications (DSRC), which uses the 5.9 GHz spectral region, and aims to enable communication distances of up to 1000 meters. However, in RF-based applications, long distance communications involve long distance interferences. Therefore, since each vehicle creates interferences on an area greater than the communication area, reliability concerns might arise [37], [79] - [83]. Furthermore, the chances of having an accident with a vehicle 1000 meters away are "*quite low*", pointing out that shorter communication distances might be envisioned in order to increase the reliability. Table I summarizes the requirements imposed by the VSCC for the eight most important communication-based vehicle traffic applications [77]. In these cases, communication distances below 300 meters are required. However, if we are to look at Table II which embodies the average inter-vehicle distances in several particular traffic situations and conditions, one can see that most of the traffic situations involve shorter distances. As it can be observed, in most environments, the involved distances are shorter than 160 m.

TABLE I - THE HIGH PRIORITY SAFETY APPLICATIONS [37].

Application	Max. Range [m]	Rate [/s]	Max. Latency [ms]	Message Length [bits]	Type
Traffic Signal Violation Warning	250	10	100	528	I2V
Curve Speed Warning	200	1	1000	235	I2V
Emergency Electronic Brake Light	300	10	100	288	V2V
Pre-Crash Sensing for Cooperative Collision Mitigation	50	-	20	435	V2V
Cooperative Forward Collision Warning	150	10	100	419	V2V
Left Turn Assistant	300	10	100	904 208	I2V and V2I
Lane Change Warning	150	10	100	288	V2V

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Stop Sign Movement Assistant	300	10	100	208 416	V2V and I2V

TABLE II - INTER-VEHICLE DISTANCE IN DIFFERENT TRAFFIC CONDITIONS [37].

Conditions	Inter-vehicle distance [m]
Traffic jam	<35
Roadway in urban areas	35 – 49
Urban highways rush hours	50 – 66
Urban highway	67 – 100
Rural highway	101 – 159
Rural areas	>160

Within the upper mentioned context, the existing VLC prototypes achieve low error communication distances that can go up to 100 meters in the case of the camera-based systems [84] - [87], and 40 - 60 meters for the photodiode based systems [60], [62], [70]. Therefore, in order to be fully compatible with the automotive domain, the communication distance needs to be further enhanced. A presentation of the technical characteristics for some of the most relevant I2V/V2V prototypes is summarized in Table III.

A specific VLC problem is the fact that unlike other wireless communication technologies, in VLC, the light wave carrier is perceivable by the human eye. Therefore, the emission power is strictly dependent on the primary application, which is lighting or signaling and also on the eye safety norms. However, as VLC are direct LoS communications, this generally maximizes the power efficiency.

From the emission point of view, one way to enhance the communication distance is by using optimized irradiation patterns and optimized LED placement within the LED light source [88]. Moreover, a VLC emitter aimed for long distance applications should also have a narrow angle emission pattern. A VLC emitter is considered a Lambertian emitter and therefore, its radiant intensity distribution $R_0(\varphi)$ can be approximated according to eq. 2 [56].

$$R_0(\varphi) = \left(\frac{m+1}{2\pi}\right) cos^m \varphi \tag{2}$$

where φ is the angle with respect to transmitter and the order m is depending on the half power angle (HPA) of the emitter, in accordance with eq. 3 [56].

$$m = -\frac{\ln 2}{\ln\left(cos\phi_{1/2}\right)} \tag{3}$$

where $\phi_{1/2}$ is the transmitter semi angle;

In this case, the irradiation pattern of the VLC emitter R_E (W/cm^2) is given by eq. 4 [56].

$$R_E = (P_t R_0(\varphi))/d^2 \tag{4}$$

where P_t is the emitter emission power, and d is the emitter receiver distance.

When wide angle emission LEDs are used, the irradiation pattern can be enhanced by using focal lenses, as in [63], [64].

TABLE III – SUMMARY OF THE EXISTING LITERATURE ON EXPERIMENTAL I2V/V2V DEMONSTRATIONS.

Reference	*Receiver type*	*Scenario*	*Receiver FOV*	*Data rate*	*Max. distance*	*Modulation and/or coding technique*	*Merits, observations, or particularities*
[84] - [86]	Camera-based	I2V static	22^0+	10-20 Mb/s	2 m	OFDM/ QAM/ Manchester code	Presented in different configurations, the prototype is probably one of the best existing VLC systems for automotive applications. However, it is also one of the most complex ones, and therefore the price makes it rather inaccessible for general usage.
				10 Mb/s	20 m		
[86]		I2V mobile		32 kb/s	70 m		
				2 kb/s	***110 m***		
[87]		V2X static		***55 Mb/s***	1.5 m	OFDM	
[62]	Photodiode based	I2V static	≈10^0	15 kb/s	50 m	OOK with Manchester or Miller codding	One of the best photodiode-based VLC system for automotive applications in terms of raw BER (<10^{-7}) and communication distance. Developed under budget constraints.
[59]	Photodiode based receiver + emitter tracking system based of low-cost camera	I2V	1.3^0	4.8 kb/s	90 m	2PPM	Combines mobility of camera-based receivers with the benefits of photodiode-based receivers. Uses a rather complex emitter tracking system.
[60]		I2V mobile	0.4^0	1 Mb/s	60 m	QPSK	
				2 Mb/s		16 QAM	
[69]	Photodiode based	V2V static	20^0+	15 kb/s	15 m	OOK with Manchester or Miller codding	Communication distance is sacrificed to increase the noise robustness. Wide FOV.
[70] - [72]	Photodiode based	I2V static	not available	20 kb/s	50 m	DSSS	Highly robust to noise due to the DSSS modulation.
[89]	Photodiode based	I2V2V	≈10^0	15 kb/s	23 m	OOK with Manchester or Miller codding	First experimental demonstration of a I2V and V2V cooperative VLC system.
[64]	Photodiode based	Emission angle 18^0 and 25 mm focal length lens at the receiver	25 mm focal length and 25 mm diameter	115 kb/s	31	OOK	Clearly points out the significant influence of the light emission angle and of the focal lens (narrow FOV).
		Emission angle 120^0	No focal lens		1		

The communication distance can be increased by using optical lenses at the receiver side as well. This solution is very efficient and even more popular. For this reason, this technique is used in most of the VLC receivers intended for long distance applications [61] - [63], [84]. The most obvious demonstration showing the impact of optical lenses usage can be found in [64]. In this case, by narrowing the beam divergence from 120° to 18°, and by using a 25 mm focal length lens at the receiver, the communication distance is increased from 1 to 31 meters.

As vehicular communications are highly dynamic applications, the emitter-receiver distance is rapidly changing. In such a case, a high gain can lead to photodiode saturation. As previously mentioned, in order to prevent photodiode saturation and to enhance the robustness to noise, in some cases [69], the gain of the receiver is limited, which in turn reduces the communication distance. A solution to overcome this problem is by using an automatic gain control (AGC) circuit, which automatically adjusts the amplification of the data signal, enabling long distance and low BER communication, even in daytime conditions [62]. For the same purpose, in [63], the AGC circuit has been replaced by a limiting amplifier, enabling variable communication distance.

Photodiode-based VLC receivers generally use Silicon PIN photodiodes, operating in the photoconductive mode. This setup offers high sensitivity and a linear response. In long distance applications avalanche photodiodes could be used instead, as they are more suitable in low power applications. However, in their case, the noise is also amplified making the receiver suitable only for scenarios in which there are no sources of parasitic light.

Another technique to increase the communication distance, especially for high priority event-driven messages is by using multi-hop transmissions. Such structures are normally used to extend the signal coverage for limited power transmissions, but in the case of VLC applications they could also be used to address network nodes that are not within the transmitter's LoS. In such a case, the source of information transmits a message which is received by the vehicles in its vicinity. The vehicles receiving the message, recognize its high priority, and forward it to the vehicles behind, creating a relay-assisted network. Such a scenario is illustrated in Fig. 6, and has been experimentally demonstrated in [89], using the VLC technology.

In addition to the upper-mentioned aspects, in the practical implementation, special attention should be focused on the optimal placement of the road side units (traffic lights, street lights, traffic displays) [15], [90]. In this case, the height and the orientation of the emitter are of maximum importance, especially when long distances are envisioned [90], [91].

Before finalizing the debate on this challenge, it must be pointed out that all the advancements in the VLC domain have been sustained by the SSL industry, which is now able to provide highly-efficient, highly-reliable, fast switching and relatively low price LEDs. The future evolution of the VLC technology is still strongly dependent on the advancements in the SSL industry. Nevertheless, even if the trends in the development of new materials encourage us to be optimistic, a special attention should be focused towards developing more efficient photosensitive elements, capable to detect even lower signal powers, and therefore to enable longer communication ranges.

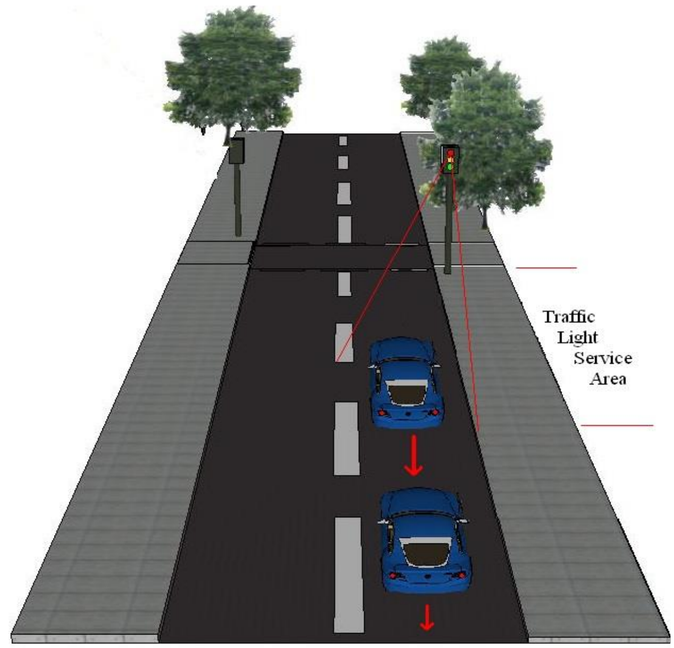

Fig. 6. Relay assisted scenario: the traffic light sends a message that is received by the first car and retransmitted to the car behind [89].

C. *Challenge 3 - Enhancing mobility*

In order to improve the SNR, the effect of the background noise is usually reduced by narrowing the receiver's FOV. Although this solution is efficient in terms of SNR enhancement, as VLC require direct LoS between emitter and receiver, the narrow signal reception angle reduces the mobility. Nevertheless, for the usage in vehicular communications, VLC also has to fully comply with the mobility of the vehicles. The VLC connection between two moving vehicles has been experimentally confirmed, for photodiode [92] and for camera based receiver. However, in most cases, the experimental evaluations of the VLC systems are performed with the emitter and the receiver relatively aligned. Nevertheless, in real situations, the traffic light, for example, is set at a height between 2.5 and 5 meters above the road [42]. This is for sure a serious issue that again, will significantly influence the performances of the system, limiting the service area.

A first solution to address this problem was the integration of a tracking mechanism based on a low cost camera with active control of the position, as in [59], [60]. The proposed technical solution consists of a narrow FOV photodiode-based receiver, a low cost camera used for emitter detection, along with horizontal and vertical motors to position the photodiode receiver. Thus, this solution combines the advantages of both photodiode and camera based receivers, while maintaining a fair tradeoff between mobility and costs. Although the solution proved to be quite efficient in terms of mobility, communication distance and robustness to noise, the high complexity of the design affected the acceptability of this method. A rather similar solution to extend the signal reception region is proposed in [93]. In this case, the camera system is replaced by a light sensors array which is used to determine the emitter – receiver received power. Based on this assessment, the receiver sensor's elevation angle is adjusted in order to compensate for the alignment angle variation. To further enhance the received power signal an optical lens is used as well. The suitability of the method is confirmed experimentally, and the results showed an increase of the received signal power for a significantly enlarged communication area.

Another solution would be to use more photodetectors orientated for different reception angles. The signal processing unit should analyze the signals from each photodetector and decide which signal(s) can be used for the message reconstruction. The problem can be solved in a similar manner by using more than one sensor on each side of the vehicle, as in [94]. This way, at least one of the sensors will be properly aligned with the emitter and it will be able to receive the incoming data. Nevertheless, this solution should be firstly focused on an optimal configuration analysis for receivers and emitters, as these parameters will be the ones determining the performances of the link. The placement parameters determining the optimum configuration are the mounting height and the mounting angle of the road side unit (RSU) emitter and the mounting angles of the on-vehicle receiver. In most cases, the RSU mounting height is determined by the enforcements in the field and not by the VLC requirements, and consequently the mounting angles of the RSU and of the on-vehicle receiver remain the main adjustable placement parameters. On the receiver's side, this evaluation will probably lead to vehicles that will have VLC transceivers optimally arranged for inter-vehicle communication and VLC transceivers optimally arranged for RSU to vehicle communication.

We should also mention that determining the optimum configuration for the RSU and for the on-vehicle receiver involves a mobility versus communication distance compromise. According to [90], the optimum configuration is the one with the longest available communication length, but as showed in Section IV.B, eq. 2 – 4, an emitter optimized for long range communication has a narrow irradiation pattern, and thus its mobility is affected. The solution we consider proper to address this problem without affecting the communication distance neither the mobility has the cost of doubling the number of LEDs inside the RSU (i.e. traffic light). Thus, the data transmission can be done alternatively, using narrow angle emission LEDs for long range communication and wide angle emission LEDs for short range wide angle transmissions, and thus enhanced mobility. Although this solution has a slightly higher cost, its hardware implementation remains simple, whereas it provides a fair solution for enhanced mobility, without affecting the communication range. In [95], an enhanced V2V and V2I communication model is proposed, taking into consideration the vehicle position and posture (i.e. horizontal and vertical deflection angles). Based on this model, the authors propose a VLC based cooperative diversity scheme which should enable enhanced cooperation between vehicles and enhanced BER results.

A different approach to compensate for the mobility of the vehicles is suggested in [96]. In this case, the authors consider the usage of laser range finders as a backup for the VLC link in an autonomous driving application. Thus, the vehicles are using the VLC technology to continuously exchange position data in order to enable an adaptive cruise control. However, in situations where due to mobile conditions, the VLC technology is not able to support communications, the vehicle is still able to maintain a safe distance from the vehicle in front with the help of the laser range finders.

In [97], the authors address the mobility problem caused by the mandatory LoS conditions by establishing a LoS link via a relay vehicle which will be dispatched to reestablish the communication. The proposed algorithm identifies the relay vehicle based on the relocation cost and the visibility analysis.

Concerning the VLC receivers, an optimized solution for the mobility problem might consider the development of optimized receivers based on the estimated emitter-receiver angle. Thus, for V2V communication, the transceivers are relatively aligned on the vertical axis and consequently, the receiver should have a wide FOV for the horizontal axis to enable data reception from the entire width of the road and a narrow FOV for the vertical axis to diminish the effect of the parasitic light. On the other hand, for I2V communication, when the emitter is placed several meters above the road (i.e. 2.5-5 m for traffic light), the FOV should be relatively narrow for the vertical axis and wide for the horizontal one. This solution could significantly enhance the mobility, while maintaining the robustness to noise, with a rather simple design. The mandatory LoS limiting mobility problem could also be mitigated using multi-hop communications, as in [89]. In this case, a node receiving a high-priority message will distribute it in its vicinity.

In indoor applications, the mobility is enhanced by using angle diversity receivers (ADRs) which contain multiple narrow FOV [98], [99] or different FOV photodiodes [100], [101]. The photocurrent is processed using different signal combining techniques to optimize the receiver's performances. Despite the fact that these solutions have confirmed results only in indoor applications, their operating principle is fully compatible to long range outdoor applications as well. A different solution to address this problem is proposed in [102]. This concept envisions an adaptive FOV receiver able to evaluate the environmental conditions with the help of several sensors. Based on the collected data, the receiver should be able to optimally adjust its FOV. The FOV adjustment would be possible using relatively simple mechanics or based on a transparent LCD display, placed in front of the photodiode, and which changes its transparency depending on the level of the background light.

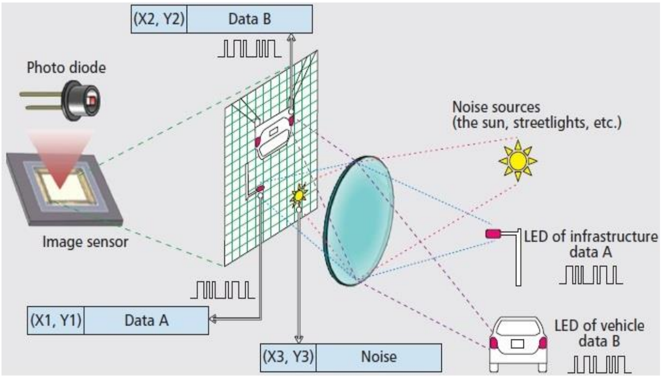

Fig. 7. Multiple emitter identification and spatial isolation of noise sources © [2014] IEEE, with permission from [86].

It should be mentioned that the FOV limitation is not so stringent for the camera-based VLC receivers. For such receivers, the FOV is significantly larger, allowing the reception of data from the entire width of the road. This is possible without affecting the robustness to noise because in this case, the lenses are capable to condense the light, permitting spatial isolation of the parasitic light sources (Fig. 7). Therefore, experimental validation of moving on-vehicle mounted VLC receivers has been confirmed [84]-[86].

Despite the fact that in their current configurations some of the existing VLC prototypes are not able to fully support mobile conditions, analytical studies in the field have showed that with an optimized emitter and receiver(s) positioning, fully mobile communications are possible [15], [90], [91], [103]. Nevertheless, future work should be concerned in clearly determining the optimal receivers positioning and the suitable designs in order to ensure full mobility.

D. Challenge 4 - Distance measurement and visible light positioning

In traffic safety applications, the information concerning the vehicle location and its surroundings are very important, either in autonomous vehicles or in driving assisting systems. At this time, the global positioning system (GPS) is the most common tool for location determination. Although it is very popular, GPS has relatively poor performances [104] due to link blockage and multipath, making it unfeasible in urban canyons, inside tunnels or underground. Besides GPS, modern vehicles use various types of positioning sensors (i.e. radar or lidar) to obtain information concerning the surroundings. Even though the accuracy of such systems is quite high, they generally come at an increased cost. Furthermore, the performances of 24 GHz or 79 GHz operating radar might be affected by severe interferences as the number of equipped vehicles increases [105], whereas LIDAR's scanning rate is quite slow (10 Hz) [106] and again, mutual interferences can appear [107], [108].

Within this context, in addition to lighting and communication, VLC could also be used to provide cost effective, low complexity, and high accuracy positioning, while using the vehicle lighting system [109]. The

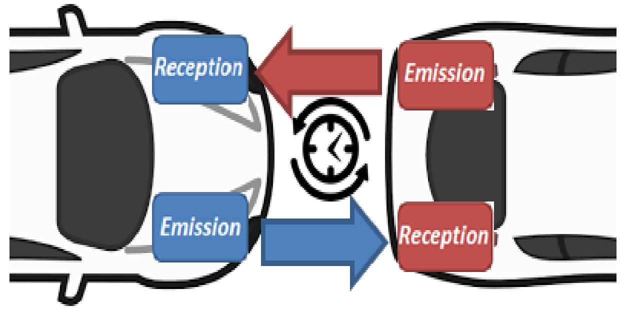

Fig. 8. Inter-vehicle distance measurement using the time of flight.

performances of visible light positioning (VLP) have already been confirmed for indoor applications. Here VLP offers 3D positioning with centimeter accuracy [110]-[112]. Nevertheless, outdoor positioning is more challenging [113] and thus, outdoor VLP solutions are one step behind.

By using the headlights and the taillights, the distance between two moving vehicle can be determined (Fig. 8). Similar to GPS, which is based on the time difference of arrival (TDOA) between two signals received from two different satellites with known positions, VLP uses a high rate repetitive on/off keying sequence to determine the phase difference of arrival, which can be used to determine the relative position [114], [115], as expressed in eq. 5 [116].

$$D = \frac{c}{2f} \cdot \frac{\varphi}{2\pi} \tag{5}$$

where D is the distance, f is the modulation frequency, φ is the phase shift and c is the light velocity. In this case, the distance measurement resolution and thus, the positioning accuracy are depending on the frequency of the signal [115], and it is given by eq. 6 [116].

$$\delta D_{min} = \frac{c}{2f} \cdot \frac{\delta\varphi_{min}}{2\pi} \tag{6}$$

where δD_{min} is the distance measurement resolution and $\delta\varphi_{min}$ is the phase measurement resolution.

Thus, considering a typical highway recommended inter-vehicle distance of 40-50 m, in order to achieve a distance estimation error below 1 m, such a system would require frequencies of few dozens of MHz [115]. However, the LEDs used in automotive applications are generally high power, and so they are slow switching devices. So, the experimental advances in this field are postponed for the moment. Considering this aspect, the authors of [116] proposed a phase-shift rangefinder using a 1 MHz square signal achieving 10 cm resolution for distances up to 25 m and 30 cm resolution for distances up to 30 m. The method relies on the concept called Distance Estimation via Asynchronous Phase Shift (DEVAPS) and was firstly presented for radio sensors [117]. Thus, instead of simply reflecting the received signal, the transceiver receives, processes and only then it makes the retransmission, restoring this way the signal's energy and enhancing the SNR.

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In other cases, VLP was considered achievable by using TDOA techniques [118]. In such a case [119], the receiver should use more than one photosensitive element for the light detection. Although suitable mostly for indoor application, VLP could also be achieved using techniques based on the received signal strength (RSS) [120]. Nevertheless, the accuracy in this case can be maintained only for several meters. More complex ranging systems involve the usage of VLC in combination with other techniques. In [121], VLP is used along with a laser radar to increase the accuracy, whereas in [122], the distance is determined using a camera system and image processing techniques. In this case, VLC is used to provide additional data concerning the vehicle's size, data which is used to ensure the proper image processing.

It should be mentioned here that as the VLC technology in general, and the automotive VLC applications in particular, are still in the early stage, long range photodiode-based VLP applications are currently at simulation level. However, as the technology evolves, fully demonstrable VLP systems are expected. On the other hand, in addition to light intensity, image sensors are also able to detect the angle of arrival (AOA), and therefore, the ranging/positioning performances of high speed image sensor are one step ahead. Thus, the experimental demonstration of VLC and VLP, using high speed image sensor has been achieved, with an estimation error below 0.3 m for distances up to 60 m [123]. Furthermore, as the system has been further improved, accurate distance measurements have been accomplished even in mobile conditions, with the vehicle rolling at 30 km/h [106], [124]. The system measures the range by using phase only correlation. For mobile conditions, the system uses an algorithm to reduce the influence of vibrations caused by the road surface irregularity. It should be also mentioned that even though the accuracy of this system is lower than the one of LIDAR systems, their measurement time is only of 2 ms, compared to LIDAR where the scanning rate is of 10 Hz. Furthermore, these results can be further enhanced by adopting high speed stereo vision processing, with two high speed image sensors. In this case, with the help of triangulation, centimeter accuracy can be obtained [106], [124].

E. Challenge 5 - Increasing data rate

In vehicle VLC applications, the robustness to noise, the communication distance, the packet delivery ratio, the low latencies are all more important than the data rate. However, it is highly desirable to increase the data rate when this enhancement does not affect the upper mentioned features. In indoor short range applications, VLC proved to be able of achieving very high data rates that can go up to more few tens of Gb/s [2], [3]. The high data rates are obtained using more complex modulations like OFDM [125] or multi-level codes [126]. In outdoor applications, the data rates are significantly lower. In most cases, the existing photodiode-based VLC systems aimed for long-distance applications achieve data rates that are lower than 100 kb/s [59], [62], [69], [70]. In the best cases, such systems achieve data rates of 1-2 Mb/s [60]. Much better results are obtained by the camera-based VLC receivers. In their case, data rates that can go up to 20 Mb/s [84] - [86] or even 55 Mb/s [87] were experimentally accomplished. However, even in these cases, the data rates are significantly decreasing when the distance increases (see Table III). The higher data rates achieved by the camera based VLC receiver are achieved with the help of MIMO techniques and are strictly determined by the performances of the camera (i.e. up to 1000 fps). In their case, each LED of the emitter can be considered as a parallel channel communicating with a pixel region on the camera. To further increase the data rate, complex modulation and coding techniques are used [51], [87].

Concerning the required data rate in vehicular communication applications, this is rather difficult to clearly define. The IEEE 802.11p standard specifies data rates from 3 to 27 Mb/s. However, in this case, due to the mutual interferences, the message generation rate is up to 10 messages per second. On the other hand, in VLC, nearby links have no influence on each other due to the high spatial reuse and therefore, the message generation rate can be significantly increased. Basically, in VLC networks, the vehicles could continuously communicate to each other without affecting the communication channel or the packet delivery ratio.

Very encouraging results concerning long-distance, high data-rate V2V VLC were found in [127]. The simulation results based on the experimental power measurements of a headlamp beam, and considering a photodiode-based receiver, indicated that a data rate of 50 Mb/s can be achieved for a distance of up to 70 m, with a BER of 10^{-4}. Therefore, as the technology gets mature, higher data rates are expected even for long distance applications.

As already mentioned, the lower data rates accomplished so far in long range vehicular applications are on one hand due to the lower SNR levels, and on the other hand, due to the fact that the LEDs used in these applications are generally high power, and thus, their switching time is slower. To address this second issue, the authors of [23] debate the usage of laser diodes in VLC application, whereas in [128], a 12 m 2.5 Gb/s VLC link using a laser diode source is experimentally demonstrated. Nevertheless, their integration is currently postponed due to the eye safety norms.

To improve the data rate of long-distance VLC applications, future research should investigate the behavior of the indoor modulation techniques in the outdoor scenario. However, it is unlikely to achieve comparable data rates. Again, the chances to accomplish this challenge are strongly related to the noise mitigation problem.

F. Challenge 6 –Developing parallel visible light communications

Developing MIMO VLC applications could offer the opportunity to increase the data rate by transmitting the info on parallel channels. Nevertheless, unlike in indoor applications, MIMO techniques could have an even more important role. Considering the fact that in communication-based vehicle safety applications the communication

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robustness, the packet delivery ratio and the reduced latencies are considered more important than the data rate, MIMO techniques could be used to divide the transmitted data according to its priority (i.e. high priority data and low priority data). Accordingly, with the help of MIMO techniques, the high priority data can be transmitted in parallel to the low priority data, but with different characteristics (i.e. modulation, data rate, power) in order to ensure the proper reception. In this case, the usage of the MIMO techniques will not be motivated by the data rate increase but it will be motivated by the reliability it brings to the envisioned application.

In MIMO VLC, multiple optical sources are treated as different transmitters, mainly with the purpose of increasing the data rate. However, unlike in RF systems, VLC MIMO links are more complex to design, because in VLC the paths between emitter and receiver are very similar. In indoor VLC applications, the development of MIMO systems is quite advanced, as its potential to increase data rate was considered even from the early stage (2004) [129], [130]. Soon after, experimental demonstration of MIMO VLC systems became available [131]. At this moment, such systems use four to sixteen or even more parallel channels, achieving multi-Gb/s data rates [132]. Currently, the research in this domain is focused on the investigation of different MIMO modulation/transmission schemes that can further enhance the performances of such systems [133]-[135].

In the case of photodiode-based receivers, the MIMO receiver consists of independent photodiodes, each dedicated to a specific data transmitting light source. In this case, the distance separating the photodiodes is very important as it significantly influences the communication BER performance [129]. Although the MIMO scenario has advantages, it is based on narrow angle VLC links (i.e. narrow angle emission and narrow FOV receivers) and so, it requires a careful alignment between emitter and receiver, whereas a small misalignment significantly affects the performances. Consequently, MIMO VLC usage in photodiode-based vehicular applications is rather unfeasible, at least for the moment. In order to address this problem, the authors of [47] and [62], evaluate the usage of a bandwidth efficient line coding technique (Miller code) that should reduce the interferences between adjacent communication channels. Their results confirm analytically and experimentally the compatibility of the Miller code with vehicular VLC applications and also the future potential in MIMO applications, but do not provide a demonstration of a MIMO VLC system using the proposed code.

On the other hand, as mentioned above, the camera based systems are not alignment sensitive, facilitating their usage in mobile MIMO VLC applications. A basic experimental demonstration of such a system was initially found in [136]. Here, a 64 LEDs emitter was modulated at a rate of 250 Hz, whereas the communication distance was up to 30 m. Over the years, subsequent developments of this method enabled communication distances of up to 70 meters and data rates of up to 64 kb/s [137]. Furthermore, the systems have been enhanced with the development of an hierarchical overlay coding which enables long distance, low BER transmissions of the high priority data [51], [137]. This transmission is made in parallel with less important data, for which the communication distance is shorter and the BER higher, increasing the reliability of the high priority data. In this case, the usage of the MIMO techniques was not motivated by the data rate increase but by the reliability it brings to the high priority data.

G. Challenge 7 – Towards heterogeneous DSRC & VLC networks

The usage of VLC does not exclude RF communication, as the two technologies are fully compatible and do not perturb each other whatsoever. Rather neglected in vehicular applications, heterogeneous networks are a hot research topic in indoor applications [138] - [140]. Here, the mobile devices (e.g. tablets, smartphones, laptops or computers) do not have a lighting function, in order to use it for data uploading. From this reason, high data rate applications are envisioned only with the help of a second wireless communication technology. So, multi Gb/s VLC links are used for data receiving and RF based links are used for the data upload, with the mention that in RF-sensitive environments, infrared can be used instead. Therefore, such hybrid networks are considered to increase data rate, throughput, and fairness [8], [140]. Furthermore, the heterogeneous networks enhance the mobility and increase the reliability of the connection. These two particular aspects are envisioned from heterogeneous networks in vehicular communications and from this reason such networks are essential in future vehicular networks.

In vehicular communications, the usage of the two solutions should be considered with the primary purpose of enhancing the reliability. Although VLC has numerous advantages for V2I and V2V use, the fact that its application is limited to LoS can act as a disadvantage. Therefore, its combination with 5.9 GHz DSRC may significantly improve link quality – a crucial issue in safety applications. As analytically demonstrated in [37], the aforementioned technologies are complementary solutions. DSRC is a mature technology able to provide long-distance communication. On the other hand, VLC is not able to provide comparable communication distances, but it is considered to have a great potential in high traffic densities, whereas its large geographical distribution also represents a great benefit.

Further in to the future, platooning applications are expected to be part of the autonomous driving. Vehicles in a platoon are expected to adjust their speed and maintain a safe distance to the vehicles in front in order to follow the platoon leader. In order to enhance the efficiency, the inter-vehicle distances should be as low as possible (3 – 5 m). Although platooning involves a high amount of high priority data, analytical studies have showed that VLC is able to support this type of applications [96], [141], [142]. In VLC, the messages for the vehicles that are not in the LoS are transmitted in a multi-hop manner. In most cases, this is not a problem, because in general, potentially dangerous situations are prevented based on the data exchange between the closest

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neighbors, whereas for the other vehicles, reasonable delays can be accepted. However, when we are talking about high priority control or event driven messages, their distribution should be made within stricter limits. In such a case, multi-hop transmissions may lead to an increased end-to-end delay, especially when the VLC data rate is low. Addressing such scenarios with the help of DSRC seems a reasonable solution. The usage of both technologies in such a scenario has showed an enhancement of the communication reliability [143] and an imprudent of the end-to-end delay [144]. The usage of 5.9 GHz DSRC – VLC hybrid networks for platooning applications was also analyzed in [145]. In this case, VLC was found to substantially improve scalability, especially when hundreds of communicating cars are involved. Moreover, VLC was considered suitable as a backup technology and also to offload the DSRC network. The authors of [146] consider DSRC an indispensable part of vehicle networks but admit the benefits of VLC and consider this technology suitable for network offloading. Technologies combination for enhanced performances has also been considered suitable in [147] with the mention that in this case DSRC is used together with IR.

A different approach for VLC – DSRC heterogeneous networks is considered in [148]. Here, the transmitted information is divided between the VLC channel and the RF channel. Thus, RF is used to transmit omnidirectional data, intended to all vehicles, whereas VLC is used to transmit directional information, for vehicles from a specific area or on a single lane. Again, the results showed that the two technologies together provide enhanced results, in terms of coverage and receivable information. Such an approach seems very convincing as it is obvious that not all the transmitted information is interesting for all the vehicles, and in such a case, VLC is suited due to its geographical data distribution, whereas in the opposite situation DSRC is suitable to achieve highly reliable long distance communication. It must be pointed out here, that in DSRC – VLC hybrid networks both technologies gain benefits. For DSRC, the main benefit is that VLC takes some of the load on it, increasing its reliability and enhancing its performances (latencies and packet delivery ratio). An illustration of such a hybrid vehicle network is shown in Fig. 9.

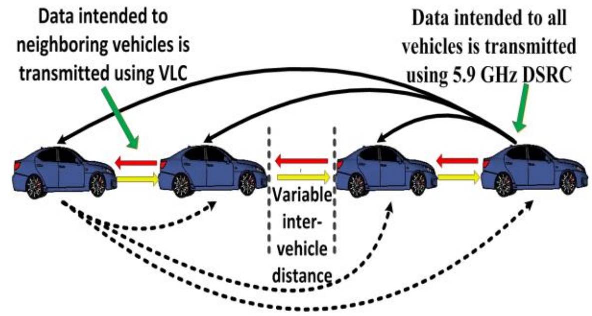

Fig. 9. DSRC and VLC vehicular heterogeneous network.

We conclude this section by pointing out that according to the ISO 26262, safety related systems integrated in series passenger vehicles should rely on the data received from more than one sensor. Thus, applying the same principle in communication-based vehicle safety applications, the two technologies, 5.9 GHz DSRC and VLC might be used together, with the potential to further improve the performances.

V. Discussions on the Road Ahead

Despite being an active research area, the outdoor VLC applications, in general, and vehicular VLC applications, in particular, attracted a smaller research effort compared to indoor VLC applications, and therefore, they are one step behind. However, this fact can be an advantage for the automotive VLC domain, as it could use some of the already existing and confirmed solutions from indoor VLC. Furthermore, vehicular VLC application could also inspire from the solutions found in RF communications in general or from the ones found in DSRC in particular, as the latest one is specially designed for the automotive domain. In such a case, technical aspects that have been conquered after years of research can be adapted and therefore the gap can be recovered much faster. Moreover, taking benefit from emerging trends and technologies could speed up the technology development. Referring to the 5.9 GHz DSRC, we should mention that this is a mature technology, with confirmed performances and which is a step away from deployment.

This survey addressed the issues related to the practical aspects regarding the implementation of the VLC systems aimed for automotive applications. Within it, the research efforts in several crucial directions have been analyzed and reviewed. However, it must be clearly outlined that at least for the next years, *the most important challenge in the field is increasing the robustness to noise*. Solving this problem will lead to tangible results for other challenges as well. Thus, noise robust VLC systems will allow long distance and high data rate communications, whereas the mobility can be enhanced with the extension of the FOV or with the help of additional VLC receivers. Regarding the development of hybrid networks, it is now rather obvious that in research, the software component is capable to rapidly adapt itself on the hardware requirements and therefore, it can be considered that once the two solutions (VLC and DSRC) will have enhanced performances and unquestionable reliability, their "software hybridization" in terms of load balancing and handover will be available. Moreover, one can expect that all the required protocols might be available even before the hardware aspects are fully finalized. After debating the current challenges and the existing approaches, the following sub-sections aim to propose several future research directions that are not currently applied in automotive VLC applications, but which might provide superior benefits once they will be addressed. As standardization provides the grounds on which a technology is evolving, existing standardization activities are also reviewed.

A. *Environment-adaptive automotive VLC systems*

Forasmuch the automotive (outdoor) VLC channel is highly

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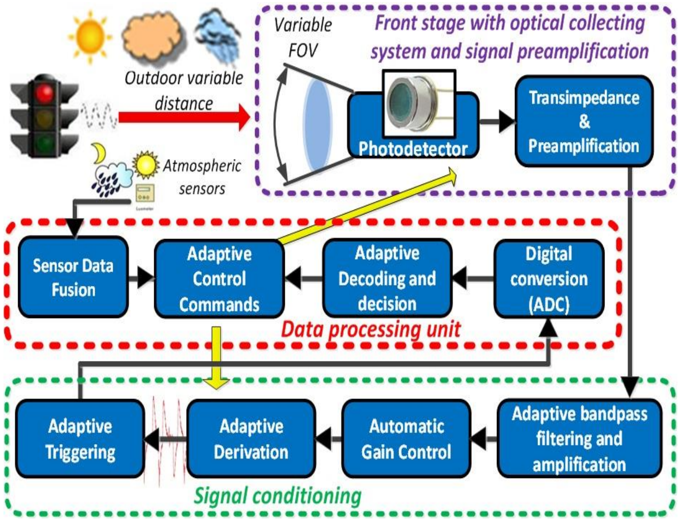

Fig. 10. Block diagram of an auto-adaptive visible light communications system. The VLC receiver, englobes adaptive FOV, automatic gain control, adaptive filters, adaptive triggering, adaptive decoding. These functions enable it to have an optimal configuration adapted to the specific atmospheric conditions [102].

dynamic and extremely noisy, whereas the uncontrolled external conditions make it very unpredictable, the initial approach in VLC prototypes design was to develop a VLC system able to provide communication in the worst case scenario. Nevertheless, such an approach is sure to limit the system's performances in favorable conditions. Thus, the receiver described in [69] was designed to support communication in direct sun exposure. However, the experimental verification has revealed that the limited gain of the pre-amplification stage and a static value of the gain in the amplification stage lead to a significant decline in communication distances, no matter the power of the parasitic light. Next, in [62], the receiver's FOV is narrowed to ± 10°, limiting the amount of parasitic light incident on the photosensitive element, whereas an AGC unit manages the optimal gain settings. These solutions were able to reduce the sunlight influence, enabling a much longer communication distance. Although the system had remarkable results, the narrow FOV negatively affected the mobility limiting its applicability. In [71], the robustness to noise is provided with the help of the DSSS modulation, affecting the data rate. Thus, *the response to mitigate the parasitic sunlight affected* in turn *the communication distance, the mobility, and the data rate*. So, it can be observed that in order to counteract a particular situation, such as the one in which the sun is directly facing the VLC receiver, the communication's performances are deteriorated for all possible situations. Similar, a disproportional response to diminish the effects of other negative conditions further affects the overall system performances.

A concept solution to address this issue and also to simultaneously address several of the upper-mentioned challenges is proposed in [102] and illustrated in Fig. 10. Inspired by organic examples, the development of self-aware [149], [150] or of context-aware [151] VLC systems has the potential to offer an adaptive, highly resilient and exceptional efficient behavior to the communication. In VLC, this concept is newly introduced and it proposes the usage of several external sensors that perceive the environment conditions (e.g. power of sun and sun's relative position, weather conditions, relative position of the other vehicles, etc.) which could influence the communication process. Based on the evaluation of the received information, the VLC devices can adapt the communication parameters (e.g. type of modulation, channel coding, data rate, etc.) in order to maximize the performances within the given setup. Furthermore, the VLC receiver can adapt its internal parameters (e.g. FOV, filters, gain, signal processing plan, etc.) in order to optimally receive the data. Thus, the implementation of context-aware adaptive VLC receivers has the potential to improve the overall performances and maximize the reliability, no matter the environment conditions. The major role of adaptive VLC systems is also pointed out in [152]. Here, the authors propose a realistic channel model for VLC, assuming a mobile user and demonstrate the benefits of link adaptation. In addition to VLC channel determination with the help of sensors, or based on a model, the channel conditions could be estimated by using neural networks [153].

B. Towards reconfigurable software-defined automotive VLC sensors for improved performances and enhanced flexibility

Another major limitation of existing automotive VLC systems is represented by their *rigidity*. Thus, as already mentioned, a VLC system designed to be very robust to noise has a relatively short communication distance, or a lower data rate, even in the absence of any noise source. Moreover, the existing VLC sensors, mainly based on analogic signal treatment are difficult to update or to be further improved once their design is completed. In their case, a functional or a standard update is possible only by designing and implementing a new hardware prototype.

A suitable solution to address this issue would be the development of software-defined VLC sensors. Such a VLC receiver entails an analog front end unit for light sensing and a digital signal processing (DSP) unit for signal treatment. In most of the current outdoor VLC receivers, the output of the transimpedance circuit is processed using analog techniques. However, future VLC prototypes could be improved by using DSP techniques [73], [74]. The central component of a DSP system is the digital filter, which can achieve significantly better results compared to the analogical ones. As the outdoor VLC channel is strongly affected by noise, the digital filters usage could represent an important advantage which could improve the next generation of outdoor VLC receivers. Furthermore, DSP techniques also benefit from an enhanced flexibility, enabling the receiver to better cope to the highly dynamic and unpredictable environment. Thus, such VLC systems can be easily reconfigured for different situations. For example, changing from a cut-off frequency to another one can be done by using a different set of coefficients, whereas in noisy environments, the filtering quality can be improved by changing the filters' order. Moreover, in noisy environments, a DSP sensor can use a more complex configuration in order to properly extract the data. So, DSP can adapt to variate

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conditions only by changing some coefficients or by modifying the signal processing plan, without any additional hardware optimizations. Furthermore, the enhanced flexibility of DSP-based VLC sensors could be given by the fact that such a receiver will be able to reshape its computing plan, introducing the concept of reconfigurable computing [154], [155] in VLC automotive systems. Thus, according to the SNR, the receiver could adopt a simplified signal processing plan in high SNR conditions, or a highly complex plan in low SNR conditions. Such a VLC receiver would be able to maintain the communication even in unfriendly environments enabling a decent BER, while optimally balancing computation resource utilization. This approach is envisioned to be used on vehicle embedded DSP systems using multi-core data processing units (Fig. 11). Thus, the basic operational plan can be processed by a VLC dedicated core (permanent), whereas when more computational power is required, an additional core can be (re)allocated (*resource sharing*).

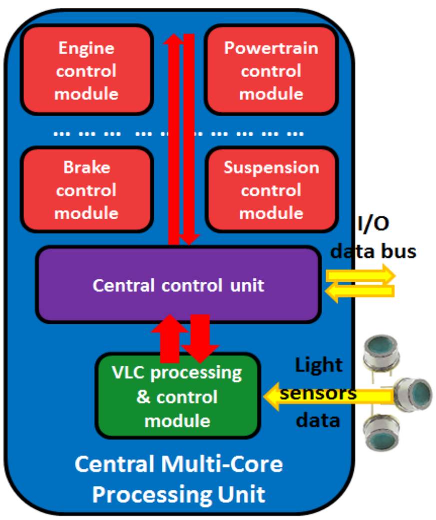

Fig. 11. Multi-core processing unit for automotive applications.

Within this context, the research efforts in the area of reconfigurable software-defined automotive VLC sensors should address two main challenges: (1) enhancing the photodiode-based analog front end circuit design and (2) developing and enhancing the digital signal processing algorithms.

C. Development and integration of OLED Visible Light Communication Systems for Automotive Applications

During last decade, organic semiconductors emerged as an alternative to inorganic semiconductors in various electronics applications such as light sources, displays, solar cells, photodetectors and integrated circuits, and contributed to the development of novel applications such as smart windows and electronic papers. This progress is especially driven by the mass production of OLED displays that has already reached approximately \$ 15 billion market value in 2016, with an expectation for more than \$ 30 billion in 2020 [156]. As opposed to area of OLED displays, which reached a certain degree of maturity, the use of OLED for both lighting and data transmissions is still in its infancy [157]. While OLED technology has provided several advantages for lighting and display applications compared to LED technology (such as lower fabrication costs, large area devices, larger visibility angle), it is lagging significantly behind in communication applications (data transfer rate is almost two order of magnitude smaller in OLED-VLC compared to LED-VLC [158]). An intensive research effort from both academia and industry in order to transition OLED visible light communications (VLC) from potential to applications is required. The current state-of-the-art research in OLED – VLC is mainly focused on indoor communications, and it is difficult to foresee short-term solutions to compete with LED – VLC with respect to data transfer rate due to the low charge mobility characterizing organic semiconductor compared to the inorganic ones.

Within this context, OLED-VLC applications could be orientated to other areas, such as road infrastructure-to-vehicle communications, where OLED advantages can play a more prominent role while the transfer data rate is significantly limited in LED-VLC, as well, due to the external noise (especially, natural and artificial light). In addition, the mixed organic-inorganic structure of the proposed OLED may also provide an improvement in the transfer data rate characteristics. This approach is encouraged by the recent developments in automotive industry, which has introduced several OLED-based illumination systems for their new luxury car models. A thin OLED lighting strip, between 0.8 mm - 1.5 mm, could open a number of exciting new options for aerodynamically optimized cars. Audi working with Philips demonstrated that the uniformity of light output from an OLED panel is an advantageous because will reduce the need for reflectors which are necessary with other lighting techniques. Ultimately automotive OLED lights printed on transparent plastics could also be fitted to the windows of cars too. BMW can already work with flat OLED panels but needs to develop the fully conformable module that can be used more widely across vehicle designs. The second challenge is that OLEDs are currently not bright enough to pass the requirements used in safety-critical vehicle lighting. Thus the industry is planning to gradually introduce OLEDs by combining them with LEDs and its forthcoming laser headlights. This will give a composite design solution with the various technologies compensating for each other's shortcomings.

Future work should contribute to new developments in this field of technology. One of the main interests should be research on the border line between organic and inorganic semiconductors towards new materials, devices and technologies based on new functional organic and organic-inorganic hybrid materials, such as new emissive materials for the visible and near infrared spectral range, new electron conducting/hole blocking materials or hole conducting materials, materials for controlling interface properties like injection barriers for holes and electrons, materials for diffusion barriers, adhesion, and for optimization of other parameters with technological importance. The research should also be directed towards new flexible integrated organic circuits, devices for display technology, and for optical information transfer and processing. These areas underpin many aspects of telecommunications, automotive and aerospace electronics, computer technology, and many other kinds of consumer electronics. The resulting technology could offer more flexibility and is expected to be more cost effective than established semiconductor technologies. The combination of organic and inorganic semiconductor technology is, however, a challenge for future developments since many problems of interface engineering, layer formation with controlled morphology, and structuring have to be solved.

D. VLC Standardization efforts

Although the upper-mentioned challenges have referred to physical enhances of the VLC systems, it must be pointed out that the domain can have plenty of benefits from standardization. A competitive and widely accepted vehicular VLC specific standard can reduce the gap between the industry and academia, stimulate the development, and speed up the deployment towards the market. Thus, the standardization of the VLC has begun right in the early stage, with the first VLC standards (CP-1221 and CP-1222) being published in 2007 by the Japan Electronics and Information Technology Industries Association (JEITA) and the VLC Consortium (VLCC). The VLCC members also worked on the CP-1223, a simplified and improved version of CP-1222, published in 2013, whereas a new standard proposal referred to as IEC 62943 was approved in 2014, and it is currently being developed by the Visible Light Communications Association (VLCA), the former VLCC [159].

In parallel to the Japanese VLC standardization efforts, the IEEE 802.15 Task Group 7 began its activity in January 2009. After publishing several draft standards in November 2010 and in early 2011, the IEEE 802.15.7 standard for *Short-Range Wireless Optical Communication Using Visible Light* has been launched in September 2011 [46]. The IEEE 802.15.7 standard addresses the issues related to the PHY and MAC layers, providing the specifications for low data rate (11.67-266.6 kb/s) outdoor and for medium data rate (2-96 Mb/s) indoor applications [160]-[162]. Nevertheless, soon after the publication of the standard, it was found that the data rates specified for indoor scenarios were too low compared to the performances of the existing prototypes [163]-[165]. Referring to inter-vehicle communications and ITS applications, the IEEE 802.15.7 standard mentions them as possible use cases but without providing any of the specific V2V or I2V regulation. Within this context, as showed in [166], the IEEE 802.15.7 standard is far from being widely accepted, as most of the VLC developers design their systems without considering the standard's specifications. Consequently, after only few years after its release, the IEEE 802.15.7 standard is being revised by task group TG7r1 [167], [168]. Regarding the ITS applications, the revised version embraces vehicular communications as a fundamental VLC use case, mentioning V2I and V2V applications. Thus, after analyzing the specific requirements of vehicular communications, the standard intends to improve mobility, robustness, data rates and to enhance the networking protocols [167]. Nevertheless, as the indoor and the outdoor VLC applications have different challenges, dissimilar expectancies, and rather different implementation approaches, future standardization efforts should aim to provide a VLC standard strictly focusing on vehicle applications [86], [166]. Therefore, the IEEE 802.15.7r1 standard might be a transitional step towards this goal. In a similar way, specific VLC standards are being requested for VLC camera communications [29] and for VLC positioning [169].

Within this context, we conclude this standardization related section by pointing out that at this moment one cannot talk about a global widely accepted point of view on VLC standardization in general and vehicular VLC standardization in particular. Actually, there is the VLCA Japanese standard [159], and then the European view [167], whereas different groups working on specific VLC applications or use cases are also demanding specific standardization.

VI. Conclusions

As communication-based vehicle safety applications are emerging as one of the best future solutions to enhance the safety of road transportation, the VLC technology struggles to gain its share in this new area. Vehicular VLC has an increased potential and numerous advantages, but the existing VLC prototypes are not capable to fully comply with the requirements imposed by road safety applications.

This article has made a survey of the VLC systems proposed for automotive applications. The article was orientated on the current challenges, but it is also providing a review of the up-to-date solutions aimed at overtaking each of the challenges. Increasing the communication range, enhancing the mobility and improving the data rate are some of the main trials in the field. However, the accomplishment of these tasks is strictly dependent on solving the main challenge: the ability of rejecting the parasitic light. As the outdoor VLC channel is subject to multiple sources of parasitic light, the ability to cope with them is crucial for the future development of the technology. In addition to the above-mentioned challenges, experimentally confirming the VLC potential use in distance measuring and in high accuracy positioning can give VLC an important advantage towards the usage in automotive applications.

As the overall vehicular communication performances could be improved by using both DSRC and VLC technologies, this article also addressed the aspects related to the development of VLC – 5.9 GHz DSRC heterogeneous networks. This mixed development can significantly increase the reliability of vehicular networks. Furthermore, the ISO 26262 standard referring to vehicle safety systems states that such a system cannot depend on the data received from only one sensor. Applying this philosophy in vehicular communications could definitely enhance the overall reliability.

We conclude this article by emphasizing the fact that the performances of VLC sensors aimed automotive for applications could be further improved by investigating and integrating innovative research trends as – *software defined architectures*, *reconfigurable computing*, *resource sharing*, *self-aware and context-aware adaptive architectures, or* *organic materials integration* – trends that are not currently implemented in this area, but which confirmed their benefits in other applications.

LIST OF ACRONYMS

ADR	angle diversity receivers
AGC	Automatic Gain Control
BER	Bit Error Ratio
DMT	Discrete Multi-Tone
DSP	Digital Signal Processing
DSRC	Dedicated Short Range Communications
DSSS	Direct Sequence Spread Spectrum
FOV	Field of View
FPGA	Field Programmable Gate Array
fps	frames per second
FSO	free space optical
GBP	Gain Bandwidth Product
HPA	half power angle
I2V	Infrastructure to Vehicle
IR	infrared
ITS	Intelligent Transportation System
LED	Light Emitting Diode
LoS	Line of Sight
MIMO	Multiple Input Multiple Output
nLoS	non Line of Sight
OFDM	Orthogonal Frequency Division Multiplexing
OLED	Organic LED
OOK	On-Off Keying
RF	Radio Frequency – within this article, the terms “radio” or “radio frequency” (“RF”) often refer to the frequency band from 3 kHz up to 300 GHz, including the frequency bands that are referred to as “radio frequency”, “microwaves” and “millimeter waves”.
RLL	Run Length Limited
RSS	received signal strength
PDR	Packed Delivery Ratio
PIN	positive-intrinsic-negative
SNR	Signal to Noise ratio
SSL	Solid State Lighting
TDOA	time difference of arrival
V2I	Vehicle to Infrastructure
V2V	Vehicle to Vehicle
VANET	Vehicle Ad-hoc NETwork
VL	visible light
VLC	Visible Light Communications
VLCA	Visible Light Communications Association
VLP	Visible Light Positioning
VPPM	Variable Pulse Position Modulation
VSCC	Vehicle Safety Communications Consortium
WAVE	Wireless Access in Vehicular Environments

REFERENCES

[1] Cisco Systems, “Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2015-2019,” Whitepaper, February 2015.

[2] A. T. Hussein, M. T. Alresheedi and J. M. H. Elmirghani, "20 Gb/s Mobile Indoor Visible Light Communication System Employing Beam Steering and Computer Generated Holograms," in *J. Lightw. Technol.*, vol. 33, no. 24, pp. 5242-5260, Dec.15, 2015.

[3] H. Chun *et al*., "LED Based Wavelength Division Multiplexed 10 Gb/s Visible Light Communications," in *J. Lightw. Technol.*, vol. 34, no. 13, pp. 3047-3052, Jul., 2016.

[4] S. Wu, H. Wang, C.-H.; Youn, "Visible light communications for 5G wireless networking systems: from fixed to mobile communications," in *IEEE Network*, vol.28, no.6, pp.41-45, Nov.-Dec. 2014.

[5] Cheng-Xiang Wang, *et al*., "Cellular architecture and key technologies for 5G wireless communication networks," in *IEEE Commun. Mag.*, vol.52, no.2, pp.122-130, Feb. 2014.

[6] M. B. Rahaim and T. D. C. Little, "Toward practical integration of dual-use VLC within 5G networks," in *IEEE Wireless Commun.*, vol. 22, no. 4, pp. 97-103, Aug. 2015.

[7] M. Ayyash *et al*., "Coexistence of WiFi and LiFi toward 5G: concepts, opportunities, and challenges," in *IEEE Commun, Mag.*, vol. 54, no. 2, pp. 64-71, Feb. 2016.

[8] L. Xuan; Z. Rong; L. Hanzo, "Cooperative Load Balancing in Hybrid Visible Light Communications and WiFi," *IEEE Trans. Commun.*, vol.63, no.4, pp.1319-1329, Apr. 2015.

[9] *Fact Sheet 296 – Electromagnetic fields and public health,* World Health Org., Geneva, Switzerland, Dec. 2005.

[10] International Agency for Research on Cancer, World Health Org., “IARC Classifies Radio Frequency Electromagnetic Fields as Possible Carcinogenic to Humans”, Press Release No. 208, 31 May 2011.

[11] *Fact Sheet 193 – Electromagnetic fields and public health: mobile phones,* World Health Org., Geneva, Switzerland, Jun. 2011.

[12] *Fact Sheet 193 – Electromagnetic fields and public health: mobile phones,* World Health Org., Geneva, Switzerland, Reviewed Oct. 2014.

[13] G. Pang, H. Liu, C. H. Chan, and T. Kwan, “Vehicle location and navigation systems based on LEDs,” in *Proc. 5th World Congr. Intell. Transp. Syst.*, Oct. 1998, pp. 1–8, paper 3036.

[14] G. Pang, T. Kwan, C.-H. Chan, and H. Liu, “LED traffic light as a communications device,” in *Proc. IEEE/IEEJ/JSAI Int. Conf. Intell. Transp. Syst.*, Oct. 1999, pp. 788–793.

[15] M. Akanegawa, Y. Tanaka and M. Nakagawa, "Basic study on traffic information system using LED traffic lights," in *IEEE Trans. Intel. Transp. Syst.*, vol. 2, no. 4, pp. 197-203, Dec. 2001.

[16] A. Sevincer, A. Bhattarai, M. Bilgi, M. Yuksel and N. Pala, "LIGHTNETs: Smart LIGHTing and Mobile Optical Wireless NETworks — A Survey," in *IEEE Commun. Surveys Tuts.*, vol. 15, no. 4, pp. 1620-1641, 2013.

[17] M. A. Khalighi and M. Uysal, “Survey on free space optical communion: A communication theory perspective,” *IEEE Commun. Surveys Tuts.*, vol. 16, no. 4, pp. 2231–2258, Nov. 2014.

[18] D. Karunatilaka, F. Zafar, V. Kalavally and R. Parthiban, "LED Based Indoor Visible Light Communications: State of the Art," in *IEEE Commun. Surveys Tuts.*, vol. 17, no. 3, pp. 1649-1678, 2015.

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

[20] D. C. O'Brien, L. Zeng, H. Le-Minh, G. Faulkner, J. W. Walewski and S. Randel, "Visible light communications: Challenges and possibilities," in *Proc. IEEE 19th Int. Symp. Personal, Indoor and Mobile Radio Commun., PIMRC 2008*, Cannes, 2008, pp. 1-5.

[21] D. C. O'Brien, "Visible Light Communications: Challenges and potential," in *Proc. Photon. Conf. (PHO), 2011 IEEE*, Arlington, VA, 2011, pp. 365-366.

[22] A. Jovicic, Junyi Li and T. Richardson, "Visible light communication: opportunities, challenges and the path to market," in *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 26-32, Dec. 2013.

[23] F. Zafar, M. Bakaul and R. Parthiban, "Laser-Diode-Based Visible Light Communication: Toward Gigabit Class Communication," in *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 144-151, Feb. 2017.

[24] M. S. Shur and R. Zukauskas, "Solid-State Lighting: Toward Superior Illumination," in *Proc. IEEE*, vol. 93, no. 10, pp. 1691-1703, Oct. 2005.

[25] I. L. Azevedo, M. G. Morgan, and F. Morgan, “The transition to solid-state lighting,” *Proc. IEEE*, vol. 97, no. 3, pp. 481–510, Mar. 2009.

[26] M. Cole, H. Clayton and K. Martin, "Solid-State Lighting: The New Normal in Lighting," in *IEEE Trans. Ind. Appl.*, vol. 51, no. 1, pp. 109-119, Jan.-Feb. 2015.

[27] Hoa Le Minh *et al*., "80 Mbit/s Visible Light Communications using pre-equalized white LED," in *Proc. 34th European Conf. Optical Commun. ECOC*, Brussels, 2008, pp. 1-2.

[28] L. Hanzo, H. Haas, S. Imre, D. O'Brien, M. Rupp and L. Gyongyosi, "Wireless Myths, Realities, and Futures: From 3G/4G to Optical and Quantum Wireless," in *Proc. IEEE*, vol. 100, no. Special Centennial Issue, pp. 1853-1888, May 2012.

[29] N. Saha, M. S. Ifthekhar, Nam Tuan Le and Yeong Min Jang, "Survey on optical camera communications: challenges and opportunities," in *IET Optoelectron.*, vol. 9, no. 5, pp. 172-183, 10 2015.

[30] R. D. Roberts, "A MIMO protocol for camera communications (CamCom) using undersampled frequency shift ON-OFF keying (UFSOOK)," in *Proc. IEEE Globecom Wkshps (GC Wkshps),* Atlanta, GA, 2013, pp. 1052-1057.

[31] R. D. Roberts, "Undersampled frequency shift ON-OFF keying (UFSOOK) for camera communications (CamCom)," in *Proc. 22nd Wireless Optical Commun. Conf.*, Chongqing, 2013, pp. 645-648.
[32] P. Ji, H. M. Tsai, C. Wang and F. Liu, "Vehicular Visible Light Communications with LED Taillight and Rolling Shutter Camera," in *Proc. IEEE 79th Veh. Technol. Conf. (VTC Spring)*, Seoul, 2014, pp. 1-6.
[33] *Fact Sheet 310—The Top 10 Causes of Death*, World Health Org., Geneva, Switzerland, Jan. 2017.
[34] *Fact Sheet 358—Road Traffic Injuries*, World Health Org., Geneva, Switzerland, May 2016.
[35] *Global status report on road safety 2015,* World Health Org., Geneva, Switzerland, 2015.
[36] *"Frequency of Target Crashes for IntelliDrive Safety Systems*," U.S. Department of Transportation Research and Innovative Technology Administration, John A. Volpe Nat. Transp. Syst. Center, Cambridge, MA, USA, Oct. 2010.
[37] A.-M. Cailean, B. Cagneau, L. Chassagne, V. Popa, and M. Dimian, "A survey on the usage of DSRC and VLC in communication-based vehicle safety applications," in *Proc. IEEE 21st Symp. Commun. Veh. Technol. Benelux (SCVT)*, Nov. 2014, pp. 69–74.
[38] O.K. Tonguz, N. Wisitpongphan, J.S. Parikh, B. Fan, P. Mudalige, V. K. Sadekar, "On the Broadcast Storm Problem in Ad hoc Wireless Networks," in *Proc. 3rd Int. Conf. Broadband Commun., Networks and Syst.*, (BROADNETS 2006), pp.1-11, Oct. 2006
[39] N. Wisitpongphan, O. K. Tonguz, J. S. Parikh, P. Mudalige, F. Bai and V. Sadekar, "Broadcast storm mitigation techniques in vehicular ad hoc networks," in *IEEE Wireless Commun.*, vol. 14, no. 6, pp. 84-94, Dec. 2007.
[40] P. Papadimitratos, A. La Fortelle, K. Evenssen, R. Brignolo, S. Cosenza, "Vehicular communication systems: Enabling technologies, applications, and future outlook on intelligent transportation," in *IEEE Commun. Mag.*, vol.47, no.11, pp.84-95, Nov. 2009.
[41] X. Long, J. He, J. Zhou, L. Fang, X. Zhou, F. Ren, T. Xu, "A review on light-emitting diode based automotive headlamps", in *Renewable and Sustainable Energy Reviews*, vol. 41, pp. 29-41, 2015.
[42] ECN, "EN 12368: Traffic Control Equipment - Signal Heads," ed:European Commitee for Standardization, April 2006.
[43] S. Kitano, S. Haruyama, M. Nakagawa, "LED road illumination communications system," in *Proc. 58th IEEE Veh. Technol. Conf., VTC 2003-Fall*, vol.5, pp.3346-3350, Oct. 2003.
[44] N. Kumar, "Smart and intelligent energy efficient public illumination system with ubiquitous communication for smart city," in *Proc. IEEE Int. Conf. Smart Structures Syst. (ICSSS)*, pp.152-157, Mar. 2013.
[45] M. Ergen, "Critical penetration for vehicular networks," in *IEEE Commun. Lett.*, vol.14, no.5, pp.414,416, May 2010.
[46] *IEEE Standard for Local and Metropolitan Area Networks—Part 15.7: Short-Range Wireless Optical Communication Using Visible Light*, IEEE Standard 802.15.7-2011, Sep. 2011, pp. 1–309.
[47] A-M. Cailean, B. Cagneau, L. Chassagne, M. Dimian, V. Popa, "Miller code usage in Visible Light Communications under the PHY I layer of the IEEE 802.15.7 standard," in *Proc. 10th Int. Conf. Commun. (COMM)*, May 2014, pp.1-4.
[48] A.-M. Cailean, B. Cagneau, L. Chassagne, V. Popa, M. Dimian, "Evaluation of the noise effects on Visible Light Communications using Manchester and Miller coding," in *Proc. Int. Conf. Dev. App. Syst. (DAS)*, pp.85-89, May 2014.
[49] C. Quintana, J. Rabadan, J. Rufo, F. Delgado and R. Perez-Jimenez, "Time-hopping spread-spectrum system for wireless optical communications," in *IEEE Trans. Consum. Electron.*, vol. 55, no. 3, pp. 1083-1088, Aug. 2009.
[50] J. Kim, D. Lee, K. D. Kim and Y. Park, "Performance improvement in visible light communication by using spread spectrum coding," in *Proc. 15th OptoElectron. Commun. Conf. (OECC)*, Sapporo, 2010, pp. 278-279.
[51] S. Nishimoto, T. Yamazato, H. Okada, T. Fujii, T. Yendo and S. Arai, "High-speed transmission of overlay coding for road-to-vehicle visible light communication using LED array and high-speed camera," in *Proc. IEEE Globecom Wkshps (GC Wkshps)*, Anaheim, CA, 2012, pp. 1234-1238.
[52] C. Kaiyun, C. Gang, X. Zhengyuan, R.D. Roberts, "Experimental characterization of traffic light to vehicle VLC link performance," in *Proc. IEEE GLOBECOM Wkshps (GC Wkshps)*, Dec. 2011, pp.808-812.
[53] J. M. Kahn, W. J. Krause and J. B. Carruthers, "Experimental characterization of non-directed indoor infrared channels," in *IEEE Trans. Commun.*, vol. 43, no. 2/3/4, pp. 1613-1623, 1995.
[54] A. Moreira, R. Valadas and A. de Oliveira Duarte, "Characterisation and modelling of artificial light interference in optical wireless communication systems," in *Proc. 6th IEEE Int. Symp. Personal, Indoor and Mobile Radio Commun., PIMRC'95. Wireless: Merging onto the Information Superhighway*, 1995, pp. 326-331.
[55] I.E. Lee, M.L. Sim, F.W.L. Kung, "Performance enhancement of outdoor visible-light communication system using selective combining receiver," in *IET Optoelectron.*, vol.3, no.1, pp.30-39, Feb. 2009.
[56] J.M. Kahn, J.R. Barry, "Wireless infrared communications," *Proc. IEEE*, vol.85, no.2, pp.265-298, Feb. 1997.
[57] F. Hossain, Z. Afroze, "Eliminating the effect of fog attenuation on FSO link by multiple TX/RX system with travelling wave semiconductor optical amplifier," in *Proc. Int. Conf. Advances in Electrical Eng. (ICAEE)*, Dec. 2013, pp.267-272.
[58] M. Ijaz, Z. Ghassemlooy, H. Le Minh, S. Rajbhandari, J. Perez, "Analysis of fog and smoke attenuation in a free space optical communication link under controlled laboratory conditions," in *Proc. Int. Wkshp Optical Wireless Commun. (IWOW)*, Oct. 2012, pp.1-3.
[59] T. Saito, S. Haruyama, M. Nakagawa, "A New Tracking Method using Image Sensor and Photo Diode for Visible Light Road-to-Vehicle Communication," in *Proc 10th Int. Conf. Adv. Commun. Technol. ICACT*, pp.673-678, Feb. 2008.
[60] S. Okada, T. Yendo, T. Yamazato, T. Fujii, M. Tanimoto, Y. Kimura, "On-vehicle receiver for distant visible light road-to-vehicle communication", in *Proc. IEEE Intell. Veh. Symp. (IV)*, Jun. 2009, pp.1033-1038.
[61] C. Liu, B. Sadeghi, E.W. knightly, "Enabling vehicular visible light communication (V2LC) networks", In *Proc. ACM Vanet'11*, pp. 41-50, 2011.
[62] A.-M. Cailean, B. Cagneau, L. Chassagne, M. Dimian, V. Popa, "Novel Receiver Sensor for Visible Light Communications in Automotive Applications," in *IEEE Sensors J.*, vol.15, no.8, pp.4632-4639, 2015.
[63] D.-R. Kim, S.-H. Yang, H.-S. Kim, Y.-H. Son, and S.-K. Han, "Outdoor visible light communication for inter-vehicle communication using controller area network," in *Proc. 4th Int. Conf. Commun. Electron. (ICCE)*, Aug. 2012, pp. 31–34.
[64] R. Corsini, *et al*., "Free space optical communication in the visible bandwidth for V2V safety critical protocols," in *Proc. 8th Int. Conf. Wireless Commu. Mobile Computing (IWCMC)*, Aug. 2012, pp.1097-1102.
[65] Sung-Man Kim, Seong-Min Kim, "Performance improvement of visible light communications using optical beamforming," in *Proc. 5th Int. Conf. Ubiquitous Future Networks (ICUFN)*, pp.362-365, Jul. 2013.
[66] Yong Hyeon Kim, W. A. Cahyadi, Yeon Ho Chung, "Experimental Demonstration of VLC-Based Vehicle-to-Vehicle Communications Under Fog Conditions," in *IEEE Photonics J.*, vol.7, no.6, Dec. 2015.
[67] U. Kurokawa, B. I. Choi, C.-C. Chang, "Filter-based miniature spectrometers: Spectrum reconstruction using adaptive regularization," in *IEEE Sensors J.*, vol. 11, no. 7, pp. 1556–1563, Jul. 2011.
[68] C.C. Chang, Y.J. Su, U. Kurokawa, B. I. Choi, "Interference Rejection Using Filter-Based Sensor Array in VLC Systems," in *IEEE Sensors J.*, vol.12, no.5, pp.1025-1032, May 2012.
[69] A. Cailean, B. Cagneau, L. Chassagne, S. Topsu, Y. Alayli, J-M. Blosseville, "Visible light communications: Application to cooperation between vehicles and road infrastructures," in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Jun. 2012, pp.1055-1059.
[70] N. Lourenco, D. Terra, N. Kumar, L.N Alves, R.L. Aguiar, "Visible Light Communication System for outdoor applications," in *Proc. 8th Int. Symp. Commun. Syst., Networks & Digital Signal Processing (CSNDSP)*, Jul. 2012, pp.1-6.
[71] N. Kumar, N. Lourenço, D. Terra, L.N. Alves, R.L. Aguiar, "Visible light communications in intelligent transportation systems," in *Proc. IEEE Intell. Vehicles Symp. (IV)*, Jun. 2012, pp.748-753.
[72] D. Terra, N. Kumar, N. Lourenco, L.N. Alves, L.A. Aguiar, "Design, development and performance analysis of DSSS-based transceiver for VLC," in *Proc. IEEE Int. Conf. Computer as a Tool (EUROCON)*, pp.1-4, 27-29 Apr. 2011.
[73] A.-M. Cailean, B. Cagneau, L. Chassagne, M. Dimian, V. Popa, "Novel DSP Receiver Architecture for Multi-Channel Visible Light Communications in Automotive Applications," in *IEEE Sensors J.*, vol. 16, no.10, pp. 3597-3602, May 2016.

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[74] A.-M. Cailean, B. Cagneau, L. Chassagne, V. Popa, M. Dimian, "Design and performance evaluation of a DSP visible light communication receiver," in *Proc. IEEE 21st Symp. Commun. Veh. Technol. Benelux (SCVT)*, Nov. 2014, pp.30-34.
[75] J. Baranda, P. Henarejos, and C.G. Gavrincea, "An SDR implementation of a visible light communication system based on the IEEE 802.15.7 standard," in *Proc. 20th Int. Conf. Telecomm. (ICT)*, pp.1-5, May 2013.
[76] A. Belle, M. Falcitelli, M. Petracca, P. Pagano, "Development of IEEE802.15.7 based ITS services using low cost embedded systems," in *Proc. 13th Int. Conf. ITS TeleCommun.*, pp.419-425, Nov. 2013.
[77] *Vehicle Safety Communications Project Task 3 Final Report*, The CAMP Vehicle Safety Communications Consortium consisting of BMW, DaimlerChrysler, Ford, GM, Nissan, Toyota, and VW, 39255 Country Club Drive, Suite B-30,Farmington Hills, MI 48331, Mar. 2005.
[78] *IEEE Standard for Information Technology—Local and Metropolitan Area Networks—Specific Requirements—Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 6: Wireless Access in Vehicular Environments*, IEEE Standard 802.11p, Jul. 2010.
[79] S. Eichler, "Performance Evaluation of the IEEE 802.11p WAVE Communication Standard", in *Proc. 66th IEEE Veh. Technol. Conf.*, Baltimore, MD, pp. 2199-2203, 2007.
[80] K. Bilstrup, E. Uhlemann, E. Strm, U. Bilstrup, "On the ability of the 802.11p MAC method and STDMA to support real-time vehicle-to-vehicle communication," in *EURASIP J. Wireless Commun.* Net. 2009, 2009:902414.
[81] Yao Yuan, Rao Lei, Liu Xue, "Performance and Reliability Analysis of IEEE 802.11p Safety Communication in a Highway Environment," in *IEEE Trans. Veh. Technol.*, vol.62, no.9, pp.4198-4212, Nov. 2013.
[82] K. Karlsson, C. Bergenhem, E. Hedin, "Field Measurements of IEEE 802.11p Communication in NLOS Environments for a Platooning Application," in *Proc. IEEE Vehic. Technol. Conf. (VTC Fall)*, pp.1-5, Sept. 2012.
[83] R. Atallah, M. Khabbaz, C. Assi, "Multi-hop Vehicle-to-Infrastructure Communications: A Feasibility Study, Modelling and Performance Analysis," in *IEEE Trans. Vehic. Techn.*, vol.66, no.3, pp.2801-2810, 2017.
[84] I. Takai, S. Ito, K. Yasutomi, K. Kagawa, M. Andoh, S. Kawahito, "LED and CMOS Image Sensor Based Optical Wireless Communication System for Automotive Applications," in *IEEE Photonics J.*, vol.5, no.5, pp.6801418-6801418, Oct. 2013.
[85] I. Takai, T. Harada, M. Andoh, K. Yasutomi, K. Kagawa, S. Kawahito, "Optical Vehicle-to-Vehicle Communication System Using LED Transmitter and Camera Receiver," in *IEEE Photonics J.*, vol.6, no.5, pp.7902513-7902513, Oct. 2014.
[86] T. Yamazato *et al.*, "Image-sensor-based visible light communication for automotive applications," in *IEEE Commun. Mag.*, vol. 52, no. 7, pp. 88–97, Jul. 2014.
[87] Y. Goto *et al*., "A New Automotive VLC System Using Optical Communication Image Sensor," in *IEEE Photon. J.*, vol. 8, no. 3, pp. 1-17, Jun. 2016.
[88] Navin Kumar, "Visible light communication for road safety applications", PhD Dissertation, Dept. of Electronics, Telecommunications and Informatics, University of Aveiro, Portugal, 2011.
[89] A.-M. Cailean, B. Cagneau, L. Chassagne, S. Topsu, Y. Alayli, and M. Dimian, "Visible light communications cooperative architecture for the intelligent transportation system," in *Proc. IEEE 20th Symp. Commun. Veh. Technol. Benelux (SCVT)*, Nov. 2013, pp. 1–5.
[90] W.-W. Shieh, W.-H. Lee, S.-H. Tung, B.-S. Jeng, C.-H., Liu, "Analysis of the Optimum Configuration of Roadside Units and Onboard Units in Dedicated Short-Range Communication Systems," in *IEEE Trans. Intell. Transp. Syst.*, Vol. 7, No. 4, pp. 565-571, Dec. 2006.
[91] N. Kumar, L. N. Alves and R. L. Aguiar, "Design and analysis of the basic parameters for traffic information transmission using VLC," in Proc. *1st Int. Conf. Wireless Commun., Vehic. Technol., Inf. Theory and Aerospace & Electronic Syst. Technol., VITAE*, Aalborg, 2009, pp. 798-802.
[92] K. Siddiqi, A. D. Raza and S. S. Muhammad, "Visible light communication for V2V intelligent transport system," in *Proc. Int. Conf. Broadband Communications for Next Generation Networks and Multimedia Applications (CoBCom)*, Graz, 2016, pp. 1-4.
[93] J. Jeong, C. G. Lee, I. Moon, M. Kang, S. Shin and S. Kim, "Receiver angle control in an infrastructure-to-car visible light communication link," *2016 IEEE Region 10 Conf. (TENCON)*, 2016, pp. 1957-1960.
[94] A. Agarwal, T. D. C. Little, "Role of directional wireless communication in vehicular networks," in Proc. *IEEE Intell. Veh. Symp. (IV)*, pp.688-693, Jun. 2010.
[95] Z. Cui, P. Yue and Y. Ji, "Study of cooperative diversity scheme based on visible light communication in VANETs," *Int. Conf. Comp., Information Telecomm. Syst. (CITS)*, 2016, pp. 1-5.
[96] M. Y. Abualhoul, P. Merdrignac, O. Shagdar and F. Nashashibi, "Study and evaluation of laser-based perception and light communication for a platoon of autonomous vehicles," in *Proc. IEEE 19th Int. Conf. Intell. Transp. Syst. (ITSC)*, Rio de Janeiro, 2016, pp. 1798-1804.
[97] M. M. Rahman, L. Bobadilla and B. Rapp, "Establishing line-of-sight communication via autonomous relay vehicles," in *Proc. IEEE Military Commun. Conf.*, (*MILCOM 2016*) Baltimore, MD, 2016, pp. 642-647.
[98] J. B. Carruthers and J. M. Kahn, "Angle Diversity for Nondirected Wireless Infrared Communication," *IEEE Trans. Commun.*, vol. 48, no. 6, pp. 960–969, Jun. 2000.
[99] Zhe Chen, N. Serafimovski, H. Haas, "Angle Diversity for an Indoor Cellular Visible Light Communication System," in *Proc. IEEE 79th Veh. Technol. Conf. (VTC Spring)*, May 2014, pp.1-5.
[100] Cuiwei He, T.Q. Wang, J. Armstrong, "MIMO Optical Wireless Receiver Using Photodetectors with Different Fields of View," in *Proc. IEEE 81st Veh.Technol. Conf. (VTC Spring)*, May 2015, pp.1-5.
[101] Cuiwei He, T.Q. Wang, J. Armstrong, "Performance of Optical Receivers Using Photodetectors With Different Fields of View in a MIMO ACO-OFDM System," in *J. Lightw. Technol.*, vol.33, no.23, pp.4957-4967, Dec.1, 2015.
[102] A.-M. Cailean, and M. Dimian, "Towards Environmental-Adaptive Visible Light Communications Receivers for Automotive Applications: A Review," in *IEEE Sensors J.*, vol. 16, no.9, pp.2803-2811, May 2016.
[103] M. Y. Abualhoul, M. Marouf, O. Shag and F. Nashashibi, "Enhancing the field of view limitation of Visible Light Communication-based platoon," in *Proc. 2014 IEEE 6th Int. Symp. Wireless Vehic. Commun. (WiVeC)*,Vancouver, BC, 2014, pp. 1-5.
[104] S. Savasta, M. Pini, and G. Marfia, "Performance assessment of a commercial GPS receiver for networking applications," in *Proc. 5th IEEE Cons. Commun. Netw. Conf.*, 2008, pp. 613-617.
[105] M. Goppelt, H.-L. Blcher, and W. Menzel, "Automotive radar - investigation of mutual interference mechanisms," in *Adv. Radio Sci.*, vol. 8, pp. 55-60, Sep. 2010.
[106] T. Yamazato and S. Haruyama, "Image Sensor Based Visible Light Communication and Its Application to Pose, Position, and Range Estimations," in *IEICE Trans. Commun*., vol.E97-B No.9, pp.1759-1765, 2014.
[107] G. Kim, J. Eom and Y. Park, "An Experiment of Mutual Interference between Automotive LIDAR Scanners," in *Proc. 12th Int. Conf. Inf. Technol. - New Generations (ITNG)*, Las Vegas, 2015, pp. 680-685.
[108] G. Kim, J. Eom and Y. Park, "Investigation on the occurrence of mutual interference between pulsed terrestrial LIDAR scanners," in *Proc. IEEE Intell. Vehic. Symp. (IV)*, Seoul, 2015, pp. 437-442.
[109] Masaki Yoshino, Shinichiro Haruyama and Masao Nakagawa, "High-accuracy positioning system using visible LED lights and image sensor," in *Proc. IEEE Radio Wireless Symp.*, Orlando, FL, 2008, pp. 439-442.
[110] S. H. Yang, E. M. Jeong, D. R. Kim, H. S. Kim, Y. H. Son and S. K. Han, "Indoor three-dimensional location estimation based on LED visible light communication," in *Electron. Lett.*, vol. 49, no. 1, pp. 54-56, Jan. 3 2013.
[111] Se-Hoon Yang, Hyun-Seung Kim, Yong-Hwan Son and Sang-Kook Han, "Three-Dimensional Visible Light Indoor Localization Using AOA and RSS With Multiple Optical Receivers," in *J. Lightw. Technol.*, vol. 32, no. 14, pp. 2480-2485, Jul. 2014.
[112] M. Yasir, S. W. Ho and B. N. Vellambi, "Indoor Position Tracking Using Multiple Optical Receivers," in *J. Lightw. Technol.*, vol. 34, no. 4, pp. 1166-1176, Feb.15, 15 2016.
[113] T. H. Do and M. Yoo, "Potentialities and challenges of VLC based outdoor positioning," in *Proc. In.l Conf. Inf. Net. (ICOIN)*, Cambodia, 2015, pp. 474-477.
[114] R. Roberts, P. Gopalakrishnan, S. Rathi, "Visible light positioning: Automotive use case," in *Proc. IEEE Vehic. Net. Conf. (VNC)*, pp.309-314, 13-15 Dec. 2010.
[115] Shun-Hsiang Yu; Shih, O.; Hsin-Mu Tsai; Roberts, R., "Smart automotive lighting for vehicle safety," in *IEEE Commun. Mag.*, vol.51, no.12, pp.50-59, Dec. 2013.

[116] B. Béchadergue, L. Chassagne, H. Guan, "Visible Light Phase-Shift Rangefinder for Platooning Applications," in *Proc. 19th IEEE Int. Conf. Intell. Transp. Syst*., 2016, pp. 2462-2468.

[117] C. Y. Wen, R. D. Morris and W. A. Sethares, "Distance Estimation Using Bidirectional Communications Without Synchronous Clocking," in *IEEE Trans. Sig. Process.*, vol. 55, no. 5, pp. 1927-1939, May 2007.

[118] H. Y. Nah, R. Parthiban and M. H. Jaward, "Visible Light Communications localization using TDOA-based coherent heterodyne detection," in *Proc. IEEE 4th Int. Conf. Photon. (ICP)*, Melaka, 2013, pp. 247-249.

[119] B. Bai, G. Chen, Z. Xu, Y. Fan, "Visible Light Positioning Based on LED Traffic Light and Photodiode," in *Proc. IEEE Vehic. Techn. Conf. (VTC Fall)*, pp.1-5, Sept. 2011.

[120] E. Gonendik and S. Gezici, "Fundamental Limits on RSS Based Range Estimation in Visible Light Positioning Systems," in *IEEE Commun. Lett.*, vol. 19, no. 12, pp. 2138-2141, Dec. 2015.

[121] A. J. Suzuki, and K. Mizui, "Laser radar and visible light in a bidirectional V2V communication and ranging system," in *Proc. IEEE Int. Conf. Vehic. Electronics and Safety (ICVES)*, Japan, 2015, pp. 19-24.

[122] N. Sasaki, N. Iijima and D. Uchiyama, "Development of ranging method for inter-vehicle distance using visible light communication and image processing," in *Proc. 15th Int. Conf. Control, Automation and Syst. (ICCAS)*, Busan, 2015, pp. 666-670.

[123] T. Yamazato and S. Haruyama, "Image Sensor Based Visible Light Communication and Its Application to Pose, Position, and Range Estimations," in *IEICE Trans. Commun*., vol.E97-B No.9, pp.1759-1765, 2014.

[124] T. Yamazato *et al*., "Range estimation scheme for integrated I2V-VLC using a high-speed image sensor," in *Proc. IEEE Int. Conf. Commun. Wkshps (ICC)*, Kuala Lumpur, 2016, pp. 326-330.

[125] D. Tsonev *et al*., "A 3-Gb/s single-LED OFDM-based wireless VLC link using a gallium nitride μ LED," in *IEEE Photon. Technol. Lett.*, vol. 26, no. 7, pp. 637–640, Apr. 1, 2014.

[126] J. Vucic, C. Kottke, S. Nerreter, K.-D. Langer, J.W. Walewski, "513 Mbit/s Visible Light Communications Link Based on DMT-Modulation of a White LED," in *J. Lightw. Technol.*, vol.28, no.24, pp.3512-3518, Dec.15, 2010.

[127] M. Uysal, Z. Ghassemlooy, A. Bekkali, A. Kadri, and H. Menouar, "Visible light communication for vehicular networking: Performance study of a V2V system using a measured headlamp beam pattern model," in *IEEE Veh. Technol. Mag.*, vol. 10, no. 4, pp. 45–53, Dec. 2015.

[128] B. Fahs, A. J. Chowdhury and M. M. Hella, "A 12-m 2.5-Gb/s Lighting Compatible Integrated Receiver for OOK Visible Light Communication Links," in *J. Lightw. Technol.*, vol. 34, no. 16, pp. 3768-3775, Aug.15, 15 2016.

[129] D. Takase and T. Ohtsuki, "Optical wireless MIMO communications (OMIMO)," in *Proc IEEE Global Telecommun. Conf. (GLOBECOM '04)*, pp. 928-932 Vol.2, 2004.

[130] S. Jivkova, B. A. Hristov and M. Kavehrad, "Power-efficient multispot-diffuse multiple-input-multiple-output approach to broad-band optical wireless communications," in *IEEE Trans. Veh. Technol.*, vol. 53, no. 3, pp. 882-889, May 2004.

[131] S. Hranilovic and F. R. Kschischang, "A pixelated MIMO wireless optical communication system," in *IEEE J. Selected Topics in Quantum Electronics*, vol. 12, no. 4, pp. 859-874, Jul.-Aug. 2006.

[132] A. H. Azhar, T. Tran and D. O'Brien, "A Gigabit/s Indoor Wireless Transmission Using MIMO-OFDM Visible-Light Communications," *IEEE Photon. Technol. Lett.*, vol. 25, no. 2, pp. 171-174, Jan.15, 2013.

[133] T. Fath and H. Haas, "Performance Comparison of MIMO Techniques for Optical Wireless Communications in Indoor Environments," in *IEEE Trans. Commun.*, vol. 61, no. 2, pp. 733-742, Feb. 2013.

[134] S. P. Alaka, T. L. Narasimhan and A. Chockalingam, "Generalized Spatial Modulation in Indoor Wireless Visible Light Communication," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, San Diego, CA, 2015, pp. 1-7.

[135] R. Tejaswi, T. Lakshmi Narasimhan, and A. Chockalingam, ``Quad-LED complex modulation (QCM) for visible light wireless communication," in *Proc. IEEE WCNC'2016 Wkshps*, Apr. 2016.

[136] S. Iwasaki, M. Wada, T. Endo, T. Fujii and M. Tanimoto, "Basic Experiments on Paralle Wireless Optical Communication for ITS," in *Proc. IEEE Intell. Veh. Symp.*, Istanbul, 2007, pp. 321-326.

[137] S. Nishimoto *et al*., "Overlay coding for road-to-vehicle visible light communication using LED array and high-speed camera," in *Proc. 14th Int. IEEE Conf. Intell. Transp. Syst. (ITSC)*, Washington, DC, 2011, pp. 1704-1709.

[138] A. M. Khalid, G. Cossu, R. Corsini, M. Presi and E. Ciaramella, "Demonstrating a hybrid radio-over-fibre and visible light communication system," in *Electron. Lett.*, vol. 47, no. 20, pp. 1136-1137, Sept. 2011.

[139] Yunlu Wang and H. Haas, "Dynamic Load Balancing With Handover in Hybrid Li-Fi and Wi-Fi Networks," in *J. Lightw. Technol.*, vol. 33, no. 22, pp. 4671-4682, Nov.2015.

[140] D. A. Basnayaka and H. Haas, "Hybrid RF and VLC Systems: Improving User Data Rate Performance of VLC Systems," in *Proc. IEEE 81st Veh. Techn. Conf. (VTC Spring)*, Glasgow, 2015, pp. 1-5.

[141] M. Y. Abualhoul, M. Marouf, O. Shagdar and F. Nashashibi, "Platooning control using visible light communications: A feasibility study," in *Proc. 16th Int. IEEE Conf. Intell. Transp. Syst. (ITSC)*, 2013, pp. 1535-1540.

[142] M. Y. Abualhoul, O. Shagdar and F. Nashashibi, "Visible Light inter-vehicle Communication for platooning of autonomous vehicles," in *Proc. IEEE Intell. Veh. Symp. (IV)*, 2016, pp. 508-513.

[143] S. Ucar, S. C. Ergen and O. Ozkasap, "Security vulnerabilities of IEEE 802.11p and visible light communication based platoon," in *Proc. IEEE Vehic. Net. Conf. (VNC)*, Columbus, OH, 2016, pp. 1-4.

[144] S. Ishihara, R. V. Rabsatt and M. Gerla, "Improving reliability of platooning control messages using radio and visible light hybrid communication," in *Proc. IEEE Veh. Net. Conf. (VNC)*, Kyoto, 2015, pp. 96-103.

[145] M. Segata, R. Lo Cigno, H. M. M. Tsai and F. Dressler, "On platooning control using IEEE 802.11p in conjunction with visible light communications," in *Proc. 12th Annual Conf. Wireless On-demand Network Systems and Services (WONS)*, Cortina d'Ampezzo (BL), Italy, 2016, pp. 1-4.

[146] A. Bazzi, B. M. Masini, A. Zanella and A. Calisti, "Visible light communications in vehicular networks for cellular offloading," in *Proc. IEEE Int. Conf. Commun. Wkshp (ICCW)*, London, 2015, pp. 1416-1421.

[147] P. Fernandes, U. Nunes, "Platooning with DSRC-based IVC-enabled autonomous vehicles: Adding infrared communications for IVC reliability improvement," in *Proc. IEEE Intell. Veh. Symp. (IV)*, Jun. 2012, pp.517-522.

[148] J. Liu, P. W. C. Chan, D. W. K. Ng, E. S. Lo and S. Shimamoto, "Hybrid visible light communications in Intelligent Transportation Systems with position based services," in *Proc. IEEE Globecom Wkshps (GC Wkshps)*, Anaheim, CA, 2012, pp. 1254-1259.

[149] P. R. Lewis *et al*., "Architectural Aspects of Self-Aware and Self-Expressive Computing Systems: From Psychology to Engineering," in *Computer*, vol. 48, no. 8, pp. 62-70, Aug. 2015.

[150] S. Kounev, N. Huber, F. Brosig and X. Zhu, "A Model-Based Approach to Designing Self-Aware IT Systems and Infrastructures," in *Computer*, vol. 49, no. 7, pp. 53-61, Jul. 2016.

[151] F. Chiti, R. Fantacci, M. Loreti and R. Pugliese, "Context-aware wireless mobile autonomic computing and communications: research trends and emerging applications," in *IEEE Wireless Commun.*, vol. 23, no. 2, pp. 86-92, Apr. 2016.

[152] F. Miramirkhani; O. Narmanlioglu; M. Uysal; E. Panayirci, "A Mobile Channel Model for VLC and Application to Adaptive System Design," in *IEEE Commun. Lett.*, vol.21, no.5, pp.1035-1038, 2017.

[153] A. Yesilkaya, O. Karatalay, A. S. Ogrenci and E. Panayirci, "Channel estimation for visible light communications using neural networks," in *Proc. Int. Joint Conf. Neural Nets. (IJCNN)*, Vancouver, BC, pp. 320-325, 2016.

[154] R. Tessier, K. Pocek and A. DeHon, "Reconfigurable Computing Architectures," in *Proc. IEEE*, vol. 103, no. 3, pp. 332-354, Mar. 2015.

[155] A. DeHon, "Fundamental Underpinnings of Reconfigurable Computing Architectures," in *Proc. IEEE*, vol. 103, no. 3, pp. 355-378, Mar. 2015.

[156] J. Kang, I. Lim, "*OLED Display Technology Tracker*," HIS Technology Report, 2016.

[157] P.A. Haigh, Z. Ghassemlooy, S. Rajbhandari, I. Papakonstantinou, "Visible light communications using organic light emitting diodes," in *IEEE Commun. Mag.*, vol. 51 (8), pp. 148-154, 2013

[158] P. Haigh, F. Bausi, Z. Ghassemlooy, et al. "Visible light communications: real time 10 Mb/s link with a low bandwidth polymer light emitting diode," *Optics Express*, vol. 22 (3), pp. 2830 – 2838, 2014

[159] http://vlca.net/standard/

[160] R. D. Roberts, S. Rajagopal and S. K. Lim, "IEEE 802.15.7 physical layer summary," *2011 IEEE GLOBECOM Wkshps (GC Wkshps)*, Houston, TX, 2011, pp. 772-776.

[161] S. Rajagopal, R. D. Roberts and S. K. Lim, "IEEE 802.15.7 visible light communication: modulation schemes and dimming support," in *IEEE Commun. Mag.*, vol. 50, no. 3, pp. 72-82, Mar. 2012.

[162] A. C. Boucouvalas, P. Chatzimisios, Z. Ghassemlooy, M. Uysal and K. Yiannopoulos, "Standards for indoor Optical Wireless Communications," in *IEEE Commun. Mag.*, vol. 53, no. 3, pp. 24-31, Mar. 2015.

[163] J. Vučić, C. Kottke, K. Habel and K. D. Langer, "803 Mbit/s visible light WDM link based on DMT modulation of a single RGB LED luminary," in *Proc. Optical Fiber Commun. Conf. and Exposition and the National Fiber Optic Engineers Conf.*, Los Angeles, CA, 2011, pp. 1-3.

[164] T. Kubo, T. Umeki, T. Kanai, H. Suzuki, H. Hadama and M. Asobe, "A high-speed visible light indoor network employing a short pulse modulation and a QPM-LN module," in *Proc. Optical Fiber Commun. Conf. and Exposition and the National Fiber Optic Engineers Conf.*, Los Angeles, CA, 2011, pp. 1-3.

[165] A. M. Khalid, G. Cossu, R. Corsini, P. Choudhury and E. Ciaramella, "1-Gb/s Transmission Over a Phosphorescent White LED by Using Rate-Adaptive Discrete Multitone Modulation," in *IEEE Photon. J.*, vol. 4, no. 5, pp. 1465-1473, Oct. 2012.

[166] A.-M. Cailean, and M. Dimian, "Impact of IEEE 802.15.7 Standard on Visible Light Communications usage in Automotive Applications," in *IEEE Commun. Mag.*, vol. 55, no. 4, pp. 169-175, Apr. 2017.

[167] V. Jungnickel et al., "A European view on the next generation optical wireless communication standard," in *Proc. IEEE Conf. Standards for Commun. and Net. (CSCN)*, Tokyo, 2015, pp. 106-111.

[168] M. Uysal, F. Miramirkhani, O. Narmanlioglu, T. Baykas and E. Panayirci, "IEEE 802.15.7r1 Reference Channel Models for Visible Light Communications," in *IEEE Commun. Mag.*, vol. 55, no. 1, pp. 212-217, Jan. 2017.

[169] J. Armstrong, Y. A. Sekercioglu and A. Neild, "Visible light positioning: a roadmap for international standardization," in *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 68-73, Dec. 2013.

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