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Interactive internet of things based on dark light system for smart room

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Abstract

Visible light communication (VLC) is a rising guaranteeing new innovation for optical wireless communication with taking part favorable circumstances not available on radio communication. Especially, as connectivity propagation, both across the world and via the Internet of Things. Any communication system is based on the LED light is luminous to verifying the connection. The major challenge in VLC is how to make a communication system to download data in the dark light when indoor lighting is not needed. This paper explains how visible light can be used to transmit data even when the light appears dark or off. We investigate VLC minimum illumination to receive power, to enable users to receive data when the light is "OFF". This paper focuses on improving the system performance including signal to noise ratio, required power and bit error rate. VLC with different modulation schemes highlighting as the On–OFF Keying, Pulse Position Modulation, L-Pulse Position Modulation, and Inverse L-Pulse Position Modulation are investigated in the dark light for communication. A short part of Pulse Width Modulation is used for dimming illumination. The paper examines the selected parameters and essential requirements of VLC dark light system which are power, bandwidth efficiency and the dimming factor of light sources. We confirm that dark light is enough to keep up information paces of a few kbps. This looks good for the eventual fate of VLC for actualizing shrewd lighting systems.

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1 Introduction

Visible light communication (VLC) or Light Fidelity (Li-Fi) have attracted a great interest in latest years in order to overcome the limited spectrum in radio frequency (RF) communications to fulfill the expanding interest for rapid communication interfaces between electronics and sensors, and to empower the vision of a profoundly interconnected world like Internet of Things (IoT), smart cities, smart homes and smart room (Bamiedakis et al. 2020).

In IoT, all the devices will have connectivity and processing. For example, televisions (TVs), microwaves, fridges and vehicles will all day be connected, every day associated, requiring significantly more resources, either from the gadgets themselves or from the supporting network system infrastructure (Matheus et. al 2019). Dark VLC can become a new IoT network architecture. We can change existent lighting infrastructure into a backbone network of the IoT.

The ceiling LED lights are connected to the Internet using power line communication technology. The ceiling lights easily switch between the VLC's normal mode when lights are on to dark VLC when lights are off. Brightening a light onto IoT devices provides them with always-on connectivity (Want et al. 2015). IoT devices not only decode data from the ceiling light, but also emit or reflect modulated lights using dark VLC to distribute their collected data (Li et al. 2015).

Illumination and communication are the two most essential elements of visible light communication that utilize a light emitting diode (LED) using off-the-shelf, low-cost LEDs and photodiodes. LEDs have points of interest over the conventional light sources having incorporate little size, long lifetime a light source with low force utilization.

In a sunny day with shining sunlight, when indoor lighting is not needed, or in the late evening during our rest, or in the night throughout our sleep, do not need bothering with the light ON. However, what happens when the light is OFF or dim? The simplest answer is light OFF (completely) = Communication OFF.

In the dark, VLC expends much lower power than the VLC in the light connections and hence is engaging for empowering VLC uplink or communication around IoT devices with limited energy budget. The difficulties of VLC commonly require the light to be ON during communication. Then, how to connect when the lights show "OFF" or dark? The communication ceaseless in any event, when the LED light seems dark. Dark light is a special mode in VLC, whenever perceptible light beams are not desired (Xia Zhou 2016). Dark light, also called invisible VLC implementation, achieves 1.6 kbps data rate and supports up to 1.3 m of communication distance while drastically reducing the power consumption of the LED from 19.8 W to 104 μW with 500 ns light pulses used in dark light and 0.007% LED duty cycle (Tian et al. 2016a, b). Dark light LED is not noticeable from an LED in light OFF mode. The key idea is to reduce the LED duty cycle to an extremely-low level and encode data into ultra-short light pulses. The light pulses are imperceptible to human eyes, so, the data could be transmitted via VLC without illumination. But, the photodiodes can detect these light pulses and decode data. Dark VLC also provides a new ultra-low power, always-ON connectivity affordable for mobile and also enable communication for IoT devices to communicate with either the ceiling light in the uplink, or other mobile devices and is appealing for IoT devices with energy constraints (Tian et al. 2016a, b).

Borogovac et al. analyzed discussed the standard for lights to appear OFF and achievable resulting data rates in varying low illuminance level (Borogovac et al.2011). Optical channel models were leveraged to derive SNR. T. Zhao reduced the LED's duty cycle to an extremely-low level and encoded data into ultra-short light pulses (Tian et al. 2016a, b).

The principle of dark light VLC is to modulate light signal into ultra-short light pulses which are imperceptible by human eye, so, the data could be transmitted via VLC without illumination. It makes VLC more energy saving. The VLC transmitter can contribute more lux in dark light mode in sunny daylight, when the signal light is not perceived. On average, the room is illuminated at 400 lx by daylight indoor (normal mode) and 0.03 lx by night time (dark mode) and sunlight illumination is over 6000 lx. Dark light expands the relevant situation of VLC, as it serves as a special mode that a VLC connection can smoothly switch to whenever perceptible light beams are not desired (sunny day). Thus, when integrated with VLC's normal mode where LEDs are visually on, dark light allows light-based communication be always-on, regardless of the actual light luminance. Furthermore, with the LED light working on an ultra-low duty cycle, dark light significantly drives down the energy consumption of the LED and thus makes VLC more moderate to cell phones with tight energy budget.

In this paper, we highlight on VLC dependence on visible light beams and keep data communication even when the LED transmits very low luminance. We discuss dark light that preserves the light-based communication even if the light appears dark or off. The key idea is to encode data into ultra-short light pulses, such that these pulses are imperceptible to human eyes yet detectable by photodiodes. We use off-the-shelf LEDs and low-cost photodiodes. We investigate VLC minimum illumination to receive power, to enable users to receive data when the light is "OFF". This paper focuses on improving the system performance including signal to noise ratio (SNR), required power and bit error rate (BER). VLC with different modulation schemes highlighting as the On–OFF Keying (OOK), Pulse Position Modulation (PPM), L-Pulse Position Modulation (L-PPM), and Inverse L-Pulse Position Modulation (IL-PPM) are investigated in the dark light for communication. A short part of Pulse Width Modulation (PWM) is used for dimming illumination. The paper examines the selected parameters and essential requirements of VLC dark light system which are power, bandwidth efficiency and the dimming factor of light sources and discuss LoS model and neglect the NLoS component in the dark light mode.

The organization of this paper is as follows, Firstly, overall view of VLC in the dark system and details of each part are presented in Sec. 2. Section 3 describes VLC model and analysis. Dimming control system is discussed in Sec. 4. Section 5 shows the schemes used in the dark system. The obtained results are displayed and discussed in Sec. 6. This is followed by the main conclusion in Sec. 7.

2 VLC system

The main components of VLC transmitter and receiver are shown in Fig. 1. The VLC system consists of VLC transmitter, optical link and VLC receiver. Intensity modulation and direct detection (IM/DD) used for data transmission through LED. Data is modulated by intensity modulation based on the instantaneous power of LED. The photodiode performs direct detection which transforms the received optical power to electrical power (Zeng et al. 2008).

LED lighting is emitted in the form of a Lambertian emission shown in Fig. 2.

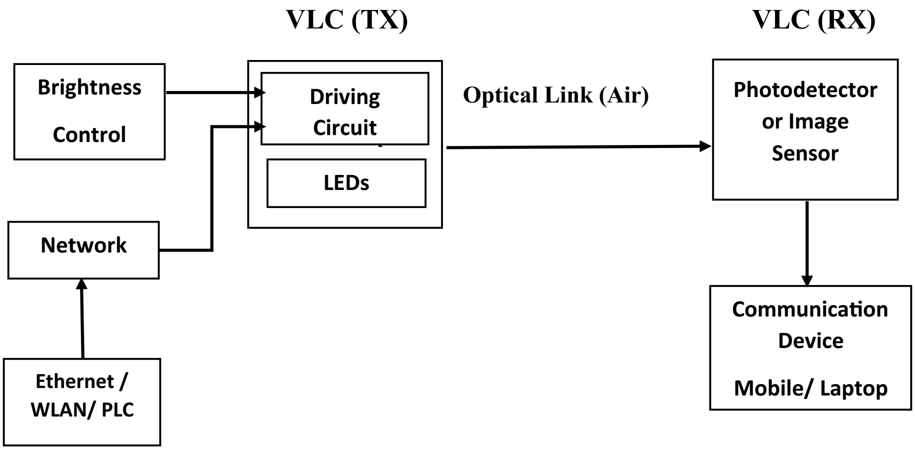


Fig. 1 The VLC transmitter and receiver

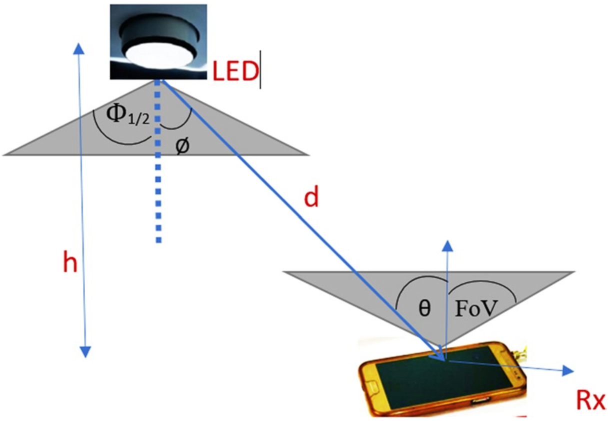


Fig. 2 Transmitter and receiver with a Lambertian emission

The angular distribution pattern of the radiation intensity can be modelled using the generalized Lambertian radiation pattern (H. Park et al. 1995) which is applied to model the LED radiant irradiance, $R_o(\phi)$.

$$R_0(\phi) = \frac{(m+1)}{2\pi}\cos^m(\phi) \tag{1}$$

where ϕ is the angle of irradiance related to the axis normal to the transmitter surface, m is the order of Lambertian emission and is defined by the LED's semi-angle at half power $\phi_{1/2}$.

$$m = \frac{(-ln2)}{\ln(\cos(\phi_{\frac{1}{2}}))} \tag{2}$$

The effective area of a receiver (photodetector) falls on the detector at the angle θ

$$A_{eff}(\theta) = A\cos(\theta) \quad 0 < \theta < 90^o \tag{3}$$

where θ is the angle of incidence with related to the axis normal to the receiver surface. No signal is taken into consideration if the angle incident is greater than the field of view for a LoS design (equal 90°).

2.1 Channel modelling

Light beams propagate from the LED to the receiver via two main channels: line of sight (LoS) and non-line of sight (NLoS).

2.1.1 LoS propagation model

Figure 3 shows the LoS and NLoS propagation models. In this paper, we focus on LoS model and neglecte the NLoS component in the dark light mode. In an indoor environment, light undergoes multiple reflections between different surfaces/objects before reaching the receiver. Thus, received power, P_r, must be extended to include the effect of the NLoS components. But, in the dark mode the received power is weak to make the NLos effect. So, we neglect this effect in this case.

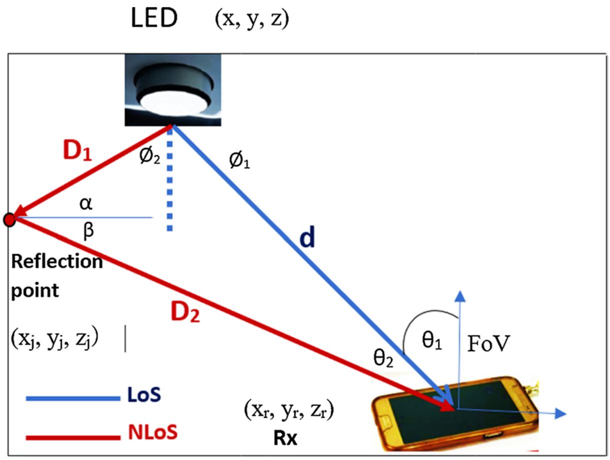
Then, the channel gain can be generally modelled by (H. Park et al. 1995)

$$H_{LOS}(0) = A \cdot\ g(\theta) \cdot\ T(\theta) \cdot \left[\frac{m+1}{2\pi}\right] \cdot \cos^m\phi \cdot \frac{\cos\theta}{d^2} \tag{4}$$

where A is receiver detector area, θ is the incidence angle, ϕ is the irradiance angle, $T(\theta)$ is the gain of optical filter, d is the distance between the LED and a detector surface, θ_{FoV} denotes the width of the field of view (FoV) at a receiver and n is the refractive index. The gain, $g(\theta)$, of the optical concentrator at the receiver is defined by (Kahn et al. 1997)

$$\boldsymbol{g(\theta)} = \frac{\boldsymbol{n}^2}{\boldsymbol{sin}^2\boldsymbol{\theta}_{\boldsymbol{FoV}}} 0 \le \theta \le \theta_{FoV} \tag{5}$$

Fig. 3 LoS and NLoS propagation models



2.2 Basic performance analysis of VLC system

2.2.1 Horizontal illuminance

The horizontal illuminance, E_{hor}, at a point (x, y) is given by (Komine et al. 2004)

$$E_{hor} = \frac{I(0)\cos^m(\phi)}{d^2 \cdot \cos(\theta)} \tag{6}$$

where the center luminous intensity is given by

$$I(0) = \frac{(m+1)}{2\pi d^2} \tag{7}$$

The radiation intensity, $I(\phi)$, at a desk surface is given by

$$I(\phi) = I(0) \cdot \cos^m \phi \tag{8}$$

2.2.2 Received power

The received power at the receiver, P_r, of the LoS link, is defined by (Qiu et al. 2016)

$$P_{r_{LOS}} = \sum_{LEDS} \left(P_t \cdot H_{LoS}(0) \right) \tag{9}$$

where $H_{LoS}(0)$ is the channel gain

$$P_{r_{LOS}} = P_t \cdot \frac{(m+1)A}{2\pi d^2} \cos^m(\phi) T(\theta) g(\theta) \cos(\theta) \tag{10}$$

2.2.3 SNR

The reflections of walls are not considered in analyzing SNR since the light from LoS is dominant. The electrical SNR can be expressed in terms of the photodetector responsivity, R, received optical power, P_r, and noise variance as (Ghassemlooy et al. 2013)

$$SNR = \frac{R^2 P^2_{r_{LOS}}}{N^2} = \frac{R^2 P^2_{r_{LOS}}}{\sigma^2_{shot} + \sigma^2_{thermal}} \tag{11}$$

where σ^2_{shot} and $\sigma^2_{thermal}$ are, respectively, the shot noise and the thermal noise variances, given by (Ghassemlooy et al. 2013)

$$\sigma^2_{shot} = 2q_r P_r B + 2q_r I_B I_2 B \tag{12}$$

$$\sigma^2_{themal} = \frac{8\pi k T_k}{G} \eta A_e I_2 B^2 + \frac{16\pi^2 k T_k \Gamma}{g_m} \eta^2 {A_e}^2 I_3 B^3 \tag{13}$$

where q_r is the electronic charge, I_B is the photocurrent due to background radiation, I_2, I_3 are the noise bandwidth factors, and B is the noise-bandwidth of the photodetector, K

is Boltzmann constant, T_k is the absolute temperature, G is the open-loop voltage gain, η is the fixed capacitance of photodetector per area, Γ is the channel noise factor, g_m is the transconductance. Finally, the SNR is (Ghassemlooy et al. 2013).

When the on–off keying (OOK) modulation scheme is considered (Komine et al. 2004), SNR is approximately:

$$SNR = \frac{A_e R P_r^2}{q_r R_b P_n} \tag{14}$$

where P_n is the optical irradiance (W/m^2) contributing to shot noise.

In the dark light, we calculate the SNR (Borogovac et al. 2011):

$$SNR = \frac{A_e R P_r^2}{q_r R_b P_n (1+\gamma)} \tag{15}$$

where γ is a noise parameter representing noise contributed by receiver electronics, but in dark environments γ must be accounted. A_e is the effective receiver area (m^2), which includes lensing gain and direction of light incidence, R is photodiode responsivity (A/W) and R_b is the bit rate.

The bit error rate at that bit rate is (Lee et al. 2011):

$$BER = Q\sqrt{SNR} \tag{16}$$

where $Q(.)$ is the Q-function, defined as (Mahdiraji et al. 2006)

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} e^{-y^2/2} dy = 0.5 \times erfc\left(\frac{x}{\sqrt{2}}\right) \tag{17}$$

3 Dark VLC model

The size of the VLC room is 6×6×3 m^3 and it is assumed to be empty except for a lighting system and a detector. The detector is placed at the plane of 0.85 m above the floor. The lighting system consists of five VLC arrays, each containing 60×60 LED chips which are arranged at the ceiling as shows in Fig. 4. A photodetector is contained in the detector, and it could receive the location code if the optical light is incident within its FoV. The IM/DD is utilized in this VLC system due to its simple Implementation. The location of the LEDs in the room in the case of five LEDs arrays is determined as follows (2,2,3), (2,4,3), (3,3,3), (4,2,3) and (4,4,3).

- For a single LED array, the location is present at the center of the room (3,3,3).
- Half power semi-angle is (θ) determined as the angle that is made between the wall and the location of the LED.
- Transmitted power for the LED source is taken as 19.8 W (normal mode) and 104 µW (dark mode) and luminous intensity at which the eye can perceive is taken between 300 1000 lx (normal mode) and from 30–100 lx (dark mode) (Ghassemlooy et al. 2013).

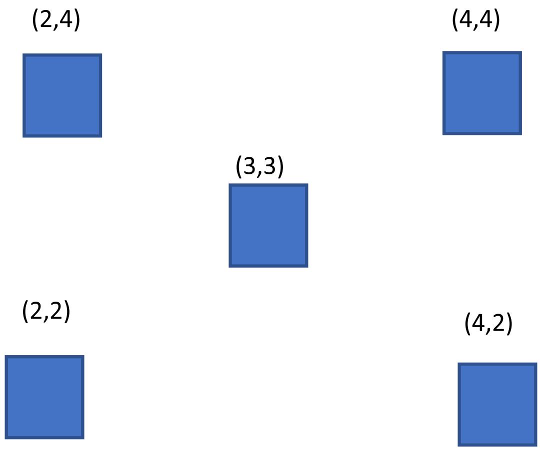


Fig. 4 The position of LEDS on the ceiling location of the 5 LED arrays in the room

A physical model is proposed for system simulation based on the single lens optical transform. The lens is a hemispherical lens (KPA034. With a focal length = 23 mm: Newport). It can provide a very wide FoV. The index of refraction of 1.5. The lens is placed above the imaging plane at a distance of Z, from the flat surface of the lens to the imaging plane (Oswaldo et al. 2014).

LED lights used to optical transmission are installed at a height of 2.5 m from the floor. The height of the desk is 0.85 m, and a user terminal is put on the desk. The number of LED modules is 5, and each one has 3600 (60 × 60) LEDs. The semi-angle at half-power of an LED is 70°. The transmitted optical power of an LED chip is 104 µW, with a center luminous intensity of 0.05 cd. The. These conditions are summarized in Table 1 .

The shot and thermal noise equations and parameters are calculated using the noise model and parameters listed in Table 2 (Khadr et al. 2016).

Table 1 System parameters for VLC link (Khadr et al. 2016); (Nguyen et al. 2010) and (Huang et al. 2017)

	Parameters	Values
Room	Size	6× 6 × 3 m^3
	Walls reflection coefficient	0.8
Source	Number of arrays	5
	Total number of LEDs	5 ×60 × 60
	Transmitted power per LED (drak light)	104 µW
	LED semi angle at half power $\phi_{1/2}$	70°
	Center luminous intensity	0.05 cd
Receiver	Receiver plane above the floor	0.85 m
	Active area	1 cm^2
	Half—angle FoV	70°
	Lens refractive index	1.5
	PD responsivity	0.54 A/W
	Gain of optical filter	1

Table 2 SNR parameters (Khadr et al. 2016)

Parameters	Values
The electronic charge, q_r	1.6×10^{-19} C
Photodiode responsivity, R	0.54
Noise bandwidth factor, I_2	0.562
Absolute temperature,T_k	298 K
Fixed capacitance per unit area,η	112 pF/cm^2
Detector area, A	1 cm^2
FET channel noise factor,Γ	1.5
FET transconductance, g_m	30 mS
Noise bandwidth factor, I_3	0.0868

4 Dimming control techniques

The light intensity is measured in Lux and illuminance range of 30–100 lx is used in dark light. While, a higher level of light intensity required for offices and residential applications in the range of 300—1000 lx Dark VLC can become a new (Faisal A. Dahri1 et al. 2018).

The natural eye can adapt to the low degree of brightening through extending the eye to allow all the lighting to enter the eye. The calculated perceived light from the measuring light as (Faisal A. Dahri1 et al. 2018)

$$\text{Perceived light}(\%) = 100 \times \sqrt{\frac{\text{Measured light}(\%)}{100}} \tag{18}$$

The main aim of the dimming control is to ensure that the data continues even when the user dims the light source. There are two techniques to implement dimming scheme over LEDs: analog dimming and digital dimming.

4.1 Analog dimming technique

Analog dimming was the first technique used for dimming control in VLC and used Continuous Current Reduction (CCR) technique to control the LED illumination. In CCR, the current flow through an LED was directly reduced by reducing the LED voltage to achieve dimming (Zafar et al. 2015; Wang et al. 2012a, b). However, this caused the LED's to be under driven and resulted in chromaticity shifts (18). Chromaticity can be defined as an objective specification that determines the color quality of the LED regardless of its luminance. Hence, the analog dimming was later supplanted by the digital pulse width modulation (PWM) dimming which changed the duty cycle to cause LED dimming.

4.2 Digital dimming technique

Digital dimming is the data to be transmitted and is modulated using modulation techniques and then is superimposed on the dimming PWM signal (Afrah Ali et al. 2016). Hence, reducing the PWM duty cycle reduces the average signal strength and was subjected to external disturbances such as noise. Simple digital modulation schemes such as Pulse Width Modulation (PWM), Pulse Position Modulation (PPM) and Pulse Amplitude Modulation (PAM) are initially used in the dimming control of VLC.

4.3 Pulse width modulation (PWM)

PWM is modulated digitally to drive the LED at a constant current level. PWM modulates the pulses with the duty cycle which is the pulses is "ON" within the time interval state, a data transfer happens (Wang et al. 2012a, b). When duty cycle is "1", the LEDs light is ON with the highest brightness. We can achieve desired dimming percentage by reducing the duty cycle of PWM signal (Wang et al. 2013).

The width of pulses is balanced based on the required dimming level while the pulses get modulation signal in the form of a digital pulse. The data is transmitted when the brightness of the LED light is completely ON. Based on dimming requirement data rate can be obliged and balanced. In (Kwon et al. 2010) J. K. Kwon showed that the higher data rates can be accomplished through any dimming level 0–100% with the modulation technique of PWM frequency. One of the most significant points of interest of PWM is that it accomplishes the dimming without changing light intensity. Therefore, it does not require any color shift like redefine on and off levels in the LED. PWM has a limited data rate up to 4.8 kbps (Kwon et al. 2010).

5 Dark VLC modulation

Different modulation schemes are used in VLC. In VLC system, encoding is done through the intensity of light waves. The demodulation relies upon the direct detection of the data receiver. The intensity modulation is also known as direct detection modulation. It should be that in VLC, *x(t)* represents optical power from LED lightings, not amplitude, and thus, the transmitted power, P_t, is (H. Park et al. 1995):

$$P_t = \lim_{T \to \infty} \frac{1}{2T} \int_{-\infty}^{\infty} x(t)dt \leq \gamma P_{avg} \tag{19}$$

And the received power is:

$$P_r = H_{LoS}(0) \cdot P_t \tag{20}$$

where H_{LoS} (0) is the Direct Current (DC) channel gain.

In OOK, the required received power P_r is:

$$P_r = \sqrt{\frac{qP_n(1+\gamma)R_b SNR}{rA_e}} \tag{21}$$

In the daytime $\gamma = 0$ and night time $\gamma = 10$. The brightness depends on the LED lighting's dimming factor and R_b is a bit rate.

Figure 5 shows the minimum required received power (W/m^2) of the transmitter for illumination with the ambient noise (W/m^2) in the (a) daytime (high ambient noise), (b) night time (low ambient noise) to achieve bit rates $R_b = 1.6$, 20 and 2 Mbps.

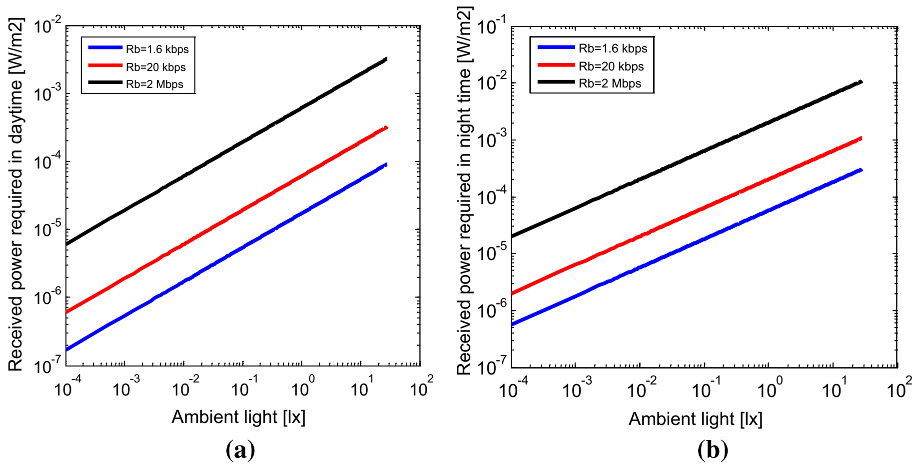


Fig. 5 Daytime and night time with bit rates **a** daytime γ = 0, **b** night time γ = 10

In dark light, the low transmit power system should consider modulations, such as pulse position modulation (PPM) to transmit data. In order to achieve the same R_b and BER performance as OOK, using L-PPM and IL-PPM require transmitted and received power to be adjusted as follows (Borogovac et al.2011).

From Eq. (21), the power required for OOK is (Lee et al. 2011)

$$P_{req\cdot\ OOK} = \sqrt{\frac{N_0 R_b}{2R^2}} Q^{-1}(BER) \tag{22}$$

The required power for L-PPM can be obtained as (Lee et al. 2011)

$$P_{req\cdot\ LPPM} = \frac{P_{req\cdot\ OOK}}{\sqrt{\frac{Llog_2 L}{2}}} \tag{23}$$

The required power for IL-PPM can be obtained as (Lee et al. 2011)

$$P_{req\cdot\ I-LLPM} = (L-1)\frac{P_{req\cdot\ OOK}}{\sqrt{\frac{Llog_2 L}{2}}} \tag{24}$$

Due to the use of ultra-short light pulses, PPM needs greater bandwidth than OOK by a factor $L/\log_2 L$. We choose PPM because it achieves low transmit power that is required in dark light and encode data. The key idea is to encode bits into the exact position of a light pulse in the time domain.

From Eq. (32), we calculate the received power for different modulation schemes, OOK, which forms the basic standard for evaluation, L-PPM and IL-PPM, where L is equal to 2^n, and n is an integer = 1, 2, 3. Figures 6, 7, 8 display the received power required in the dark mode with different bit rate and the ambient noise for various modulation techniques for the VLC system.

It is observed that the IL-PPM requires more power than OOK and L-PPM and the noise (sunlight in daylight- ambient light in night time) decreases gradually. As long as L increases,

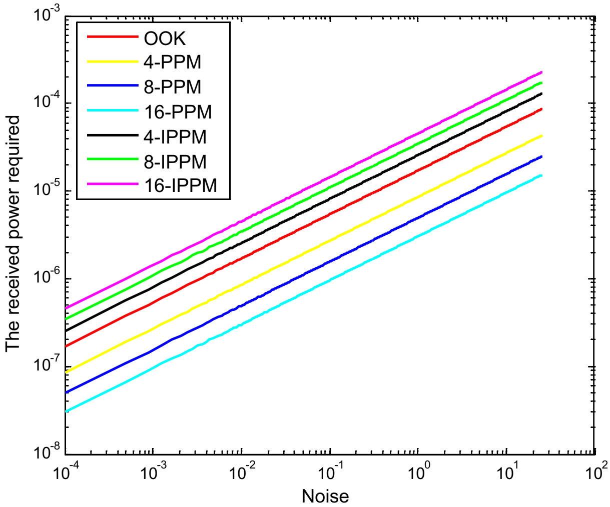


Fig. 6 Received power required for OOK, LPPM, IL-PPM modulation schemes at $R_b = 1.6$ kbps in the dark

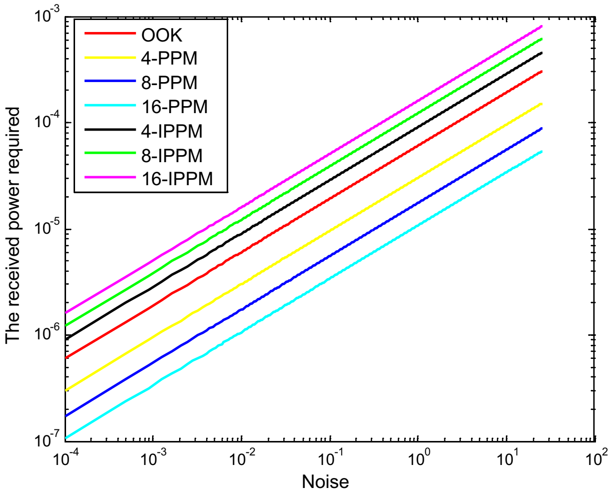
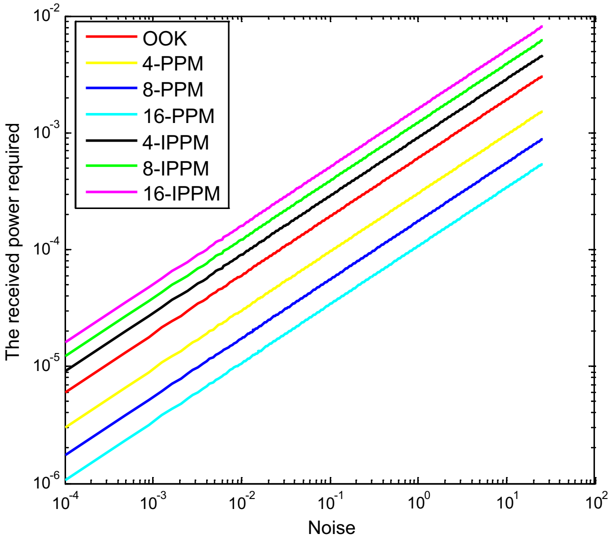


Fig. 7 Received power required for OOK, LPPM, IL-PPM modulation schemes at $R_b = 20$ kbps in the dark

the OOK and PPM requires less power but IL-PPM requires more power. For OOK, the power required decrease with duty cycle but the bandwidth increases accordingly. In PPM, the average optical power required decreases and the bandwidth increase as L increases. We conclude that the minimum power of illumination by using OOK, L-PPM and IL-PPM schemes. We use L-PPM to boost that lowest data rate by using inverse PPM (IL-PPM) to improve SNR and BER.

Fig. 8 Received power required for OOK, LPPM, I-LPPM modulation schemes at $R_b = 2$ Mbps



6 Simulation results and discussion

We measure the received power of the LED when using VLC in the dark (same setting as the illuminance measurement) at 1.6 kbps bit rate, at a semi angle half power, θ, of 10° and 70°. The low transmitted power in the dark light does not make VLC in prone to interference, therefore we do not discuss the diffuse power NLoS in the dark mode.

Figures 9 and 10 show the distribution of received optical power and SNR using Eqs. (12) and (13) in case of a receiver with FoV of 70°. While FoV = 10° in Fig. 11 and simulation distribution of power received and SNR for VLC. Clearly, both the received power and SNR decrease when increasing FoV.

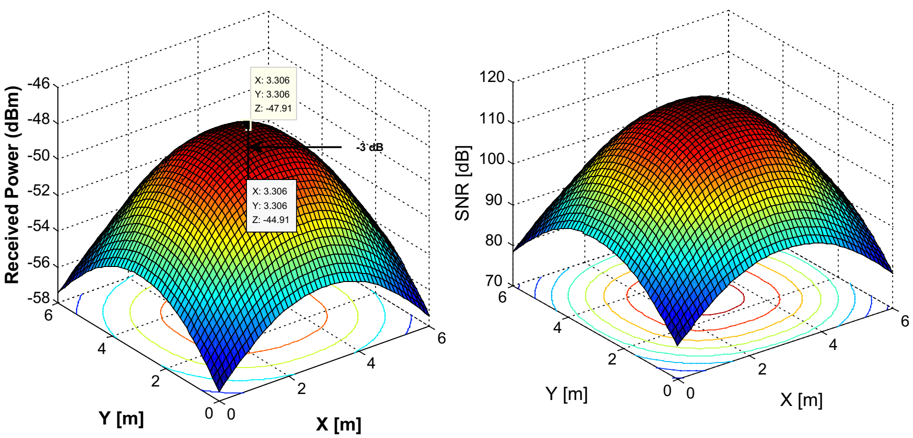


Fig. 9 Received power distribution and SNR in the dark light at $\theta = 70°$, FoV = 70°, $R_b = 1.6$ kbps

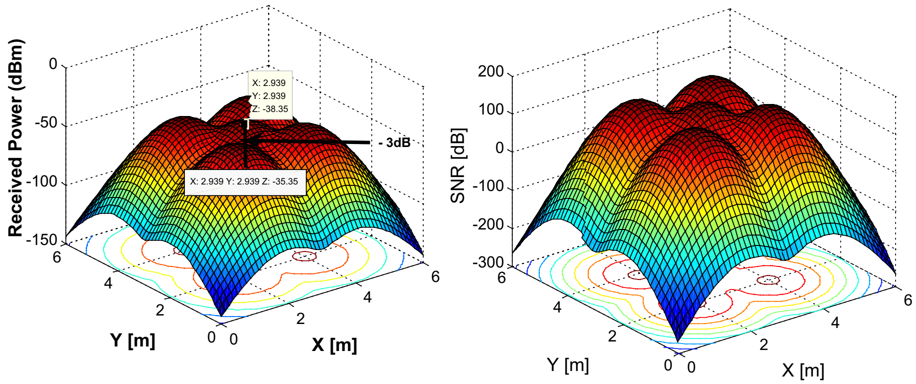


Fig. 10 Received power distribution and SNR in the dark light at $\theta = 10°$, FoV = 70°, $R_b = 1.6$ kbps

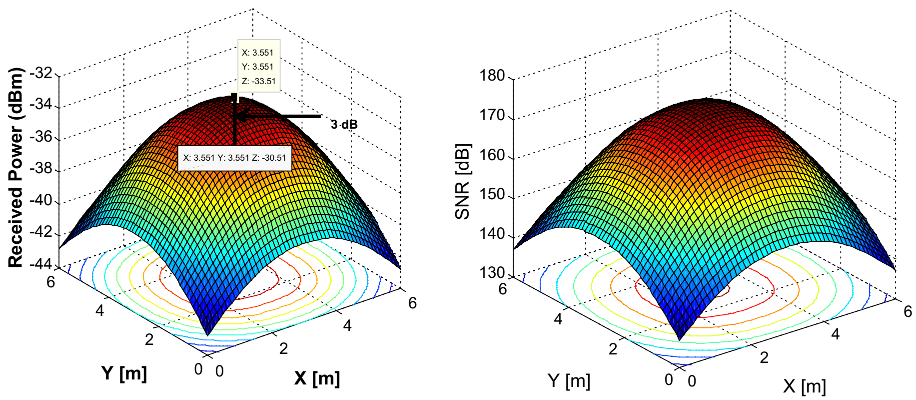


Fig. 11 Received power distribution and SNR in the dark light at $\theta = 70°$, FoV = 10°, $R_b = 1.6$ kbps

A simulation program is performed for indoor VLC system based on MATLAB. This simulation aims to demonstrate the power distributed over a certain area, in order to accomplish network coverage in dark light. The optical power distribution for at receiver plane in a LoS path (ignoring the reflection of walls) is shown in Figs. 10 and 11, in case of FoV of 70° and 10°, respectively. Clearly, in both figures, the received power decreases when increasing FoV. An almost uniform distribution of optical power is noticed at the center with a maximum power of − 38.35 and − 33.51 dBm, in Figs. 10 and 11, respectively. However, depending upon the semi-angle at half-power $\theta = 10°$, such uniform power distribution is not possible to achieve, Fig. 10. For the semi-angle at half-power $\theta = 70°$, 3 dB below the maximum value, a power level of − 30.51 dBm is obtained in all the places of the room. The received power, which is very small to received data in the dark, will make broadband communication possible.

The distribution of horizontal illuminance is obtained through Eqs. (8) and (9) and is displayed in Fig. 12 at a user terminal equipped with the LED lights listed in Table 2. According to the standardized by International Organization for Standardization (ISO),

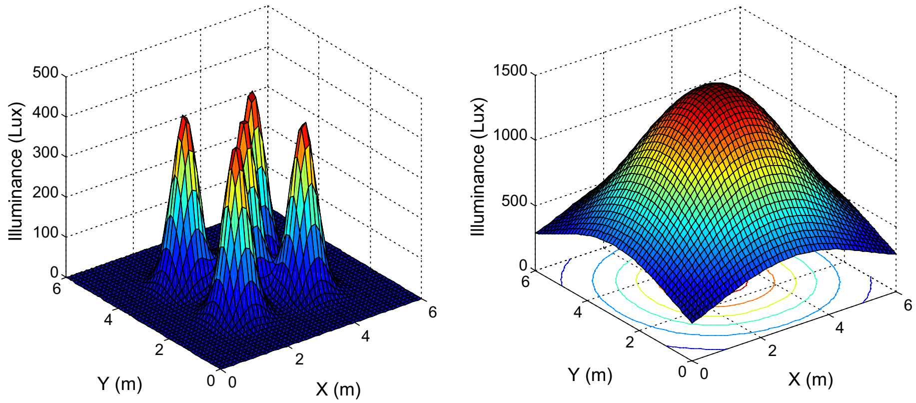


Fig. 12 Distribution of illuminance in case of 5 transmitters **a** $\phi_{1/2} = 10°$, **b** $\phi_{1/2} = 70°$

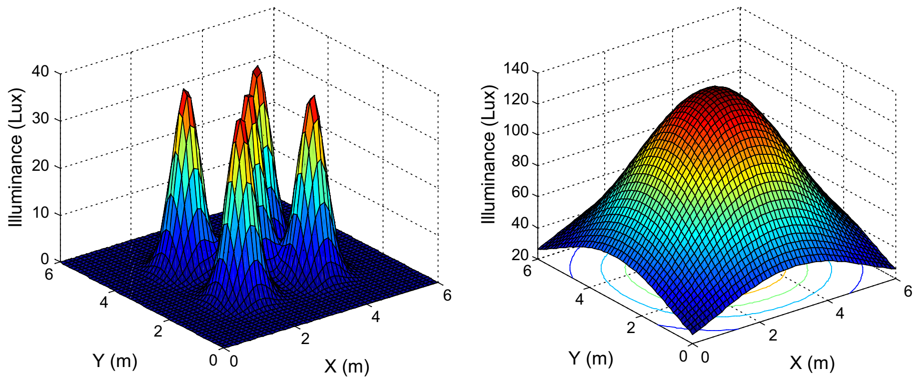


Fig. 13 Distribution of illuminance in case of 5 transmitters in the dark **a** $\phi_{1/2} = 10°$, **b** $\phi_{1/2} = 70°$

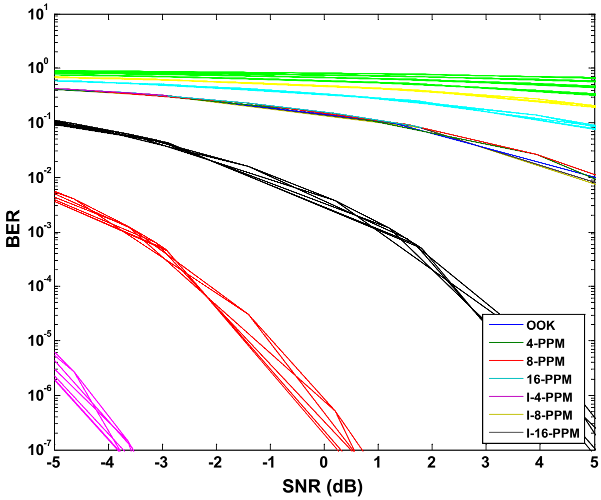
the illuminance of this system is from 300 to 1500 lx is obtained in all the places of the room and is sufficient for office work.

Figures 12 and 13 shows the horizontal illuminance distribution of such arrangement, where sufficient illuminance is obtained in all the places of the room. However, it is obvious that illumination is not equally distributed throughout the room, where it has much higher value at the center than the corners.

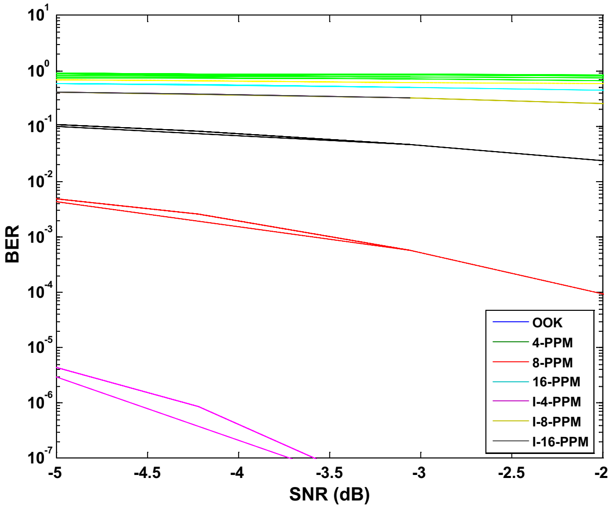
6.1 System BER

The BER for the OOK scheme is actually calculated by the same equations as in 2-PPM, Eqs. (16) and (17). In Fig. 14, we compare the BER performance of OOK, with that of L-PPM and IL-PPM, where it is obtained as (Mahdiraji et al. 2006)

$$BER_{L-PPM} = Q\left(\sqrt{\frac{Llog_2L}{2}}\sqrt{SNR}\right) \tag{25}$$



(a) In the light mode.



(b) Dark mode.

Fig. 14 BER against SNR for OOK, 4-PPM, 8-PPM, 16-PPM, I-4-PPM, I-8-PPM and I-16-PPM. In the light and dark mode

$$BER_{IL-PPM} = Q\left(\frac{1}{L-1}\sqrt{\frac{Llog_2L}{2}}\sqrt{SNR}\right) \tag{26}$$

Figure 14 shows that the BER is better case of IL-PPM modulation than L-PPM while OOK is considered as a moderate modulation technique.

7 Conclusion

We presented dark VLC, a new communication primitive, that encodes data into imperceptible, ultra-short light pulses, allowing a VLC link to be sustained even when the light appears dark or off. We used off-the-shelf LEDs and low-cost photodiodes. Dark VLC broadens the applicable scenario of VLC and significantly drives down the power consumption of a VLC transmitter. It provides a new ultralow power, always-on connectivity affordable for mobile and IoT devices. This work discusses the possibility to communicate date indoor even when LED lights appear dark, which achieves 1.6 kbps with 1.3 m supporting distance. We improved this case to minimize the required power received to send the data in the dark light mode is suitable. Furthermore, we showed that very low light emission (104 μW) is sufficient to maintain data rates of several kbps.

PPM, L-PPM and IL-PPM modulation schemes are investigated and compared with the simplest OOK one. Assuming L = 4, 8, and 16, for L-PPM, the average power required decreases steadily with increasing *L*, but, in the expense of the used bandwidth. PPM requires less power as L increases, but its bandwidth increments too. Therefore, it is desired to choose such modulation scheme that can limit the effects of dimming and gives better results regarding data rate. From the review and observation, we have concluded that IL-PPM provides reliable communication as compared to many other schemes used for VLC such as OOK, L-PPM, power requirement, and data rates and suitable to reduce the transmitted power to improve data rate, SNR and a BER.

It is smarter to utilize low order modulation techniques to accomplish high-speed data with less mistakes by satisfying the dimming and communication requirements. In addition, we should go for a fitting and significant modulation technique that is reasonable for channel quality to transmit high-speed data in significant distance efficiently under dimming control. Duty cycle, bit rate, transmission distance are the considering parameters for good communication link.

We have researched and dissected the performance of VLC system under dimming control scheme. To keep up the communication quality in terms of number of transmitted bits and a BER of less than 10^{-3}, the data rate must be expanded when the duty cycle of PWM dimming control signal is decreased.

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