Exploring BER performance of a SC-LPPM based LOS-VLC system with distinctive lighting

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This paper introduces an optimization parametric study for a sub-carrier pulse position modulation (SC-LPPM) based line of sight-visible light communication (LOS-VLC) indoor system. The optimization process targets achieving optimum possible communication and illumination performance. The obtained results show that, to satisfy enough illumination level ($\geq$ 300 Lux) the operating bit rate should be $\leq$ 3 Mbps. Increasing the subcarrier modulation factor (SCMF) in the range 0 to 40% at 3 Mbps provides a remarkable BER (up to 10^{-6}) and a reasonable illumination performance ($\sim$400 Lux) with an acceptable increase in the total required system lighting power. Increasing the modulation level (L) enhances the BER performance at the cost of the illumination performance especially at low bit rate regions. The choice of L = 8, SCMF increases by 40% and a bit rate $\leq$ 3 Mbps provides a BER of 2.254×10^{-6} and an illumination level of 420 Lux through the room and 4.54×10^{-5}, $\sim$140 Lux respectively, when moving towards the room corners. The work is extended to study the effects of: 1) different modulation levels and SCMF, 2) distance between transmitter and receiver, and 3) transmitter semi-radiation angle and SCMF on system performance and power requirements.

1. Introduction

Recently visible light communication (VLC) gained a growing interest in research and development at a global level as a supplement to radio frequency (RF) technology [1 - 4]. Compared to RF, VLC offers many advantages such as free license bandwidth, available infrastructure, no interference with surrounding electronic and RF circuits, privacy and security [5]. The VLC technology combines communications with lighting, where using LEDs has become a valuable means for wireless communications. LEDs offer many advantages over the existing incandescent sources such as longer life times, improved robustness, smaller sizes, and faster switching. So, LEDs can be efficiently used for VLC systems [6, 7].

VLC is used in various applications, including high bit rate data transmission in indoor environments, electromagnetic interference, sensitive environments like aircraft, and underwater data transmission. The traffic control systems also use VLC to enable vehicles and infrastructure-to-vehicle communications [8 - 10].

Another interesting research area regarding VLC is the reduction of the total power consumption while satisfying lighting and communication requirements. Two of the main objectives of LED based system are the achievement of dimming and communication support. Although these two objectives are relevant to each other, they are generally treated separately. Dimming and communication support are achieved using different modulation techniques [7]. Dimming support can be achieved by using pulse width modulation (PWM) and pulse amplitude modulation (PAM), while data transmission can be achieved by using on-off keying (OOK) and pulse position modulation (PPM) [11].

For achieving power and bandwidth efficiency, PPM and its variants L-ary pulse position modulation (LPPM), inverted L-ary pulse position modulation (I-LPPM) and multi-pulse PPM (MPPM)) are considered as effective techniques [12]. Yet, they are not considered as effective VLC modulation techniques as most of these modulation techniques are designed for free space optical communications based on infrared (IR) transmission, which supports communication only. Hence, dimming support was not taken into account.

Recent studies considering the above mentioned issue are conducted to achieve both dimming and communication support simultaneously.

Several modulation schemes had been introduced to

achieve both communication and illumination criteria. Design aspects to achieve dimming and communication support includes: 1) reduction of power consumption, 2) enhanced throughput, 3) higher operating data rates, 4) spectral efficiency, 5) complexity reduction, 6) range and levels of dimming control, and 7) flicker free operation. SC-LPPM scheme has the advantage of power saving and design simplicity as an extra advantage.

A variable-rate MPPM technique for combined brightness control and data transmission was presented in [13] to achieve brightness control by varying the number of information-carrying slots per symbol, resulting in changing the data transmission rate with the change in brightness.

Other PPM schemes like, overlapping pulse position modulation (OPPM) [14], overlapping MPPM (OMPPM) [15], differential PPM (DPPM) [16], expurgated PPM (EPPM) [17, 18], Multi-level EPPM (MEPPM) [19] and variable PPM (VPPM) [20] are nominated examples.

However, another two methods for joint control of brightness and data transmission are proposed in [21]. The first method proposed the use of subcarrier pulse position modulation (SC-LPPM) for data transmission, and PWM for brightness control. Communication and dimming are controlled independently; however, changing the brightness affects the communication signal power. The second method proposed the use of SC-LPPM for data transmission, while dimming control is achieved by varying the modulation depth of SC-LPPM. The second scheme successfully achieves a steady data transmission rates even if the brightness is varying in the range of 12.5 - 87.5% [21].

In their work on SC-LPPM [7], I. Din and H. Kim focused on the reduction of the total LED power consumption while satisfying both lighting and communication requirements. No further investigation on SC-LPPM parameters or system optimization was done to enhance the merits of such modulation scheme. It is noteworthy to mention that there is a lack in investigating the system limitations for supporting both communication and lighting across the proposed room.

In this paper, we introduce an optimization parametric study for a SC-LPPM based LOS-VLC system and a distinctive lighting layout. A performance analysis for BER, minimum required power, $P_{req.}$ and the illumination under different operating bit rates and modulation levels is carried out to determine the optimum operating conditions for the proposed scheme. Another aspect of this study is to analyze the system performance across the proposed room layout (i.e. under the light source and at the room corners). This work indicates the operation system rates limitations of the proposed scheme as a VLC system that supports both communication and illumination requirements in a typical room. Optimized SC-LPPM parameters can maintain an acceptable communication and illumination performance which are the main advantages of SC-LPPM.

The remainder of the paper is organized as follows. Section 2 describes the system environment. The channel model is introduced in Sec. 3. Section 4 is devoted for the proposed system design including its parameters. The obtained results are presented and discussed in Sec. 5. This is followed by the main conclusions in Sec. 6.

2. System environment

In the present work, I identical LED modules are assumed that are equally spaced on the celling of a (5×5×3 m3) room at the positions (1.25, 1.25, 2.5), (1.25, 3.75, 2.5), (3.75, 1.25, 2.5), (3.75, 3.75, 2.5), while the receiver is assumed to be at desk level of height (0.85 m) and under the LED modules, as shown in Fig. 1.
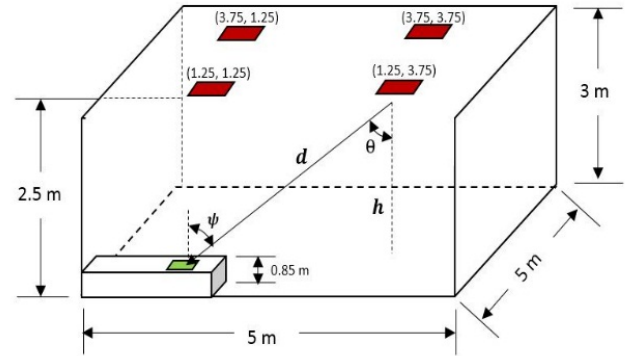

Fig. 1. Room configuration

A direct component (DC) and a subcarrier component (SC) are the main components required to construct the structure of SC-L-PPM. L equal time slots can form a symbol interval (T), as (T_S = T/L).

The optical signal is carried in one of these L slots, i.e., SC component, while the rest of the symbol interval (L-1) has a constant amplitude, i.e., DC component. While L has the power of two, i.e., L = 2^k, each symbol interval corresponds to ($\log_2$ L) data bits, and the position of the subcarrier component corresponds to its decimal value.

Fig. 2 shows the wave form of a SC-4 PPM scheme. The value of (c-a) represents the amplitude of the signal [22], and (b) represents the amplitude of the DC component.
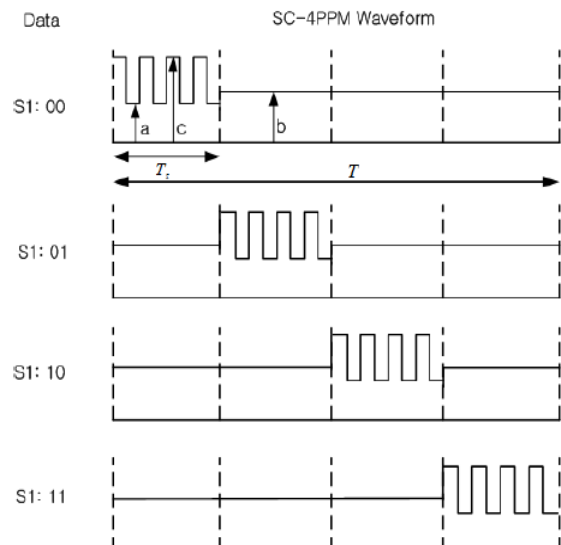

Fig. 2. SC-4 PPM waveform [7]

3. Channel model

3.1. Illumination

The output luminous flux generated by a LED lamp can be calculated as [7]

$$\varphi_i = N \times \varphi_{max} \tag{1}$$

where i is the lamp index and φ_{max} is the maximum luminous flux generated by each LED. It is generated when the input waveform has a DC component with maximum amplitude.

The brightness factor, N, can be obtained through [7]

$$N = \frac{(\tau_1 \times (a+c) + \tau_2 \times b)}{T} \tag{2}$$

where τ_1 and τ_2 are $T_S/2$ and $3\ T_S$, respectively.

Hence, Eq. (1) can be written as

$$\varphi_i = (\tau_1(a_i + c_i) + \tau_2 \times b)\ \varphi_{max} \tag{3}$$

The brightness control can be achieved by varying the values of a, b, and c. Varying the b levels will result in achieving 75% of dimming control without affecting the communication link, while varying both a and c levels will result in achieving the remaining 25% of dimming control. Since illuminance expresses the brightness of an illuminated surface, the illuminance level at a work place j can be obtained by adding the illuminance form all LED lamps. Hence, the total illuminance level E_j can be expressed as [7]

$$E_j = \sum_{i=1}^{I} e_{ij} \tag{4}$$

where e_{ij} is the illuminance received at work place j from a LED lamp i.

Assuming that the source has a Lambert radiation characteristics, e_{ij} can be expressed as [7]

$$e_{ij} = \frac{(m+1)\varphi_i}{2\pi d_o^2} \cos^m(\theta)\ \cos\psi \tag{5}$$

where m is the Lambert index, do is the distance between the LED lamp and the photodiode (PD) receiver, θ is the angle of irradiance, and ψ is the angle of incidence.

3.2. Communication

The signal strength in an optical communication link is determined by the transmitted optical power, which is irradiated by the LED [7]. To calculate the signal strength of an SC-LPPM signal, only the transmitted power through the subcarrier component is considered; hence it can be calculated as

$$P_i^t = M \times P_{max}^t \tag{6}$$

where P_i^t is the optical transmitted power from the ith LED, P_{max}^t is the maximum optical transmitted power by the LED, while the optical power factor or subcarrier modulation factor, SCMF, or simply M, for a SC-LPPM waveform can be formulated as

$$SCMF = c - a \tag{7}$$

For a wireless optical channel, the optical power received by the PD can be derived as follows [7]

$$P_j^r = \sum_{i=1}^{I}(H(0) \times P_i^t) \tag{8}$$

where P_j^r is the optical power received at workplace j, and H(0) is the channel response, which can be obtained for a LOS channel using [7]

$$H(0) = \frac{A_{eff}(m+1)}{2\pi d_0^2} T_s(\theta)\ g(\theta) \cos^m(\theta)\ \cos\psi \tag{9}$$

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

Using Eqs. (6), (8), and (9), the total received optical power can be represented as

$$P_j^r =
\begin{cases}
(c_i - a_i) \times P_{max}^t \times \frac{A_{eff}(m+1)}{2\pi d_0^2} T_s(\theta)\ g(\theta) \cos^m(\theta) \cos\psi, \\
\qquad\qquad \theta \leq FOV \\
\\
\qquad 0, \\
\qquad\qquad \theta > FOV
\end{cases} \tag{10}$$

where FOV is the receiver field of view.

The bit error rate (BER) is a main parameter used for evaluation the performance of a communication system. For a SC-LPPM, it can be obtained as [7]

$$BER = \frac{L/2}{L-1} Q\left(\frac{1}{2}\sqrt{\frac{3\ A_{eff}^2\ L\left(P_j^r\right)^2 \log_2 L}{N_o R_b}}\right) \tag{11}$$

where R_b is the bit rate, 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 the SC-LPPM to achieve a given BER which is given by [7]

$$P_{req} = \frac{2}{A_{eff}} Q^{-1}\left(\left(\frac{L-1}{L/2}\right) \times BER\right)\sqrt{\frac{N_o R_b}{3\ L \log_2 L}} \tag{12}$$

4. System design

This work assumes the famous configuration of a 5×5×3 m^3 empty room, under LOS assumption. There are

four LED modules that work together as an access point mounted at a height of 2.5 m, as mentioned in Section 2. Table 1 shows different room, source, and receiver parameters. These values ensure both proper lighting and communication processes.

Table 1. Simulation parameters [3]

	Parameter	Value
Room	Room size	$5\times5\times3$ m^3
	Height of desktop surface	1 m
Source	Number of LEDs	3600 (60×60)
	LED transmitted power	20 mW
	Semi-angle half power	60°
	Center luminous intensity	0.73 cd
	power spectrum density	10^{-21} W/Hz
Receiver	Area	1 cm^2
	Field of view (FOV)	120°
	Responsivity	0.4 A/W
	Concentrator refractive index	1.5
	Filter gain	1

5. Results and discussion

To provide an acceptable/remarkable communication performance, the proposed system is tested and a structural parametric study is carried out. A MATLAB code is constructed to express the mathematical model presented in Section 3, which is required to evaluate the system performance under a wide range of bit rates.

The effect of different modulation levels, transmitter semi-radiation angle $(\theta_1/2)$, and the distance between transmitter, Tx, and the receiver at a distance h, Rx(h), will be investigated at different SCMF for a SC-LPPM modulation scheme to evaluate the system performance (BER), power requirements ($P_{req.}$), illumination and power distribution.

It is noteworthy to mention that, such evaluation is performed using theoretical analysis and simulation. It can be shown from other experimental work investigating the performance of PPM based schemes, that the experimental results show a fair agreement with the theoretical analysis [23]. Accordingly, our simulation results show a fair agreement the experimental results.

5.1. Communication requirements

5.1.1. Effect of different modulation level and SCMF on system performance and power requirements

Fig. 3 represents the BER against operating bit rate, R_b, for the proposed system at different values of L and SCMF.

Under the assumption that the receiver is located under the light sources, the system BER performance decreases with increasing the operating bit rate. This

behavior can be enhanced by using higher values of L at a fixed SCMF.

Hence, appreciable enhancement can be achieved by operating at 40% SCMF increase as shown in Fig. 3 (b). A remarkable BER of 4×10^{-5} can be achieved at a relatively high bit rate of 15 Mbps, L=8 and 40% increase of SCMF.

The SC-LPPM based LOS/VLC system performance shows a noticeable BER improvement at lower bit rates especially with higher values of L and SCMF. For bit rate = 3 Mbps, an optimum BER of 2.254×10^{-6} is achieved with L=8 and 40% increase of SCMF. More BER enhancement can be observed at bit rates less than 3 Mbps.
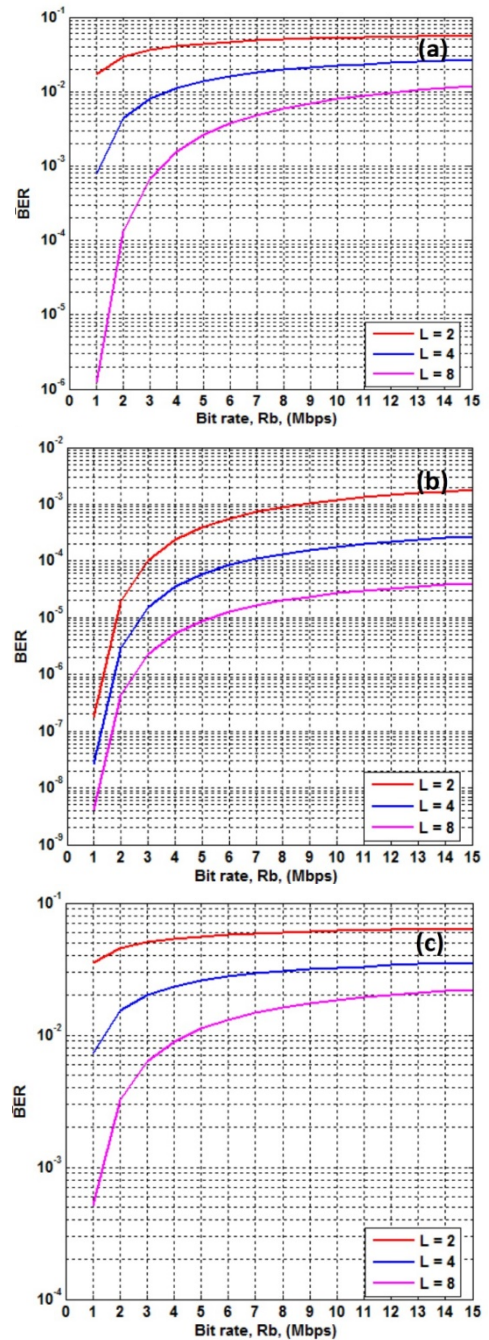

Fig. 3. BER vs. bit rate at different modulation levels (L) for (a) moderate SCMF, (b) increasing the SCMF by 40%, (c) decreasing the SCMF by 40%

The minimum required power is displayed in Fig. 4 for SC-LPPM against the operating bit rate at different values of L and SCMF.

It is clear that, $P_{req.}$ decreases with the decreasing SCMF, regardless to the operating bit rate and L. Therefore, Fig. (4-c) provides the minimum power requirements especially at high modulation levels and low bit rates. However, operating at lower values of SCMF, as shown in Fig. 4 (c), shows bad BER performance as indicated in Fig. 3(c).
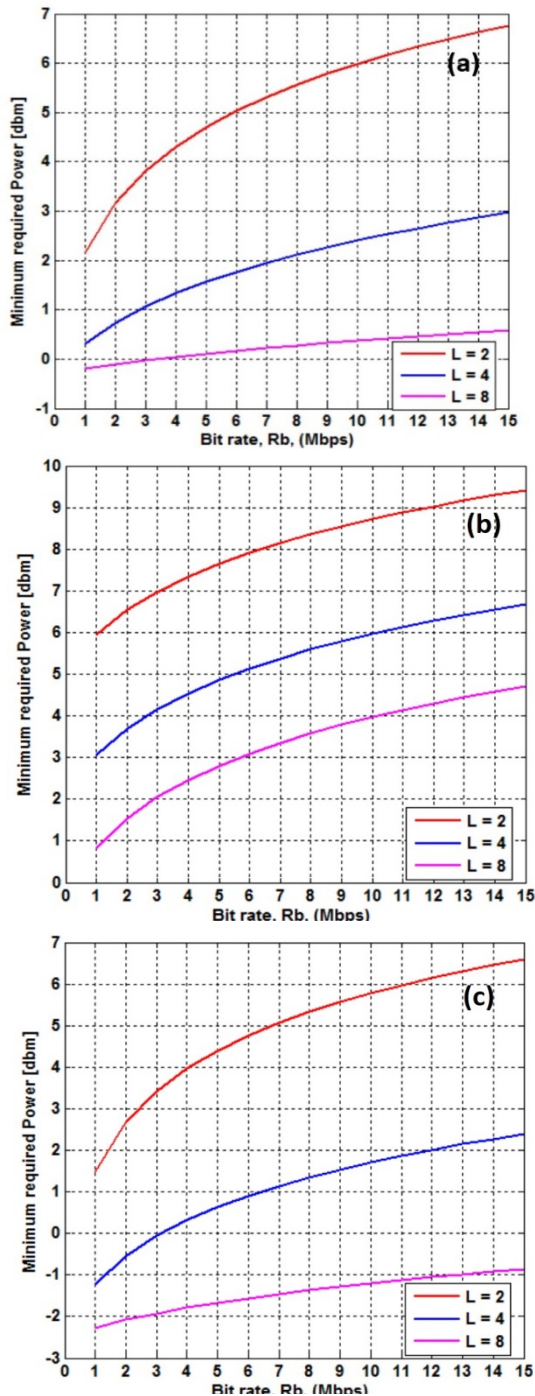
According to Fig. 4 (a, c), it is noteworthy to mention that for moderate SCMF and 40% decrease at higher bit rates, the effect of the modulation level L becomes more noticeable compared to the case of SCMF 40% increase of Fig. 4(b). From Fig. 4(c), at L=8, one needs ~ 1 dBm to transfer from low bit rate of 1 Mbps operation to high bit rate operation of 15 Mbps. While at L=2, one needs ~ 5 dBm to get the same transfer.

Hence, increasing SCMF by 40% means that the LED transmitted power will be increased by 8 mW. In other words, and according to the lighting system layout assumed, an LED module that consists of 60×60 LED array will consume after SCMF 40% increase a total power of 100.8 Watt which is lower that some types of conventional lighting systems incandescent and florescent which consumes 60 W/lamp and 14 W/lamp respectively [22].

This will be considered as an acceptable price paid for achieving a good BER performance especially at high bit rates environment as indicated in Fig. 3. Another aspect for assuming SCMF increase by 40% is that this value is essential for the second important merit of SC-LPPM based LOS/VLC system which is satisfying the illumination requirements as will be shown in the next section.

5.1.2. Effect of distance between Tx and Rx(h)

The BER against operating bit rate, R_b, at different values of (h) and SCMF is shown in Fig. 5.

It is noticed that, the system BER increases as the distance between Tx and the Rx(h) decreases. This behavior can be enhanced by increasing the SCMF by 40% as shown in Fig. 5(b). From Fig. 5 (a), it is observed that, the system performance increases from 2.491×10^{-2} to 1.21×10^{-3} at a bit rate of 3 Mbps as h decreases from 2.5 to 2.1 m, respectively. While for the same operating bit rate, Fig. 5 (b) shows that, as the SCMF increases by 40 %, the system performance enhances from 2.086×10^{-2} at h=2.5 m to 9.119×10^{-5} at h=2.1 m. Yet, decreasing the SCMF by 40 % results in a noticeable decrease in the system performance as for h=2.5 m, the system achieves a BER of 5.913×10^{-2} while for h=2.1 m a BER = 8.058×10^{-3} is achieved.
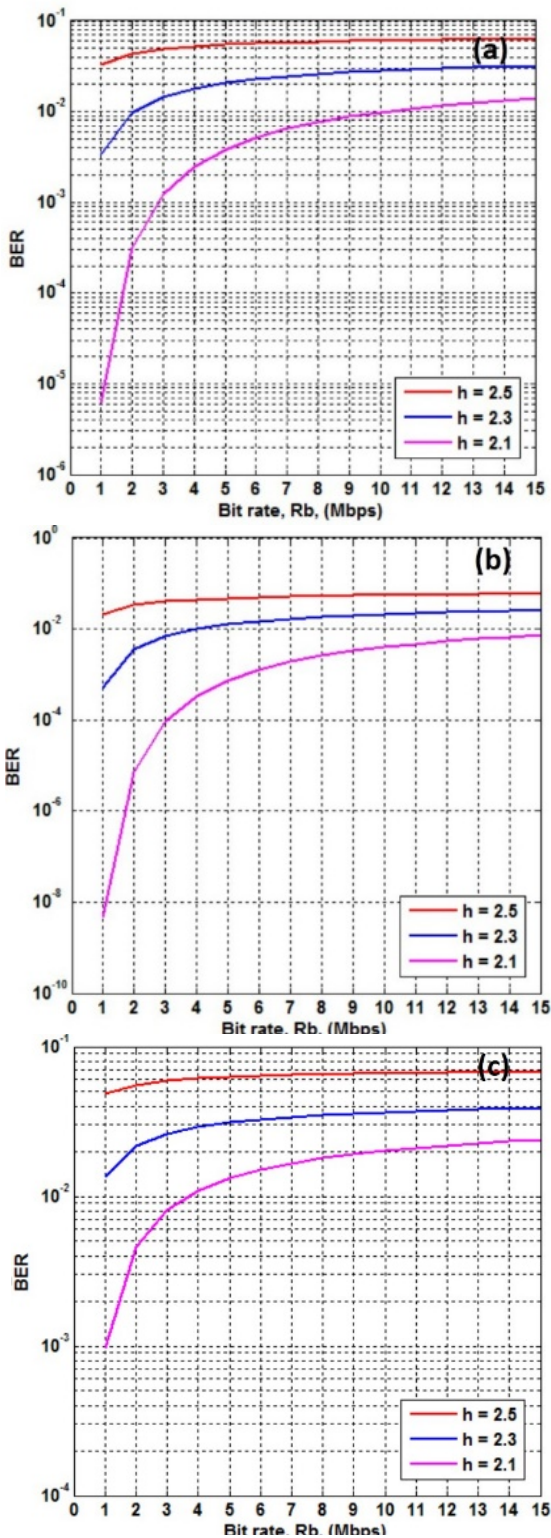

Fig. 4. Minimum required power vs. bit rate at different modulation levels (L) for (a) moderate SCMF, (b) increasing the SCMF by 40%, (c) decreasing the SCMF by 40%

It is observed from Fig. 6(b) that, at lower bit rates (< 2 Mbps), the value h=2.1 m requires more P_{req} than h=2.3 m. Hence, it can be assumed that for choosing to increase the SCMF by 40%, choosing h=1.9 m is not the optimum choice regarding power requirements. Hence, choosing the distance between Tx and Rx(h) to be 2.1 m with increasing the SCMF by 40% is the best choice regarding the power requirements of the proposed system.

Fig. 5. BER vs. bit rate at different receiver heights, h, for (a) moderate SCMF, (b) increasing the SCMF by 40%, (c) decreasing the SCMF by 40%

Fig. 6 (a) shows that P_{req} decreases as the distance between Tx and Rx(h) decreases. From Fig. 6 (c), it is observed that the power required decreases by decreasing the SCMF by 40%, leading to a decreased system performance as shown in Fig. 5 (c).
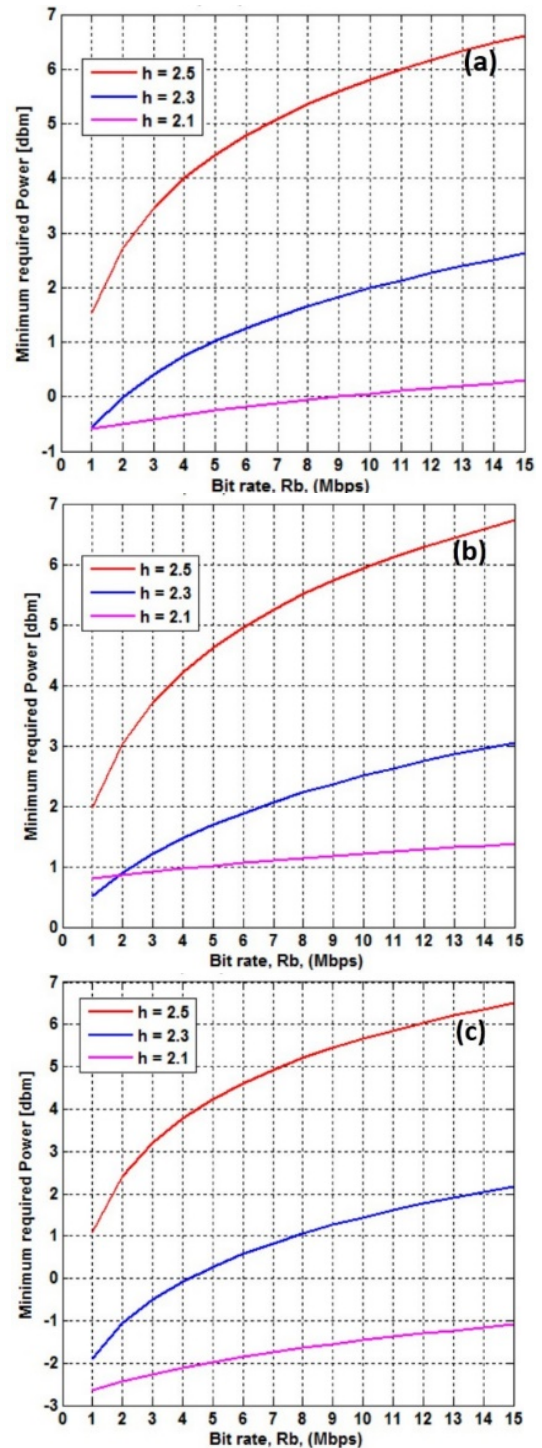

Fig. 6. Minimum required power vs. bit rate at different receiver heights, h, for (a) moderate SCMF, (b) increasing the SCMF by 40%, (c) decreasing the SCMF by 40%

5.1.3. Effect of transmitter semi-radiation angle ($\theta_{1/2}$) and SCMF

Fig. 7 shows the BER against operating bit rate, Rb, at different values of Tx semi-radiation angle ($\theta_{1/2}$) and SCMF. It can be observed that, the system performance enhances as $\theta_{1/2}$ varies from 60° to 90° (i.e. becomes narrower). This, comes from the fact that the Tx directivity increases as the angle minimizes. Hence, the received optical power resulting from all the sources within the room increases.

Fig. 7(a) shows that at a bit rate of 3 Mbps, the BER enhances from 9.698×10^{-3} to 6.68×10^{-4} as $\theta_{1/2}$ varies from 90° to 60°, respectively. This can be enhanced by increasing the SCMF by 40% as shown in Fig. 7 (b). Hence, for the same bit rate, the system performance enhances from 5.33×10^{-3} to 9.129×10^{-5} as $\theta_{1/2}$ varies from 90° to 60°, respectively.

Fig. 7(c) shows the effect of decreasing the SCMF by 40%, resulting in a noticeable degradation in the system performance as the BER performance of the system increases from 2.005×10^{-3} to 6.29×10^{-3} as $\theta_{1/2}$ varies from 90° to 60°, respectively.
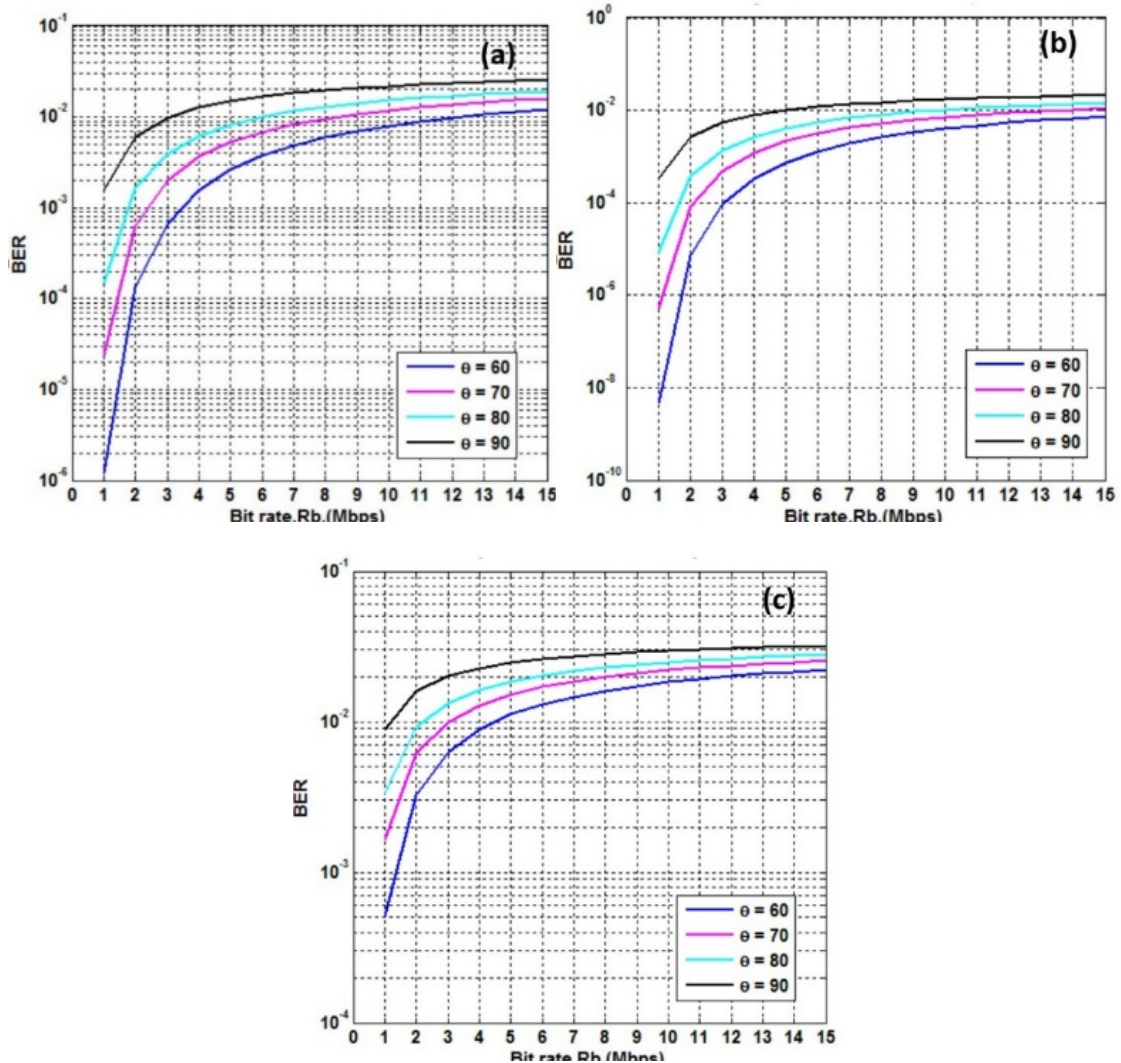

Fig. 7. BER vs. bit rate at different Tx semi-radiation angle ($\theta_{1/2}$) for (a) moderate SCMF, (b) increasing the SCMF by 40%, (c) decreasing the SCMF by 40%

The minimum required power for SC-LPPM at $\theta_{1/2}$ and SCMF against operating bit rate is displayed in Fig. 8. Fig. 8 (a) shows that P_{req} levels enhance as $\theta_{1/2}$ becomes narrower. From Fig. 8 (b), it is shown that the power required increases with increasing the SCMF by 40%. Such increase is a reasonable price for increasing the system performance. Decreasing the SCMF by 40% results in enhancing the system power requirements but on the expense of the system performance.
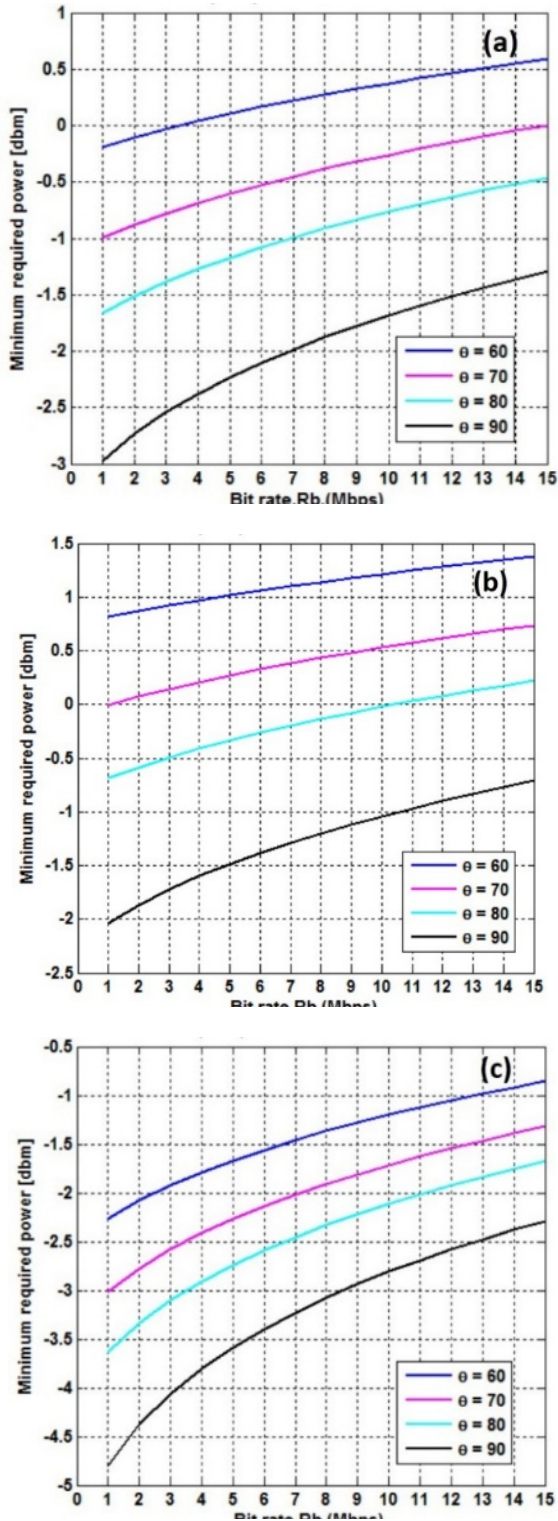
Fig. 8. Minimum required power vs. bit rate at different Tx semi-radiation angle ($\theta_{1/2}$) for (a) moderate SCMF, (b) increasing the SCMF by 40%, (c) decreasing the SCMF by 40%

5.2. Illumination requirements

Another aspect of the study is to evaluate the illumination performance under a wide range of bit rates,

different modulation levels and increasing and decreasing the SCMF by 40% from its moderate levels (i.e. normal levels). Hence, one can determine the capabilities and the limitations of the proposed scheme.

5.2.1. Effect of different modulation levels and SCMF on illumination requirements

Fig. 9 shows an evaluation for the illuminance levels from a single source in the proposed room structure against the bit rate (R_b) at different modulation levels (L) and SCMF.
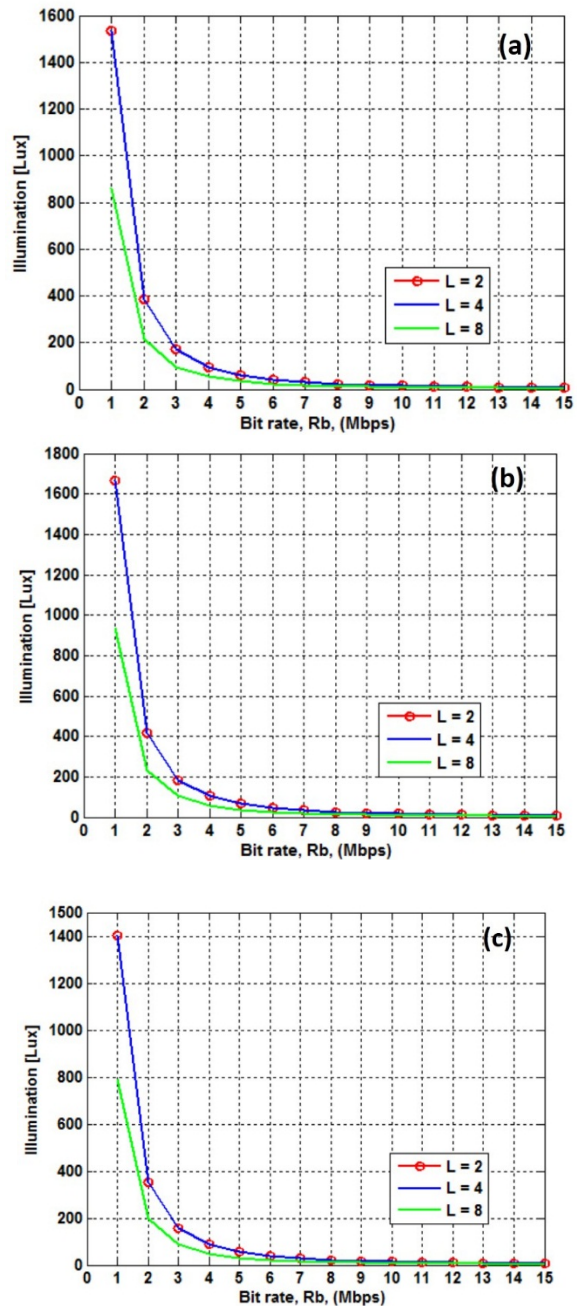

Fig. 9. Illuminance levels at different modulation levels against the bit rate at (a) moderate SCMF, (b) increasing the SCMF by 40%, (c) decreasing the SCMF by 40%

As indicated in Fig. 9, increasing the operating bit rate decreases the illuminance level. A better performance for illumination levels can be observed with lower L at any value of SCMF. It is observed that, the illuminance levels for both modulation levels (L =2) and (L=4) is the same, that comes from the SC-LPPM nature as discussed at Section 2, the symbol interval (T) corresponds to $\log_2 L$ and is divided into equal time slots (Ts = T/L). Hence, for L=2 and L=4 the time slot interval will be the same resulting in the producing the same illuminance levels.

For a fixed value of L, naturally illumination levels enhances as SCMF enhances, hence providing another reason for choosing SCMF 40% increase as the preferable condition in the end of Section 5.1.1.

From Fig. 9, it can be observed that, when L decreases, the illumination level enhances but with insignificant ratio especially in high bit rates (in the range of bit rate > 3Mbps). This will lead to an essential observation for this work that is; to join (effectively) both illumination and communication requirements for SC-LPPM based LOS/VLC system, 3 to 4 Mbps operation cannot be exceeded. At this rage, system can achieve an acceptable BER performance with reasonably low required power and sufficient illumination.

According to the previous discussion and Fig. 9 (b), to achieve sufficient illumination, an operating bit rate < 3 Mbps will be the area of interest. At L=2 and bit rate =3 Mbps, the illuminance levels will equal to 185 Lux which corresponds to a BER of 1×10^{-4} and $P_{req.}$ of 7 dBm. For the same bit rate at L=8, the illuminance levels will equal to 105 Lux, BER = 2.254×10^{-6} and $P_{req.}$= 2 dBm.

So, even at low bit rate (i.e. ≤ 3 Mbps), the difference between illumination levels at L=2 and L=8 is not significant while the difference in BER and $P_{req.}$ is observable. With a modulation level L=8, an illuminance of 105 Lux per LED module is generated. This will provide a total lighting of 420 Lux which is just sufficient [7] but with an acceptable BER and $P_{req.}$ levels as previously discussed. Hence, choosing higher modulation level (i.e. L= 8) is the preferable choice. It is noteworthy to mention that, the illuminance of the proposed room is generated by four LED modules. Hence, it is essential to meet the illumination standard while operating at high bit rates.

5.2.2. Effect of distance between Tx and Rx(h) and SCMF on illumination requirements

The illuminance levels from a single source in the proposed room structure against the bit rate (R_b) at different distances between Tx and Rx(h) and SCMF is shown at Fig. 10.
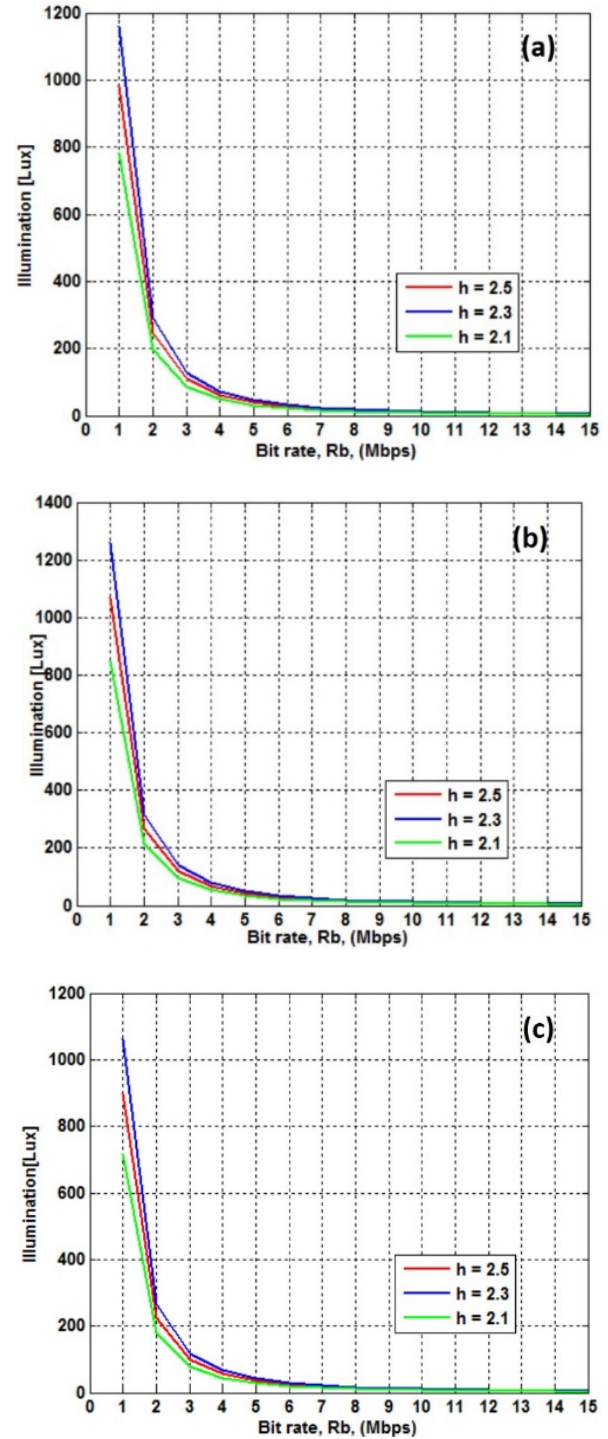

Fig. 10. Illuminance levels at different distance between Tx and Rx(h) against the bit rate at (a) moderate SCMF, (b) increasing the SCMF by 40%, (c) decreasing the SCMF by 40%

Fig. 10 shows that, increasing the operating bit rate causes a decrease in the illumination level. As indicated in Fig. 8 (a), for h=2.3 m and a bit rate of 3 Mbps, the illumination performance of the proposed system is 129 lux, while decreasing the distance between Tx and Rx to 2.1 m results in decreasing the system illumination to 89 lux. Also, increasing the distance between Tx and Rx to

2.5 m results in decreasing the system illumination to 109 lux for the same bit rate.

From Fig. 10(b), it is indicated that increasing the SCMF by 40% will increase the illumination of the proposed system to 145 lux, 96 lux, 120 lux for h=2.3 m, h=2.1 m, h=2.5 m, respectively. Also, decreasing the SCMF by 40% results in a noticeable decrease in the illumination as indicated from Fig. 10(c), providing another reason for not choosing to decrease the SCMF in the proposed system.

Therefore, the best choice is increasing the SCMF by 40% and using 2.3 m for the distance between Tx and Rx. But, as previously indicated in Sec.5.1.2, choosing h = 2.3 m results in a noticeable decrease in the system performance and power requirements compared to h=2.1

m. Hence, it can be assumed that such difference on the illumination performance is affordable compared to the remarkable BER performance shown in Sec.5.1.2, especially at the bit rates > 3Mbps.

5.2.3. Effect of TX semi-radiation angle ($\theta_{1/2}$) and SCMF on illumination requirements

Fig. 11 shows the illumination levels from a single source in the proposed room structure against the bit rate (R_b) at different values of Tx semi-radiation angle ($\theta_{1/2}$) and SCMF.

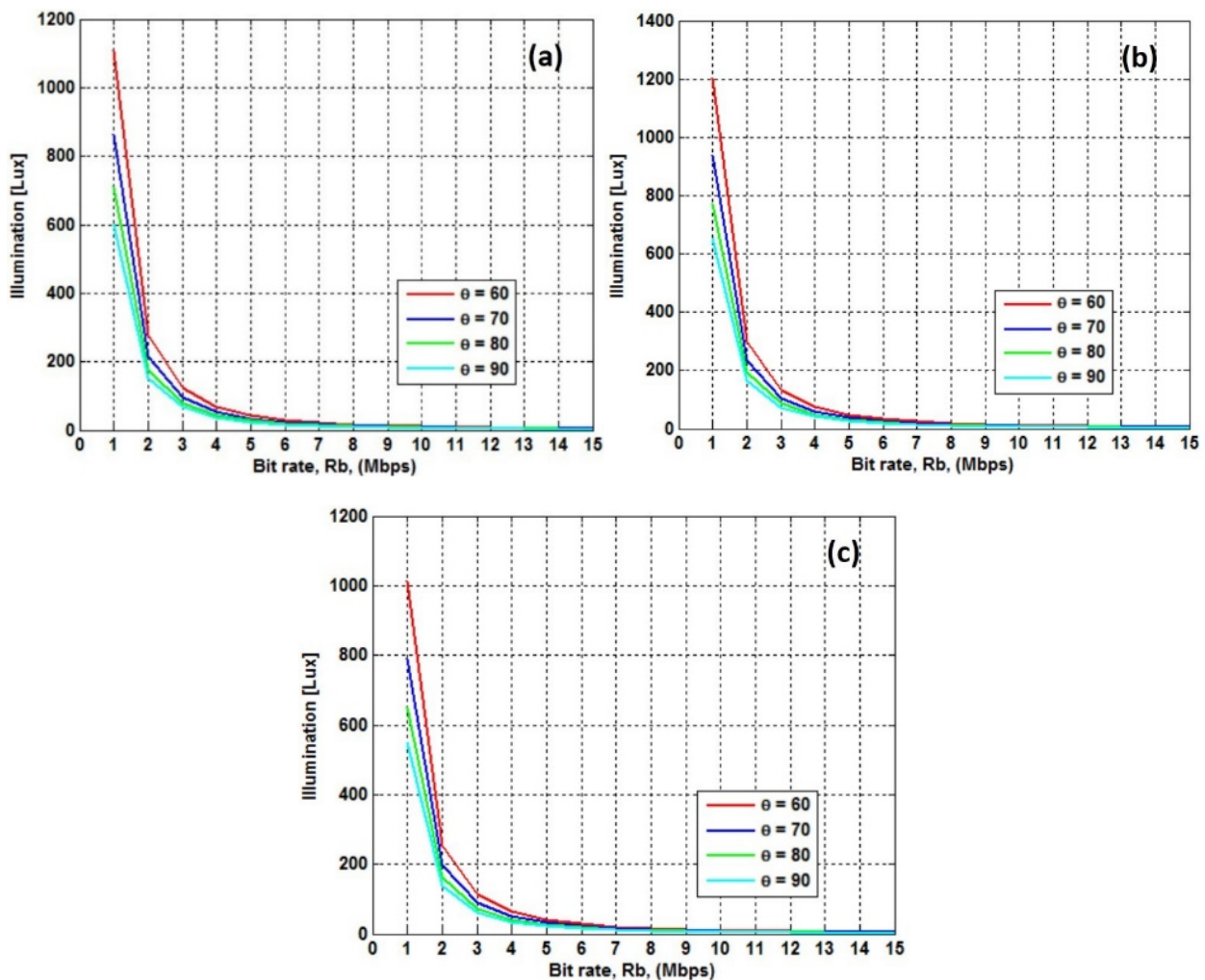*Fig. 11. Illuminance levels at different Tx semi-radiation angle ($\theta_{1/2}$) against the bit rate at (a) moderate SCMF, (b) increasing the SCMF by 40%, (c) decreasing the SCMF by 40%*

Fig. 11 shows that, the illumination decreases as the operating bit rate increases. Also, at operating bit rate of 3 Mbps, the illumination of the system decreases from 125 to 75 lux as $\theta_{1/2}$ varies from 60° to 90° (i.e. becomes narrower), respectively. For the same bit rate, Fig. 11(b) shows that, increasing SCMF by 40% results in increasing

the system illumination to 140 and 80 lux for $\theta_{1/2}=60^o$ and $\theta_{1/2}=90^o$, respectively.

As previously discussed and from Fig. 11(c), it is indicated that decreasing the SCMF will result in decreasing the illumination of the system, which will not be the optimum operating choice.

It can be shown from Fig. 11 (b) that, choosing $\theta_{1/2}=60^{\circ}$ and increasing the SCMF by 40 % is the best choice for illumination requirements and will result in a remarkable system performance.

5.3. Optimized 3D power and illumination distribution

Fig. 12 represents the power and illumination distribution respectively at a modulation level L=8, SCMF increase by 40 % and bit rate of 3 Mbps. These values are chosen as the optimum operating parameters through this work. According to previous sections, it is noteworthy to mention that these values cannot lead to best performance but they provide acceptable BER and $P_{req.}$ at a reasonable operation bit rate on the price of illumination level.

Based on Fig. 12 (a), the received power varies from 2.75 dBm at the corner of the room to $\sim$ 8 dBm under the ceiling lights along the room. The strongest LOS components are under the four LED modules and gradually fall as the receiver moves to the four corners of the room. This will reflect of the value of the BER to increase from (2.254×10^{-6}) at the room center to (4.54×10^{-5}) at room corner.

The illuminance distribution shows that, sufficient illumination for a typical room is achieved as shown in Fig. 12(b). An illumination level of 420 Lux is approximately maintained through the room except when moving towards the corners to reach $\sim$140 Lux.
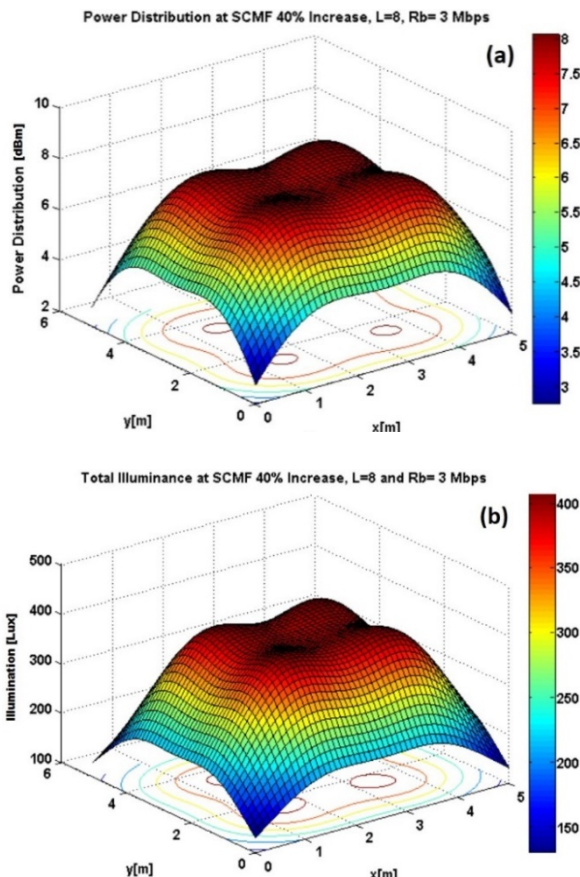
6. Conclusion

This work presents a parametric study for BER, power and illuminance of a data transmission and brightness control scheme. This scheme efficiently minimizes the energy consumption of a VLC system operating in a typical room construction while satisfying users' communication and lighting requirements. Choosing the optimal parameters for the input waveform of LED module, the scheme replaces the conventional iterative approach for brightness control, which reduces the total energy consumption of LED modules while ensuring the communication link quality and the desired brightness.

As concluded from this parametric study for the scheme an optimum operating bitrate of 3 Mbps with modulation level (L=8) and by increasing the SCMF by 40% provides a remarkable BER ($\sim10^{-6}$) and a reasonable illumination performance ($\sim$400 Lux) with an acceptable increase in the total required system lighting power ($P_{req.}$ = 2 dBm).

The work is extended to study the effects of: 1) different modulation levels and SCMF, 2) distance between transmitter and receiver, and 3) transmitter semi-radiation angle and SCMF on system performance and power requirements. It is found that, the best choice is increasing the SCMF by 40% and using 2.3 m for the distance between Tx and Rx, as well as the transmitter semi-radiation angle to be 60°.

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Fig. 12. Optimized 3D distribution for (a) received power, (b) total illuminance

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