Implementation of a Visible Light Communication Link - Li-Fi

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Abstract — **The bandwidth per user increases every year and it is necessary to present alternatives that can satisfy this growth. One possible solution is to explore the increased use of LEDs (Light Emitting Diodes). Visible Light Communications (VLC) is an emerging technology that shows many advantages comparing to other alternatives that we currently know. This solution can be simultaneously combined with illumination being a more economical alternative. Quick switching, increased uptime, increased bandwidth and the lack of interference with other electromagnetic sources are other advantages of VLC. There are several applications in indoor environments but the main implementations difficulties and the interference in communications are higher in outdoor environments. Li-Fi (Light-Fidelity) is a VLC system capable of transmitting data at high data rates. This system uses the LED light, exploring its operating characteristics, showing up as an alternative to the existing wireless system. This work initially presents an analysis to the VLC state of the art, evolving to Li-Fi and then going on to analyse a solution that uses appropriate intensity modulation techniques to the situation under study. The main purpose of this work is to implement three variations of the Li-Fi system (front camera as a receiver, photodiode as a receiver and RGB system as a transmitter) and the subsequent optimization of the proposed solution.**

Keywords – Optical Communications, Visible Light Communications, Light Emitting Diodes, Colour-Shift Keying, Li-Fi.

I. INTRODUCTION

In the last decades the world has seen a huge growth in the traffic transported by telecommunication networks. The increase of devices capable of accessing mobile networks and the high demand for internet services that use high transmission rates (social networks, video calls, cloud-based services, mobile applications, etc.) has warned for the research and development of new technologies that are capable of delivering to users extremely high transmission rates [1]. According to CISCO, mobile traffic will growth around seven times in 2021 when compared to 2016 [2].

Radiofrequency (RF) based communication systems suffer from multipath propagation effects in dense urban environments, which reduce the performance and available connection. The bandwidth of these systems combined with spectrum congestion implies that in a given area only a few high definition channels can be used. To increase the system capacity, it would be possible to release a new spectrum and thus we would have a greater bandwidth. Another solution consists in improve spectral efficiency. However, these two solutions imply very high costs and an increase of complexity in the design and management of the emitter and receiver [1]. Depending on the frequency used, RF communications may also cause safety problems (waves penetrate walls easily), affect human health (if used with transmit power above a certain limit) and cause interference in many systems, as communication and navigation in aircrafts [3].

One possible solution is the use of the visible band, which occupies the spectrum between the 380 nm and 750 nm. Communications in this band are known as Visible Light Communications (VLC). This communication type has an extremely high range of frequency (in the order of THz) and don't suffers of electromagnetic interference. In this way it provides a high degree of special confinement, making reuse of frequency practically unlimited. This significantly reduces licensing costs and increases security in data transmission [1]. This light can be generated by using of light-emitting diodes (LEDs) or laser diodes [4], allowing the use of this technology simultaneously for illumination and data transmissions at very high speeds. Li-Fi is one of the variants of the VLC and allows the transmission of information by modulating the light and can in the future a complement or even a substitute for Li-Fi. Li-Fi is a sustainable and ecological technology, with potential to revolutionize the way how we will use light in the near future.

The structure of the paper is the following order: Section I – Introduction; Section II - Basic concepts and state of the art of the problem under study; Section III – Theoretical development of the models and its implementation; Section IV – Analysis of results; Section V - Conclusions.

A. *State of the Art*

Regarding the state-of-the-art in Visible Light Communications, we can split in two groups: indoor and outdoor communications. Focusing on studies related with Li-Fi the current experiences are mainly based on the indoor environments.

In [5] is presented an alternative to Wi-Fi, being called Li-Fi. The authors note that is possible to use Color Shift Keying (CSK), an intensity modulation that has de advantage of ensuring a constant illumination flow. In the emitter they used a chip developed in the UPVLC (Ultra-parallel visible light communication) design and the receiver is based on an APD (Avalanche photodiode. By combining the LED light with wireless data networks, it was possible to archive a considerable reduction in the size of the cells and consequently an increase in the transmission rate, the number of users served and the total traffic. Thus, the authors showed that is possible to achieve, with small equipment, transmission rates in the order of 1 Gb/s. In this study, a comparison is made between Wi-Fi and Li-Fi, concluding that the performance is higher when both techniques are used simultaneously, in a balanced way.

In 2017 pureLiFi [6] launched the Li-Fi-XC, a device that allows wireless communications at very high transmission rates, in a safely way using LEDs. The Li-Fi-XC is a certified plug and play system that works with USB devices and because of its small size, it can be integrated into computers, tablets or smart devices. Allows transmission up to 43 Mbps from each LED that supports Li-Fi, enabling two-way communication in Full Duplex mode. This system also allows the user to walk between different LEDs, maintaining the connection and avoiding interruptions in the connection.

In 2018 Philips launched two models of LED luminaires ready to illuminate and transmit information simultaneously, the LuxSpace PoE [7] and the PowerBalance gen2 [8]. Both have a Power-over-Ethernet (PoE) technology that allows them to receive power and data through a single standard Ethernet cable, thus allowing a transmission rate up to 30 Mb/s in a connection that can be unidirectional or bidirectional. Depending on the chosen model, for an input power varying from 9.2 X and 16.2 W, a luminous flux of 1200 lm and 2200 lm can be obtained. This allows a reduction of 80% in the electric consumption [9].

MyLifi was introduced in 2018 and is another example of LED lighting prepared for Li-Fi use [10]. Produced by Oledcomm, it can reach transmission rates up to 23 Mbps in download and 10 Mbps upload and can be used simultaneously for illumination as a conventional lamp. This device is also considered more efficient, since the lamp with 800 lumens uses 13.5 watts, less than the 20 watts consumed by a conventional Wi-Fi router [11]. In a Li-Fi system it is necessary for the receiver to capture the emitted light. In this way Oledcomm also as a USB device that allows any device with this interface to be able to use the Li-Fi connection. Even when the light appears to be off, the device is in operation and has light sensors and an application (web and mobile) that allows full illumination control [10].

B. *Dissertation objectives and Outline*

The main objectives of this work can be summarized in the following topics:

- Development and implementation of a Li-Fi system that allows the communication in free space, using appropriate modulation schemes.
- Analysis and optimization of the system implemented using a smartphone.

II. THEORICAL BACKGROUND

A. *VLC system structure*

The typical (simplified) structure of a VLC system it is composed by a transmitter, which has the function of emitting the desired signal, a propagation channel and a receiver that receives and decodes the signal. From the emitter side, the light is generated using converters and LEDs or Laser Diodes. The emitted light is sent through an optical channel until it is detected by the receiver. The receiver is typically composed by an amplifier circuit, an optical filter and a photodetector (PIN/APD Detector).

B. *Emitter*

The emitter in a VLC can be used for communication and for illumination. The main component of the transmitter is the LED, which has the dual function of lighting and data transmission. The laser can also work as an emitter, being only useful for communication. Figure 1 shows a block diagram with the different components that make up a typical emitter of a VLC system.

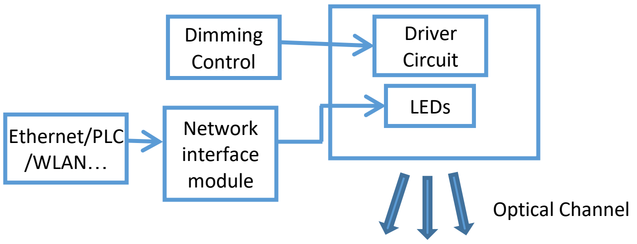

Figure 1 - VLC emitter structure (adapted from [12]).

There are several types of LEDs with varying powers. Using the CREE, it is possible to select a model with the desired characteristics. An RGB LED (Cree XLamp MC-E Color [13]) has been selected, allowing the use of these three colours in a single LED. The spatial radiation pattern of the selected LED is not constant. It is necessary to take this factor into account when analysing the received power values.

VLC is based on intensity modulation and direct detection (IM/DD) for data transmission. ON/OFF keying (OOK) is a very popular modulation technique due to its simplicity of application. Also known as binary PAM, it is the simplest form of IM/DD [1]. Depending on the information that is transmitted, a pulse is generated, simplifying the design of the emitter and the receiver [14].

The structure of the LED driver circuit must consider the type of signals that we intend to modulate. In the transmission of signals with digital modulation format we use ON/OFF drivers. The ON/OFF drivers can be used for LED modulation in the digital domain.

To use the LED simultaneously for communication and lighting it is necessary to combine the data signal with the signal responsible for dimming. In this way the modulation of the optical output of a white LED is typically made using a bias tee, combined with an appropriate DC current [14]. This device consists of three ports, one for the input signal, one for polarization and the third that represents the combination of both signals.

Units that describe the output intensities of LEDs emitting visible light are photometric units. On the other hand, the sensitivity of the photodiode is expressed in terms of radiating units (radiometric units). To compare the two systems a conversion is necessary.

C. *Receiver*

The receiver in the VLC system is responsible for receiving and processing the light emitted by the emitter. It is generally composed by an amplification circuit, an optical filter, a photodiode and a signal recovery circuit, as show Figure 2.

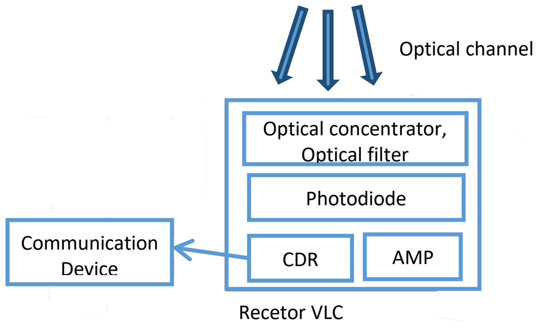

Figure 2 - VLC receiver structure (adapted from [12]).

In the receiver, the light is detected by a photodiode and then converted to an electrical signal. The APD photodiode has a better performance to act as a receiver in a free space optical communication system when compared to the PIN photodiode. PIN photodiode as a lower cost and a larger active area [15].

The resulting current from the conversion of the optical signal is generally very small. It is necessary to use an amplifier to amplify the signal to suitable levels, for further processing. The transimpedance amplifiers (TIAs) are used to convert the current from the photodiode into voltage [16].

III. LI-FI SYSTEM DESIGN

A. *General Description*

The initial solution proposed for the VLC system is composed by a transmitter a free space transmission channel and a receiver. The emitter consists of a white LED with an electrical power of approximately 1W. The signal can be generated using a signal generator using OOK modulation. On the receiver the signal is filtered using and optical filter and then concentrated in the PIN photodiode through a converging lens. The received optical signal is then converted into an electrical signal and amplified through a TIA. The proposed initial solution scheme is presented in Figure 3.

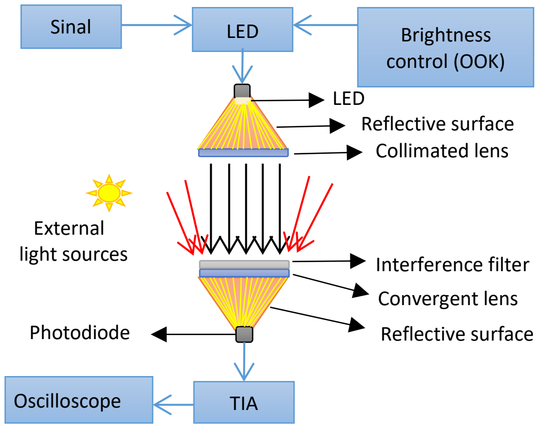

Figure 3 - Proposed solution design.

B. *Theoretical analisys*

Three situations were considered. The first case corresponds to the situation were a collimated lens is not used, resulting in flux dispersion in a constant way, according to the opening angle of the LED (Figure 4). In the second case (Figure 5), to minimize dispersion a lens is used, concentrating the flux at the output of the LED in a giver diameter. In the last situation, the effect of the received power is analysed (Figure 6). In all situations the noise that would be introduced by external light sources is not considered.

- **Situation 1 – Divergent beam:**

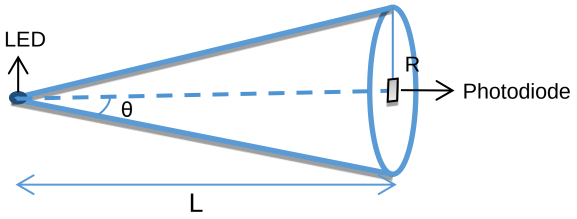

Figure 4 - Situation when a lens is not used.

In Figure 4, R is the radius of the illuminated surface, L is the distance and θ corresponds to half of the angle of the total aperture. R is given by:

$$R = L\tan(\theta) \qquad (1)$$

Considering the power emitted in the LED (P_e) and the air absorption coefficient (α), it is possible to obtain the intensity of radiation at a distance L, being given by:

$$I_r = \frac{P_e}{\pi R^2} e^{-\alpha L} \qquad (2)$$

Considering that the PIN photodiode has a certain area (A_f) it is possible to obtain the received power on his surface at a certain distance:

$$P_r = I_r A_f \qquad (3)$$

In this case the photodiode lies in the centre of the circumference aligned with the emitter, with the angle φ = 0 °. Considering the radiation pattern, the relative luminous intensity for this angle has the value of 100% and does not change the result. Seeing the atmospheric absorption effect ($\alpha = 0.001$ m^{-1} [17], with L = 2 m, using the white LED shown in the previous section (with P_e = 1.03W and θ = 60 °) a PIN photodiode (PD70-01B TR7) with an active area of 4.4x3.9 mm^2, we obtain the values presented in Table 1.

Parameter	Value
R	3.46 m
$\boldsymbol{I_r}$	0.03 W/m^2
$\boldsymbol{P_r}$	0.47x10^{-6} W

Table 1 - Obtained values for situation 1.

- **Situation 2 – Collimated beam:**

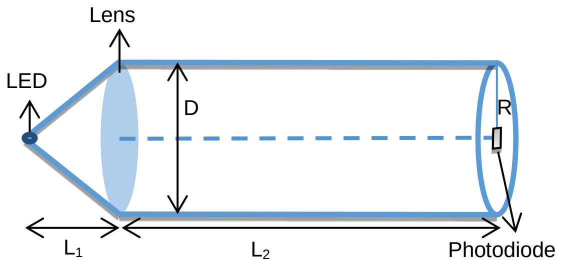

Figure 5 - Solution when a collimated lens is used.

Considering that the distance L_1 is very small (L_1 = 5 cm), we can discard the exponential factor in equation 5. The radiation intensity at distance L_1 is given by:

$$I_e = \frac{P_e}{\pi R^2} \tag{4}$$

With the use of lens, the light keeps concentrated inside the diameter D. To obtain the radiation intensity at distance L_2 (I_r) we only must consider the atmosphere absorption effect. I_r is given by:

$$I_r = I_e e^{-\alpha L_2} \tag{5}$$

As considered in situation 1, the photodiode is in the centre of the circumference. In the radiation diagram the angle φ = 0º and luminous intensity of 100% not changing the result. Considering L_2 = 2m and using equation 6 it is possible to obtain the received power. Taking in consideration the effect of atmospheric absorption (α = 0.001 m^{-1} [17]), using the same PIN photodiode presented in situation 1 (PD70-01B / TR7), with an active area of 4.4x3.9 mm^2 and the same white LED (P_e = 1.03 W) we obtain the results presented in Table 2.

Parameter	Value
R	0.087 m
I_e	43.71 W/m^2
I_r	43.63 W/m^2
P_r	0.75x10^{-3} W

Table 2 - Obtained values for situation 2.

In situation 2, the emitted flux is concentrated in the diameter D, the intensity of light received at the same distance is much higher when compared to situation 1. It is possible to verify that the use of lens decreases the scattered light and therefore increases the received power.

- **Situation 3 – Beam profile effect:**

Returning the example shown in Figure 4, we studied the variation in the received power but, in this case, we considered that the photodiode moves changing the angle of φ. Since we are using the same system of situation 1, we used the same distances and the same emitted power to compare with the situation where φ = 0º. The scheme used is shown in Figure 6.

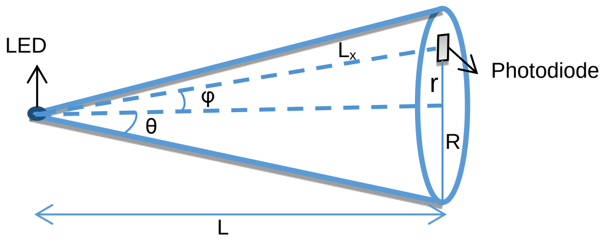

Figure 6 - Solution changing the position of the photodiode, in which a lens is not used.

For the solution presented in Figure *6* we intend to analyze the variation with the angle φ. After the analysis of the radiation path of the white LED, we considered 3 different situations: φ = 0º, φ = 30º and φ = 60º. For the first case where the angle φ is nonzero, the received power corresponds to the value of the light intensity when φ = 0º multiplied by the relative luminous intensity (RLI) of the corresponding angle. For the white LED, L = 2m, with the same emitted power (P_e = 1.03 W) and emission angle (θ = 60°), considering the atmospheric absorption effect (α = 0.001 m^{-1} [17]) and the PIN photodiode used in the first situation (A = 4.4x3.9 mm^2), we obtain the values presented in Table 3.

Angle φ	R	r	L_x	RLI (%)	I_r	P_r
0º	3.46 m	0 m	2 m	100	0.03 W/m^2	0.47x10^{-6} W
30º	3.46 m	1.15 m	2.3 m	80	0.024 W/m^2	0.41 x10^{-6} W
60º	3.46 m	3.46 m	3.97 m	40	0.012 W/m^2	0.21x10^{-6} W

Table 3 - Variation of the received power when the position of the photodiode is changed.

The results in Table 3 show that when the photodiode moves away from the central axis, the received power decreases significantly, according to the radiation pattern of the LED. In this situation, for the angle φ = 30º, the received power decreases around 20%, while in the most extreme situation (with φ = 60º) the received power decreases approximately 60% when compared to the situation with φ = 0º.

C. *Smarthphone Camera as a Li-Fi receiver*

In this situation a smartphone camera is used as a receiver. The system studied is shown in Figure 7. The signal was generated in Matlab, with a certain sampling frequency, and then sent to the Adalm1000. The final connection is made using an LED driver (model T-Cube LEDD18 ThorLabs) that allows to drive the current to the LED. Capture is done using an application that allows to detect the light intensity that the camera receives and how this intensity changes. The application is called *Luximetro* and allows to maximum acquisition of 10 values per second, being limited by the characteristics of the camera. The application allows to export the acquired data to a text file (.txt). Figure 8 outlines the process used in demodulation. The modulation used was OOK (On Off Keying) and the signal can be demodulated analyzing the average levels captured and determining if the intensity values are above or below a certain limit value. With this method its possible to decode the received signal. If the sample studied shows an intensity level higher than the average value, it corresponds to a bit ‘1’, otherwise it is a bit ‘0’. The process is repeated for all sample sets and the signal is decoded.

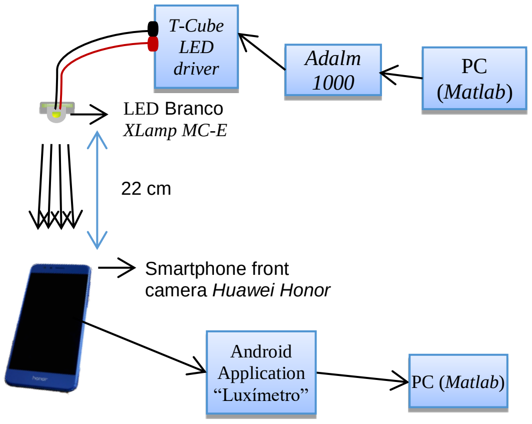

Figure 7 - Circuit diagram used for the situation where the front camera is used as a receiver.

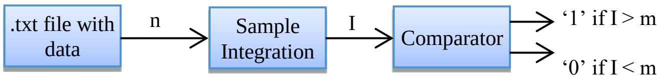

Figure 8 - Demodulation process used, when we use the front camera as a receiver.

This solution allows to use the smartphone as a Li-Fi receiver, without having to change the Hardware of the smartphone. On the other hand, the camera used has some limitations, making the transmission rate theoretically lower.

D. *Photodiode as a Li-Fi receiver*

To remove the limitations imposed by the camera, a photodiode is used. The photodiode allows the light to be transformed into electric current, making possible to acquire a higher value of samples when compared with the camera that is limited by the maximum number of frames that can acquire per second. Figure 9 shows the proposed system for this situation. Using Matlab, is generated a signal with a certain sampling frequency. Adalm1000 has a fixed sampling frequency of 100 kHz. The signal sent through the converter is then modulated in the LED driver, which connects the LED and the Adalm1000. The emitter ends with the LED that uses light to send the signal that is received by the photodiode. As in the previous example, the intensity received of each sample set is analyzed. If its value is higher than the average, then it corresponds to the logical value ‘1’, otherwise the value ‘0’ is assigned in the decoding. The demodulation process is shown in Figure 9. This process is repeated for all sets of samples until it is fully decoded.

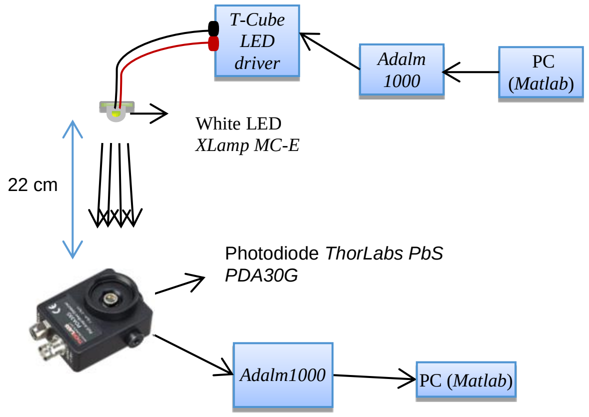

Figure 9 - Circuit diagram used for the situation where the photodiode is used as a receiver.

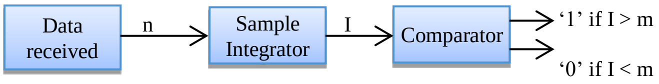

Figura 10 - Demodulation process used when we use a photodiode has a receiver.

A Li-Fi system can be used for illumination and data transmission. It is essential that variations that are used to send information can not be distinguish. The distinction reason analyzes the difference between the presented power in bit ‘1’ in relation to bit ‘0’. This concept is presented is in equation 9, where P_1 and P_0 correspond respectively to the power associated with bit ‘1’ and bit ‘0’. The intention is that the difference of this two power be the minimum possible.

$$ER = 10log(\frac{P_1}{P_0}) \qquad (6)$$

E. *Transmission using Color-Shift Keying modulation*

Using the white led it was shown that through the intensities it is possible to demodulate the signal. Generating three signals simultaneously makes it possible to transmit in the same signal three times the number of samples. The front camera has some limitations, the alternative is to use the back camera that enables 60 fps. The scheme used in this situation its presented in Figure 11. The signal that is placed on the green color is generated in Matlab and transmitted through the Adalm1000. This device as a fixed sampling frequency, that allows to send up to 100k samples per second. The signal is then modulated through the T-Cube LED driver and sent to the RGB LED. The signal for colors Red and Blue were generated using two signal generators, with different frequencies for each color. In the receiver the signal is captured using the back camera, which through video allows to capture the intensities. Figure 12 outlines the process used in demodulation. The process allows to see if in a given frame, the intensity of each of the received colors corresponds to a bit ‘0’ or ‘1’. To make this distinction is made an analyze of the average value of each of the colors throughout the entire video. If the average intensity of the analyzed color present in each frame is greater that this level, it corresponds to a bit ‘1’, if its lower it is a bit ‘0’. The process is repeated for all the frames and the colors that make up the video and becomes possible to decode the received signal that corresponds to each color.

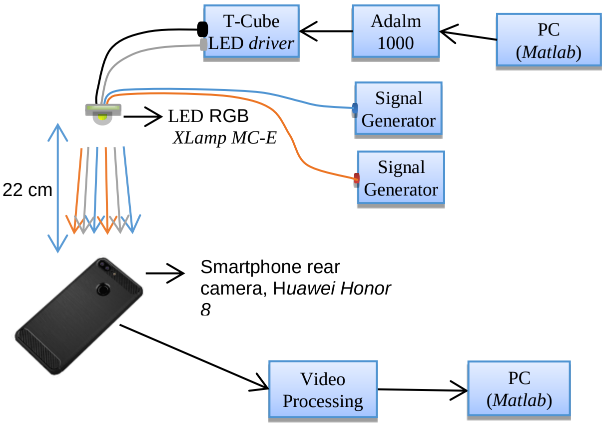

Figure 11 - Circuit diagram used for the situation where a RGB LED is used, with a smartphone rear camera as a receiver.

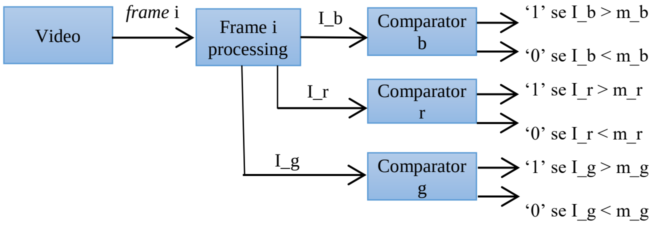

Figure 12 - Demodulation process scheme when a RGB LED is used as a emitter.

F. *RGB Matrix*

By analyzing independently the signals with blue, green and red colors, we can conclude that there is a component of each of the RGB colors always present. Thus it becomes possible to obtain the total intensity of color in each analyzed LED, separating each of the 3 colors. The present RGB components can be described by the following equations:

$$S_B = b_1\hat{B} + r_1\hat{R} + g_1\hat{G} \quad (7)$$

$$S_R = b_2\hat{B} + r_2\hat{R} + g_2\hat{G} \quad (8)$$

$$S_G = b_3\hat{B} + r_3\hat{R} + g_3\hat{G} \quad (9)$$

Using equations 10, 11 and 12 it is possible to construct a matrix model that allows to understand the RGB component that is present in each of the LEDs studied. In these equations, b_x, r_x and g_x are the percentage of blue, red and green color present in each of the individually studied LEDs. The parameters $\hat{B}$, $\hat{R}$ and $\hat{G}$ are the intensity present each of the colors when we transmit the three colors simultaneously. To characterize a system that uses RGB colors for transmission we can used the matrix S (equation 13).

$$S = \begin{bmatrix} b_1 & r_1 & g_1 \\ b_2 & r_2 & g_2 \\ b_3 & r_3 & g_3 \end{bmatrix} \begin{bmatrix} \hat{B} \\ \hat{R} \\ \hat{G} \end{bmatrix} \quad (10)$$

To obtain the parameters that allow to fill the matrix S, a medium was used where the external light interference was minimal, placing the system in a dark room. A certain voltage is assigned to each of the LEDs, corresponding to the same intensity value for the three colors. Voltage value V_1 corresponds to bit '1' and $V_0 = 0$ V to the logic value '0'. In this situation we are using the smartphone camera, so the intensity is the average of the color intensity present in the pixels of each frame. Using Matlab, studing the different frames of the received signal, it is possible to analyze the intensity of each color and thus understand the corresponding percentage in the signal that is captured. It is necessary to perform the test for each of the LEDs separately, to make possible to fill each line of the matrix. The circuit used is presented in Figure 11, but in this case we transmit one signal at a time. To avoid saturation in the smartphone camera, the intensity value set for the three LEDs was 6.3 mW at a distance of 22 cm. The applied voltage for each LEDs are presented in Table 4.

LED	V_0	V_1	Frequency
Blue	0 V	5.3 V	2 Hz
Green	0 V	0.06 V	0.5 Hz
Red	0 V	5.1 V	1.2 Hz

Table 4 - Applied voltage for each LED to obtain the Matrix S parameters.

In Table 4, the voltage applied to the green LED is much lower than the others colors. This happens because of the LED driver, that amplifies the signal and allows the same intensity that the output of the green LED. For these situations it was possible to obtain a graph (Figure 13) which describes the intensity of each of the colors over the time in the receiver.

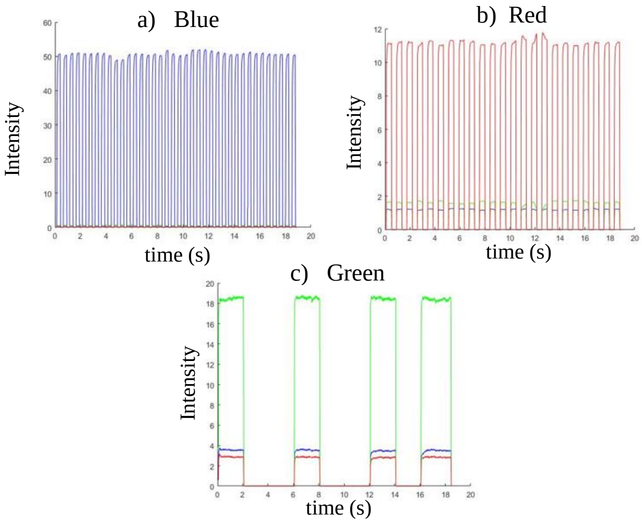

Figure 13 - Average intensity received from each of the colors over time. a) Blue, b) Red and c) Green.

In Figure 13, since the only relevant situation is where the applied voltage is maximum, we chose to study the time interval between 6 and 8 seconds. For a scale between 0 and 255 we obtained the values presented in Table 5.

LED	b_x	r_x	g_x
Blue	50.7	0.4	0.6
Red	1.2	11.2	1.6
Green	3.5	3	18.5

Table 5 - Obtained intensity for the three colors.

Normalizing the values presented in Table 5, we obtain the entries of the Matrix S. This values are presented in Table 6 and equation 14.

LED	b_x	r_x	g_x
Blue	0.98	0.01	0.01
Red	0.09	0.82	0.09
Green	0.14	0.12	0.74

Table 6 - Normalized intensity values for the three colors.

$$S = \begin{bmatrix} 0.98 & 0.01 & 0.01 \\ 0.09 & 0.82 & 0.09 \\ 0.14 & 0.12 & 0.74 \end{bmatrix} \begin{bmatrix} \hat{B} \\ \hat{R} \\ \hat{G} \end{bmatrix} \qquad (11)$$

Analyzing the obtained matrix S, there is a higher percentage in the diagonal of the matrix, corresponding to the visible RGB colors. Although in a smaller number, it is possible to notice that there are also components corresponding to the two remaining colors presented in each row.

IV. EXPERIMENTAL RESULTS

A. *Results with Smartphone*

Using the application *Luximetro* (developed by Crunchy ByteBox, available for Android devices on Google Play and the front camera as a receiver, the first experiment was carried out. The signal generated in Matlab is presented in Figure 14, corresponding to the 9-bit sequence 100100101. Each bit has a duration Tb = 2s with 100k samples generated per second.

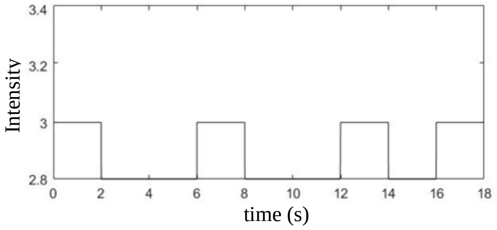

Figure 14 - signal sent to the emitter through Adalm1000.

Due to the limitation imposed by the smartphone camera, the capture is limited to 100 samples per second. In this case we decided to adjust to 3 samples per second, since above this value the application presented some failures. For a distance of 22 cm, it was possible to obtain a constant sampling rate in the receiver. The samples received over the time are presented in Figure 16. In the first analysis the samples were normalized simplifying their analysis. The result is presented in Figure 16.

In the received signal we can see some slightly overlapping symbols. This happens because of the application, that in some cases does not make a capture and reading in constant time intervals. Even this it is possible to decode successfully the received signal, that is presented in Figure 17.

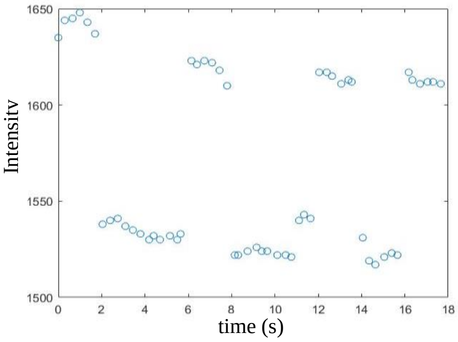

Figure 15 - Captured samples using the front camera and the application *Luximetro*.

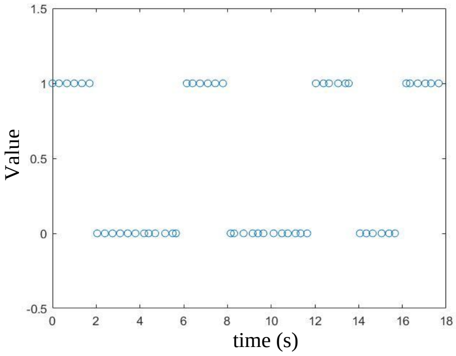

Figure 16 - Normalized samples after analysis and intensity comparing.

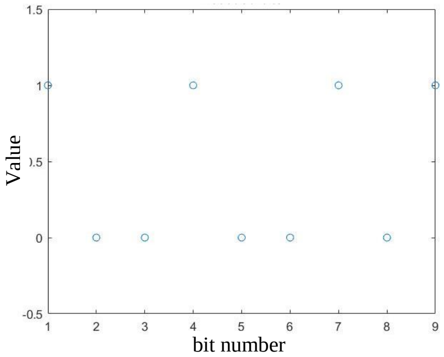

Figure 17 - Binary message received after demodulation.

The result presented in Figure 17, shows that the number of samples is reduced and it is only possible to use in very simplified situations, where only a few bits are required. This limitation happens due to the resources that were available for this teste, since the application and the camera used to measure the intensities, imposed some limitation in the maximum transmission rate.

B. *Results with Photodiode*

To overcome the limitations imposed by the smartphone camera, in this situation we used a photodiode (ThorLabs PbS PDA30G) . This receiver allows to increase the transmission rate and analyze different situations associated with a Li-Fi transmission. In this simulation we used the White LED. Analyzing the Datasheet of this LED we conclude that for an applied voltage of 3-4 V it is possible have a good operation.

To calculate the received power at a distance of 21 cm, we used a photo detector (IF-PM200) which has a reception area of 1 cm^2. The area of the receiver used in this case is 9 mm^2. By calculating the corresponding value to this dimension, using the results from the photodiode with 1 cm^2 we obtained the results presented in Table 7.

For the results presented in Table 7, it is possible to calculate the distinction ratio. Using equation 9, whit P_0 = 0.1962 mW and P_1 = 0.284 mW a ER = 1.025 is obtained. This value is considered acceptable for the system used.

To understand the behavior of the proposed system, we studied the error evolution as the transmission rate increases. By gradually increasing the transmission rate, the graph shown in Figure 18 was obtained. For transmission rates up to 1175 bit/s it is possible to obtain a BER of less than 1/1175. After this value has the transmission rate increases, the BER also increases, being within acceptable values ($<10^{-3}$) up to 1185 bit/s.

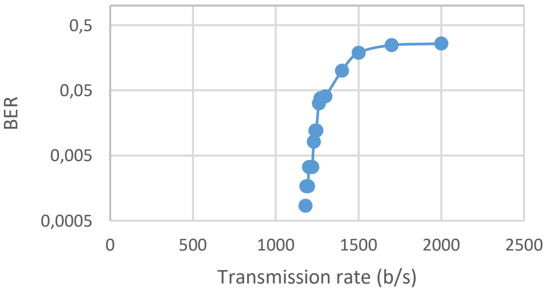

Figure 18 - BER evolution as the transition rate increases, with d = 21 cm.

To understand how the received power influences the quality of the received signal we studied the BER evolution with the received power. The transmission rate used was 2 kbit/s, since in the previous analysis the acceptable values approached this limit. With distances of less than 6 cm, the photodiode showed some saturation, so we decided to studied values between 6 and 21 cm. Varying the distance of the photodiode in intervals of 1 cm we obtain the graph shown in Figure 19.

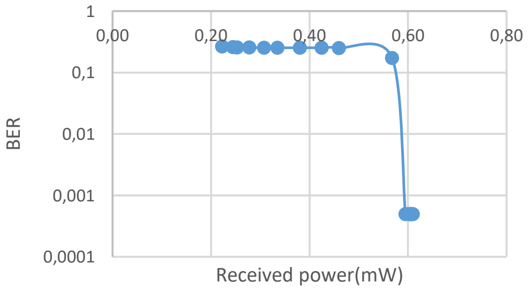

Figure 19 - BER evolution with received power variation.

Figure 19 shows that as the distance increases, the power received in the photodiode decreases. For values above 11 cm BER becomes to high, retching values that are not considered acceptable for transmission ($>10^{-3}$).

To understand the highest transmission rate that this photodiode can achieve we studied the BER evolution as transmission rate increases. The selected distance was 7 cm, because for values below 6 cm the photodiode saturates. We started the test with a transmission rate of 2 kbit/s since the BER has a value lower than 0.0005 in this case. The obtained results are presented in Figure 20. The result shown note that is possible to have a transmission rate up to 10 kbit/s with a BER below 0.0001. Since the Adalm1000 is limited to 100 kHz, this value is considered quite satisfactory.

Parameter	Applied voltage	Received power (1 cm²)	Received power (9 mm²)
V_1	4 V	2.76 mW	0.2484 mW
V_0	3 V	2.18 mW	0.1962 mW

Table 7 - Received power for the applied voltage in bits '0' and '1', for a receiver with 1 cm^2 and 9 mm^2.

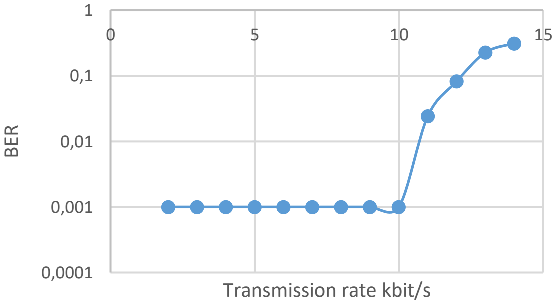

Figure 20 - BER evolution with the increase of transmission rate, for a fixed distance of 7 cm.

To evaluate the quality of the signal received at 10 kbit/s the eye diagram to this transmission was obtained (Figure 21). The result shows that it has a width of approximately 0.025 s. In this situation, ate about 0.04 s we have an approximate height of 0.00625 V, which corresponds to the system noise margin. Finally, by analyzing the shape of the eye diagram, the signal appears to be non-distorting, verifying the good quality of the received signal.

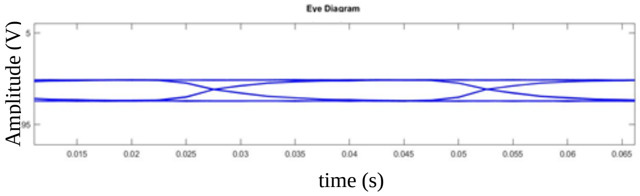

Figure 21 - Eye diagram for a 10 kbit/s transmission rate, d = 7 cm and n = 400.

C. *Results using a RGB LED as emitter*

To increase the transmission rate, it was decided to use a RGB system. To better distinguish the transmitted signals, we used different working frequencies for the three LEDs. The voltages of the three LEDs were adjusted to obtain a maximum intensity of 7.2 mW. The minimum voltage applied corresponds to an intensity of 5.9 mW. The data used this situation is presented on TABLE X. As explained before, the lower voltage value used on the green LED is related with the LED driver used.

LED	V_0	V_1	Frequency
Blue	0.78 V	0.86 V	2 Hz
Red	0.78 V	0.86 V	1.2 Hz
Green	0.06 V	0.08 V	0.5 Hz

Table 8 - Voltage and frequencies used for the RGB system.

To understand the influence of the external light sources in this system, two studies were made using the same values presented in Table *8*. In this first experience we started with a test were the external light interference was reduced using a dark environment. Using the diagram presented in Figure 11, for this first situation we obtain the signal presented in Figure *22*.

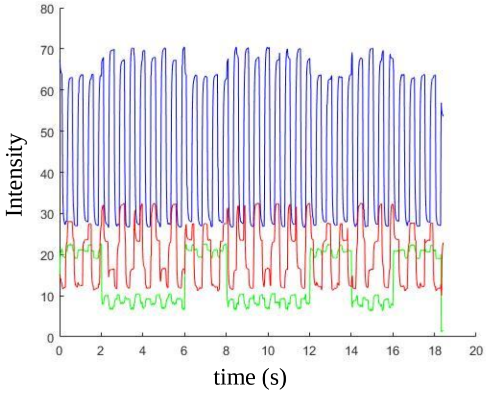

Figure 22 – Signal received for the RGB system, when a dark environment is used.

Since the three signals are sent in different frequencies, it become possible to distinguish the three signals. In the blue signal we can see a oscillation in the intensity. This situation occurs due to the frequency of the electric current. Through an individual analyses using the methods described in section 3.F, it is possible to demodulate the received signals. The resultant signals are shown in Figure 23.

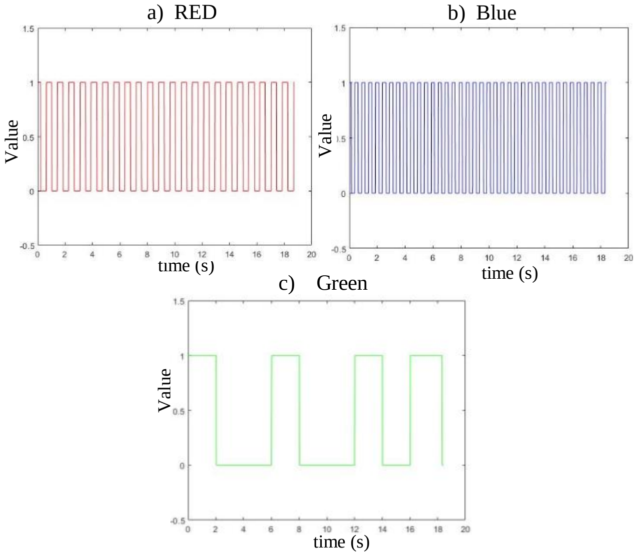

Figure 23 - Demodulated signals received using the RGB system, in a dark environment.

To understand the influence of external light sources in the results and compare with Figure 23, a second test was performed. In this situation the environment used corresponds to the room with natural light. Using the same values presented in Table 8 the results presented in Figure 24 were obtained.

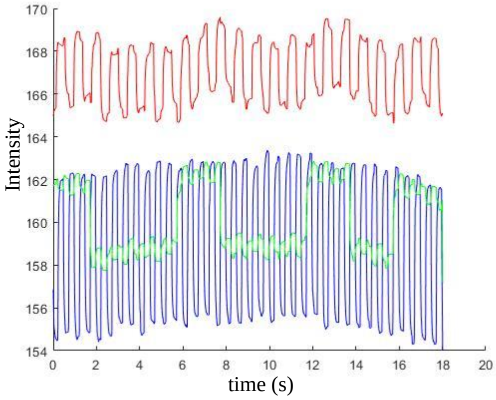

Figure 24 – Signal received for the RGB system, when a natural environment is used.

In Figure 24 it can be seen that the received signal has intensity levels much higher when compared with Figure 22. This situation is due to the presence of external light, which makes the intensity levels received higher. Despite this difference it is possible to demodulate this signal. Appling the methods presented in section 3.F we obtain the same result described in Figure 23. Although there is presence of external light, only a variation in the received color intensity becomes visible. The received signal does not change, making possible to demodulate and obtain the signal that has been transmitted.

To analyze the matrix presented in equation 14, and in order to compare with the two previous tests, three signals were simulated. Since this is a simulation and there is no problems related with saturation in the receiver, the same voltage was applied to the three colors. The values used for this situation are presented in Table 9. Using this values, combined with Matrix S, it is possible to simulate the received signal. The result of this simulation is presented in Figure 25.

LED	V_0	V_1	Frequency
Blue	2.8 V	3 V	2 Hz
Red	2.8 V	3 V	1.2 Hz
Green	2.8 V	3 V	0.5 Hz

Table 9 – Used values for the simulation through Matrix S.

In Figure 25 is possible to understand the influence that the three colors have with each other. Comparing with Figure 22, although with different intensities, the three received signals have the same shape. Using the same modulation method applied in the two previous situations we obtained the same signal presented in Figure 23. This shows that the Matrix S is able to predict how the signal will be after being received at the receiver.

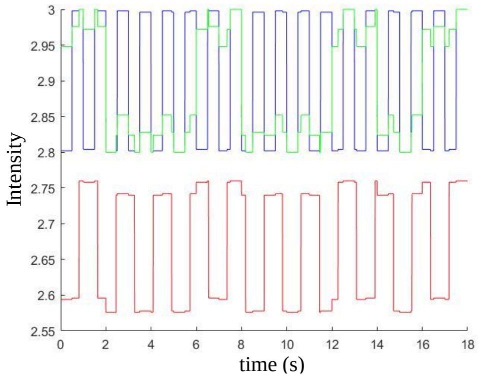

Figure 25 - Signals obtained through simulation with Matrix S.

V. CONCLUSIONS

VLC systems are an alternative to the technologies that we currently use for transmission. Li-Fi is considered an emerging technology that will help complement the existing systems such as Wi-Fi.

Using a mobile phone front camera combined with an application that analyze the received light intensity we concluded that it is possible to receive data through a camera. This camera and the application used imposed some limitations on the transmission, reducing the number of samples received to three per second.

In the system using a photodiode with a reduced area of 9 mm^2 we conclude that it would be possible to receive at a distance of 21 cm, a transmission rate of 1185 b/s. By changing the received power, we show that to obtain an error rate lower than 10^{-3}, the received power needs to be higher than 0.6 mW. It has also been shown, for 7 cm that is possible to make a transmission with a transmission rate of 10kbit/s. Since intensity modulation has been used, we conclude that this value is considered acceptable, since the Adalm1000 is limited to 100 kHz.

The third system tested used three colors simultaneously to send information. We conclude that that its possible to transmit and demodulate the information transmitted simultaneously, using a cellphone back camera. The simultaneous use of three LEDs allows to transmit three more times information, besides being able to be used as illumination. The cellphone back camera has proved to be a valid alternative to operate as receiver

In conclusion, the three systems presented allowed the operation of a Li-Fi system. In situations were the existing cameras were used as receivers, we concluded that, data transmission is possible without changing existing systems. The photodiode allowed a much higher transmission rate, but requires installation and adaptation in systems current systems.

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