Three-Dimensional Spatial Coding Based on Hybrid Pulse Width and Pulse Position Modulation for Simultaneous Data Transmission and Brightness Control on RGB LED Arrays

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***Abstract*—A three dimensional (3D) spatial coding scheme is proposed for simultaneous control of illumination and data transmission in a Visible Light Communication (VLC) system with RGB LEDs arrays . The proposed and experimentally tested coding is based on hybrid Multi-Pulse Position Modulation (M-PPM) for data encoding, in which the number of pulses (slots) control the amount of current delivered to the LED such as the Pulse Width Modulation (PWM). The implemented VLC system complies with the dual functionality, indoor lighting and data transmission, also proposes an alternative solution for the problem of the interdependence between the speed of data transmission and the variation of the levels of illumination. In this paper, the feasibility of implementing the proposed scheme using low cost elements and using digital demodulation is demonstrated. A constant transmission speed of 6 Kbps was obtained with two 10W RGB LEDs at 0.9 meters from the OPT101 photodetector of Texas Instruments, with a range of illumination ranging between 25% and 85% of the possible light power of the sources LED.**

***Index Terms*— Control of illumination, RGB LEDs, M-PPM, PWM, VLC**

I. Introduction

The Optical Wireless Communication (OWC) is an application of Visible Light Communication networks (VLC) for indoor use, allowing in short time the implementation of Internet of Things (IoT) services [1]. For this purpose, standards on acceptable levels of illumination and simultaneously high data rates must be provided for a variable number of users and devices. In fact, the design of IoT technologies deals with remarkable challenges to achieve an adequate level of Quality of Service (QoS), like the great amount of unregulated bandwidth, the use of low complexity intensity modulation techniques with direct detection (IM/DD) and the absence of interference with RF systems. Therefore, the support of VLC systems have been put at the forefront of this type of wireless access technology. [1], [2]. Nonetheless, a VLC system could enable an efficient and manageable wireless connectivity (for all devices in the network), coming together with the sustainable power consumption and fast reconfiguration in heterogeneous environments; so an intelligent indoor lighting setup can be implemented to achieve significant reductions in power consumption energy and productivity gain [3], [4]. To date, VLC techniques are based on Solid State Lighting (SSL) devices, focused mainly on achieving high data transmission rates in the order of gigabits per second (Gbit/s) [5]. Transmission speeds of 3.4 Gbit/s, and 10 Gbit/s have been reported for light sources based on Light Emitting Diodes (LEDs) and Laser Diodes (LD), the latter with modulation bandwidth that surpasses the hundreds of MHz than the offered by the former. Moreover, the addition of Color Shift Keying (CSK) modulation scheme on the operation of LEDs and LDs gives remarkable improvement in the data rate, allowing narrow-band operation at different wavelengths where each chromatic channel (Red-Green-Blue) are separetely modulated by intensity [5]. So, a correct CSK design on RGB-SSL (either LD or LED) gives a synthesized ”white” light, emulating indoor lighting. However, there are limitations in the quality of the illumination for most tested VLC system designs [4]. To cope with these limitations, reduction of flicker by maintaining standardized high data transmission speeds could obtain satisfactory human-perception levels of illumination guaranteeing the role of VLC systems in wireless networks. An automatic brightness control reduces flicker occurrence, using

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Pulse Width Modulation (PWM) technique. The main feature of this control is the simplicity of the duty cycle variations, proportional to the percentage of attenuation required [5], [6]. At the end, hybrid PWM/Variable Pulse Position Modulation (VPPM) scheme reduces lighting saturation levels [7]. This combined use of the PPM and PWM technique has been proposed in other works for the control of luminosity and the simultaneous transmission of data, leading to cases where the PPM signal over the PWM pulse is superimposed with a 50% duty cycle [6]. However, it does not give brightness control options since the detection of the PPM pulse position is difficult when the percentage of the useful cycle is changed. Fig. 1 shows the PPM pulse added to the PWM one [8], with a PPM pulse width of 5.0 S within a slot period of 50.0 μS and the period of PWM signal 1.0 mS.

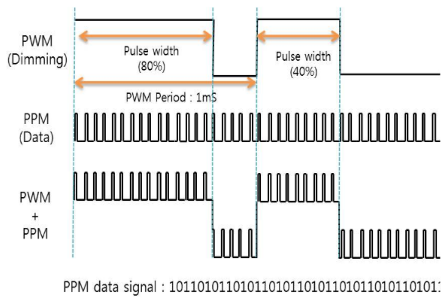

Fig. 1. PPM-PWM signal format in [8].

In this work we propose a novel three dimensional (3D) spatial coding scheme using power RGB LEDs for simultaneous control of illumination, and data transmission in a Visible Light Communication (VLC) system. The proposed and experimentally tested encoding and decoding, combines the benefits of the PWM modulation for the control of the brightness, and Multi-Pulse Position Modulation (M-PPM) coding without superposition for the creation of data words in a same bit frame.

In the proposed encoding the amount of slots in high state over the time of symbol, control the amount of current delivered to the LED (as it happens in PWM). The system was assembled and tested using low cost components such as Arduinos Uno and commercial power RGB LEDs.

At the receiver side, once the VLC signal is digitized and store, the off-line digital signal processing is applied. The demodulation consists of four main stages: *i)* smoothing to remove the noise, *ii)* sampling and thresholding to determine the slots in high state contained in the signal, *iii)* extraction of the M-PPM pattern and *iv)* data recovery.

The proposed digital demodulation allows implement a MISO system (transmission diversity), since data are transmitted redundantly from different transmitters because the system is composed of several RGB LEDs where each color channel is a transmitter and the same channel in each of the LED, transmit the same data. The receiver receives the signal in an additive way, which can be used for the extraction of the required data.

The proposed modulation scheme uses the theory underlying the PWM technique and the M-PPM coding for data transmission by visible light, in order to achieve two main purposes: lighting control based on the variation and rate of independent transmission of the luminous intensity.

II. Coding and Brightness Control

A. Lighting control

The most efficient way to perform the luminosity control in LEDs, is the Pulse Width Modulation (PWM). During the ON cycle in the PWM pulse, the LED work at the Voltage-Current recommended operating point, ensuring that variations in the Correlated Color Temperature (CCT) are within the parameters of the data sheet.

There are two modes for implement PWM: Balanced Mode and Mark Space Mode. The difference between these two modes is the timing sequence of voltage high and low values that are transmitted.

In Mark Space Mode, the time of high voltage is a single and continuous at the beginning of the cycle. The Duty Cycle D (ratio between pulse duration and the signal period) of the PWM signal, determines the average current and, therefore, the perceived brightness (Fig. 2a).

With Balanced Mode, the high voltage time is multiple and are distributed over an entire cycle (Fig. 2b).

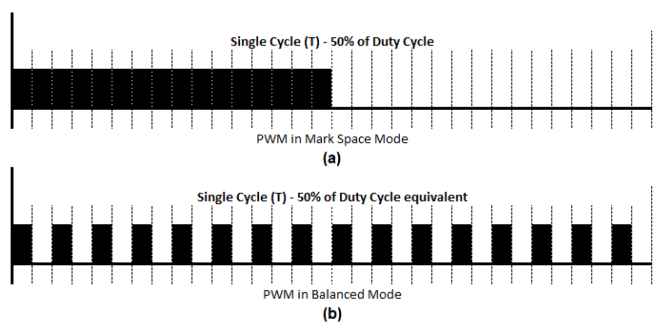

Fig. 2. (a) PWM in Mark Space Mode. (b) PWM in Balanced Mode.

B. M-PPM Coding for Symbols Representation

In the Multi-Pulse Position Modulation coding (M-PPM), we have a symbol time (t_s) divided in time slots where each one can have a high level (1) or low (0), the position and the number of slots in high state, determines the value of the symbol.

From the combinatorial calculation ($\frac{m}{n}$), it is possible obtain X number of symbols, where is m the number of slots into which ts is divided and the n the number of slots that will be used to represent the symbol [9]. The whole part of Log_2 ($\frac{m}{n}$) [10] indicate the number of bits that can be coded for each symbol x_i.

C. Coding Data and Signal Format

This frames digitally generated in the process system and dedicated for each of the RGB channels in the LED, have 32 slots distributed as follows: *i)* 5 slots for synchronization, *ii)*

19 used in the lighting control and, *iii)* 8 data slots, where the M-PPM coding is performed. Figure 3 shows the proposed scheme.

The generated frame and according to the amount of slots in high state in field used for dimming, acts as a PWM modulation in balanced mode (we will call it pseudo-balanced mode).

The number of slots in high state (1) in the synchronization and data parts is always the same. Slots for brightness control, allow to vary the luminous intensity of the LED between 25% (0 slots in high state) and 84.375% (19 slots in high state), in combination with the slots of synchronization and data.

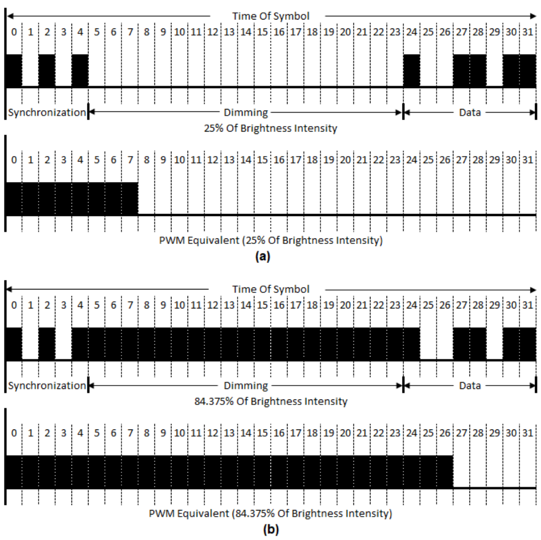

Fig. 3. For the same data: (a) 25% of Brightness Intensity. (b) 84.375% of Brightness Intensity.

D. Calculation of T_S (symbol period)

The minimum T_S symbol period is determined by the maximum frequency at which the LED can operate (modulation rate). The maximum modulation rate is measured between 10% and 90% of the light intensity. The above means, that the rate or modulation ratio for the LED, must consider t_r (rise time) and t_f (fall time), thus:

$$t_\gamma > t_r + t_f \quad (t_\gamma = minimun\ time\ slot) \tag{1}$$

For 32 slots the symbol time T_S must be:

$$T_S > 32 t_\gamma \tag{2}$$

E. Coding

In M-PPM (with $M = 5$) over eight slots it is possible to obtain 56 symbols, with symbol length of $L(x_i) = 5$ bits. to minimize the probability of error, we choose 32 symbols (out of 56 possible) that maximize the distance between adjacent symbols, for which the following code we conveniently chosen (Table I).

In the previous code the distance $(d_{i-1}, d_i) = (d_i, d_{i+1}) = 4$.

TABLE I
TABLE OF EQUIVALENCE BETWEEN BIT PATTERN AND M-PPM FORMAT PROPOSED

Bit Pattern	Code in M-PPM Format							
00000	0	1	1	1	0	1	1	0
00001	0	0	0	1	1	1	1	1
00010	0	1	1	0	0	1	1	1
00011	0	1	1	1	1	0	1	0
00100	1	0	0	1	1	0	1	1
00101	1	1	1	0	0	0	1	1
00110	0	0	1	1	1	0	1	1
00111	0	1	0	1	1	1	1	0
01000	0	1	1	0	1	0	1	1
01001	1	0	0	0	1	1	1	1
01010	1	0	1	1	0	1	0	1
01011	1	1	0	0	1	1	0	1
01100	1	1	1	1	0	1	0	0
01101	0	1	1	0	1	1	1	0
01110	1	0	1	0	1	0	1	1
01111	1	1	0	1	0	0	1	1
10000	1	0	0	1	1	1	1	0
10001	1	1	1	0	0	1	1	0
10010	1	1	0	1	1	0	1	0
10011	1	0	1	1	0	1	1	0
10100	1	1	1	0	1	0	1	0
10101	0	1	1	1	0	0	1	1
10110	1	0	1	1	1	0	0	1
10111	1	1	0	1	0	1	0	1
11000	1	1	1	0	1	0	0	1
11001	1	0	1	1	0	0	1	1
11010	0	1	1	1	0	1	0	1
11011	1	0	1	0	1	1	0	1
11100	1	1	0	1	1	0	0	1
11101	1	0	1	1	1	0	1	0
11110	1	1	0	0	1	0	1	1
11111	1	1	1	1	0	0	0	1

The symbol speed R_S, is given by:

$$R_S = 1/(32T_\gamma) \tag{3}$$

In general, $L(X_i) = Log_2\ (\frac{m}{n})$, then the bit rate R_b equals to:

$$\begin{aligned} R_b &= R_s L \\ &= L/(32T_\gamma) \end{aligned} \tag{4}$$

The bandwidth (B_W):

$$B_W = 1/T_\gamma \tag{5}$$

The spectral efficiency (E), for the proposed model is:

$$\begin{aligned} E &= R_b/B_W \\ &= L/32 \end{aligned} \tag{6}$$

Although in the M-PPM format, a guard slot is used to minimize the ISI (Inter Symbol Interference), in this model it is not necessary because the $3/4$ parts of the frame are used for clock and brightness control (the data goes in the last 8 bits). On the other hand, in the M-PPM format all the symbols have the same energy.

III. Experimental Framework

In this section, the feasibility of data transmission and the simultaneous brightness control are verified.

The transmitter of the VLC system is composed of RGB LED, with three independent embedded systems (Arduino Uno) as an information-processing center, and a linear current regulator (driver) with inputs for PWM signal for control of the LED. For the simultaneous control of lighting and data transmission, three 32-bit frames are generated (one in each embedded system), each frame is divided into three sub-frames, one for synchronization (5 bits), one for lighting control (19 bits) and last for data (8 bits) where M-PPM coding is found. The average of generated electrical signal, is equivalent to a PWM signal of the same period and duty cycle necessary for the specified luminous intensity.

A. Transmission with brightness control

The schematic diagram of the transmitter is shown in Fig. 4. In this model, the objective is the brightness control and data transmission at constant speed, the system is composed of two parts: a transmitter and a receiver.

The transmitter is composed of a driver that manage the power of the RGB LEDs and injects, as a control signal the bit stream generated in one of the digital outputs of an embedded system and is responsible for performing the coding and "armed" of the bit pattern that make up the signal. This signal is composed of three parts: clock for synchronization, brightness control and data in inverse M-PPM format.

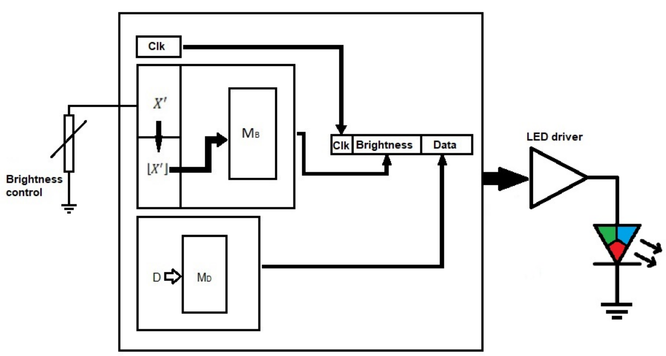

Fig. 4. Block diagram of the transmitter.

The armed of the frame of bits comprises four processes: In the first process, the brightness control is obtained by the digital analog converter which is part of the ATmega 328 system (a potentiometer makes a voltage divider to control the brightness level), this A/D converter has a resolution of 10 bits that throws values between 0 and 1023. The read value is normalized to obtain a value between 0 (25% brightness) and 19 (84.75% brightness) according to the following formula:

$$\lfloor X' \rfloor = (X' * 19)/1023 \tag{7}$$

Where $\lfloor X' \rfloor$ is the integer part, it represents a value in the brightness matrix (Table II) where synchronization pulses are always at the beginning of the bit pattern and occupy the first 5 slots. This value is stored in a variable (B) type unsigned long that occupies 4 bytes (32 bits).

In the second, the format of the symbol is obtained from the Table I, this acts as a dictionary where in the first column found the code to be sent (symbol) and in the second column, the corresponding sequence of bits in the proposed format. This sequence is stored in a variable unsigned long type of 32 bits (D), this variable has a length of 8 bits and is stored in a variable of 32 bits, leaving the highest 24 bits in zeros.

Once the previous steps have been completed, variables B and D are concatenated by operator "Or" and stored in the variable E of 32-bit, where the bit pattern corresponding to the desired brightness level and symbol to be sent.

In the fourth step, the parallel-series conversion is made that allow extract bit by bit from the frame. This conversion is carried out by successive shifts to the right in the variable E, in each shift an "And" operation with the PORTB register where only the least significant bit (associated with the D8 pin of the Arduino UNO) are in "1".

The previous operation moves the bits from variable E (bit by bit) to pin D8. The receiver (Fig. 5) is composed of: *i)* Physical color filters (lenses) to allow the passage of the radiation corresponding to the color of the filter and to block the remaining ones. *ii)* Photodetector (Texas Instruments OPT101 integrated circuit), which is composed of a photodiode and a transimpedance amplifier to capture the signal corresponding to its color channel and *iii)* decoder.

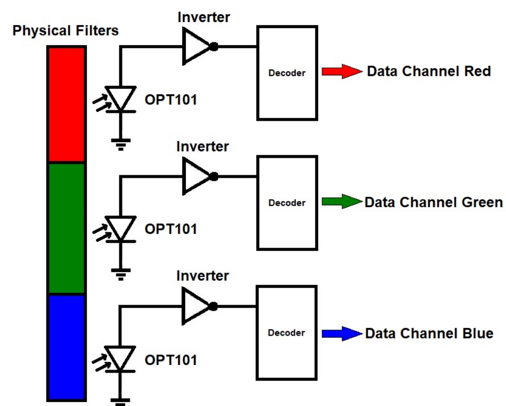

Fig. 5. Block diagram of the receiver.

The waveform measurements in the transmitter and the receiver were taken (and stored) with a virtual oscilloscope model ISDS220B, with a bandwidth of 60 MHz, and maximum sampling rate of 200 Msps (Millions of samples per second).

Each RGB LED is driven by the electrical signal generated in the embedded subsystem previous interfaced by the driver (built with N-channel MOSFETs - IRF530). The embedded subsystem is an Arduino UNO with Microcontroller ATmega 328 of 16 MHz.

IV. Analysis and Results

The results are analyzed under the following parameters: *i)* brightness levels that are represented in the RMS value of the signal, where the maximum value is 5 V (100% of luminosity) and the minimum 0 V (0% of luminosity). *ii)* The same data pattern, in order to have a constant reference that would allow verifying the exposed.

TABLE II
FRAME BRIGHTNESS WITHOUT DATA EQUIVALENCY TABLE

		Output Pattern (only synchronization and brightness, without adding the data)																															
$\lfloor X^{\backprime} \rfloor$	Brightness percentage	synchronization					Dimming																			Data in M-PPM format							
0	25 %	1	0	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	28.125 %	1	0	1	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	31.25 %	1	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	34.375 %	1	0	1	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	37.5 %	1	0	1	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	40.625 %	1	0	1	0	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	43.75 %	1	0	1	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	46.875 %	1	0	1	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	50 %	1	0	1	0	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	53.125 %	1	0	1	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	56.25 %	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	59.375 %	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	62.5 %	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	65.625 %	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	68.75 %	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
15	71.875 %	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
16	75 %	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
17	78.125 %	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
18	81.25 %	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
19	84.375 %	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0

The transmission speed achieved is 6 Kbps with brightness levels between 45.6% and 83.4%.

The analysis is done for a single channel since the results are extensive to the others.

A. Brightness and position of data in the waveform

Fig. 6 shows the waveform at the transmitter and receiver, for a 53.125% calculated brightness level, B = 10101111111111000000000000000000 (brightness pattern) and Data = 10111001. The resulting frame is 10101111111111000000000010111001.

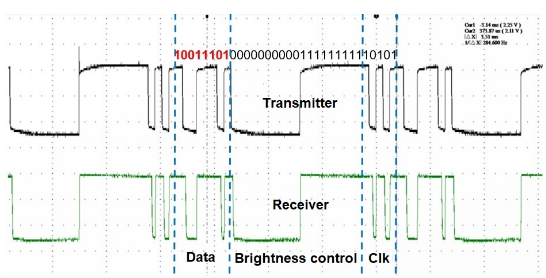

Fig. 6. Waveform for a calculated brightness level of 53.125%.

The measured RMS value in LED is 2.89 V, which is equivalent to 57.8% of brightness.

B. Down-Conversion and Three-Dimensional Constellation

The proposed modulation composed of three channels (red, green and blue) is applicable for the proposed VLC system given the inherent nature of data transmission due to the following facts:

- The multidimensional constellation is constructed with contribution of three channels in which the data is encoded.
- The sources associated to each channel (R, G and B), send different values in their data field which are mapped in their respective coordinate, thus forming a point of the 3D constellation.

The signals captured in the receivers are subjected to decoding process, where the bits corresponding to the brightness and clock control are removed according to the process (this process is same for each channel) shown in Fig. 7.

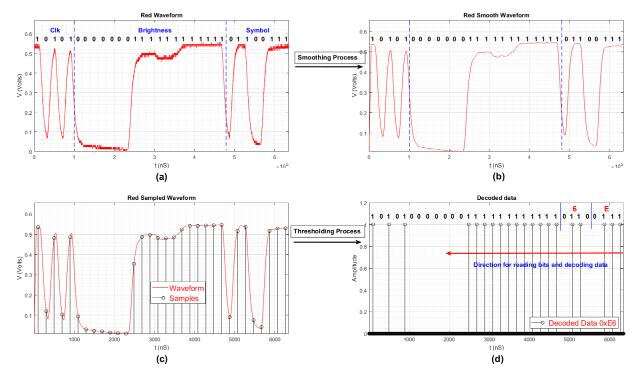

Fig. 7. *(a)* Position of the bits in the VLC received signal. *(b)* Signal after the smoothing process *(c)* Sampled signal. *(d)* Pattern of bits and data recovery

Once the signal is captured by means of a transimpedance amplifier, the following processes are carried out in order to obtain the data sent from the transmitter:

- **Smoothing process:** In this process, a moving-average filter process is applied to the signal for smoothing noisy as shown in the Fig. 7 *(b)*. High frequency components are present and must be removed in order to increase the accuracy of the demodulation process.
- **Sampling** is done by the multiplication of the analog signal present at the receiver (see Fig. 7 *(c)*) by a train of impulses whose amplitude is the unity. The goal of this function is taking samples per obtain the bits contained in the signal.
- **Thresholding** the obtained discrete signal after sampling in order to extract the pattern of bits.
- **Extraction the pattern of bits:** In this process, the values obtained after the thresholding process are saved in a vector of size 32, Fig. 7 *(d)*).

- **Data recovery:** In the data recovery, the last eight positions of the previously obtained vector are taken and an inversion process is made (the last position becomes the first and the first be the last). Then, the dot product is made with the vector $V = [128, 64, 32, 16, 8, 4, 2, 1]$ and the result is the decoded data (see Fig. 7 *(d)*).

The BER curves obtained for each channel (Fig. 8), are very close to the theoretical ones and presenting better performance than the BER calculated in low SNR values.

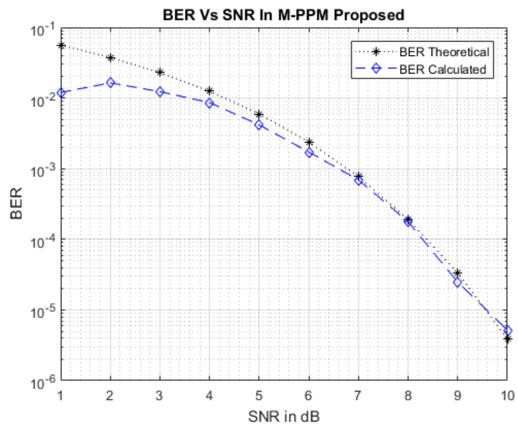

Fig. 8. Theoretical BER Vs Measured BER.

The obtained 3D data symbol is the result of two processes: *(a)* the MPPM decoding and *(b)* concatenation. The concatenation is done with the data obtained in each color channel (R, G, B) and can be represented in a three-dimension constellation (Fig. 9).

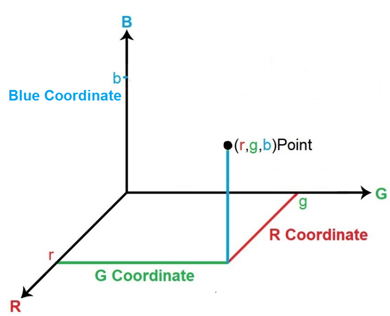

Fig. 9. Three-Dimensional Constellations in VLC.

V. Conclusion

It was proposed and satisfactorily demonstrated that it is possible to implement a system that has the dual functionality, data transmission and brightness control in a Visible Light Communications system (VLC), with the restrictions due to the elements used.

The proposed system can be implemented with low cost elements, since it does not use advanced modulation and coding techniques.

The transmission speed of the system is limited only by the quality and sensitivity of the elements used, therefore, makes it adaptable to current transmission technologies, and can reach regulatory speeds.

In the graphs of the oscilloscope, it can be observed that it is possible obtain simultaneously luminosity control and data transmission. Some of the following aspects must be take into account in relation to the equipment used to generate the bit frames (Arduino Uno).

The time of reading and conversion of the A/D input is included in the total symbol time; this process is performed within the loop used for the parallel-serie conversion of the frame.

The use of low cost elements allows this system be implemented in scenarios where technology and infrastructure are difficult to access, such as rural areas and a population with connectivity deficiencies. It could also be used in communication between cars for data exchange and security control management, aircraft entertainment and monitoring in hospitals, where electromagnetic signals can be harmful, etc.

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