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PERFORMANCE EVALUATION OF UTILIZING M-QAM OFDM WITH SC- LPPM FOR INDOOR LOS-VLC SYSTEMS

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ABSTRACT

In this paper, a combination process for sub-carrier pulse modulation (SC- LPPM) technique with M-ary Quadrature Amplitude Modulation OFDM (M-QAM OFDM) under distinctive and uniform lighting topologies assumption in a typical room is introduced. It was indicated from previous literatures that SC-LPPM fails to achieve the minimum performance required to achieve and sustain a reliable communication link; hence, it can be predicted that utilizing optical OFDM techniques can enhance the scheme performance allowing it to sustain a reliable communication link performance while achieving a higher operating data rate with an acceptable BER performance. However, the presented study can be more informative if the investigation is carried for different room and lighting topologies which will indicate the capabilities and the limitations of the proposed combination scheme. It can be shown in the manuscript that under distinctive lighting topology assumption, utilizing M-QAM OFDM with a single carrier modulation technique (SCM) like SC- LPPM can enhance the operating bit rate performance up to 50 Mbps with a remarkable BER performance of 8.6×10^{-5} at modulation level (L=8), which can maintain a reliable communication link for Visible Light Communication (VLC) systems. Meanwhile, further improvement to the BER performance up to 9.56×10^{-6} can be achieved for the same modulation level at a 5 Mbps rate. Moreover, an investigation for the power performance of the proposed technique, the minimum required power, and the power distribution across the presented rooms topologies is presented in the manuscript under two scenarios (i.e., with and without utilizing SC- LPPM with M-QAM OFDM), which will help identifying the most suitable room and lighting layout to utilize the proposed scheme and give an insight into the performance enhancement that occurred due to the utilization of optical OFDM.

Keywords: *Visible light communication, Sub-carrier pulse position modulation, Multi-carrier modulation, Bit error rate, M-QAM OFDM.*

1. INTRODUCTION

Light Fidelity (Li-Fi) is the commercial acronym for Visible Light Communication (VLC) which had gained huge attention in the research and development globally as an alternative to Radio Frequency (RF) technology [1-5]. VLC unlike RF provides multiple advantages like unlicensed bandwidth, infrastructure availability, lack of interference with both surrounding electronics and RF circuits, enhanced privacy, and high security [6]. Moreover, Li-Fi had become a state-of-the-art optical communication technology. It can be considered as an advanced version of free-space optical communication (FSO) especially for indoor environments [7]. Several optoelectronic/ photonic devices/platforms such as Mach Zehnder Interferometer (MZI), Fiber Bragg grating (FBG), and semiconductor optical amplifiers (SOAs), began to focus and switch some of their applications to keep up with the noticeable widespread of Li-Fi technology especially in indoor optical communication environments [8 - 13].

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Although photonic crystals and other all-optical devices shows a promising integration ability and a remarkable power consumption performance, they suffer from complex system and structure designs compared to VLC technology [13 - 17].

VLC technology uses light as a method of communication, unlike conventional illumination devices, LEDs provide many advantages like durability, enhanced robustness, high switching rate, and smaller sizes which leads to the conclusion that LEDs can be more efficient in VLC systems [18, 21, 22].

VLC has many applications which includes high data rate transmission, underwater communications and transmission in sensitive electromagnetic interference environments, also it can be utilized in the traffic control systems to enable, control, and automate the infrastructure-to-vehicle communication [23,24, 25].

Another advantage of VLC is the power consumption enhancement to provide communication while maintaining the required lighting and illumination strength, thus, the two major purposes of LED-based systems are the efficient accomplishment of both dimming and communication support.

Dimming and communication can be fulfilled by different modulation techniques [21], dimming support can be accomplished using Pulse Width Modulation (PWM) and Pulse Amplitude Modulation (PAM). Meanwhile, data transmission (i.e., communication) can be accomplished using On-Off Keying (OOK) and Pulse Position Modulation (PPM) [27]. Despite the power consumption penalty of OOK based techniques, these techniques are considered as straight forward , simply designed and known as Single-Carrier Modulation (SCM) techniques. However, some of these techniques lacks the required illumination capabilities required for Li-Fi enabled systems (i.e., dimming support while maintaining a reliable communication link).

To achieve both bandwidth and power efficiency, SCM techniques like PPM and its variants, such as Inverted L-ary Pulse Position Modulation (I-LPPM), L-ary Pulse Position Modulation (LPPM), and Multi-Pulse PPM (MPPM) are considered as effective techniques [28].

However, these techniques are not the most effective techniques that can be utilized as VLC modulation techniques, since most of these modulation techniques are designed for free-space-optical communication utilizing infrared (IR) transmission which can only support data transmission (i.e., communication support). Hence, it can be assumed that these techniques did not support dimming.

Moreover, techniques suffer from the effect of Inter Symbol Interference (ISI), and their performance decreases at high data rates. leading to the introduction of several equalization techniques that can be used as a reliable method to enhance the system performance at high data rates [29 - 31].

Although, utilizing these techniques with SCM shows a noticeable enhancement in the system performance but the system design complexity was very high due to the dispersive nature of the optical channel that leads to a noticeable decrease in their spectral efficiency. Hence, utilizing Multi-Carrier Modulation (MCM) techniques such as Orthogonal Frequency Division Multiplexing (OFDM) was introduced as a reliable substitute for these equalization techniques for Li-Fi systems [32].

In [33], Z. Wang presented a technique that applies dimming control to a scheme that combines OFDM with Multi level-Quadrature Amplitude Modulation (M-QAM). A modification to this scheme is presented in [34] that can achieve excess data transmission by merging Multi Pulse-Position Modulation (MPPM) pulses with M-QAM OFDM. The excess transmitted information will result in reducing the required data rate to achieve a reliable communication link, which leads to enhancing the overall power consumption and complexity.

In [20], the authors focused on reducing the total power consumption of the LED while achieving both lighting and communication requirements.

SC-LPPM technique performance was investigated in [35] as a power efficient SCM technique, it was shown in [35] that SC-LPPM can sustain a reliable illumination performance and a power saving performance while achieving a remarkable BER performance at lower operating data rates (i.e., up to 3 Mbps). Also, it can be indicated that the presented investigation was limited to only 15 Mbps under a distinctive lighting topology assumption which fails to present the scheme's performance at higher operating data rates.

Another study was presented in [36] to investigate the effect of different system and environmental parameters on the scheme performance under Non-Line of Sight (NLOS) link assumption for distinctive lighting topology. But the study showed that the NLOS component can enhance the system power, BER, and illumination performance for the same operating data rates as [35].

It can be concluded from [35, 36] that, although SC- LPPM showed a remarkable performance as a power-saving modulation technique with a remarkable illumination performance, it has several operation limitations due to its lack of endurance against the effect of ISI.

Hence, it can be predicted that SC-LPPM can show an improvement in its overall performance as a reliable power-saving VLC technique if combined with M-QAM OFDM, especially at higher operating data rates.

In [37] several SCM techniques are combined with M-QAM OFDM under distinctive and uniform lighting topologies assumption and investigated as a reliable dimming control scheme for VLC based systems, which showed the remarkable capabilities of SC-LPPM as power saving technique, that can sustain a reliable illumination performance.

But the work presented in [37] assumed a BER of 10^{-3} and failed to present the BER performance of the scheme at higher operating data rates along with the power distribution performance across the proposed room and lighting topology.

It can be indicated that previous literature investigated the combination process of SCM techniques with M-QAM OFDM, assumed a BER performance of 10^{-3} to produce their analysis, which does not reflect the capabilities of the proposed technique as Li-Fi enabled scheme that can support a reliable communication link at increased operating data rates [33, 34, 37].

Moreover, literatures investigated the BER, power, and illumination performance of SC- LPPM scheme under low data rates assumption (i.e., up to 15 Mbps) due to the low BER performance of the scheme at higher data rates reflects to the power requirements and the overall performance of the scheme in a noticeable way, which will result in increased power consumption.

Hence, it can be predicted that utilizing optical OFDM techniques can enhance the scheme performance allowing it to sustain a reliable communication link performance while achieving a higher operating data rate with an acceptable BER performance.

In this work, the BER performance of SC-LPPM scheme is investigated at higher operating data rates (i.e., up to 50 Mbps), as a SCM modulation scheme and after being combined M-QAM OFDM for a line of sight (LOS) environment under distinctive and uniform lighting topologies assumption.

Which represents an insight into the scheme performance and determine the capabilities and the limitations of the scheme as reliable VLC scheme that can sustain a reliable communication link in both lighting topologies. Followed by an analysis for the minimum required power, ($P_{req.}$) to investigate the performance enhancement of utilizing OFDM with SC-LPPM for the two proposed rooms topologies.

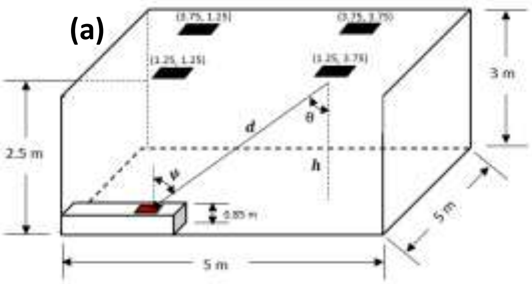
Another side of this study is to analyze the performance and stability of the system across the presented rooms layout (i.e., Under the light source and the room corners). This analysis can help investigating the operation system rate limitations of the presented technique as a reliable VLC system.

The rest of this paper is organized as follows, Section 2 describes the system environment, where the channel model will be presented in section 3, section 4 holds the presented system design and rooms topologies parameters, in section 5 the obtained results will be presented and discussed. Section 6 presents a survey on different modulation techniques utilized by different literatures. Finally, section 7 will hold the main conclusion of the manuscript.

2. SYSTEM MODEL

The presented distinctive room topology consists of four identical LED sources that are equally placed and spaced on the room ceiling of a (5×5×3 m^3) room at a center position of (1.25, 1.25, 2.5), (1.25, 3.75, 2.5), (3.75, 1.25, 2.5), (3.75, 3.75, 2.5). Meanwhile, the receiver is assumed to be at desk level of height (0.85 m), as shown in Fig. 1(a).

A 20×25 LED chip triangular array is assumed for the uniform lighting topology. The LED chips are distributed of the ceiling of the proposed room in an equilateral triangle with side length of 0.24 m, as shown in Fig. 1(b).



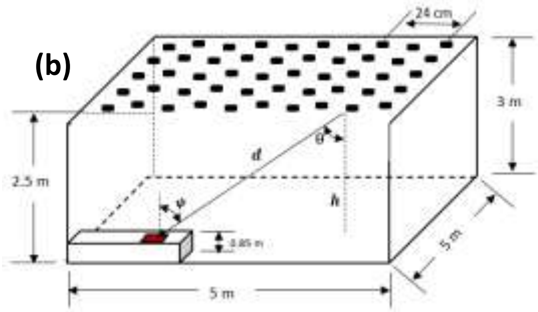


Fig. 1. Room configuration for (a) distinctive lighting layout, (b) uniform lighting layout.

To construct an SC- LPPM symbol, a direct current component and a subcarrier component (SC) are required. Where the symbol interval (T) can be formed by *L* equal time slots. Moreover, it can be indicated that only one of these *L* slots carries the optical signal, while a constant current amplitude is carried by the rest of the symbol interval *(L-1)*. Fig. 2 demonstrates the waveform of an SC-4 PPM symbol. where c is the maximum value of the optical signal, *a* is the minimum value of the optical signal, *(c-a)* represents the amplitude of the optical signal [26], and (b) represents the amplitude of the DC component [35].

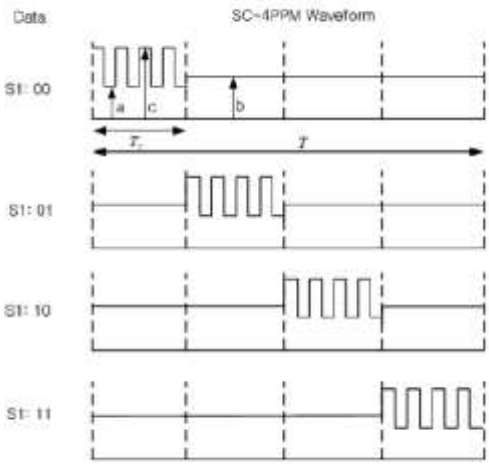


Fig. 2. SC-4 PPM waveform [21, 35].

3. CHANNEL MODEL

The signal intensity in optical communication is controlled by the transmitted optical power radiated by the LED [21]. To evaluate the transmitted optical signal strength of an SC- LPPM symbol, only the transmitted power through the subcarrier component is accounted for, thus it can be described as follows

$$P_i^t = (c - a) \times P_{max}^t \qquad (1)$$

where P_i^t is the optical transmitted power from i^{th} LED source, P_{max}^t is the maximum optical power transmitted by the i^{th} LED source, and *(c-a)* is the amplitude of the optical signal.

For an optical wireless channel, the power received by a photodiode (PD) can be acquired from [21]

$$P_j^r = \sum_{i=1}^{I} (H(0) \times P_i^t) \qquad (2)$$

where P_j^r is the optical power received at the receiving location j across the room from the LED sources, and $H(0)$ is the channel response, which can be presented as follows [36, 37]

$$H(0) = \frac{A_{PDr}\,(m+1)}{2\pi d_0^2}\, T(\theta)\, g(\theta) \cos^m(\theta)\ \cos\psi \qquad (3)$$

where A_{PDr} is the effective area of the PD, $T(\theta)$ is the optical filter gain, and $g(\theta)$ is the concentrator gain.

Hence, from Eq. (1), (2), and (3), the total received optical power can be represented as follows

$$P_j^r = \begin{cases} (c_i - a_i) \times P_{max}^t \times \frac{A_{PDr}\,(m+1)}{2\pi d_0^2}\, T(\theta)\, g(\theta) \cos^m(\theta) \cos\psi, & \theta \le FOV \\ 0, & \theta > FOV \end{cases} \qquad (4)$$

where FOV is the receiver Field of View.

The BER is the lead parameter that can be used to assess the performance of a communication system, for SC-LPPM, it can be acquired from [21]

$$BER|_{SCM} = \frac{L/2}{L-1}\, Q\left(\frac{1}{2}\sqrt{\frac{3\, A_{PDr}^2\, L\, (P_j^r)^2 \log_2 L}{N_o R_b}}\right) \qquad (5)$$

where R_b is the bit rate, and N_o is the power spectral density of additive white Gaussian noise channel.

The received optical power P_j^r should be greater than or equal to the minimum power required, P_{req}. for SC-PPM to accomplish a given BER which is stated in [21]

$$P_{req} = \frac{2}{A_{PDr}}\, Q^{-1}\left(\left(\frac{L-1}{L/2}\right) \times BER|_{SCM}\right) \sqrt{\frac{N_o R_b}{3\, L \log_2 L}} \qquad (6)$$

Meanwhile, for MCM techniques, at the receiver end of view, the DC component of the signal detected by the PD is filtered out. Hence, by assuming a Gaussian noise distribution the SNR of the output signal can be presented as follows [34]

$$SNR = \frac{\overline{f(t)^2}\, (R_r P_j^r M_i)^2}{\sigma^2} \qquad (7)$$

where R_r is the responsivity of the PD, σ^2 is the noise variance, M_i is the modulation index, *f(t)* is the normalized signal and $\overline{f(t)^2}$ is its average power. Under the assumption that the noise variance consists of shot and thermal noise added together [36]

$$\sigma^2 = \sigma_{shot}^2 + \sigma_{thermal}^2 \qquad (8)$$

$$\sigma^2 = 2q\left[R\left[P_j^r\left(1 + \left(M_{index}\overline{f(t)}\right)^2\right)\right] + I_{bg} I_2\right]B + 8\pi k T_k \eta A_{PD} B^2\left(\frac{I_2}{G} + \frac{2\pi\Gamma\eta A_{PD} B I_3}{g_m}\right) \qquad (9)$$

where $P_j^r\left(1 + \left(M_{index}\overline{f(t)}\right)^2\right)$ is the total received power, R is the transmitted symbol rate, q is the electron charge, T_k represents the absolute temperature, k is the Boltzmann constant, and B is the equivalent noise bandwidth. The rest of the parameters are listed in Table 1.

The BER of the M-QAM modulation scheme depends on M, total received power, and noise variance as a function of the symbol rate; hence it can be presented as [33]

$$BER|_{MCM} \le 0.2 \exp\left[\frac{-1.5\, \overline{f(t)^2}\, (R_r P_j^r M_i)^2}{(M-1)\, \sigma^2(P_j^r)}\right] \qquad (10)$$

Where M is the signal constellation.

Hence, the required LED lamp power $P^t_{req.}$ can be obtained from Eq. (10) as follows,

$$P^t_{req.} = \frac{1}{R_r\, H(0)\, M_i} \sqrt{\frac{\ln\left(\frac{BER|_{MCM.}}{0.2}\right)(1-M)\,\sigma^2(P^r_j)}{1.5\,\overline{f(t)}^2}} \quad (11)$$

The proposed combination process of the scheme with M-QAM OFDM is shown in Fig.3 and described as follows. A bipolar data stream is mapped through SC-LPPM, then the generated signal is modulated through the M-QAM OFDM (i.e., asymmetrically clipped optical (ACO-OFDM) or DC-Biased optical (DCO-OFDM)).

The generated optical signal is transmitted through the channel under AWGN assumption by the LED source.

After the optical signal is received at the receiving end by the PD, the signal is demodulated to decompose it into the M-QAM OFDM signal and the SC-LPPM signal.

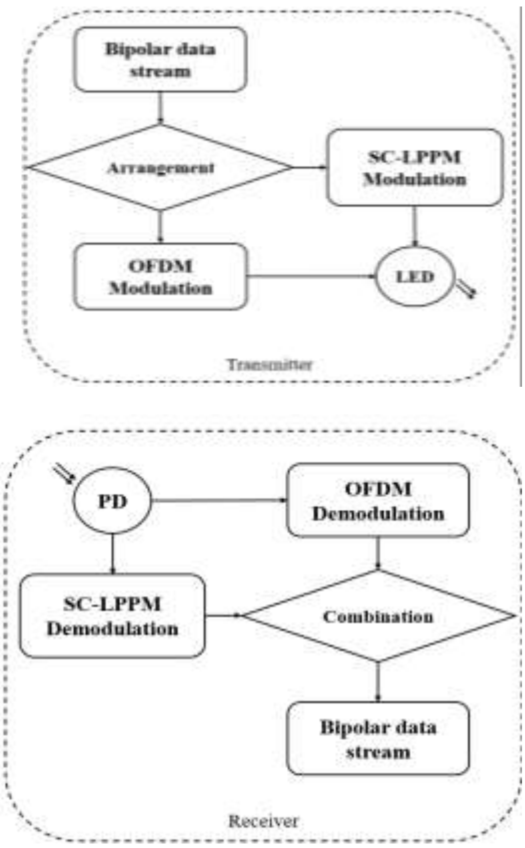


Fig. 3. Block diagram for the proposed combination process.

4. SYSTEM SPECIFICATIONS

The presented work assumes a typical configuration of a 5×5×3 m^3 empty room that utilizes the lighting topologies presented in section 2, under a LOS assumption.

Table 1 presents the proposed room, sources, and receiver parameters. These values guarantee acceptable lighting and communication performance.

Table 1. Simulation parameters [35].

	Parameter	Value: Distinctive lighting layout	Value: Uniform lighting layout
Source	Number of LEDs	3600 (60×60)	500 (20×25)
	LED transmitted power	20 mW	
	Semi-angle half power	60^o	
	Center luminous intensity	0.73 cd	
	power spectrum density	10^{-21} W/Hz	
Room	Room size	5×5×3 m^3	
	Height of desktop surface	0.85 m	
Receiver	Area	1 cm^2	
	Field of view (FOV)	120^o	
	Responsivity	0.4 A/W	
	Concentrator refractive index	1.5	
	Filter gain	1	
Noise Parameter	Background current (Ibg)	5100 µA	
	Noise bandwidth factor (I_2)	0.562	
	Field-effect transistor (FET)	30 mS	
	FET channel noise factor (Γ)	1.5	
	Fixed capacitance (η)	112 pF/cm^2	
	Open-loop voltage gain (G)	10	
	I_3	0.0868	

5. RESULTS AND DISCUSSION

By considering the proposed room and system specifications presented in section 2 and section 4, the following section holds the results of combing SC-LPPM with optical OFDM techniques which will present an insight of the overall system BER and power performance under a wide range of operating bit rates.

Fig. 4 presents the BER performance of the system to the operating bit rate (R_b) for the presented system at various values of modulation levels (L) under distinctive lighting topology assumption.

With the presumption that the receiver is allocated under the light sources, it can be shown that the system BER performance is inversely proportional to the operating bit rate. Moreover, it can be shown that the BER performance and behavior can be enhanced by using larger values of *L*.

From Fig. 4(a), It can be indicated that at low operating bitrate (i.e., 1 Mbps), a remarkable BER performance of 1.6×10^{-6} can be achieved for L=8, meanwhile utilizing the scheme at L=2 and L=4 failed to achieve the minimum BER performance required for sustaining a reliable communication link.

Increasing the data rates (i.e., 50 Mbps), resulted in achieving a BER performance of 10^{-1} modulation level L=2, and a BER performance of 3×10^{-2} at L=8, which demonstrates the limitations of the scheme at higher data rates.

It can be indicated from Fig. 4(b) that a considerable improvement can be accomplished by utilizing OFDM techniques with SC- LPPM. It can also be shown that the performance of the scheme at low data rates (i.e., 1-2 Mbps) is enhanced compared to the performance indicated in Fig. 4(a), as a BER performance of 10^{-6} is achieved for L=2 and 8.5×10^{-8} for L=8.

Meanwhile, an exceptional BER of 8.6×10^{-5} can be accomplished at a bit rate of 50 Mbps, and at L = 8. Another observation can be made from Fig. 4(b), is that for high operating data rates, all of the modulation levels can meet the minimum BER of 10^{-3}.

Moreover, it can be shown that the analysis at increased data rates, shows that the BER behavior of the scheme will start to saturate as the operating bit rates reaches 35 Mbps, which demonstrates the stability of the scheme as the data rates increases for more than 50Mbps.

Finally, it can be indicated that LOS/VLC systems utilizing SC- LPPM combined with MCM (i.e., OFDM) modulation techniques show a distinguishable BER improvement at lower bit rates and larger values of *L*. For a bit rate of 5 Mbps, a remarkable BER of 9.56×10^{-6} is accomplished at L = 8.

It is noteworthy to mention that previous literature indicates that a BER performance of 10^{-3} is considered as the minimum acceptable BER to achieve a reliable communication link [33, 34].

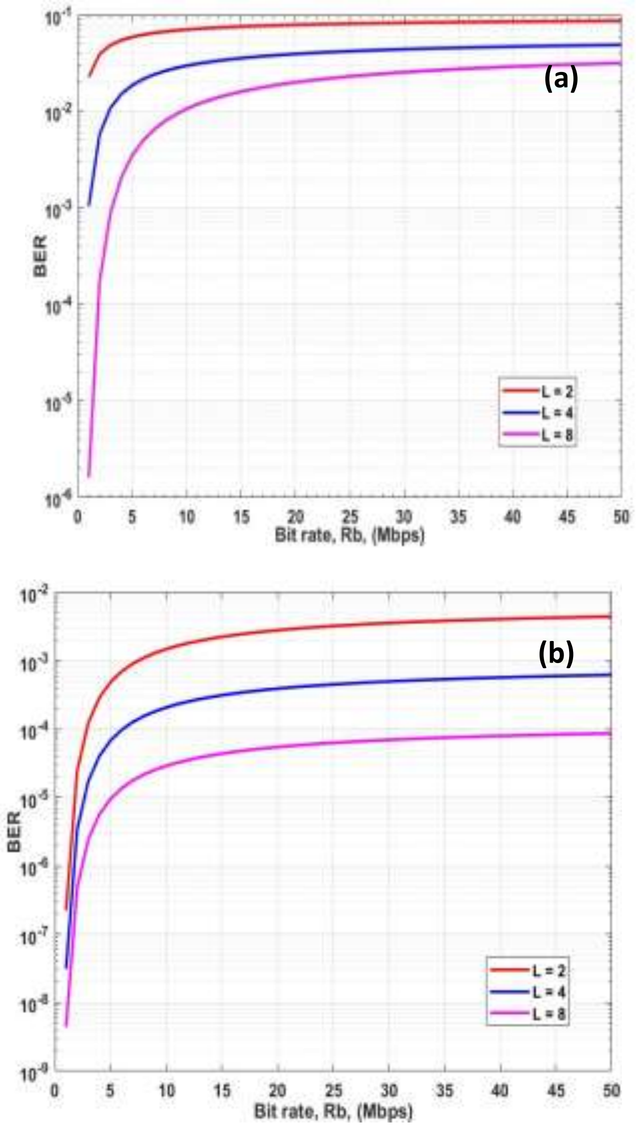


Fig. 4 BER vs. bit rate at different modulation levels (L)

under distinctive lighting topology assumption for (a) without utilizing OFDM techniques, (b) by utilizing OFDM techniques.

For uniform lighting topology, Fig. 5 indicates the BER performance of the system to the operating bit rate (R_b) for the presented system at various values of modulation levels (L).

It can be indicated from Fig. 5(a) shows at bitrate of 1 Mbps, a BER performance of 3.7×10^{-3} at L=8, meanwhile, the scheme BER performance decreases to 1.9×10^{-2} and 5.9×10^{-2} for L=4 and L=2, respectively.

Which can indicate that the scheme can barely achieve the minimum BER requirements of a reliable communication link at modulation level L=8.

For higher operating data rates (i.e., 2 to 50 Mbps), it can be shown from Fig. 5(a) that the scheme will fail to achieve the minimum BER requirements for all of the modulation levels (i.e., L=2, L=4, and L=8). It can be shown that for a data rate of 50 Mbps and for L=8 a BER performance of 4.5×10^{-2} can be achieved.

It can be indicated from Fig. 5(b) that utilizing OFDM techniques with SC-LPPM resulted in a noticeable enhancement to the BER performance. the performance of the scheme enhanced to 10^{-5} at data rate of 1 Mbps for L=8 and L=4, and 5×10^{-4} for L=2.

Another observation can be made from Fig. 5(b), by increasing the data rates to 50 Mbps while utilizing optical OFDM techniques resulted in an acceptable BER performance for the scheme. It can be shown that the BER performance enhanced to 1.2×10^{-4} at L=8, 8.8×10^{-4} at L=4, and 6.3×10^{-3} at L=2.

Moreover, it can be indicated that utilizing optical OFDM techniques with SC- LPPM scheme resulted in satisfying the minimum BER required to sustain a reliable communication level at increased operating data rates.

Same behavior can be detected as indicated in Fig. 4(b), as the BER behavior of the scheme will start to saturate as the operating bit rates reaches 35 Mbps, which demonstrates the stability of the scheme as the data rates increases for more than 50Mbps.

Finally, it can be can be concluded that utilizing the scheme under distinctive lighting topology assumption will result in enhanced BER performance compared to uniform lighting topology assumption.

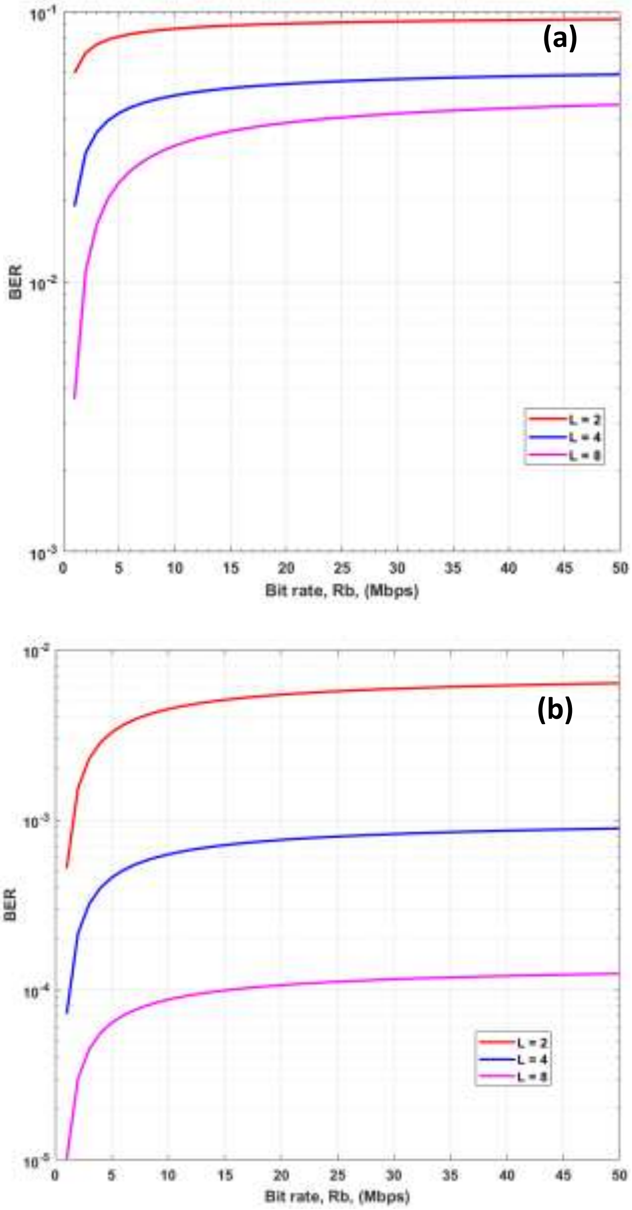


Fig. 5 BER vs. bit rate at different modulation levels (L) under uniform lighting topology assumption for (a) without utilizing OFDM techniques, (b) by utilizing OFDM techniques.

Fig. 6 presents the minimum power required to utilize SC-LPPM technique for VLC systems versus the operating bit rate at various modulation levels (L) under distinctive lighting topology assumption. It can be indicated from Fig.6 that utilizing optical OFDM slightly increases the required transmitter power at lower modulation levels.

Fig. 6(a) indicates that the performance of SC-LPPM scheme at low data rates (i.e., 1 Mbps), it can be shown that the power requirements increased by approximately 2 dBm as the modulation level changes from L=8 to L=2.

Moreover, it can be indicated from Fig. 6(a) that at 50 Mbps the power requirements will increase to 8.8 dBm for L=2. Moreover, it can be observed that for L=2 and L=4, the required power will continue to increase in a noticeable way as the data rate increases, while for L=8 the required power increases in a small margin which nominate this modulation level (i.e., L=8) to be used to save power.

However, analyzing the scheme performance at increased data rates, indicated the power saving capabilities of the scheme, as it can be shown that at L=2, the power requirements increased by 30% as the data rate increased from 15 Mbps to 50 Mbps. While at L=8 the power requirements increased by 20% for the same increase in the data rates.

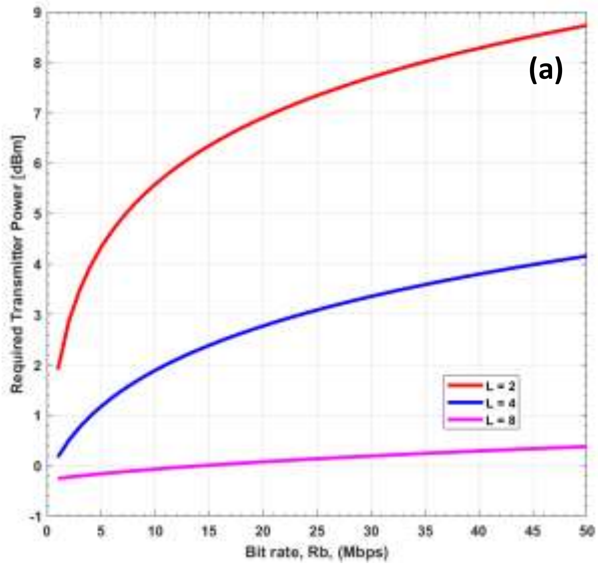
Fig. 6(b) demonstrates the power requirements of the scheme due to the utilization of optical OFDM schemes.

It can be shown that at low data rates (i.e., 1-5 Mbps), the power requirements increase by an approximate of 2 dBm as the modulation level changes from L=8 to L=4, and increases approximately by 3 dBm as the modulation level changes from L=4 to L=8.

Meanwhile, increasing the operating data rates (i.e., 50 Mbps) will approximately increase the power requirements of the scheme by the same ranges compared to the power performance at lower data rates.

Finally, Fig.6 shows that utilizing optical OFDM slightly increases the required transmitter power at higher modulation levels. It can be shown that by utilizing optical OFDM techniques, the LED transmitted power will be increased by 16 mW. In other words, according to the lighting system layout assumed an LED module that consists of 60×60 LED array will consume a total power of 129.6 Watt by utilizing optical OFDM with SC-LPPM.

These power consumption levels can be considered to be lower than most types of conventional lighting systems (i.e., incandescent and fluorescent) which consume 60 W/lamp and 14 W/lamp respectively [38]. Which can be assumed as an admissible cost for achieving an enhanced BER performance especially at high operating system rates.



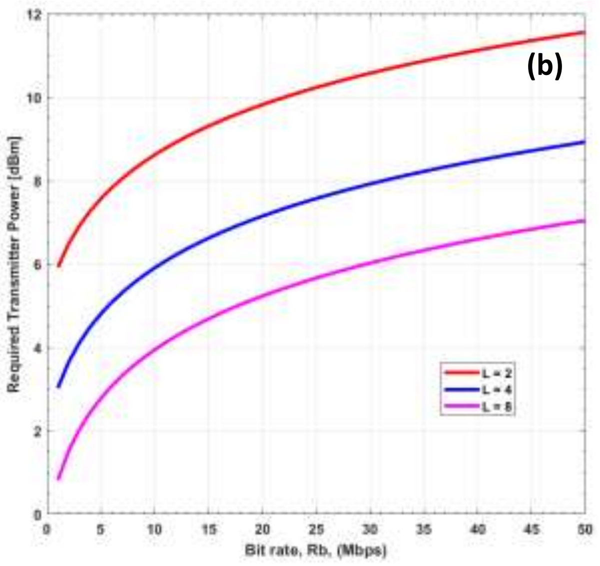


Fig. 6 Minimum transmitter power required vs bit rate at different modulation levels (L) under distinctive lighting topology assumption for (a) without utilizing OFDM techniques, (b) by utilizing OFDM techniques.

Under uniform lighting topology assumption, Fig. 7 indicates the minimum required power for utilizing SC-LPPM technique for VLC systems versus the operating bit rate at various modulation levels (L) under uniform lighting topology assumption. from Fig. 7, it can be indicated that utilizing optical OFDM shows the same behavior as in Fig. 6, the power requirements is increased as the data rate increases.

From Fig. 7(a), same behavior as in distinctive lighting topology can be identified, but at lower levels. At 1 Mbps, a transmitter power of -3.714 dBm is required at L=8, -2.357 dBm at L=4, and 0.822 dBm at L=2.

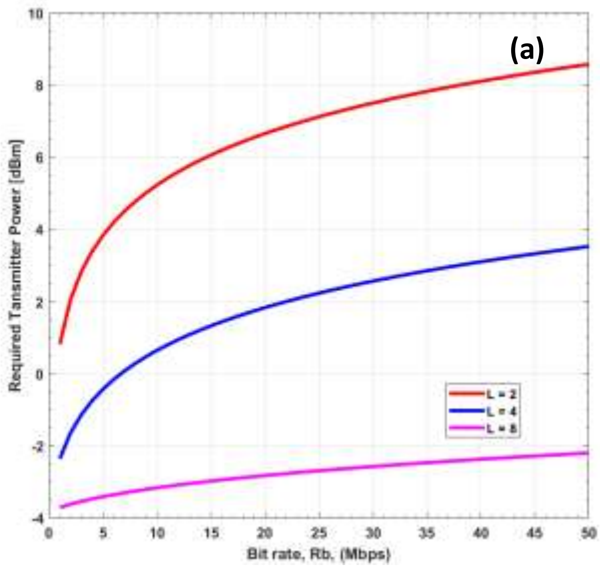
Moreover, it can be indicated from Fig. 7(a) that at 50 Mbps the power requirements will increase to 8.6 dBm for L=2 which is almost an identical requirement as for the distinctive lighting topology. However, for a minimum LED power of 3.5 dBm and -2.2 dBm are required at L=4 and L=8, respectively, which is lower power requirement compared to the distinctive lighting topology requirements.

Same behavior is indicated as in Fig. 6(a); at L=8 the required power increases by a small margin which nominate L=8 to be used for power saving purposes, while for L=2 and L=4, power requirements will continue to increase in a noticeable way as the data rate increases.

However, analyzing the scheme performance at increased data rates, it can be indicated that increasing the data rates under uniform lighting topology assumption will increase the power requirements margin compared to the distinctive lighting topology, it can be shown that at L=8 the power requirements increased by 26% as the data rate increased from 15 Mbps to 50 Mbps, while at L=2, the power requirements increased by 42% for the same increase in the data rates.

Fig. 7(b) shows the power requirements of the scheme due to the utilization of optical OFDM schemes under uniform lighting topology assumption.

It can be indicated that, for a data rate of 50 Mbps utilizing optical OFDM under uniform lighting topology assumption increases the power requirements by 414% at L=8, 148% at L=4, and 32% at L=2. Which demonstrates the low power performance of scheme when utilized for uniform lighting topology especially when compared to the power performance of the distinctive lighting topology.



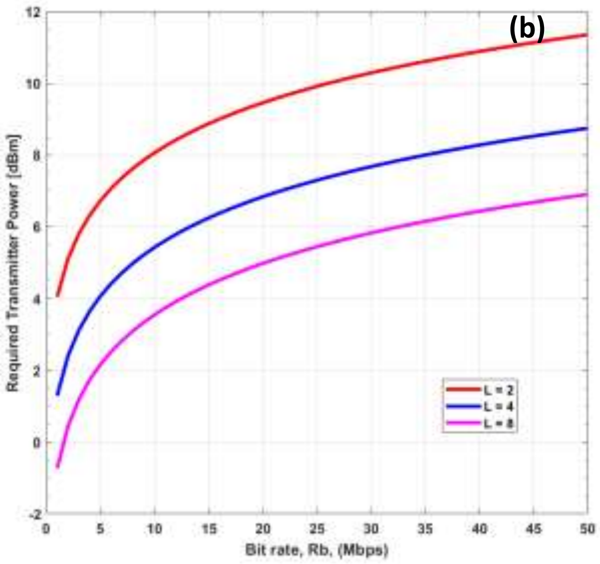
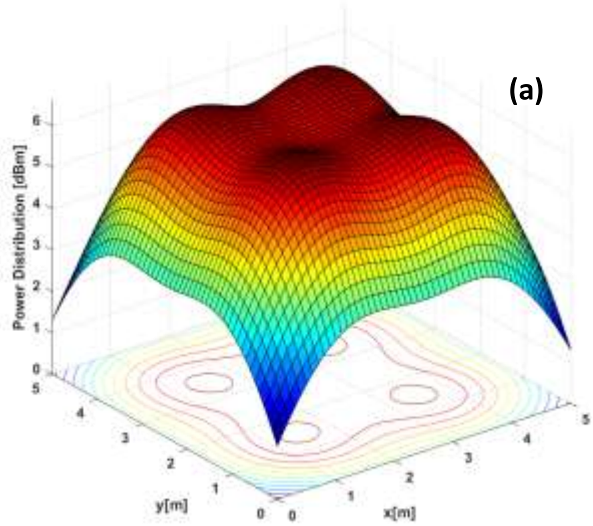


Fig. 7 Minimum transmitter power required vs. bit rate at different modulation levels (L) under uniform lighting topology assumption for (a) without utilizing OFDM techniques, (b) by utilizing OFDM techniques.

The power distribution across the proposed distinctive lighting topology for utilizing SC- LPPM techniques as an SCM technique and combined with optical OFDM techniques is presented in Fig. 8.

From Fig. 8(a) it can be indicated that the received optical power increases from 2.69 dBm at the room corners to 6.59 dBm under the ceiling lights of the room. The most powerful LOS components are under four LED modules and moderately fall as the receiver moves to the room corners.

Fig. 8(b) indicates that although utilizing optical OFDM increases the required transmitter power, the optical power received by the receiver is enhanced, which is an extra advantage to enhance the operating data rates at a remarkable BER performance as previously discussed. The optical power received under the light source is 10.12 dBm which decreases as the receiver is located towards the room corners to 6.13 dBm.



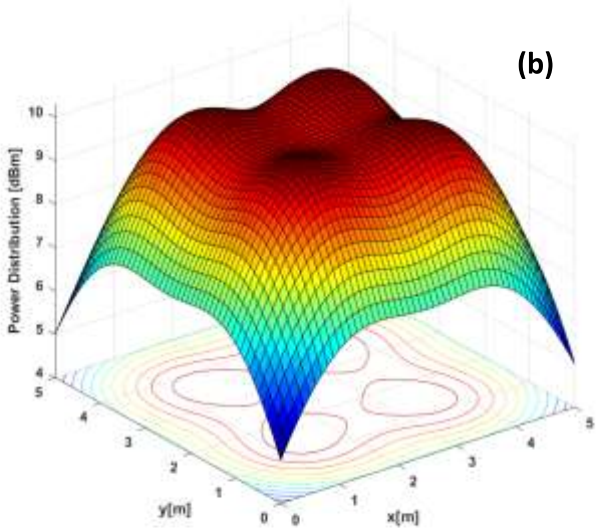


Fig. 8 Power distribution across the proposed room under distinctive lighting topology assumption for SC- LPPM (a) without utilizing OFDM techniques, (b) by utilizing OFDM techniques.

Meanwhile, for uniform lighting topology, Fig. 9 shows the power distribution for utilizing SC- LPPM techniques as an SCM technique and combined with optical OFDM techniques.

Fig. 9(a) shows the power performance of the scheme as a SCM modulation technique, it can be indicated that the strongest received component of -3.3 dBm will be detected by the receiver at the room center, meanwhile, the received optical power will decrease as the receiver locates towards the room corners to -6.575 dBm.

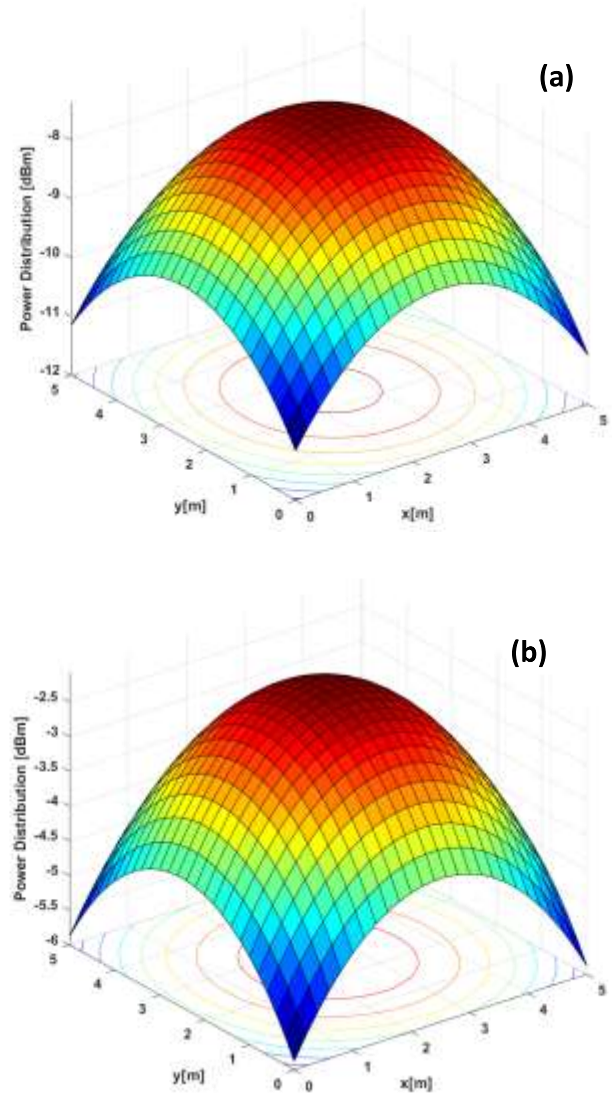


Fig. 9 Power distribution across the proposed room under uniform lighting topology assumption for SC- LPPM (a) without utilizing OFDM techniques, (b) by utilizing OFDM techniques.

Fig. 9(b) indicates that utilizing optical OFDM with SC-LPPM will show the same behavior as in the distinctive lighting topology by increasing the total received power.

It can be observed from Fig. 9(b), that the maximum received optical power across the room will increase to -2 dBm (i.e., 39 %) at the center of the room when optical OFDM is utilized, while the minimum optical power received at the corners of the room is increased to -4.5 dBm (i.e., 31.6 %).

6. SURVEY ON DIFFERENT MODULATION TECHNIQUES PRESENTED IN PREVIOUS LITERATURE

Several works of literature investigated and evaluated the performance of different SCM techniques, moreover, this literature aims to achieve a unique BER performance at enhanced data rates. But, due to design complexity not all of this literature investigated the combination process with optical OFDM techniques.

Moreover, it is noteworthy to mention that a lack in investigating different VLC modulation techniques under uniform lighting topology assumption can be indicated through scanning previous literatures.

Table 2 holds a survey on several techniques investigated by previous literature, their maximum achieved BER and power performance. This data is then compared with the results obtained from the presented work.

From Table 2, it can be indicated that SC- LPPM technique can achieve high operating data rates up to 50 Mbps with a remarkable power-saving performance when combined with optical OFDM techniques.

Table 2. Survey on different modulation techniques presented in previous literature.

Ref.	Evaluated techniques	OFDM utilization										
		Without utilizing optical OFDM						After utilizing optical OFDM				
		No. of LED lamps	Achieved BER	Achieved data rate	$P^{t}_{req.}$ [dBm]	Min. P^{r}_{j} [dBm]	Max. P^{r}_{j} [dBm]	Achieved BER	Achieved data rate	$P^{t}_{req.}$ [dBm]	Min. P^{r}_{j} [dBm]	Max. P^{r}_{j} [dBm]
39	CSK	1	3×10^{-1}	2×10^{6}	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated
40	PPM	1	10^{-6}	19.4×10^{6}	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated
35	SC- LPPM	4	2.25×10^{-6}	3×10^{6}	-0.0307	2.75	8	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated
41	DIPPM	4	10^{-6}	1×10^{6}	11	21	26.5	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated
	SC- LPPM	4	10^{-6}	1×10^{6}	-0.1064	1.5	7	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated
	M-VPPM	4	10^{-5}	23×10^{6}	16	23	29	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated
16	PWM	1	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	10^{-3}	50×10^{6}	36.13	Not Evaluated	Not Evaluated
17	PWM	1	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	10^{-3}	50×10^{6}	42.28	Not Evaluated	Not Evaluated
	MPPM	1	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	10^{-3}	49×10^{6}	40.68	Not Evaluated	Not Evaluated
37	PWM	4	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	10^{-3}	50×10^{6}	36.31	Not Evaluated	Not Evaluated
	MPPM	4	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	10^{-3}	49×10^{6}	36.27	Not Evaluated	Not Evaluated
	VPPM	4	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	10^{-3}	40×10^{6}	35.83	Not Evaluated	Not Evaluated
	CSK	4	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	10^{-3}	49.17×10^{6}	36.26	Not Evaluated	Not Evaluated
	SC- LPPM	4	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	Not Evaluated	10^{-3}	37.5×10^{6}	35.69	Not Evaluated	Not Evaluated
In this work	SC- LPPM	4	2.25×10^{-6}	3×10^{6}	-0.1064	2.69	6.59	8.6×10^{-5}	50×10^{6}	7.048	6.13	10.12

7. CONCLUSION

In the presented work SC-LPPM modulation technique performance is investigated after being combined with M-QAM OFDM under the assumption of two lighting topologies (i.e., distinctive lighting topology and uniform lighting topology).

For distinctive lighting topology, it can be indicated through the manuscript that utilizing optical OFDM with SC- LPPM resulted in increased operating bit rates up to 50 Mbps with a remarkable BER performance of 8.6×10^{-5} with an acceptable increase in the required transmitter power of 16 mW. Meanwhile, it can be shown that utilizing optical OFDM with SC- LPPM enhances the received optical power distribution across the proposed room topology to 10.12 dBm.

By investigating the scheme under uniform lighting topology assumption, it was found that the scheme BER performance was decreased compared to the performance under the distinctive lighting assumption. for the uniform lighting topology, utilizing SC-LPPM as a SCM technique, the BER performance will fail to achieve the minimum BER performance required to sustain a reliable communication link.

Meanwhile, combining the scheme with M-QAM OFDM will enhance the BER performance up to 10^{-5}.

By comparing the power performance under uniform lighting topology assumption to the distinctive lighting topology. It can be found that the minimum required transmitter power increases (i.e., up to 42%) when SC-LPPM scheme is utilized as a SCM technique for uniform lighting topology. Moreover, a significant increase (i.e., up to 414 %) can be indicated when M-QAM OFDM is utilized.

Finally, it was found that for uniform lighting topology, the minimum power required to achieve an acceptable BER performance cannot be detected when the receiver is located at the corners of the proposed room.

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