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# VLC system for the determination of a vehicle's position and speed

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*Abstract* — **In recent years, lighting solutions have gradually been replaced by more efficient features, taking advantage of Light Emitting Diodes (LEDs) that have progressively conquered the market with increasingly high optical powers,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 paper 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 using a small-scale prototype. The results show that with the proposed system it is possible to transmit information between road infrastructure and vehicles.**

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

## I. Introduction

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 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 it 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 signaling, 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 characteristics that are completely attractive in telecommunication systems, such as its short propagation distance and its inability 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 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 particular application 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 used 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'.

## II. 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 1).

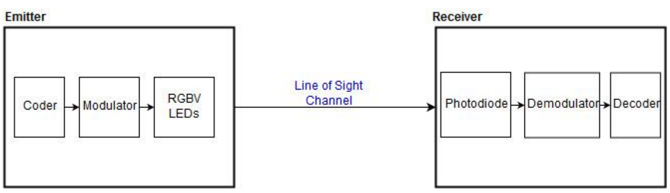


Fig. 1. Block diagram of the VLC system for illumination, positioning and data transmission

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.

### *A. 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 [1].

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 2 it is plotted the normalized output spectra of the RGB white LEDs used in this experiment.

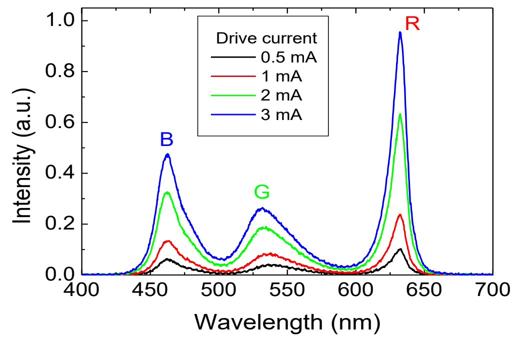


Fig. 2. Output Normalized Spectrum of the RGB White LED using different values of driving currents in the range 0.5mA – 3 mA.

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 [2]. This experiment was done using different driving currents for the emitters of the RGB white LED. 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 covers 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 maximum (FWHM) is 22 nm for the blue chip, nearly 48 nm for the green and 13 nm for the red chip. Usually the FWHM 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 [3] [4].

In Fig. 3 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.

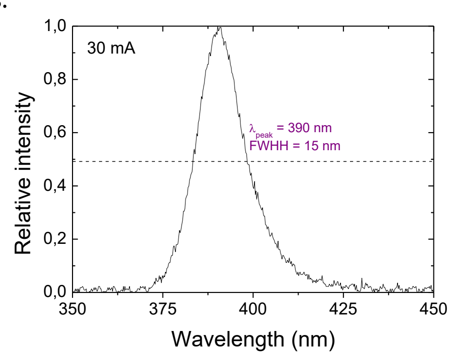


Fig. 3. Normalized Emission Spectrum of the Violet LED of the Background Light

The violet LED used for the background exhibits a s single peak centered at 390 nm and a narrow full width half maximum (FWHM) of 15 nm.

TABLE I
OPTICAL CHARACTERISTICS OF THE RGB AND VIOLET LEDS AT 25 ºC

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

*B. 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 must be designed considering 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 signal 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 regarding the device capacitance, 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 4 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.

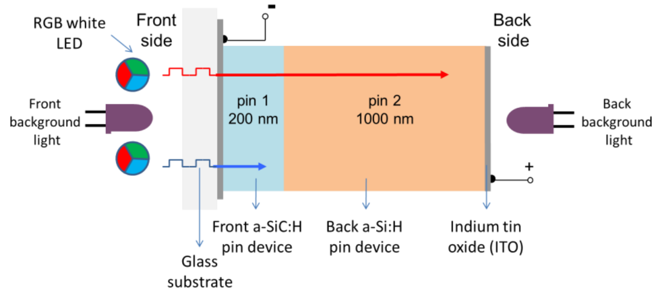


Fig. 4. PINPIN Photodiode Used in Receiver Prototype [5]

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 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 [5] [6].

Background steady state light was supplied by violet LEDs (390 nm, 15 nm of FWHM) 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 and 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 5 using background light from both front and back sides, and without any background light (which corresponds to the condition of not having any optical bias).

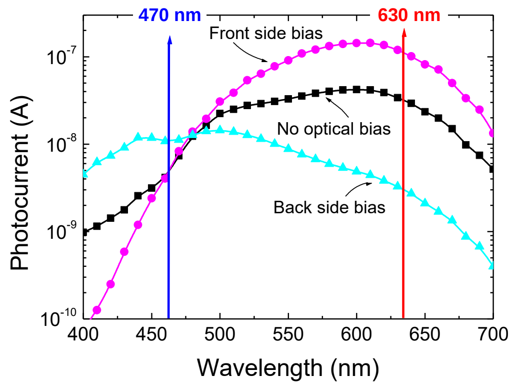


Fig. 5. Spectral Photocurrent Under Dark Conditions and Using Front and Back Violet Light

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 [7]. In Figure 6 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.

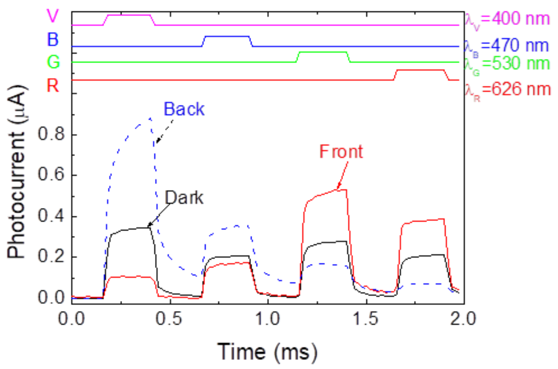


Fig. 6. Transient photocurrent without (Dark) and under front (Front) and back (Back) 390 nm irradiation

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 (αF and αB for the front and back gains, respectively), defined at each wavelength (λ) as the ratio between the signal magnitudes measured with and without optical bias. The gain assigned to each channel is displayed in Figure 7.

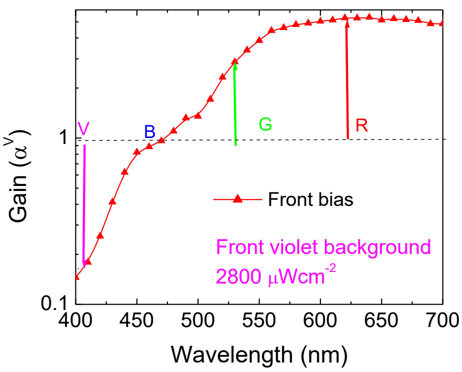


Fig. 7. Spectral gain Under Violet Front Optical Bias (αV) Only. The Arrows Point Towards the Optical Gain at the Analyzed R, G, B and V Input Channels [8]

The photocurrent produced by photodiode is then 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 a signal, or not, respectively [9] [10].

### *C. 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 [8].

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 [11].

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 shown in the Figure 8.

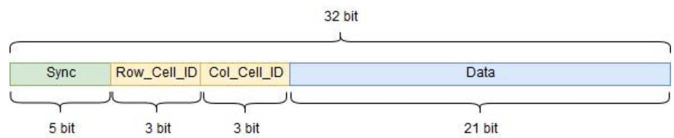


Fig. 8. Dataframe Structure

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 color 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 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 now 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 send 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 9, 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.

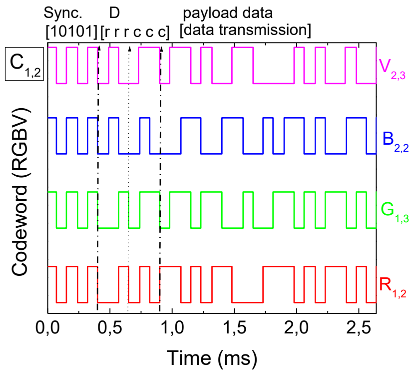


Fig. 9. Representation of One Original Encoded Message, in a Time Slot With R12, G13, B22 and V23

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:

$$f_{datagram} = \frac{f_{bit}}{32} \Leftrightarrow f_{datagram} = \frac{5\times10^3}{32} = 156.25\ Hz, \qquad (1)$$

As the data frame frequency is nearly 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 must 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:

$$\int_0^{T_{frame}} I_{DC}\,.dt = \int_0^{T_{frame}} I_{bit\,1}\,.dt, \qquad (2)$$

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

$I_{bit1}$ – 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, if 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 10 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', to stabilize the produced light intensity.

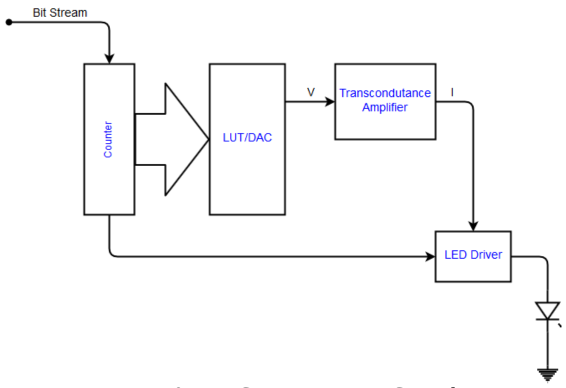


Fig. 10. Bias Current Dynamic Control

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, 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.

## III. Network Topology

To meet the application of the VLC I2V communication technology and, a topology has been developed for the network, in order to. Figure 11 shows an overview of the elements in a I2V VLC network and how they can interact between them.

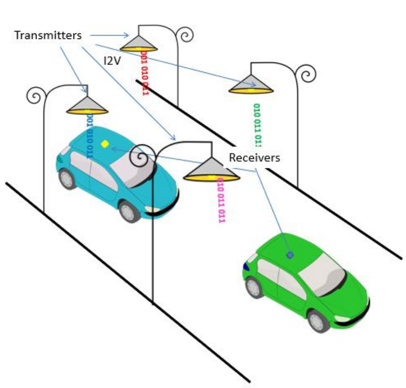


Fig. 11. I2V Network Topology With Full Elements

Along the roads, street lamps are distributed in a square topology, for data transmission and lighting purposes. In this model it was 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 Figure 11 [12].

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 in the frames sent by each emitter.

### *A. 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 [13] [14]. Figure 12 represents a cluster of emitters with the distribution of the nine subzones.

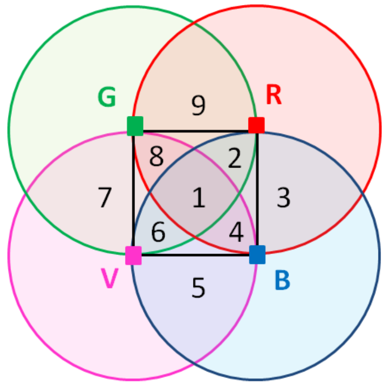


Fig. 12. Subarea Delimitation in a Cluster Example

Thus, under the assumption that only one of the RGBV LEDs is modulated at each corner, it is presented in Table 2, the nine possible allowed subzones defined inside the cluster.

TABLE II
ALLOWED SUBZONES DEFINED INSIDE THE CLUSTER

| **Footprint regions** | #1 | #2 | #3 | #4 | #5 | #6 | #7 | #8 | #9 |
|---|---|---|---|---|---|---|---|---|---|
| **Overlap** | R G B V | R G B | R B | R B V | B V | G B V | G V | R G V | R G |

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 13.

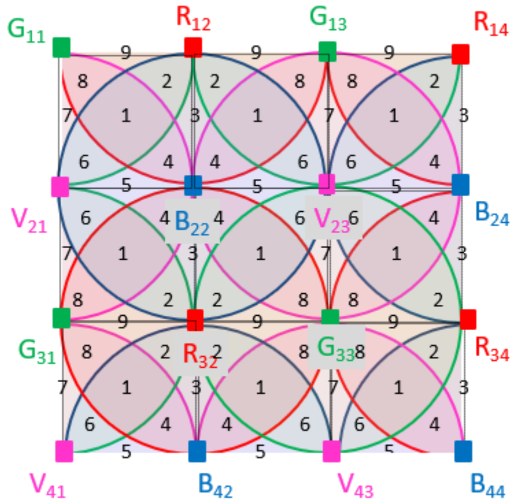


Fig. 13. Cell Cluster Repeat Pattern

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 14 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.

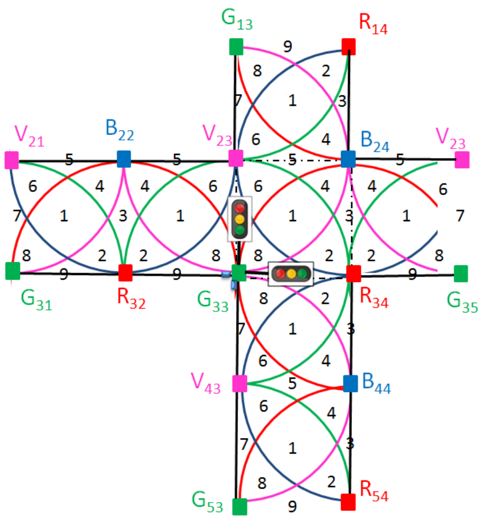


Fig. 14. Road Network Topology Overview

*B. Position and Speed determination*

Figure 15 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 vehicle on the road. This may be useful to infer if any user is driving in opposite direction.

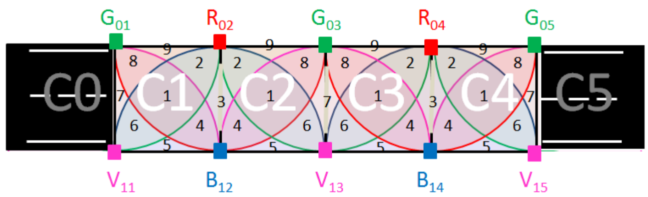


Fig. 15. Straight Road Coverage With Subarea Delimitation

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:

$$\begin{cases} AO.L(Zone_7) + BO.L(Zone_6) + CO.L(Zone_1) + \\ \quad DO.L(Zone_4) + EO.L(Zone_3) = Dist_{emitters} \\ AB.L(Zone_7) + BB.L(Zone_6) + CB.L(Zone_1) + \\ \quad DB.L(Zone_4) + EB.L(Zone_3) = Dist_{emitters} \end{cases}, \quad (3)$$

Where:

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

L(Zonex) – Travelled distance inside each subzone inside the cell

$Dist_{emitters}$ – Distance between consecutive cells.

The network registers the time when each vehicle enters and exits each subarea. The time period 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 15, related to C1 and assuming uniform speed between the emitters, this period of time can be extrapolated by the difference between t the time when the vehicle is under the coverage of B12 and the moment it undergoes on the coverage of V13. 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:

$$V = \frac{Dist_{emitters}}{\Delta t_{cell}} \Leftrightarrow V = \frac{25}{\Delta t_{cell}}, \quad (4)$$

Where:

V – speed of the vehicle inside the cell,

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

Analysing the case of the orange trajectory:

$$\begin{cases} AO.Zone_7 + BO.Zone_6 + CO.Zone_1 + \\ DO.Zone_4 + EO.Zone_3 = 25 \\ \Delta t_{Zone7}.Zone_7 + \Delta t_{Zone6}.Zone_6 + \Delta t_{Zone1}.Zone_1 + \\ \Delta t_{Zone4}.Zone_4 + \Delta t_{Zone3}.Zone_3 = \Delta t_{cell} \end{cases}, \quad (5)$$

Then:

$$\begin{cases} AO = V.\Delta t_{Zone7} \\ BO = V.\Delta t_{Zone6} \\ CO = V.\Delta t_{Zone1} \\ DO = V.\Delta t_{Zone4} \\ EO = V.\Delta t_{Zone3} \end{cases}, \quad (6)$$

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 V13 domain to entry into B12 domain, assuming that the vehicle arrives first to B12 than the V13. 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, V13 and B12). 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 feature 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.

## IV. 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 inter-operational. However, in this paper the focus has been the communication of the infrastructure to vehicles - I2V.

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. Have been seen that the repeating cycles of these wavelengths in the network create subzones where, in each of them, there is a specific combination of channels which they cover. 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 the algorithm that allows the network to extract this information and thus to make intelligent traffic management.

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