IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 25 September 2023, accepted 26 October 2023, date of publication 1 November 2023,
date of current version 7 November 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3329304

RESEARCH ARTICLE

Coverage Improvement of Laser Diode-Based Visible Light Communication Systems Using an Engineered Diffuser

KRISHNENDU BERA[1], **RAJENDRAN PARTHIBAN**[1,2], **(Senior Member, IEEE), AND NEMAI KARMAKAR**[1], **(Senior Member, IEEE)**
[1]Department of Electrical and Computer Systems Engineering, Monash University, Melbourne, VIC 3800, Australia
[2]School of Engineering, Monash University Malaysia, Subang Jaya 47500, Malaysia

Corresponding author: Krishnendu Bera (krishnendu.bera@monash.edu)

ABSTRACT A combination of a blue laser diode (LD) and a warm white light emitting diode (LED) has been used for indoor lighting and visible light communications (VLC). Contrary to LD and phosphor based white lighting communication, no blue LD power is lost due to phosphor conversion. As a result, a longer communication distance has been achieved. The laser beam is diffused in a hat-top profile by an engineered diffuser in such a way that the received signal strength remains flat over a large area, thus improving the coverage area of the communication system. The experiment demonstrates a 1.7 Gbits/s communication speed over a distance of 1.85 m keeping bit error rate (BER) below 2.8×10^{-3} over a large area. The coverage area has been improved by 238% to 2.27 m^2 using the hat-top diffuser from 0.95 m^2 for a phosphor diffuser. This is the largest reported coverage area for the achieved VLC speed at a 1.85 m distance to the best of the authors' knowledge. A correlated color temperature (CCT) of 2952 and a color rendering index (CRI) of 86 have been achieved and the blue light exposure has been kept under the permitted limit. As the radiation standards for eye safety are more relaxed for the infrared (IR) spectrum compared to the visible spectrum, a near-IR LD has been utilized to achieve higher data rates. A data rate of 2.55 Gbits/s has been achieved using the near-IR LD and the proposed diffuser for the same coverage area and distance.

INDEX TERMS Visible light communications, VLC coverage, optical wireless communications, free space optics, hybrid LED-LD, OWC, engineered diffuser.

I. INTRODUCTION

The demand for high speed wireless data is increasing rapidly due to the growing number of internet enabled devices worldwide. Visible light spectrum can provide the extra bandwidth to solve spectrum crunch in radio frequency communication systems [1]. VLC utilizes visible light as the information carrier and is attracting growing attention due to license free available spectrum, high spatial reuse, and high security [1]. VLC and in general optical wireless communications (OWC) have many applications in indoor positioning, intelligent transport systems, and the Internet of Things (IoT) among others [2], [3]. Researchers have utilized commercial LEDs as the optical front end of the transmitter and achieved impressive results. A speed of 15.73 Gbits/s has been attained by Bian et al. [4]. However, due to the use of low power LEDs, the distance and coverage of communication in state-of-art works are not sufficient. High power lighting grade LEDs suffer from intrinsic bandwidth limitation in the order of a few MHz due to high radiative recombination time [5]. Researchers have explored the prospects of micro-LEDs as a VLC transmitter [6]. Micro-LEDs are LEDs with an active area of a few micrometers. High speed VLC systems have been implemented through high modulation bandwidth of micro-LEDs [7], [8], [9]. Though the communication speeds achieved using micro-LEDs are impressive, the distance and coverage of communication are poor due to the small output power. Moreover, the

The associate editor coordinating the review of this manuscript and approving it for publication was Barbara Masini.

efficiency of the micro-LEDs is compromised to achieve higher modulation bandwidth through higher injected current density [10]. As LDs can operate at much higher current densities (1-10 kA/cm^2) than LEDs (10-100 A/cm^2) without the 'efficiency droop' issue, LDs can be more suitable than LEDs for high speed VLC applications [11]. The main advantage of LDs over micro-LEDs is their high modulation bandwidth and moderate electrical to optical power efficiency. Thus, LDs can be used both for lighting and communications. Denault et al. [12] have studied white light generation using blue LD and yellow-emitting cerium-doped YAG (YAG:Ce) phosphor achieving a luminous efficacy of $76lm/W$ and a CRI of 57. LDs are already being considered both for lighting and for VLC transmitter [13]. Chi et al. [14] have presented a 5.6 Gbits/s white lighting communication for 60 cm distance using a blue LD and phosphor as the transmitter. Lee et al. [15] employed a near-ultraviolet laser diode along with RGB-emitting phosphors for a Gbps class VLC system. Wu et al. [16] achieved 1.6 Gbits/s speed over a communication distance of 1 m. With a blue LD and remote phosphor setup, Yeh et al. [17] attained a communication speed of 1.25 Gbits/s. In another approach, LDs in different wavelengths have been used for white light generation and optical wavelength division multiplexing (WDM) based high speed VLC systems [18], [19], [20], [21]. Though the communication speed is higher in WDM based systems, the system complexity significantly increases and the white light generated from LDs of multiple wavelengths has a poor color rendering index due to the narrow optical spectrum of individual LDs.

In the literature, most of these high speed (Gbps class) VLC systems have been demonstrated for short distances (below 1 m) or for long distances with a focused beam. Gbps class VLC systems for practical distances and wide coverage are necessary for practical implementation. The coverage aspect of LD based VLC systems has mostly been ignored or compromised to achieve higher speed. Beam steering can be a promising method to improve the coverage of VLC systems. However, in the current state of the art of beam steering based VLC systems, most works have shown high data rates without supporting user movement tracking [20], [22], [23]. A complex micro-electromechanical systems (MEMS) mirror based beam steering without any tracking mechanism has been used to improve VLC coverage [20], [24] which is unreliable for randomly moving indoor users. Piezo-electric actuator based beam steering has been implemented to serve multiple users [23], [25]. However, beam steering without feedback and locking the beam towards the mobile receiver is not useful in practical scenarios as the users can move randomly inside a room. Researchers have utilized a large number of fiber optic-based sources and wavelength tuning using wavelength-dependent beam diffraction to cover a large area [22], [26], [27]. This method uses external modulation, laser wavelength tuning, and a large number of transmitters to cover the entire area thus it needs costly components. Optical phased array-based beam steering system can be a useful solution but it needs external modulation and it is still an expensive solution for handheld electronic devices [28]. Locking a user's location using a pencil beam is highly unreliable for randomly moving users. One work [29] has implemented beam steering using liquid lenses with feedback and a locking mechanism, however, the time delay to lock the user's location is too long to be useful for practical scenarios. Relay-based cooperative network has been proposed to improve the VLC coverage [30], [31], [32] but these approaches add extra hardware to the system. A simulation based study of transmitters arrangement and power allocation has been proposed for consistent communication performance in a room where multiple transmitters are installed [33].

In this paper, a white lighting communication using a hybrid LED-LD approach and an engineered hat-top diffuser has been implemented to improve the communication distance and coverage area of a single VLC transmitter. The LD performs the communication and complements the LED in lighting. By avoiding the use of phosphor, the loss of blue light power has been reduced. As a result, the SNR of the received signal has improved and thus, the communication range has been increased. The second research component of this paper is to improve the coverage area of VLC systems by modifying the optical radiation profile using an engineered hat-top diffuser. In LD and phosphor based VLC, the transmitted power profile is Lambertian. As a result, the received signal strength drops quickly when the receiver moves away from the transmitter. In this paper, using the engineered hat-top diffuser, the spatial optical power distribution profile of the transmitter is modified in such a way that it complements the receiver photo-diode (PD) sensitivity profile and the effect of distance. As a result, the received signal strength profile is flat over a larger area at the receiver end. This leads to a uniform communication performance over a larger area thus improving the coverage area of the VLC system [34]. Finally, a near-infrared (IR) LD has been used as the light source instead of the blue LD to achieve higher data rates because the eye safety standards are more relaxed for IR frequencies and as a result, a higher transmitted power is allowed compared to the visible spectrum.

The rest of the paper is organized as follows: Section II explains the methods of achieving the results through calculation and simulation, Section III explains the experiment process, Section IV presents and discusses the experimental results, and finally, in Section V, conclusions are drawn.

II. METHODS

The goal of this research is to achieve high speed (Gbps class) VLC for practical indoor distances and large coverage areas. The existing works on blue LD based white lighting communication mainly use YAG:Ce along with blue LD to generate white light and for wireless communication. Researchers have already achieved Gbps range speed in VLC systems. However, with blue LD and phosphor based

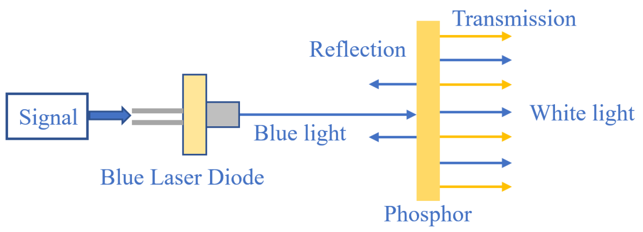


FIGURE 1. Drawbacks of generating white light using blue LD and phosphor: large reflection and absorption of costly LD light.

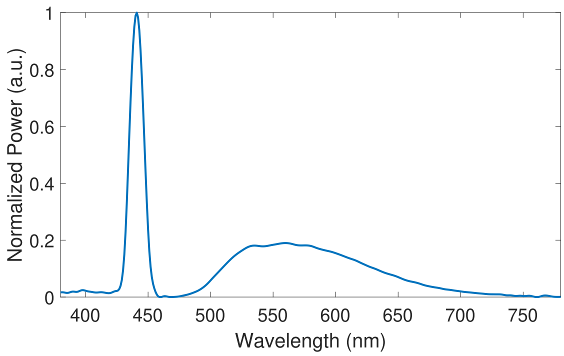


FIGURE 2. Optical spectrum of white light generated using a 450 nm blue LD and Intematix CL-827-R75-PC phosphor, captured by SEKONIC C-7000 optical spectrometer.

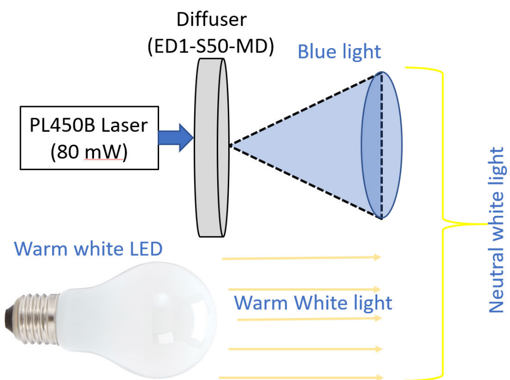


FIGURE 3. White light generation combining warm LED and diffused 450 nm LD output.

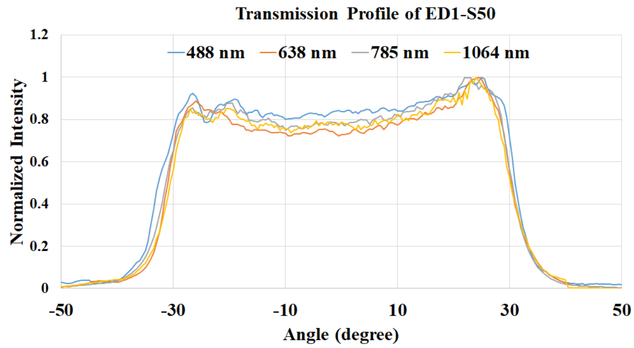


FIGURE 4. Normalised optical power distribution profile of the proposed engineered diffuser.

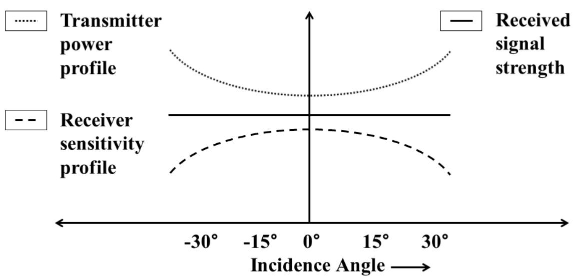


FIGURE 5. Hypothesis behind improving VLC coverage area using hat-top diffuser.

approach, there are four problems: (1) Blue laser light is used to create red, yellow, and green light components to generate white light. Due to the reduced blue component, signal to noise ratio (SNR) at the receiver gets degraded. Thus, the communication distance is limited. (2) When compared to LEDs, LDs are costly, and extra energy is needed to cool them down while in operation to maintain operating temperature. So, an array of laser and phosphor combinations is not power efficient considering the low power plug efficiency of lasers and the high power consumption of thermo-electric coolers (TEC). Therefore, it is impractical to use LDs alone for large scale lighting applications. (3) A large part (35%) of the blue light is reflected and scattered from the phosphor [14]. This reduces the light output in the forward direction thus adversely affecting the lighting and communication performances. (4) There is a trade-off between lighting and communication performance. The blue light is the information carrier as the converted yellow light is slow changing component of the phosphor converted white light. Reducing the phosphor concentration allows passing more blue light resulting in better communication performance. However, the higher blue component in the white light results in a cooler light which is not good for the eyes to see for an extended period of time. In terms of lighting, a neutral color temperature (4000 K) can be considered optimum for different environments. Additionally, the performance of the phosphor may degrade over time due to the high power density of the laser beam on the phosphor.

In LD-phosphor based VLC systems, white light is generated by exciting a phosphor material with blue or violet light from an LD as shown in Fig. 1. When the blue light passes through the phosphor material, the phosphor absorbs a part of the blue light and converts it into a broader spectrum consisting of green, yellow, and red colors and this is how the white light is generated. Only the unconverted blue light is useful for communication due to the slow response of the phosphor [14]. To estimate the amount of blue light lost in this process, white light is generated using a blue LD (OSRAM PL450B) and a YAG phosphor (Intematix CL-827-R75-PC). The optical spectrum of the generated white light is captured using an optical spectrometer (Sekonic C-7000). The measured spectrum as shown in Fig. 2 is then used to

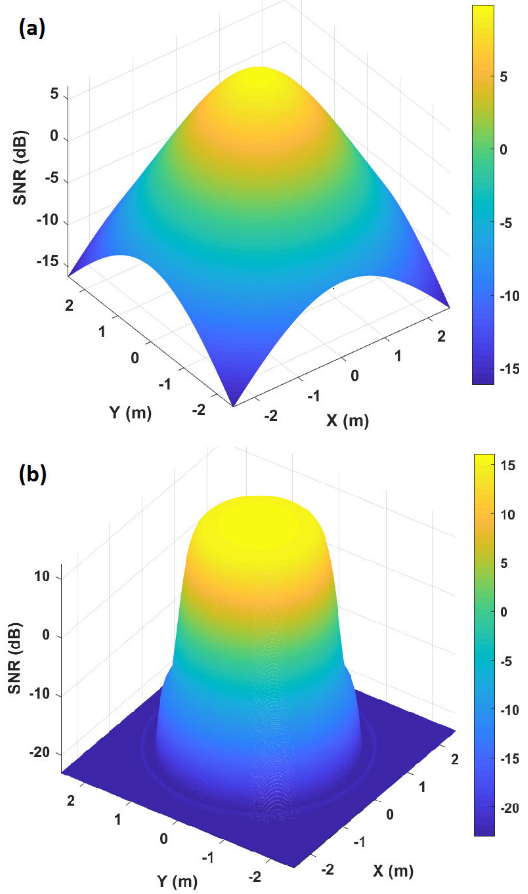


FIGURE 6. Simulation results: SNR distribution of a VLC system with a (a) Lambertian (b) Hat-top diffuser; Hat-top diffuser demonstrates a uniform performance over a larger area.

calculate the power loss of the blue light output. Adding the 35% reflection loss, it is calculated that the phosphor causes a loss of 6.7 *dB* in the blue light power. In addition, the quality of the white light generated using phosphor is poor due to low CRI and high color temperature [17].

One way to avoid this loss of blue light power is to generate white light without converting the blue light. In hybrid LED-LD VLC systems, the LED output is mainly used for lighting and the LD mainly serves the communication purpose and complements the LED in lighting. In this paper, a hybrid LED-LD based VLC system is presented where a warm white LED (2700 K) and a blue LD are combined for lighting as shown by Fig. 3 and for optical wireless communication.

In phosphor based Lambertian diffuser, the combined effect of the transmitted power profile, receiver sensitivity profile and effect of increased distance causes the received signal strength to fall very quickly when the angle of incidence increases. As a result, the coverage area is reduced. To improve the coverage area, instead of a Lambertian diffuser, a hat-top engineered diffuser (Thorlabs ED1-S50-MD) is used to distribute the blue light. The optical power distribution profile of the proposed diffuser is shown in Fig. 4. At 0° transmission angle the normalized intensity is 0.8 and it gradually increases to 1.0 at around 25°. This transmitted power profile complements the effect of the PD's sensitivity profile and the effect of distance at the receiver side as shown in Fig. 5. This is why the signal-to-noise ratio (SNR) varies very little over a large area on the receiver's plane thus improving the coverage area and resulting in uniform communication performance. Simulation results presented in Fig. 6 show that the area with an SNR variation of below 3 dB improves to 16.91% for the proposed diffuser from 9.44% for the Lambertian diffuser [34]. The details of the simulation results can be found in the authors' previous article [34].

III. EXPERIMENTS

To study the communication and lighting performances, a laboratory experimental setup has been established as shown in Fig. 7 with individual components marked. The modulation bandwidth of the blue LD (OSRAM PL450B) has been measured using a network analyzer (Agilent E8362B). A signal with a frequency sweep starting from 10 MHz to 2 GHz is generated from port 1 of the network analyzer. The signal is biased using a biasing network (Bias-T, Mini Circuits ZFBT-4R2G+) and then fed to the LD. The light is detected using a photo-detector (New Focus 1601FS-AC) and the photo-detector output is applied to port 2 of the network analyzer to measure the transmission coefficient which expresses the modulation bandwidth. The 3 dB bandwidth of the photo-detector is 1 GHz and it has been taken into

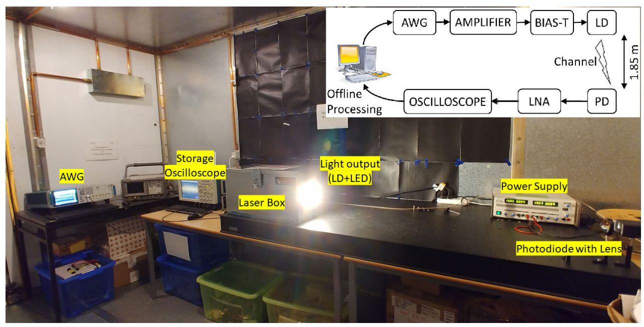


FIGURE 7. Experimental setup: The communication test bed is demonstrated here. The signal is generated in the AWG. The transmitter's front end is placed inside the laser box. The inset shows the flow of the signal.

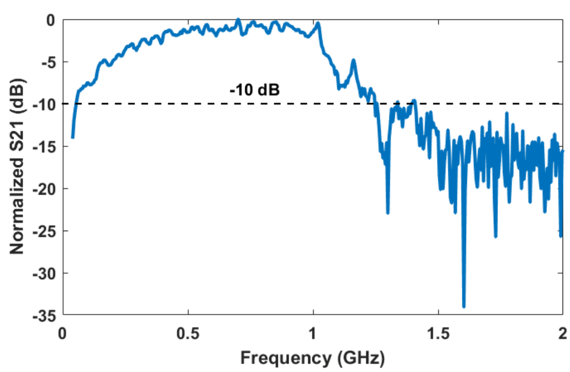


FIGURE 8. Measured modulation bandwidth of the blue LD.

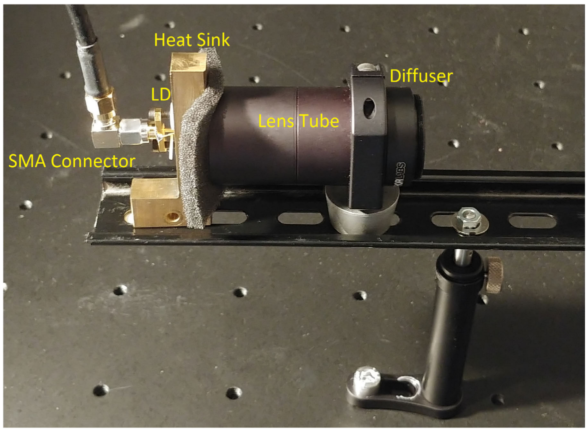


FIGURE 9. Transmitter front-end of the VLC system: individual components have been highlighted. The signal is fed to the LD through an SMA connector. The metal case of the LD is inserted in a drilled hole in the copper heat sink. The lens tube houses an aspheric condenser lens (Thorlabs ACL2520U) inside to concentrate the laser beam on the diffuser which is placed at the front of the lens tube.

account while calculating the modulation bandwidth of the LD. The 10 dB modulation bandwidth of the LD is found to be 1.2 GHz as seen in Fig. 8. For communication, orthogonal frequency division multiplexing (OFDM) modulation has been used for its high spectral efficiency and robustness against channel dispersion [35]. First, M-ary Quadrature Amplitude Modulation (M-QAM) symbols are generated from the binary signal. The QAM symbols are distributed over the entire bandwidth in discrete frequency components. Then, inverse Fourier transform (IFFT) is used to convert the frequency domain QAM constellation into a time domain signal. Next, a cyclic prefix (CP) is added to minimize the effect of intersymbol interference (ISI). In VLC, only real valued signals can be transmitted through the optical front ends. So, the OFDM method used in radio frequency systems must be modified here. To convert complex valued QAM symbols into real valued signal, a Hermitian symmetry is used before the QAM symbols are given as input to the IFFT operation. Then, the real valued bipolar signal is amplified and a DC current is used to bias the signal to make it unipolar. This signal generation is done in the MATLAB platform. The MATLAB code is transferred in an arbitrary waveform generator (AWG, Tektronix AWG5204) to generate the actual signal during the experiment. The generated DCO-OFDM signal is amplified by a broadband amplifier (Mini Circuits ZFL-1000H+) and then applied to a biasing network (Bias-T, Mini Circuits ZFBT-4R2G+) to add a DC bias. To keep the signal in the operating range of the LD, the LD is biased at 60 mA DC current. The biased signal is finally fed to the LD (OSRAM PL450B). The LD output is concentrated using an aspheric condenser lens (Thorlabs ACL2520U) placed inside the optical lens tube as shown in Fig. 9. The concentrated LD output is diffused using an engineered diffuser (Thorlabs ED1-S50-MD). The diffused blue laser light is mixed with the output of a commercially available 20 Watt warm white (2700 K) LED bulb. The diffused laser light travels 1.85 m through the indoor free space channel. At the receiver side, the optical signal is first collected using an aspheric condenser lens (Thorlabs ACL5040U) and then filtered using a blue optical bandpass filter (Thorlabs FBH450-10) to filter out the unwanted light from the LED and other ambient light sources. The filtered light is then detected and converted to an electrical signal by a high speed PIN photo-detector (New Focus 1601FS-AC) with a 3 dB bandwidth of 1 GHz. There is an in-built trans-impedance amplifier in the photo-detector module which converts the current output of the photo-detector into a voltage signal. The output of the photo-detector is further amplified by a low noise amplifier (LNA, Mini-Circuits, ZKL-1R5+) with a 40 dB gain and a noise figure of 3 dB. The amplified signal is then sampled and stored in a storage oscilloscope (Tektronix TDS7154B). The stored signal is finally processed offline in MATLAB to study the overall communication performance.

In the second part of the experiments, the blue LD and the PD module have been replaced with a near-IR LD and a near-IR detector (New Focus 1611FS-AC) to achieve higher data rates, and the entire process is repeated. As the proposed diffuser works up to 1100 nm wavelength, a 1064 nm near-IR LD (Thorlabs M9-A64-0200) has been tested. The transmitted power is 200 mW and it is similarly diffused using the engineered diffuser. As the transmitted power of the near-IR LD is higher than the blue LD and the IR PD performance is better than the visible PD module, the transmitted binary data is encoded into 64-QAM instead of 16-QAM to achieve higher communication speed.

IV. RESULTS AND DISCUSSIONS

A. COMMUNICATION PERFORMANCE

At the receiver end, the signal is stored and processed offline to calculate the BER. First, the signal is synchronized to the transmitted signal using a synchronization pulse. Then the CP is removed. Afterward, the signal is mapped to complex symbols in the frequency domain by performing FFT. The complex QAM symbols are finally converted to a binary signal. The received binary signal is compared to the transmitted one to calculate the BER. The BER is found to be 2.8×10^{-3} which is under the forward error correction (FEC) limit of 3.8×10^{-3}. The data rate has been calculated after excluding the CP and synchronization pulses. The synchronization pulses have been used to detect the start and the end of the data stream. The total time required to transmit the data is measured from the storage oscilloscope. The entire OFDM signal carrying a total of 2^{14} bits of binary data is transmitted in $9.6\mu S$ leading to a net data rate of 1.7 Gbps. The constellation diagram of the demodulated QAM symbols is shown in Fig. 10 in which a distinctive constellation expresses reliable communication performance.

The distance between the transmitter and the receiver is $1.85m$ which is an improvement compared to the existing literature [14], [17]. The measured SNR of the received

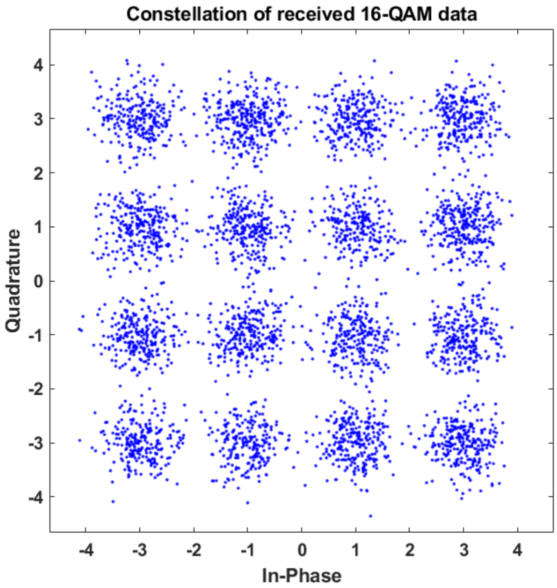


FIGURE 10. **Communication performance of LED-LD hybrid VLC: Constellation plot of the decoded 16-QAM symbols.**

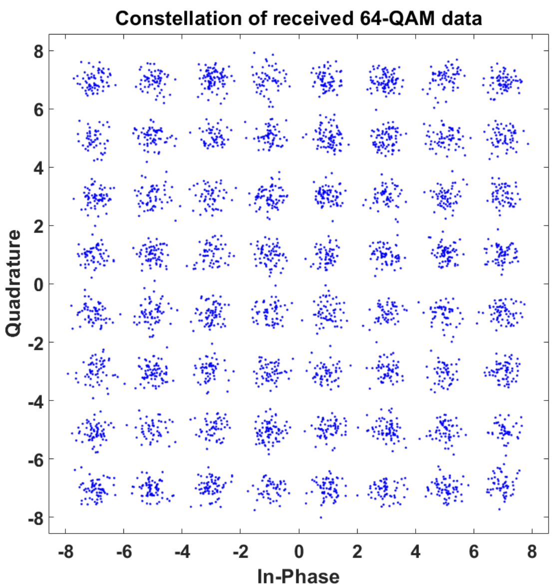


FIGURE 11. **Communication performance of near-IR based OWC: Constellation plot of the decoded 64-QAM symbols.**

signal detected at the oscilloscope is 16 dB and 7 dB for the proposed diffuser (Thorlabs ED1-S50-MD) and for the phosphor diffuser (Intematix CL-827-R75-PC) respectively. This improvement of the SNR has contributed to the improvement of the communication distance in the case of a hybrid LED-LD approach.

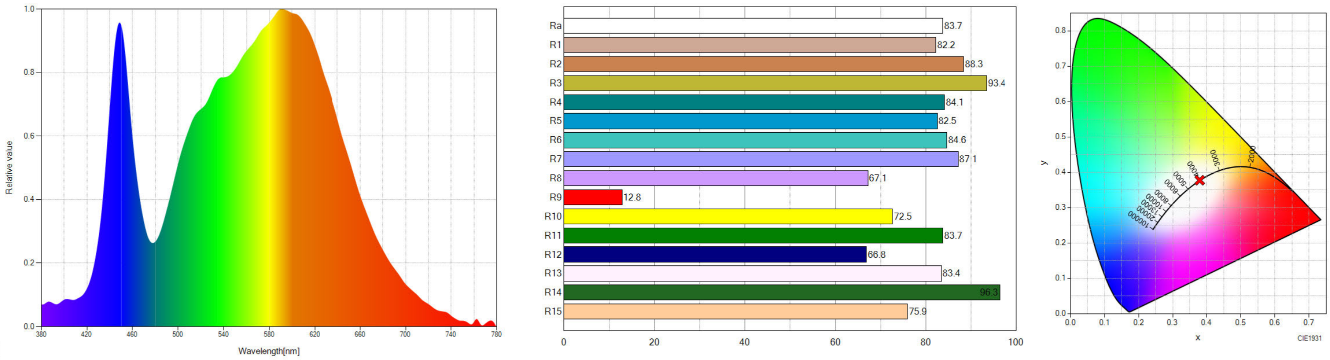
The same demodulation process is followed after replacing the blue LD with the near-IR LD. The measured SNR in this case is 24 dB. The 64-QAM OFDM demodulated signal in this case results in an achieved data rate is 2.55 Gbps with a BER of 2.2×10^{-3}. The data rate has improved due to the higher order modulation. A higher order modulation has been possible for the near-IR wavelength because of the improved SNR. The SNR has improved due to the higher transmitted power of the IR LD, higher responsivity, and lower noise floor of the IR photo-detector.

B. COVERAGE IMPROVEMENT

To calculate the coverage area of the LD based VLC system, the receiver is moved horizontally on the optical table gradually to measure the SNR of the received signal at 5 cm intervals. As the diffuser characteristics are symmetrical, the two dimensional coverage is calculated from the one dimensional measurements. The threshold SNR is 3 dB below the maximum SNR value. The total area where the SNR is above the threshold has been considered as the coverage area. Within this area, the communication speed has been maintained above 1.7 Gbps keeping the BER within the FEC limit of 3.8×10^{-3}. According to the experimental results, the coverage area for the hat-top diffuser and phosphor diffuser is 2.27 m^2 and 0.95 m^2 respectively thus establishing the hat-top diffuser as a better choice to achieve a larger coverage area in VLC systems. The coverage area for the near-IR based communications is expectedly unchanged due to similar optical power distribution profiles for both 450 nm and 1064 nm wavelengths.

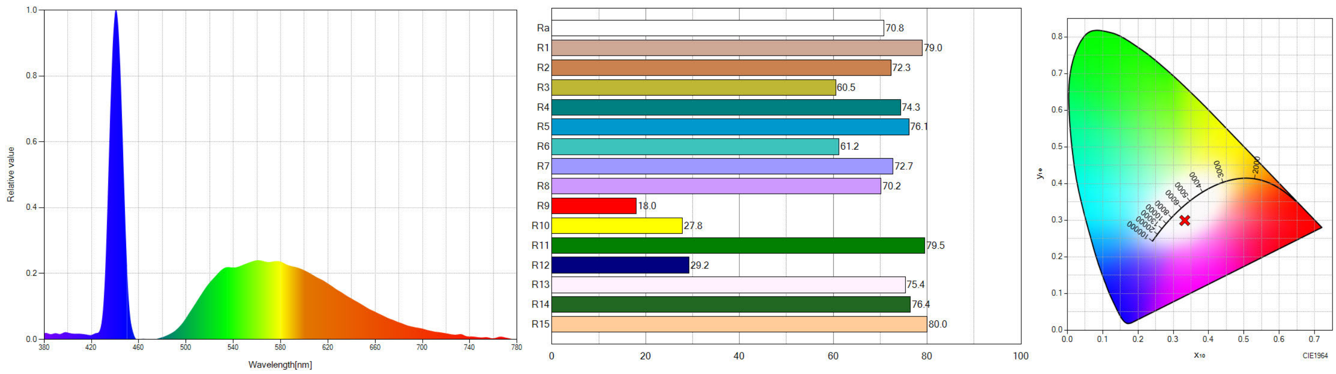
C. LIGHTING PERFORMANCE

In VLC systems, the lighting quality is an important factor for the end users. The light output is expected to match the standard office or home lighting quality. To determine the lighting quality in the proposed system, the light is captured using an optical spectrometer (Sekonic C-7000) to analyze the lighting parameters. Standard office light, LD-phosphor based white light, and hybrid LED-LD based light are compared. In Fig. 12 the characteristics of the LED light used in standard office environments are presented. The light is neutral white with CCT and CRI of 4060K and 83.7 respectively. This light has been taken as a standard to compare. The properties of the light generated by LD-phosphor combination have been shown in Fig. 13 where it can be understood that the blue light component is dominating. The CCT is 5422K which is on the cooler side and the CRI is 70.8 which is below the standard desired value of 80. On the other hand, the hybrid LED-LD approach produces a CCT and CRI of 2952K and 86 respectively as seen from Fig. 14. It offers a lower CCT and higher CRI. As the LD output power is quite small compared to the LED, the CRI, CCT, and other lighting parameters are dominated by the LED and similar to that of the LED. As a result, the variation of light output characteristics at different angles is negligible though the radiation pattern of the LED and the diffused LD output are different. The optical spectrum of the hybrid LED-LD based light matches that of the standard office lighting. In terms of CRI, the lighting is in fact better than the standard office light. When the near-IR LD is used



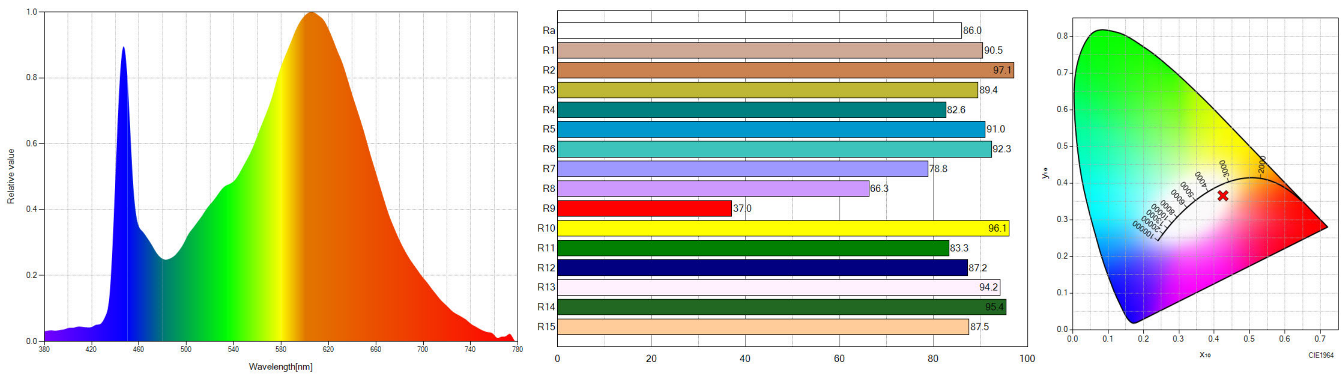
(a) White light spectrum (b) CRI (c) CIE

FIGURE 12. Properties of white light from standard office LED lighting: CCT:4000K, CRI:83.7.



(a) White light spectrum (b) CRI (c) CIE

FIGURE 13. Properties of white light from LD-phosphor based lighting: The blue component is dominant, CCT:5000K, CRI:70.8.



(a) White light spectrum (b) CRI (c) CIE

FIGURE 14. Properties of white light from Hybrid LED-LD lighting: CCT:2952, CRI:86.

for communication, the light quality is the same as the high power LED bulb.

D. EYE SAFETY CONSIDERED

The far field radiation pattern of the diffused laser light and the hybrid LED-LD light output has been captured separately on a white wall by a camera as presented in Fig. 15. It can be seen that the light output is equally distributed without any visible speckle pattern. In addition, light with lower CCT contains less blue light component which is harmful to the eyes [16]. Considering the CCT of the proposed hybrid LED-LD output being below 3000 K, the blue light is less. The blue light exposure has been calculated to satisfy eye safety standards recommended in [36]. Considering the pupil

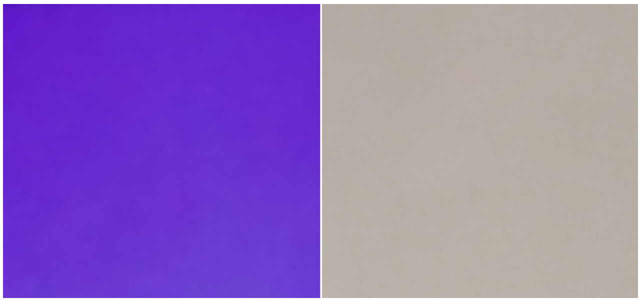


FIGURE 15. Distribution of light from hybrid LED-LD transmitter: no visible speckle pattern is present in the hybrid LED-LD lighting (left) diffused blue light on a white wall (right) hybrid LED-LD output on white wall.

diameter of 7 mm, at 1 m distance, the blue laser light exposure is $2598Wm^{-2}Sr^{-1}$ which is under the MPE limit of $10000Wm^{-2}Sr^{-1}$ for 450 nm wavelength. The MPE is crossed when the user's eyes come closer than 51 cm to the diffused blue LD. Exposure within 51 cm is unlikely if the transmitter is installed at the ceiling and warning signs are necessary like all other instruments having a laser diode transmitter. During maintenance, a technician can wear laser safety glasses to avoid the risk of any harm. When the 1064 nm LD is used as the transmitter, the IR exposure value at 1 m distance is $6495Wm^{-2}Sr^{-1}$ which is again well below the MPE value of $241580Wm^{-2}Sr^{-1}$. For the 1064 nm LD, the MPE is crossed at a distance of 16.7 cm which is even lower compared to the blue visible light. Thus, from a safety point of view, the IR frequency band is safer for the eyes due to a higher allowable MPE limit.

V. CONCLUSION

Though Gbits/s speeds have been achieved in VLC literature, the communication distance and coverage area need to be improved. In this work, a 1.7 Gbits/s VLC system with a communication distance of 1.85 m has been implemented using a hybrid LED-LD approach. The costly blue laser output power has been fully utilized for communication without wasting it to convert to other wavelengths for generating white light. Thus, the distance of communication has significantly increased compared to prior literature. Compared to LD-phosphor based VLC, the coverage area has also been improved by 238% through modifying the diffused optical beam profile using an engineered diffuser. The achieved light quality is also better in terms of lower CCT and higher CRI. The eye safety standard has been maintained for its applications in white lighting communications. It is also shown that the proposed diffuser can work in the near-IR spectrum and a higher data rate has been achieved using a near-IR LD as the transmitter. Therefore, this paper presents a useful way to implement high speed VLC and OWC systems in general for practical communication distance and coverage area without compromising the light quality.

ACKNOWLEDGMENT

The authors would like to thank Andrew Linzner, Ian Reynolds, Dr. Bill Corcoran, and Dr. Arthur Lowery from Monash University for their support in designing the laser safety system.

REFERENCES

[1] D. Karunatilaka, F. Zafar, V. Kalavally, and R. Parthiban, "LED based indoor visible light communications: State of the art," *IEEE Commun. Surveys Tuts.*, vol. 17, no. 3, pp. 1649–1678, 3rd Quart., 2015.

[2] H. Yang, W.-D. Zhong, C. Chen, and A. Alphones, "Integration of visible light communication and positioning within 5G networks for Internet of Things," *IEEE Netw.*, vol. 34, no. 5, pp. 134–140, Sep. 2020.

[3] W. Costa, H. Camporez, M. Hinrichs, H. Rocha, M. Pontes, M. Segatto, A. Paraskevopoulos, V. Jungnickel, R. Freund, and J. Silva, "Toward AI-enhanced VLC systems for industrial applications," *J. Lightw. Technol.*, vol. 41, no. 4, pp. 1064–1076, Feb. 15, 2023.

[4] R. Bian, I. Tavakkolnia, and H. Haas, "15.73 Gb/s visible light communication with off-the-shelf LEDs," *J. Lightw. Technol.*, vol. 37, no. 10, pp. 2418–2424, May 15, 2019.

[5] S. Rajbhandari, J. J. D. McKendry, J. Herrnsdorf, H. Chun, G. Faulkner, H. Haas, I. M. Watson, D. O'Brien, and M. D. Dawson, "A review of gallium nitride LEDs for multi-gigabit-per-second visible light data communications," *Semicond. Sci. Technol.*, vol. 32, no. 2, Feb. 2017, Art. no. 023001.

[6] S. Rajbhandari, H. Chun, G. Faulkner, K. Cameron, A. V. N. Jalajakumari, R. Henderson, D. Tsonev, M. Ijaz, Z. Chen, H. Haas, E. Xie, J. J. D. McKendry, J. Herrnsdorf, E. Gu, M. D. Dawson, and D. O'Brien, "High-speed integrated visible light communication system: Device constraints and design considerations," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 9, pp. 1750–1757, Sep. 2015.

[7] R. X. G. Ferreira, E. Xie, J. J. D. McKendry, S. Rajbhandari, H. Chun, G. Faulkner, S. Watson, A. E. Kelly, E. Gu, R. V. Penty, I. H. White, D. C. O'Brien, and M. D. Dawson, "High bandwidth GaN-based micro-LEDs for multi-Gb/s visible light communications," *IEEE Photon. Technol. Lett.*, vol. 28, no. 19, pp. 2023–2026, Oct. 1, 2016.

[8] H. Chun, S. Rajbhandari, G. Faulkner, D. Tsonev, E. Xie, J. J. D. McKendry, E. Gu, M. D. Dawson, D. C. O'Brien, and H. Haas, "LED based wavelength division multiplexed 10 Gb/s visible light communications," *J. Lightw. Technol.*, vol. 34, no. 13, pp. 3047–3052, Jul. 1, 2016.

[9] L. Wang, Z. Wei, C.-J. Chen, L. Wang, H. Y. Fu, L. Zhang, K.-C. Chen, M.-C. Wu, Y. Dong, Z. Hao, and Y. Luo, "1.3 GHz E-O bandwidth GaN-based micro-LED for multi-gigabit visible light communication," *Photon. Res.*, vol. 9, no. 5, p. 792, 2021.

[10] M. Monavarian, A. Rashidi, A. A. Aragon, M. Nami, S. H. Oh, S. P. DenBaars, and D. Feezell, "Trade-off between bandwidth and efficiency in semipolar (20$\bar{2}\bar{1}$) InGaN/GaN single- and multiple-quantum-well light-emitting diodes," *Appl. Phys. Lett.*, vol. 112, no. 19, May 2018, Art. no. 191102.

[11] F. Zafar, M. Bakaul, and R. Parthiban, "Laser-diode-based visible light communication: Toward gigabit class communication," *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 144–151, Feb. 2017.

[12] K. A. Denault, M. Cantore, S. Nakamura, S. P. DenBaars, and R. Seshadri, "Efficient and stable laser-driven white lighting," *AIP Adv.*, vol. 3, no. 7, Jul. 2013, Art. no. 072107.

[13] Y. G. Y. Guo, O. A. O. Alkhazragi, C. H. K. C. H. Kang, C. S. C. Shen, Y. M. Y. Mao, X. S. X. Sun, T. K. N. T. K. Ng, and B. S. O. B. S. Ooi, "A tutorial on laser-based lighting and visible light communications: Device and technology [invited]," *Chin. Opt. Lett.*, vol. 17, no. 4, 2019, Art. no. 040601.

[14] Y.-C. Chi, D.-H. Hsieh, C.-Y. Lin, H.-Y. Chen, C.-Y. Huang, J.-H. He, B. Ooi, S. P. DenBaars, S. Nakamura, H.-C. Kuo, and G.-R. Lin, "Phosphorous diffuser diverged blue laser diode for indoor lighting and communication," *Sci. Rep.*, vol. 5, no. 1, p. 18690, Dec. 2015.

[15] C. Lee, C. Shen, C. Cozzan, R. M. Farrell, J. S. Speck, S. Nakamura, B. S. Ooi, and S. P. DenBaars, "Gigabit-per-second white light-based visible light communication using near-ultraviolet laser diode and red-, green-, and blue-emitting phosphors," *Opt. Exp.*, vol. 25, no. 15, p. 17480, 2017.

[16] T.-C. Wu, Y.-C. Chi, H.-Y. Wang, C.-T. Tsai, C.-H. Cheng, J.-K. Chang, L.-Y. Chen, W.-H. Cheng, and G.-R. Lin, "White-lighting communication with a $Lu_3Al_5O_{12}$:Ce^{3+}/$CaAlSiN_3$:Eu^{2+} glass covered 450-nm InGaN laser diode," *J. Lightw. Technol.*, vol. 36, no. 9, pp. 1634–1643, May 1, 2018.

[17] C.-H. Yeh, C.-W. Chow, and L.-Y. Wei, "1250 Mbit/s OOK wireless white-light VLC transmission based on phosphor laser diode," *IEEE Photon. J.*, vol. 11, no. 3, pp. 1–5, Jun. 2019.

[18] T.-C. Wu, Y.-C. Chi, H.-Y. Wang, C.-T. Tsai, Y.-F. Huang, and G.-R. Lin, "Tricolor R/G/B laser diode based eye-safe white lighting communication beyond 8 Gbit/s," *Sci. Rep.*, vol. 7, no. 1, pp. 1–10, Jan. 2017.

[19] Y.-F. Huang, Y.-C. Chi, M.-K. Chen, D.-P. Tsai, D.-W. Huang, and G.-R. Lin, "Red/green/blue LD mixed white-light communication at 6500K with divergent diffuser optimization," *Opt. Exp.*, vol. 26, no. 18, p. 23397, 2018.

[20] H. Chun, A. Gomez, C. Quintana, W. Zhang, G. Faulkner, and D. O'Brien, "A wide-area coverage 35 Gb/s visible light communications link for indoor wireless applications," *Sci. Rep.*, vol. 9, no. 1, p. 4952, Mar. 2019.

[21] L. Issaoui, S. Cho, and H. Chun, "High CRI RGB laser lighting with 11-Gb/s WDM link using off-the-shelf phosphor plate," *IEEE Photon. Technol. Lett.*, vol. 34, no. 2, pp. 97–100, Jan. 15, 2022.

[22] T. Koonen, F. Gomez-Agis, F. Huijskens, K. A. Mekonnen, Z. Cao, and E. Tangdiongga, "High-capacity optical wireless communication using two-dimensional IR beam steering," *J. Lightw. Technol.*, vol. 36, no. 19, pp. 4486–4493, Oct. 2018.

[23] Y. S. Eroglu, C. K. Anjinappa, I. Guvenc, and N. Pala, "Slow beam steering and NOMA for indoor multi-user visible light communications," *IEEE Trans. Mobile Comput.*, vol. 20, no. 4, pp. 1627–1641, Apr. 2021.

[24] P. Brandl, S. Schidl, A. Polzer, W. Gaberl, and H. Zimmermann, "Optical wireless communication with adaptive focus and MEMS-based beam steering," *IEEE Photon. Technol. Lett.*, vol. 25, no. 15, pp. 1428–1431, Aug. 2013.

[25] Y. S. Eroglu, I. Guvenc, A. Sahin, N. Pala, and M. Yuksel, "Diversity combining and piezoelectric beam steering for multi-element VLC networks," in *Proc. 3rd Workshop Visible Light Commun. Syst.*, Oct. 2016, pp. 25–30.

[26] C. W. Oh, E. Tangdiongga, and A. M. J. Koonen, "42.8 Gbit/s indoor optical wireless communication with 2-dimensional optical beam-steering," in *Proc. Opt. Fiber Commun. Conf. Exhib. (OFC)*, Mar. 2015, pp. 1–3.

[27] F. Gomez-Agis, S. P. van de Heide, C. M. Okonkwo, E. Tangdiongga, and A. M. J. Koonen, "112 Gbit/s transmission in a 2D beam steering AWG-based optical wireless communication system," in *Proc. Eur. Conf. Opt. Commun. (ECOC)*, Sep. 2017, pp. 1–3.

[28] C.-W. Chow, Y.-C. Chang, S.-I. Kuo, P.-C. Kuo, J.-W. Wang, Y.-H. Jian, Z. Ahmad, P.-H. Fu, J.-W. Shi, D.-W. Huang, T.-Y. Hung, Y.-Z. Lin, C.-H. Yeh, and Y. Liu, "Actively controllable beam steering optical wireless communication (OWC) using integrated optical phased array (OPA)," *J. Lightw. Technol.*, vol. 41, no. 4, pp. 1122–1128, Feb. 15, 2023.

[29] F. Ahmad, R. N. Sathisha, K. M. Jyothsna, and V. Raghunathan, "Hybrid laser-LED transmitter with closed-loop beam-steering control for indoor optical wireless communication," *J. Lightw. Technol.*, vol. 40, no. 12, pp. 3557–3566, Jun. 15, 2022.

[30] P. Pesek, S. Zvanovec, P. Chvojka, Z. Ghassemlooy, N. A. M. Nor, and P. Tabeshmehr, "Experimental validation of indoor relay-assisted visible light communications for a last-meter access network," *Opt. Commun.*, vol. 451, pp. 319–322, Nov. 2019.

[31] M. de Oliveira, L. C. Vieira, F. P. Guiomar, L. N. Alves, P. P. Monteiro, and A. A. P. Pohl, "Experimental assessment of the performance of cooperative links in visible light communications," *Opt. Commun.*, vol. 524, Dec. 2022, Art. no. 128771.

[32] A. R. Bastos, G. Lyu, T. Silvério, P. S. André, R. C. Evans, and R. A. S. Ferreira, "Flexible blue-light fiber amplifiers to improve signal coverage in advanced lighting communication systems," *Cell Rep. Phys. Sci.*, vol. 1, no. 4, Apr. 2020, Art. no. 100041.

[33] F. Wang, F. Yang, C. Pan, J. Song, and Z. Han, "Joint illumination and communication optimization in indoor VLC for IoT applications," *IEEE Internet Things J.*, vol. 9, no. 21, pp. 20788–20800, Nov. 2022.

[34] K. Bera, G. Ma, and N. Karmakar, "Coverage improvement of visible light communications using an engineered diffuser," in *Proc. Asia Commun. Photon. Conf. (ACP)*, Nov. 2022, pp. 1056–1059.

[35] R. Mesleh, H. Elgala, and H. Haas, "On the performance of different OFDM based optical wireless communication systems," *J. Opt. Commun. Netw.*, vol. 3, no. 8, pp. 620–628, Aug. 2011.

[36] *Safety of Laser Products—Part 1: Equipment Classification and Requirements*, Standard IEC60825-1:2014, IEC, Geneva, Switzerland, 2014.

KRISHNENDU BERA received the Bachelor of Engineering degree in electronics and communication engineering from Bengal Engineering and Science University, Shibpur, India, in 2012, and the Master of Technology degree in microwave communication engineering from the Indian Institute of Engineering Science and Technology, Shibpur, in 2016. He is currently pursuing the Ph.D. degree with Monash University, Australia. He was a Software Developer with Ericsson, India, from 2012 to 2014. His research interests include optical wireless communication, visible light communication, visible light positioning, indoor positioning, and intelligent transport systems.

RAJENDRAN PARTHIBAN (Senior Member, IEEE) received the Bachelor of Engineering degree (Hons.) and the Ph.D. degree in optical networks from the University of Melbourne, Australia, in 1997 and 2004, respectively. He joined as a Lecturer with the School of Engineering, Monash University Malaysia, in 2006. In 2022, he was a Professor with the School of Engineering, where he has been the Deputy Head of School (Education), since August 2010. He moved to the Faculty of Engineering, Monash University, Australia, as the Associate Dean (Education) and has been a Professor, since August 2022. He is a Senior Member of Optica [formerly known as the Optical Society of America (OSA)]. His research interests include optical networks, visible light communications, vehicular communication, the Internet of Things, and engineering education.

NEMAI KARMAKAR (Senior Member, IEEE) received the master's degree in electrical engineering from the University of Saskatchewan, Canada, in 1991, and the Ph.D. degree from The University of Queensland, Australia, in 1999. He has over 20 years of teaching, design, development experience in antennas, microwave active and passive circuits, and RFIDs in Canada, Australia, and Singapore. He is currently an Associate Professor with the Department of Electrical and Computer Systems Engineering, Monash University, Australia. He has authored or coauthored over 400 refereed journals and conference papers, 24 book chapters, and eight books. His research interests include RFID, smart antennas for mobile and satellite communications, the Internet of Things (IoT), and visible light communication.