

# Theoretical and Experimental Analysis of LED Lamp for Visible Light Communications

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Accepted: 14 April 2022 / Published online: 20 May 2022 © The Author(s) 2022

## Abstract

Visible light communications (VLC) are an emerging technology that uses light-emitting diodes (LEDs) and photodiodes to provide high-speed communication between devices employing the visible light spectrum. Taking advantage of a large unregulated spectrum with capacity for gigabit per second data rates, VLC has the potential to enable the more recent and future telecommunications technologies, such as IoT, 5G and beyond, to unlock their full capabilities, either acting as a sole solution or supporting traditional radiofrequency communications. One of the goals of VLC is to employ illumination LEDs as access points. In this paper we analyze the communication and illumination performance of an LED lamp. Both theoretical and experimental analysis are conducted and results compared. Theoretical analysis are conducted with VLC mathematical model and also with ray-tracing simulations employing the a commercial software. We show that the LED lamp is capable of providing both communication and illumination simultaneously under the proposed scenario. Our results present strong correlation between theoretical and experimental results, indicating that the theoretical model is robust.

**Keywords** Visible-light-communication (VLC)  $\cdot$  Optical-wireless-communications (OWC)  $\cdot$  LED

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# 1 Introduction

The optical wireless communications (OWC) have been proposed as a high-capacity complementary technology to radiofrequency (RF) communications, widely employed today in wireless communications such as cellular networks, local area networks and radio and television broadcasting [1]. However, the RF spectrum, defined as wavelengths between a few kHz to 300 GHz, has its limitations. Although technology has demonstrated an increased spectral efficiency of RF systems in the last decades, the occupancy below 6 GHz is nearly saturated, and above 6 GHz almost all electromagnetic spectrum is regulated and it has been already allocated. This spectrum shortage is often referred to as spectrum crunch [2].

Among the OWC, the visible light communications (VLC) are a current research topic with the potential to unlock 5G and beyond technologies and alleviate spectrum crunch [2, 3]. VLC uses the visible light spectrum (electromagnetic radiation frequencies between 400 and 790 THz) to transmit information by modulating the intensity of visible light [4].

In the last decades, VLC data rates have been increasing with more recent papers reporting transfer speeds in the order of gigabits per second, employing different techniques [5, 6], but still at very short distances. Also, specific applications have also been studied, such as underwater communications [7], vehicular communication [8] and positioning [9]. Besides point-to-point communication between devices, a complete wireless communication protocol employing VLC has been proposed in the form of the Li-Fi standard [10].

Advantages of VLC include a wider and unregulated spectrum (near 10,000 times higher than the RF spectrum); inherent security, given that light waves do not pass through opaque structures such as walls; a low-cost solution to deploy, due to the fact that part of the infrastructure (the transmitter) is already installed; and is environmental-friendly, since LEDs are a green technology that has low power consumption and a longer lifespan than older illumination technologies [1, 10].

Besides several benefits, VLC also has limitations that are challenging for researchers. The uplink channel, from the user side to the access point, is one of the main concerns, given that the user's unit could consume too much power for a portable device, as well as may present a bright light near the user that could be unpleasant and not acceptable [1]. While VLC does not suffer from multipath fading [11], shadowing is a concern due to the fact that visible light does not pass through opaque structures [12]. Another challenge is the commercialization of VLC technologies, given that both transmitters and receivers must be deployed, requiring the illumination and telecom industries to work together [13], imposing a quest for a common standard.

VLC has the capability of offering both illumination and communication concurrently and, therefore, any LED lamp is a potential wireless access point [14]. However, when providing communication while illuminating, the system must be designed in a way that its modulation format would not cause flickering, i.e., the user must not perceive any variation in the illumination level [15]. This phenomenon may happen, for instance, when a modulation format such as OOK (on-off keying) presents several sequential equal bits, without a technique to prevent the flickering. While this dual capability is interesting, one of the concerns for the adoption of VLC is the need of always maintaining the lights on. In this sense, research has been conducted and it has been shown that (perceptively) lights-off VLC is possible while providing robust communication [16].

In VLC, the transmitters are light sources, mainly light-emitting diodes (LEDs). At the receiver side, photodiodes (PDs) are used to detect the emitted light and convert it to an electric signal to be demodulated and processed. In one standard way, the LEDs are



Fig.1 Luminaire reproduced in SolidWorks and employed in APEX simulations. On the left the LEDs fitted to the concentrator element is observed. On the right, the whole set is seen in its support

modulated using intensity modulation (IM) and direct detection (DD) is employed at the receiver end. In this case, VLC systems are called IM/DD systems [14].

This work presents an analysis of a VLC link, both theoretically and experimentally. We use a LED module SP-02-T1 SinkPAD-II [17] equipped with seven LX18-P150-3 high power white LEDs. The light emitted by these LEDs is focused in a narrow-angle by using a polycarbonate concentrator, in order to improve performance in line-of-sight links. As for simulations, we employ the VLC channel model to evaluate mathematically our results. Finally, we model our light emission setup in the Apex add-in for SolidWorks software package [18] in order to run ray-tracing simulations and compare with theoretical and experimental results. We evaluated the received power, signal to noise ratio (SNR) and the bit error ratio (BER) for the communication link, comparing the different approaches.

Besides communication performance, given the illumination aspect of VLC, we also focus on evaluating the illumination features of the studied luminaire (LED lamp), both by ray-tracing simulations and also experimentally. We simulate the lamp in the Apex domain and also measure the illuminance distribution over a surface by using a lux meter. We present the measured illuminance distribution at a  $1 \times 1$  m surface for different consumed electrical power values. We also analyze the illumination impinging on a  $5 \times 5$  m room area by using various lamps.

Results for the communication and illumination aspects show that the lamp are suitable for both. Also, the theoretical, ray-tracing and experimental results are correlated, providing different approaches for the evaluation and design of VLC systems.

This work is organized as follows. In Sect. 2 our setup is presented, as well as the characterization of the luminaire, that is then reproduced in the Apex simulation software. In Sect. 3, the optical wireless channel is described. Section 4 presents the analysis and results for illumination, while in Sect. 5 analysis and results of the communication performance are discussed. Finally, conclusions are given in Sect. 6.

## 2 Characterization and Reproduction of the Luminaire in Apex

In order to compare theoretical and experimental results, we reproduced our components in SolidWorks. The employed luminaire is a SP-02-T1 SinkPAD-II [17] module containing seven LED LX18-P150-3 white LEDs, mounted in a mechanical holder to facilitate



Fig. 2 Irradiation distribution [W/mm<sup>2</sup>] on the floor in a  $4.8 \times 4.8 \times 2.5$  m room: **a** no concentrator and **b** with concentrator

experimentation on a table. We attached an optic array, model PL121140 [19], to the LED module which works as a light concentrator, which allows focusing the output of the seven LEDs into a narrower beam of light. Both these pieces were reproduced in the SolidWorks domain in order to setup ray-tracing simulations using the Apex add-in [18]. The modeled components are shown in Fig. 1.

The light sources were defined as Lumiled's LXML-PW31 [20], which are available in the APEX software's library and are similar to our physical components. Polycarbonate was employed as the material of the concentrator element. The LEDs were configured to generate 3 million rays at multiple wavelengths. To visualize the influence of the concentrator in the reception, we refer to Fig. 2. In this simulation, we placed the luminaire at the center of a room and obtained the irradiation distribution over an area of 1 m<sup>2</sup>, 2.5 m away from the light sources.

## 3 Optical Wireless Channel

Figure 3 shows the geometry of the channel model. We consider the LED source as a Lambertian emitter [11]. As such, we define the Lambertian order of the source as

$$m = -\frac{\ln(2)}{\ln(\cos(\varphi_{1/2}))},\tag{1}$$

where  $\varphi_{1/2}$  is the half-power semiangle, i.e., the angle at which the optical power from the source is reduced by half of its maximum value. For the optical wireless channel model, we refer to Fig. 3, where a line-of-sight (LOS) model consisting of a transmitter and a receiver is presented.

In the geometry depicted in Fig. 3,  $\varphi$  is the emission angle,  $\theta$  is the incidence angle, d is the distance and *FOV* is the field of view of the photodetector, i.e., the maximum angle at which it can detect light. The received optical power  $P_r$  is defined as the transmit power  $P_t$  times the channel DC gain H(0).



$$P_r = H(0)P_t,\tag{2}$$

The channel gain is given as

$$H_{los}(0) = \begin{cases} \frac{A(m+1)}{2\pi d^2} cos^m(\varphi) T_s(\theta) g(\theta) \cos(\theta), & 0 \le \theta \le FOV \\ 0, & \text{otherwise} \end{cases},$$
(3)

where A is the photodetector's area, d is the distance between source and destination, and  $T_s(\theta)$  and  $g(\theta)$  represent, respectively, gains from the optical filter and concentrator, if they are implemented in the system.

#### 3.1 Noise Model, SNR and BER

The signal-to-noise ratio (SNR) of a VLC system is calculated as [11, 12]

$$SNR = \frac{\gamma^2 P_r^2}{\sigma_{total}^2},\tag{4}$$

where  $\gamma$  is the photodetector's responsivity, given in A/W, and  $\sigma_{total}^2$  represents the total noise components, which is the combination of shot, thermal and intersymbol interference (ISI) noises [12]:

$$\sigma_{total}^2 = \sigma_{shot}^2 + \sigma_{thermal}^2 + \gamma^2 P_{rISI}^2.$$
 (5)

The intersymbol interference noise is mainly due to the reflection of light rays in the walls and surfaces of the surrounding environment. These light rays arrive with a delay at the photodetector, therefore acting as noise. The  $P_{rISI}$  means the total received power after the first ray of light and is modeled as

$$P_{rISI} = \int_{T}^{\infty} \left( \sum_{i=1}^{\text{LEDs}} h_i(t) \otimes X(t) \right) dt, \tag{6}$$

where *T* is the time for the first light ray to reach the detector,  $h_i(t)$  is the channel gain and X(t) is the transmitted signal.

The shot noise is inherent to photodiodes. It is caused by the signal and ambient light and describes the fluctuation in the number of detected photons and, therefore, the variation of the photocurrent generation [10, 11]. This shot noise component is given by

$$\sigma_{shot}^2 = 2q\gamma(P_r + P_{rISI})B + 2qI_{bg}I_2B,\tag{7}$$

in which q is the elementary charge, B is the equivalent noise bandwidth,  $I_{bg}$  is the current generated by the backlight and  $I_2$  is a noise factor.

The thermal noise is caused by the electronic pre-amplification in the receiver's frontend, usually a transimpedance amplifier, to convert the photocurrent into a voltage [10, 11], and is given by

$$\sigma_{thermal}^{2} = \frac{8\pi kT_{k}}{G}\eta A I_{2}B^{2} + \frac{16\pi^{2}kT_{k}\Gamma}{g_{m}}\eta^{2}A^{2}I_{3}B^{3},$$
(8)

in which the two terms represent, respectively, noise from the feedback resistor and from the FET channel. k is the Boltzmann's constant,  $T_k$  is the absolute temperature, G is the open-loop gain,  $\eta$  is the fixed capacitance of the photodiode per area unit,  $\Gamma$  is the FET's noise factor,  $g_m$  is the FET's transconductance and  $I_3$  is also a noise factor [12].

In our experimental setups and simulations, we employ OOK (on-off keying) modulation, which is a usual VLC modulation format [10, 21]. In this case, the bit error ratio (BER) for OOK is given by

$$BER_{OOK} = Q(\sqrt{SNR}),\tag{9}$$

where

$$Q(a) = \frac{1}{\sqrt{2\pi}} \int_{a}^{\infty} e^{-b^{2}/2} db.$$
 (10)

## 4 Illumination Characterization and Analysis

#### 4.1 Ray-Tracing Analysis

First, we characterize the luminaire's illumination features in Apex. To determine the total luminous flux ( $\psi_{\nu}$ ) for the luminaire, we refer to the LXML-PW31 LED's datasheet, which states that its typical luminous flux is 105 lm. In order to define the radiant flux within the Apex domain, the source generated 10 wavelengths in the range of 350–800 nm and we defined the total radiant flux of the system containing only one LED to be 1 W, as a reference value. In this scenario we obtained a total luminous flux of 282.70 lm and, to obtain a luminous flux of 105 lm, in agreement with the LED's datasheet, we calculate the total power of the system as



Fig. 4 Adjustment of the radiometric flux of the LXML-PW31 LED obtained with the APEX simulation. The circular shape in the images is due to the LED's own radiating geometry



**Fig. 5** Illuminance distribution over a 1 m<sup>2</sup> surface, at a distance of 1.7 m, for electrical supply power values of **a** 1.9 W ( $\psi_{\nu} = 207.2 \text{ lm}$ ) and **b** 5.5 W ( $\psi_{\nu} = 599.1 \text{ lm}$ )

$$P = \frac{1 \text{ W} \times 105 \text{ Im}}{282.7 \text{ Im}} = 371 \text{ mW}.$$
 (11)

The increment of LED devices in the simulation must follow this premise, i.e., seven LXML-PW31 LEDs must be calibrated for the emission of a radiant flux of 2.6 W (7 × 371 mW). Therefore, when the seven LEDs are subjected to the adjustment of radiated power, the result is a total luminous flux,  $\psi_{\nu}$ , of 725.9 lm. In Fig. 4 simulations performed to obtain these results are presented.

An important aspect of VLC is the capability of providing illumination and communication at the same time [10]. Thus, we have evaluated the luminaire's illumination features by analyzing the illuminance distribution over a surface, similar to the previously presented irradiation distribution simulation, over a  $1 \times 1$  area, distant 1.7 m from the source. We do not employ the concentrator in this simulation and corresponding results are presented in Fig. 5, considering the luminous flux of 725.9 lm, for two different power supply values.



Fig. 6 Room modeled in the Apex software for the simulation of illuminance coverage, considering the lamp  $\mathbf{a}$  without concentrator and  $\mathbf{b}$  with concentrator



Fig.7 Illuminance distribution over a  $5 \times 5$  m room, considering the lamp **a** without concentrator and **b** with concentrator

In order to analyze the illumination in a whole environment, such as a room or office, we simulated the use of 9 luminaires equally distributed over the ceiling of a  $5 \times 5$  m room, as depicted in the Apex modelling of Fig. 6. The floor is distant 2.5 from the ceiling. We considered scenarios with and without the use of the concentrator. Results are presented in Fig. 7.

According to the EN 12464 standard, at least 20–50 lx are recommended for public areas with low occupation and at least 300–500 lx in spaces with high occupations [22]. In the scenario without the light concentrators, the illuminance values range from 170 to 300 lx. We see that, at this distance, the luminaires may be not considered suitable to illuminate a crowded room, but are suitable for a low occupation room. On the other hand, when employing the concentrator, there is a wider range of illuminance values, from 45 to 830 lx. In this case, the areas directly below the lamps are well within the crowded environment light requirement, while areas near the walls present much lower illuminance values.



Fig. 8 Optical power and illuminance measured as function of electrical power variation consumed by the luminaire at 1 m distance



Fig. 9 Measured illuminance distribution over a surface of  $1 \text{ m}^2$  for power consumption values of **a** 1.9 W and **b** 5.5 W. The distance between luminaire and illuminated area is 1.7 m

#### 4.2 Experimental Analysis

In order to observe the effect of the current supplied to the luminaire in the received optical power and the provided illuminance, we varied the applied current from 10 mA (light near off) to 280 mA, at incremental steps of 10 mA. In this experiment, we employed the



Fig. 10 Environment for communication simulation in Apex. The 7.1 mm<sup>2</sup> photodetection area is placed at the center

concentrator element and the distance between the LEDs and the detector was 1 m. Results are presented in Fig. 8.

Similar to the simulation presented in Fig. 5, we experimentally measured the illuminance distribution over a  $1 \times 1$  m surface. Results are presented in Fig. 9. As in the simulation of Fig. 5, the distance between the luminaire and the illuminated area is 1.7 m. The maximum illuminance at the center was 248 lx and 689 lx, respectively, when 1.9 W and 5.5 W, are consumed by the luminaire. The minimum values obtained are 33 lx (1.9 W) and 106 lx (5.5 W), located at the borders. According to the EN 12464 standard illuminance requirements, as mentioned in the previous subsection, even with the use of the concentrator, the luminaire could satisfy lighting requirements in less crowded scenarios. As for the measurement equipment, we employed the Criffer X-08 Flex Sensor lux meter.

### 5 Communication Simulations and Experimental Analysis

We will now evaluate the communication aspect of our setup. Typically, LED datasheets only provide luminous flux or luminous intensity information, which is useful for illumination design, but not for communication, where optical power is the main parameter of interest [23]. The scenario is depicted in Fig. 10.

#### 5.1 Received Power Analysis

First, we simulate the received power as a function of the transmission distance. Results are presented in Fig. 11. In these simulations, the seven LEDs of the luminaire were adjusted for the emission of four different consumed electrical power values by the luminaire and radiometric fluxes ( $\psi_e$ ): 1.9 W (209 lm), 3.9 W (425 lm), 5.5 W (605 lm) and 7 W (770 lm), considering a luminous efficiency of 110 lm/W. To evaluate this analysis, in the same figure the theoretical curves (employing Eq. 3) are drawn as reference for comparison purposes, considering  $\phi_{1/2} = 20^{\circ}$ .



Fig. 11 Detected optical power in a round surface of  $7.1 \text{ mm}^2$  area as a function of the distance related to the luminaire for different transmitted power values. Comparison between theoretical curves and Apex ray-tracing simulations

Parameter	Symbol	Value
Room temperature	$T_k$	300 K
Open loop gain	G	10
Fixed capacitance	η	12 pF/cm <sup>2</sup>
Effective photodetection area	Α	7.1 mm <sup>2</sup>
Noise factor	$I_2$	0.562
Noise factor	$I_3$	0.0868
Equivalent noise factor	В	100 MHz
FET channel noise factor	Г	1.5
FET's transconductance	$g_m$	$30 \times 10^{-3} \mathrm{S}$
Photodetector's responsivity	γ	0.42 A/W
Backlight current	$I_{bg}$	5.1 mA
Filter gain at reception	$T_s(\beta)$	0 dB
Lens gain at reception	$g(\beta)$	0 dB

## 5.2 Communication Performance Analysis

Table 1 Parameters for the SNR

calculation

Lastly, we analyze the parameters for the communication performance of the setup. In Table 1 we list the noise parameters employed in the theoretical simulations. We used parameters that correspond to our experimental setup wherever possible; otherwise, we employed reference parameters as listed in [12].



Fig. 12 Block diagram for BER versus distance measurement setup



Fig. 13 BER versus distance for OOK modulation between theoretical and experimental values

Our communication experimental setup is represented in Fig. 12. The LED module is driven by a bias-t that combines the modulated signal from an arbitrary waveform generator with the power supply. The OOK-NRZ signal is generated in Matlab and embedded into the AWG. As the signal from the AWG is generated with a small amplitude, the signal is amplified before being combined at the bias-T. Our receiver is a Hamamatsu C12702-12 module [24], which has an APD with a 7.1 mm<sup>2</sup> photodetection area. After the transmission in the optical wireless channel, the received signal at the photodetector module is captured with an oscilloscope and then processed off-line in Matlab.

In Fig. 13, theoretical and experimental BER versus distance curves are plotted for a power input of 7 W, evaluated for distances from 1.4 to 2.2 m with OOK modulation at 2 MHz data rate.

We note that the two curves have a similar behaviour. The experimental measured results have a slightly worse performance than the theoretical model, which may be the result of not ideal component behaviour and other unforeseen effects in the communication channel.

## 6 Conclusions

In this paper, we analyzed the illumination and communication features of a LED luminaire. While VLC is emerging as a communication solution for future high-performance links, it is important to develop evaluation tools for the performance of the components. As one of the main features of VLC is its double ability to illuminate and to communicate, we focused on both these aspects for a more embracing evaluation. By applying theoretical analysis employing the VLC channel model and ray-tracing simulations, we obtained a comprehensive understanding of the setup, which was then validated through experimental measurements.

The LiFi standard is a proposal of a complete wireless networking solution employing VLC while also providing illumination to the environment [25]. In this sense, the analysis of the capabilities of communication and illumination of off-the-shelf LED consumer luminaires, as proposed in this work, is relevant.

The evaluated luminaire showed satisfactory communication and illumination performance for small to medium distances, which can be expanded by using more lamps or high power LED devices. As the studied luminaire is not designed towards environmental lighting, illumination results were mixed depending on the scenario, being suitable for illuminating small areas at relatively small distances, but not so appropriate for a whole room illumination. Experimental results for the communication link presented a BER near  $10^{-6}$ , which may be considered a satisfactory target ratio for some applications [12, 16], at distances up to 1.4 m. It should be noted that these communication performance values may be improved by amplifying the photocurrent at the receiver, by installing lenses before the photodetector or by using more robust modulation formats.

The simulated scenarios showed correlation between each other, indicating that these approaches may be employed to support one another in the design of VLC systems. Further studies related to the adopted approach may include fine-tuning in the theoretical to experimental transposition and also analysis considering other luminaire setups available in the market, as well as scenarios where multiple light sources are employed.

Acknowledgements Authors thank the Multi-User Photonics Facility-UTFPR-CT used during the experimental work.

**Funding** This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Finance Code 001 and by the European Regional Development Fund (FEDER), through the Competitiveness and Internationalization Operational Programme (COMPETE 2020) of the Portugal 2020 framework, Project LANDmaRk (POCI-01-0145-FEDER-031527) and Financial Support National Public (FCT)(OE).

Availability of data and material Not applicable.

Code availability Not applicable.

## Declarations

Conflict of interest Not applicable.

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