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Investigation of Multiple LED Array Failure on DCO-FBMC Modulation for Indoor Visible Light Communication

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ABSTRACT

Visible light communication (VLC) is a high-speed and power-efficient optical wireless communication method that has gained momentum for data transmission in indoor environments. Indoor VLC systems often use multiple LED arrays to increase the uniformity of brightness and enhance the received energy and the four LED array model is the most commonly used. To suppress the impact of intersymbol interference (ISI) and achieve higher data rates, multicarrier modulation techniques such as orthogonal frequency division multiplexing (OFDM) and filter bank multicarrier (FBMC) have been introduced in VLC systems. The FBMC technique is a promising candidate for the 5G communication system and it has recently been applied to VLC systems. FBMC has several advantages: higher spectrum efficiency, narrower out-of-band radiations and asynchronous transmission. This study investigates the performance of an FBMC-based VLC system when one or more lamps in the multiple LED arrays experience failure. The VLC- FBMC model was implemented using a 4-QAM and 16-QAM format with three various LED array configurations while assuming a line of sight (LOS) model. The LED array model was evaluated based on its ability to achieve good bit error rate (BER) performance, communication quality and high bit rate and meet the required signal-to-noise ratio (SNR). The proposed FBMC model simulation's outcome indicates that the system is still able to transmit data reliably, even in the event of a failure of up to 50% of the lamps. The results indicate that the 2- and 4-lamp models yielded good BER performance, achieving a value of 3.6×10^{-5} and 5.4×10^{-5} respectively. Furthermore, the simulation demonstrated that the optical FBMC-based VLC system attained a high bit rate of 73.2 Mbit/s in the 4-QAM format using the 2-lamp model and a bit rate of 29.3 Mbit/s in 16-QAM format using the 4-lamp model, while maintaining acceptable BER performance.

1. Introduction

Visible light communication (VLC) is a new area of optical wireless communication (OWC) that has emerged to improve data transmission, especially in indoor devices, due to its high-power

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efficiency and free spectrum and thus, considered a promising technology for 5G and 6G applications as in the papers by Khalighi and Uysal [1]; Ariyanti and Suryanegara [2] and Ghassemlooy, Popoola and Rajbhandari [3]. The VLC method uses the light-emitting diode (LED) as both a means of illumination and communication as stated by Khan *et al.,* [4]. The LED transmits the input signal as power via the intensity modulation direct detection (IM/DD) method, which requires the transmitted signal to be real and non-negative as explained by Ghassemlooy [5] and Armstrong and Schmidt [6]. Multiple LED arrays are used in indoor VLC to ensure that the brightness of the light is evenly distributed throughout the room and that the received energy is maximised as introduced by Gismalla *et al.,* [7]. However, according to Gismalla *et al.,* [8] the multiple lamp propagation may lead to multipath and intersymbol interference (ISI) issues and affect the system performance. In optical wireless communication and VLC systems, the ISI is a severe problem caused by signal delay and the use of multiple LED arrays. ISI reduces system performance and raises the bit error rate (BER) as found by Gismalla *et al.,* [9]. Single carrier modulation techniques such as on-off keying (OOK) employed by Gismalla *et al.,* [10] are typically used in VLC systems for low-to-moderate data rate applications. Orthogonal frequency division multiplexing (OFDM) implemented by Tsonev *et al.,* [11] and filter bank multicarrier (FBMC) are two examples of multicarrier modulations that are used in the VLC system to achieve a high data rate and overcome the ISI issue [12-14].

Given its higher spectrum efficiency and resistance to the ISI effect, FBMC is a promising scheme for future wireless communications involving 5G and 6G communication, particularly for VLC as discussed by Qasim *et al.,* [15] and Oyewobi, Djouani and Kurien. [16]. FBMC with offset quadrature amplitude modulation (OQAM/FBMC) has higher spectrum efficiency, narrower out-of-band radiations, asynchronous transmission and lower spectral sidelobes due to the use of the prototype filter instead of a rectangular window of OFDM as shown by Nissel, Rupp and Marsalek [17]. New methods have been proposed to produce the optical domain IM/DD of the FBMC signal as discussed by Qasim *et al.,* [18,19]. The two main types of optical FBMC are DC-biased optical FBMC (DCO-FBMC) and flip-FBMC as introduced by Qasim *et al.,* [20]. The effectiveness and spectrum efficiency of optical OFDM and FBMC within the VLC system have been investigated by Kumar *et al.,* [21]. When employing a 25% cyclic prefix (CP), optical FBMC was 0.96 dB more power efficient and had a 20% larger spectral efficiency than optical OFDM.

Focusing on the VLC systems with multiple LED arrays, Gismalla *et al.,* [22] investigated the effect of root mean square (RMS) delay spread and bit rates on the VLC system with various LED array arrangements using four and five LED array models; however, the study employed the less efficient single carrier modulation OOK technique. Kaim *et al.,* [23] demonstrated a VLC system that achieved a bit rate of up to 2.55 Mbit/s using OOK modulation and a few LEDs. In addition to the limited bit rate, the communication distance was only 80 cm between the transmitter and receiver. Hong *et al.,* [24] employed a four-lamp arrangement using multicarrier DCO-OFDM and proved that optical OFDM effectively suppresses ISI. The researchers increased the illumination distribution and received power; however, the effect of increased bit rates and propagation delay has not been considered in the analysis. Chen *et al.,* [25] used DCO-FBMC for the VLC system. Even though the DCO-FBMC model's BER performance was better than DCO-OFDM's, only one transmitter was employed and its distance from the receiver side was just 20 cm. The reviewed literature indicates that no comprehensive research has been done on the application of multiple LED arrays and the investigation of lamp failure with the utilisation of FBMC modulation (DCO-FBMC)-based VLC system. Therefore, this research contributes towards the evaluation of three LED lamp configurations on the optical FBMC model-based VLC system while taking propagation delay and channel loss characteristics into account. Furthermore, this study uses a variety of metrics to evaluate the system performance, including LED illumination, received power, channel loss and delay, bit error rate (BER) and the signal-to-noise ratio (SNR). Additionally, the study analysed the effects of various bit rates on the BER performance for the three LED array models. The VLC-FBMC model was assessed using 4-QAM and 16-QAM formats, considering the BER performance, communication quality based on the constellation diagram and bit rate.

The remainder of this paper is organised as follows: The VLC system model and the equations used to analyse and assess the optical FBMC-VLC system performance are included in Section 2. The results and analysis of FBMC-VLC with multiple LED lamps at various bit rates are presented in Section 3. Finally, Section 4 concludes this study.

2. VLC System Model

This research aims to study the failure of one or more lamps in terms of illumination, power received and system BER performance because of channel loss and latency. Hence, a VLC system with various LED array topologies was evaluated together with the use of an optical FBMC with excellent spectral efficiency.

2.1 Configuration for Lamp Failure

The VLC system parameters for an indoor setting are covered in this section. Three distinct configurations were created to assess the failure of the LED lamps in terms of lighting, received power and BER performance. The transmitter of the suggested VLC model comprised LED arrays that were positioned in various locations along the ceiling of a standard 5 × 5 × 3 m^3 room. The 2-lamp model contains a 2 × 1 LED array, the 3-lamp model has a 3 × 1 LED array and the 4-lamp model consists of a 2 × 2 LED array. Each LED lamp has 60 × 60 LEDs and the total power transmitted by one lamp is 72 W (20 mW per LED as Aydin *et al.*, [26]). The receiver was situated 2.15 m from the ceiling and had a field of view (FOV) of 70° and the area of the photodetector (PD) was 1 cm^2. The VLC model for the indoor environment and the specific positions of the LED lamps are shown in Figure 1 and Figure 2, respectively.

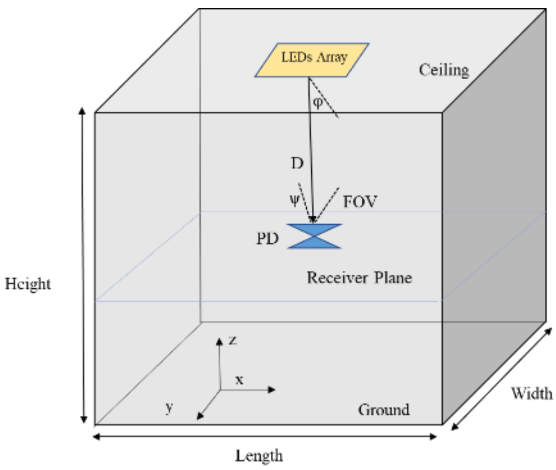


Fig. 1. VLC system for indoor environment

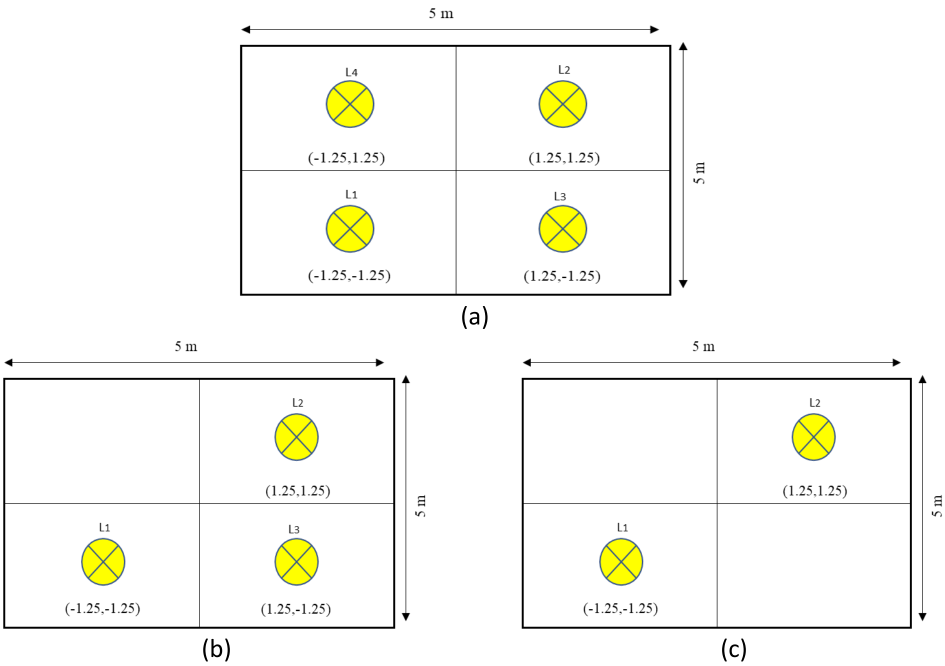


Fig. 2. Lamp location at the room ceiling: (a) 4-lamp model (b) 3-lamp model (c) 2-lamp model

2.2 VLC Lamp Illumination, Received Power and RMS Delay Spread

In the VLC LOS model, the horizontal illuminance intensity for indoor use is given by Ganjian, Baghersalimi and Ghassemlooy [27]:

$$E_{hor} = I(0)\cos^{m}(\phi)/D^{2}.\cos(\psi) \tag{1}$$

where $I(0)$ denotes the centre luminous intensity of the LED lamp, ϕ is the irradiance angle, D is the distance between the light source and receiver and ψ is the angle of incidence. The total power received by the PD in the VLC LOS model is adopted from the paper by Fuada *et al.,* [28]. Characterising the dispersion in propagation delay is crucial and it is commonly measured using the root mean square (RMS) delay spread. In the context of investigating interferences from multiple LED lamps on the channel, the RMS delay spread is employed and expressed by Mahfouz *et al.,* [29]:

$$D_{rms} = \sqrt{\mu^{2} - (\mu)^{2}} \tag{2}$$

where μ denotes the excess delay's mean.

2.3 DCO-FBMC System Model

Figure 3 depicts the architecture of the DCO-FBMC-based VLC system. In the multicarrier modulation FBMC method, the data is sent via pulses that often overlap in time and frequency, resulting in frequency-selective broadband channels that divide into numerous subchannels (subcarriers). In the FBMC model, the time-domain mathematical equation for the transmitted signal, which consists of M subcarriers across N symbol periods, is written by Nissel [30]:

$$x(t) = \sum_{n=1}^{N} \sum_{l=1}^{M} a_{l,n} g_{l,n}(t) \tag{3}$$

where l stands for the subcarrier index, n is the nth symbol, $a_{l,n}$ is the symbol transmitted and the function g(t) is used in FBMC synthesis to transform $a_{l,n}$ into the signal space.

The signal in the time domain $x(t)$ should be real and non-negative because FBMC-VLC uses the IM/DD technique. Thus, by separating the complex signal into real R(x(t)) and imaginary J(x(t)) portions and juxtaposing them, the output complex signal x(t) is changed to real. The FBMC symbol thus has a 2M signal length. Consequently, the FBMC real signal $x_R(t)$ is written as:

$$x_R(t) = \sum_{n=1}^{N}\left[\left[R\left(\sum_{m=1}^{M} a_{m,n} g_{m,n}(t)\right), J\left(\sum_{m=1}^{M} a_{m,n} g_{m,n}(t)\right)\right]\right] \quad (4)$$

Additionally, a DC bias is incorporated in the FBMC modulation to achieve the unipolar signal; thus, the optical signal becomes Wu *et al.,* [31]:

$$x_{dc}(t) = x_R(t) + C\sigma^2 \quad (5)$$

where C is a positive integer and σ^2 is the variance of $x(t)$. Hence, the transmitted optical signal becomes:

$$x_{op}(t) = h_{los}(t) * x_{dc}(t) \quad (6)$$

where $h_{los}(t)$ is the channel impulse response (CIR) for the LOS channel represented as:

$$h_{los}(t) = L_{los}\delta(t-\tau) \quad (7)$$

where τ is the signal propagation delay expressed as (D/c) and c is the speed of light symbol. L_{los} is the total channel attenuation in the LOS model expressed by Gismalla and Lew Abdullah [32] as:

$$L_{los} = \begin{cases} \frac{(m+1)A}{2\pi D^2}\cos^m(\phi)T_s(\psi)g(\psi)\cos(\psi) & 0 \le \psi \le \Psi_c \\ 0 \; \psi > \Psi_c \end{cases} \quad (8)$$

where m is the Lambertian order emission, A is the photodetector area, $T_s(\psi)$ is the optical filter gain, Ψ_c denotes the width of a field of view at a receiver and $g(\psi)$ is the gain of the optical concentrator. As a result, the combined optical signal from the four transmitters at the receiver will be:

$$x_r(t) = \sum_{\mathrm{k}=1}^{4} x_{op,k}(t) \quad (9)$$

where k denotes the number of LED arrays. The transmitted optical signal $x_r(t)$ is received at the receiver end by the PD and converted to an electrical signal as:

$$r(t) = R * x_r(t) + n(t) \quad (10)$$

R is the PD responsivity and n(t) represents the noise of additive white Gaussian. The sampling procedure is then used to find the ideal sampling point of the received signal. And the proposed optical FBMC system's BER performance is evaluated by comparing the received data bit-for-bit with the input data.

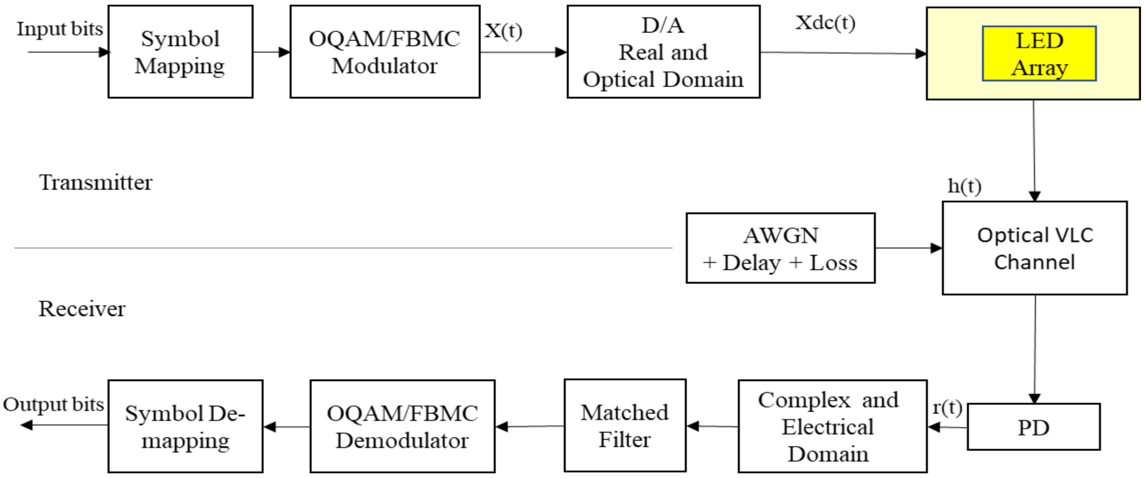


Fig. 3. The proposed DCO-FBMC model schematic

The performance analysis was conducted with three different LED array arrangements at the location directly receiving the signal (1.25,1.25), which has the highest received power and SNR. The proposed VLC-FBMC system was simulated with 4-QAM and 16-QAM formats using bit rates of 14.6 Mbit/s and 29.3 Mbit/s, 100 symbols and 600 input data. The simulation aims to guarantee the same input capacity for both QAM formats, hence the 4-QAM and 16-QAM were developed with different FFT lengths as stated in Table 1.

Table 1
FBMC system parameters

QAM format	FFT No.	SNR (dB)
4-QAM	1024	9
16-QAM	512	17

3. Result and Discussion

3.1 VLC Lamp Illumination, Received Power and RMS Delay Spread of Lamp Failure

Three LED array models were evaluated to investigate system performance if one or more lamps (bulbs) fail. First, the indoor VLC parameters were obtained for the 2-, 3- and 4-lamp models: LED illumination, received power and RMS delay. Figure 4 and Figure 5 show that the illumination and received power increased as the number of lamps increased and vice versa. The 4-lamp model had the highest illumination and received power with 859.9 lx and 1.9 dBm, respectively.

Journal of Advanced Research in Applied Mechanics
Volume 127, Issue 1 (2025) 41-52

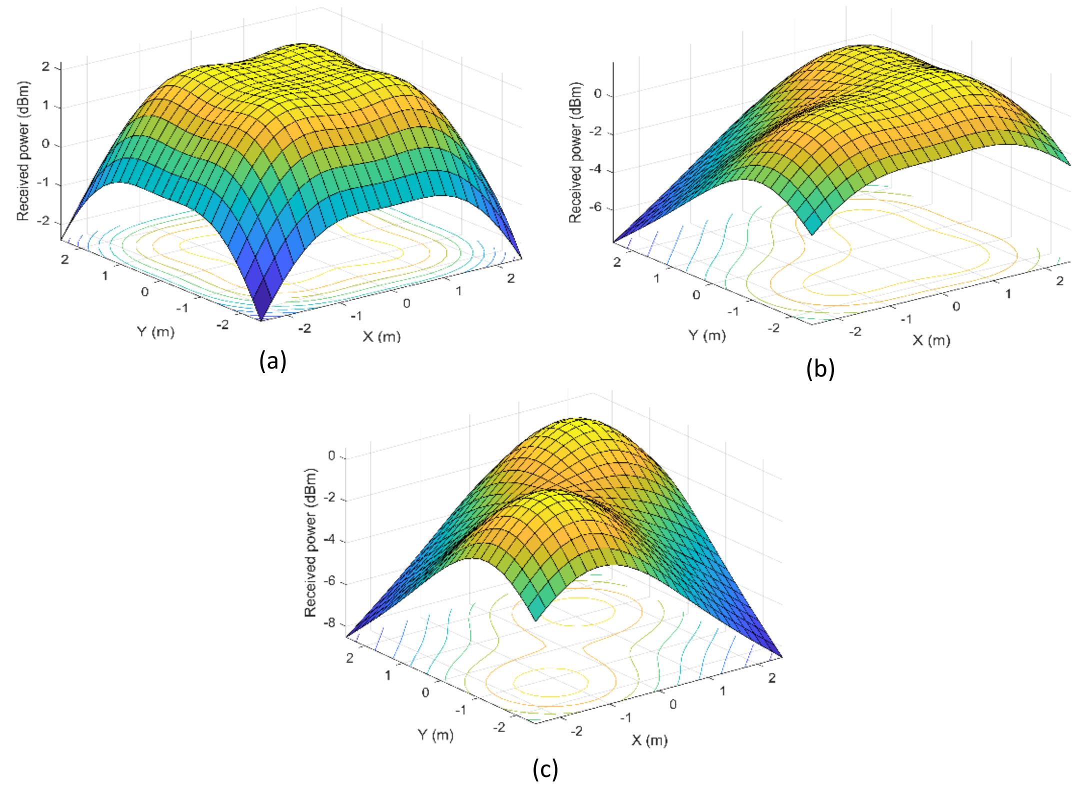


Fig. 4. Indoor received power for (a) 4-lamp model (b) 3-lamp model (c) 2-lamp model

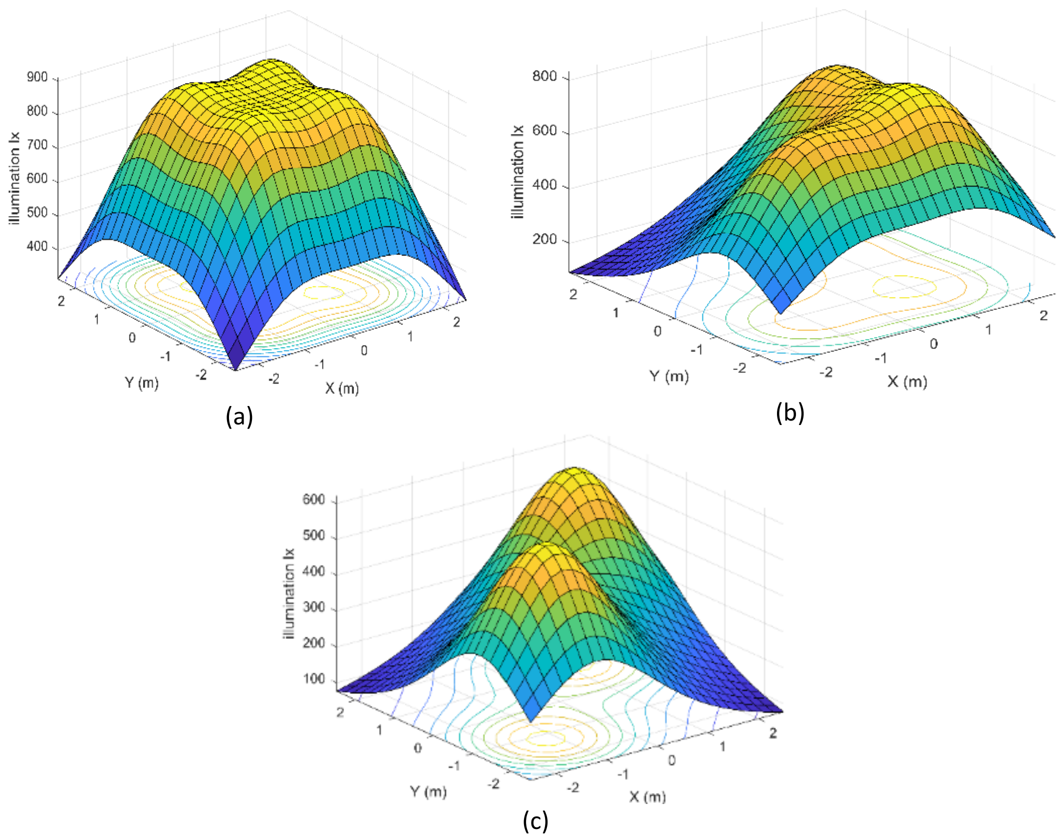


Fig. 5. Indoor lamp illumination for (a) 4-lamp model (b) 3-lamp model (c) 2-lamp model

The 2-lamp model exhibited the smallest RMS delay spread with an average of 0.68 ns and the 4-lamp model had the highest RMS delay with an average of 1.8 ns as shown in Figure 6. This shows that the number of lamps determines the amount of ISI produced and establishes a trade-off between high illumination and energy and low RMS delay and loss.

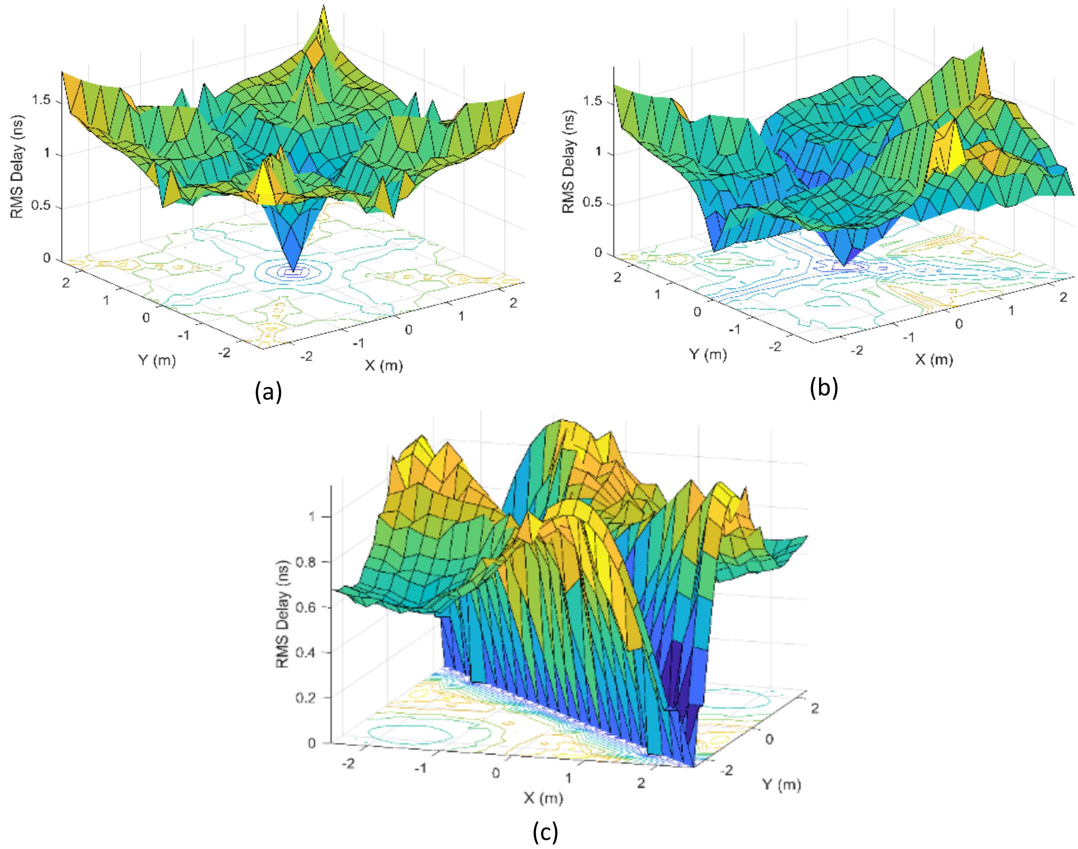
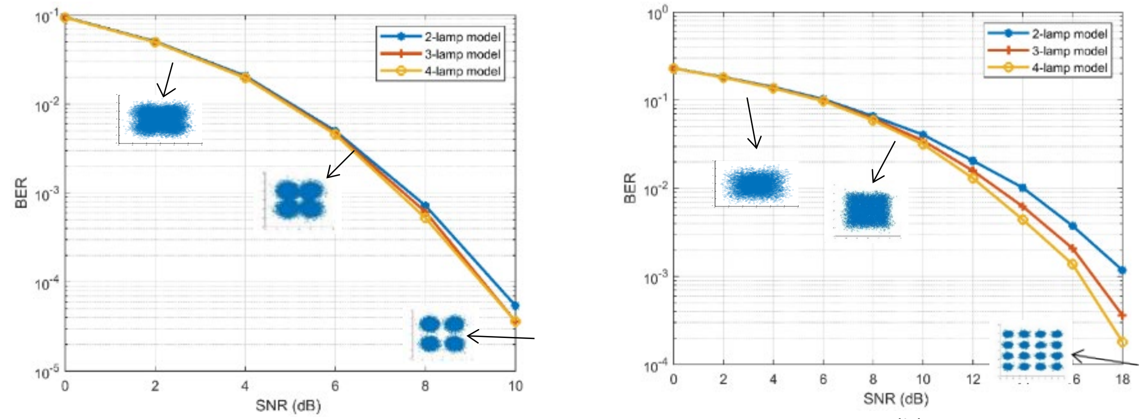


Fig. 6. Indoor RMS delay spread for (a) 4-lamp model (b) 3-lamp model (c) 2-lamp model

3.2 FBMC-VLC System Performance

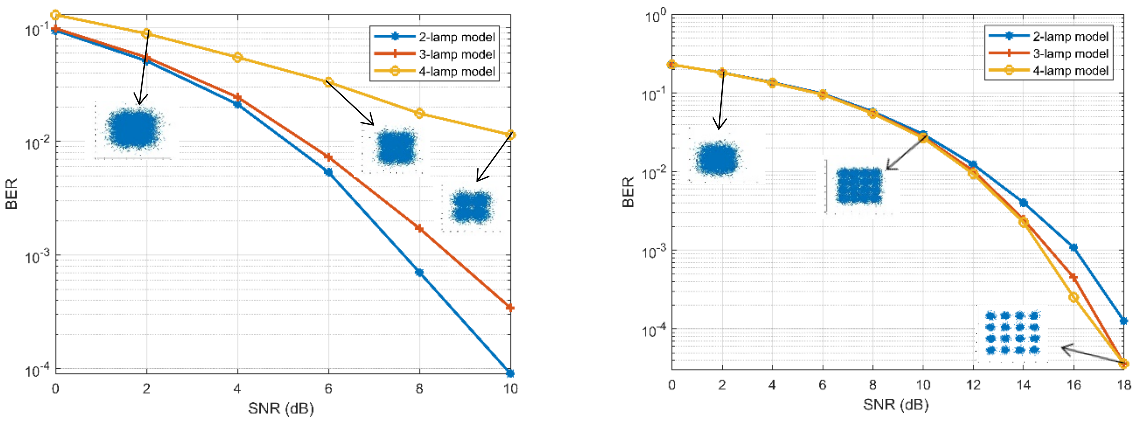
Figure 7 and Figure 8 depict the BER performance of the various lamp models under the influence of channel loss and delay at bit rates of 14.6 Mbit/s and 29.3 Mbit/s, respectively. At 14.6 Mbit/s (Figure 7), the 2-, 3- and 4-lamp models exhibited superior BER performance and established more reliable communication links with lower SNR requirements. Notably, the 4-lamp model demonstrated the most impressive performance as shown by the constellation diagram, achieving a BER of 3.6×10^{-5} at an SNR of 10 dB in 4-QAM and a BER of 1.8×10^{-4} at an SNR of 18 dB in the 16-QAM format. In comparison, the 2-lamp model yielded a BER of 5.4×10^{-5} in 4-QAM and a BER of 1.2×10^{-3} in 16-QAM at the same SNR level.



(a) (b)

Fig. 7. FBMC performance at 14.6 Mbit/s for (a) 4-QAM (b) 16-QAM

Furthermore, at a high bit rate of 29.3 Mbit/s, the 2-lamp model achieved the best BER performance in the 4-QAM format (Figure 8 (a)) due to the small delay amount with BER values of 9.1×10^{-5} and the 4-lamp model failed to achieve good BER performance with BER of 1.1×10^{-2} as the 4-lamp constellation diagram illustrates. In contrast, in the 16-QAM format, the 4-lamp model demonstrated an excellent BER performance as seen in the constellation diagram with a value of 3.6×10^{-5} compared to BER of 1.3×10^{-3} for the 2-lamp model as shown in Figure 8(b). This indicates that increasing modulation order helps to achieve low BER with a high number of LED arrays and high bit rate, where the 4-lamp model achieved good performance in the 16-QAM due to its small FFT length. Also, it is noteworthy that the optical FBMC-VLC model can achieve good performance even with a failure of half of the LED lamps and can suppress ISI because of the multiple LED array.



(a) (b)

Fig. 8. FBMC performance at 29.3 Mbit/s for (a) 4-QAM (b) 16-QAM

The relation between the bit rate, the number of LED lamps and the BER performance for the FBMC system with the effect of delay and loss is seen in Figure 9. The number of LED arrays and QAM format are crucial to achieving high bit rates with low BER values. For example, in 4-QAM format, the 2-lamp model achieved a bit rate of up to 73.2 Mbit/s with a BER of 10^{-4}, whereas the 4-lamp model at the same bit rate had a higher BER value of 10^{-2}, as shown in Figure 9(a). On the other hand, in a 16-QAM format, all three lamp models achieved up to 29.3 Mbit/s bit rate with a BER less than 10^{-3}; however, for a higher bit rate, the BER value increased to 10^{-1} as shown in Figure 9(b). Generally, minimising the bit rate and increasing modulation order help to achieve low BER with a high number of LED arrays. Hence, the BER performance of the FBMC-VLC system is determined by the number of LED arrays and system speed, highlighting a trade-off between large LED arrays and high bit rates.

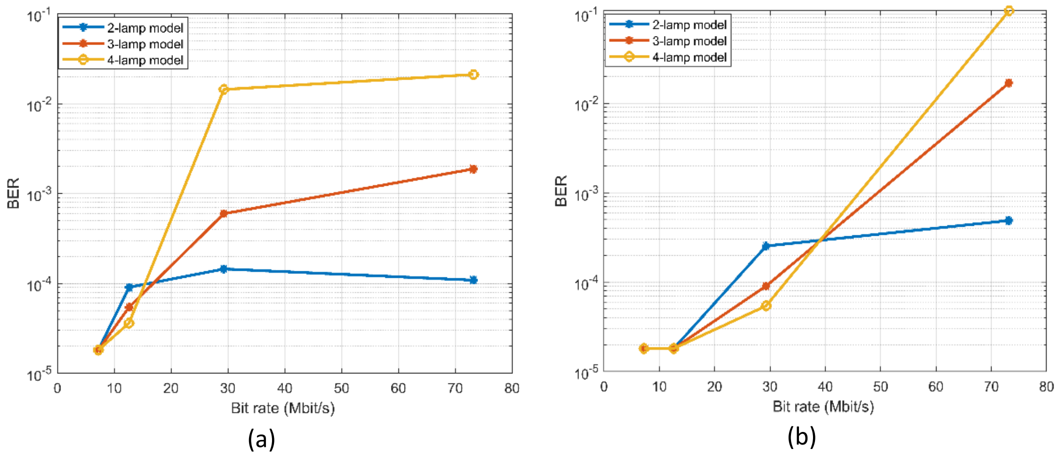


Fig. 9. FBMC performance vs bit rate: (a) 4-QAM with SNR of 9 dB (b) 16-QAM with SNR of 17 dB

4. Conclusions

FBMC is a multicarrier modulation that offers a high data rate and has better performance due to its spectral efficiency, making it a promising technique for 5G applications including VLC systems. In this paper, an optical FBMC-based VLC system with multiple LED lamp configurations is evaluated in terms of lamp failure. The VLC-FBMC model was designed using 4-QAM and 16-QAM formats in the LOS model at bit rates of 14.6 Mbit/s and 29.3 Mbit/s. The performance of the three LED arrays was compared in terms of LED illumination, received power and the effect of channel delay and loss. Besides, the performance analysis was obtained through BER performance, constellation diagram, SNR requirement and the achieved bit rates. The outcome shows that the FBMC-VLC system maintained high BER performance even when half of the lamps experienced failure. The best results of BER of 3.6×10^{-5} and 5.4×10^{-5} were achieved for the 2- and 4-lamp models respectively, in the 4-QAM format at 14.6 Mbit/s. Also, at 29.3 Mbit/s, the 2-lamp model yielded the best performance in the 4-QAM with a BER of 9.1×10^{-5}, whereas in the 16-QAM, the 4-lamp model attained an excellent performance with a BER of 3.6×10^{-5}. Moreover, the simulation revealed that the proposed optical FBMC-based VLC system achieved a bit rate of up to 73.2 Mbit/s in 4-QAM with the 2-lamp model and a bit rate of 29.3 Mbit/s in 16-QAM format with the 4-lamp model, with both exhibiting high BER performance. It is important to highlight that the optical FBMC model demonstrated strong performance despite the failure of one or two lamps and effectively mitigated the ISI effect.

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