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Master in Photonics

MASTER THESIS WORK

Tuneable and portable Lighting system for Visible Light Communications (TP-VLC)

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Presented on date 8th September 2014

Registered at

Escola Tècnica Superior d'Enginyeria de Telecomunicació de Barcelona

Tuneable and portable Lighting system for Visible Light Communications (TP-VLC)

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Abstract This work presents a low cost prototype implementing new IEEE 802.15.7 standard for Visible Light Communications (VLC). Mbed development platform is used to implement the firmware controlling the system. The system is tested with different LED luminaires achieving data rates of 100 kbps over a distance up to 8 meters. Brightness control of the LED while transmitting data can be achieved allowing for a tuneable VLC system.

Keywords: VLC, LED lighting, indoor communications, smart lighting

1. Introduction

Actually, light-emitting diodes (LED) are replacing the conventional fluorescent and incandescent lamps and becoming the principal indoor and outdoor lighting source. LEDs offer many advantages over conventional lighting devices such as long life, high power efficiency, high durability, emission in a concrete region of the spectrum, spectrum tuneability and environmental friendliness [1]. In addition, its long life time reduces the maintenance costs. Besides illumination, LEDs have been finding new applications in data communications such as Visible Light Communications (VLC).

VLC is a data communication technology which makes use of visible light (between 780 nm and 380 nm) to encode and transmit data also providing illumination functions at the same time. VLC mostly uses LEDs as light source due to LED efficiency, reliability, and the possibility of high frequency switching [2]. In addition, using LED for VLC provides many other advantages, such network security, non-interference with radio bands, such as the used for Wifi, or mobile communications, and the use of a non-licensed portion of the spectrum [3]. Data transmission in VLC is done by high frequency switching and light intensity changes, according to the signal to be transmitted, similarly to infrared optical communications. As human can see the light carrier, modulation process shouldn't introduce any noticeable intensity variations noticeable by humans [4]. These intensity variations are called flickering, to avoid it, the changes in brightness should be lower than the maximum flickering time period (MFTP), which is generally accepted to be 1ms, this is 1KHz (MFTP < 20ms) [5]. In addition, a VLC system has to be able to transmit information meanwhile supporting average light intensity changes, i.e. adjust the brightness of the source, this is commonly known as dimming [6]. The most simple modulation which can be used with VLC is on-off keying (OOK) which consists on turning on and off the LED according to the data to be transmitted [7]. Another option is to use discrete multitone modulation, which makes a better use of the available bandwidth of the LED [8]. White LEDs are used for lighting purposes due to its capability to emit a light spectrum similar to sunlight or different color temperatures which can give comfort for humans. A typical white lighting LED consists on a blue LED and a phosphor coating which shifts the wavelength of the light to the red. Due to this shifting, the temporal response of the LED is increased, and the bandwidth is reduced to a few MHz [9].

In 2011, the Institute of Electrical and Electronics Engineers introduced the IEEE 802.15.7 VLC standard [10]. In the standard, a physical (PHY) and a medium access control (MAC) layers are defined. The physical layer defines the Although other VLC standards had been proposed in the past, such as the one proposed by Japan Electronics and Information Technology Industries Association's (JEITA) [11] or another one by the Home Gigabit Access project (OMEGA) [12] in Europe, none of them addressed flickering suppression and dimming support. IEEE 802.15.7 has been defined taking into account these issues, some of the proposals from the OMEGA project were included in the standard.

Most of the works on the field focus on achieving high data rates, the bandwidth of LEDs (tenths of MHz) can be best used depending on the modulation scheme and equalization (i.e. means for removing distortion introduced by the channel). An almost error free data communication at 150 Mbps has been achieved in [13] using non-return-to-zero on-off keying (OOK-NRZ) modulation and digital post-equalization. Also 340 Mbps has recently been reported in [14] using a single white LED and OOK-NRZ, by using analog equalization at the receiver. Alternatively, white light can be produced by using a combination of different colored LEDs such as red, green and blue (RGB). This last method has the advantage that it can be used in VLC to transmit light at different carrier wavelengths, increasing the total bandwidth of the system, by using the appropriate color filter at the photodetector [15]. Data rates up to 1 Gbps have been achieved by using discrete multitone (DMT) modulation in [16] or 3 Gbps with optical frequency division multiplexing (OFDM) using a gallium-arsenide microled [17], although the link distance in both of them is in the order of centimeters which is not practical. In addition these experiments have not been implemented in a real time environment due to the complexity of the hardware needed to implement these modulations. Recently, in [18], color control has been reported in a VLC link using RGB LEDs and DMT modulation, but at a distance of only a few centimeters. There have been only a few reports on 802.15.7 standard, for example performance simulations of the physical layer have been done in [19] using Monte Carlo simulations which are widely used for network simulations due to its capability to simulate different scenarios. Also in 2013 an implementation of the physical layer using software defined radio (SDR) was reported in [20] achieving data rates of 100 Kbps, using OOK.

In this work, a real time implementation based on IEEE 802.15.7 is presented. A low cost mbed microcontroller development platform has been used for networking interfacing, modulation and demodulation functions. The prototype is interfaced to a Local Area Network with the built-in Ethernet connection. The performance of the VLC prototype is evaluated when using different LED luminaries as a first step for implementing a tunable VLC system.

The organization of this paper is the following: Section II introduces a theoretical background and a description of prototype to accomplish with the 802.15.7 standard. In Section III, hardware design and the software flow chart and development methodology of the prototype is presented. The results are discussed in section IV. Finally the conclusions are explained in Section V.

2. Theoretical Background

A VLC system consists on a transmitter and a receiver. The transmitter is in it most simple form an LED which can be modulated according to the data to be transmitted by an LED driver. The receiver consists on a photodetector and means for demodulating the received signal.

Figure 1 shows the VLC system architecture. The data to be transmitted is converted to an electrical signal using some digital modulation. This electrical signal is used to modulate an LED with a driver which supplies the high current intensity needed for high power LEDs. The transmitted optical signal is detected with a photodiode which converts the light into current. Silicon based photodiodes are used as they can detect visible light, although Avalanche Photodiodes (APD) have high sensibility, PIN photodiodes are the most used due to lower levels of noise, parasitic capacitance and cost [21]. The received signal is amplified by a transimpedance amplifier and demodulated to recover the original binary data.

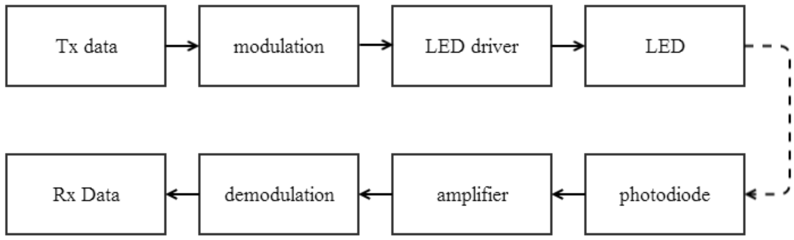

Figure 1: VLC system architecture

2.1 IEEE 802.15.7 Standard

Three physical layers have been defined in IEEE 802.15.7 standard, they are grouped by data rate and digital modulation as it can be seen in table 1. On-off keying (OOK) and variable pulse-position modulation (VPPM) have been chosen for the first two modes. In PHY III operates with color shift keying (CSK) modulation. Line coding, i.e. the method to encode the binary digits into a voltage signal, is introduced to avoid flickering problem by achieving DC balance. An optical clock rate has been defined for each PHY mode, the distinct data rates are obtained by introducing different levels of redundancy which allow forward error correction (FEC). In this work, PHY I has been implemented.

Table 1: IEEE 802.15.7 PHY I operating modes.

Modulation	**RLL code**	**Optical clock rate**	**FEC**		**Data rate**
			Outer code(RS)	**Inner code(CC)**	
OOK	Manchester	200 KHz	(15,7)	1/4	11.67 kb/s
			(15,11)	1/3	24.44 kb/s
			(15,11)	2/3	48.89 kb/s
			(15,11)	none	73.3 kb/s
			none	none	100 kb/s
VPPM	4B6B	400 KHz	(15,2)	none	35.56 kb/s
			(15,4)	none	71.11 kb/s
			(15,7)	none	124.4 kb/s
			none	none	266.6 kb/s

2.2 PHY I and OOK

The line code used with OOK modulation is Manchester encoding [22]. It uses two different levels of intensity and the binary data is encoded using the intensity transitions: logic “zero” is expressed by a low-to-high transition and logic “one” by high-to-low transition. Every bit has a determined time duration T, at $T/2$ a voltage transition always happens, therefore the result is a 50% “ON” average time.

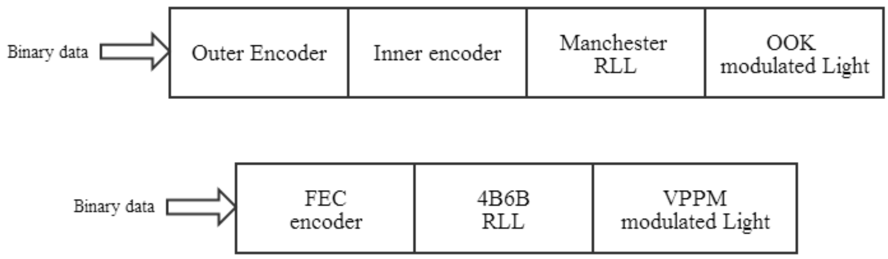

Figure 2: OOK and VPPM transmitter block diagram

Dimming is achieved by changing the average duty cycle of the waveform by sending compensation symbols between data frames. As the average brightness level of the transmitted signal is at 50%, compensation symbols can be easily calculated. An algorithm is implemented to calculate the dimming pattern with the required mean brightness level. Three parameters have to be provided, the number of visibility patterns $K,$ which have equally spaced brightness levels, and are expressed as $V_o, V_1 \dots V_K$ the desired precision p (expressed as a logarithm value), and finally the desired brightness level dv. Eleven different visibility patterns are defined with a mean brightness from 0% to 100% in steps of 10%, therefore $K = 0$. The patterns are selected in the following way, where to achieve a desired visibility dv, $V_{sel1pat}$ is repeated $reppat1$ times and $V_{sel2pat}$ is repeated $reppat2$ times.

$$sel1pat = \left\lfloor \frac{dv \cdot K}{100} \right\rfloor,$$

$$sel2pat = sel1pat + 1,$$

$$reppat2 = 10^{-p}\left(dv - \frac{100 \cdot sel1pat}{K}\right)$$

$$reppat1 = 10^{1-p} - reppat2$$

2.3 PHY I and VPPM

VPPM is a combination between pulse position modulation (PPM) and pulse-width modulation (PWM). It encodes the logic one and zeros by varying the pulse position within a predefined unit time period. Dimming is achieved by changing the “ON” time pulse-width depending on the required dimming level. VPPM uses 4B6B line coding to achieve DC balance: Every 4 arbitrary four bits are encoded to a 6 bit code which is DC balanced, the resulting average brightness level is 0.25 if duty cycle is set at 50%.

2.4 802.15.7 Data Frame

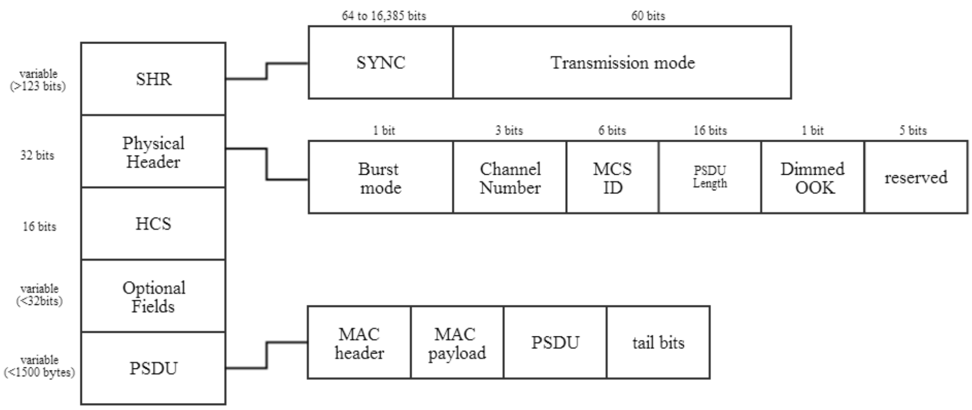

Figure 3: IEEE 802.15.7 data frame

In figure 3, an IEEE 802.15.7 PHY protocol data unit (PDU) is defined The preamble field contains a synchronization sequence of at least 64 alternate zeroes and ones and a 60 bit field in which the topology of the network is defined. Then a 32 bit PHY header is transmitted, containing information about the frame and the mode of operation. While using OOK with dimming, the PHY header is extended with additional data about the dimming frame. Then the

Medium Acces Control (MAC) layer PDU is encoded. It consists on a MAC Header (MHR) containing the source and destination MAC address followed by the MAC payload, which has a maximum size of 1023 bytes. A minimum interframe spacing (IFS) is used to provide spacing between frames. For PHY I, the minimum IFS period is 40 clock cycles.

3. Development methodology

In this section the methodology used to design the VLC prototype is described. First the hardware of the system was designed, and then the software layer was implemented.

3.1 Hardware

According to IEEE 802.15.7 VLC standard, the transmitter should be able to implement OOK and VPPM modulations. A custom high speed led driver has been designed to provide fast switching times and the possibility of being used with different luminaries. The schematic of the transmitter is illustrated in figure 4. An MBED microcontroller with networking functions is used to convert the data stream to be transmitted to an analog signal. The analog signal is amplified and used to drive a fast power MOSFET that switches on and off the LEDs.

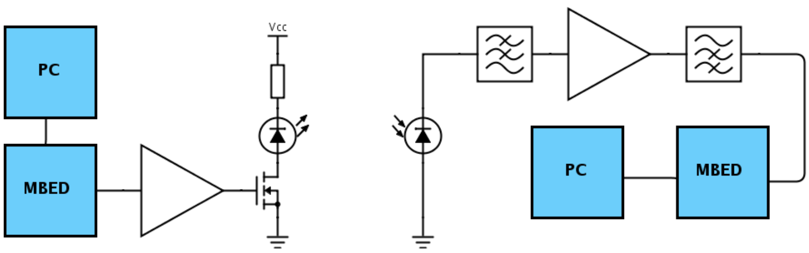

Figure 4: VLC prototype's hardware block diagram.

Figure 4 shows the block diagram of the system. The received light is focused by a bi-convex glass lens onto a silicon-based PIN Centronic OSD5-5T photodiode which converts the received light into current. Then, this current is amplified and converted to voltage by a high speed and high bandwidth two-stage transimpedance amplifier specifically designed for the photodiode, with a gain of 50dB. A high pass filter is included on to the design in order to reduce the low frequency or continuous light interferences, such as sun's light and fluorescent lights, and a low pass filter removes high frequency noise. The photodiode has an active area of 5 mm2, low dark current, and a noise equivalent power (NEP) of 2.4e-13 $WHz^{-1/2}$ at 432nm. The amplified and filtered signal is introduced to a microcontroller which performs analog to digital conversion and demodulation.

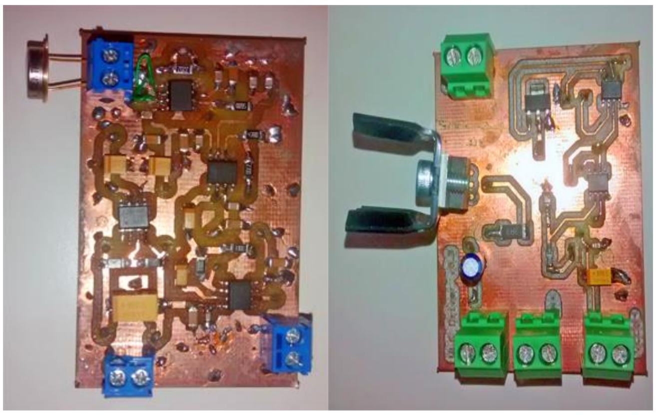

Figure 5: Printed circuit boards of the transmitter (left) and the receiver (right).

Custom PCB boards have been designed for both transmitter and receiver, as it can be seen in figure 5, resulting in compact devices. Each part can be powered by just plugging it to an standard wall power outlet, which makes the system portable. An mbed LPC1768 microcontroller development board [23] is used to implement the software layer in both transmitter and receiver, due to its fast prototyping possibilities. Mbed LPC1768 includes USB and Ethernet connectivity and a 32-bit ARM® Cortex™-M3 running at 96MHz, 12KB FLASH and 32KB RAM.

3.2 Software

Custom firmware implementing 802.15.7 VLC standard has been developed for the mbed microcontroller. The data is sent from a PC running Ubuntu 14.04 to the microcontroller via Ethernet network. Then the data is encapsulated according to VLC standard, modulated and sent to a digital output of the mbed board. A digital input pin of the MBED microcontroller reads the output signal of the analogue part of the receiver. The microcontroller can detect voltage changes on its inputs. When an off to on transition is detected by the microcontroller, an interrupt is triggered periodically and used to read the analogue signal. The timing has been carefully measured with software tests, in order to ensure a correct synchronization. If the microcontroller detects the synchronization pattern, it proceeds to read the packet, if not, it waits until another off to on transition is detected and the process is repeated. Then the IEEE 802.15.7 packet is decoded and sent to a pc via the Ethernet interface controller. A Network protocol analyzer software, Wireshark, has been used to extract each packet and recover the data payload.

3.3 *Tuneable VLC system*

A tuneable VLC system requires changing the brightness while transmitting data of at least 3 RGB LEDs simultaneously. As we are transmitting with LEDs of different emission spectrum, different data can be sent to each LED and using three different receivers with an adequate optical filter each one, the global data rate of the system can be increased. As IEEE 802.15.7 does provide methods for dimming, an algorithm to set the required brightness level of each LED is needed.

4. Results

4.1 LEDs characterization

Several LED and OLED luminaries were characterized in order to determine its modulation bandwidth, which can be determined from its rise time, i.e. when turning off to on (10% to 90%), by using the following relation $BW = 0.35/t_r$ [24]. OSRAM's Golden Dragon Plus [25] LED family was selected due to its high brightness, fast switching times and different color availability. Single LEDs and Strips mounting 6 LEDs from Intelligent LED Solutions were used. Their characteristics are summarized in table 2 and table 3 respectively. Golden dragon white LEDs have fewer bandwidth than RGB due to the phosphor coatings. It should be noted that the power mosfet switching time on the driver, limits the bandwidth of the RGB LEDs.

Table 2: Single different colored LED characteristics

Colour	Dominant wavelength	Flux	Bandwidth
Red	625 nm	60 lm	~ 20 MHz
Green	528 nm	93 lm	~ 20 MHz
Blue	470 nm	28 lm	~ 20 MHz

Table 3: 6 white LEDs strips with different color temperature

Colour	Colour Temperature (K)	Flux	Bandwidth
Warm White	3000	558 lm	~ 9 MHz
White	5700	642 lm	~ 10 MHz

Cool White	6500	750 lm	~ 9 MHz

4.2 Data transmission

Although the 802.15.7 standard defines an optical clock rate of 200 KHz for PHY I, we have tested the system using different switching frequencies for OOK modulation. A strip of 6 Osram's Golden Dragon white LEDs was used as luminaire. The distance between the transmitter and the receiver was 3 meters. The test room was in our lab, which is illuminated by fluorescent lamps and sunlight as they are the worst conditions in which the prototype is designed to work. A frame consisting on a training field of 64 bits long and a predefined sequence of 512bits was continuously transmitted over 360 seconds, the receiver compares the received data with the expected sequence in order to count the errors and calculate the bit error rate (BER). Up to 200 KHz no errors were detected, therefore the BER is lower than the inverse of the order of magnitude of the number bits transmitted. The results are shown in table 4.

Table 4: BER at different optical clock rates at 3 meters

Optical clock rate	Bitrate	BER
50 KHz	25 Kbps	$<10^{-6}$
100 KHz	50 Kbps	$<10^{-6}$
200 KHz	100 Kbps	$<10^{-7}$
300 KHz	150 Kbps	$6.6\cdot10^{-4}$
400 KHz	200 Kbps	$8.5\cdot10^{-3}$
500 KHz	250 Kbps	$1.6\cdot10^{-2}$
600 KHz	300 Kbps	$2.5\cdot10^{-2}$
700 KHz	350 Kbps	$3.3\cdot10^{-2}$
800 KHz	400 Kbps	$6.2\cdot10^{-2}$

As we increment the frequency, the system performs worst and the BER increases. This is due to the difficulty of synchronization, although until 400 KHZ the BER is lower than 10^{-3} which is the limit for forward error correction. In figure 5, we can observe the output signal from the microcontroller when operating at an optical clock rate of 200 Khz, and the received signal which is converted to digital by the receiver microcontroller. At this rate, the measured signal-to-noise ratio (SNR) is 38 dB, and there is no intersymbol interference (ISI) as the bandwidth required at this frequency is lower than the available bandwidth of the system. We have successfully tested our system up to 6 MHz switching frequency, but not implemented in realtime due to MBED processing power limitations.

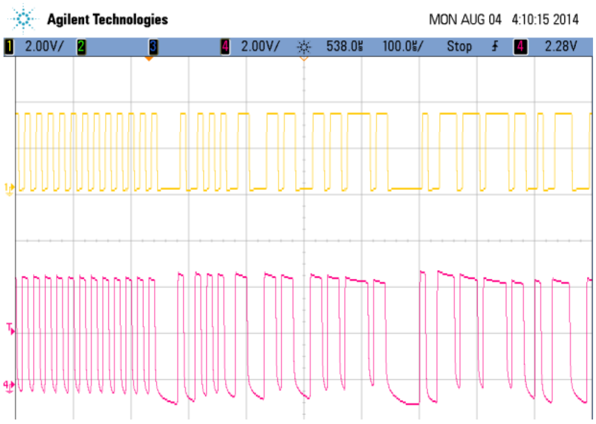

Figure 6: Transmitted and received signal at an optical clock rate of 200 KHz and 3 meter separation.

The same test was repeated at the optical clock rate specified by the standard, but varying the distance from 2 to 8 meters in steps of 1 meter and using different LED strips luminaires as they are more powerful, with different colour temperature. Up to 4 meters, no errors were detected therefore as the order of magnitude of the number of transmitted bits is 10^7, the BER value is set to 10^{-7}. The results are shown on figure 6. The BER increases with the distance, but it is still lower than 10^{-4}. The white LED strip performs better than the other ones, due to its higher brightness. The previous test was repeated but this time the data was transmitted as specified in 802.15.7 Standard to determine the maximum bitrate available. The payload was set to 1023 bytes, which is the maximum permitted. As it can be seen in figure 6, the effective data rate decreases with the distance, although it achieves 96.6 Kbps in the worst case, which is near to the maximum value.

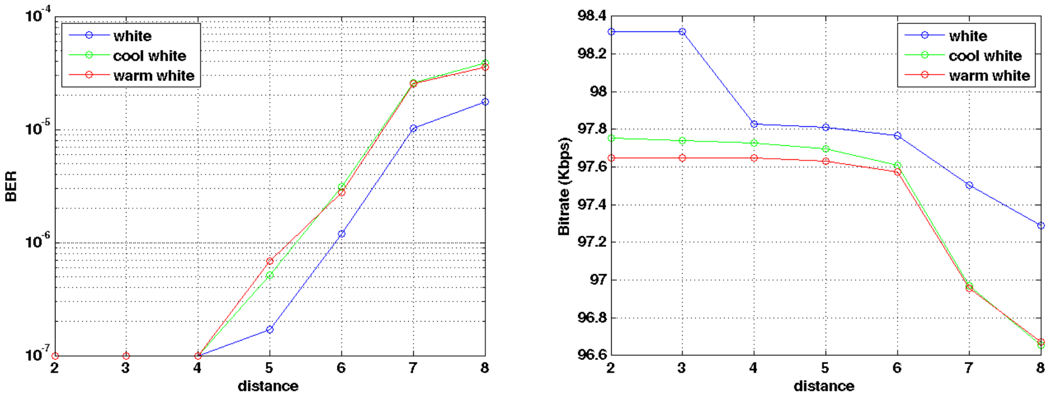

Figure 7: Left: BER with respect the distance. Right: Effective bitrate with respect the distance

4.3 Dimming

The two different methods for dimming proposed with VLC standard were tested. We used the RGB LEDs in order to characterize them for implementing a tuneable system. The brightness was measured at a distance of 20 cm. For both OOK and VPPM dimming methods, we defined a brightness resolution of 1%. For VPPM the method is straightforward as it consists on varying the duty cycle of the pulse. In OOK, the dimming sequences are introduced inside the IEEE 802.15.7 data frame. In this test, the dimming sequence has defined size of 1000 bytes and it is introduced as data payload. The results are shown in in figure 8: the horizontal axis represents the required brightness level, and the vertical axis the measured level. The measurements are normalized with respect the maximum brightness level of each LED. The results are similar for the different LEDs with small differences. It can be observed that for OOK, the measured levels slightly differ the the expected, this is due to the 50% average brightness of the frame’s header sequence, therefore this overhead has to be taken into account. It also should be noted that when we are dimming the light source in OOK, the bitrate is reduced depending on the required brightness. For VPPM, the results are as expected with small variations due to the header, but it stands as the best option for dimming and transmitting data at the same time in IEEE 802.15.7.

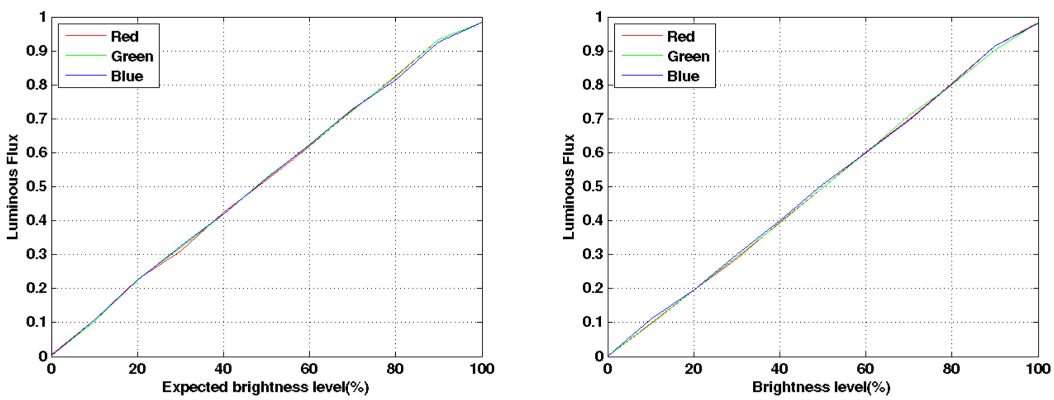

Figure 8: Measured and normalized luminous flux (Y-axis) with respect the required brightness level (X-axis) for OOK (left) and VPPM (right).

5. Conclusions

A prototype implementing the PHY I of the IEEE 802.15.7 VLC standard has been developed. Mbed development platform has been used to implement the firmware for the VLC system, in both transmitter and receiver. The prototype supports bitrates up to 100 Kbps with a low BER over distances up to 8 meters, which makes it suitable for indoor communications, smart lighting, smart cities or intelligent transportation systems for vehicle to vehicle (V2V) communications. At the PHY I data rates, there is no important difference when using LEDs with different color , as the bandwidth required is less than the intrinsic of the LEDs. The prototype can be used to implement a tuneable VLC system as the average brightness of the LED can be controlled while transmitting data. VPPM is more effective than OOK modulation when dimming and transmitting data as the bitrate is not reduced.

In future, the VLC prototype will be improved by using three RGB or more different colored LEDs to transmit data simultaneously and a more powerful hardware platform will be used to control each channel increasing the total data bitrate. Higher optical clock frequencies can also be implemented to further increase the total data rate. Complex modulations should also be tested as they offer a better use of the LEDs modulation bandwidth, although the overall complexity of the system increases.

Acknowledgments

I would like to thank specially Dr. Jorge Higuera and the members of IREC's lighting group for they advices and support during the development of this project.

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