Research Article 2018, **3**(9), 544-549 Advanced Materials Proceedings

Smart vehicle lighting system based on a-SiCH technology

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DOI: 10.5185/amp.2018/1405
www.vbripress.com/amp

Abstract

In this paper the use of Visible Light Communication (VLC) in Vehicle Communication Systems is analyzed. The system aims to ensure communication between LED based emitters and SiC based receivers located at the vehicles. The proposed smart lighting system combines the functions of lighting, positioning, and communications. The SiC receivers is used as a encoder/decoder device. This photosensitive element features active filter properties, it multiplexes the modulated polychromatic signal coming from the LEDs in an electrical signal, performs multiplexing/demultiplexing techniques and decode the received information. A traffic scenario is established and two connected vehicular communications simulated. Infrastructure-to-Vehicle (I2V) follow by Vehicle-to-Vehicle (V2V) communications are analyzed. In the V2V communication, the emitter is based on the front headlights of the vehicle, while for the study of the I2V communication system, the emitter was built on the streetlights. The VLC receiver acts as a Wavelength Division Multiplexer (WDM) and increases the signal conditioning capability to decode the transmitted information. Each receiver is a two terminal p-i'(a-SiC:H)-n/p-i(a-Si:H)-n heterostructure located on both the tails and on the top roof of vehicles. The spectral sensitivity of the receiver and its optical gain are analyzed. For message transmission, the individual chips of the white trichromatic RGB LEDs are modulated acting, for data transfer, as individual VLC channels. A violet LED is used for error control and to identify the ID position of the transmitter. Free space is the medium of transmission. An on-off modulation scheme (OOK) is used to transmit data. An algorithm for decoding information is established. The connected I2V2V system was tested. The experimental results show that using white modulated LEDs for lighting and data transmission and a SiC WDM device to decode the information is possible to build a VLC vehicular system that ensures de communication between the outside infrastructures and the cars.

Keywords: Amorphous SiC technology, light emitting diodes, visible light communication, intelligent transportation system, photosensitive detectors, WDM.

Introduction

Wireless communication systems between vehicles and vehicles and infrastructures are an emerging technology. Its development allows the exchange of messages in the network, including road safety warnings.

Several types of vehicle communication can be considered such as communication between vehicles (V2V), between vehicles and infrastructure (V2I) and between the infrastructure and the vehicles (I2V). The integration of these different forms of communication allows the development of a concept of connected cars. Driven by the navigation safety measures, this concept increases safety requirements for navigation, being already adopted by car manufacturers.

The emergence of new scenarios that allow navigation safety, accident reduction, content distribution, safe emergency operations and urban sensing constitute a new branch of services in the vehicular transport network [**1**].

Recently, wireless communication using pulsed LED light has been proposed to be used in the transfer of messages between cars. LEDs are reliable, efficient and have a longer lifetime than classic light sources. These features lead automakers to replace classic halogen lamps with LED lighting. The use of LEDs imposes Line of Sight (LoS) being so appropriate for direct short-range communications.

LEDs emitters have advantages. They can be switch to different light intensities at fast rates. This feature led to the emergence of a new technology (Visible Light Communication - VLC) that uses LED-based lamps for illumination and also for high-speed information transmission [**2, 3**]. VLC promise to become the wireless technology of the future. VLC seems to be solving problems so far without solution. It carries the benefits of the visible light namely: safety for human body and for electronic equipments, enlarged bandwidth and unlicensed spectrum. VLC is also safer than RF, thus providing data transmission beyond the lighting function. VLC is an easy-to-implement, low-cost technology. Taking into account the advantages of LED-based communication and since LED lighting is widely spread in the transport networks (in traffic lights, street lighting and vehicle lighting systems) VLC seems to be suitable for providing wireless data exchange for automotive applications.

In previous works, we have presented a WDM device that improves the visible range transmission capacity. The device is a dual pin / pin amorphous SiC photodiode with optical active filtering properties under irradiation. This semiconductor device, operates in the visible range and is capable, through amplification, switching, and wavelength conversion procedures to perform multiplexing / demultiplexing operations **[4, 5]**. For an encode optical path the device multiplexes the different optical channels, and decodes the encoded signals recovering the transmitted information. This device can be used as receiver and helps developing new vehicular technologies that allow cars to communicate each other and with the infrastructures [**6**]. Through an adequate safety system, an alert warning can be sent to the driver or be automatically slowed down in advance, reducing the severity of a possible collision or even avoiding it.

In this paper, a cooperative I2V2V traffic scenario is established. The optoelectronic characterization of both transmitters and receivers is presented and the cooperative system evaluated. Code and parity MUX/DEMUX signals are designed, transmitted and analyzed. As proof of concept, a traffic scenario is presented and tested.

The integration of smart sensors, wireless communications, navigation support algorithms and optical source networks allow for a trans disciplinary approach that fits into cyber-physical systems.

Experimental

A VLC system consists of two fundamental blocks: the transmitter and the receiver separated by the VLC channel. The transmitter is used to modulate the light from white trichromatic LEDS and the receiver receives the coded signals and decodes them. The two blocks are apart. The interconnection is made in free space through the VLC channel. Line of Sight is a mandatory condition in this VLC system.

The VLC transmitter

The crucial section of the VLC emitter is the encoder whose main function is to convert the data into a modulated message. The encoder controls the switching of the LEDs according to the binary data and data rate. So, the binary data is converted into an amplitude modulated light beam that impinges on the receiver.

Modulated LEDs are used for a dual purpose, lighting and to transmit data. The use of trichromatic LEDs as emitters increases data rate transmission since it enables the demultiplexing of the polychromatic signal at the receiver.

The optical sources used for the dual function of lighting and data transmission are commercial RGB white LEDs of high intensity light output and wide viewing angle. They exhibit a wide divergence angle (2x60º), since they are also designed for general lighting and allow a wide delivery of VLC signal around the surrounding area. Datasheet specifications indicate peak wavelengths located in the ranges 619 nm – 624 nm, 520 nm – 540 nm and 460 nm – 480 nm for the red, green and blue emitters. In the experiment, a dedicated three channel LED driver with multiple outputs was developed to modulate the optical signals. The modulator converts the coded message of each transmission channel into a modulated driving current signal that actuates the emitters of each tri-chromatic white LED. In every LED, the driving current of each emitter is controlled independently of the other emitters but limited by a maximum value which is equal for all LEDS. The current is controlled by a programmable LED driver circuit TLC5922, which is connected to an Embed (embed NXP LPC1768) platform with an ARM Cortex-M3 - 96MHz microcontroller. A graphical user interface developed in Java allows controlling the system, which includes the setting of the driving current, bit sequence and frequency of each emitter. Each chip of the LED, is switched *on* and *off* individually at a desired bit sequence [R G B]. Here *1* means that the light is on an *0* that is off. A violet modulated LED [V] is also used to increase data transmission and to generate parity bits [**7**] allowing error control [**8**]. Using the available four input channels a (7,4) code is used for data transmission. The encoder takes four input data bits [R G B V] and generates three additional parity bits [9]. The parity bits are SUM bits of violet signal with other two additional RGB bits and are defined as:

$$P_R = V + R + B \tag{1}$$

$$P_G = V + R + G \tag{2}$$

$$P_B = V + G + B \tag{3}$$

Besides, at the output of the encoder a seven-bit codeword [R G B V; P_R P_G P_B] is generated, with the data bits separated from the parity bits. To transmit the data we use an On-Off Keying (OOK) modulation scheme.

Fig. 1, displays an encoded message in a frame of time. The digital signals (codewords) are used to drive the LEDs. In the code data (solid lines), all the sixteen (2^4) *on/off* input channels (RGBV) combinations of the are reported. The calculated (Equations 1, 2, 3) eight parity bits (dotted lines) are also shown. The arrow point towards the [1001:001] and [1111:111] seven bit codewords.

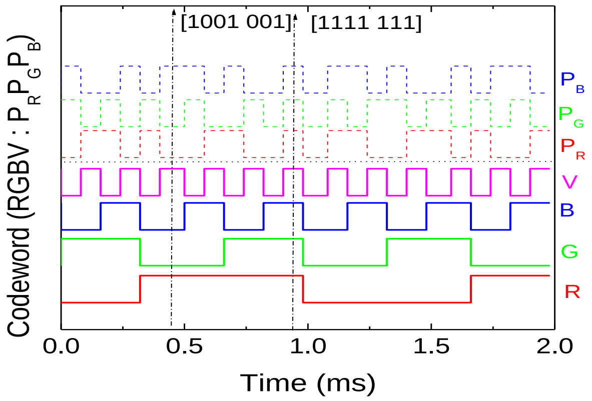


Fig. 1. Example of an original encoded message [R G B V; P_R P_G P_B].

The VLC receiver

The VLC receiver extracts the data from the modulated light beam. The beam impinges on the receiver is absorbed according its wavelength, generating a multiplexed electrical signal. Wavelength detection and demultiplexing techniques are then performed and the transmitted signal demodulated and decoded.

The VLC receiver is two terminal double, p-i'(a-SiC:H)-n/p-i(a-Si:H)-n hetero structure made by PECVD (Plasma Enhanced Chemical Vapor Deposition). Transparent conductive contacts (TCO) are used to bias the device. The device configuration and operation are shown in **Fig. 2**.

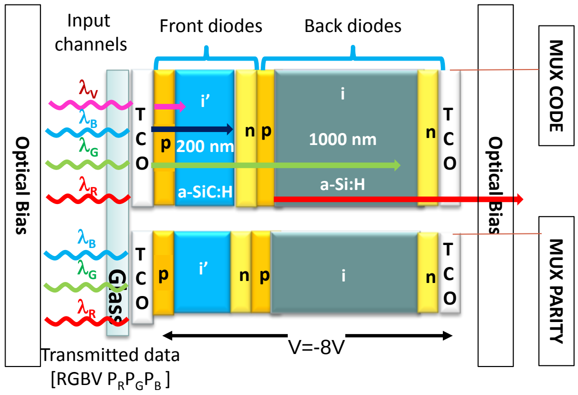


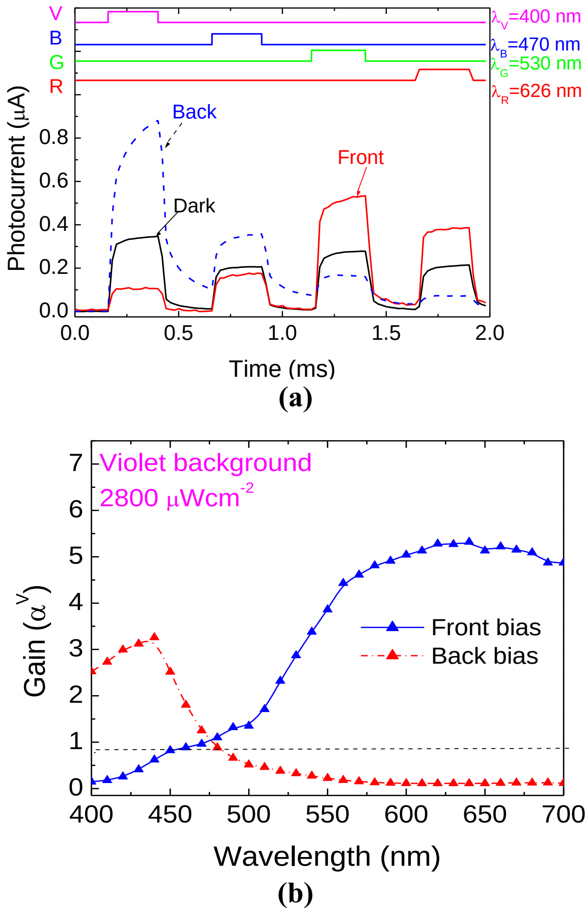
Fig. 2. Receiver configuration and operation.

The absorbers of each photodiode are based on different band gap materials, a-SiC:H in the front structure and a-Si:H in the back. Further information related to film and device production and optoelectronic characterization are described in previous publications [**4, 10**]. Collection of blue light and transmittance of red light is optimized using 2.1 eV band gap material of 200 nm thick for the front absorber and a 1.8 eV material of 1000 nm thickness. So, both diodes work as optical filters able to confine the optical carriers produced by the blue and red light, at the regions where they are generated.

The device is designed to operate with visible signals. For data transmission modulated low power light provided by a violet (V) and a trichromatic RGB-LED are used. Here, the LEDs are used not only to transmit the channel location and payload data but also for illumination purposes.

In this work, four modulated input channels (transmitted data) with different wavelength ($\lambda_{R,G,B,V}$) simultaneously focus on the receiver and are absorbed according to their wavelength (see the amplitude of the arrows in **Fig. 2**). Each channel has its own bit frequency (payload data; see **Fig. 1**). By reading out, under negative electrical bias (-8V), the generated photocurrent (multiplexed signal; received data) the transmitted data is analyzed and decoded.

A front and back violet background lighting (390 nm) is used to select the different wavelengths [**11**].



(a)

(b)

Fig. 3. (a) Transient photocurrent with front (Front) and back (Back) violet lighting and without it (Dark). (b) Spectral gain under violet irradiation (α^V).

Fig. 3a, displays the multiplexed signal (MUX signal) obtained when four RGBV monochromatic channels impinges on the device. Front and back irradiation was applied and compare with the signal without optical bias. The driving signal applied to each R, G, B and V LED are presented on the top of the figure. The bit sequence used imposes that when one channel is *on* the others three are *off*. The optical gain (α^V) can be defined as the quotient between the photocurrent with and without irradiation. In **Fig. 3b,** displays the α^V under front and back optical bias.

Data shows that, for each wavelength value, the magnitude of the photocurrent depends mainly on the irradiated side.

Front irradiation improves the long wavelength signals while back irradiation quench them. The opposite occurs with back irradiation. The irradiation side acts as an optical selector for the input channels. The device can be considered as an active long-pass filter under front irradiation and as a low-pass filter under back lighting. Gains over the unit were obtained for wavelengths above 500nm resulting in an amplification of the green and red spectral ranges under front optical bias. Back irradiation has an opposite effect. It should be noted that, under back background, as the wavelength increases the signal strongly decreases while, under front irradiation, the reverse happens. The decoding algorithm of the multiplexed signal in the receiver is based on the existence of this non-linearity.

The VLC architecture

The emerging technologies will allow drivers to advise other vehicles of possible dangers, while an emergency braking system is installed to prevent accidents. The information obtained is more precise than data coming from conventional sensors installed in some streets. Dynamic sensors can measure any street condition where a car is passing (low, fluid, cool, disturbed, heavy, satured and blocked traffic).

An illustration of the proposed hybrid scenario for vehicular communication is outlined in **Fig. 4**.

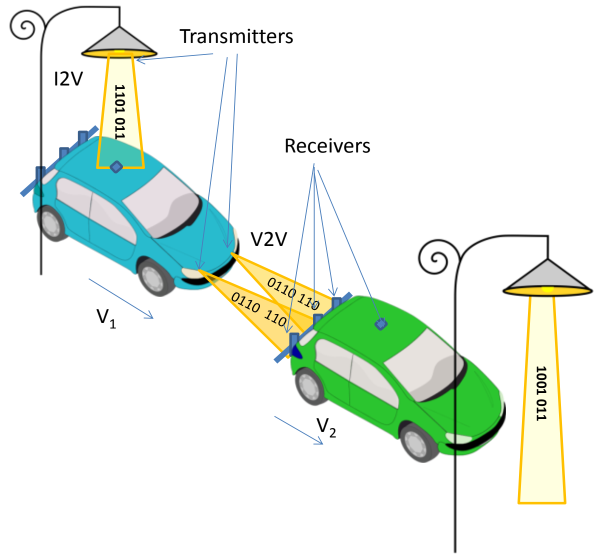


Fig. 4. Drawing of the proposed scenario: V2V and I2V hybrid systems.

The streetlights, located on roadside are used for lighting purposes. If modulated, at high rate, can also be used as transmitters. In the I2V communication system, we considered them as the emitters. The street lights emit light signals within a capture range across the road lane. They send a codeword message [RGBV: P_R, P_G, P_B] composed by a 4-binary bits (four input data bits [R G B V]) and generate three additional parity bits [P_R, P_G, P_B] for easy decoding and error control [**12**]. The transmitted information is received and decoded in the SiC pi'npin device located at the car roof. When the vehicle enters the street light´s capture range, the receivers at the roof top respond to the light signal and assigns an ID and a traffic massage in that frame of time. This data can be transmitted to the other leader vehicles. Hence, the transmitter (street lamp) can send a traffic message that is receive at the roof top of the follower (I2V) and retransmitted, using their front headlights, to a leader vehicle (V2V).

The V2V system allows feedback between vehicles. In the V2V system the follower vehicle is equipped with two headlamps transmitters. Three a-SiC pinpin receivers, located at the tail of the leader vehicle detect optical messages sent by the follow, as in **Fig. 4**. Here, the message received by the leader can be retransmitted to the next car or to another infrastructure equipped, also with a SiC receiver. We have only considered straight paths. Turning and zigzag paths should be considered in future experiments.

Results and discussion

Coding/decoding techniques used in VLC

Fig. 5, shows the multiplexed signal (solid lines), under front bias, acquired when four R, G, B, and V input channels overlaps simultaneously. The corresponding synchronized parity MUX signal is also displayed as dash lines, for the same frame time.

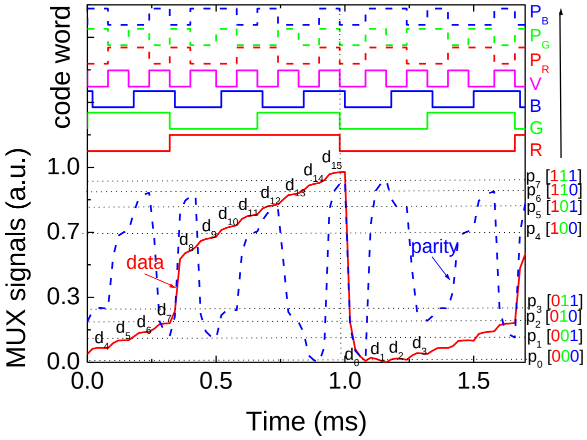


Fig. 5. MUX/DEMUX data code and parity signals under front irradiation. The transmitted channels [R G B V: P_R P_G P_B] are decoded on the top.

In this experiment the coded signal was chosen so that all the sixteen *on/off* states were present. Results show that the MUX signal presents so many levels apart as the different combinations of existing states [**13**]. In the figure, the levels of the coded signal are arranged (d_0-d_{15}) and indexed at the corresponding levels. The horizontal lines, dotted lines, indicate the eight levels associated with the parity MUX signal (p_0-p_7). In the right-hand part of **Fig. 5,** the matching between parity levels and the parity bits is exemplified (see **Fig. 1**). At the top, the decoded seven-word [R, G, B, V: P_R, P_G, P_B] associated with the transmitted signal is shown. It is important to note that to each of the sixteen states corresponds one and only one amplitude of the multiplexed signal. By matching each level with a 4 digits binary code [X_R, X_G, X_B, X_V], with X = 1 if the channel is on and X = 0 if off, the signal is decoded.

The proximity of the levels in the multiplexed signal can cause errors in the demultiplexing process. These errors can be controlled through the parity bits.

We can exemplify the error control through the parity bits´. For example, the levels d_8, d_9 and d_{10} are very close and may be confused. However, if we look at the amplitude of the corresponding parity levels, p_6, p_1 and p_3 we find that they are quite different. In the decoding process, we first assign to each level the corresponding 4- bit binary code and then buy compare with the correspondent parity bits. The word is accepted if there is a correspondence between both (code word and parity bit) and rejected otherwise. In this case, an error was detected and it is necessary to correct it [**12**].

We can thus conclude that the use of trichromatic RGB LED as transmitters and a-SiC:H pi'npin optical detectors as receivers allow the use of multiplex/demultiplex techniques increasing the transmission rate. The maximum transmission speed achieved was 30 kbps.

Cooperative VLC System evaluation

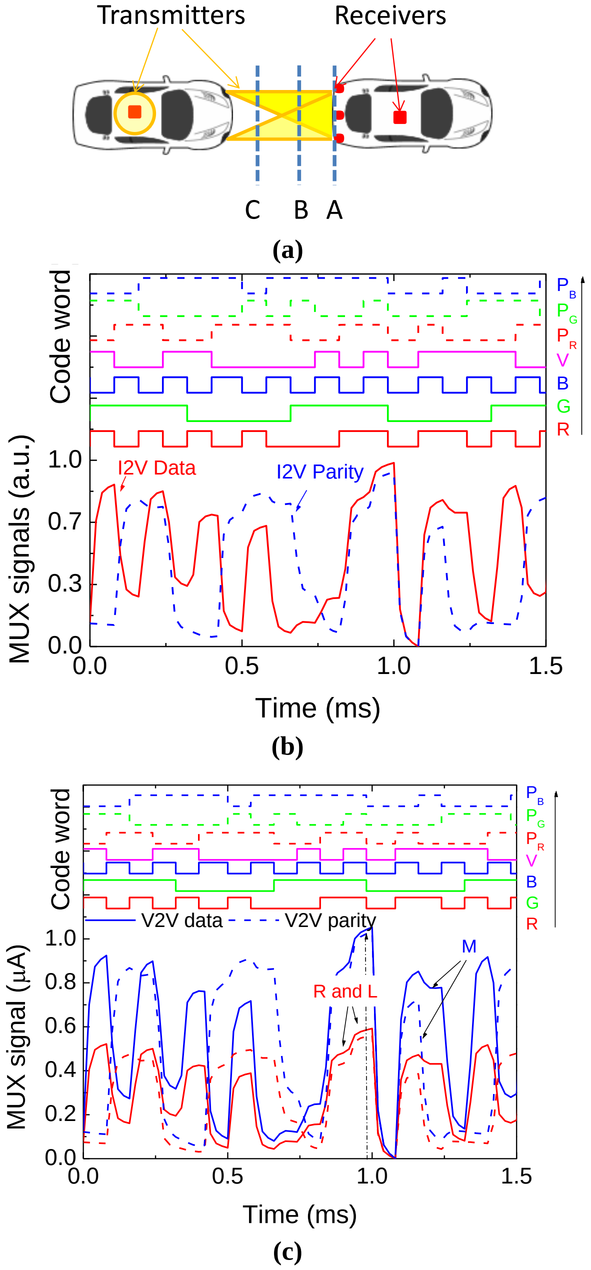
A traffic scenario was established for the I2V and V2V communication. A proof of concept was simulated in the laboratory and is depicted in **Fig. 6a**. A follow and a leader vehicle are considered. A, B and C are the inter distances between them in different instants.

The street light sends a coded message (traffic message) that includes its ID (violet channel) and traffic information (RGB channels). This message is received and decoded by the follower vehicle and retransmitted to the leader. It is likely that as the distance between vehicles decreases the photocurrent in all three receivers changes.

In **Fig. 6b,** the I2V MUX data (solid line) and parity (dash line) signals received by the roof sensor are displayed. In top the decoded signal is shown. After decoding the signal the received information is retransmitted to a leader vehicle by modulating the lights of its own front headlamps.

Let us consider that the signal is transmitted through a narrow cone of light perpendicular to the surface of the receivers. In this case, the front vehicle (leader) receives and decodes the message sent by the back vehicle (follow) using three receivers located on the tail of the car. It compares the intensities of the multiplexed signals with each other as well as the content of the received messages.

Different situations may occur depending on the intervehicle distance: The vehicles are at a safety distance (A) and the three receivers receive the same message with the same intensity. The vehicles are at a warning distance (B) and the right and left receivers receive the same message with the same intensity while the medium receives it with a doubling intensity. If the vehicles are close enough (C), a similar message is received by the side receivers and no message is read out by the one in the middle. By comparing the intensities of the received messages the driving range distance can be calculated and, if necessary a warn can be sent.



(a)

(b)

(c)

Fig. 6. Proof of concept: a) Driving range scenario. b) MUX and parity signals (solid and dash line) detected by the roof sensor in I2V communication system. c) MUX and parity signals (solid and dash lines) in a V2V communication system (R, right; L, left; and M middle tail receivers).

The scenario B was simulated to prove the concept (see **Fig. 6a**). We have used the same drive current to activate the two headlamps-like transmitters (RGB-LEDs) and impose similar lighting conditions in both transmitters. **Fig. 6b** shows the MUX code (data) and parity I2Vsignals received at the roof top sensor. In **Fig. 6c,** the MUX signals at the right (R) and left (L) sensors and in the middle (M) one are presented. In solid and dash lines we visualize, respectively, the MUX data word and the correspondent MUX parity signals. On the top of the figure, the seven bit information sent, simultaneously, by both LEDs is presented (codeword). We have applied to the RGB LED a current of the order of 4 mA and 30 mA to the violet one. As expected, all the three sensors decode the same message. However, the intensity of the MUX signal in the middle receiver (≅1 µA) is twice the one received by the other two (≅0.5 µA).

Future trends

Given the benefits of VLC, this type of communication is expected to play an important role in road safety applications.

To take the step towards implementation, we have to test the vehicular communication system in real environment. Taking into account transmission system failures and overcoming them as well as more advanced modulation systems must be tested. Further efforts should be made in connection with research and development of a system compatible with Multiple Input Multiple Output (MIMO) applications. Our goal is to finalize the integrated I2V2V application and enlarge the connect car paradigm to I2V2V"I. Several road configurations with either static or moving vehicles has to be tested in future.

Conclusion

Using communication through visible light (VLC), this work presented preliminary experimental results obtained through a cooperative system that incorporates two prototypes of vehicular communication: I2V and V2V. The module is built with RGB LEDs transmitters that are used for lighting purposes and to transmit a code message, and by VLC receivers, based on a-SiC: H pi'npin photo detectors, which encode and decode the emitted signals. The results of the tests confirm that the two I2V and V2V systems together allows to increase the range of the communication, allowing the communication of the central station with vehicles outside its area of service. The results are highly enhanced by integration error correction codes.

Acknowledgements

This work was founded by FCT – Fundação para a Ciência e Tecnologia, in the Research Unit CTS - Center of Technology and Systems, under the reference UID / EEA / 00066/2013 and also by the projects financed by the Polytechnic Institute of Lisbon (IPL) with references: IPL / 2016 / VLC_MIMO / ISEL and IPL / 2017 / SMART_VeDa / ISEL.

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