Inter-Building PLC-VLC Integration Based on PSK and CSK Techniques

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***Abstract*—This paper presents the implementation of an integration technique used to combine power line communications (PLC) and visible light communications (VLC) channels in inter-building scenarios. It considers the narrow band PLC (NBPLC). Phase-shift keying (PSK) is used to convey the information over the PLC link and colour shift keying (CSK) technique is used on the VLC link. The colour wheel method is exploited to map PSK symbols to colours. We define a parameter x, which represents different magnitudes of the PSK complex symbol observed over the PLC channel. x is adjusted to an optimal value to meet the requirement of the CSK design. The bit error rate (BER) is analysed and the performance of the system is presented for multiple values of the modulus of the detected PSK symbol. A practical implementation is performed to verify the PSK-CSK mapping method. The impact of the sun's rays on the red-green-blue (RGB) symbols is analysed and the interference source is highlighted.**

***Index Terms*—PLC-VLC integration, PSK to CSK mapping, Inter building communication, PSK modulation, CSK technique, RGB colour space, RGB-LED; chromaticity.**

I. INTRODUCTION

Firstly, orthogonal frequency division multiplexing (OFDM), spread frequency shift keying (S-FSK), phase-shift keying (PSK), and quadrature amplitude modulation (QAM) are examples of applicable modulation schemes used in power line communications (PLC) technology. Secondly, visible light communication (VLC) makes it possible to use the visible spectrum for data transmission applications. It promises to transmit data at rate up to 100 Mbps. Modulation techniques such as on-off keying (OOK), variable pulse position modulation (VPPM), and colour shift keying (CSK) are used in VLC. CSK is preferably used in high data rate applications [1]. The recent successful standardisation of PLC (CENELEC EN50065-1, IEEE 1901, ITUT G.9960/61) and VLC (IEEE 802.15.7), has enabled the opportunity to consider the integration of both technologies. Basically, PLC is being considered as the logical backbone for VLC: they both share the electric power wires and they both represent a communication technology.

Various ways are proposed in the literature to combine PLC and VLC. In [2], a semi-hidden Markov modelling of a low complexity FSK-OOK in-house PLC and VLC integration is proposed. The system provides an illumination using power-saving Light Emitting Diodes (LEDs) on one side and it gains from the advantages provided by PLC technology on the other side. A novel and cost-effective indoor broadband broadcasting system based on the deep integration of PLC and VLC is proposed in [3]. The PLC-VLC system is analysed through practical implementation and prototyping to validate the PLC-VLC channel proposed model. In reference [4], a system of white LEDs is integrated with the PLC channel using binary phase-shift keying (BPSK). In [5], an interface between PLC and VLC channels using spread frequency shift keying (SFSK) on the PLC link and OOK on the VLC link for low data rate applications is proposed. A PLC-VLC cascaded channel is studied and presented in [6], it uses OFDM on the PLC channel and VLC over the VLC channel. The result shows that in a cascaded PLC-VLC channel, the performance of the system is imposed by the bad channel. Suitable channel models and noise models are proposed for PLC technology [7], [8] and for VLC technology as highlighted in [9], [10]. Both channels have impulsive noise (PLC channel) and shot noise (VLC channel). Both noise are modelled using Poisson distribution.

In this paper, we propose a system based on PSK and CSK modulation techniques to link PLC and VLC channels for inter-building applications. The CSK technique exploits the colour wheel method to map complex symbols to colours. A CSK transmitter redistributes the observed PLC symbols over the VLC channel using red-green-blue LEDs (RGB-LEDs). A parameter x based on the magnitude of the PSK received symbol is used to optimise data re-transmission. The performance of the system is analysed for different values of x and the good trade-off is obtained between optimal transmission and illumination for $x = 0.133$. We practically implement the system to validate the PSK-CSK combination method for PLC-VLC. The influence of the daylight background on the red-green-blue (RGB) channel is also highlighted.

The reminder of the paper is organised as follows: the system model is proposed in Section II. In Section III, details are given on the simulation method and results, while practical implementation issues and results are discussed in the next section. The equipment, including PLC and VLC modulators and demodulators are presented. Concluding remarks are proposed in Section V.

II. DESCRIPTION OF THE SYSTEM MODEL

The system under consideration is characterised by its capability to connect to PLC and VLC channels simultaneously. Fig. 1 depicts the communication model. The k^{th} symbol observed over the PLC channel is a PSK complex symbol given by $Z_k = a_k + jb_k$. Z_k is converted into colours using the colour wheel method. The colour wheel is a representation of complex numbers using colours [11], [12]. It uses the three colour parameters hue (H), saturation (S) and value (V). The argument of the complex number corresponds to hue H, its magnitude provides the values of V and S. In general, this method maps the complex set $\mathbb{C}$ to the HSV colour coordinates in such a way that each point $a + jb$ of the complex space is associated with the colour code $HSV(a + jb)$. H, V and S are given by

$$HSV(a+jb) : \begin{cases} H = arg[a+jb] & \text{(a)}, \\ S = 0.5 + 0.5sin(2\pi r) & \text{(b)}, \\ V = 0.5 + 0.5cos(2\pi r) & \text{(c)}, \end{cases} \tag{1}$$

where $r = log[1 + |a + jb|]$ is the radius of the wheel. A description of the colour wheel is shown in Fig. 2. The origin is chosen in such a way that +1 (0^o) and -1 (180^o) are assigned to red and cyan colours, respectively. The colours are organised by rotation of the wheel. The argument of the complex number (1-a) gives the position of the colour on the wheel. Brightness and saturation are constants for all complex symbols that have the same modulus. Later, this position is matched to the position of the PSK symbol in the constellation. Knowing that Z_k is the k^{th} PSK complex symbol observed over the PLC channel (k = 1, 2, . . ., M, M being the PSK constellation sise), we exploit the following general knowledge of PSK modulation: information in PSK is conveyed by the phase of the complex symbol Z_k, not its magnitude. This implies that the magnitude of Z_k can be altered (reduced or increased) without affecting the message conveyed. Let us denote the variation of the magnitude of PSK symbols by $x = \lambda|Z_k|$, where $\lambda \in \mathbb{N}$. We show that different values of x result in different performances of the system. Afterwards, Z_k is converted into the hue H_k, the saturation S_k, and the brightness V_k. $Z_k \longrightarrow (H_k, S_k, V_k) \longrightarrow (R_k, G_k, B_k)$, where H_k, V_k and S_k are the HSV parameters corresponding to the k^{th} symbol, and, R_k, G_k and B_k are the intensities of the red, green and blue LEDs required to produce the corresponding colour C_k.

III. SIMULATION AND RESULTS

In VLC technology, the design must always meet the constraints and requirements of a CSK constellation design. We analyse the HSV parameters and look at their influence on the illumination and communication throughput. Colour purity and brightness are calibrated by S and V, given in (1-b) and (1-c), respectively. We use the average value of 85.33% of $(S + V)/2$. 0.8533 is the maximum common value for V and S corresponding to specific values of x. This is shown in Fig. 3. Afterwards, we analyse the HSV parameters that affect the communication performance of the system. The aim is to find the best trade-off between illumination and communication. We analyse the communication system based on different values of x that provides 85.33%, common value to V and S. The simulation is divided into two parts: the first part is performed on two sets of values of x: $\mathbf{X}_1 = \{0.05, 0.075, 0.133, 0.175, 0.25\}$ and $\mathbf{X}_2 = \{0.25, 0.4, 0.65, 0.8, 0.866\}$. $\mathbf{X}_1$ and $\mathbf{X}_2$ are chosen from either side of A. A is the first upper crossing point between V and S (see Fig. 3). The values of x are chosen on the assumption that 0.79 is the threshold value of $(V + S)/2$ required to provide good lighting. The second part of the simulation looks at the performance of the communication system for the values of $(V + S)/2 < 0.79$, corresponding

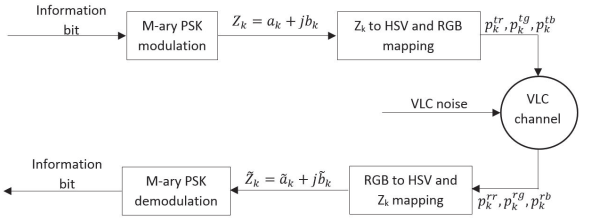

Figure 1. Communication system model for hybrid PLC-VLC (PSK-CSK) systems proposed for inter-building communications

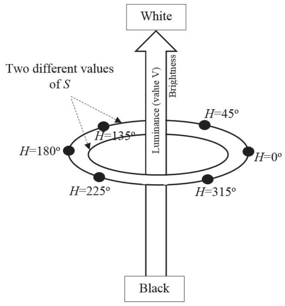

Figure 2. Description of the colour wheel principle used to map complex symbols to colours in HSV colour space

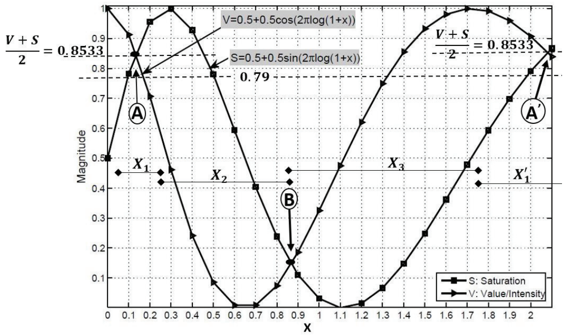

Figure 3. Variation of S and V for different values of x, highlighting the upper and lower crossing points.

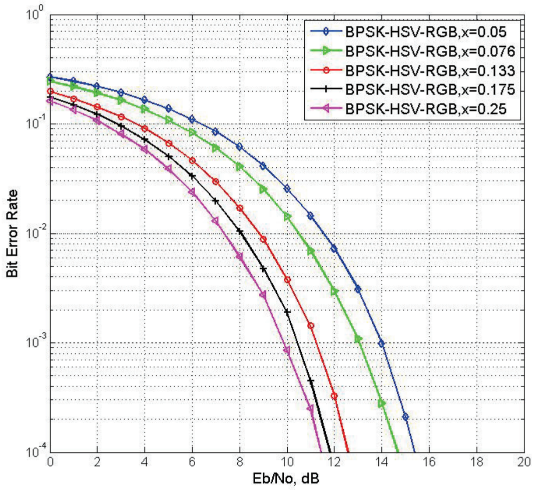

Figure 4. Performance of the Hybrid PLC-VLC (PSK-CSK) system for x = 0.05, 0.075, 0.133, 0.175, 0.25.

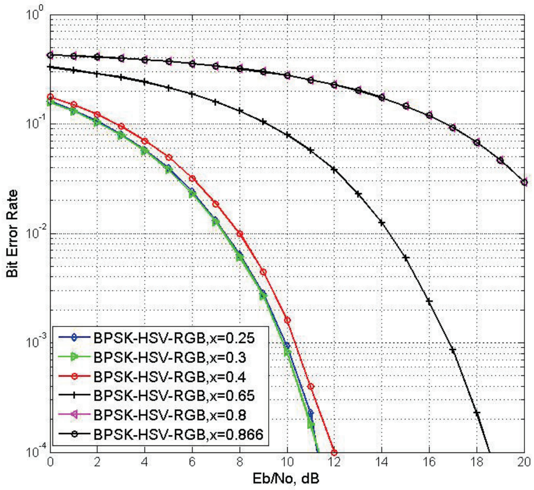

Figure 5. Performance of the Hybrid PLC-VLC (PSK-CSK) system for x = 0.25, 0.4, 0.65, 0.8, 0.866.

to the values of x around the lower crossing point between V and S (see Fig. 3). Let C_k^r ($[C_{rk}^r, C_{gk}^r, C_{bk}^r]^T$) be the k^{th} received colour corresponding to the k^{th} symbol. C_k^r differs from the sent colour C_k^s ($[C_{rk}^s, C_{gk}^s, C_{bk}^s]^T$) and its expression is given by

$$C_k^r = \begin{cases} C_{rk}^r = C_{rk}^s + n_r \ \text{(a)}, \\ C_{gk}^r = C_{gk}^s + n_g \ \text{(b)}, \\ C_{bk}^r = C_{bk}^s + n_b \ \text{(c)}, \end{cases} \tag{2}$$

where n_r, n_g and n_b are the noise affecting the RGB components of the received colour. Equation (2) is written assuming that the channel does not produce any distortion and crosstalk. In this simulation, we also assume that n_r = n_g = n_b = n, with n having a Gaussian distribution with zero mean. On the VLC receiver, the currents induced in the colour photodetectors are exploited to reconstruct the symbols based on the threshold selection technique.

We performed simulations for BPSK and QPSK constellations observed over the PLC channel. In all cases, the results confirm better performance of BPSK-CSK with respect to QPSK-CSK. Here we present only the results of BPSK symbols. The results are shown in Figs. 4 and 5. The system performs better for the value of x close to the upper crossing point A (see Fig.4). The best performance for the average values of $(V + S)/2$ between 79% and 85.33% is obtained for x = 0.25, owing to the fact that 0.25 is very close to the maximum chromaticity that the system can realise (Since the PDs are sensitive to colours and the maximum chromaticity enables better colour detection). Fig. 5 shows that for the values of x close to the lower crossing point B, the performance of the system is poor. The worse case is obtained for x = 0.866, but further investigation will show a worse communication performance for x = 1.1, corresponding to S = 0. It is worthy to highlight that the full analysis of this technique is submitted to Telecommunication Systems (Journal) and here we present only an excerpt.

IV. PRACTICAL IMPLEMENTATION AN INTERFERENCE ANALYSIS

As shown in Figs. 1 and 6, there are two half PLC links: one in the first building, before the VLC channel and the other is in the second building. This system finds its application in urban area where buildings are very close to each other. We can use the VLC to interconnect buildings and release the radio frequency spectrum. The full architecture of the inter-building PLC-VLC integration is depicted in Fig. 6. In order to realise the circuit proposed in Fig. 6 and meet our desire to integrate PLC and VLC systems as discussed in the overall system setup in Section II, two computers, four ST7580 PLC evaluation boards and two microcontrollers (Arduino UNO REV3) are required. The ST7580 evaluation shield presented later in Section IV-B, is used as PLC modem. The first (Tx) and the last (Rx) ST7580 modules serve as sending and receiving PLC modems, respectively. The other two modems (showed in Figs. 6 and 8) serve in PLC to VLC and VLC to PLC conversion modules, respectively.

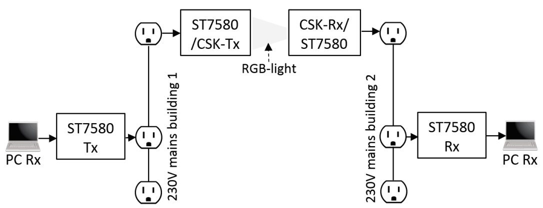

Figure 6. Full PLC-VLC architecture for inter-building communication

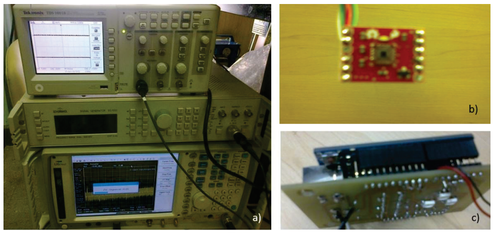

Figure 7. Built VLC communication module, the CMOS colour sensor and the measurement equipment. a)- from the top: a Tektronix TDS 1001B digital oscilloscope, a SCHOMANDL SG 1000 signal generator and a LIG Nex1 30D Spectrum Analyser, b)- the single pixel CMOS colour sensor, c)-the bottom side of the circuit containing the three RGB-LEDs that make the transmitter

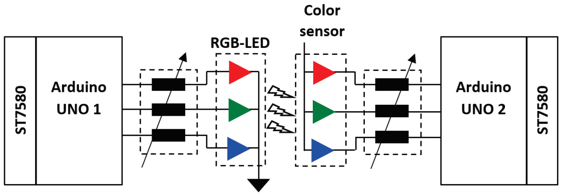

Figure 8. Circuit used to convey the information through the VLC channel

A. VLC link implementation

As in any other communication technology, the VLC system architecture groups a data source, a modulator and the coupling device (LED) on the sender end and a photodetector, a demodulator and a data recipient on the receiver position [1]. In our case, the VLC link integrates a CSK modulator on one side and a CSK receiver on the other side. The CSK modulator is made up of three RGB-LEDs of 3W each characterised by the following rated values: red 2.5 V - 3 V, 350 mA, 20.7 lm, 620 - 630 nm, green and blue 3.2 V - 3.5 V, 350 mA, 16.5 lm, 520 - 530 and 460 - 470 nm, light diffusion beam 140^o. The CSK receiver is a single pixel RGB complementary metal-oxide semiconductor (CMOS) sensor. It is a high performance, small in size and cost effective light to voltage converting sensor. The sensor combines a photodiode array and three trans-impedance amplifiers in a single monolithic integrated circuit. Three colour filters are coated over the photodiode array. The irradiance responsivities are 645 nm, 542 nm and 460 nm for the red, green and blue photodiodes, respectively. Fig. 7 shows the measuring equipment, the CSK transceiver and the single pixel colour sensor. Both sender and receiver are equipped with an arduino UNO REV3 used for the analogue to digital conversion and vice versa. The circuit used to convey the information through the VLC channel is shown in Fig. 8. It shows one side a CSK transmitter composed of a RGB-LED in series with a current limiting resistor connected to the arduino. From the receiver end, we have a single colour sensor connected to another arduino. The colour sensor collect the message from the channel and the arduino tries to polish the received signal to reproduce the message. The message detected over the PLC channel by one ST7580 is buffered in the microcontroller and delivered to the RGB-LED at the frequency of 200 ms per packet to synchronise with the frequency of the ST7580. We realise a 4CSK, which means four colour changes are made during the transmission of one set of symbols. We then inject in the RGB-LED three different currents depending on the final desired colour. We impose [350, 0, 0] mA for transmitting the first symbol under 2.75 V across each red LED to obtain about 2.887 W stream power. To transmit the second and third symbols, we inject [0, 350, 0] mA and [0, 0, 350] mA into the circuit. This gives about 3.15 W per group of LEDs under 3.5 V across the green and blue LEDs. To transmit the last symbol, we inject [120.9, 129.63, 129.63] mA, by then, producing a total of 3.062 W.

B. PLC link implementation (The ST7580 PLC evaluation shield)

The ST7580 PLC evaluation shield is developed by STMicroelectronics and is pre-built with a double modulation technique: binary frequency Shift Keying (BFSK) and binary phase shift keying (BPSK). The modem is designed to work under the 110/240 V, 50/60 Hz supply and is suitable for the European Committee for Electrotechnical Standardisation (CENELEC) standard EN50065 and the part 15 of the Federal Communications Commission (FCC) compliant applications. Fig. 9 shows a picture of the ST7580 PLC evaluation shield. The communication between the EVALKITST7580-1 and the personal computer (PC) is managed through the onboard STM32 microcontroller, whose embedded default code acts as a universal serial bus (USB) to the universal asynchronous receiver/transmitter (UART) bridge. In order to allow the PC to properly recognize this microcontroller application, the installation of a proper software driver is necessary. The following steps are carried out to prepare the module for transmission:

- Download the latest available virtual COM port (VCP) drivers from the ST website (at www.st.com) and unzip them to a location on the host PC;
- Launch the setup file $VCP_V 1.3.1\_Setup.exe$ to install the virtual COM port driver on the PC;
- When the welcome screen is displayed, click $Next$ to proceed with the installation;
- After the installation been completed, connect the EVALKITST7580-1 to a spare USB port on the host computer: an “STMicroelectronics virtual COM port” is recognised by the PC device manager and the EVALST7580-1 is installed and ready to be use.

To have complete control of the ST7580 device, with full access to all settings and functions, the ST7580 graphic user interface (GUI) software is loaded to the computer; this is required only for the first (Tx) and the last (Rx) ST7580. The intermediate ST7580 are not connected to a computer since they serve in the PLC-VLC bridges.

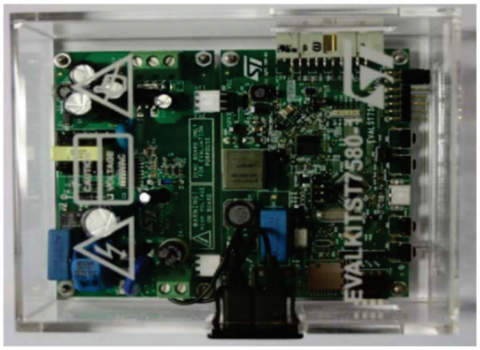

Figure 9. The ST7580 evaluation kit

C. PSK to CSK mapping and magnitude correction

We set all the PLC link to a BPSK (0^o and 180^o) uncoded mode. We transmit a 200 ms packet with 50 % duty cycle and a 90 kHz carrier frequency. Since the ST7580 evaluation shield uses the ST7580 chip on its physical layer, we exploit the physical capacity of the ST7580 chip to detect the phase information of the detected signal. The ST7580 supports three PSK modes with a symbol rate of 9600 baud: uncoded BPSK, QPSK and 8PSK; coded BPSK and QPSK, and coded BPSK with peak noise avoidance algorithm. None of these modes provides the phase information required for our conversion. Nevertheless, the built-in main receiving block of the ST7580 chip has two wide input range components: the analog and programmable gain amplifier (PGA) and the analog to digital converter (ADC). The PGA is controlled by an embedded loop algorithm, adapting the PGA gain to amplify or attenuate the input signal according to the input voltage range for the ADC. It uses the zero crossing synchronisation technique to calculate the phase information of the received signal. The zero crossing filter circuit is connected on pin 18 (ZC_IN) of the chip while the incoming signal is sent to pin 19 (RX_IN). Both are compared to each other to decide on the phase of the incoming signal and provide a digital output. This output is used to trigger our first microcontroler (arduino UNO 1 in Fig. 8), knowing that a ″one″ and a ″zero″ correspond to 0^o and 180^o, respectively. The input of the PGA varies with the PGA gain, it goes from 0.0625 to 8 V respectively for -18 to 30 dBμVrms PGA gain [13]. This gain represents the parameter x used in the simulation. It is set accordingly with the manufacturer recommendation using PGA codes from 0 to 8, where 0 corresponding to -18 dB and 8 to 30 dB. This gain varies with the current flowing in the RGB-LEDs and consequently, changes the HSV parameters of the light.

D. Practical measurement and results

Due to the transmission range of the RGB-LED used, Fig. 6 is executed in an open laboratory under the outdoor conditions. The electrical networks of the Centre for Telecommunications' laboratory (B2 LAB 210, faculty of Engineering, University of Johannesburg) is used as mains building 1 while main building 2 is replaced by a group of isolated power line outlets. We set a 1 metre distance between the RGB-LEDs and the single pixel colour sensor. The power amplifier gain control of the first ST7580 is used to control the received signal amplitude. We set the PA_OUT gain in such a way to obtain 0.8 V, 1.1 V and 1.3 V at RX_IN pin of the second ST7580. We send symbols over the PLC channels, which are detected and converted into light, resent, and collected later by the last ST7580. Figs. 10 and 11 are extracted from the bank of results to show how the system behaves as the background sun light increases its intensity. They both represent the errors measured over a set of values of the PGA code of the ST7580 and confirm that as the magnitude of the PSK received symbol increases, we have better performance of the CSK transmission. Fig. 10 is obtained around 9:00 am with a week background sunlight while Fig. 11 is obtained around 11:00 am. Both figures show that the error rate increases as the sun gets more intense and stronger. The VLC section of the communication system of this experience becomes less efficient and affect the overall system. .

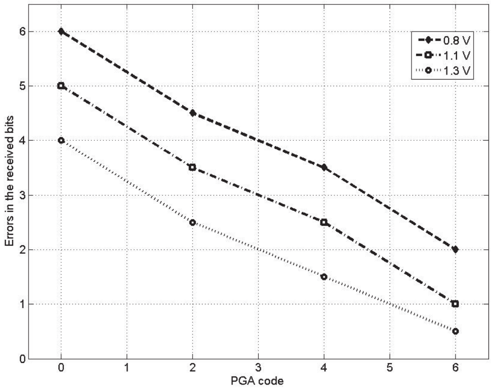

Figure 10. Measured in the received bits for different RMS values of the detected signal for a usual background sun light, measured around 9 AM

E. Interference source analysis

Two main parameters are responsible of the degradation of the BER described in Figs. 10 and 11 between 9:00 am and 11:00 am: the sun's rays diffusion parameters and the colour mixture parameters.

a) The sun's rays diffusion parameters: The beam and the intensity of the sun light at the surface of the earth depend on two main elements: the sun spectrum and the diffusion beam. The Sun emits electromagnetic radiation across most of the electromagnetic spectrum [14]. Isaac Newton showed that sunlight is a mixture of all colours [15]. Thus, in the sun rays, are found the rainbow colours and all the other components of the electromagnetic spectrum. However, the percentage of distribution of those

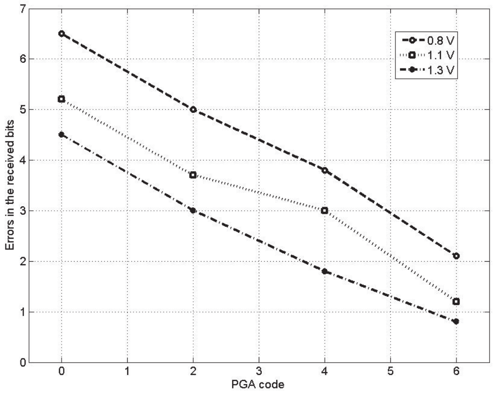

Figure 11. Measured in the received bits for different RMS values of the detected signal for a usual background sun light, measured around 10 AM

component is not equal. Visible light (VL), ultraviolet (UV) and infra-red (IR) lights are the most important component present in the sun rays. For example at noon, we have about 44% VL, 3% UV and 53% IR [16]. The VL present in the sun rays is going to interfere with our RGB light produced for communication. It is going to affect the communication following the colour composition techniques described in the next paragraph. Nevertheless, the beam direction and the angle between the VL ray of the sun and our RGB ray is very important.

b) The Colour mixture parameters: In colour composition, according to the orientation of the beam and the time of the day, the colour from the sun will be in addition or subtraction situations with the RGB light produced for transmission. The colour addition responds to $Red + Green + Blue = White$, while the subtraction responds to $Magenta + Yellow + Cyan = Black$, but all depends on which colour is considered as primary colour. This means that the amount of colour in the VL spectrum of the sun is of great importance. These explanations point to the origin of interference on the outdoor VLC transmission. A proper investigation of the outdoor environment is ongoing. this will provide full understanding of the behaviour of the system presented in Figs. 10 and 11.

V. CONCLUSION

This paper presents the design and implementation of a hybrid PLC-VLC communication systems to be use in inter-building applications. The magnitude of the observed PSK symbol is used to create a trade-off between communication and illumination. The best performance for both communication and lighting for the average value of $(V+S)/2$ = 85.33% is obtained for x = 0.133. Nevertheless, for a threshold of 79% taken before and after the upper crossing points between V and S, the system still gives off a substantial amount of brightness and enhances better communication throughput. The system is analysed by simulation and a practical implementation is proposed to validate the simulation results and confirm the effect of the sunlight on the VLC outdoor applications.

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