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ARTICLE

Modelling and Performance Analysis of Visible Light Communication System in Industrial Implementations

Mohammed S. M. Gismalla[1,2], Asrul I. Azmi[1,2], Mohd R. Salim[1,2], Farabi Iqbal[1,2], Mohammad F. L. Abdullah[3], Mosab Hamdan[4,5], Muzaffar Hamzah[4,*] and Abu Sahmah M. Supa'at[1,2]

[1]Faculty of Electrical Engineering, Faculty of Engineering, Universiti Teknologi, Malaysia, Skudai, 81310, Malaysia

[2]Lightwave Communications Research Group (LCRG), Faculty of Electrical Engineering, Universiti Teknologi, Skudai, Johor, Malaysia

[3]Department of Communication Engineering, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), Parit Raja, Batu Pahat, Johor, 86400, Malaysia

[4]Faculty of Computing and Informatics, Universiti Malaysia Sabah, Kota Kinabalu, 88400, Malaysia

[5]Department of Computer Science, University of São Paulo, São Paulo, Brazil

*Corresponding Author: Muzaffar Hamzah. Email: muzaffar@ums.edu.my

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ABSTRACT

Visible light communication (VLC) has a paramount role in industrial implementations, especially for better energy efficiency, high speed-data rates, and low susceptibility to interference. However, since studies on VLC for industrial implementations are in scarcity, areas concerning illumination optimisation and communication performances demand further investigation. As such, this paper presents a new modelling of light fixture distribution for a warehouse model to provide acceptable illumination and communication performances. The proposed model was evaluated based on various semi-angles at half power (SAAHP) and different height levels for several parameters, including received power, signal to noise ratio (SNR), and bit error rate (BER). The results revealed improvement in terms of received power and SNR with 30 Mbps data rate. Various modulations were studied to improve the link quality, whereby better average BER values of 5.55×10^{-15} and 1.06×10^{-10} had been achieved with 4 PAM and 8 PPM, respectively. The simulation outcomes are indeed viable for the practical warehouse model.

KEYWORDS

Visible light communication (VLC); industrial applications; warehouse model; light fixtures; bit error rate (BER)

1 Introduction

Radio frequency (RF) technology suffers from several restrictions that limit its performance in many applications. These restrictions include capacity crunch, electromagnetic interference, bandwidth bottleneck, high power, and cost [1–3]. Therefore, visible light communication (VLC) utilising light-emitting diodes (LED) seems to be a promising technology that can be employed to overcome all RF restrictions, besides supporting the upcoming fifth generation and beyond (5 GB) [4,5]. A laser diode (LD) based VLC was employed as an alternative technology to RF, mainly because LD is

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more efficient in operating power and has good reliability, and coherent light with high output power, especially in free space and long-distance communication [6,7]. The VLC occupies a high frequency that varies from 400 to 800 THz [8,9], while simultaneously offering low power consumption, no license fee, high data rate, robustness against electromagnetic interference, and many other advantages over the existing RF technology [10–13]. Additionally, VLC has dual functionality as it can be used in illumination and fast data communication concurrently [14,15], thus having a pivotal role in the fourth industrial revolution (IR 4.0) framework.

The transition of VLC from theory to industrial standardisation is discussed in [16]. Based on a recent market analysis, the universal VLC market has been targeted to hit US$ 51 billion by 2023 with a compound annual growth rate (CAGR) of 70% [16]. The VLC can be used in intelligent manufacturing and smart factory systems [17,18], primarily due to its low power consumption and cost; in comparison to incandescent and fluorescent fixtures [15,19]. The VLC has been applied in conference rooms [20], parking lots [21,22], aviation systems [23,24], mining areas [25], smart homes [26], and hospitals [27]. It has also been implemented in underwater scenarios [28,29] and other essential applications [30–32].

The rest of this paper is organised as follows: Section 2 describes the related works, while Section 3 illustrates the warehouse system model with illumination analyses, the top view of light fixture distribution, equations of channel model, and modulation techniques. Section 4 describes the simulation results and analyses of the proposed model. Finally, this paper ends with a conclusion in Section 5.

2 Related Works

VLC is a promising technology for 6G networks and uses LEDs to generate visible light for illumination and communication. It is expected to be used in many new applications in indoor environments. Practically, VLC has been deployed in room and office models, where various light fixtures are distributed on the ceiling to provide an efficient communication system [33–35]. A number of parameters, algorithms, optimisation methods, and modulation techniques have been investigated to improve communication quality [36–38]. However, only a few studies have looked into the industrial environment despite the fact that various companies are developing light fixture products with specific characteristics for industrial environments (i.e., manufacturing, warehouse, transportation, sports facilities, and cold storage) besides mere incandescent and fluorescent fixtures [39,40].

Plenty of problems, potentials, and implementations of VLC in the industrial environment have been discussed in [1,41], where experimental designs were evidenced. The initial actual VLC results in industrial environment were reported by Berenguer et al. in [42], whereby acceptable data rate was achieved. Therefore, the objective of this paper is to investigate the VLC system for a warehouse model and to design a new model that can enhance the quality of the communication system. Different solutions were investigated and proposed to improve the VLC system quality in terms of received power, signal to noise ratio (SNR), and low bit error rate (BER) for industrial environment. One of these conceivable solutions is the distribution of light fixtures on warehouse ceilings [43–45].

Two models of light fixtures are proposed for warehouse implementation. They consist of various high-powered commercial light fixtures made by Philips and OSRAM and designed for industrial regulations with output power and different beam angles [45]. Performance evaluation of the two models was carried out, where acceptable communication quality with a data rate of up to 10 Mbps was obtained. A broadband of 8×6 multiple input multiple output (MIMO) VLC system was implemented in the industrial model [46] and the results showed that the line of sight (LOS) link provided acceptable link quality in terms of SNR, while fading was observed as the LOS link was blocked. A new distributed multiuser MIMO is discussed in [41], where improvement in coverage area and link quality had been recorded.

The authors in [47] were analysed the effect of industrial environment, such as dust, artificial light, industrial processes, and other particles, on the VLC system. They prescribed considering these effects when designing VLC systems to avoid attenuation. The distribution of multiple light fixtures for factory automation was elaborated in [48], where advanced modulations and systems were suggested to meet the communication requirement for 5 GB. More wireless network structures for the warehouse model were investigated [49]. In [50], an experimental test using three-dimensional (3D) visible light positioning algorithm was conducted to trace a drone in the industrial setting. The authors executed the experiment by tilting the receiver and the multipath reflections [51].

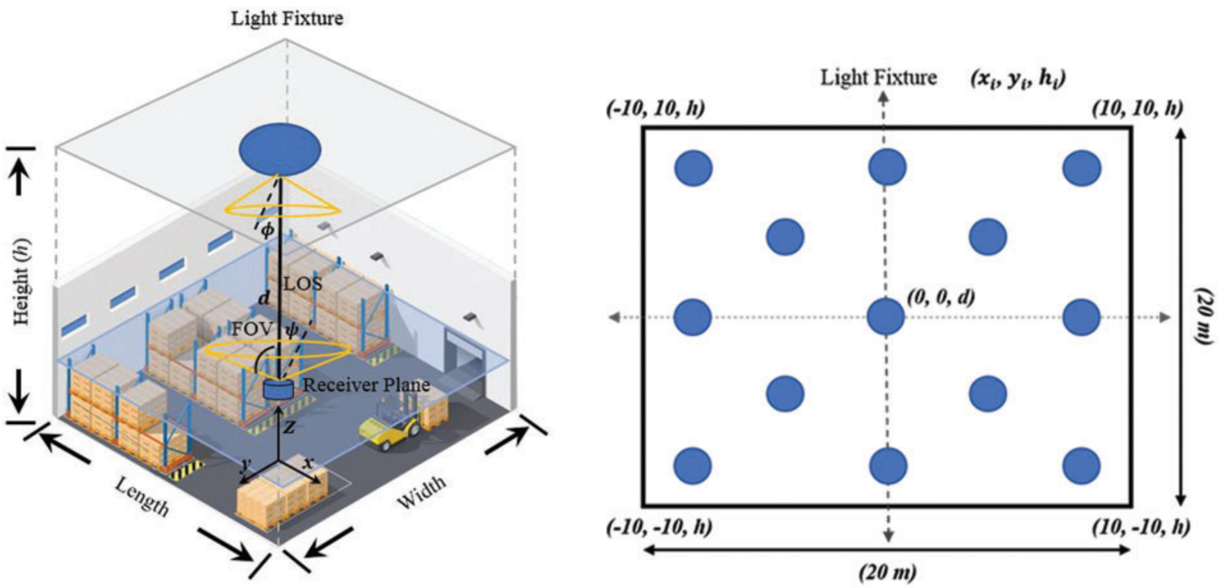
There is an increasing interest in VLC research work to cater to a wide range of indoor and outdoor implementations. However, few studies have been conducted to evaluate the VLC system in industrial settings, such as warehouses and manufacturing plants [52]. The suitable distribution and the number of light fixtures needed for the room model are discussed extensively to produce an acceptable performance, especially in terms of uniform distribution in the entire room [33–35,53,54]. Notably, the distribution of 13 light fixtures outperformed the others [55]. As a result, this number of light fixtures with high power was used in this study for viable distribution in warehouse applications. The proposed warehouse model's results were compared to the outcomes reported in [45].

The main contributions of this paper are to propose a distribution system of 13 high bay (HB) light fixtures for the warehouse model and identification of the impact of different semi-angle at half power (SAAHP), as well as various height levels, received power, SNR, and average BER. Additionally, this study evaluated the behaviour of average BER against various SAAHP for the first time in a warehouse model, where several modulation techniques are discussed to determine the most suitable one for a practical VLC system.

3 System Model

The general warehouse model is illustrated in Fig. 1. The dimension of the warehouse model is 20 m × 20 m × h m for length, width, and height, respectively. h refers to the variable height level that depends on the application scenarios included in warehouse, workplace, lab, etc. In this study, 120 W AGC HB light fixtures were distributed on the warehouse ceiling [56] instead of the 155 W of power applied in the previous model [45]. Therefore, the new model portrayed in Fig. 1 can save 22.58% of power; signifying improved power efficiency. Table 1 tabulates the technical specifications of the light fixtures used in the proposed warehouse model. The height level from the light fixtures to the receiver plane varied from 5, 7.5, to 10 m, while the height level of the receiver plane or forklift to the ground surface was 2 m.

The LOS link was considered to examine the proposed model. Various modulation techniques were investigated to minimise the BER value. Table 2 lists the main simulation parameters mentioned in [8] and [39].



(a) (b)

Figure 1: The proposed VLC system: (a) warehouse model, (b) top view of light fixtures distribution and coordinates on the ceiling

Table 1: 120 W AGC HB light fixture specifications [56]

Electrical data		Optical data	
Input voltage	AC100–277 V	System efficacy	110LM/W (CCT = 5000 K)
Output current	2.8 A	Beam angle	60°, 120°
Power efficiency	>93%	Luminous flux	13200LM
Power factor	>0.93	System efficiency	>90%
System power consumption	120 W ± 3 W	LED power consumption	112 W ± 3 W

3.1 Horizontal Illuminance

The light fixtures should fulfil the illumination requirements while providing an acceptable communication performance [1]. Therefore, the illumination intensity level at angle ϕ was computed as follows:

$$I(\phi) = I(0)\, cos^m\ (\phi) \tag{1}$$

where I (0) represents the centre luminous intensity from a group of LEDs, while ϕ and m denote the angle of irradiance and the order of Lambertian emission, respectively; where m is related to light fixture semi-angle of half illumination $\phi_{\frac{1}{2}}$ and it is expressed in (2):

$$m = \frac{-\ln 2}{\ln\left(\cos\phi_{\frac{1}{2}}\right)} \tag{2}$$

The illumination of 3D points (x, y, & z) is defined by E_{hor}, as follows:

$$E_{hor}\left(x,y,z\right)=\frac{I\left(0\right)cos^{m}\left(\phi\right)}{d^{2}.\ \cos\left(\psi\right)} \tag{3}$$

where ψ and d refer to the angle of incident and distance between light fixture and receiver, respectively. Light fixtures can be distributed on the ceiling of the warehouse model by using several configuration methods illustrated in [45].

Table 2: Simulation parameters of the VLC system model

Parameters	Value
Length × width × height	$20 \times 20 \times h$ m^3
Height level of light fixtures (h)	4 to 20 m
Height level of forklifts	2 m
Photodetector effective area	1 cm^2
Photodetector responsivity	0.54 A/W
Walls reflectivity	0.86
Floor reflectivity Walls	0.34
AGC HB semi-angle	60°
AGC HB power	120 W
Field of view	40°
Data rate	30 Mbps

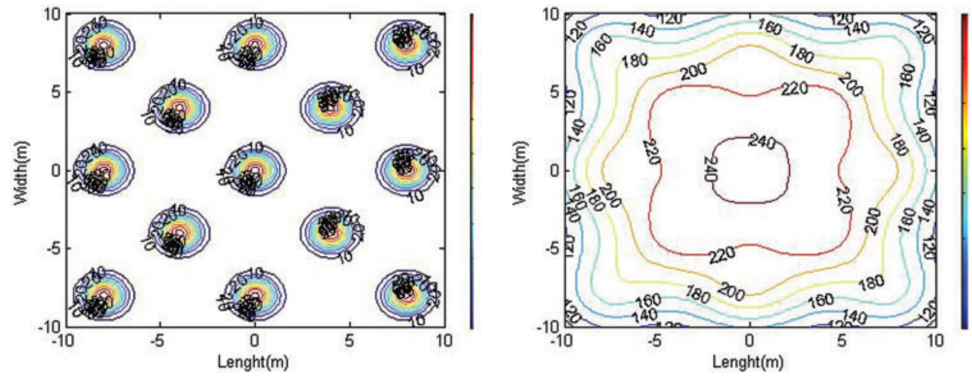
Fig. 2 shows the contour of illumination distribution at a small 10° (a) and wide 70° (b) SAAHP for 5 m height level. From the illumination results, the wide SAAHP should be considered to improve illumination distribution, while many blinds or uncovered zones were observed at the small SAAHP. The SAAHP is the angle from an axis perpendicular to the light fixture by which the illuminating intensity is just 50%. It is also called the 'viewing angle' and may vary from 10° at no diffusion to 70° for maximum diffusion [57].

3.2 Received Power and SNR Calculations

Upon considering the LOS link, the channel DC gain was computed as follows [45,58]:

$$H_{d}\left(0\right)=\begin{cases}\dfrac{\left(m+1\right)A}{2\pi d^{2}}cos^{m}\left(\phi\right)T_{s}\left(\psi\right)g\left(\psi\right)\cos\left(\psi\right), & 0\leq\psi\leq\psi_{c}\\ 0, & \psi>\psi_{c}\end{cases} \tag{4}$$

where A represents the physical area of the photodiode (PD) detector, ψ is the FOV angle of the receiver, $T_s(\psi)$ and $g\ (\psi)$ refer to the optical filter gain and the gain of an optical concentrator, respectively, while ψ_c is the SAAHP.



(a) (b)

Figure 2: Contour of illumination distribution for the proposed warehouse model

For the 3D coordinates, as shown in Fig. 1, the light fixtures were installed at the position of (x_i, y_i, h_i), while the receiver or forklift at the position of (x, y, h). Therefore, $\cos(\phi)$ was computed as follows:

$$\cos(\phi) = \frac{h_i - h}{\left[(h - h_i)^2 + (x - x_i)^2 + (y - y_i)^2\right]^{\frac{1}{2}}} \tag{5}$$

Moreover, it can be expressed that $g(\psi) \approx g$ and $\cos(\psi) = \cos(\phi).sincT_s(\psi) \approx T_s$. By substituting Eqs. (5), (4) is written as follows:

$$H_d(0) = \frac{T_s\ g\ A\ (m+1)\ (h_i - h)^{m+1}}{2\pi^2\left[(h - h_i)^2 + (x - x_i)^2 + (y - y_i)^2\right]^{\frac{(m+3)}{2}}} \tag{6}$$

The received power (P_r) at photodetector (PD) can be calculated from the transmitted power of light fixture (P_T) and the channel DC gain, as shown in (7):

$$P_r = H_d(0) \times P_T \tag{7}$$

The SNR can be further computed by:

$$SNR = \frac{[RP_r]^2}{\sigma_{shot}^2 + \sigma_{thermal}^2} \tag{8}$$

where R refers to PD responsivity and it can be measured in amperes per watt. P_r was defined and calculated in (7), where $\sigma_{thermal}^2$ and σ_{shot}^2 refer to the variances of thermal and shot noises, respectively, expressed as follows:

$$\sigma_{thermal}^2 = 8\pi kT_k\eta AB^2\left(\frac{I_2}{G} + \frac{2\pi\Gamma}{g_m}\eta AI_3B\right) \tag{9}$$

$$\sigma_{shot}^2 = 2q\left[RP_R + I_{bg}I_2\right]B \tag{10}$$

where $I_3 = 0.0868$, while k and q are constants of Boltzmann and electronic charge, respectively, T_k refers to the absolute temperature, η is a fixed capacitance of PD per unit area, B denotes the equivalent noise bandwidth, I_2 indicates the noise bandwidth factor, G signifies an open-loop voltage gain, Γ refers to the channel noise factor of the field-effect transistor (FET), g_m is the FET transconductance, and I_{bg} represents the current of background light.

3.3 Modulation Techniques

Upon further investigation, several modulation techniques were discussed to assess the performances of BER and data rate. The simulation work performed in [45] had applied the on-off keying (OOK) modulation, which gave a data rate of 10 Mbps. Turning to this present study, it looked into the modulation techniques in the warehouse model and the effects of various SAAHP aspects on the average BER performance for the first time. The modulation techniques included binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), pulse position modulation (L-PPM), and pulse amplitude modulation (M-PAM). Eqs. (11) to (15) show the BER calculations for the mentioned modulation techniques, respectively, where L and M refer to the order of modulation [59]. The BER performance was executed in the presence of Gaussian noise.

$$BER_{NRZ-OOK} = \frac{1}{2} erfc\left(\frac{1}{2\sqrt{2}}\sqrt{SNR}\right) \tag{11}$$

$$BER_{BPSK} = \frac{1}{2} erfc\left(\sqrt{SNR}\right) \tag{12}$$

$$BER_{QPSK} = erfc\left(\sqrt{SNR}\right) = 2BER_{BPSK} \tag{13}$$

$$BER_{L-PPM} = \frac{1}{2} erfc\left(\frac{1}{2\sqrt{2}}\sqrt{SNR\frac{L}{2}log_2 L}\right) \tag{14}$$

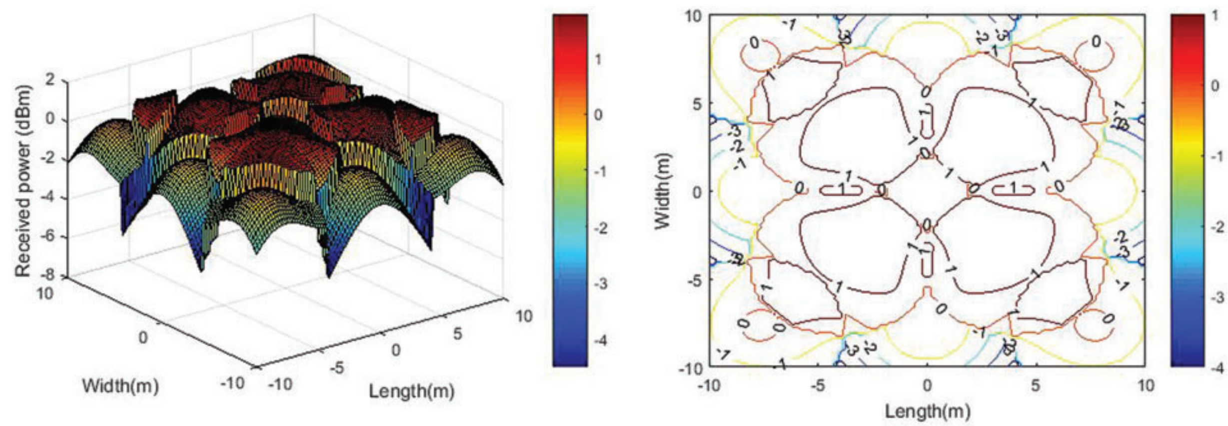
$$BER_{M-PAM} = \frac{1}{2} erfc\left(\frac{\sqrt{SNR log_2 M}}{2\sqrt{2}\,(M-1)}\right) \tag{15}$$

4 Simulation Results and Discussion

This section demonstrates the simulation results and the analyses of the proposed warehouse model in terms of received power, SNR, and BER, so as to enhance communication performance. Fig. 3 shows the received power and the contour of received power distribution at 5 m height level. The average received power of 0.0753 dBm was obtained at wide SAAHP 70°, which fluctuated from −4.4898 to 1.7734 dBm. Next, the average received power of −0.6065 and −1.3652 dBm had been achieved at height levels 7.5 m and 10 m, respectively. The maximum, minimum, and average received power for height levels 7.5 and 10 m are presented in Table 3.

Fig. 4 portrays the SNR distribution and its contour at wide SAAHP 70° for 5 m height level. The maximum, minimum, and average SNR values of 73.2095, 60.6838, and 69.8135 dB were produced. The average SNR values of 68.45 and 66.9328 dB were obtained at 7.5 and 10 m height levels, respectively (see Table 3). Referring to Table 3, the short height level yielded better average received power and SNR, which are adequate for practical VLC systems. However, the performance decreased as the height level increased.

Figs. 5 and 6 demonstrate the behaviour of average received power and SNR performances at different height levels, where various SAAHP values were considered. The received power of 0.0753, −0.6065, and −1.3652 dBm had been recorded at wide SAAHP 70° for height levels 5, 7.5, and 10 m, respectively. Next, the SNR values of 69.8135, 68.45, and 66.9328 dB were obtained at height levels 5, 7.5, and 10 m, respectively. Based on these results, better performance in terms of received power and SNR was observed at 5 m height level, but the performance deteriorated with increasing height level and SAAHP.

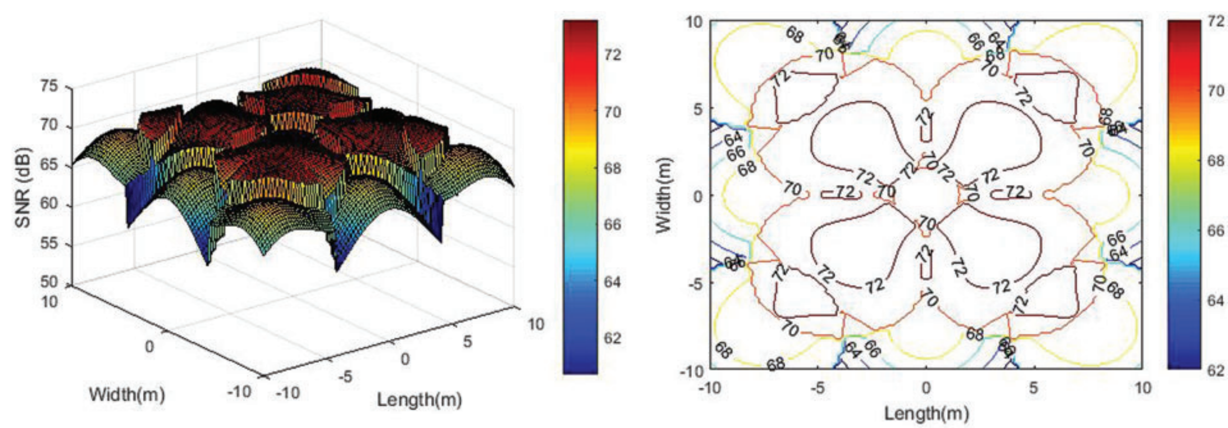


(a) (b)

Figure 3: (a) Received power and (b) contour of power of the proposed model at 5 m height level

Table 3: Received power and SNR against various height levels for the proposed model

Height (m)	Received power (dBm)			SNR (dB)		
	Maximum	Average	Minimum	Maximum	Average	Minimum
5	1.7734	0.0753	−4.4898	73.2095	69.8135	60.6838
7.5	1.3781	−0.6065	−3.8055	72.419	68.45	62.0524
10	0.1459	−1.3652	−4.7065	69.9547	66.9328	60.2504



(a) (b)

Figure 4: (a) SNR and (b) contour of SNR of the proposed model at 5 m height level

The results of the proposed model at wide SAAHP and height levels of 7.5 and 10 m were acceptable and better, when compared to previous models [45]. The variation of SAAHP led to a trade-off between received power and SNR with the coverage area in the entire warehouse model. Referring to Figs. 5 and 6, small SAAHP produced the lowest average received power and SNR distribution at 5 m height level. This is ascribed to the LOS link that bounded the light distribution downward from the light fixture, which failed to cover all areas in the warehouse model. However, both received power and SNR distribution were increased by increasing the SAAHP. Although higher SAAHP can degrade both received power and SNR, it can still yield an acceptable level that guaranteed the link quality. This trade-off was diminished with increased height level, mainly because the coverage area increased when the height of light fixture increased both light diffuses and angular range.

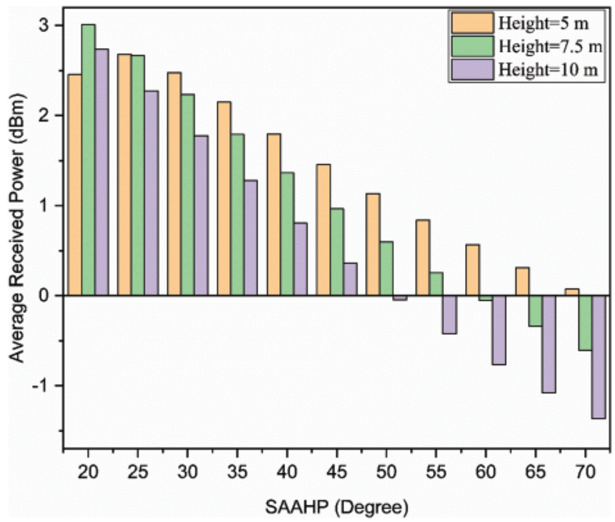


Figure 5: Average received power against various SAAHP for different height levels

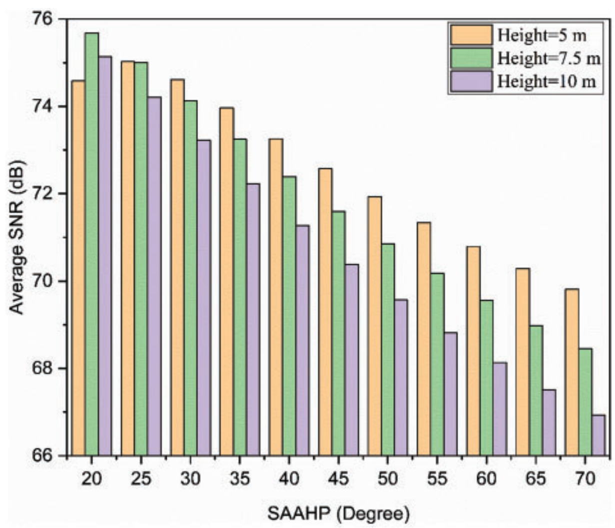


Figure 6: Average SNR against various SAAHP for different height levels

Table 4 summarises the received power and SNR results for the past models that used 9 Philips HB and 12 OSRAM HB light fixtures with the proposed model when SAAHP was set at 70°. From Table 4, better maximum, minimum, and average received power and SNR were obtained from the new model of 13 AGC HB at various height levels.

Table 4: Parameters of performance for the warehouse models

Parameters		9 Philips HB light fixtures	12 OSRAM HB light fixtures	Proposed 13 AGC HB light fixtures	Height level (m)
Received power (dBm)	Max	1.6556	0.3657	1.7734	5
	Avg	−0.2683	−1.1319	0.0753	
	Min	−9.7168	−5.4311	−4.4898	
	Max	0.1057	−0.5781	1.3781	7.5
	Avg	−1.1928	−2.0292	−0.6065	
	Min	−4.5164	−5.3776	−3.8055	
	Max	−0.7138	−1.4407	0.1459	10
	Avg	−2.1318	−2.7966	−1.3652	
	Min	−5.0032	−5.2484	−4.7065	
SNR (dB)	Max	72.9739	70.3942	73.2095	5
	Avg	69.1264	67.3993	69.8135	
	Min	50.23	58.8012	60.6838	
	Max	69.8744	68.5068	72.419	7.5
	Avg	67.2775	65.6048	68.45	
	Min	60.6307	58.9083	62.0524	
	Max	68.2355	66.7818	69.9547	10
	Avg	65.3996	64.0702	66.9328	
	Min	59.657	59.1667	60.2504	

For further investigation on improving the link quality in terms of BER, different modulation techniques were assessed. Apparently, the lowest BER yielded the best communication quality. A trade-off was noted when various modulation techniques were applied for communication systems, which successfully improved both power and bandwidth efficiencies, apart from minimising BER [60]. Fig. 7 displays the BER performance for OOK-NRZ, BPSK, QPSK, 4 PPM, 8 PPM, and 4 PAM at 5 m height level.

Both 8 PPM and 4 PAM produced minimum BER with a data rate of up to 30 Mbps, which met the required BER of 10^{-6} for acceptable communication links. However, OOK-NRZ, BPSK, and QPSK yielded high BER that exceeded 10^{-6} (see Table 5). Therefore, better average BER at 5.55×10^{-15} was achieved by using 4 PAM. Table 5 tabulates the performance of average BER for all the studied modulations at various height levels.

Fig. 8 presents the behaviour of average BER performance against various SAAHP and different height levels. At small SAAHP of 10° or less, the average BER performance had deteriorated (i.e., BER exceeded 10^{-6}), except for higher orders of L-PPM and M-PAM modulation techniques, while the average BER minimised as the SAAHP increased (see Figs. 8a–8c). Relative stability in the average BER performance was observed for SAAHP above 30°. Better average BER of 5.55×10^{-15} was attained at 5 m height level, while the average BER values of 7.5×10^{-15} and 1.27×10^{-14} were recorded at height levels 7.5 and 10 m, respectively, as shown in Table 5. Notably, the average BER degraded with increased height level, as portrayed in Table 5 and Figs. 8b and 8c.

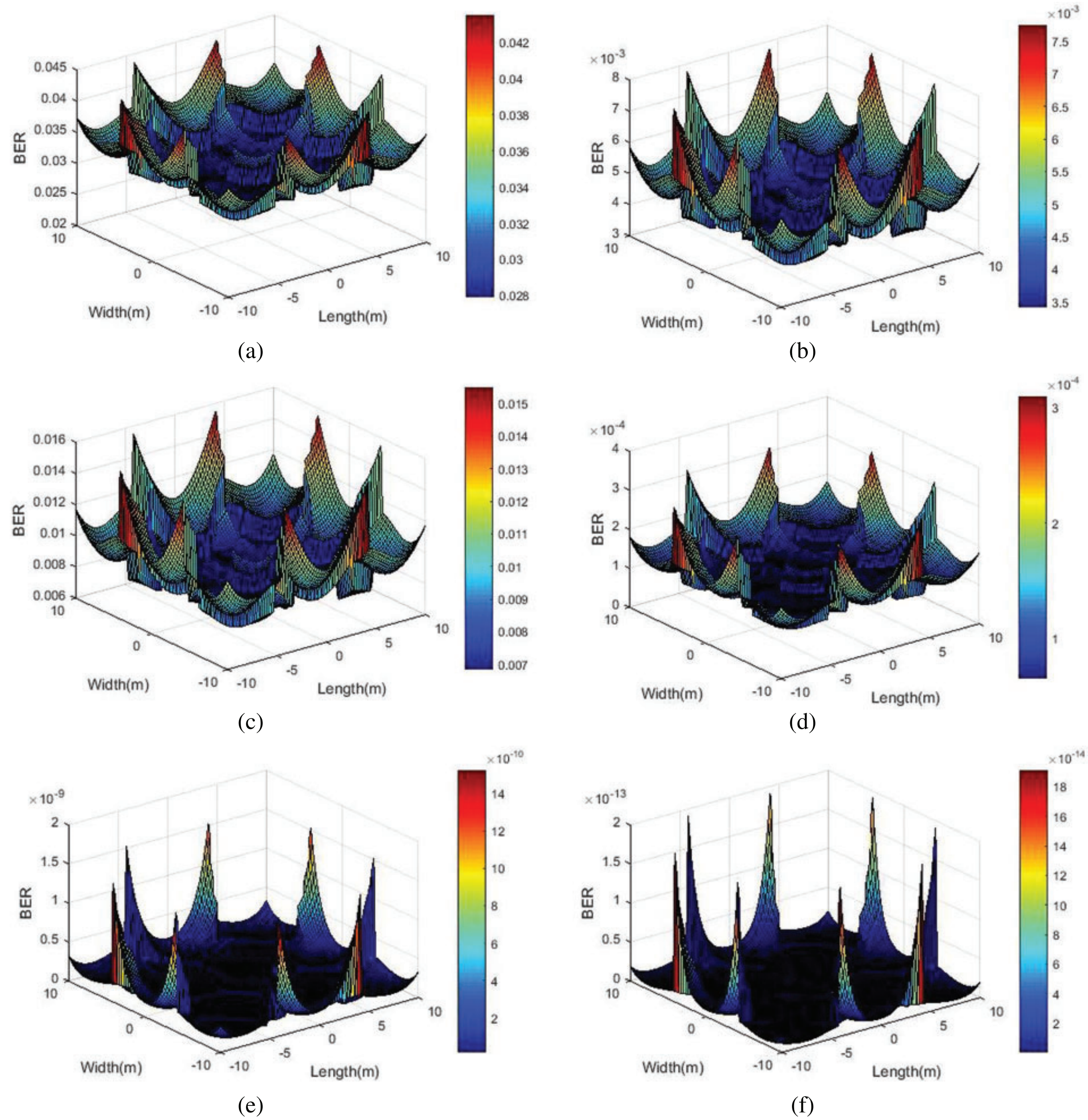
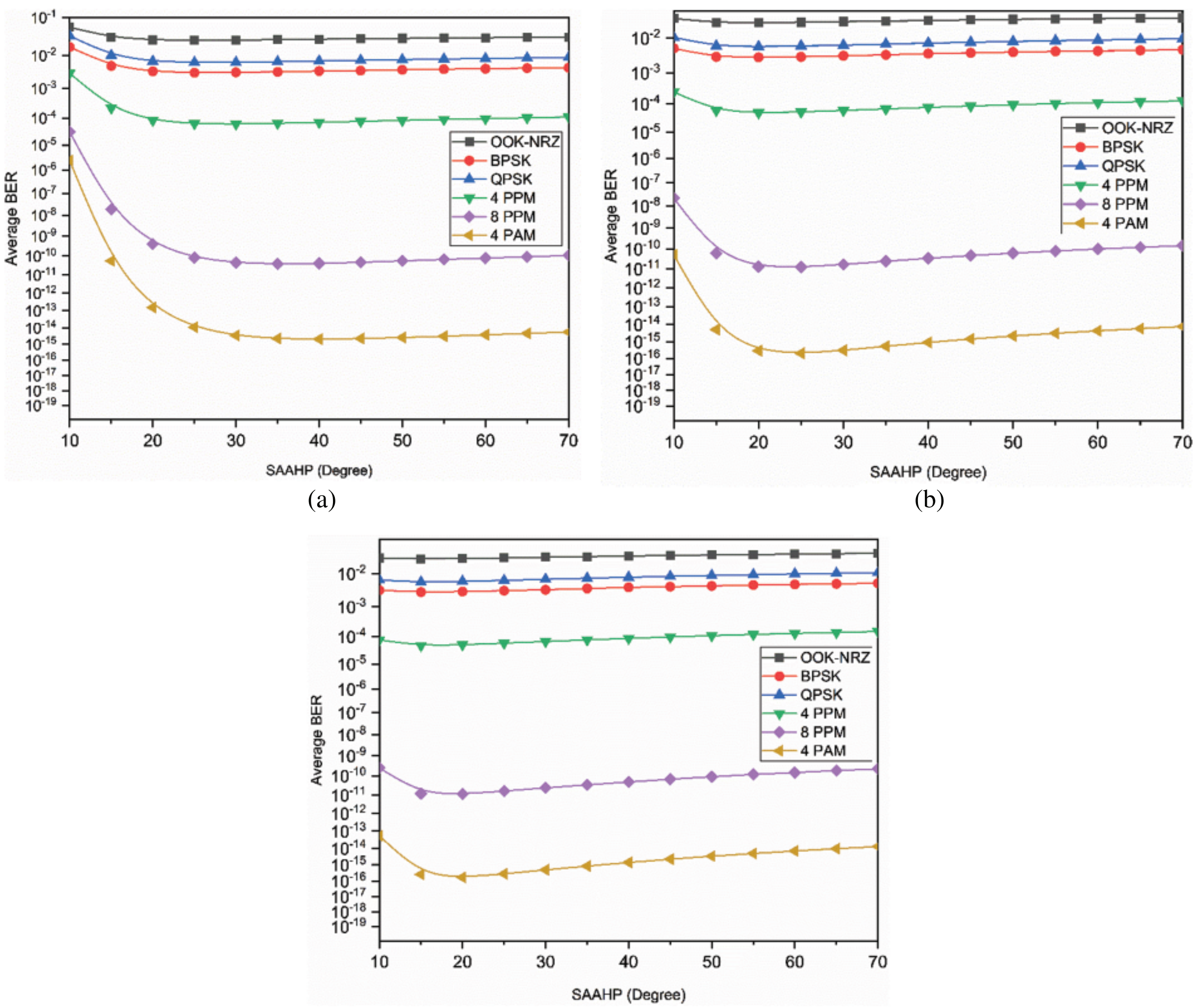


Figure 7: BER performance of the proposed model for 5 m height level: (a) OOK-NRZ, (b) BPSK, (c) QPSK, (d) 4 PPM, (e) 8 PPM, and (f) 4 PAM

Table 5: Average BER performance of different modulation techniques at SAAHP 70°

Height level (m)	Modulation techniques					
	OOK-NRZ	BPSK	QPSK	4 PPM	8 PPM	4 PAM
5	3.18×10^{-2}	4.4×10^{-3}	8.8×10^{-3}	1.08×10^{-4}	1.06×10^{-10}	5.55×10^{-15}
7.5	3.34×10^{-2}	4.8×10^{-3}	9.6×10^{-3}	1.26×10^{-4}	1.44×10^{-10}	7.52×10^{-15}
10	3.53×10^{-2}	5.3×10^{-3}	1.06×10^{-2}	1.52×10^{-4}	2.24×10^{-10}	1.27×10^{-14}



(a) (b) (c)

Figure 8: Evaluation of average BER performance against different SAAHP for height levels (a) 5 m, (b) 7.5 m, and (c) 10 m

The proposed model of 13 AGC HB light fixtures for the warehouse displayed improvements in terms of received power, SNR, and data rate. Better BER values were obtained when compared with the results reported by Almadani et al. Referring to the BER performance, higher order of L-PPM and M-PAM generated better average BER than other modulations. As depicted in [60], L-PPM was more efficient in terms of power, while M-PAM had better efficiency in terms of bandwidth. Hence, both modulations are suitable for the design of VLC system in a practical warehouse model.

5 Conclusion

In this paper, a new modelling of light fixtures is proposed for a warehouse to investigate the performance of communication system in terms of received power, SNR, and BER. The LOS link was considered and different height levels (5, 7.5, & 10 m) were used in the evaluation. The average received power values of 0.0753, −0.6065, and −1.3652 dBm had been obtained at height levels of 5, 7.5, and 10 m, respectively. Next, the average SNR of 69.8135 dB was recorded at 5 m height level, whereas SNR values of 68.45 dB and 66.9328 dB were achieved at 7.5 and 10 m, respectively. The behaviour of average received power and SNR over various SAAHP and height levels had been assessed. The new model showcased better performance than that reported by Almadani et al. Several modulation techniques, including OOK-NRZ, BPSK, QPSK, 4 PPM, 8 PPM, and 4 PAM, were investigated to evaluate the BER performance over various SAAHP and height levels. The average BER values of 1.06×10^{-10}, 1.44×10^{-10}, and 2.24×10^{-10} had been achieved by using 8 PPM for height levels of 5, 7.5, and 10 m, respectively. Next, 4 PAM produced average BER values of 5.55×10^{-15}, 7.52×10^{-15}, and 1.27×10^{-14} at 5, 7.5, and 10 m, respectively. Overall, the new model displayed exceptional performance that is suitable for warehouse application. The higher order of both L-PPM and M-PAM yielded better link quality in terms of BER performance. Therefore, more modelling and analyses are required in future endeavour to produce a general model for warehouses and other industrial applications.

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References

[1] Y. Almadani, D. Plets, S. Bastiaens, W. Joseph, M. Ijaz *et al.,* “Visible light communications for industrial applications—Challenges and potentials,” *Electronics*, vol. 9, no. 12, pp. 1–38, 2020.
[2] S. Wu, H. Wang and C. H. Youn, “Visible light communications for 5G wireless networking systems: From fixed to mobile communications,” *IEEE Network*, vol. 28, no. 6, pp. 41–45, 2014.
[3] J. Lian, Z. Vatansever, M. Noshad and M. Brandt-Pearce, “Indoor visible light communications, networking, and applications,” *Journal of Physics: Photonics*, vol. 1, no. 1, pp. 1–29, 2019.

[4] A. Al-Saman, M. Mohamed, M. Cheffena and A. Moldsvor, "Wideband channel characterization for 6G networks in industrial environments," *Sensors*, vol. 21, no. 6, pp. 1–18, 2021.
[5] M. Katz and I. Ahmed, "Opportunities and challenges for visible light communications in 6G," in *2020 2nd 6G Wireless Summit (6G SUMMIT)*, Levi, Finland, pp. 1–5, 2020.
[6] T. C. Wu, Y. C. Chi, H. Y. Wang, C. T. Tsai, Y. F. Huang *et al.,* "Tricolor R/G/B laser diode based eye-safe white lighting communication beyond 8 Gbit/s," *Scientific Reports*, vol. 7, no. 1, pp. 1–10, 2017.
[7] Y. C. Chi, D. H. Hsieh, C. Y. Lin, H. Y. Chen, C. Y. Huang *et al.,* "Phosphorous diffuser diverged blue laser diode for indoor lighting and communication," *Scientific Reports*, vol. 5, no. 1, pp. 1–9, 2015.
[8] N. Chi, Y. Zhou, Y. Wei and F. Hu, "Visible light communication in 6G: Advances, challenges, and prospects," *IEEE Vehicular Technology Magazine*, vol. 15, no. 4, pp. 93–102, 2020.
[9] S. Rehman, S. Ullah, P. Chong, S. Yongchareon and D. Komosny, "Visible light communication: A system perspective—Overview and challenges," *Sensors*, vol. 19, no. 5, pp. 1–22, 2019.
[10] A. E. Ibhaze, P. E. Orukpe and F. O. Edeko, "High capacity data rate system: Review of visible light communications technology," *Journal of Electronic Science and Technology*, vol. 18, no. 3, pp. 241–265, 2020.
[11] M. S. M. Gismalla, M. F. L. Abdullah, B. Das, W. A. Mabrouk and N. E. Mahfouz, "Design of an optical attocells configuration for an indoor visible light communications system," *AEU-International Journal of Electronics and Communications*, vol. 112, pp. 1–6, 2019.
[12] M. A. de Oliveira, E. S. Lima, M. S. P. Cunha, M. Abreu and A. C. S., "RGB-based VLC system using 5G NR standard," *Optics Communications*, vol. 481, pp. 1–7, 2021.
[13] S. Arai, M. Kinoshita and T. Yamazato, "Optical wireless communication: A candidate 6G technology?" *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences*, no. 1, pp. 227–234, 2021.
[14] M. Z. Chowdhury, M. Shahjalal, M. K. Hasan and Y. M. Jang, "The role of optical wireless communication technologies in 5G/6G and IoT solutions: Prospects, directions, and challenges," *Applied Sciences*, vol. 9, no. 20, pp. 1–20, 2019.
[15] S. Riurean, M. Leba, A. Ionica, O. Stoicuta and C. Buioca, "Visible light wireless data communication in industrial environments," *IOP Conference Series: Materials Science and Engineering*, vol. 572, pp. 1–10, 2019.
[16] M. Uysal, "Visible light communications: From theory to industrial standardization," in *2019 Optical Fiber Communications Conf. and Exhibition (OFC)*, San Diego, CA, USA, pp. 1–3, 2019.
[17] X. Li, D. Li, J. Wan, A. V. Vasilakos, C. F. Lai *et al.,* "A review of industrial wireless networks in the context of industry 4.0," *Wireless Networks*, vol. 23, no. 1, pp. 23–41, 2017.
[18] A. Aijaz, "Private 5G: The future of industrial wireless," *IEEE Industrial Electronics Magazine*, vol. 14, no. 4, pp. 136–145, 2020.
[19] H. Haas, L. Yin, C. Chen, S. Videv, D. Parol *et al.,* "Introduction to indoor networking concepts and challenges in LiFi," *Journal of Optical Communications and Networking*, vol. 12, no. 2, pp. A190–A203, 2020.
[20] S. M. Mana, S. Mohammadi Kouhini, P. Hellwig, J. Hilt, P. W. Berenguer *et al.,* "Distributed MIMO experiments for LiFi in a conference room," in *2020 12th Int. Symp. on Communication Systems, Networks and Digital Signal Processing (CSNDSP)*, Porto, Portugal, pp. 1–5, 2020.
[21] A. Uyrus, B. Turan, E. Basar and S. Coleri, "Visible light and mmWave propagation channel comparison for vehicular communications," in *2019 IEEE Vehicular Networking Conf. (VNC)*, Los Angeles, CA, USA, pp. 1–7, 2019.
[22] Y. Shen, G. Chen, X. Xu, C. Xu, G. Shen *et al.,* "Poster: A VLC solution for smart parking," in *Proc. of the 23rd Annual Int. Conf. on Mobile Computing and Networking*, Snowbird Utah, USA, pp. 579–581, 2017.
[23] A. Singla, D. Sharma and S. Vashisth, "Data connectivity in flights using visible light communication," in *2017 Int. Conf. on Computing and Communication Technologies for Smart Nation (IC3TSN)*, Gurgaon, India, pp. 71–74, 2017.

[24] R. Martinek, L. Danys and R. Jaros, "Visible light communication system based on software defined radio: Performance study of intelligent transportation and indoor applications," *Electronics*, vol. 8, no. 4, pp. 1–36, 2019.

[25] H. Farahneh, F. Hussain and X. Fernando, "A new alarming system for an underground mining environment using visible light communications," in *2017 IEEE Canada Int. Humanitarian Technology Conf. (IHTC)*, Toronto, ON, Canada, pp. 213–217, 2017.

[26] S. V. Tiwari, A. Sewaiwar and Y. H. Chung, "Smart home multi-device bidirectional visible light communication," *Photonic Network Communications*, vol. 33, no. 1, pp. 52–59, 2017.

[27] W. Ding, F. Yang, H. Yang, J. Wang, X. Wang *et al.,* "A hybrid power line and visible light communication system for indoor hospital applications," *Computers in Industry*, vol. 68, pp. 170–178, 2015.

[28] C. Shen, Y. Guo, H. M. Oubei, T. K. Ng, G. Liu *et al.,* "20-meter underwater wireless optical communication link with 15 Gbps data rate," *Optics Express*, vol. 24, no. 22, pp. 25502–25509, 2016.

[29] J. Xu, A. Lin, X. Yu, Y. Song, M. Kong *et al.,* "Underwater laser communication using an OFDM-modulated 520-nm laser diode," *IEEE Photonics Technology Letters*, vol. 28, no. 20, pp. 2133–2136, 2016.

[30] I. Chew, D. Karunatilaka, C. P. Tan and V. Kalavally, "Smart lighting: The way forward? Reviewing the past to shape the future," *Energy and Buildings*, vol. 149, pp. 180–191, 2017.

[31] M. Uysal, F. Miramirkhani, O. Narmanlioglu, T. Baykas and E. Panayirci, "IEEE 802.15.7r1 reference channel models for visible light communications," *IEEE Communications Magazine*, vol. 55, no. January, pp. 212–217, 2017.

[32] Z. N. Chaleshtori, S. Zvanovec, Z. Ghassemlooy, H. B. Eldeeb and M. Uysal, "Coverage of a shopping mall with flexible OLED-based visible light communications," *Optics Express*, vol. 28, no. 7, pp. 10015–10026, 2020.

[33] M. S. M. Gismalla and M. F. L. Abdullah, "Performance evaluation of optical attocells configuration in an indoor visible light communication," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 14, no. 2, pp. 668–676, 2019.

[34] M. S. M. Gismalla, M. F. L. Abdullah, M. Sami, N. S. M. Shah, B. Das *et al.,* "Effect of optical attocells deployment on the RMSD spread in indoor visible light communication systems," in *2020 Int. Conf. on Information Science and Communication Technology (ICISCT)*, Karachi, Pakistan, pp. 1–6, 2020.

[35] F. Miramirkhani and M. Uysal, "Channel modelling for indoor visible light communications," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, vol. 378, no. 2169, pp. 1–35, 2020.

[36] M. S. M. Gismalla, M. F. L. Abdullah, M. S. Ahmed, W. A. Mabrouk, N. Al-Fadhali *et al.,* "Design and analysis of different optical attocells deployment models for indoor visible light communication system," *International Journal of Integrated Engineering*, vol. 13, no. 6, pp. 253–264, 2021.

[37] C. Chen, H. Yang, P. Du, W. D. Zhong, A. Alphones *et al.,* "User-centric MIMO techniques for indoor visible light communication systems," *IEEE Systems Journal*, vol. 14, no. 3, pp. 3202–3213, 2020.

[38] M. Z. Afgani, H. Haas, H. Elgala and D. Knipp, "Visible light communication using OFDM," in *2nd Int. Conf. on Testbeds and Research Infrastructures for the Development of Networks and Communities, 2006: TRIDENTCOM 2006*, Barcelona, Spain, pp. 1–6, 2006.

[39] B. Bechadergue and B. Azoulay, "An industrial view on LiFi challenges and future," in *2020 12th Int. Symp. on Communication Systems, Networks and Digital Signal Processing (CSNDSP)*, Porto, Portugal, pp. 1–6, 2020.

[40] Warehouse lighting, "LED high bay lights," [Online]. Available: https://www.warehouse-lighting.com/collections/led-high-bay-lights

[41] V. Jungnickel, P. W. Berenguer, S. M. Mana, M. Hinrichs, S. M. Kouhini *et al.,* "LiFi for industrial wireless applications," in *2020 Optical Fiber Communications Conf. and Exhibition (OFC)*, San Diego, CA, USA, pp. 1–4, 2020.

[42] P. W. Berenguer, P. Hellwig, D. Schulz, J. Hilt, G. Kleinpeter *et al.,* "Real-time optical wireless mobile communication with high physical layer reliability," *Journal of Lightwave Technology*, vol. 37, no. 6, pp. 1638–1646, 2019.

[43] M. Füchtenhans, E. H. Grosse and C. H. Glock, "Smart lighting systems: State-of-the-art and potential applications in warehouse order picking," *International Journal of Production Research*, vol. 59, no. 12, pp. 3817–3839, 2021.
[44] V. Georlette, J. S. Melgarejo, S. Bette, N. Point and V. Moeyaert, "Potential and challenges of visible light communication for industrial assembly lines with mobile workstations," in *2021 IEEE Int. Conf. on Industry 4.0, Artificial Intelligence, and Communications Technology (IAICT)*, Bandung, Indonesia, pp. 228–234, 2021.
[45] Y. Almadani, M. Ijaz, S. Rajbhandari, B. Adebisi and U. Raza, "Application of visible light communication in an industrial environment," in *2018 11th Int. Symp. on Communication Systems, Networks & Digital Signal Processing (CSNDSP)*, Budapest, Hungary, pp. 1–6, 2018.
[46] P. W. Berenguer, D. Schulz, J. Hilt, P. Hellwig, G. Kleinpeter *et al.,* "Optical wireless MIMO experiments in an industrial environment," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 1, pp. 185–193, 2018.
[47] D. Schneider, A. Shrotri, H. Flatt, O. Stübbe, A. Wolf *et al.,* "Impact of industrial environments on visible light communication," *Optics Express*, vol. 29, no. 11, pp. 16087–16104, 2021.
[48] B. Holfeld, D. Wieruch, T. Wirth, L. Thiele, S. A. Ashraf *et al.,* "Wireless communication for factory automation: An opportunity for LTE and 5G systems," *IEEE Communications Magazine*, vol. 54, no. 6, pp. 36–43, 2016.
[49] A. Karaagac, J. Haxhibeqiri, W. Joseph, I. Moerman and J. Hoebeke, "Wireless industrial communication for connected shuttle systems in warehouses," in *2017 IEEE 13th Int. Workshop on Factory Communication Systems (WFCS)*, Trondheim, Norway, pp. 1–4, 2017.
[50] Y. Almadani, M. Ijaz, W. Joseph, S. Bastiaens, S. Rajbhandari *et al.,* "A novel 3D visible light positioning method using received signal strength for industrial applications," *Electronics*, vol. 8, no. 11, pp. 1–20, 2019.
[51] Y. Almadani, M. Ijaz, B. Adebisi, S. Rajbhandari, S. Bastiaens *et al.,* "An experimental evaluation of a 3D visible light positioning system in an industrial environment with receiver tilt and multipath reflections," *Optics Communications*, vol. 483, pp. 1–11, 2021.
[52] D. Schneider, A. Shrotri, O. Stuebbe, R. Lachmayer and C. A. Bunge, "Optical wireless communication in industrial areas: Potential performance and actual demand," in *Photonic Networks; 22th ITG Symp.*, pp. 1–8, 2021.
[53] F. Seguel, A. D. Firoozabadi, P. Adasme, I. Soto, N. Krommenacker *et al.,* "A novel strategy for LED re-utilization for visible light communications," *Optik*, vol. 151, pp. 88–97, 2017.
[54] H. Zheng, J. Chen, C. Yu and M. Gurusamy, "Inverse design of LED arrangement for visible light communication systems," *Optics Communications*, vol. 382, pp. 615–623, 2017.
[55] M. S. M. Gismalla, M. F. L. Abdullah, M. I. Niass, B. Das and W. A. Mabrouk, "Improve uniformity for an indoor visible light communication system," *International Journal of Communication Systems*, vol. 33, no. 8, pp. 1–13, 2020.
[56] AGC Lighting, "120W LED high bay, hot sale high bay light with competitive price-AGC lighting," [Online]. Available: https://www.agcled.com/120w-led-high-bay.html
[57] M. Khadr, A. Abd El Aziz, H. Fayed and M. Aly, "Bandwidth and BER improvement employing a pre-equalization circuit with white LED arrays in a MISO VLC system," *Applied Sciences*, vol. 9, no. 5, pp. 1–14, 2019.
[58] Z. Ghassemlooy, W. Popoola and S. Rajbhandari, "Visible light communications," in *Optical Wireless Communications: System and Channel Modelling with Matlab®*, 2nd ed., vol. 1. Boca Raton, USA: CRC Press, pp. 443–494, 2019.
[59] M. S. M. Gismalla, M. F. L. Abdullah, W. A. Mabrouk, B. Das and M. I. Niass, "Data rate and BER analysis for optical attocells configuration model in visible light communication," in *2019 Int. Conf. on Information Science and Communication Technology (ICISCT)*, Karachi, Pakistan, pp. 1–6, 2019.
[60] T. Y. Elganimi, "Studying the BER performance, power- and bandwidth-efficiency for FSO communication systems under various modulation schemes," in *2013 IEEE Jordan Conf. on Applied Electrical Engineering and Computing Technologies (AEECT)*, Amman, Jordan, pp. 1–6, 2013.

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