IRS-Enhanced LED Number Modulation with Adaptive LED Selection for MIMO-OWC

1st Lin Zeng
School of Microelectronics and Communication Engineering
Chongqing University
Chongqing, China
202012021008@cqu.edu.cn

2nd Chen Chen
School of Microelectronics and Communication Engineering
Chongqing University
Chongqing, China
c.chen@cqu.edu.cn

3rd Cuiwei He
School of Information Science
Japan Advanced Institute of Science and Technology
Ishikawa, Japan
cuiweihe@jaist.ac.jp

4th Min Liu
School of Microelectronics and Communication Engineering
Chongqing University
Chongqing, China
liumin@cqu.edu.cn

2023 Opto-Electronics and Communications Conference (OECC) | 978-1-6654-6213-6/23/$31.00 ©2023 IEEE | DOI: 10.1109/OECC56963.2023.10209948

***Abstract*—In this paper, we propose and investigate an intelligent reflecting surface (IRS)-enhanced LED number modulation (LNM) scheme with adaptive LED selection for multiple-input multiple-output optical wireless communication (MIMO-OWC) systems. By performing LNM with location-aware adaptive LED selection, additional information bits can be transmitted through varying the number of activated LEDs and improved diversity gain can also be harvested. Moreover, an IRS is further applied to substantially enhance the overall performance of the MIMO-OWC system using LNM with adaptive LED selection. Simulation results verify the feasibility and superiority of the proposed LNM scheme with adaptive LED selection and IRS enhancement for MIMO-OWC systems.**

***Index Terms*—Optical wireless communication, multiple-input multiple-output, LED number modulation.**

I. Introduction

We are witnessing an explosively increasing demand for high-speed and secure wireless data communication lately, while the existing radio frequency (RF) communication systems might struggle to meet this demand due to the nearly saturated RF spectrum and the security issues. However, this has motivated the growth of innovative technologies applying frequencies outside the RF band to relieve the overcrowded RF spectrum [1], [2]. As a promising complementary technology to RF communication, optical wireless communication (OWC) possesses many advantages such as abundant and license-free spectrum, inherent security and no electromagnetic interference radiation, which has been arousing great interest in both academia and industry [3]. In OWC systems, light-emitting diodes (LEDs) are generally utilized as transmitters, but the practically available modulation bandwidth of LEDs is relatively small, especially for commercial white LEDs [4].

To solve the bandwidth limitation issue of LEDs, various capacity-enhancing techniques have recently been reported for OWC systems. More specifically, multiple-input multiple-output (MIMO) transmission has been considered as a promising technique for bandlimited OWC systems [5]–[7]. As a digitized MIMO scheme, optical spatial modulation (OSM), which activates only one LED to transmit the constellation symbol at each time slot, has attracted growing attention in OWC systems [8]. However, the spectral efficiency of OSM systems increases logarithmically rather than linearly with the number of the LEDs. Therefore, it is extremely difficult for practical OSM systems to reach high spectral efficiencies. In [9]–[11], generalized OSM (GOSM) schemes have been proposed to transmit more spatial index bits and improve the diversity gain by activating more than one LED to transmit the same constellation symbol at each time slot. Nonetheless, both OSM and GOSM activate a fixed number of LEDs to transmit constellation symbols, which also neglect the impact of user's distinctive spatial locations.

Recently, intelligent reflecting surface (IRS) has been proposed to enable a smart and reconfigurable environment for wireless networks [12], which has also been introduced in OWC systems lately [13], [14]. In this paper, we for the first time propose a novel intelligent reflecting surface (IRS)-enhanced LED number modulation (LNM) scheme for MIMO-OWC systems. Differing from OSM and GOSM, the proposed LNM scheme transmits additional information bits by varying the number of activated LEDs. A location-aware adaptive LED selection strategy is further proposed to improve the diversity gain that can be harvested. Moreover, a low-complexity energy-based detection algorithm are also designed.

II. IRS-Enhanced MIMO-VLC System

Fig. 1 illustrates the model of a typical IRS-aided MIMO-OWC system, which consists of N pairs of LEDs and photodetectors (PDs) and an IRS with multiple specular reflectors. Assuming $\mathbf{s} = [s_1, s_2, \cdots, s_N]^T$ denote the transmitted signal

This work was supported in part by the National Natural Science Foundation of China under Grant 62271091 and 61901065, and in part by the Natural Science Foundation of Chongqing under Grant cstc2021jcyj-msxmX0480.

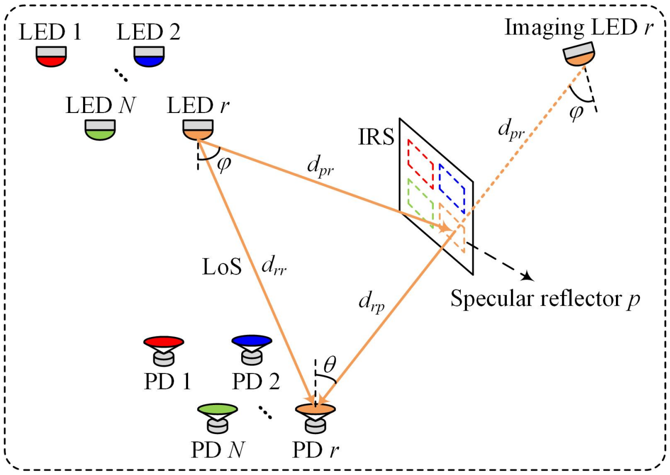

Fig. 1. Model of the IRS-enhanced MIMO-VLC system.

vector, the received signal vector $\mathbf{y} = [y_1, y_2, \cdots, y_N]^T$ can be given by

$$\mathbf{y} = \mathbf{H}\mathbf{s} + \mathbf{n}, \tag{1}$$

where $\mathbf{H}$ is the $N \times N$ MIMO channel matrix, which can be expressed as follows:

$$\mathbf{H} = \begin{bmatrix} h_{11} & \cdots & h_{1N} \\ \vdots & \ddots & \vdots \\ h_{N1} & \cdots & h_{NN} \end{bmatrix}, \tag{2}$$

where the element h_{rt} represents the channel gain between the t-th LED and the r-th PD. Considering only the line-of-sight (LOS) transmission, h_{rt} can be calculated by [15]

$$h_{rt}^{\text{LoS}} = \frac{(m+1)\rho A}{2\pi d_{rt}^2} \cos^m(\varphi) T_s(\theta) g(\theta) \cos(\theta), \tag{3}$$

where $m = -\ln 2/\ln(\cos(\Psi))$ is the order of Lambertian emission with Ψ being the semi-angle at half power of the LED; ρ and A represent the responsivity and the active area of the PD, respectively; the distance between the t-th LED and the r-th PD is denoted by d_{rt}. Furthermore, φ and θ represent the angles of emission and incidence, respectively. $T_s(\theta)$ denotes the gain of optical filter; the gain of optical lens is represented by $g(\theta) = \frac{n^2}{\sin^2 \Phi}$ with Φ and n being the refractive index and the half-angle field-of view (FOV) of the optical lens, respectively.

When the IRS is adopted, the channel gain between the t-th LED and the r-th PD reflected by the p-th specular reflector in the IRS can be approximated by [16]

$$h_{rt,p}^{\text{IRS}} = \frac{\delta(m+1)\rho A}{2\pi(d_{pr} + d_{rp})^2} \cos^m(\varphi) T_s(\theta) g(\theta) \cos(\theta), \tag{4}$$

where δ is the reflection coefficient of the specular reflector, d_{pt} represents the distance between the t-th LED and the p-th specular reflector and the distance between the p-th specular reflector and the r-th LED is denoted as d_{rp}.

Moreover, $\mathbf{n} = [n_1, n_2, \cdots, n_N]^T$ represents the additive noise vector. The additive noise usually includes the thermal noise, shot noise and possibly excess noise, which can be generally modeled as a real-valued additive white Gaussian noise (AWGN) with zero mean and a variance (i.e., power) σ_n^2. The noise power can be defined as $\sigma_n^2 = N_0 B$, where N_0 denotes the power spectral density (PSD) and B is the signal bandwidth.

TABLE I
NUMBER MAPPING TABLE FOR LNM WITH $N = 4$

Number bits	Number of activated LEDs
00	1
01	2
11	3
10	4

III. LNM FOR MIMO-VLC

In this section, we first describe the principle of LNM, and then two LED selection strategies are introduced.

A. Principle

Fig. 2 depicts the schematic diagram of the LNM-based MIMO-OWC system with a low-complexity energy detector. At the transmitter side, the incoming bits are first partitioned into two groups: one group is modulated into a constellation symbol, while the other group specifies a certain number of activated LEDs through spatial mapper. The number mapping table for LNM with $N = 4$ is given in Table I. As we can see, taking the information bits ”01” as an example, only two LEDs are selected for signal transmission. After performing LNM mapping, parallel OFDM modulation is further conducted. Generally, intensity modulation with direct detection (IM/DD) is applied in OWC systems and thus only real-valued and positive signals can be transmitted. Therefore, the Hermitian symmetry (HS) is imposed on the subcarriers before performing inverse fast Fourier transform (IFFT) [17].

At the receiver side, as shown in Fig. 2, the optical signal is first detected through N PDs and then the resultant analog signal is converted to the digital signal through analog-to-digital (A/D) conversion. In order to successfully de-multiplex the signals, zero-forcing (ZF) equalization is applied. Hereafter, parallel OFDM demodulation is executed, and a low-complexity energy-based detection algorithm is further designed for signal detection. More specifically, the minimum energy value of all the candidate constellation symbols is first calculated and then a threshold equal to half of the minimum energy value is obtained. Subsequently, for a received symbol on a subcarrier, it is considered to be a constellation symbol if its energy is larger or equal to the threshold, otherwise it is considered to be a noise symbol. After energy detection, the number bits can be directly obtained, and meanwhile the

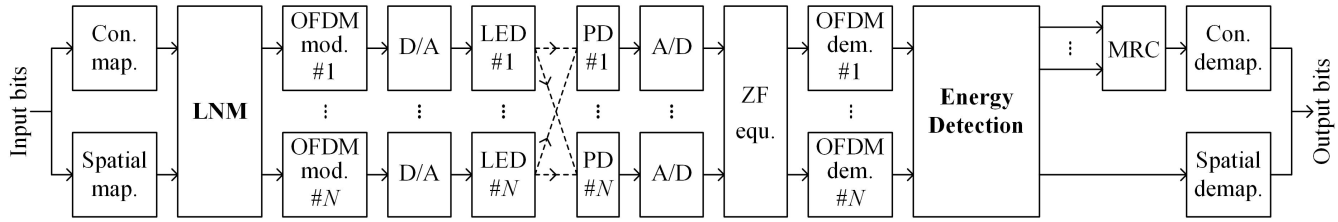

Fig. 2. Schematic diagram of LNM-based MIMO-OWC system with a low-complexity energy detector. Con.: constellation; map.: mapping; mod.: modulation; equ.: equalization; dem.: demodulation; demap.: demapping

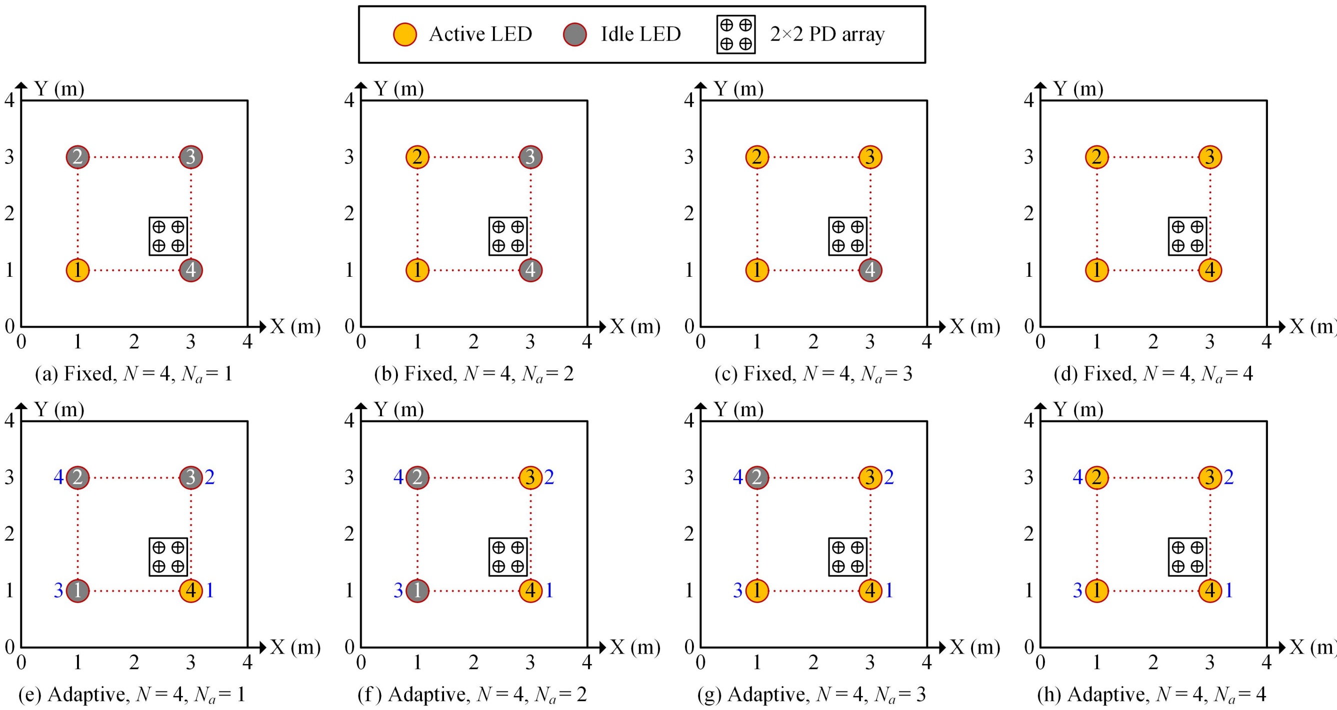

Fig. 3. Fixed LED selection with (a) $N_a = 1$, (b) $N_a = 2$, (c) $N_a = 3$ and (d) $N_a = 4$, and adaptive LED selection with (e) $N_a = 1$, (f) $N_a = 2$, (g) $N_a = 3$ and (h) $N_a = 4$, for $N = 4$.

estimated constellation symbols are combined via maximal-ratio combining (MRC) for further demapping. Finally, the output bits can be recovered by combining both number bits and constellation bits together.

B. LED Selection Strategies

Two LED selection strategies are introduced in the following, including fixed LED selection and adaptive LED selection.

1) Fixed LED selection: In the LNM-based MIMO-OWC system with $N = 4$, as shown in Figs. 3(a)-(d), the selection of activated LEDs is fixed with is not related to the location of the user. For example, as can see from Fig. 3(b), LED $\#1$ and LED $\#2$ are selected to transmit the same signal for $N_a = 2$, although the user is closer to LED $\#4$.

2) Adaptive LED selection: To improve the diversity gain that can be harvested, an adaptive LED selection strategy is designed by considering the user's specific spatial location. As illustrated in Figs. 3(e)-(h), the to-be-activated LEDs are selected according to the specific spatial location of the user, i.e., the N_a nearest LEDs among all the N from the user are selected. The LED selection is adaptively performed when the user is moving around the receiving plane in the MIMO-OWC system.

IV. Simulation Results

In this section, simulations are conducted to evaluate the performance of the IRS-enhanced LNM-based MIMO-OWC system. In our simulations, we setup a 4×4 IRS-aided MIMO-OWC system in a typical indoor 4 m × 4 m × 3 m room. Four LEDs are mounted on the ceiling and the user equipped with a 2 × 2 avalanche PD (APD) array is located over receiving plane, which is 1 m above the floor. Moreover, we consider an IRS with four specular reflectors which are evenly distributed around (4 m, 2 m, 1.5 m) and the area of each specular reflector is 1 × 1 cm^2. The reflection factor, i.e., δ, is 0.9. Particularly, a simpel IRS configuration is adopted here, i.e., the four specular reflectors in the IRS are respectively associated with four LED/PD pairs in the MIMO-

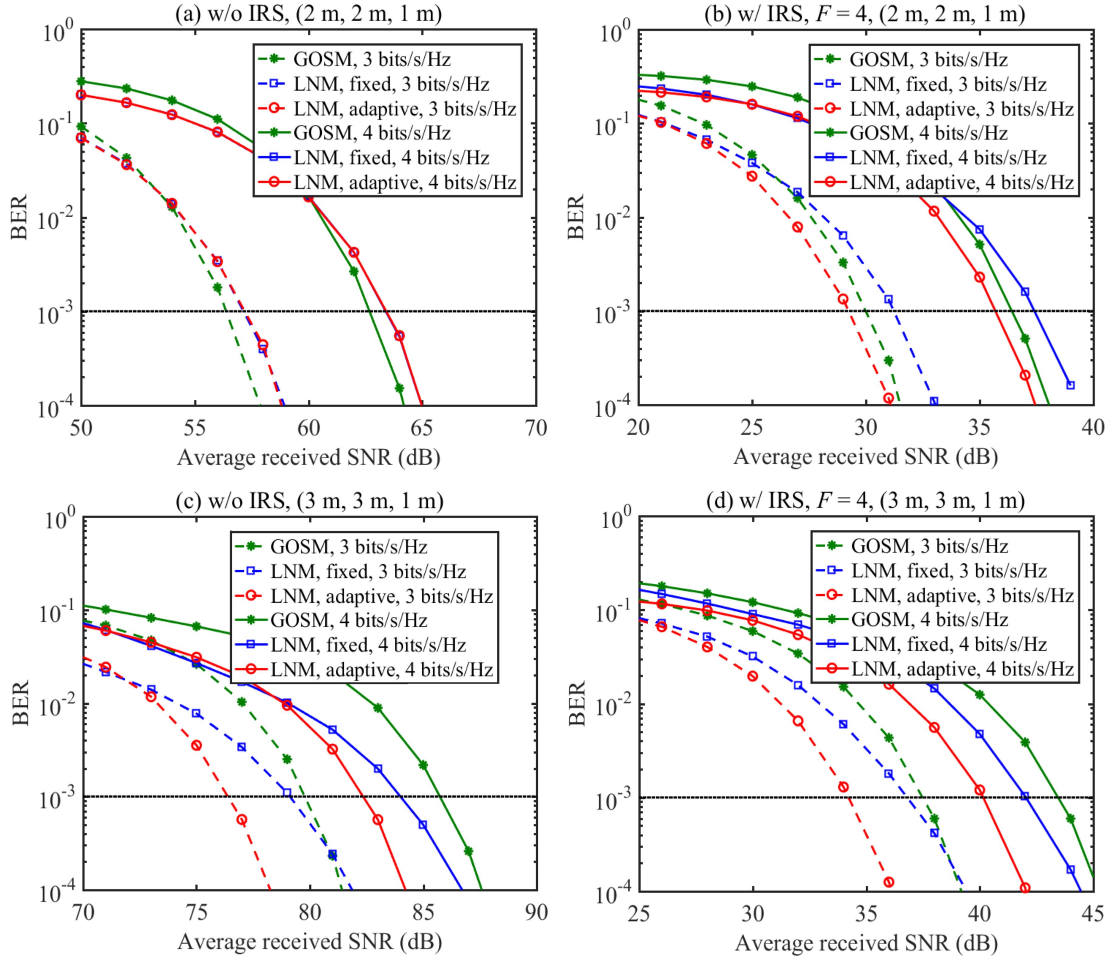

Fig. 4. BER vs. average received SNR for (a) without IRS, receiver location (2 m, 2 m, 1 m), (b) with IRS, F = 4, receiver location (2 m, 2 m, 1 m), (c) without IRS, receiver location (3 m, 3 m, 1 m), and (d) with IRS, F = 4, receiver location (3 m, 3 m, 1 m).

TABLE II
SIMULATION PARAMETERS

Parameter	Value
Room dimension	4 m $\times$ 4 m $\times$ 3 m
Height of receiving plane	1 m
LED spacing	2 m
APD spacing	10 cm
Semi-angle at half power of LED	65°
Gain of optical filter	0.9
The reflection factor	0.9
The area of each specular reflector	1 cm $\times$ 1 cm
Refractive index of optical lens	1.5
Half-angle FOV of optical lens	65°
Responsivity of APD	15 A/W
Active area of APD	19.6 mm^2
Noise PSD	10^{-22}A^2/Hz
Modulation bandwidth	20 MHz

OWC system. In addition, two different spatial locations, i.e., (2 m, 2 m, 1m) and (3 m, 3 m, 1m), are taken into consideration for performance evaluation. For performance comparison, the OFDM-based GOSM scheme with two active LEDs selected out of four LEDs is used as the benchmark. The key simulation parameters can be found in Table II.

Fig. 4 depicts the BER versus averaged received SNR for two MIMO schemes, i.e., LNM and GOSM, under different conditions. When the user is located at (2 m, 2 m, 1m) and the IRS is not applied, as shown in Fig. 4(a), the same BER performance is achieved for both fixed and adaptive LED selection strategies, which is because the user is located at the center of the room. Moreover, GOSM slightly performs better than LNM for both two spectral efficiencies of 3 and 4 bits/s/Hz. However, when the IRS is utilized, as can be seen in Fig. 4(b), GOSM performs the worst, while LNM with adaptive LED selection obtains the better BER performance than that with fixed LED selection for both spectral efficiencies. By comparing Figs. 4(a) and (b), we can see that the use of IRS can substantially enhance the overall performance of the MIMO-OWC system using either LNM or GOSM, due to its ability to provide relatively large additional channel gain. Moreover, the IRS-enhanced LNM scheme can outperform

GOSM and the adaptive LED selection strategy also performs better than the fixed LED selection strategy. When the user is moving to the location (3 m, 3 m, 1m) and the IRS is not applied, as shown in Fig. 4(c), LNM with fixed LED selection outperforms better than GOSM, while the best BER performance is obtained by LNM with adaptive LED selection for both spectral efficiencies. More specifically, SNR gain of 3.4 and 3.2 dB are achieved by LNM with adaptive LED selection in comparison to GOSM for spectral efficiencies of 3 and 4 bits/s/Hz, respectively. Similarly, as shown in Fig. 4(d), more than a 40-d B overall SNR reduction can be obtained by employing a simple IRS with four specular reflectors.

V. Conclusion

In this paper, we have proposed and investigated an IRS-enhanced LNM scheme with location-aware adaptive LED selection for MIMO-OWC systems. By transmitting additional information bits via changing the number of activated LEDs and adaptively select the activated LEDs according to the user's specific location, more diversity gain can be harvested to improve the BER performance. Moreover, the overall BER performance of the MIMO-OWC system can be significantly enhanced by the use of a simple IRS consisting of four specular reflectors. Our simulation results show that, for a spectral efficiency of 3 bits/s/Hz, a remarkable 3.4-dB SNR gain can be achieved by LNM with adaptive LED selection when compared with the conventional GOSM scheme. Therefore, the proposed IRS-enhanced LNM scheme with location-aware adaptive LED selection can be a promising candidate for practical MIMO-OWC systems.

References

[1] T. Cogalan and H. Haas, "Why would 5G need optical wireless communications?" in *Proc. IEEE Ann. Int. Symp. Pers., Indoor Mobile Radio Commun. (PIMRC)*, 2017, pp. 1–6.

[2] H. Elgala, R. Mesleh, and H. Haas, "Indoor optical wireless communication: potential and state-of-the-art," *IEEE Commun. Mag.*, vol. 49, no. 9, pp. 56–62, 2011.

[3] Z. Ghassemlooy, S. Arnon, M. Uysal, Z. Xu, and J. Cheng, "Emerging optical wireless communications-advances and challenges," *IEEE J. Sel. Areas Commun.*, vol. 33, no. 9, pp. 1738–1749, 2015.

[4] S. Rajagopal, R. D. Roberts, and S.-K. Lim, "IEEE 802.15. 7 visible light communication: modulation schemes and dimming support," *IEEE Commun. Mag.*, vol. 50, no. 3, pp. 72–82, 2012.

[5] T. Fath and H. Haas, "Performance comparison of MIMO techniques for optical wireless communications in indoor environments," *IEEE Trans. Commun.*, vol. 61, no. 2, pp. 733–742, 2012.

[6] C. He, T. Q. Wang, and J. Armstrong, "Performance of optical receivers using photodetectors with different fields of view in a MIMO ACO-OFDM system," *J. Lightw. Technol.*, vol. 33, no. 23, pp. 4957–4967, 2015.

[7] C. Chen, H. Yang, P. Du, W.-D. Zhong, A. Alphones, Y. Yang, and X. Deng, "User-centric MIMO techniques for indoor visible light communication systems," *IEEE Syst. J.*, vol. 14, no. 3, pp. 3202–3213, 2020.

[8] R. Mesleh, H. Elgala, and H. Haas, "Optical spatial modulation," *J. Opt. Commun. Netw.*, vol. 3, no. 3, pp. 234–244, 2011.

[9] S. Alaka, T. L. Narasimhan, and A. Chockalingam, "Generalized spatial modulation in indoor wireless visible light communication," in *Proc. IEEE Global Commun. Conf. (GLOBECOM)*, 2015, pp. 1–7.

[10] C. Chen, L. Zeng, X. Zhong, S. Fu, M. Liu, and P. Du, "Deep Learning-Aided OFDM-Based Generalized Optical Quadrature Spatial Modulation," *IEEE Photon. J.*, vol. 14, no. 1, pp. 1–6, 2021.

[11] C. Chen, X. Zhong, S. Fu, X. Jian, M. Liu, H. Yang, A. Alphones, and H. Fu, "OFDM-based generalized optical MIMO," *J. Lightw. Technol.*, vol. 39, no. 19, pp. 6063–6075, 2021.

[12] Q. Wu and R. Zhang, "Towards smart and reconfigurable environment: Intelligent reflecting surface aided wireless network," *IEEE Commun. Mag.*, vol. 58, no. 1, pp. 106–112, 2019.

[13] S. Aboagye, T. M. Ngatched, O. A. Dobre, and A. R. Ndjiongue, "Intelligent reflecting surface-aided indoor visible light communication systems," *IEEE Commun. Lett.*, 2021.

[14] S. Sun, F. Yang, and J. Song, "Sum rate maximization for intelligent reflecting surface-aided visible light communications," *IEEE Commun. Lett.*, vol. 25, no. 11, pp. 3619–3623, 2021.

[15] T. Komine and M. Nakagawa, "Fundamental analysis for visible-light communication system using LED lights," *IEEE Trans. Consum. Electron.*, vol. 50, no. 1, pp. 100–107, 2004.

[16] A. M. Abdelhady, A. K. S. Salem, O. Amin, B. Shihada, and M.-S. Alouini, "Visible light communications via intelligent reflecting surfaces: Metasurfaces vs mirror arrays," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 1–20, 2020.

[17] M. Z. Afgani, H. Haas, H. Elgala, and D. Knipp, "Visible light communication using OFDM," in *Proc. Int. Conf. Testbeds Research Infrastructures Development Networks Communities (TRIDENTCOM)*, 2006, pp. 6–pp.