A Review of Modulation Schemes for Visible Light Communication

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Abstract
Visible Light Communication is one of the most researched topics because of high data rates and handles the today's data requirement of the world. VLC uses optical sources; such as Light Emitting Diode (LED) and Light Amplification by Stimulated Emission of Radiation (LASER) for optical wireless communication. The promising features of VLC are higher bandwidth, high data rates, reliability and a secure communication compared to other wireless technologies (such as Wi-Fi, LTE). This paper aims to review the impact of the different modulation schemes, single carrier and multicarrier as highlighted as Multiple Pulse Position Modulation, Variable Pulse Amplitude Position Modulation, Pulse Position Modulation, Color Shift Keying Modulation, Pulse Width Modulation, Double Inverse Pulse Position Modulation, Orthogonal Frequency Division Multiplexing Modulation and Non-return-to-zero modulation. The paper explores the performance of modulation schemes for VLC, the selected parameters and fundamental requirement of VLC system are power, bandwidth efficiency, spectral efficiency and the dimming factor of light sources. The efficiency and reliability of the communication system are analyzed based on tabulated parameters of VLC technology; such as data rate, Signal to Noise Ratio (SNR) and Bit Error Rate (BER). In this study, a review of various modulation schemes have been undertaken by numerous researchers and it provides advantage and limitation of modulation schemes. This review contributes a fruitful data for visible light communication with suitable modulation schemes.

Keywords:
Visible light communication, LEDs,

1. Introduction

The features of visible light communication have transformed the interest of researcher to conduct more research in this area due to its wide spectrum, energy efficient system because of LEDs and latest progress in LED technology with higher switching time considered in nanoseconds. Conventional radio frequency could not able to provide higher data rates below 6 GHz.VLC is able to access the 300 THz of bandwidth, higher data rates could be offered over a short range of communication, to get higher data rate from VLC system, and there is need of implement light sources (LEDs) in a multiple-input-multiple-output (MIMO) approach [4]. Moreover, the communication held through simple LEDs and photodetectors, LEDs provide dual functions with gigabit-per-second as compared to complex and costly RF solutions which required high power utilization for data transmission, generating gigabit-per-second information and the testing of the system. The two fundamental defies for data communication with visible light spectrum are a flickering improvement and dimming sustainability to offer optimal data rates for communication. The variation of light intensity is considered as flickering, any possible fluctuation effecting from the modulated light source for communication, it should be minimized because fluctuation of light intensity can cause visible, negative impact on physiological changes in human beings. To mitigate fluctuations, there is a way to limit the light intensity fluctuations through maximum flickering time period (MFTP). The MFTP is characterized as to improve light fluctuations without human eye can recognize it. The accepted and optimal fluctuation number is considered as safe and sound over the frequency greater than 200 Hz (MFTP<5) [2]. Hence, modulation process in visible light communication is not able to initiate any visible fluctuation either amid the frame or within data frames. Power saving and energy efficiency are possible through dimming support in VLC communication. The dim light sources are desirable to maintain communication. The human eye reacts to low light levels by amplifying the pupil, while enable more light to enter the eye. The response results in a difference between received and measured levels of light. The various modulation schemes for VLC have been discussed in this work as shown in Fig. 1.

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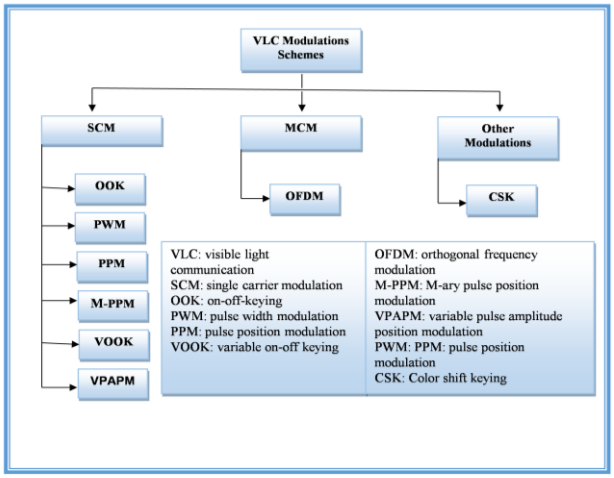

Fig. 1. Modulation schemes considered in this paper

The rest of paper is organized as follows section 2 outline the previous work has been done in the area of VLC; Section 3 describes the comparison of modulation schemes, results discussion and conclusion have been drafted in section 4.

2. Modulation schemes

With comprehension of signal loss due to the distance range occurred is considered as path-loss, environmental noises, and signal to noise ratio (SNR). Various modulation schemes are used in VLC. The most prominent difference in VLC and RF technology is the VLC could not be encoded over phase and amplitude [3]. It implies that phase and amplitude encoding can't be employed 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. The modulation schemes from other types of communications, VLC achieved higher data rates and convene the necessities of visible light to humans. The prerequisites about recognize light can be portrayed under below techniques.

2.1 Dimming

It was proposed in [4] that various levels of lighting intensities are needed while performing different types of actions. The light intensity is measured in Lux and illuminance range of 30-100 Lux is sufficient for diminishing the darkness to perform the visual task in open spots. Conversely, a higher level of light intensity required for offices and residential applications in the range of 300 – 1000 Lux. The advancement in LED driver circuits day by day, it has turned out to be promising to dim an LED to a random level contingent upon the application needs to save energy source. It is necessary to understand the impact of random level of LED light intensity which is visible to human eye. It is shown in [5] that the nonlinear response has been observed between the measured and perceived light as shown in Fig. 2. The human eye is able to acclimatize to the low level of illumination through expanding the pupil to permit more light to enter the eye. The calculated [5] perceived light from the measuring light as in Equation (1)

$$\text{Perceived light (\%)} = 100 \times \sqrt{\frac{\text{Measured light(\%)}}{100}} \qquad (1)$$

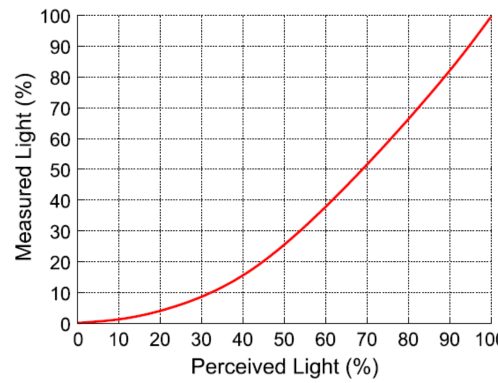

Fig. 2 The human eye perceives the actual measured light differently due toenlargement/contraction of the pupil.

It has been observed that the lamp is darkened 1% of its measured light but human eye perceived it with an increase of 9% and overall light intensity is 10%. The users have an authentication to select the arbitrary level depending on the application and required energy saving but dimming could not impact the communication. The modulation is deployed on the data which supports the dimming level for receiving complete information without affecting the data transmission.

2.2 Flicker mitigation

The extra requirement for VLC modulation schemes are that it should not bring human eye perceive fluctuations in the intensity of light. It has been observed in [6] that fluctuations can cause genuine unfavorable physiological changes in humans. Therefore, it is important that fluctuations in the light intensity should occur faster than the human eye can perceive it. IEEE 802.15.7 standard [7] proposes that the flickering in the intensity of light should be faster than 200 Hz to escape any unsafe impacts. It was noted that the modulation schemes for VLC should alleviate the fluctuations while offering higher data rate for communication. The most prominent reason for flickering is the long run of 0s and 1s which can decrease the rate at which light intensity changes and cause the fluctuation. Long run of 0s and 1s can be alleviated by using the Run Length limited (RLL) codes. It guarantees that the output sequence has balanced reiterations of 0s and 1s. Manchester, 4B5B, and 8B10B are commonly used for RLL codes. In Manchester coding "0" is substituted with "down" transition ("10") and "1" is denoted "up" transition ("01"). The mapping of 4B6B is done through 4 bits symbol to 6-bit symbol that has to adapt the duplications. In the same way, the 8-bit symbol is mapped into 10 bits symbol in 8B10B. The number of extra data bits are included is required in Manchester coding make it a reasonable and suitable choice for low data rate services that require better control of the 0s and 1s balance. The poor performance of 8B10B has been observed in the DC balancing and it removes the additional bits added for high data transmission. The discussion of modulation schemes is deliberated and used for VLC communication (1) On-Off Keying (2) Pulse Modulation (3) Orthogonal Frequency Division Modulation (OFDM) and (4) Color Shift Keying modulation. The mentioned above schemes are discussed and how they help in VLC communication to dimming factor.

2.2.1 On-Off Keying (OOK)

In OOK, the data bits 1 and 0 are represented by LED on-off respectively. In off state, the intensity of light decreased not completely turned off. The main feature of OOK is its simplicity and easy implementation. It is mostly adopted by the wireline communication. In early work, the majority of the researchers have used OOK modulation for VLC using White LED. It produces the blue emitter with a yellow phosphor. The significant limitation of white LED is its restricted transfer speed (few megahertz [8]) because of the slow response time of yellow phosphor. It is proposed by [9] to utilize NRZ (Non-Return-to-Zero) OOK with the white LED and VLC link was demonstrated with the data rate of 10 Mbps. The blue filter is used to remove the slow response rate of the yellow component resulting in a data rate of 40 Mbps [8]. Thus, [10] and [11] has proposed to consolidate the blue filtering with simple equalization at receiver to confine and achieve data rates of 100 Mbps and 125Mbps respectively. The performance can be enhanced through suitable photodiode selection. The authors in [12] demonstrated that the avalanche photodiode works well rather than the P-I-N photodiode at the receiver side. Through avalanche photodiode, the data rate was achieved up to 230 Mbps. The white light is produced by the combination of RGB frequencies. The main factor of the white LEDs is that they have not the slow response time. RGB white LEDs needs three separate driving circuits to escape the white light. In this paper [13] a distinctive approach is used and it has been observed that the RGB white LED was utilized but only the red LED is modulated by the data transmission while remaining to provide illumination. The authors have used P-I-N photodiode and achieved a data rate of 477 Mbps but could not provide the range of distance.
The two methods were proposed in IEEE Standards in [7] as IEEE 802.15.7 which offers dimming support OOK is used as a modulation scheme.

1) Redefine ON and OFF levels: To accomplish the desired level of dimming, the different levels of light intensity are allocated to the ON and OFF levels. The benefit of this technique is that desired level of dimming can be acquired without adding an overhead bit. It retains the data rate which is same as NRZ-OOK modulation, similarly, the communication range reduces at low dimming levels. The noticeable drawback is utilizing lower intensities of light for ON/OFF makes the LEDs be worked at low power driving circuits which is, in turn, has shown to acquire changes in rendering (radiated shade of LED changes) [14].

2) Compensation periods: The solution of the problem is the additional compensation periods are added with the same ON and OFF level of modulation when the LED fully turned on is known as ON periods or off (OFF periods). The term duration of compensation periods is determined based on the desired level of dimming. In particular, if the required dimming level should be more than 50% the ON periods are added otherwise the OFF periods are added. In [15] authors have presented a calculating method of dimming level based on the percentage time of active data transmission (γ) within the transmission interval T to obtain a dimming level of D as

$$\gamma = \begin{cases} (2-2D)\times 100 & : D > 0.5 \\ 2D\times 100 & : D \le 0.5 \end{cases} \tag{2}$$

When the desired dimming level is D with OOK, the maximum communication efficiency E_D can be calculated [15] using information theoretic entropy as

$$E_D = -D\log_2 D - (1-D)\log_2(1-D) \tag{3}$$

It implies that communication system efficiency is a triangular function of the dimming level with maximum proficiency at dimming level of 50%. The efficiency drops linearly when the dimming level decrease in between 0% to 100%. The data rate is reduced due to compensation periods used in dimming. The ON/OFF modulations have unchanged intensity property and also the range of communication is unchanged. To mitigate this problem of low data rate with compensation periods, in [16] suggested using inverse source coding to preserve high data rate while achieving the desired level of dimming.

2.2.2 Pulse Modulation Methods:

Pulse Modulation Methods: OOK offers different features such as simple and feasible implementation; the main restriction is its lower data rates particularly when maintaining various dimming levels. It is the motivation for design alternative modulation schemes based on pulse width and position which are expressed as follows:
Pulse Width Modulation (PWM): A proficient method of accomplishing modulation and dimming through the use of PWM. In this scheme, the width of pulses is balanced based on the required dimming level while the pulses themselves take modulation signal in the form of a digital pulse. The data is transmitting when the brightness of the LED light is full. Based on dimming requirement data rate can be accommodated and adjusted. In [17] authors observed that the higher data rates can be achieved through any dimming level 0% to 100% with the modulation technique of PWM frequency. One of the most important advantages of PWM is that it achieves 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 rates up to 4.8kbps [17]. To cater this restriction, in [18] intended to consolidate PWM with Discrete multitone for jointing dimming control and communication. On transmitter-side communication based on DMT disjointed with dimming based on PWM. The Quadrature Amplitude Modulation (QAM) is bit-streamed and mapped to symbols as shown in Fig. 3.

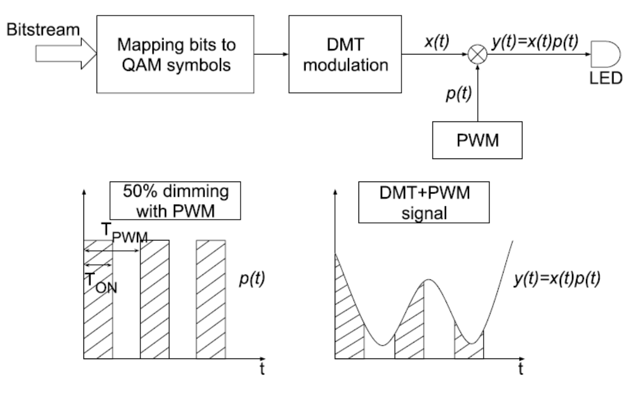

Fig. 3 Transmitter block diagram of DMT transmitter with dimming control (top). An example of how 50% PWM-controlled dimming signal can be combined with a DMT signal.

Pulse Position Modulation (PPM): In visible light communication another modulation depends upon the pulse position. The symbol duration is segmented into t time slots of equal duration in PPM technique. In one time slot, the pulse is transmitted. The transmitted pulse is recognized through the position of the pulse due to its simplicity and numerous early designs [18], [19] of optical wireless communication adopt the PPM as a modulation. PPM is used for infrared communication in earlier work, in this work [20] has recommended the use of rate adaptive transmission schemes where redundancy coding is used to elegantly reduce data throughput in presence of poor channel condition. Researchers have proposed in [21] a rate variable penetrated convolution coded PPM applied in infrared communication systems and it adopts modulation order with the channel conditions through Convolution codes. For higher data rates both rate adaptive techniques were used. One is the repeated and another one is punctured convolution coded PPM [22]. Because of the restrictions of lower spectral efficiency and data rate of PPM (only one pulse per symbol duration), a different variation of pulse position based modulation has been suggested over time. The overlap PPM (OPPM) which enables the more symbols duration transmitted through one pulse [20] and the different symbols can be seen in Fig. 4. [24] Demonstrated that OPPM not only acquired higher spectral efficiency but also a wide range of dimming levels can be achieved along with higher data rates. The other type of PPM was proposed by [25] which is known as Multi-pulse PPM (MPPM). OPPM, it enables numerous pulses to be transmitted amid the single symbol duration, however, the pulses within symbol duration do not need to be consistent as shown in Fig. 4. It has been observed and shown in [20] that MPPM can acquire a higher spectral efficiency contrasted to OPPM. In [26] authors have suggested with introducing variation in PPM through a combination of OPPM and MPPM schemes is known as Overlapping MPPM (OMPPM). In this technique, more than one pulse position represents a single optical signal. It was observed that the OMPPM can improve the spectral efficiency of MPPM without the extension of data transfer capacity in noiseless photon tallying channel. Additional noisy channel performance analysis is demonstrated in [27]. In [28] OPPM with a low number of time slot and more number of pulses per symbol has better cutoff rate performance. In presence of background noise, the effectiveness in terms of direct detection addressed in Trellis-coded OMPPM [29]. [30], including other modulation schemes for VLC is differential PPM (DPPM) was proposed in [31] which is similar to PPM but the OFF symbol was removed and next symbol starts right after the pulse of the previous symbol. The DPPM requires low power than PPM for given bandwidth in the optical communication channel. Authors in [32] have proposed differential overlapping PPM (DOPPM) where differential cancellation of OFF symbols is used to OPPM and presents that it accomplish better spectral and cutoff performance than PPM, DPPM, and OPPM. This paper [31] has proposed EPPM (Expurgated PPM) where the symbol of MPPM are purged to maximize the inter-symbol distance. The number of pulses per symbol and length of symbols is changed to support dimming support through EPPM rather than PPM [32]. The flickering can be mitigated by EPPM as with the PPM modulation technique. Multi level

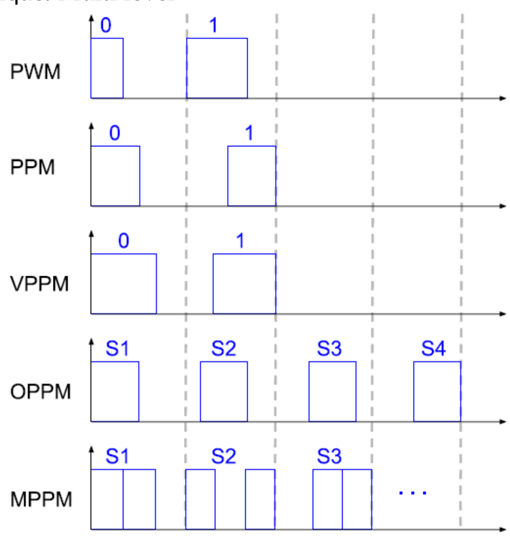

Fig. 4 Schematic diagram showing the difference between Pulse Width Modulation (PWM), Pulse Position Modulation (PPM), Variable Pulse Position Modulation (VPPM), Overlapping Pulse Position Modulation (VPPM) and Multi-pulse Pulse Position Modulation (MPPM); Sn refers to the nth symbol.

EPPM (MEPPM) broadens the EPPM design with support to multiple amplitude levels in order to increase the constellation size and spectral efficiency [33]. IEEE 802.15.7 [7] standard proposed a pulse modulation scheme call it a variable PPM (VPPM) which is the consolidation of PPM and PWM. In this, different position of pulses is encoding with bits. The width depends on the requirement. VPPM holds that simplicity and heftiness of PPM while permitting distinctive dimming levels by change the pulse width.

2.2.3 Orthogonal Frequency Division Multiplexing (OFDM)

The one constraint for single carrier modulation schemes is already discussed. Single carrier experiences the high Intersymbol interference (ISI) due to its nonlinearity in the frequency response of visible light communication channels.

OFDM is multicarrier modulation technique and generally accepted and utilized due to its capabilities effectively mitigate the conflict of symbol interference and multipath fading. OFDM was first proposed for visible light communication in [34]. The operation of OFDM divides the complete bandwidth into multiple subcarriers and the data is sent in the parallel sub-streams modulated over the subcarriers. The use of OFDM in VLC it reduces complex equalizers and intersymbol interference, though, multiple challenges in realizing its implementation. The first adopted modulation technique in VLC system is Intensity Modulation/ Direct Detection (IM/DD).

This is because OFDM generates complex-valued bipolar signals which need to convert to real-valued signals. This can be achieved by enforcing Hermitian symmetry constraint on the sub-carriers and then converting the time-domain signals to unipolar signals. Depending on how the bipolar signals are converted to unipolar, there are two types of OFDM techniques:

1) Asymmetrically-Clipped Optical OFDM (ACO-OFDM) and 2) DC-biased Optical OFDM (DCO-OFDM). In ACO-OFDM, only odd subcarriers are modulated [35] which automatically leads to symmetric time domain signal. While in DCO-OFDM [34], [35], [36], all subcarriers are modulated but a positive direct current is added to make the signal unipolar. [37] has demonstrated a comparison of both the OFDM schemes and showed that LED clipping distortion is more significant in DCO-OFDM compared to ACO-OFDM. The biggest challenge in the OFDM VLC system is the non- linearity of LED [38] which is that the relationship between the current and the emitted light of the LED is non-linear. This especially affects the OFDM-based VLC systems which have higher Peak-to-Average Power Ratio (PAPR). The effect of this non-linearity was studied in [39], [40] and a solution was proposed to cater it by operating the LED in a small range where the driving current and optical power are quasi-linear. Apart from the non-linearity, there is only a limited support for dimming [41] in OFDM-based modulation schemes. Despite these challenges, OFDM for VLC holds great potential with achievable link rates in the scale of multiple Gbps [42], [43] using only single LED.

4) Color Shift Keying (CSK): To overcome the lower data rate and limited dimming support issues of other modulation schemes, IEEE 802.15.7 standard [7] proposed CSK modulation which is specifically designed for visible light communication. CSK has attracted increasing amount of attention from the research community in the last couple of years [44]–[49]. As we discussed before, generating white light using blue LED and yellow phosphorus slows down the fast switching ability of LED and hinders high data rate communication. An alternative way of generating white light which is recently becoming more and more popular is to utilize three separate LEDs—Red, Green, and Blue (RGB). This combined source with RGB LEDs is often referred as TriLED (TLED). CSK modulates the signal using the intensity of the three colors in the TLED

source. CSK modulation relies on the color space chromaticity diagram as defined by CIE 1931 (see Fig. 5). The chromaticity diagram maps all colors perceivable by the human eye to two chromaticity parameters—x and y.

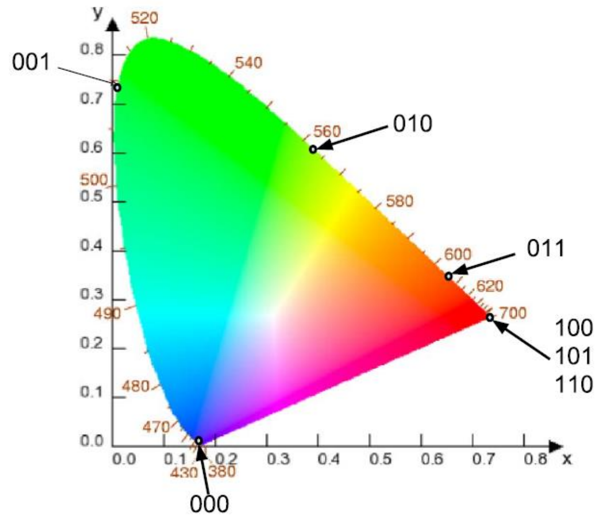

Fig. 5 CIE 1931 chromaticity diagram. The seven color codes correspond to the centers of seven bands dividing the visible spectrum

3. Modulation schemes and results comparative analysis

In this paper, various modulation schemes are compared such as MPPM, VPAPM, PPM, CSK, PWM, DIPPM, OFDM and OOK-NRZ modulation. These modulation schemes, with different parameters, have been observed such as BER, SNR, and data rate. Table.I present the comparison of given modulation schemes in terms of their BER, SNR and data rate. Results are considered for comparing various modulation schemes under different circumstances.

Table I. Comparison of BER, SNR and Data Rate

Modulation Scheme	***BER***	***SNR (dB)***	***Data Rate***
PWM	High[50]	Low	Lowest
PPM	High[51]	Medium	Low
CSK	Lower[52]	Medium	Medium
OOK	Lowest[53]	High	Medium
MIMO OFDM	High[54]	Low	Highest
MPPM	Lower[55]	High	High
VPAPM	Lower[56]	High	High
DIPPM	Lower[57]	Medium	High

Fig.6 demonstrates the entailed power concerning dimming factor for modulation schemes such as VOOK, MPPM, and VPPM. VOOK and VPPM have the same requirement of power, however, MPPM requires less power in comparison to VOOK and VPPM. In MPPM each symbol duration is divided into n chips for dimming control, so MPPM with fixed (n=20) is shown in Fig 1. Hence from the figure, we have observed that VOOK and VPPM require more power around 8 dB to achieve the minimum value of diming factor 0.02, while MPPM has need of less value of power around 4.2 dB for the same value of diming factor. If the value of the diming factor is increased from its average value 0.5, the required value for power should increase accordingly. MPPM provides much better results than VOOK and VPPM both require more power. Fig. 7 demonstrates the spectral efficiency relating to dimming factor. It is observed that VOOK with the same power as VPPM provides better results than VPPM regarding spectral efficiency. As for the minimum value of dimming factor around 0.02, the spectral efficiency of VPPM is low at 0.02, VOOK has the value around 0.1, MPPM with n=20 provides spectral efficiency of 0.2, and MPPM has the value of 0.3. For the average value of dimming factor 0.5, MPPM and VOOK provide maximum spectral efficiency, MPPM with n=20 provides better results except for few values of dimming factor, as VOOK drastically increases and decreases with dimming factor, therefore for better results MPPM is preferred. The spectral efficiency is a function of a diming factor with an inverse relation to its average value.

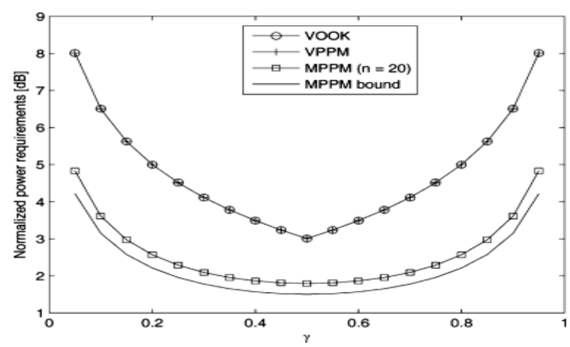

Fig. 6 Normalized power requirements of several modulation schemes [7]

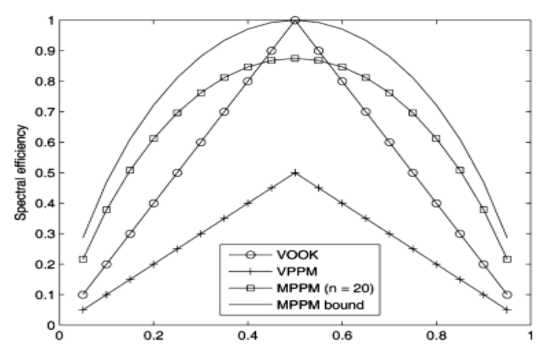

Fig. 7 Spectral efficiencies of several modulation schemes [7]

VPAPM provides better results concern of power requirements in regard to dimming factor value than overlapping pulse position modulation (OPPM) but it requires larger power than VPPM and RZ-OOK shown in Fig 8. VPAPM requires around 5dB of power to achieve the dimming level of 0.5 value at given dimming factor value M=4. The dimming factor value VPPM and RZ-OOK require less power of about 2dB and 1.5dB to achieve same dimming level of 0.5. Fig. 8 shows that VPAPM provides much better bandwidth efficiency at the given values of dimming factor than VOOK, VP-PM, OPPM, and RZ-OOK. 0.5 diming factor the VPAPM with M=4 offers maximum bandwidth efficiency.
Fig.5 demonstrates that DIPPM requires less power for the same BER as compared to VPPM for all dimming factor values. At the dimming factor 0.5, DI-PPM gives best results in terms of power requirement. While as dimming factor value increases, power requirement will also increase.

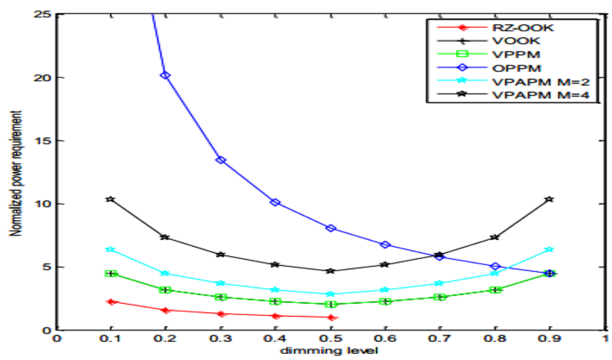

Fig.8 Normalized power requirement of modulation schemes [8]

4. Conclusion

In this paper performance of different modulation schemes on VLC is analyzed. VLC has diverse applications such as used in hospitals, streets, underwater communication, hazardous environments, vehicle and transportation, defense and security, and Wi-Fi Spectrum. As VLC uses lights and lights with dim feature also can provide a good quality signal to for communication. The most important factor in VLC is to control the dimming level of VLC sources. Therefore it is desired to choose such modulation scheme which can minimize the effects of dimming and provides better results regarding data rate. From the review and observation, we have concluded that MPPM provides reliable communication as compared to many other schemes used for VLC such as VPPM, VO-OK, PWM, VPAPM, OFDM, NRZ, and DIPPM power requirement, spectral efficiency, and data rates.

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