



Visible light communication (VLC) using Internet of Things (IoT) in 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.

Keywords: VLC · Dark light · PWM · IoT

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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 μ W 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 with-out 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. Further-more, 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 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).

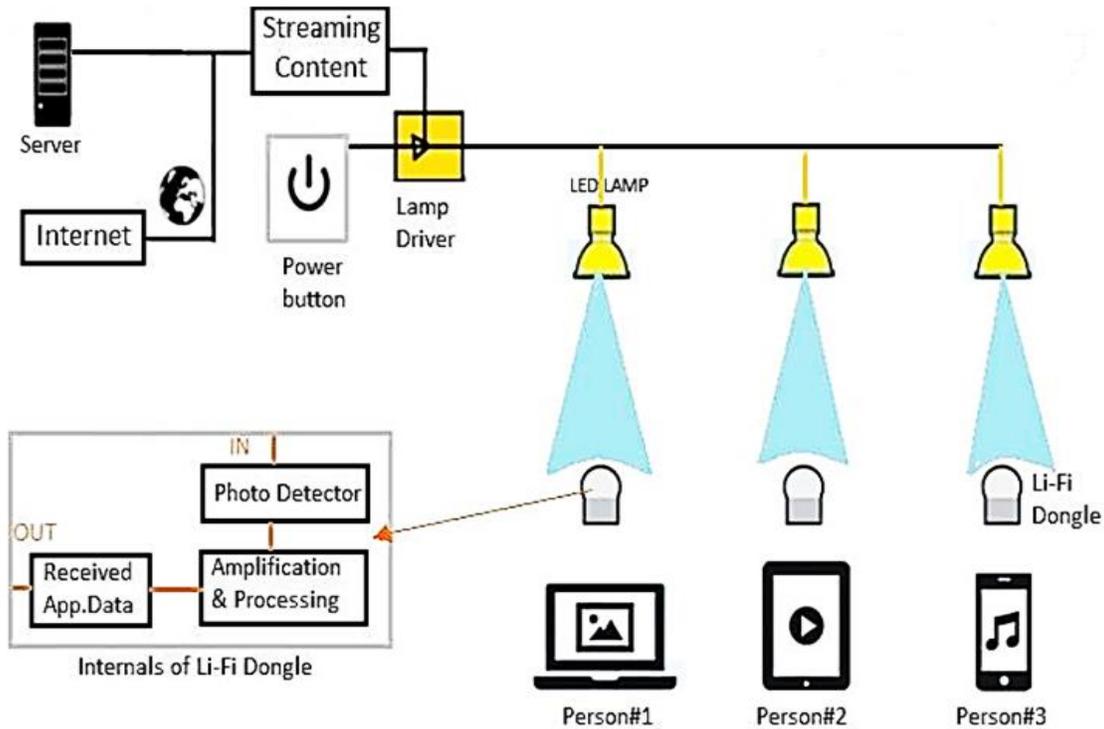


Fig. 1 The VLC transmitter and receiver.

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 neglect the NLoS component in the dark light mode. In an indoor environment, light undergoes multiple reflections between different surfaces/objects before reaching the receiver.

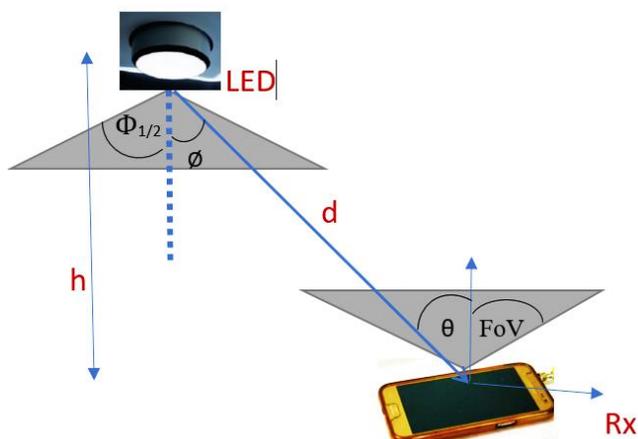


Fig. 2 Tx and Rx with a Lambertian emission.

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) 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)

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

Dark VLC model

The size of the VLC room is $6 \times 6 \times 3 \text{ m}^3$ 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).

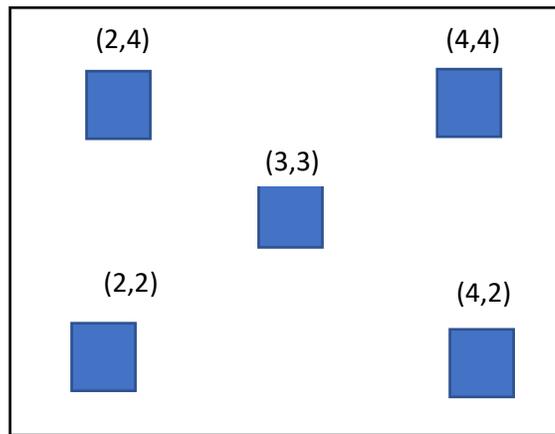


Figure 3 The position of LEDs on the ceiling location of the 5 LED arrays in the room.

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 $104 \mu\text{W}$ (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).(14 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 $104 \mu\text{W}$, with a center luminous intensity of 0.05 cd.

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. Dahril 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. Dahri et al. 2018)

The main aim of the dimming control is to ensure that the data continues even when the user dims the light source.

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).

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.

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).

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):

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

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).

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.

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 .

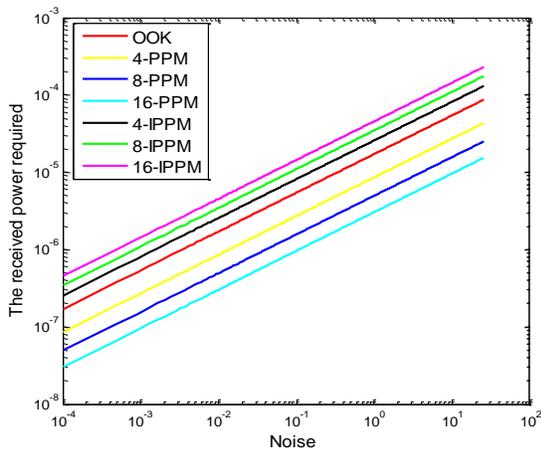


Figure 4 Received power required (W/m^2) for OOK, LPPM, IL-PPM modulation schemes at $R_b=1.6$ kbps in the dark.

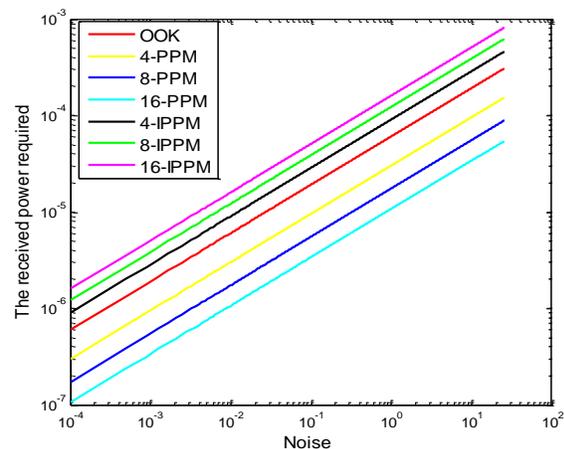


Figure 5 Received power required (W/m^2) for OOK, LPPM, IL-PPM modulation schemes at $R_b=20$ kbps in the dark.

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.

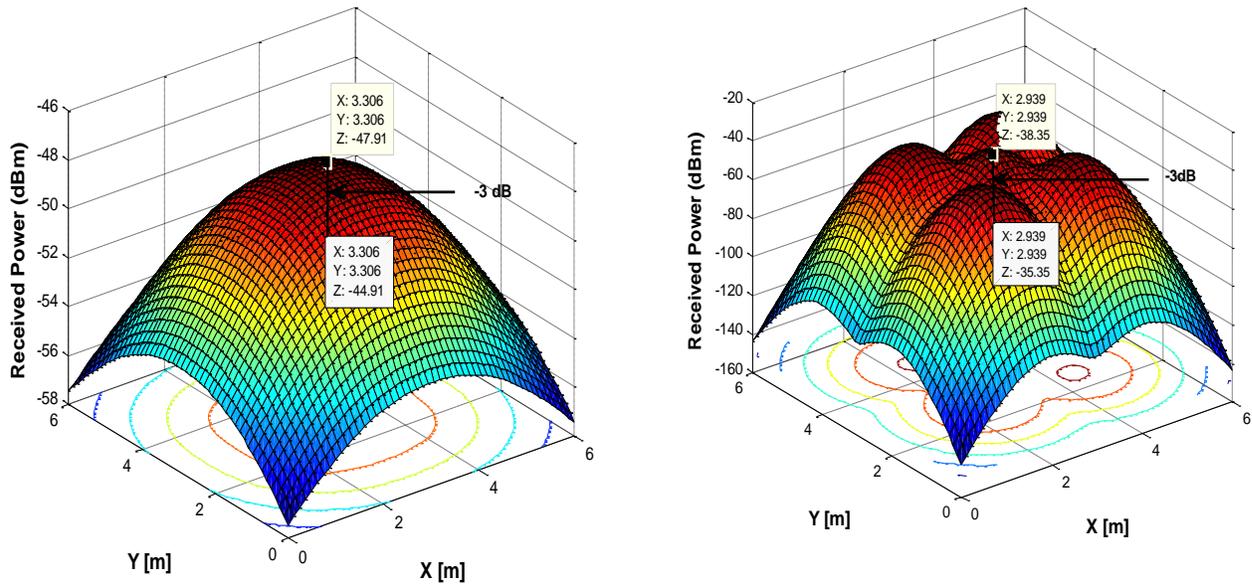


Figure 6 Received power distribution and SNR in the dark light at $\theta=70^\circ$, FoV= 70° , $R_b=1.6$ kbps.

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.

However, depending upon the semi-angle at half-power $\theta = 10^\circ$, such uniform power distribution is not possible to achieve, Fig. 10. For the semi-angle at half-power $\theta = 70^\circ$, 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.

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 data 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 $L = 4, 8, \text{ and } 16$, 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.

References

- Ali, A., Abdulaziz, N.: Dimming control in visible light communication using RPO-OFDM and concatenated RS-CC. *Int J Comput Inf Sci* 12(1), 51–60 (2016)
- Bamiedakis, N., Penty, R.V., White, I.H.: Carrierless amplitude and phase modulation in wireless visible light communication systems. *Philos Trans R Soc A: Math, Phys Eng Sci* 378(2169), 20190181 (2020). <https://doi.org/10.1098/rsta.2019.0181>
- Borogovac, T., Rahaim, M. B., Tuganbayeva, M., and Little, T. D. C.: “Lights-off” visible light communications”. 2011 IEEE GLOBECOM Workshops (GC Wkshps), pp. 797–801 (2011). doi:<https://doi.org/10.1109/glocom.2011.6162564>
- Dahril, F.A., Ali, S., Jawaid, M.: “A review of modulation schemes for visible light communication.” *IJC-SNS Int J Computer Sci Netw Secur* 18(2), 117–125 (2018)
- Ghassemlooy, Z., Popoola, W., Rajbhandari, S.: *Optical wireless communications; system and channel modelling with MATLAB*. CRC Press, Boca Raton (2013). ISBN 9781138074804
- Huang, C., and Zhang, X.: “Impact and feasibility of dark light LED on indoor visible light positioning system.” 2017 IEEE 17th International Conference on Ubiquitous Wireless Broadband (ICUWB), M. M. El Gamal et al. 13 493 Page 18 of 19
INSPEC Accession Number: 17471733, Salamanca, Spain, 12–15 Sep. 2017. doi: <https://doi.org/10.1109/ICUWB.2017.8250973>
- Kahn, J. M., and Barry, J. R.: “Wireless infrared communications”. *Proceedings of the IEEE*, vol. 85, no. 2, pp. 265–298. (1997). doi:10.1109/5.554222
- Khadr, M. H., Fayed, H. A., Aziz, A. A. E., and Aly M. H.: “Bandwidth extension of an enhanced SNR with a higher light uniformity of a phosphorescent white LED based visible light communication system”. 2016 10th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP). (2016). doi:<https://doi.org/10.1109/csnds.2016.7573985>
- Komine, T., Nakagawa, M.: Fundamental analysis for visible-light communication system using LED lights. *IEEE Trans. Consum. Electron.* 50(1), 100–107 (2004). <https://doi.org/10.1109/tce.2004.1277847>
- Kwon, J.K.: Inverse source coding for dimming in visible light communications using NRZ-OOK on reliable links. *IEEE Photonics Technol. Lett.* 22(19), 1455–1457 (2010). <https://doi.org/10.1109/lpt.2010.2062498>
- Lee, K., Park, H.: Modulations for visible light communications with dimming control. *IEEE Photonics Technol. Lett.* 23(16), 1136–1138 (2011). <https://doi.org/10.1109/lpt.2011.2157676>
- Li, J., Liu, A., Shen, G., Li, L., Sun, C., and Zhao, F.: “Retro-VLC”. *Proceedings of the 16th International Workshop on Mobile Computing Systems and Applications – HotMobile*, Vol. 15, pp. 21–26. (2015). doi:<https://doi.org/10.1145/2699343.2699354>
- Mahdiraji, G. A., and Zahedi, E.: “Comparison of Selected Digital Modulation Schemes (OOK, PPM and DPIM) for Wireless Optical Communications”. 2006 4th Student Conference on Research and

Development. pp. 5–10. (2006). doi:<https://doi.org/10.1109/score.d.2006.4339297>

Matheus, L.E.M., Vieira, A.B., Vieira, L.F.M., Vieira, M.A.M., Gnawali, O.: Visible light communication: concepts, applications and challenges. *IEEE Commun Surv Tutor* 1–1, 1–59 (2019). <https://doi.org/10.1109/comst.2019.2913348>

Nguyen, H. Q., Choi, J.-H., Kang, M., Ghassemlooy.: “A MATLAB-based simulation program for indoor visible light communication system,” 2010. 7th International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP 2010), INSPEC Accession Number: 11535434, New Castle, UK, 21–23 July 2010. doi:<https://doi.org/10.1109/csnds.p16145.2010.5580355>

Oswaldo, G., Marcos, F., Medina, G., Martín, I.R.: Open access peer reviewed chapter “multiuser visible light communications,” In: Das, N. (ed.) *Advances in optical communication*. In Tech, Rijeka Croatia (2014). <https://doi.org/10.5772/59053>

Park, H. and Barry, J. R.: “Modulation analysis for wireless infrared communications”. *Proceedings IEEE International Conference on Communications ICC 1995*. pp. 1182–1186. doi:<https://doi.org/10.1109/icc.1995.524287>

Qiu, Y., Chen, H.-H., Meng, W.-X.: Channel modeling for visible light communications-a survey. *Wirel Commun and Mob Comput* 16(14), 2016–2034 (2016). <https://doi.org/10.1002/wcm.2665>

Tian, Z., Wright, K., and Zhou, X.: “The darklight rises: visible light communication in the dark”. *Proceedings of the 22nd Annual International Conference on Mobile Computing and Networking - MobiCom '16*. pp. 495–496. (2016). doi:<https://doi.org/10.1145/2973750.2987384>

Tian, Z., Wright, K., and Zhou, X.: “Lighting Up the Internet of Things with DarkVLC”. *Proceedings of the 17th International Workshop on Mobile Computing Systems and Applications - HotMobile '16*. pp. 33–38. (2016). doi:<https://doi.org/10.1145/2873587.2873598>

Wang, Z., Chen, J., Zhong, W.-D., Yu, C., and Chen, W.: “User-oriented visible light communication system with dimming control scheme”. *The 2012 11th International Conference on Optical Communications and Networks (ICOCN)*. (2012). doi:<https://doi.org/10.1109/icocn.2012.6486243>

Zhong, W.-D., Wang, Z., Yu, C., Chen, J., Francois, C.P.S., Chen, W.: Performance of dimming control scheme in visible light communication system. *Opt. Express* 20(17), 18861–18868 (2012a). <https://doi.org/10.1364/oe.20.018861>

Wang, J. B., Wang, J. Y., Chen, M., and Song, X.: “Dimming scheme analysis for pulse amplitude modulated visible light communications”. *2013 International Conference on Wireless Communications and Signal Processing*. (2013). doi:<https://doi.org/10.1109/wcsp.2013.6677037>

Want, R., Schilit, B.N., Jenson, S.: “Enabling the internet of things.” *Computer* 48(1), 28–35 (2015)

Zafar, F., Karunatilaka, D., Parthiban, R.: “Dimming schemes for visible light communication”, the state of research. *IEEE Wirel. Commun.* 22(2), 29–35 (2015). <https://doi.org/10.1109/mwc.2015.7096282>

Zeng, L., O'Brien, D., Le-Minh, H., Lee, K., Jung, D., and Oh, Y.: "Improvement of Data Rate by using Equalization in an Indoor Visible Light Communication System," 2008 4th IEEE International Conference on Circuits and Systems for Communications. pp. 678–682. (2008). doi:<https://doi.org/10.1109/iccsc.2008.149>

Zhong, W.-D., Wang, Z., Yu, C., Chen, J., Francois, C.P.S., Chen, W.: Performance of dimming control scheme in visible light communication system. *Opt. Express* 20(17), 18861–18868 (2012b). <https://doi.org/10.1364/oe.20.01886>

Zhou, X.: Dartmouth Researchers; "DarkLight" Prototype Enables Visible Light Communication in the Dark, *MobiCom 2016; The 22nd Annual International Conference on Mobile Computing and Networking*.

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