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# **Infrastructure to Vehicle Communication Using Visible Light Communication**

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**DISSERTAÇÃO PARA OBTENÇÃO DO GRAU DE MESTRE  
EM ENGENHARIA DE ELECTRÓNICA E TELECOMUNICAÇÕES**

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# Abstract

In recent years, lighting solutions have gradually been replaced by more efficient features, taking advantage of Light Emitting Diodes (LEDs) that have progressively conquered the market with increasingly high optical powers, low energy consumption and variable color temperatures. Along with this evolution, Visible Light Communication (VLC) technology has also been developed to use this existing lighting infrastructure and the inherent characteristic of LEDs being easily switched to high frequency to build data transmission systems. The applications of this communication technology using electromagnetic signals in the visible range are currently in a development stage with promising applications in several domains.

This dissertation intends to study an optical communication system based on VLC to establish communication between road infrastructures and. Vehicles. For this purpose, four communication channels established through the modulation of white trichromatic LED emitters are used. Detection of the optical signals is performed with a photodiode based on two stacked pin structures made of a-Si:H and a-SiC:H. This device works as an optical filter in the visible spectrum and its spectral sensitivity can be adjusted through stationary optical bias. On-Off-Keying (OOK) modulation is used. The structure of the data blocks to be transmitted was designed to avoid undesirable effects related to ambient light (flickering and/or perceptible variations in color temperature of the white light). The experimental tests of the proposed model were performed in the Optoelectronics laboratory using a small-scale prototype. The results show that with the proposed system it is possible to transmit information between road infrastructure and vehicles. In addition to data transmission, other security features have been addressed, such as the determination of the speed of vehicles movement by the network, as well as the determination of the position of the vehicles and their direction of travel in the road.

**Keywords:** Visible Light Communication, Infrastructure To Vehicle Communication, Light Emitting Diode, Photodiode, On-Off-Keying, Multiplexing, Dynamic Current Control, Dataframe, Semiconductor, Wavelength, Absorption Coefficient.



# Resumo

Nos últimos anos as soluções de iluminação têm vindo a ser gradualmente substituídas por recursos mais eficientes, tirando partido das lâmpadas baseadas em *Light Emitting Diodes* (LEDs) que progressivamente têm inundado o mercado com potências óticas cada vez mais elevadas, baixos consumos energéticos e temperaturas de cor variáveis. A par desta evolução, a tecnologia *Visible Light Communication* (VLC) tem vindo igualmente a ser desenvolvida no sentido de utilizar esta infraestrutura de iluminação já existente e a característica inerente aos LEDs de poderem ser facilmente comutados a alta frequência para construir sistemas de transmissão de dados. As aplicações desta tecnologia de comunicação usando sinais eletromagnéticos no domínio do visível está neste momento em fase de desenvolvimento e revela-se promissora em diversos domínios de aplicação. Nesta dissertação pretende-se estudar um sistema de comunicação ótico baseado em VLC para estabelecer comunicação entre infraestruturas rodoviárias e veículos. Para o efeito usam-se quatro canais de comunicação estabelecidos através da modulação dos emissores de LEDs brancos tricromáticos, assim como LEDs violeta. A deteção dos sinais óticos é realizada com um fotodíodo baseado em duas estruturas pin empilhadas realizadas com a-Si:H e a-SiC:H. Este dispositivo funciona como um filtro ótico no domínio do visível, cuja sensibilidade espectral pode ser ajustada através de polarização ótica estacionária. Utiliza-se a modulação *On-Off-Keying* (OOK), sendo a estrutura dos blocos de dados a transmitir desenhada por forma a evitar efeitos indesejáveis em termos de iluminação ambiente (*flickering* e/ou variações perceptíveis na temperatura de cor da luz branca). Os testes experimentais do modelo proposto foram realizados no laboratório de Optoeletrónica usando um protótipo em escala reduzida. Os resultados obtidos demonstram que com o sistema proposto é possível a transmissão de informação entre a infraestrutura rodoviária e os veículos. Para além da transmissão de dados, outras funcionalidades no domínio da segurança foram abordadas. Como por exemplo a determinação da velocidade de deslocação dos veículos por parte da rede, assim como a determinação da posição dos veículos e o seu sentido de deslocamento na faixa de rodagem.



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# List of Acronyms

ACO-OFDM	Asymmetrically-Clipped Orthogonal Frequency Division Multiplexing
AoA	Angle of Arrival
CAP	Contention Access Period
CCA	Clear Channel Assessment
CCM	Code Cycle Modulation
CRC	Cyclic Redundancy Check
CSK	Color Shift Keying
CSMA-CA	Carrier Sense Multiple Access - Collision Avoidance
DC	Direct Current
DCO-OFDM	Direct Current biased Optical Orthogonal Frequency Division Multiplexing
DMT	Discrete MultiTone
DSRC	Dedicated Short-Range Communication
FOV	Field Of View
FPS	Frames Per Second
FWHH	Full Width Half Height
Gbps	Gigabits Per Second
GPS	Global Positioning System
HCI	Human Computer Interaction
HetNets	Heterogeneous Networks
I2V	Infrastructure to Vehicle
kbps	Kilobits Per Second
LCD	Liquid-crystal-display
LED	Light Emitting Diode
LNA	Low Noise Amplifier
LOS	Line Of Sight
MAC	Medium Access Control
Mbps	Megabits Per Second
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MU-MIMO	Multiple User - Multiple Input Multiple Output

NFC	Near Field Communication
NRZ	Non Return to Zero
OCDMA	Optical Code Division Multiple Access
OFDMA	Orthogonal Frequency Division Multiple Access
OOC	Optical Orthogonal Codes
OOK	On Off Keying
PPM	Pulse Position Modulation
PWM	Pulse Width Modulation
QAM	Quadrature Amplitude Modulation
RC	Repetition Coding
RF	Radio Frequency
RGB	Red Green Blue
RGBV	Red Green Blue Violet
RLL	Run Length Limited
RTC/CTS	Request to Send/Clear to Send
SFO	Sampling Frequency Offset
SMP	Spatial Multiplexing
SM	Spatial Modulation
SNR	Signal to Noise Ratio
V2V	Vehicle to Vehicle
V2I	Vehicle to Infrastructure
VLC	Visible Light Communication
WDM	Wavelength Division Multiplexing

# List of Symbols

$\Delta t$	Interval of Time in Seconds
$^{\circ}\text{C}$	Temperature in Celsius Degrees
3D	Three Spatial Dimensions
a-SiC:H	Amorphous Hydrogenated Carbon Silicon
A	Ampere
C	Carbon
cm	Centimeters
cm <sup>2</sup>	Square Centimeters
eV	Electron-Volt
Hz	Hertz
H	Hydrogen
I	Electrical Current in Ampere
m	Meters
nm	Nanometers
Si	Silicon
T	Period in Seconds
V	Volt
v	Speed in Meters Per Second
W	Watt
$\alpha$	Optical Gain
$\lambda$	Wavelength



# 1. Introduction

## 1.1. Motivation

In the past few years, lighting solutions are passing through a disruptive change in many ways. Energy issues are a priority in a global agenda and making everything more efficient is a demand, that also includes lighting solutions. In that way, in the past almost twenty years, the traditional incandescent bulbs were replaced, first for fluorescent and fluorescent compact bulbs and, more recently, for LED based bulbs.

The major advantage of LEDs – Light Emitting Diodes – is related to high power saving, comparatively to incandescent bulbs, or even to fluorescent bulbs. This brings new options for different kinds of illumination, for instance, at home, with light dimmable options and with different color temperatures accordingly if the room is intended to work or to stay comfortably in living rooms, or even for decoration purposes. Its use is also being adopted in public spaces, industry facilities, for signalling, etc.

As LED technology for lighting purposes becomes ubiquitous, the LED's switching capability brought a new possibility for data access networks in a whole new frequency range, without all the inconveniences that a brand-new infrastructure installation would cause. Besides that, the use of visible spectrum offers some interesting characteristics that are completely attractive in telecommunication systems, such as its short distance propagation and its incapability to cross walls and objects. This establishes new challenges and brings new possibilities. A new emerging field for optical communication, i. e., Visible Light Communication (VLC) that found in the possibility of LED modulation an efficient way of taking advantage of the visible part of the electromagnetic spectrum to transmit information. This technology can be used in different application fields extending from indoor to outdoor applications.

The communication through visible light holds special importance when compared to existing forms of wireless communications. The visible light spectrum is completely untapped for communication and can complement the Radio Frequency (RF)-based mobile communication systems. Modern vehicles are equipped with many electronic sensors, which monitor the vehicle's speed, position, heading, and lateral and

longitudinal acceleration. Although the technology already exists, vehicles rarely communicate this information wirelessly to other vehicles or roadside infrastructure. Researchers are anticipating the deployment of wireless vehicle communication to improve safety and reduce congestion. This use case is known as connected vehicles. Recently, the transportation lighting infrastructure such as street lamps, traffic lights, automotive lamps, etc., is changing to Light Emitting Diodes (LEDs). In the case of an ITS based on Visible Light Communication (VLC), it will be possible to make use of the conventional automotive and traffic LEDs. Compared to RF-based communications, VLC offers robustness against jamming attacks, a smaller interference domain, and a large license-free spectrum.

Vehicular Communication Systems are an emerging type of network in which vehicles and roadside units are the communicating nodes, providing each other with information, such as safety warnings and traffic information. The vehicular communication is composed of infrastructure-to-vehicle (I2V), vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. The I2V applications focus on utilizing the traffic related infrastructure, such as traffic light or streetlight to communicate useful information. So, VLC can be realized as a secondary application in LED arrays that are placed for lighting.

In the recent past, we have developed a Wavelength Division Multiplexing (WDM) device that enhances the transmission capacity of the optical communications in the visible range. The device was based on tandem a-SiC:H/a-Si:H pin/pin light controlled filter with two optical gates to select different channel wavelengths. When different visible signals are encoded in the same optical transmission path, the device multiplexes the different optical channels, performs different filtering processes (amplification, switching, and wavelength conversion) and finally decodes the encoded signals recovering the transmitted information. This device can be used as receiver, and helps developing automated vehicle technologies that allow vehicles to communicate with the surrounding 'environment'.

## 1.2. Thesis Structure

In Chapter 2, the state of art about VLC will be presented. This includes the principles of VLC technology, the benefits achievable and some issues and practical challenges, based on studies and improvements achieved until now. Additionally, some standards that begin to emerge in the field of topologies that can overcome some questions related with this technology, as well as components and performance, as it happens in other technologies like WiFi. Here an overview about ideas, potentialities and practical applications thought to take advantage from this new, growing technology will be presented.

Chapter 3 explains and focuses on the system architecture, such as components like the emitter and its characteristics, the receiver that detects the VLC signals and the principles behind its functionality and operation. Then the modulation scheme designed to define the different data blocks that provides adequate signal decoding at the reception end will also be discussed in this chapter. The main constraints of the system, such as the reuse of the lighting infrastructure will be analyzed in order to propose solutions to keep the system performance without deteriorating the light quality from the illumination side.

In Chapter 4 the network topology side will be presented and discussed. This includes all the features that will be needed in the network, based on lighting infrastructure already built to lighting purposes. It will be addressed how such features can be reached.

Chapter 5 includes the results of the developed laboratorial work, which is the way to support the ideas and prove the concept.

At last, Chapter 6, encloses main conclusions about this work and some suggestions to future works

### 1.3. Main contributions

This thesis is part of the research work of project IPL/2013/SMART\_VeDa/ISEL. From the work developed along the past year a paper has been published and another one is under preparation:

- P. Louro, F. Rodrigues, J. Costa, M. A. Vieira, M. Vieira, "Design of a transmission system for indoors navigation based on VLC," Proc. SPIE 10680, Optical Sensing and Detection V, 106800I (9 May 2018); doi: 10.1117/12.2306898.
- F. Rodrigues, P. Louro, M. Vieira, "VLC system for the determination of a vehicle's position and speed", i-ETC Journal, Special issue "Master Thesis 2018", under preparation.

## 2. State of the art

### 2.1. The VLC technology

Visible Light Communication (VLC) technology uses the visible range of the electromagnetic spectrum to define telecommunication data systems operating in the range from 390 nm to 780 nm [1]. One difference that is immediately noticeable, comparatively with traditional RF mobile communication systems, is that in VLC the signals are visible to the human eye, which entails additional constraints on how they are generated and transmitted. In order to be able to encode the information into visible light signals, the light source used, i.e. the VLC emitter, must allow switching at relatively high frequencies so as to achieve bit rates that make communications feasible and do not produce signals that are uncomfortable or harmful to human health. As an example, phenomena such as flickering are unwanted, as it will be perceived by the human eye and will also be awkward to the user. These characteristics were not feasible with traditional light sources, such as incandescent and fluorescent lamps. However, with the development of LED technology and its wide spread in lighting infrastructures, there is a basis with high potential to define VLC networks at low cost and with low installation complexity. The ubiquity associated to the use of LEDs lighting systems is undoubtedly an important driving force for the growth of VLC technology. LEDs constitute simultaneously lighting infrastructures and communication networks.

The LED is a device built from doped semiconductors that, due to the constant improvements in the manufacture technology are able to generate output spectra with increasing specifications related to central wavelength, optical brightness, divergence angle, color temperature and frequency of operation. It presents periods of life increasingly long, between 25,000 and 50,000 hours (when the fluorescent lamps are around 10,000 hours). It offers the ability to produce light with high energy efficiency and can be switched at high frequency. Currently, luminous flux efficiency in the order of 113 lumen/W is achieved using LEDs and it is estimated that this efficiency will reach 200 lumen/W by 2020. In contrast, fluorescent lamps achieve a luminous flux efficiency of around 60 lumen/W and the incandescent was only 15 lumen/W. The maximum

theoretical efficiency that an LED can achieve is 683 lumen/W (radiometric-fotometric conversion). These factors give solid support to the growth of LED technology in lighting solutions, and it is estimated that by 2030, 75% of all lighting will be based on LED technology [2].

With this current trend of strong, sustained growth of LED technology for lighting purposes, the use of this infrastructure offers not only the advantages of cost and low complexity referred above, but a wide growing network that can be used for enlarging the coverage of a communication network [1].

The idea of using LEDs in lighting solutions, with the simultaneous purpose of transmitting information in data access networks, goes back to the year 2000 [3]. In the last two years, VLC connections have reached bit rates above 1Gbps, with a tendency to increase, and using the specific standard defined by IEEE, IEEE 802.15.7, 100 Mbps [4].

As the primary purpose of an illumination infrastructure is to illuminate, the communication part must be implemented in a way that does not harm the quality of the light produced.

As for the issue of flickering, it causes serious effects on the human health and, in general, makes the light uncomfortable. The problem disappears if the modulation frequency is higher than 200 Hz [5]. The major cause of VLC flickering is related to the bursts of 0's or 1's that make noticeable the variation of light intensity. To overcome this problem, RLL codes are used, such as Manchester 4B6B and 8B10B - in Manchester, 0 is replaced by a Down transition "10" and 1 by a Up transition "01" [2].

The possibility of adjusting the light intensity with a dimming control, is another requirement that should be possible to implement without affecting the communication performance. An additional difficulty related to this condition is that the relation between the measured light and the light perceived by the human eye is not linear.

As the range used in VLC operates in a frequency too high to propagate through walls, doors and other objects, the environment itself contributes to the definition of small and contained cells. This provides greater control over intercellular interference and also the possibility of spectrum reuse with greater efficiency. In this way, VLC presents itself as a good solution to complement RF communication systems. This is especially important nowadays, when the traffic in mobile networks grows fast and the RF spectrum

begins to be insufficient to the demand, even using the most efficient codes, due to the increase of the spectral efficiency [6].

As a disadvantage, the modulations for VLC are more limited than for RF, which is a point of study, for future research and development. In addition, the use of VLC in uplink communication is difficult to implement, for several reasons, such as energy consumption of LEDs in mobile devices, where autonomy is a critical factor. The mobility of these same devices, make difficult the alignment with the receiver. This is also dependent on the fact that LEDs may be more or less directive. But above all, the greatest disadvantage would be related to discomfort that the light produced by the emitting LED would cause to the user of the device [7]. In these cases, the use of RF is still preferable [7] [8].

## 2.2. Systems topologies and components

Depending of the VLC network purpose, the constrains and the technological limitations, studies and developments have been carried out in order to develop the components used in the VLC network, emitters and receivers, the topologies of these same networks, where some standards and modulations optimized for this area are already beginning to be defined.

### 2.2.1. *Emission and reception*

Typically, emitters in VLC are restricted to the use of LEDs. In applications that merge lighting with data transmission, the optical emitters are white LEDs. White LEDs can be of two types, RGB LEDs, where the combination of the three components is made to get the white color (cold white or warm white), or blue LEDs with a phosphor layer, which results also in a white color. Because blue LEDs with phosphor are cheaper, this option is more commonly used in lighting solutions. From a communication point of view, it is the less appealing option because it only provides one wavelength, i.e. one channel, while RGB LEDs provide three wavelengths, enhancing thus the transmission bit rate. However, VLC connections using blue LEDs with a blue filter, to remove the

yellow phosphor component, have already been reported with bit rates up to 125 Mbps [1].

From the point of view of signal detection, there are currently two possible solutions. The use of discrete photodiodes, which convert the light signal into an electric current, and image sensors, which are also photodiodes, but arranged in a matrix configuration. As an image sensor involves sampling multiple photodiodes, the scanning process is much more time consuming than with only one. So image sensors typically have a much lower rate of transmission [9].

Besides the transmitter and the receiver, the channel plays also a critical role in communication. The transmission capacity of the system is related to the power received from the transmitter, which depends on the position and orientation of the receiver (which is mobile) against the transmitter, as well as the distance between both and the incidence angle and angle of radiation. It depends also on the interference result, for example, from multipath. Consequently it is necessary to understand the impact of signal reflections on walls and objects as a function of wavelength and how they affect the performance of the connection. Besides that, the transmission capacity depends on noise sources, such as solar radiation (which even in indoor scenarios can enter through windows or doors), light from other coexisting lamps (not involved in the VLC network, such as fluorescent lamps or incandescent lamps), shot noise introduced by the photo-detector (resulting from ambient light or signal) and thermal noise in the photo-detector. Previous studies assume noise to be constant over time, however so far, no systematic studies on this subject have been presented in the literature. Noise levels affect the SNR, but VLC technology is particularly sensitive to variations in SNR caused by the shadowing of receivers due to the movement of people, animals or even objects. There are studies that analyze the conditions caused by human mobility and suggest the use of multiple emitters, spatially dispersed, to mitigate this problem. However the shadowing of the VLC receptor has not yet been studied in the existing literature.

As each LED lamp typically consists of more than one single LED, these different LEDs can be considered as multiple distinct emitters. Thus, the use of Multiple Input Multiple Output (MIMO) technology can also be useful in VLC. Comparing to RF, MIMO in VLC is difficult to implement because of the required spatial alignment between the transmitter and the receiver, which is very demanding due to the receiver's field of view (FOV). For MIMO purposes, image sensors have the advantage of offering a wide field

of view due to the lenses, thus eliminating almost the need for precise alignment with the transmitter. However, the issue of the low sampling rate, compared to a discrete photodiode, remains. Moreover, the gains of the photodiodes that make up the array of the image sensor have a more limited gain than the discrete photodiodes. A possible way to mitigate these disadvantages would be replacement of the scanning method at the image sensor with a procedure where only the relevant photodiodes would be sampled, reducing thus the time required to scan the sensor. There are also developments that point to a hybrid solution between image sensors and discrete photodiodes at the receiver, in order to develop a MIMO receiver [2].

### 2.2.2. *Modulations*

In VLC the type of modulations commonly used are a heritage of RF communication. However, due to the issues already mentioned, there are limitations that indicate that not all types of modulations can be used, or that development work has to be done in order to improve or adapt some modulation techniques to VLC technology.

IEEE 802.15.7 specifies 3 physical layer standards, with different modulation schemes applicable to different VLC usage scenarios, such as outdoor or indoor and different bit rates.

The modulations used in VLC are On Off Keying - OOK, Pulse Modulation - PM, Orthogonal Frequency Division Multiplexing - OFDM and Color Shift Keying - CSK. These different modulations offer advantages and disadvantages in several aspects, such as connection performance at the level of binary output and energy efficiency, or complexity.

OOK is the easiest implementation modulation to improvement. However it offers some strain under dimming conditions. IEEE proposes two ways to implement dimming support in the OOK modulation. One is to redefine On and Off levels and the other is the introduction of compensation periods. This modulation does not allow bit rates as high as other alternative modulation schemes, especially when dimming support is introduced. However, systems that use Non Return to Zero – NRZ, On Off Keying - OOK and an avalanche photodiode as receiver has been reported with speeds up to 230 Mbps. With

RGB LEDs, where only the red emitter is used for signal transmission and the remaining two wavelengths for illumination, the use of NRZ-OOK modulation and a PIN photodiode at the receiver resulted in connections with bit rates up to 477 Mbps.

Pulse modulations can be obtained by variation of the pulse width, (Pulse Width Modulation – PWM) or by variation of the pulse position in a time window (Pulse Position Modulation – PPM). The OFDM modulation can be Asymmetric-Clipped Optical OFDM – ACO-OFDM – or DC-biased Optical OFDM – DCO-OFDM. In ACO-OFDM only the odd subcarriers are modulated, which automatically guarantees symmetry in the time domain. In DCO-OFDM all subcarriers are modulated and a positive current is added to make the signal unipolar. The use of OFDM for VLC has a great challenge related to the LEDs non-linearity observed in the relation between the driving current and the produced light. One way to struggle this issue is to use LEDs in a quasi-linear zone, although this is a compromise that cannot always be assumed. It is a very limited modulation in the dimming support, otherwise, it is a modulation with great potentialities in terms of bit rates, where multi-Gbps rates can be achieved only with one LED [2].

In CSK modulation, the signal is modulated by varying the wavelength. As the amplitude does not change, it presents the particular advantage of flickering minimizing effects [10].

The use of MIMO in VLC technology can be used through several techniques, namely Repetition Code, Spatial Multiplexing and Spatial Modulation. The Repetition Code technique consists on sending the same signal from all MIMO transmitters so that they interfere constructively in the receiver which results in an increased gain. In Spatial Multiplexing, each transmitter and receiver of the MIMO system sends and receives, respectively, its correspondent signals. This technique requires a very precise alignment among receivers and emitters. In Spatial Modulation, each LED of the MIMO emitter is assigned to a specific symbol and, at each moment, the binary sequence corresponding to a symbol makes its LED active. This technique allows to obtain higher spectral efficiency and, at the same time, to be more flexible regarding the need of alignment between the emitter and the receiver. The light emitted by LEDs that work as emitters can be focused towards the receiver using a Spatial Light Modulator (SLM). With this technique, SNR levels can be improved [11].

### 2.2.3. *Medium access*

In VLC, three medium access control (MAC) topologies were defined so far. They are Peer-to-Peer, Star and Broadcast. The Peer-to-Peer topology consists of communication topology between two devices, where one of them acts as a coordinator (or master). It is typically used in high-speed communication, such as Near-Field Communication. The Star topology consists of having multiple client devices communicating with a master device. The Broadcast topology differs from the Star topology in the sense that client devices can only receive information from the master device without being able to perform any uplink communication.

For media access control, three types are also defined. Carrier Sense Multiple Acquisition (CSMA), Orthogonal Frequency Division Multiple Access (OFDMA) and Code Division Multiple Access (CDMA) [2].

In CSMA, as the channel is not divided into frames, when a device is ready for transmission, it begins by doing a random waiting period before checking if the channel is busy or if it is clear. If it is busy it expects another random period of time, otherwise it starts the transmission. When the channel is divided into frames, these frames are divided into subframes, which constitute the Contention Access Periods (CAP) and the Contention Free Periods (CFP). When a device is ready for transmission, it locates the start of the next back-off slot and waits for a random number of back-off slots before checking if the channel is available - Clear Channel Assessment (CCA).

In OFDMA, different devices are assigned to different subcarriers in time for communication. The use of OFDMA for multiple access in VLC is a natural extension of the use of OFDM in the physical layer modulation. The complexity of the demodulation, the interference between subcarriers and energy efficiency represent major challenges in the application of this technique to VLC. On the other hand, the spectral efficiency that it provides justifies more research to improve the technique.

In CDMA (OCDMA) optical orthogonal codes are used to give simultaneous access of several devices to the same channel. The principle is the same used in communication by fiber optics, where this technique is already well studied. The limitation that this technique presents is that longer codes (to be sufficient and orthogonal)

correspond to smaller possible bit rate. Besides that, the number of users makes more difficult to generate the required number of orthogonal codes. In addition, the problem of inter-symbolic interference caused by reflections (for example in walls) and the degradation that this interference causes, increases as the number of users increases.

#### 2.2.4. *Cells and coverage techniques*

The cells in VLC can be very different in size and shape, depending on how much light is provided by the lamps and on the type of area that is intended to be covered. For example, it is common to have in each room only one light source in the center, which may be a lamp containing multiple LEDs. In the case where a cell consists of a single lamp and transmits data to multiple devices it is called attocell. Typically, they are not more than 10 meters in radius. Zeptocells are even smaller cells, less than 5 meters in radius, usually formed by less intense bulbs, to illuminate small spaces, such as desk lamps.

Wide interior spaces are covered with the use of attocells. Zeptocells, because of their small size are typically spaced from each other, and usually do not face with the problem of intercell interference.

The optimization of cell topologies in order to reduce interference, increase binary throughput, and meet lighting requirements is a topic that requires further research [6].

In the common cases where there is only one lamp in the center of a room to provide illumination the cell created by this lamp exhibits high SNR variation throughout the room space. This difference can be very harmful to the performance of the connection for users located at the edges of the room. When, alternatively, the light points are distributed at the same luminous power, the power of the signal received along the points of the room is much more constant.

In order to overcome the problem of intercellular interference, adjacent cells should not use the same frequency band (wavelength), however, the frequency hopping depends on the type of LED used in the lamps. The use of a central controller to manage all the cells of a VLC network would make easier the control of mobility and inter-cellular interference, but its installation in the infrastructure would turn the network more

complex and expensive. This would obviously contradict the advantages that the use of existing lighting solutions for communication by VLC would bring [2].

One possible solution to the issue of interference is the formation of clusters, where each cell uses different and orthogonal frequency resources to the others. However, the drawback of this solution would be the reduction of the available bit rate due to the bandwidth limitation for each cell in the cluster.

## 2.3. Practical applications

The capabilities that VLC technology provides are numerous and continue to expand. At present, the practical applications that have received some interest from a research point of view are indoor positioning services, Screen-Camera Communication (NFC), vehicular communication and human-computer interaction applications - Human-Computer Interaction (HCI).

### 2.3.1. *Indoor localization*

Current geolocation services are heavily dependent on the Global Positioning System (GPS) system, however this solution is not implementable in indoor environments. The alternative that has proven to be the most interesting is the location based on WiFi, however it has a limited precision and to the detriment of an improvement in accuracy it is necessary to implement multi-path cancellation techniques of high complexity. VLC presents itself as a good alternative to WiFi [12], for geolocation, to allow greater accuracy [13]. Contributing to increasing location accuracy using VLC over WiFi is that there are typically many more VLC (lamp) emitters than WiFi transmitters. It is estimated that VLC transmitters are, on average, about 10 times more than WiFi transmitters.

Epsilon [5] presented the first practical VLC locating system. This is based on the sending of a different identification and location information for each emitter LED, and the receiver estimates the distance to each of the LEDs that it can "see" and uses the

triangulation method to determine its position. The precision achieved is around 0.4 m, in contrast to the 3 to 6 meters achieved with WiFi. Another localization system using VLC is the Luxapose [14]. This involves the use of an image sensor at the receiver that processes the acquired in order to extract the information from the emitting LEDs that arrive to it and the angle of arrival (AoA) of the information from each LED. Based on the orientation of the device with the image sensor and the AoA, the receiver calculates its location using triangulation. This method allows location accuracy in the order of 0.1 m.

There are already available commercial VLC location solutions, such as ByteLight [15 - 22].

### 2.3.2. *Screen-Camera communication*

Screen-Camera Communication is a form of device-to-device communication, where the sender can be a display of the sending device, for example from a smartphone, computer, information board ... and the receiver can be a camera from another device of the same type.

The main challenges of Screen-Camera Communication are perspective distortion and blurring. Perspective distortion consists on the appearance of some pixels being larger than others as they are closer or further away from the camera which is capturing, due to the tilt of the display. Blurring consists on a blur caused by the movement of the display. This effect can be considered as a low-pass filter, and the ambient light, as a DC component. In order to overcome these issues, it was proposed to use the PixNet encoder system, which encodes bits in a two-dimensional form and includes a perspective distortion correction algorithm, with blur-adaptive OFDM coding and ambient light filtering [23].

Another technique of Screen-Camera Communication is the COBRA system, which is a unidirectional communication system. It consists of creating a two-dimensional bar code, where each block maps a sequence of bits in a color (Red, Green or Blue). COBRA has already suffered a successful Android smartphone implementation and it

was experimentally demonstrated that it can achieve bit rates of 172 kbps, which is higher than bit rate of 10 kbps achieved with PixNet [23].

### 2.3.3. *Vehicular communication*

The application of VLC for vehicular communication, which is characterized as an outdoor application, is a purpose that differs a lot from indoor applications with regard to interference due to ambient light from the sun, the infrastructure composed of roads and buildings lighting infrastructures, etc. There are two categories of vehicle communication by VLC, vehicle-infrastructure communication (V2I), vehicle-vehicle communication (V2V) and infrastructure-vehicle (I2V).

In V2I communication, two types of cells are used, cells defined by road lighting lamps, which define cells with radius on the order of 50 to 100 meters, and cells defined by light signals such as traffic lights. This type of cells are particularly suitable for road safety applications and offer the advantage of being always available, day and night. The cells defined by the lighting lamps provide greater coverage, even on roads where there are no light signals, but during the daytime they tend to be switched off.

In V2V communication, the transmitters are the headlights and taillights of vehicles. Photodiodes or image sensors can be installed for reception. Image sensors offer the advantage of being more resistant to interference, however photodiodes can withstand higher bit rates [24].

A V2V communication application, using an image sensor as receiver, allowed to demonstrate that at greater distances from the traffic light signals that were working as VLC emitters, the decoding of the signal was difficult due to the small size of the pixel and due to the LED light non uniformity. However, this problem especially affects high frequencies regime, and the information transmitted at lower frequencies could be recovered. This characteristic can be explored in order to transmit the most important information at low frequencies and the lowest priority information at the highest frequency [25].

As communication between vehicles has become increasingly important, there is a solution in the field of RF with special adoption in this issue, which is Dedicated Shor-

Range Communication (DSRC), that uses the 5.9GHz band of the electromagnetic spectrum. VLC has a few following advantages over DSRC. It provides less complexity and cost, as well as greater scalability, because for VLC only line-of-sight (LOS) vehicles are in the same containment domain, resulting in much lower interference condition. Localization capability, is another advantage because localization based on RF does not allow sub-metric accuracy, while VLC, promises to offer localization capability with sub-metric accuracy. Finally security, as in VLC, an attacker will have to be in line of sight with the victim, thus being much more exposed [26] [27].

#### *2.3.4. Human-Computer interaction*

The VLC technology also has as a practical application context, human-computer interaction solutions - Human-Computer Interaction (HCI). There are already many commercial solutions where the interaction between human and computer is made using light, such as optical mice, which use LEDs and photodiodes to detect movements with high granularity. Similarly, the Kinect system uses a combination of visible light and infrared to do 3D gesture recognition. The problem is that this system is expensive due mainly to the very sophisticated image sensors that uses, as well as advanced image processing techniques [2].

### 3. System architecture

The proposed VLC system includes an outdoor scenario of infrastructure-to-vehicle communication. The LED luminaires are used to perform two tasks, street illumination and transmission. The block diagram of the VLC system is depicted in (Figure 3-1).



Figure 3-1: Block diagram of the VLC system for illumination, positioning and data transmission

From infrastructure side, luminaires working as data emitters define a VLC network with clusters of four emitters. Receivers are implemented in vehicles, which are mobile users of the network.

#### 3.1. Emitter

The vehicular communication system emitter for data transmission between the road infrastructure and the vehicle (I2V) is based on the use of RGB LEDs, together with an additional violet LED, placed in public luminaries, which will take the role of VLC emitters, as well as public illumination. For illumination purposes, just RGB LEDs have an active role, as the three wavelengths, together, result in white light. For VLC emitter purpose, the four wavelengths are used. So, four communication channels will be available. Details related to the use of the emitter channels will be further explained in the chapter regarding the network topology [14].

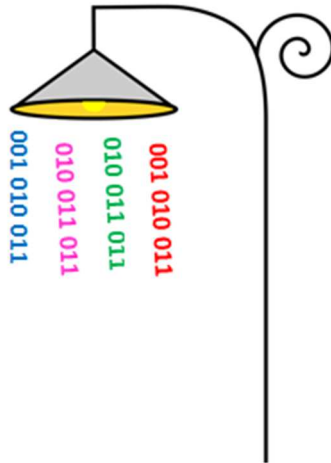


Figure 3-2: General Emitter Example (4 channels)

The characterization of the optical sources was done through the measurement of the output spectra of each biased chip junction of the RGB white LED with the driving current. In Figure 3-3 it is plotted the normalized output spectra of the RGB white LEDs used in this experiment.

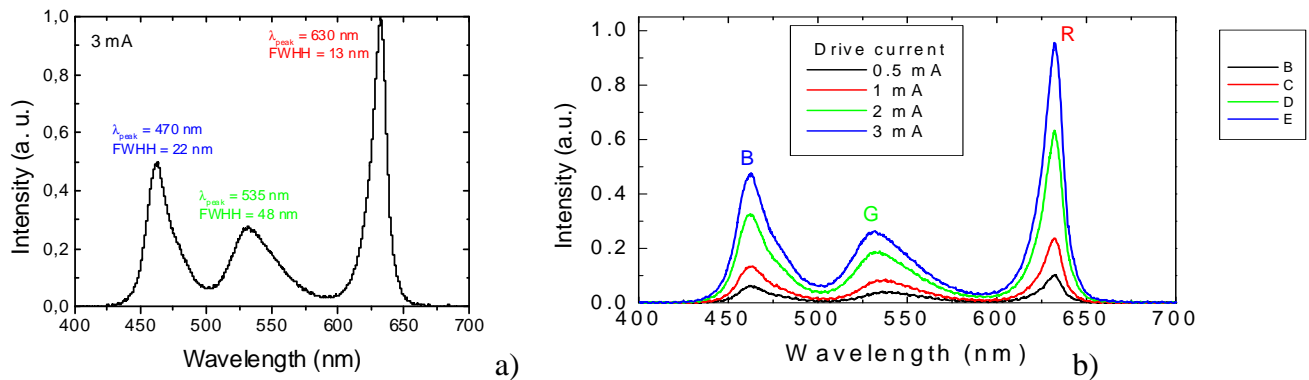


Figure 3-3: Output Normalized Spectrum of the RGB White LED using different values of driving currents: a) 3 mA, b) range 0.5mA – 3 mA.

The measurement was done using a compact CCD spectrometer from Thorlabs, model CCS 200/M, that allows spectral characterization of optical sources in the 200 - 1000 nm spectral range with a 2 nm accuracy [16]. This experiment was done using different driving currents for the emitters of the RGB white LED (Figure 3-3b). However, in the Figure 3-3 a) it is only displayed the result obtained with the driving currents normally used during the subsequent experiments of this work. Results demonstrated that the central wavelength and linewidth were similar. Main difference was obviously related

to the peak intensity, as the increase on the magnitude of the driving current results in an increase of the output optical power delivered by the LED.

The output spectrum cover the wavelengths assigned to the blue, green and red regions, with wavelengths centered, respectively at 470 nm, 535 nm and 630 nm. The full width half high (FWHH) is 22 nm for the blue chip, nearly 48 nm for the green and 13 nm for the red chip. Usually the FWHH of LED devices increases with the wavelength. However as this is a white LED, the magnitude and width of each RGB peaks are optimized for the white. The green component is lowest because the human eye has a maximum sensitivity at 530 nm [24] [28].

In Fig. 3-4 it is plotted the normalized output spectra of the emission spectrum of the violet LEDs used to soak the device with steady state background light either from the back or front sides.

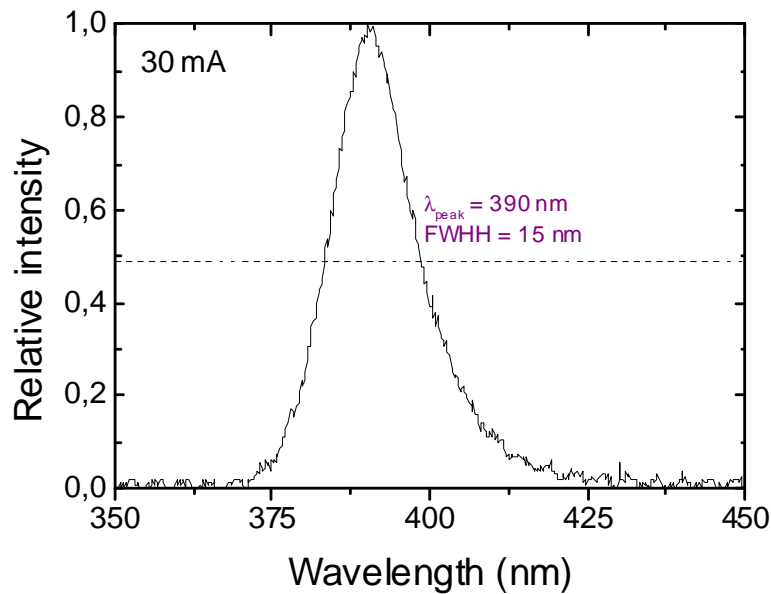


Figure 3-4: Normalized Emission Spectrum of the Violet LED of the Background Light

The violet LED used for the background exhibits a single peak centered at 390 nm and a narrow full width half height (FWHH) of 15 nm. The experimental results related to the LEDs spectral characterization are summarized in Table 3.1.

	Red	Green	Blue	Violet
<b>Dominant wavelength (nm)</b>	619 - 624	520 - 540	460 - 480	370 – 425
<b>Luminous intensity (mcd)</b>	355 - 900	560 - 1400	180 - 505	-
<b>FWHH</b>	24	38	28	15

Table 3-1: Optical Characteristics of the RGB and Violet LEDs at 25 °C

In Figure 3-5 it is displayed the dependence of peak intensity with the driving current for the red and blue emitters of the white RGB LED.

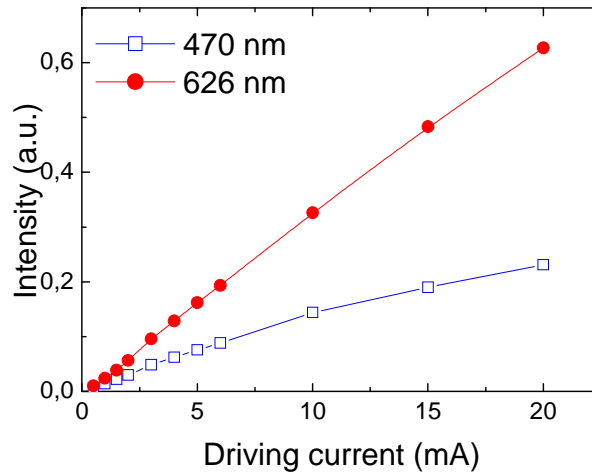


Figure 3-5: Driving Current vs peak intensity of the Red and Blue LED

When the current increases, the minority carrier concentration increases also, and thus the rate of recombination is enhanced, which results in an increased output of light intensity. However, the increase in the output light power is not linear with the LED current. At high current levels a strong injection of minority carriers occurs, which leads to the recombination time to be dependent on this concentration, and hence on the current itself. This leads to a nonlinear recombination rate with the current.

The far field pattern of the LED, with a Gaussian distribution is displayed in Figure 3-6. At half width of full height of the relative luminous intensity the divergence angle is around  $2 \times 60 = 120^\circ$ .

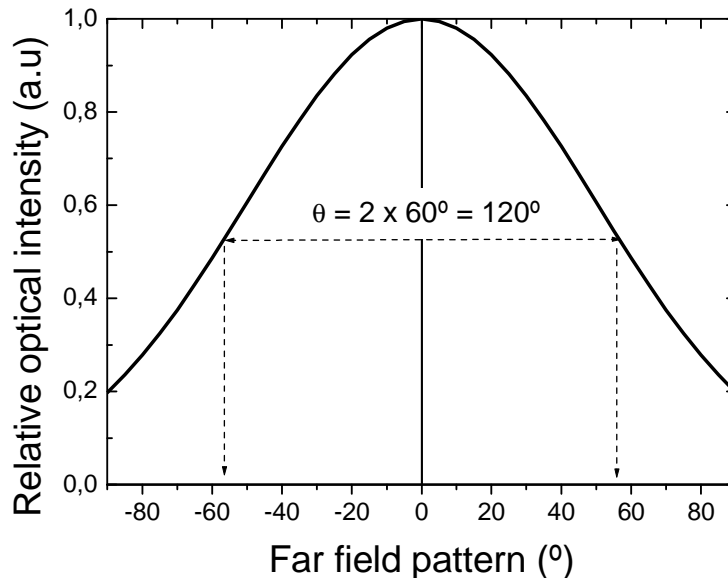


Figure 3-6: Far Field Pattern of the White RGB LED

The used white LEDs exhibit a wide divergence angle, which is set deliberately as they are designed for general lighting. For data transmission this represents also a wide delivery of the VLC signal around the surrounding area.

Light produced by the LEDs is assumed to propagate as a Gaussian Beam. Under this assumption, in agreement with the datasheet of the LEDs used for the laboratory measurement, the intensity of the electric field propagates in free space in its unique fundamental mode. Light intensity ( $I$ ) at distance  $z$  emitted by a LED with wavelength  $\lambda$  and divergence  $\theta$ , can be calculated recurring to the following expression [6] [29]:

$$I = I_0 \left( \frac{\omega_0}{\omega} \right)^2 \exp \left( -2 \left( \frac{r}{\omega} \right)^2 \right) \quad (1)$$

Where  $I_0$  is the emitted light intensity,  $r$  is the distance from the central axis,  $\omega_0$  is the beam waist and  $\omega$  the spot size parameter at a distance  $z$ :

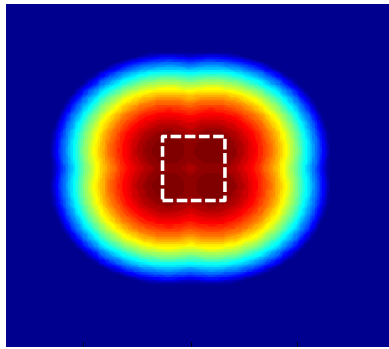
$$\omega_0 = \frac{2\lambda}{\pi\theta} \quad (2)$$

$$\omega = \omega_0 \sqrt{1 + \left( \frac{z}{z_R} \right)^2} \quad (3)$$

calculated as a function of the Rayleigh distance  $z_R$ :

$$z_R = \frac{\pi\omega_0}{\lambda} \quad (4)$$

Following this model it was calculated the light intensity projected on the target screen based on the LED characteristics: wavelength (Table 1), intensity and divergence angle (60 °). In Figure 3-7 the simulation of the projected light intensities is shown for the unit triangular cell.



*Figure 3-7: Simulated light intensity in a square unit cell.*

It is also important to point out that these white LEDs were designed specifically for lighting, and thus their major requirement is the production of white light. Issues related to data communication based on white LEDs are not yet being taken into account by the LED industry. However with the growth of VLC technology it is expected that LED design will also include additional specifications.

## 3.2. Receiver

The VLC receiver that will be installed in vehicles, and integrates the VLC vehicular communication I2V system, should be able to detect the different wavelengths (channels) that are being used. In this case, these wavelengths are located at 620nm(r), 530nm(g) , 470(b) and 400nm(v). The device will be able to convert a visible light signal to an electrical signal, in a way that it can be demodulated and extracted the information related to each input signal. For this purpose, the receiver must include a photodiode.

Through the wavelength that is supposed to detect, that means, through the wavelength that the photodiode should absorb, it has to be designed taking into account the absorption coefficient of the semiconductor material of the absorber layer. The used photodiode must consider the frequency of the signal to be detected, as the time constant, resultant from the photodiode junction capacity, limits the maximum frequency of the emitted signals modulations. The penetration depth of a wavelength is the inverse of its absorption coefficient. The depth penetration of the wavelength of interest must reach the depletion region of the photodiode. PIN photodiodes, composed by one P and one N semiconductor layers, separated by an intrinsic (I), active layer, offer improved characteristics on capacity, allowing higher frequencies. Besides that, they exhibit a wider depletion region, which increase the detection efficiency of the spectral range.

The chosen semiconductor bandgap is an important attribute for receiver sizing, as this material should be chosen in order to increase the number of electron-hole pairs produced by the wavelength that is supposed to detect. Figure 3-8 shows the simplified cross-section view of the photodetector. It is based on two pin heterostructures on a glass substrate with two transparent electrical contacts of indium tin oxide. The device presents an asymmetrical configuration. The front pin photodiode (pin1) is a thin structure with 200 nm and it is based on a-SiC:H. The back device (pin2) is manufactured with a-Si:H and is 1000 nm thick.

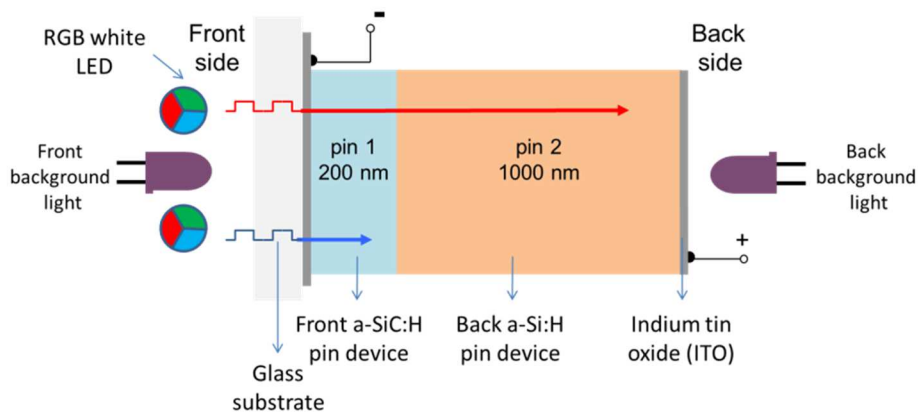


Figure 3-8: PINPIN Photodiode Used in Receiver Prototype [30]

Due to the bandgap differences of the sensitive materials of both front and back devices, the front one with a bandgap of 2.1 eV is sensitive to wavelength light up to 550 nm, which includes the blue and green parts of the visible spectrum and excludes the red

part. The back device, with a bandgap of 1.8 eV is sensitive to wavelength light higher than 520 nm which corresponds to the range of green light of longer wavelengths and also to the red spectrum. The thickness of both structures optimizes the detection of light of short wavelength to the front photodiode and the longer wavelengths to the back device [30] [31].

Background steady state light was supplied by violet LEDs (390 nm, 15 nm of FWHH) that illuminate the device by the back or the front side. The white light produced by the RGB LEDs is directed to the front side and in each LED the red of the blue chips were modulated with a specific bit sequence. The device was reverse biased at  $-8V$  and the photocurrent was measured between the front and back electrical contacts.

The output spectral characteristics of the photodetector are shown in Figure 3-9 using background light from both front and back sides, and also without any background light (which corresponds to the condition of not having any optical bias).

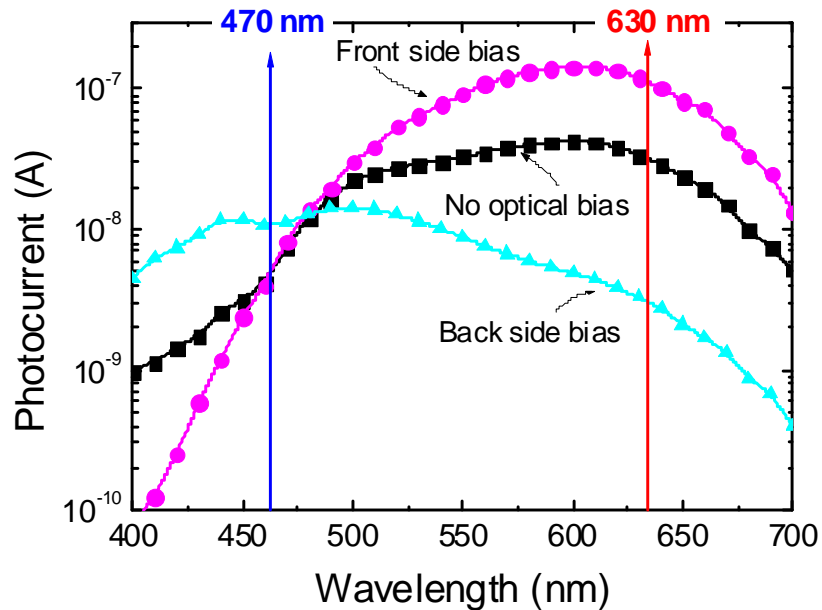


Figure 3-9: Spectral Photocurrent Under Dark Conditions and Using Front and Back Violet Light

Results show that the use of steady state illumination as a background light changes the device spectral sensitivity. For long wavelengths (red at 630 nm) it is observed an amplification of the photocurrent under front optical bias while under back optical bias the signal is reduced. For shorter wavelengths the opposite trend is observed

with a small amplification under back bias and a minor reduction under front bias. This means that the modulated signal of the red chip will be enhanced under front light and shortened under back illumination, while the blue signal will be amplified under back light and slightly reduced under front light.

The analysis of the device transient photocurrent to the optical excitation from the different emitters was done with a square waveform driving current. The optical signals illuminated the photodetector from the front side [32]. In Figure 3-10 it is displayed the measured signal due to the overlap of the four independent input channels without applied optical bias (dark) and under front and back irradiation. On the top the driving signal applied to each R, G, B and V LED is presented, the bit sequence was chosen in order that when one channel is on the others are always off.

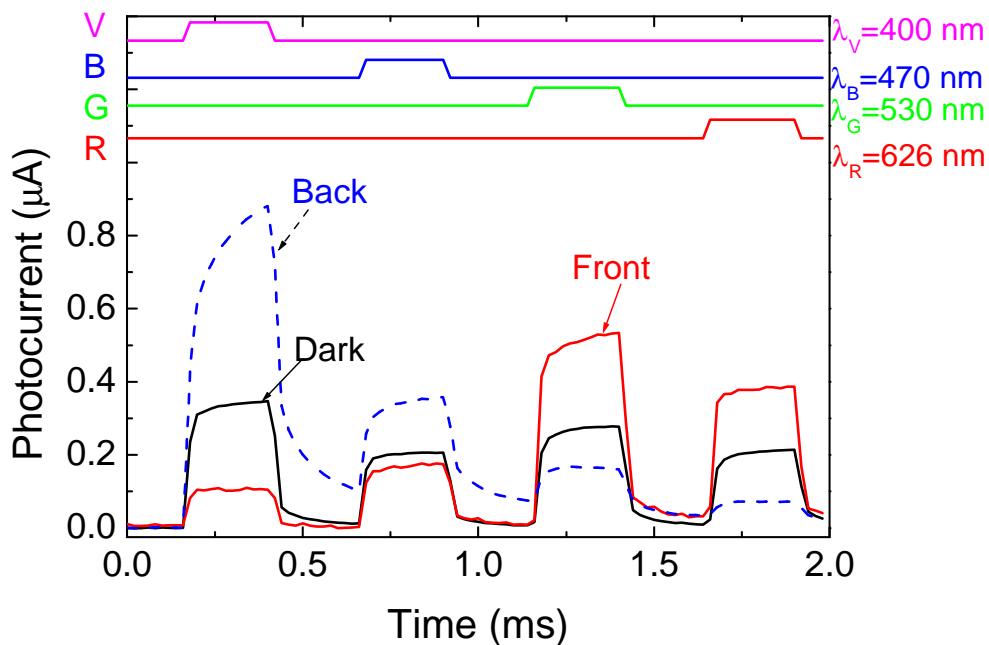


Figure 3-10: Transient photocurrent without (Dark) and under front (Front) and back (Back) 390 nm irradiation.

Data analysis shows that the photocurrent depends, under irradiation, on the irradiated side and on the incoming wavelength, the irradiation side acting as the optical selector for the input channels. Under front irradiation, the long wavelength channels are enhanced and the short wavelength channels quenched while the opposite occurs under back irradiation. Note that, under back lighting, as the wavelength increases the signal strongly decreases while the opposite occurs under front irradiation.

The quantification of the signal amplification under front and back bias is determined by the optical gain ( $\alpha_F$  and  $\alpha_B$  for the front and back gains, respectively), defined at each wavelength ( $\lambda$ ) as the ratio between the signal magnitudes measured with and without optical bias. The gain assigned to each channel is displayed in Figure 3-11.

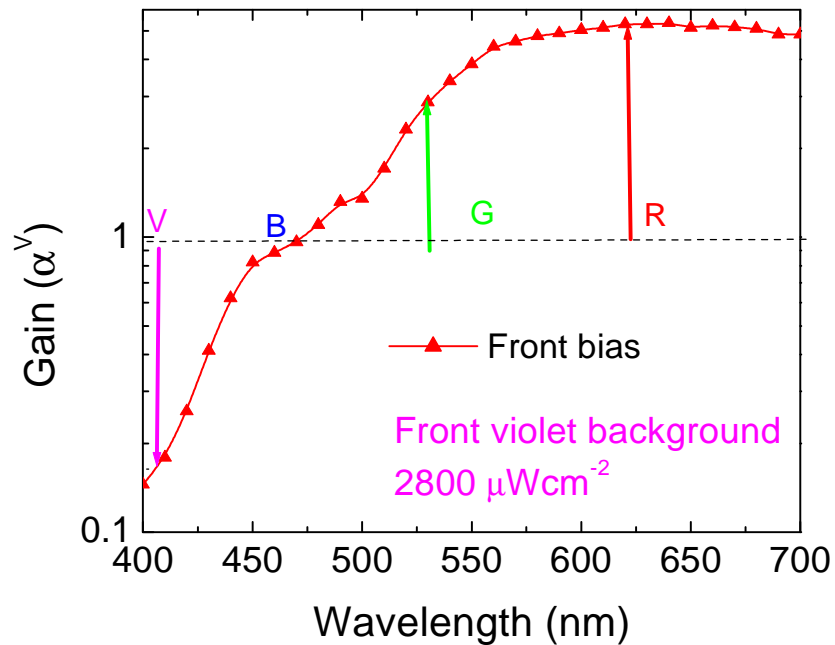


Figure 3-11: Spectral gain Under Violet Front Optical Bias ( $\alpha_V$ ) Only. The Arrows Point Towards the Optical Gain at the Analyzed R, G, B and V Input Channels [33]

The photocurrent produced by photodiode is after converted into a voltage signal, using a transimpedance LNA., Afterwards it will be demodulated and the transmitted information recovered and decoded. Since the used modulation is OOK, ‘1’ or ‘0’ bits are represented by the existence of signal, or not, respectively. [34] [35]

### 3.3. Modulation scheme and dataframe

One of the system requirements is related to the quality of the perceived light by the users. This affects the modulation schemes as it is necessary to prevent flickering effect, or changes in the perceived light color [33].

The modulation of the emitted light was done through the modulation of the driving electrical current of the semiconductor chips of each white LED. In OOK, the data bits ‘1’ and ‘0’ are transmitted by turning each LED on and off, respectively.

Once we would like to use the OOK modulation, the data frame structure must be carefully designed to avoid any flickering effects. Thus, the data frame structure must prevent that the emitting LEDs do not stay too much time turned off. This would correspond to the transmission of many ‘0’s in a row, which could make the human eye realize that the LED lamp is switching. From the point of view of the quality of provided light (in order to achieve a bright white light), it is necessary to combine the three wavelengths (red, green and blue) in such intensities that, for the human eye response to each of these wavelengths, together it will be perceived as white color [36].

To create a communication protocol to ensure the required system performance and overcome the technology constraints, a 32 bits dataframe was designed. These 32 bits are divided in three control fields, one for synchronism and two for the identification of the cell (ID). This sequence is followed by a fourth block that is for the payload, as it showed in the figure 3-12.

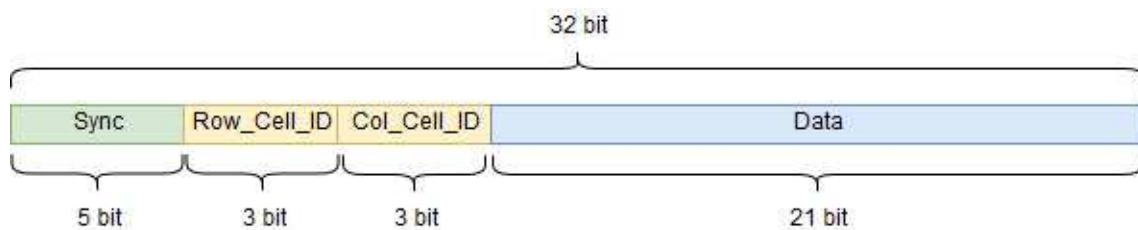


Figure 3-12: Dataframe Structure

It was considered a network comprising a single access point (mobile terminal) and several nodes that periodically generate data, at different rates. Time synchronization is required for successful communication between nodes. Nodes must quickly report the results to the receiver. Here, the first five bits are used for time synchronization. The same sequence [10101...] is imposed simultaneously to all the emitters. Each colour signal (RGBV) must carry, also, its own ID-BIT. So, the next three bits give the ID of the row and the other three the ID of the column where the node is located in the network. Cell’s IDs are encoded using a binary representation for the decimal number. For instance, an

ID\_BIT [001 010] for the R12 (Red emitter at row 1 and column 2 location) light spot will be sent inside the message whereas in case of G2,3, an ID\_BIT [010 011] will be sent by the green LED. With this information, the method will give an exact, unique answer, i.e., the location in the cluster and its position inside the unit cell. The allocated time slots depend on the used topology and on the node packet generation rate. Therefore, in a time slot, each node has a packet to transmit. The tested 32 bit packet includes: synchronization, node address and payload data. To the first five bits a synchronization header [10101] in an ON-OFF pattern have been assigned, the next six [rrr;ccc] for the binary node address and the last ones for the message.

In Figure 3-13, an example of the digital optical signals codification (codewords), used to drive the LEDs, is illustrated. It corresponds to the simultaneous transmission of the four nodes of a unit cell number, where the nodes are labeled R12, G13, B22 and V23, corresponding to the modulation of the red, green, blue and violet emitters of the LEDs located respectively at position 12, 13, 22 and 23 (further developed in chapter 4). Thus, R12, G13, B,2 and V23 are the transmitted node packets, in a time slot, from this cell in the network.

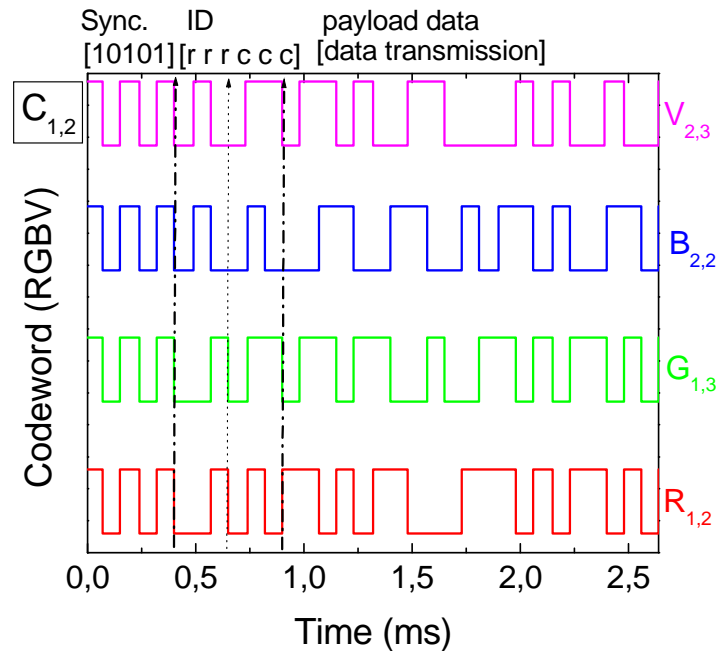


Figure 3-13: Representation of One Original Encoded Message, in a Time Slot With R12, G13, B22 and V23

As the designed emitter prototype hardware is the limiting element, regarding the bit rate achievable, it was determined that the transmission bit rate would be

5 kbps/channel. This means that the bit frequency is 5 kHz. From the bit frequency, we can assess that the dataframe frequency is:

$$f_{datagram} = \frac{f_{bit}}{32} \Leftrightarrow f_{datagram} = \frac{5 \times 10^3}{32} = 156.25 \text{ Hz} \quad (5)$$

As the data frame frequency is neraly 160 Hz, and bit transitions will necessarily occur in the 3 control fields (sync. row and col. ID) the minimum frequency in the emitter can easily be duplicated or even tripled. Thus flickering effect does not appear at frequencies above 200 Hz, this issue hardly becomes a problem.

Correct handling of the light quality requires a more complex approach. The intensity of light that the human eye can see in a certain wavelength, i. e. in a certain color, can be managed in two ways. It can be done through the effective brightness of that light source or, due to the memory effect of the retina, through the amount of time that the source is emitting in a time period (duty cycle). This period just has to be short enough to the frequency to overcome the flickering threshold. Although in public illumination the dimming control is not a feature that should be implemented, in principle, the light intensity should be proper, as well as the resulting color. As at each emitter just one channel is used for data transmission at each time, the major problem could be the observation of some shift of tonality, especially due to intensity variation, caused by dataframes, whose binary content can have more or less bits '1' or '0'. This effect results in a larger or smaller percentage of time that the respective LED is on or off.

To overcome this constraint, the option could be a combination from both solutions, creating thus a hybrid solution. That means that the brightness of the LEDs perceived by the human eyes can manipulate by controlling the amount of the LED driving current as well as the fraction of time that those LEDs are on, in each period, at the same time.

By studying the response of each LED, from the point of view of the light produced in function of the current, it is necessary to determine how much current, in a DC regime (that is when the LEDs are immutable and permanently connected) that each should receive to produce a luminous intensity such that, in conjunction with the remaining wavelengths (RGB), provides the desired tonality of light. In the LED corresponding to the wavelength that is being used to transmit data in each transmitter,

the time that the LED is off, i. e. transmitting the '0' logic level, must be compensated with an increase of current so that the following equation is verified:

$$\int_0^{T_{frame}} I_{DC} \cdot dt = \int_0^{T_{frame}} I_{bit\ 1}(t) \cdot dt \quad (6)$$

$I_{DC}$  – Driving current needed by each LED to produce white color light, when it is not taking the role of data emitter.

$I_{bit\ 1}$  – Driving current needed by data emitter LED, when it sends bit '1', in order to achieve the right brightness to produce white color light.

$T_{frame}$  – Period of the dataframe.

Once again, taking advantage of the memory effect of the human eye's retina, this adjustment of the driving current of the LED may suffer some delay, as long as the sampling window used for this purpose represents short periods of time, thus simplifying the process.

To evaluate the value that the current  $I_{bit\ 1}$  can take, it is necessary determine, in addition to the size of the sampling window, which are the extreme cases that the time ratio in which the LED is connected is maximum and minimum. For this it is necessary to analyze the structure of the dataframe.

Figure 3-14 shows the block diagram that represents a dynamic control system of the biasing current of the LED emitter, through the ratio of bits with the logic value '0' or '1', in order to stabilize the produced light intensity.

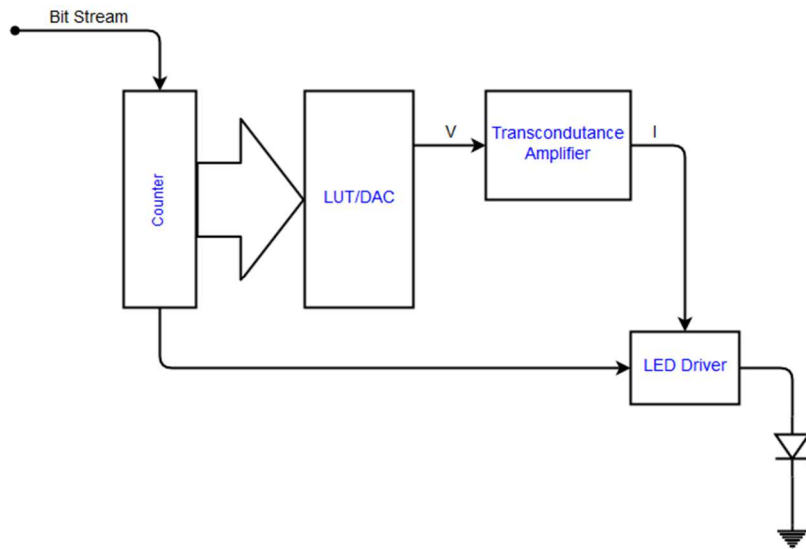


Figure 3-14: Bias Current Dynamic Control

Once the sampling window was properly defined, that means, a sampling windows whose number of bits is such that it results in a sampling period suitable for the bias current calibration of the LED, it will be possible to size the Counter block, which function is to count how many bits with the logic value '1' exist in each sampling window. This Counter block can consist of two binary counters, one that receives the bitstream of data and increments its value to each bit '1'. The other counter receives a clock signal with the same frequency of the binary rate, and counts the total amount of bits. Its function is to make auto-clear to the first counter whenever the number of transmitted bits corresponding to the size of the sampling window that has been achieved.

The next block is responsible for converting the calculated count to each sampling of the bitstream into a voltage signal. The signal shall describe a curve such that the output value decreases as the number of bits '1' increases and reflects the boundary conditions, i. e. the cases where the number of bits is maximum and minimum, in order to offer a proper offset. In this sense, the block can be constituted by a LUT - Look Up Table - and a DAC. The DAC converts the binary signal into a voltage signal as intended, but the LUT offers the possibility of easily modeling this linear signal so that the response is adequate and allows to make the resolution of the controller independent of the size of the sampling window.

The Transconductance Amplifier block has the function of transforming the received voltage signal from the previous block into a current suitable for the utilized

LED. For this, the amplifier must be sized to get a gain according to the maximum current that the LED can receive and must be as linear as possible.

Finally, the LED Driver consists just in a switch, possibly a MOSFET, that switches the LED according to the value of the bits that it receives at any moment. When the logic value is '0' the driver must enter in the cut status, turning off the LED, and when the logic value is '1' it must enter in the drive status, allowing the LED to be biased with the current previously determined, thus producing adequate light.

# 4. Network Topology

In order to meet the application of the VLC I2V communication technology, a topology has been developed for the network, in order to achieve coverage of road traffic routes. Figure 4-1 shows an overview of the elements in a I2V VLC network and how they can interact between them.

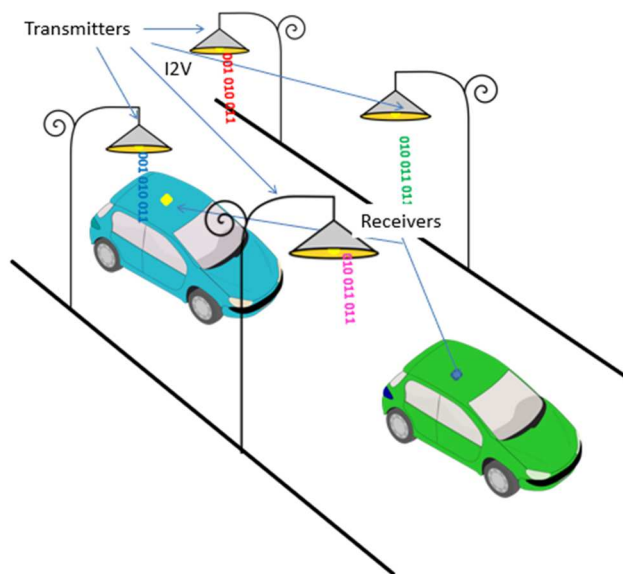


Figure 4-1: I2V Network Topology With Full Elements

Along the roads, street lamps are distributed in a square topology, for data transmission and lighting purposes. In this model it were used commercially available violet (V: 400 nm) and white RGB-LEDs. The network coverage space is therefore a two-dimensional plane, where the location of the cells is defined by the lighting lamps of the treads lanes, being assumed that their distribution is regular and equidistant, creating a foursquare pattern of clusters of four, as shown in the same figure [37].

Each cell is defined by an emitter which can be the Red, Blue, Green or Violet. It is characterized by a set of three attributes, namely, the cell line ID, the cell column ID and the transmission wavelength. The cell lines and column IDs are transmitted/broadcasted in the frames sent by each emitter.

## 4.1. Coverage area of each cell

The coverage area of each cell consists of a circular area around it, where the radius is equivalent to the distance between the emitters. In this way, nine areas of coverage are created in a regular pattern, where each of these subzones is served by a certain number of emitters and therefore has a certain capacity [18] [38]. Figure 4-2 represents a cluster of emitters with the distribution of the nine subzones.

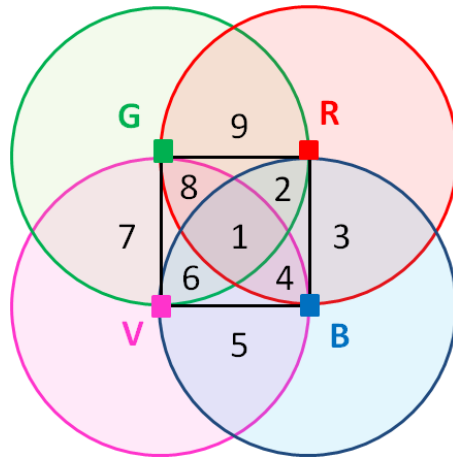


Figure 4-2: Subarea Delimitation in a Cluster Example

Thus, under the assumption that only one of the RGBV LEDs is modulated at each corner, it is presented in Table 1, the nine possible allowed subzones defined inside the cluster.

Footprint regions	#1	#2	#3	#4	#5	#6	#7	#8	#9
Overlap	RGBV	RGB	RB	RBV	BV	GBV	GV	RGV	RG

Table 4-1: Allowed subzones defined inside the cluster.

If the signal comes only from one LED, the position of the LED is assigned to the device's reference point. If the device receives multiple signals, *i.e.*, if it is in an overlapping region of two or more LEDs, it finds the centroid of the received coordinates and stores it as the reference point. So, inside the cell, nine reference points are considered. Thus, the overlap region is used as an advantage to increase the accuracy in

position estimation because more overlapping region means more reference points. For wider areas the cluster pattern will be repeated as can be understood by the illustration of figure 4-3.

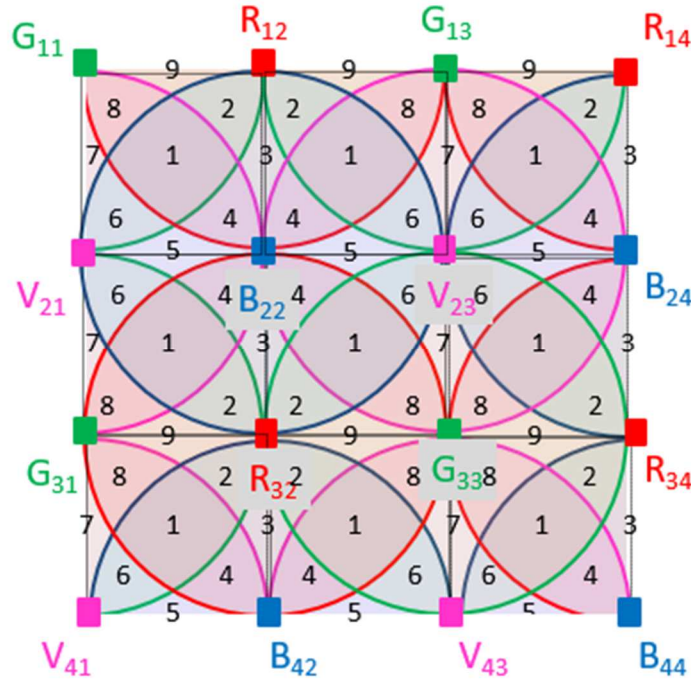


Figure 4-3: Cell Cluster Repeat Pattern

This uniformity in the distribution of cells and therefore in the resulting coverage of the subzones gives the network the ability to determine the speed at which vehicles are moving. This functionality is of high importance for the level of intelligent traffic control and management.

With the definition of these attributes to the cells, the static network can be easily managed (north will be assumed as a reference). Main features that characterize the adopted topology are related to the modulation wavelength, Cell line ID and Cell column ID. The wavelength of the transmission channel changes alternately from west to east between Red and Green or Blue and Violet, and from north to south between Red and Blue or Green and Violet. The cell line ID takes values between 0 and 7 that starts in the west and increments for east, repeating in a cyclical manner. The cell column ID takes values between 0 and 7 that starts to the north and increments to the south, repeating in a cyclical way.

Figure 4-4 intends to illustrate a road section that includes a crossover and that has VLC network coverage. Here it is shown the ID of each modulated emitter (line and column), as well as the wavelength (R, G, B or V) that will transmit the modulated signal. The different clusters are also identified in the area covered by the network.

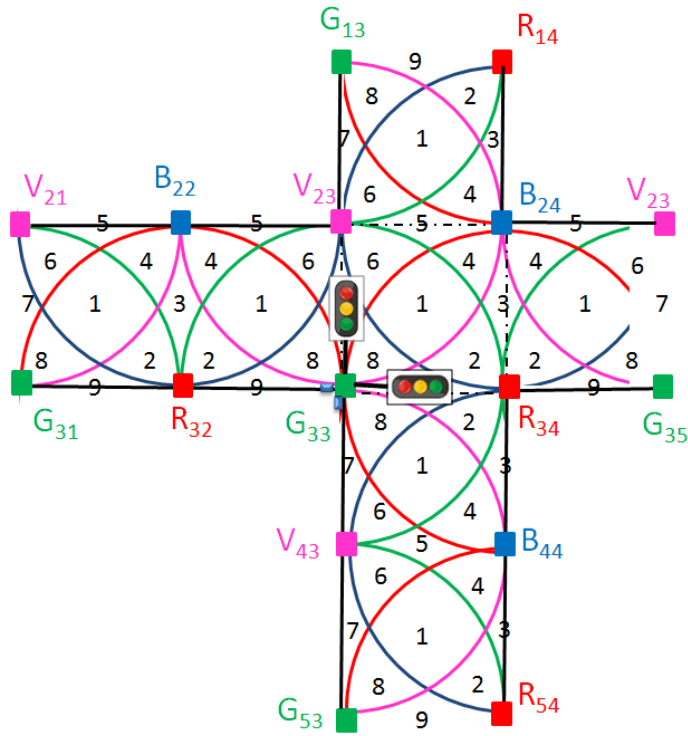


Figure 4-4: Road Network Topology Overview

## 4.2. Position and Speed determination

Figure 4-5 illustrates the example of a two-way road (one for each direction) covered by a I2V VLC network. Assuming the case of a vehicle moving from west to east (left to the right), it is known that at its displacement it will go through subzone 7, 6, 1 or 5, 4, 3, 4, 1 or 5 and 6, in this order, in a repetitive manner. The speed at which the vehicle moves can be extrapolated by assuming that between at least two emitters the speed of the vehicle is uniform and that its position in relation to the width of the road is also constant between the emitters.

Although it is expected that the vehicle moves as close as possible to the right side of the lane it may not happen. Therefore, it is also important to determine the position

of the the vehicle on the road.. This may be useful to infer if any user is driving in opposite direction.

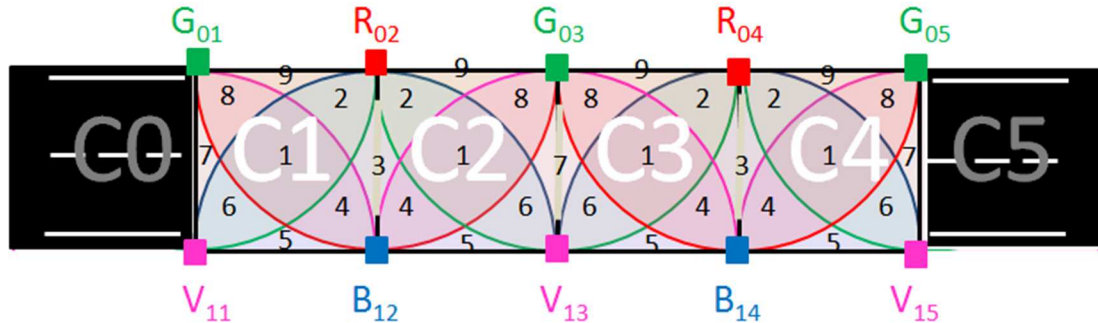


Figure 4-5: Straight Road Coverage With Subarea Delimitation

Figure 4-6 illustrates two possible trajectories for the movement from west to east along the road, one represented by the orange line and the other one represented by the blue line. Taking as example cell C1, consider that the length between V<sub>11</sub> and B<sub>12</sub>, or G<sub>01</sub> and R<sub>02</sub> is the total distance between two adjacent emitters along the road. In the case of the orange trajectory, the components of subzone 7, 6, 1, 4 and 3 are different from those of the blue line trajectory.

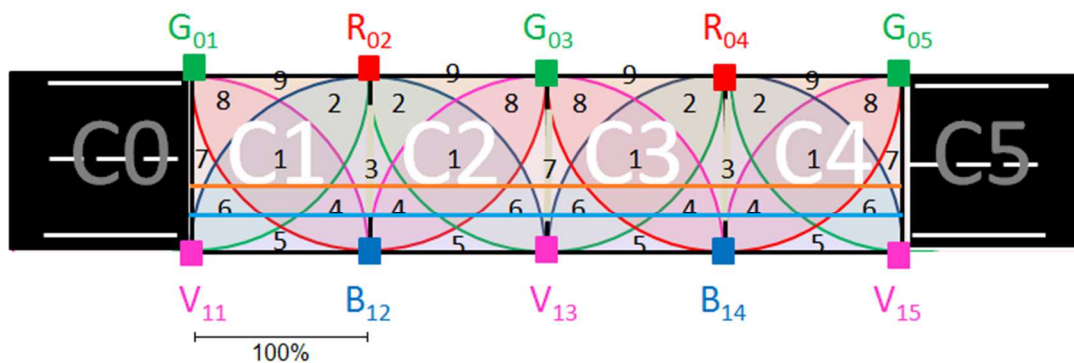


Figure 4-6: Straight Road Coverage With Trajectorys Example

As so, it can be defined coefficients that represent the percentage of each subarea in each of the trajectories. Consider AO, BO, CO, DO and EO as the coefficients for the

orange trajectory (meaning A- subzone 7, B-subzone 6, C-subzone 1, D-subzone 4, E-subzone 3) and AB, BB, CB, DB and EB as the coefficients for the blue trajectory. Inside cell, the traveled path through the subzones inside the cell will follow equation:

$$\begin{cases} AO.L(Zone_7) + BO.L(Zone_6) + CO.L(Zone_1) + DO.L(Zone_4) + EO.L(Zone_3) = Dist_{emitters} \\ AB.L(Zone_7) + BB.L(Zone_6) + CB.L(Zone_1) + DB.L(Zone_4) + EB.L(Zone_3) = Dist_{emitters} \end{cases} \quad (7)$$

Where:

AO – Time of stay inside subzone 7 when travelling along the orange trajectory

L(Zone<sub>x</sub>) – Travelled distance inside each subzone inside the cell

Dist<sub>emitters</sub> – distance between consecutive cells.

The network registers the time when each vehicle enters and exits each subarea. The period of time while the vehicle is located inside each cell ( $\Delta t_{cell}$ ) can also be evaluated through the network. Based on the example of the Figure 4-6, related to C1 and assuming uniform speed between the emitters, this period of time can be extrapolated by the difference between the time when the vehicle is under the coverage of B<sub>12</sub> and the moment it undergoes on the coverage of V<sub>13</sub>. Assuming a distance between emitters as 25 meters (spacing typically used between public lighting lamps), then, the speed of the vehicle (V) inside the cell is:

$$V = \frac{Dist_{emitters}}{\Delta t_{cell}} \Leftrightarrow V = \frac{25}{\Delta t_{cell}} \text{ [m/s]} \quad (8)$$

Where:

V – speed of the vehicle inside the cell,

$\Delta t_{cell}$  – period of time inside the cell.

Analyzing the case of the orange trajectory:

$$\begin{cases} AO \cdot Zone_7 + BO \cdot Zone_6 + CO \cdot Zone_1 + DO \cdot Zone_4 + EO \cdot Zone_3 = 25 \\ \Delta t_{Zone7} \cdot Zone_7 + \Delta t_{Zone6} \cdot Zone_6 + \Delta t_{Zone1} \cdot Zone_1 + \Delta t_{Zone4} \cdot Zone_4 + \Delta t_{Zone3} \cdot Zone_3 = \Delta t_{cell} \end{cases} \quad (9)$$

Then:

$$\begin{cases} AO = V \cdot \Delta t_{Zone7} \\ BO = V \cdot \Delta t_{Zone6} \\ CO = V \cdot \Delta t_{Zone1} \\ DO = V \cdot \Delta t_{Zone4} \\ EO = V \cdot \Delta t_{Zone3} \end{cases} \quad (10)$$

Assuming that the speed is uniform between cells, it is possible to extract the coefficients from each subzone and map these coefficients in a trajectory that represents the position of the vehicle in the road. This will give information on the position of the vehicle on the track.

In the previous example it was analyzed a hypothetical vehicle moving from west to east along the orange trajectory. The speed can be determined at the level of the handover between cells and based on that speed and the amount of time the vehicle takes in each subarea, it is extrapolated that the position of the vehicle corresponds to the orange trajectory. In this example, conveniently, the speed was determined by the difference between the entry in the  $V_{13}$  domain to entry into  $B_{12}$  domain, assuming that the vehicle arrives first to  $B_{12}$  than the  $V_{13}$ . This may not be the case, as it would be in the event of the vehicle moves in the opposite direction. This means that at the level of the processing done on the network, it is necessary to verify the coherence of the available measured data. It will be necessary evaluate the difference between the arrival times between two adjacent cells along the road (for instance,  $V_{13}$  and  $B_{12}$ ). This will infer about the driving direction.

In other words, it is necessary for the network to check the direction of the displacement before calculating the speed. The question of the displacement direction, together with the position of the vehicle in the track, allows the network to determine whether the vehicle is doing an overtaking maneuver or to is just moving in the opposite way of the direction of the track. This capability can be a valuable asset since it allows

the network to identify dangers and send this information to the users of the network. In this case the network is aware of a dangerous condition and this information can be re-transmitted to all the vehicles under the coverage of that area. In a scenario where the track is shared with autonomous vehicles and human driving vehicles, this feature can be especially interesting.

# 5. Laboratory Tests

A model for laboratory tests was built that seeks to simulate a cluster of cells of a VLC I2V network and a receiver located in the center of the cluster, that means at the same distance from the four transmitters, each of them with the respective wavelength for emission, R, G, B or V.

The model representing the cluster consists of an acrylic platform where four LEDs, RGB or Violet are inserted, in a shape of square, as it happens in a real model, but at such a scale that they are separated by a distance of 2 centimeters, as the Figure 5-1 a) represents. The receiver consists on a photodiode PINPIN, as described in Chapter 3.2, supported by a sheet of glass, allowing it to receive background illumination both front or back side, depending on the wavelength that is intended to highlight at every moment of reception. For the tests carried out, the receiver is positioned also about 2 centimeters from the plane where the LEDs are located and aligned with the center of the cluster, as illustrated by the Figure 5-1 b) and c).

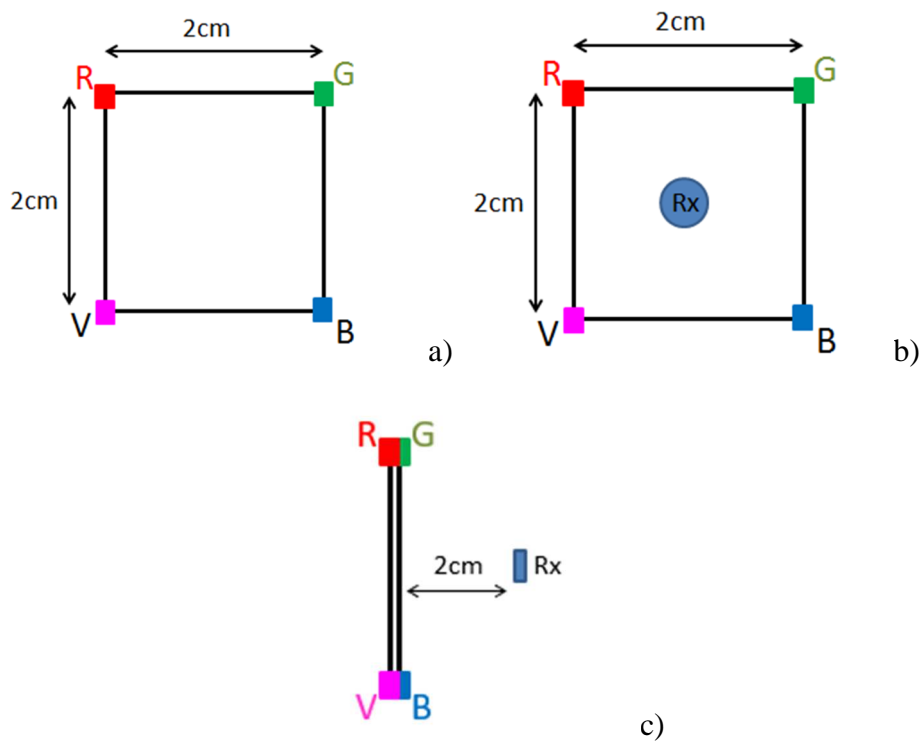


Figure 5-1: Laboratory Four Emitter Cluster Scheme in Up View a), Up view With Receiver Position b) and Side View With Receiver Position c)

To control the different white LEDs in order to create the scenarios that are intended to test, hardware and software previously developed for this purpose was used. This allows to control the four LEDs simultaneously, i.e. to define the binary sequences that each LED must transmit in a certain scenario, as well as the driving currents either to the data emitters LEDs or from the other ones, such as the driving currents of the other non-VLC LEDs in each RGB chip, so that the light perceived is white color. As already mentioned before, this is a factor of great importance to the performance of the system.

At hardware level, a multi-output driver LED has been developed that allows the modulation of the encoded messages in the binary sequences to the current signals that will drive the LEDs. The control of the of the LEDs driving currents is done through the TLC5922 led driver circuit which is connected to the embed NXP LPC1768 which incorporates an ARM Cortex-M3 microcontroller to operate of 96MHz.

System control is done from a PC where the configuration and control software runs with a graphical user interface developed in Java. The communication between the PC and the hardware is done via a USB connection [39].

The Figure 5-2 introduces the software interface that allows to configure and control the various parameters of the laboratory setup.

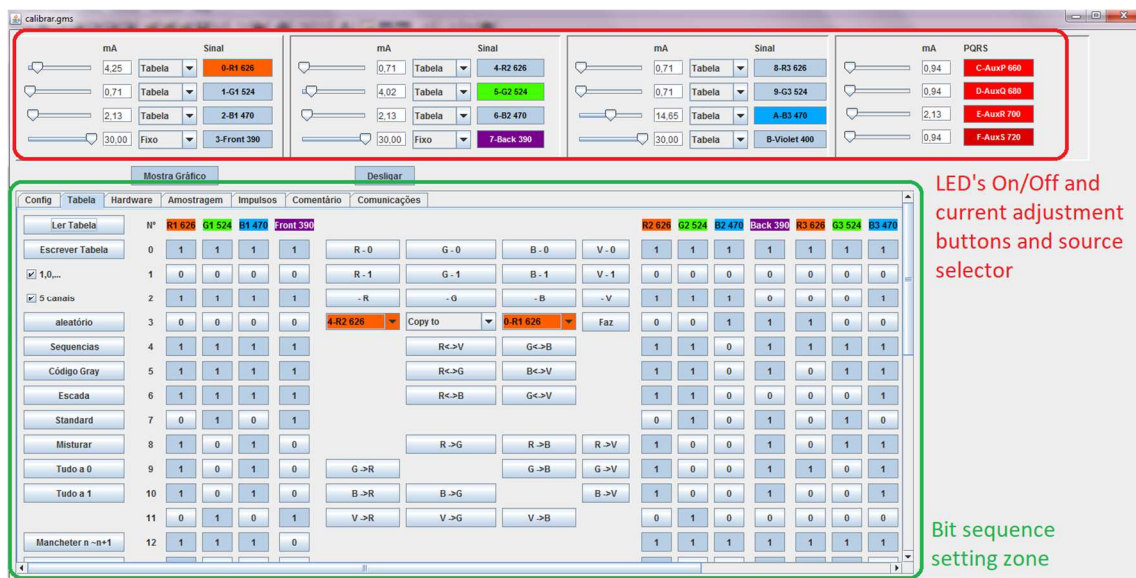


Figure 5-2: User Interface of Laboratory Model Control and Configuration Software

## 5.1. Performed Tests

In the laboratory environment it was intended to recreate and test various aspects and features that the I2V VLC network should validate and perform.

The tests carried out have covered the following aspects:

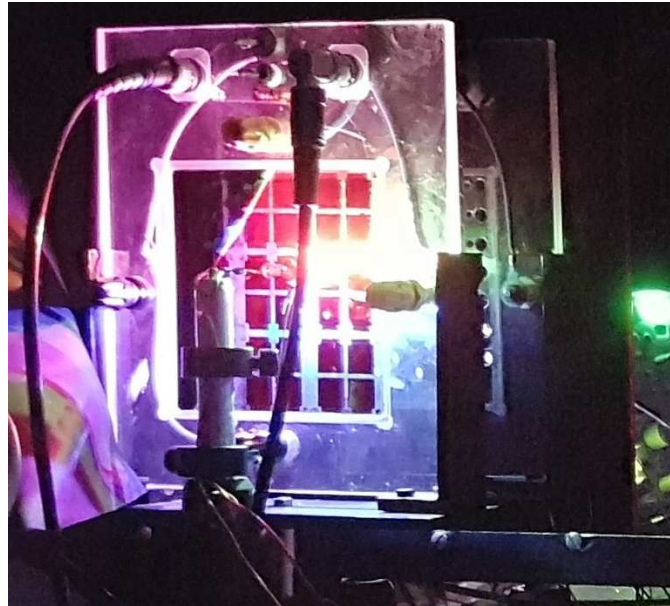
- White light quality produced with different binary sequences, against the white light produced with the steady state LEDs;
- Required driving currents for the different channels, i.e. different wavelengths of transmission, and evaluation of the effect of the binary sequences on the driving current for the maintenance of an unchanged light tonality;
- Receiver's performance evaluation for the different wavelengths of transmission, with or without front or rear background illumination – gains achieved;
- Evaluation of the receiving/decoding capacity of the receiver with different transmission channels, single one at time or in combination of few simultaneously, for different transmission sequences;
- Transmission simulation of the designed dataframes.

### 5.1.1. *Light quality and LEDs driving currents*

Having the lighting quality as a requirement in the design of the VLC communication system, several binary sequences have been tested in laboratory using the different channels, Red, Green, Blue or Violet. The effect in tonality of the light produced with different driving currents was analyzed, both for the emitter LED as well as for the static LEDs whose sole purpose is to illuminate, and together produce white light.

With the dataframe structure defined and presented in Chapter 3 (see Figure 3-10), even without the bias current dynamic control system, the light tone remains stable during the transmission and does not notice any flickering effect. However, it was observed that, keeping the driving currents equal in the transmitting LEDs and the lighting only LEDs, when the system is not transmitting, the perception of the light produced is actually white, but when the system was placed in transmission the tonality of the light

changed a little, making the white hotter – white more yellow – when the transmission channel is Blue, or cooler – more bluish white, when the transmission channel is Red or Green. As the lab model does not include the Violet LED in the same chip, as with the remaining three wavelengths, this more qualitative analysis of the light tonality cannot be performed including also the Violet, although the principle and the necessary care of its incorporation in the public lighting lamps with the function of VLC transmitters, are the same.



*Figure 5-3: Laboratory Model of Receiver and Emitters in a Four Cluster Arrangement*

In the light of the results obtained from this test, it can be concluded that, at the level of control of the emitters, in this case the control of the driving current, three viable options are presented:

1. The most versatile and robust option is certainly to implement a dynamic control system of the LEDs driving current, which responds according to the binary sequence, presented in Chapter 4, and which makes the emitter virtually immune to whatever the sequence of bits to transmit. This is also the most complex and costly solution to implement, either by the high complexity that it inserts into the system, either by inserting active elements, energy consumers, which do not produce light, which means that we are entering an increase energy consumption that is due solely to control and not to the actual transmission of information, however it is also important to mention that this does not mean that such a solution

represents a lower energy efficiency solution than other existing communication technologies, such as those used in traditional mobile communications networks, where the system has as its only function the transmission of data and does not verify the reuse that VLC offers when using the energy that would already be used to illuminate, also to transmit information. In short, the consumption caused by the introduction of a system control of this kind, solely used for the communication strand, would always be capable of being optimized and is far below the powers of transmission of other radio technologies.

2. Another option would be to implement a hybrid alternative, where a much more simplified driving current control system would be applied, which would count with only two levels of LEDs driving current intensity, one to use during the transmission of information and another to use when the channel was silent. As in a silent channel the emitting LED is always connected, like the other LEDs that are not data emitters, in that state its driving currents would be the same. In transmission, as the LED is switched and so part of the time is switched off, a higher driving current would be required so that during the time it is turned on its brightness would be more intense than the rest. The principle is exactly the same as the solution of the previous point and explained in Chapter 4, the difference is that the cost of this simplicity lies in the inability to ensure that, regardless of whatever the binary sequence, that means, whatever the combination of bits that will be verified, the stability of the light tonality produced is guaranteed. The driving current applied to the LEDs is determined on the basis of an experimental analysis and therefore is based solely on the observation of random binary sequences.
3. The third option would be to implement a solution that eliminates the possibility of the channel being silent, even when there is no data to transmit. The solution is based on a continuous transmission of dataframes, similar to that used in other older transmission methods, for example like in ATM, and in this case it would be necessary to slightly change the format of the dataframe, incorporating another bit of control that would indicate whether this dataframe carries data or if it is just filling and its payload is dummy. Like the previous solution, it would continue to not give a response to the possibility, albeit remote, of the long sequences of '1's or '0's, and for those cases only the first option would be enabled to counterbalance these scenarios.

### 5.1.2. *Receiver's gain using front and rear background illumination*

Using the software control, it was analyzed the effect of the backlighting of the receiver, with a wavelength of 390nm, in the gain that it presented in the capture of the signals of different wavelengths, whether received individually, one by one, or received in combination of two or more. Knowing that the front-facing backlight promotes the absorption of wavelengths in the green and red range and attenuates the wavelengths in the blue and violet range, and that the backlight applied behind promotes the opposite, that is, the absorption of the blues and violets and the attenuation of the greens and reds, the following tests were carried on:

- Study the effect of the driving current of the LEDs on the gain achieved in the receiver;
- Analysis of the gain in the photocurrent generated in the receiver for each wavelength, with the two types of backlight;
- Analysis of the gain in the photocurrent generated in the receiver with the various combinations of wavelengths to be received simultaneously.

Regarding to the driving current, it was found that, to a certain extent, with the increase of the driving current of the LEDs, the gain in the receiver also increased. From a certain level, the effect was the opposite, the increase of the current caused a loss in the gain of the receiver. This effect was generally verified for all wavelengths and with the backlight to be applied either front or rear. The optimal spot checked was sensibly in the 4mA for Red, Green and Blue and 1mA for Violet. As the receiver's own backlighting is also at the wavelength close to that of the Violet, the photodiode saturates more quickly.

Table 5-1 presents the gains obtained for each of the wavelengths, when they transmitted binary sequences of clock type. Transmissions were tested at the maximum attainable rate, 5 kbps, as well as half of that rhythm, one quarter and one eighth. There were no variations in gain that would allow a relationship between the bitrate and the gain.

<u>Gain</u>	<b>Red</b>	<b>Green</b>	<b>Blue</b>	<b>Violet</b>
<b>Current</b>	4,02 mA	4,02 mA	4,02 mA	0,94 mA
<b>Front</b>	4,23	3,32	1,33	1,38
<b>Back</b>	0,7	0,69	1,38	5,24

Table 5-1: Single Channel (R, G, B or V) Reception Gain

The values shown in the Table 5-1 confirm the expectation of obtaining a gain in the wavelengths of the reds and greens with front backlighting and an attenuation in the same wavelengths with rear backlight. Regarding to the blue and violet wavelengths, the results diverged somewhat from the expected, in the sense that the front backlighting attenuation was not verified for any of the cases and the gain with the rear backlighting was only expressive to Violet. In the case of Blue, the gain was little higher than that obtained with front backlight, but no big difference. The conclusion is, with the photodiode used in the laboratory, the use of backlight to promote the absorption of some wavelengths, inhibiting the absorption of others has not proved useful in the case of blue, where the gain is always positive, independently of the direction of the backlight comes from, but it is also not expressive to the point of being convenient or inconvenient to a good discretization of the signals.

The performed tests with several wavelengths simultaneously only admit the possible combinations in the clusters, it means, only the combinations that occur in each existing subarea were tested.

The binary sequences used in the tests were standard sequences that consist of all possible combinations of transmission, assuming the set of four channels as a four-bit binary word.

<u>Gain</u>	<b>Red+Green</b>	<b>Red+Blue</b>	<b>Blue+Violet</b>	<b>Green+Violet</b>
<b>Current</b>	4,02 mA+4,02 mA	4,02 mA+4,02 mA	4,02 mA+0,94 mA	4,02 mA+0,94 mA
<b>Front</b>	4,77	2,82	0,94	1,52
<b>Back</b>	0,72	0,74	1,39	0,79

Table 5-2: Two Simultaneous Channel (Red and Green, Red and Blue, Blue and Violet, Green and Violet) Reception

Gain

By matching the gains of the different combinations in the Table 5-2 with the individual gains in the Table 5-1, it can be perceived the constructive effect in the gain or attenuation, when the combination is between Red and Green or between Blue and Violet, or the contradictory effect, when the combination is between Red and Blue or between Green and Violet. In the case of the combination of Red with Blue, there is a decrease, either of the attenuation or of the gain, against the verified in the red alone. As the blue always gets a small gain, regardless of the backlight being front or rear, it could be expected that a decrease in attenuation is observed, when the backlighting is rear, but also an increase in gain, when the backlighting is frontal. The second premise does not occur due to the weighting of the number of bits to ' 1 ' that the Red has relative to the Blue in the same time interval. Because the sequence of bits transmitted on each channel is of clock type and the bitrate of the Red is  $\frac{1}{4}$  of the bitrate of the Blue, the time that the red LED is on is only  $\frac{1}{4}$  of the time than the blue LED is on, as can be verified by the graph of the Figure 5-4.

In the case of the combination of Green with Violet, the observed phenomenon is the same as that for Red and Blue, but adding there is also the driving current factor of the violet LED to be significantly lower, resulting in a less intense brightness and consequently in a photocurrent generated in the receiver to its charge, also lower.

In the subzone where the combination is three wavelengths, shown in Table 5-3, a definite trend is observed indicating a global gain when the backlighting is frontal, as well as a global attenuation when the backlighting is rear.

<b>Gain</b>	<b>Red+Blue+Violet</b>	<b>Red+Green+Violet</b>	<b>Green+Blue+Violet</b>	<b>Red+Green+Blue</b>
<b>Current</b>	4,02 mA+ 4,02mA+ 0,94 mA	4,02 mA+ 4,02 mA+ 0,94 mA	4,02 mA+ 4,02 mA+ 0,94 mA	4,02 mA+ 4,02 mA+ 4,02 mA
<b>Front</b>	1,65	2,16	1,27	2,99
<b>Back</b>	0,77	0,82	0,84	0,74

*Table 5-3: Three Simultaneous Channel (Red and Blue and Violet, Red and Green and Violet, Green and Blue and Violet, Red and Green and Blue) Reception Gain*

The same trend is maintained when the combination is with the four channels, as shown in the Table 6-4 data.

<b>Gain</b>	<b>Red+Green+Blue+Violet</b>
<b>Current</b>	4,02 mA+4,02 mA+4,02 mA+0,94 mA
<b>Front</b>	1,65
<b>Back</b>	0,8

Table 5-4: : Four Simultaneous Channel (Red and Green, Red and Blue and Violet) Reception Gain

The graphic in the Figure 5-4 represents the reception of the standard sequence, without background light and with front and back background light, as shown in the T4 table. This data shows that the photodiode with backlighting on the front allows for a perfectly effective decoding of all possible combinations. The sixteen levels corresponding to all possible combinations of the four channels are perfectly identifiable. It is concluded that for the purposes of receiving and decoding the information in the receiver, the most favorable option is with exclusively frontal backlighting. [40]

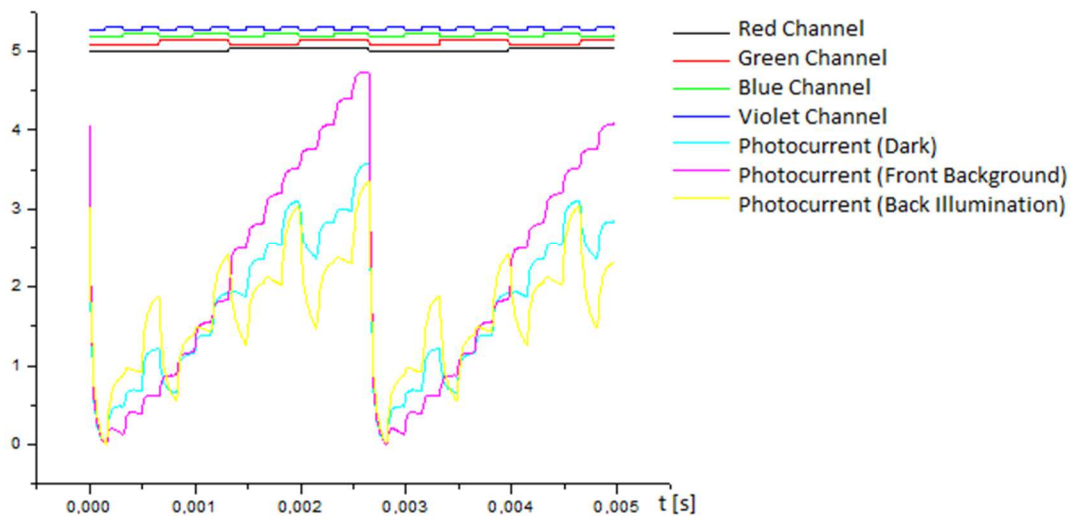


Figure 5-4: Cluster Standard Sequence Reception With Receiver On Dark and With Background Illumination

### 5.1.3. *Dataframe reception and decoding*

The graphs in the following figures present the results of the tests reproducing the transmission of random data carried in the payload of the dataframes, according with was been designed, as shown in the Figure 3-10.

In Figure 5-5, the bit sequence was chosen to allow all the on/off sixteen possible combinations of the four channels. On top, the signals used to drive LEDs are shown to guide the eyes into the on/off states of each input. In Figure 5-6, the MUX signal acquired by the receiver, located at the crossroad, position #1, #9 and #7 (see Figure 5-10), are displayed. The decoded packet of transmitted information when all the channels are received is presented in the top of the figure.

Results from Figure 5-5, show that the MUX signal presents as much separated levels as the on/off possible combinations of the input channels, allowing decoding the transmitted information. On the right hand side, the match between MUX levels and the 4 bits binary code ascribed to each level is shown. The MUX signal presented is used for calibration purposes.

The signal is decoded by assigning each output level to a 4- digit binary code, [XR, XG, XB, XV], with X=1 if the channel is on and X=0 if it is off.

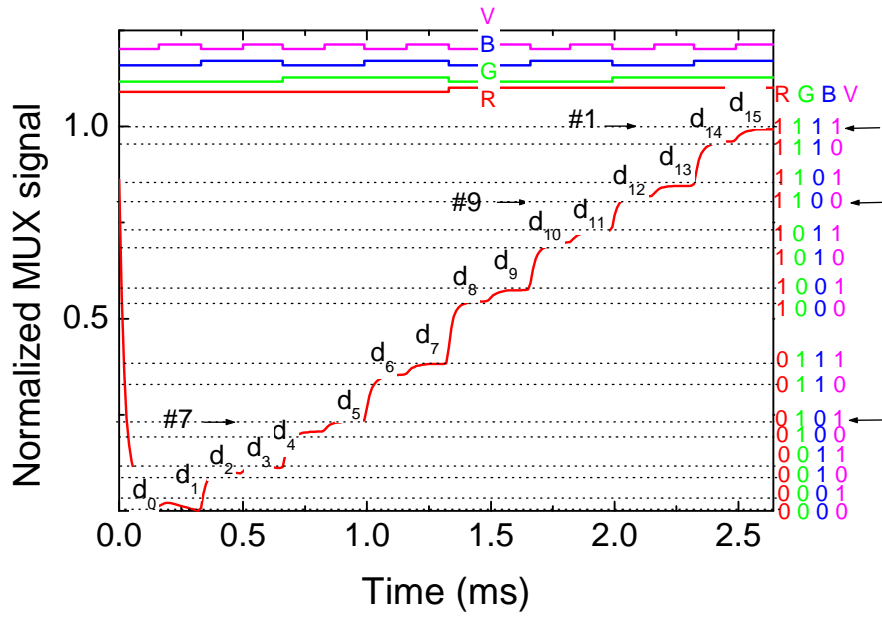


Figure 5-5: MUX/DEMUX signals under 390 nm front irradiation. On the top the transmitted channels packets [R, G, B, V] are decoded.

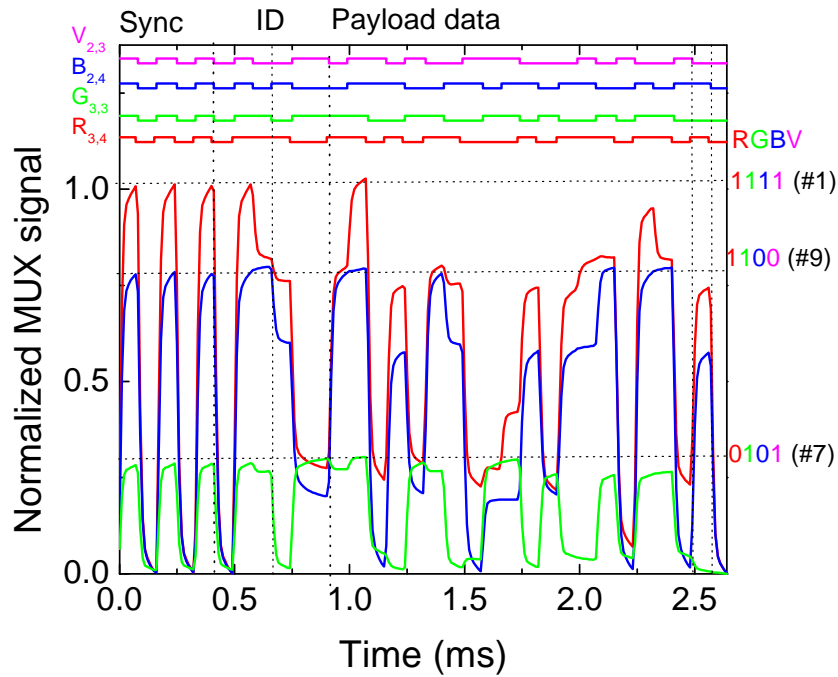


Figure 5-6: MUX signal at positions #1, #7 and #9.

After decoding the MUX signals, the localization of the mobile target is direct. Taking into account the frame structure (Figure 3-10), the position of the receiver inside the navigation cell and its ID in the network is revealed. The ID position comes directly

from the synchronism block, where all the received channels are, simultaneously, on or off. The 4-bit binary code ascribed to the higher level identifies the receiver position in the unit cell. Those binary codes are displayed in the right hand of the figure. For instance, the level [1 1 0 0] corresponds to the level d5 where the green and the violet channels are simultaneously on (see arrow in Figure 5-5). The same happens to the other footprints (#1 and #9). Each decoded message carries, also, the node address of the transmitter. So, the next block of six bits gives the ID of the received node. In #7 the location of the transmitters, in the network, are  $G_{3,2}$  and  $V_{2,3}$  while in #1 the assigned transmitters are  $R_{3,4}$   $G_{3,2}$   $B_{2,4}$  and  $V_{2,3}$ . The last block is reserved for the transmission of the traffic message (payload data). [41]

In Figures 5-8 and 5-9 the signals received correspond to a hypothetical vehicle that is curving. In these specific cases the speed of the vehicle cannot be determined, as the initial condition is not verified, that is the vehicle moving on a straight path along the road.

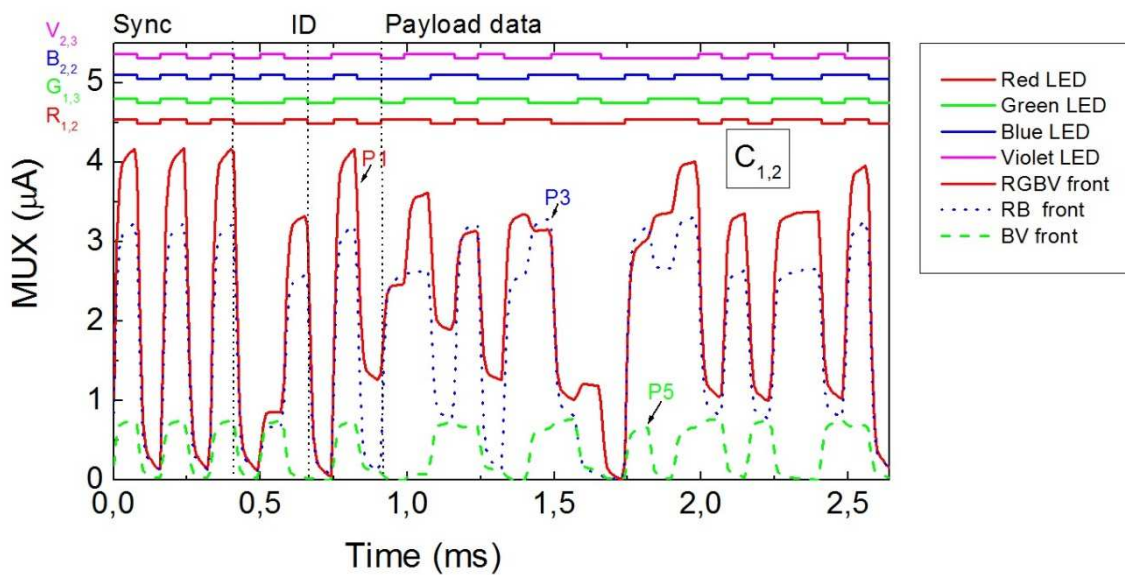


Figure 5-7: Dataframes Received in subarea 1 (RGBV), 3 (RB) and 5 (BV), in Cluster Formed by Cell  $R_{1,2}$   $G_{1,3}$   $B_{2,2}$  and  $V_{2,3}$

The Figure 5-9 presents a simulation where the speed can be determined, as shown in Chapter 4. The hypothetical vehicle has gone through subzone 3, 1 and 7. Assuming

this order, can be determined that the said vehicle moves from east to west and, also by the arrangement of these subzone in the cluster, it can be assumed that the vehicle moves in a straight line, maintaining a constant position relatively to the road, thus allowing the speed determination, as well as its effective position on the road, since this is a validation factor as already mentioned.

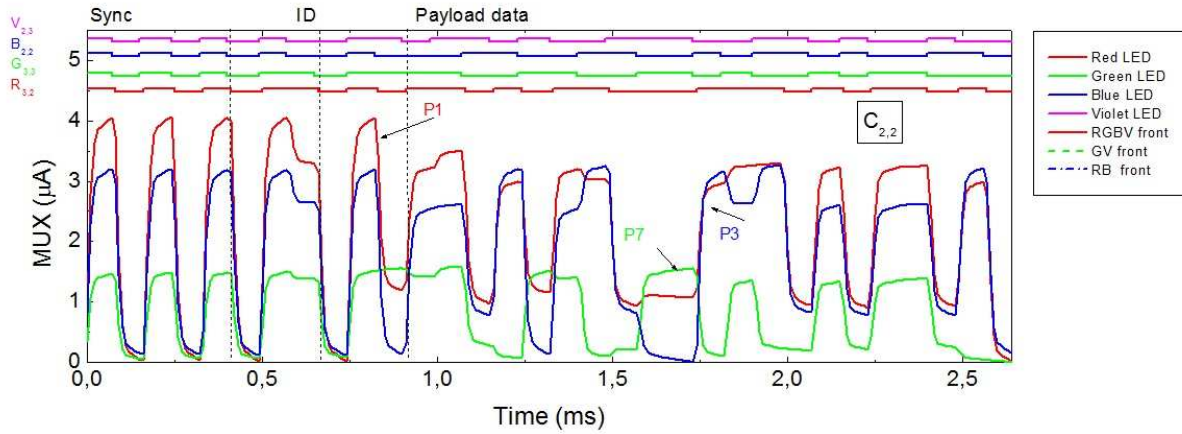


Figure 5-8: Dataframes Received in subarea 3 (RB), 1 (RGBV), and 7 (GV), in Cluster Formed by Cell  $R_{3,4}$   $G_{3,3}$   $B_{4,4}$  and  $V_{4,3}$

Figure 5-8 shows the scenario described above, where the vehicle trajectory allows the speed determination.

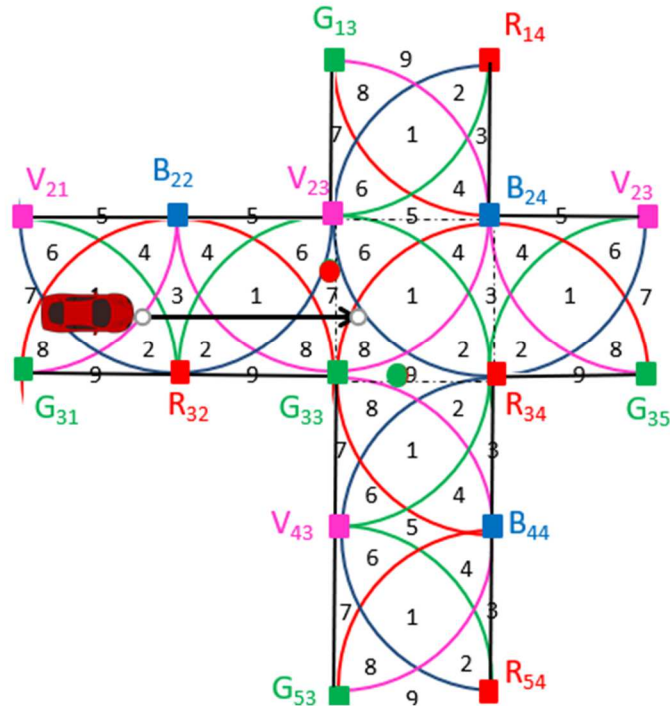


Figure 5-9: Vehicle Moving in Straight Line Crossing Subzones 3, 1 and 7

Regarding to noise that the system experiment in real conditions, like the solar light, some tests under white light coming from fluorescent lamps and, since this is a DC signal, it didn't interfere with the good reception of the data was proceeded. However, as future work more tests should be done in a real-life environment.

# 6. Conclusions

## 6.1. Final conclusions

This work has focused on the development of a VLC network – Visible light Communication, for vehicular communication, where it is intended to provide a road infrastructure with the ability to communicate with the vehicles moving on it and analyze the way they do it. The final goal for this technology is that road traffic reaches a stage where communication between vehicles, infrastructure to vehicles and vehicles to the infrastructure is completely integrated and interoperational. However, in this work the focus has been the communication of the infrastructure to vehicles - I2V.

The advantages and obstacles that VLC presents was analyzed and compared with RF communication. Different solutions that have been developed, as well as their evolution such as available modulations, achieved performances concerning transmission rates (both in downlink and in uplink), as well as in matter of limitations that are emerged to the different applications and that have been overcome. It was found that the advances achieved recently in LED technology, which resulted in its wide dissemination in lighting solutions due to the energy efficiency, and that was critical to the emergence of VLC as an alternative for communication systems. In this chapter there were still some of the applications for which VLC is promising, notably for the vehicular communication, but also in other areas as in the indoor location, where the GPS system does not present itself as a solution, in the communication between devices in the near field (NFC), through, for example, communication between screen-camera and in human-computer interface solutions.

VLC receiver specifically designed for the application concerned was studied. For this purpose, a photodiode of the PINPIN type was been used and the principles and characteristics to be taken was analyzed, such as dimensions, in order to receive the used wavelengths, in the range of red, green, blue and violet. Background illumination of the photodiode, when applied by the front or behind, favors or inhibits the absorption of certain wavelengths. It was also notice that for our system, backlighting is only

advantageously applied to the front, in order to better discriminate the different levels of the signals received.

VLC emitter is the basic element in the structure of the network and the common point between the communication system and the lighting system. The structure of the data frame used in communication was defined. Mode of operation of the emitter and the structure of the data frame are intrinsically connected. It has been studied the influence that the binary sequences to transmit have in the quality of the light produced by the emitters whose function of illumination cannot be sacrificed. A bias current dynamic control system of the LEDs has been dimensioned, in order to maintain the correct brightness and tonality of the light produced, regardless of the data transmitted at every single moment. Alternatives have also been studied to this dynamic control system based on a commitment between the complexity of the solution and the robustness of the system to harmful phenomena to the quality of light, such as the existence of long chains of bits to '1' or '0'.

Regarding to network topology, it was concluded that the placement of public lighting lamps is the basis for this topology determination and based on this starting point, the solution found has gone through the definition of clusters of four emitters square-shaped, corresponding to the repeating cycle of spectral resources, i.e. of the four wavelengths used for transmission, which correspond to four emission channels. It has been concluded that the repeating cycles of these wavelengths in the network create subzones where, in each of them, there is a specific combination of channels covered by them. These subzones follow a pattern through which it is possible to realize the direction of the movement of the vehicles, their speeds and the position they occupy on the road. It was defined an algorithm that allows the network to extract this information and thus to make intelligent traffic management.

Lastly, the laboratory model which allows to carry on the tests necessary for the development and validation of the project has been tested. The response of the photodiode used in the receiver was analyzed, as well as the gains with the background illumination, front or back, for each of the wavelengths. This was the study which has allowed to conclude that backside background illumination does not represent an added value for the system. Good reception and decoding of one or more channels simultaneously, simulating the reception in different subzones was also confirmed.

## 6.2. Future works

Subsequently to the work performed along this dissertation, these are a few topics that can be adressed in future works to improve the proposed system.

Test the reception of the signals with the receiver in motion. Test scenarios to verify the suitability of the designed dataframe for the system, verifying that there is a good synchronization and decoding of the messages in a motion scenario, as well as the efficacy of the algorithm mentioned in the previous point.

Test the reception of the signals on a real scale, with real conditions, similar to those observed in outdoor environments, allowing the validation of the work developed, as well as the identification of any constraints that have not been anticipated.

Develop a proper luminaire lenses for calibration of each lamp lighted area, in order to get all equal subzones amount the network.



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