Performance analysis of ACO-OFDM NOMA for VLC communication

Jayashree Pradhan · Pratiksha Holey · Vinod Kiran Kappala · Santos Kumar Das

Received: 22 October 2021 / Accepted: 7 June 2022 / Published online: 18 July 2022
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2022

Abstract
Visible light communication (VLC) has been seeking much attention in recent years due to its high bandwidth, low cost, and ease of implementation. VLC can be used for illumination as well as communication at the same time. Light emitting diode (LED) acts as a transmitter for data transmission, and photo detector is used on the receiver side. Intensity Modulation (IM) converts an electrical signal into an optical signal, where only real and positive signals need to be transmitted. Optical orthogonal frequency division multiplexing (O-OFDM) is used in the VLC to enhance the bandwidth limitation due to LED. Using O-OFDM for VLC does not provide massive connectivity in a multi-user environment. Nonorthogonal multiple access (NOMA) is the further expansion where the user can use both the time and frequency resources but distinguished in the power domain with successive interference cancellation (SIC) at the receiver to decode the signal of each user. Also, Asymmetrically clipped optical orthogonal frequency division multiplexing (ACO-OFDM) for NOMA is used to get the positive signal with enhanced spectral efficiency. The proposed method was analyzed by considering simulations and analytical results for LOS and NLOS communication.

Keywords Visible light communication · NOMA · Power allocation · SIC · ACO-OFDM
1 Introduction

Visible light communication (VLC) is a promising technology for next generation high-speed wireless communication in an indoor scenario. VLC operates in the unlicensed spectrum with high security, large bandwidth and provides strong immune to electromagnetic interference. These advantages drive VLC for broad area of application such as military application, hospital area, flight during travel and underwater communication (Chen et al. 2017). VLC has been developed to support the needs of fifth generation (5G) wireless communication and Internet-of-Things (IoT) terminals for indoor communication with higher data rate (Mohsan and Amjad 2021). Most of the research in VLC communication is devoted to establish communication under line of sight (LOS) gain of the channel (Rodoplu et al. 2020).

Apart from the advantages, VLC is limited in operation due to the bandwidth constraint of LED (i.e operates in MHz), due to the internal RC circuit (Yeh et al. 2015). There are different approaches proposed in the literature to enhance the bandwidth, one such technique is O-OFDM (Lee et al. 2012). Further, O-OFDM is categorized into three types, i.e. Asymmetrically clipped optical orthogonal frequency division multiplexing (ACO-OFDM), DC-biased optical orthogonal frequency division multiplexing (DCO-OFDM) and Asymmetrically clipped DC-biased optical orthogonal frequency division multiplexing (ADO-OFDM). Out of them ACO-OFDM is power efficient at lower SNR (Saju et al. 2015). DCO-OFDM has extra bias circuit though it has high spectral efficiency at higher SNR. Asymmetrically clipped DC-biased optical (ADO-OFDM) is proposed for higher spectral efficiency, which increases the receiver design complexity and also effect of clipping noise (Hameed et al. 2021; Dissanayake and Armstrong 2013).

The further improvement can be obtained using different modulation technique of higher order quadrature amplitude modulation (16-QAM). Different multiple access (MA) techniques are proposed for multiuser environment operating at different frequency (Orthogonal frequency division multiple access), time (Time division multiple access), and space (space division multiple access) (Lian and Brandt-Pearce 2019). OFDMA is one such MA technique that operates in different frequencies for each user, such that each frequency is orthogonal in nature and using OFDMA degrades the spectral efficiency (Al-Ahmadi et al. 2018). To overcome the above constraint Non-orthogonal multiple access (NOMA) is used to operate in the same frequency band and time block with different power allocation among the users. NOMA can be implemented efficiently for the VLC communication due to high spectral efficiency and multi-user communication (Benjebbour et al. 2013). OFDM is limited in operation due to peak to average power ratio (PAPR) problem that can be reduced by using NOMA. Single carrier frequency division multiplexing (SCFDM) is performed on NOMA to reduce the PAPR but the method achieved low data rate (Ye et al. 2017).

Few of the research work using OFDMA-NOMA with optimum power allocation ratios (PAR) for uplink and downlink is analyzed for multiuser with specific frequency (Lin et al. 2017; Lian and Brandt-Pearce 2020). 4-QAM OFDM is used in the VLC to improve the bandwidth of LED and is suitable for NOMA application (Komine and Nakagawa 2004). In Verma and Selwal (2018), Selvendran et al. (2019), a 4-QAM OFDM VLC is studied in optisystem using laser and white LED as transmitter source respectively. In Wang et al. (2017), Marshoud et al. (2017) the authors approximated the closed-form expression under noisy channel state information (CSI) is obtained for different dimming control techniques of NOMA-VLC model which results in lower data rate.
In Marshoud et al. (2015), the transmitter side with superposition coding (SC) is used and SIC is used at the receiver side. A gain ratio power allocation (GRPA) technique to maximize the sum rate for users is introduced for the higher order of modulation. In Fu et al. (2018), the authors explain the enhanced power allocation algorithm (EPA) for multi-carrier, which allocates power at both user level and subcarrier level. An OFDM NOMA VLC, is designed for LOS but the constraint on type of optical OFDM is not explained (Ren et al. 2018).

DCO-OFDM NOMA is further studied in Shi et al. (2019) where DCO-OFDM based on Zero-tailed approach is proposed with subcarrier power allocation and dynamic power allocation for OFDM NOMA based VLC systems. For low SNR the average optical power of ACO-OFDM is better than DCO-OFDM and also extra bias circuit is not needed in case of ACO-OFDM. In Liu et al. (2019), Barrami et al. (2014) a co-operative NOMA-based DCO-OFDM VLC system is analysed with DCO OFDM. In Deepthi and Visalakshi (2021) proposed optical OFDM method for high data rate including MIMO OFDM, but this method is limited for NLOS VLC. Based on the above limitations, this work proposes an ACO-OFDM NOMA for LOS and Non-LOS channel condition in a multi-user environment.

The main contributions of papers are as follows:

- An ACO-OFDM NOMA VLC communication system is designed for both LOS and NLOS environment.
- ACO-OFDM-NOMA VLC is implemented for a 2-user indoor scenario with optimum power allocation.
- A closed form expression of the proposed system is derived and performance is evaluated in terms of BER.

The remaining part of the paper is organized as follows. Section 2 describes the system model of VLC communication. Section 3 presents the proposed ACO-OFDM for NOMA VLC. Section 4 presents the simulations and results of the proposed method. Section 5, finally provides the concluding remarks.

2 Channel and system model

VLC uses LEDs to transmit the data in an indoor environment, where it supports for multi-user by modulation the intensity of the light in both LOS and NLOS scenario. The power is divided for two user, where the user are located at different distance. To calculate the optimal response of power for both LOS and NLOS using bit error rate among the users is the backbone of system.

2.1 The VLC channel

VLC channel gain for LOS scenario where optical signals received directly in an indoor communication, can be represented as Jiang et al. (2020)

\[
H_{LOS} = \frac{(m_l + 1)A_z}{2\pi d^2} \cos^m(\phi)g(\psi)T_s(\psi)\cos(\psi),
\]

where \(\phi\) is the angle of irradiance with the axis normal to the surface of transmitter, \(\psi\) is an incidence angle with the axis normal to the receiver surface, \(T_s(\psi)\) is the transmission...
coefficient for optical filter, \(g(\psi)\) is the concentrator gain and \(d\) is the distance between the transmitter and the receiver. \(A_z\) is the area of photo detector. The order of Lambertian emission denoted as \(m_l\), which is expressed as

\[
m_l = \frac{\ln(2)}{\ln \cos(\phi_{1/2})},
\]

(2)

where \(\phi_{1/2}\) is the semi-angle at half illuminance of an LED. To reduce optical noise due to ambient light, an optical filter is integrated such that the signal-to-noise ratio (SNR) is improved. Optical concentrator at a receiver whose gain can be derived as,

\[
g(\psi) = \frac{n^2}{\sin^2(\psi_c)} \text{ for } 0 \leq \psi \leq \psi_c,
\]

(3)

where \(\psi_c\) denotes the field of view (FOV) at the receiver and refractive index \(n\). In NLOS environment the reflections from wall are taken into account and hence the corresponding VLC channel for NLOS indoor can be expressed as Komine and Nakagawa (2004),

\[
H_{\text{Non-LOS}} = \frac{(m_l + 1)A_z}{2(\pi d_1 d_2)^2} dA_{\text{wall}} \cos^{m_l}(\phi_{r_1}) \cos(\psi_{r_1}) \\
\times \cos(\phi_{r_2}) \cos(\psi_{r_2}) T_s(\psi_{r_2}) g(\psi_{r_2}),
\]

(4)

where \(dA_{\text{wall}}\) is the effective area of the wall, \(d_1\) and \(d_2\) denotes the distances from LED transmitter to wall and from wall to photo detector respectively. \(\phi_{r_1}\) and \(\phi_{r_2}\) are the corresponding angle of irradiance from LED and wall respectively. \(\psi_{r_1}\) and \(\psi_{r_2}\) are the angle of incidence to wall and photo detector respectively as shown in Fig. 1 Ghassemlooy et al. (2019). The overall channel gain is the addition of both LOS and NLOS gain components derived as,

\[
H = H_{\text{LOS}} + H_{\text{NLOS}},
\]

(5)

Fig. 1 VLC channel model
2.2 NOMA VLC transmission

In NOMA, the LED transmits real and positive signal to the users placed at variable distances, which associates with different power accordingly. Consider a signal is transmitted with power $P_i$ for $i^{th}$ user out of total $N$ users. Hence the total transmitted signal is derived as,

$$x = \sum_{i=1}^{N} \sqrt{P_i} x_i,$$

where $x_i$ is superimposed signal of the $i^{th}$ user and $i = 1, \cdots, N$. For simplicity, assume that $N = 2$ i.e. 2 users, $i = 1$ denotes the far user hence allocated with high power whereas $i = 2$ is the near user from receiver and allocated with less power i.e. $P_2 = (1 - P_1)$. The received signal in time domain written in Marshoud et al. (2017).

$$y = h \otimes \sum_{i=1}^{N} \sqrt{P_i} x_i + w,$$

where $h$ is the channel coefficient from transmitter to the $i^{th}$ user in time domain, $w$ is used to denote the additive white Gaussian noise (AWGN) with zero mean and $\sigma_n^2$ variance.

3 Proposed ACO-OFDM NOMA for VLC communication

Figure 2 represents the block diagram representation of ACO-OFDM NOMA system. Consider a two user scenario, where data from each user is 4-QAM modulated and correspondingly allocated with power $P_1$ and $P_2$. In ACO-OFDM only odd subcarrier are used for data and the pilots, modulated data are fed to Hermitian symmetry block, which produces the real data. Inverse fast Fourier transform (IFFT) converts data from frequency domain to time domain signal. A cyclic prefix is added to eradicate the effect of inter symbol interference (ISI) and zero clipping are performed to get the real and positive signal which are

![Fig. 2 Block diagram representation of ACO-OFDM for NOMA system](image)
directly fed to transmitter. As intensity modulation (IM) as well as direct detection (DD) techniques are used in VLC to send the information for which phased components cannot be used to convey the message. Light intensity of the LED is modulated with the help of transmitted electrical signal which must be real and positive in nature. In DCO and ACO-OFDM techniques the Hermitian symmetry is applied to get the real data and then negative signal are clipped to zero to get positive signal. In proposed work basic model for ACO-OFDM is used for NOMA VLC system. At the receiver pilots are removed to get original signal after removing cyclic prefix and performing fast Fourier transform (FFT).

Since VLC is an intensity modulation and direct detection (IM/DD) where conventional complex symbols cannot be transmitted directly. A real signal is suitable for transmission and is achieved using Hermitian symmetry. A Hermitian symmetry is applied to the complex symbols of 4-QAM, to produce real signal. In ACO-OFDM only odd subcarriers are used for data and even subcarriers are zero and is expressed as Hao et al. (2019),

$$X_i = [0, X_1, 0, X_3, ..., X[N - 1]]$$

where \( N \) is the total number of subcarriers. The \( N \) subcarriers at the transmitter is converted to complex symbols by 4-QAM. In the Hermitian symmetry \( N/2 \) number of subcarriers carries the information data and rest subcarriers consists of complex conjugate of the same data presented in reverse order. It exhibits an anti-symmetric properties on frequency domain signal and can be expressed as Marshoud et al. (2017),

$$X_k = -X^*_N-k \text{ for } 0 < k < \frac{N}{2}$$

The output of Hermitian symmetry is given as input to IFFT which convert a frequency domain data to time domain data and that can be derived as,

$$x_k = \frac{1}{N} \sum_{k=0}^{N-1} X_k e^{j\pi nk/N}$$

where \( x_k \) is the input data. The parallel \( N \) time domain data is added with a cyclic prefix (CP) and corresponding negative signal is clipped serially. Although, the data is real but not necessarily positive. In ACO OFDM all even subcarriers are assigned to zero so that the negative time domain samples are clipped to zero. The odd subcarrier carries the useful information are free from distortion (Zhang et al. 2017; Armstrong and Lowery 2006). Anti symmetric does not lead to any loss of information. The received optical signal from the photodiode is given as input to FFT through serial-to-parallel converter. ACO-OFDM is a power efficient system carries half of the subcarriers for data transmission. Average optical power is low due to less number of subcarriers involved and does not require any DC bias for communication. Due to less number of subcarrier it is having higher energy efficiency but with limited spectral efficiency. (Armstrong and Schmidt 2008; Ma et al. 2021).

The SIC scheme is applied after equalization to get modulated decoded data for the another user. Demodulation is performed to retrieve the actual data. At the receiver the power domain NOMA, successive interference cancellation (SIC) is implemented to retrieve the desired signal from the superposed signal. The basic operation involves the decoding the desired user signal by considering the adjacent signal as an interference and is subtracted from the superposed signal. Consider a two user scenario for 4-QAM ACO-OFDM NOMA transmitted over same time with power \( P_1 \) and \( P_2 \) respectively. The distance
from the two users to the VLC transmitter is different with separate power allocation factor. Here SIC is initially performed on the user 1 to remove the interference associated with user 2 and decode the signal with the following data rates

\[ R_2 < \log_2 \left( 1 + \frac{P_2 |H|^2}{P_1 |H|^2 + W} \right), \]  

(11)

where \( P_2 \) is the power carried by user 2; \( P_1 \) is the power of user 1 acts as interference to user 2; \( R_1 \) is the rate of user 1; \( W \) is the overall noise. User 1 signal is directly decoded without SIC process with achievable data rate given by

\[ R_1 < \log_2 \left( 1 + \frac{P_1 |H|^2}{W} \right) \]  

(12)

It is evident that the rate can be controlled by varying the ratio of power allocation and attains higher multiuser capacity.

The corresponding received signal in frequency domain can be derived from equation (7) as,

\[ Y = H \times \sum_{i=1}^{N} \sqrt{P_i}X_i + W, \]

(13)

where \( H \) is the channel impulse response and \( W \) is the overall AWGN noise of the system in frequency domain. The received signal divided by a factor of \( H \sqrt{P_1} \) to user 1 is expressed as,

\[ Y_1 = X_1 + \sum_{i=2}^{N} \sqrt{\frac{P_i}{P_1}}X_i + \frac{W}{H \sqrt{P_1}}. \]

(14)

After removing the term of \( X_1 \) from above equation and dividing the received signal by \( H \sqrt{P_2} \), the decoded signal for user 2 as follows,

\[ Y_2 = X_2 + \sum_{i=3}^{N} \sqrt{\frac{P_i}{P_2}}X_i + \frac{W}{H \sqrt{P_2}}. \]

(15)

Similarly, all the \( N \) signals by SIC can be decoded. From the received signal, the SNR is calculated to analyze the bit error rate (BER) of the signal at receiver. Consider a 4-QAM constellation diagram where points on constellation are represented with \((\pm \beta_1 \pm \beta_2)\) and \(j(\pm \beta_1 \pm \beta_2)\). The transmitted signal in terms of constellation points is represented as,

\[ x = \sqrt{P_1}P_t(A_{I1} + jA_{Q1}) + \sqrt{P_2}P_t(A_{I2} + jA_{Q2}), \]

(16)

where \( P_t \) is the total transmitted power, \( A_{Ii} \) and \( A_{Qi} \) represents real and imaginary part for \( i^{th} \) user. Probability of error is calculated by calculating probability of error for each bit as

\[ Pe_{bj} = \sum_{j,k=0}^{3} (P_{s_1 = j, s_2 = k}) \]

(17)

where \( s_1 \) and \( s_2 \) are the signal for user 1 and 2. Considering the case, now using Eq. (17) the probability of error for this point on constellation is given as,
Similarly, calculating probability of error for each point and adding to get the final expression for probability of error for user 1 and for user 2 considering the interference of user 1 which are given as follows, Eqs. (19) and (20) for user 1 and 2 respectively.

\[
Pe_{b11} = \frac{\left(\sqrt{P_1} - \sqrt{P_2}\right)H}{\sigma},
\]  

(18)

\[
BER_1 = \frac{1}{2} Q\left(\frac{H}{2\sigma}\left(\sqrt{P_1} + \sqrt{P_2}\right)\right) + \frac{1}{2} Q\left(\frac{H}{2\sigma}\left(\sqrt{P_1} - \sqrt{P_2}\right)\right).
\]

(19)

\[
BER_2 = Q\left(0.54 \times \sqrt{\frac{P_2H}{P_12\sigma}}\right) - 2Q\left(4 \times \left(\frac{H}{2\sigma} + \sqrt{\frac{P_2H}{P_12\sigma}}\right)\right) + Q\left(\frac{H}{2\sigma} + \sqrt{\frac{P_2H}{P_12\sigma}}\right).
\]

(20)

\(Q(x)\) is the \(Q\) function of \(x\) and \(\sigma^2\) is the noise variance.

4 Simulation results

An indoor environment for ACO-OFDM-NOMA in VLC is designed, which has a dimension of \(5m \times 5m \times 3m\). The parameters for simulation of above VLC model is mentioned in Table 1. Here a single LED is used to transmit the data for two user placed at distance of 0.5\(m\) and 3\(m\). For LOS communication the field of view (FOV) of photo detector is 85° where as for Non-LOS the FOV is 70°. The NLOS communication of VLC is having more sensitive towards distance and FOV of receiver. All the reflection from walls and floor are considered for channel designing of NLOS VLC.

| SR.NO. | PARAMETERS                        | VALUES  |
|--------|-----------------------------------|---------|
| 1      | Power of LED                      | 3 watt  |
| 2      | Field of view (FOV)               | 85 degrees |
| 3      | Semi angle at half power          | 70 degrees |
| 4      | Refractive index                  | 1.5     |
| 5      | Photo detector area               | 1e-4 (sq. m) |
| 6      | Room dimensions                   | 5 \(\times\) 5 \(\times\) 3 (m) |
| 7      | Room Transceiver distance         | 3(m)    |
In NLOS case reflections from walls are considered hence the channel gain for each reflection is considered separately and then overall channel gain is used by adding the individual gains.

Figure 3 shows the performance of ACO-OFDM NOMA for VLC in terms of BER. It can be observed a higher performance at lower SNR (i.e., 20 dB) that the BER has improved significantly. Fig. 4 shows the performance of ACO-OFDM NOMA for NLOS. The NLOS performance is evaluated which consists of all the reflections of the room.

The BER performance asymptotic with the simulation and BER is high of user 2 with the user 1 as shown in Fig. 4. A higher order constellation increases the receiver complexity and degrades the BER performance. Superposition of multiple higher order QAM signals requires a complex receiver using SIC technique. Also, the superposed signal due to more users increases the constellation size. Figure 5 represents the comparison of the proposed ACO-OFDM NOMA with conventional ACO-OFDM (Hao et al. 2019) and OOK NOMA (Marshoud et al. 2017). It can be observed that the BER performance of the proposed ACO-OFDM NOMA method is nearly 9 dB less BER than OOK NOMA. Also, ACO-OFDM NOMA performs better than conventional ACO-OFDM in an multiuser environment.

ACO-OFDM NOMA VLC model is verified experimentally using OptiSystem. Mathematical channel model for LOS and Non-LOS that consists of all the parameter and reflections and the model is designed in MATLAB and co-simulated with Optisystem. An Optisystem simulation of OFDM NOMA LOS propagation model is as shown in Fig. 6. In this model the pseudo random bit sequence generator is used to generate the continuous no of bits and then NRZ pulse generator is used to supply the data signal for the white LED. The transmitter power of LED is distributed among two users as 0.2 and 0.8, i.e., the near user is allocated with 20 percent and the far user with 80 percent of the total power respectively. The power can be allocated to the two users but total power must be same as input power. The sum of divided power is equal to the total transmitted power, that can be

![Fig. 3 BER of ACO-OFDM NOMA VLC for LOS](image-url)
visualized in Fig. 6 of optical power meter reading. The transmitted power is 255.5 mw and that power is divided for two user according to their distance from the source. User 1 is achieved 204.5 mw power and user 2 is achieved 51.1 mw power for the distance 3m and 0.5m respectively. LED encodes the optical information, which is passed through a MATLAB. At the receiving end, use a PIN photodiode as a receiver, where the optical signal is converted to electrical signal. Different parameters and their values can be visualized from the layout picture. The BER analyzer output is shows in the Fig. 7, which explains
the values of min BER, max Q factor and eye height, are as shown. The output of BER analyzer explains the error rate of each received samples (Selvendran et al. 2019). Oscilloscope visualizer is used for viewing data at input and output. The Figs. 8 and 9 represents the oscilloscope output at transmitter and receiver respectively. The oscilloscope visualizer
Fig. 8 OFDM-NOMA input data stream visualizer

Fig. 9 OFDM-NOMA output data stream visualizer
transmitter helps to visualize the input sampled signal, where oscilloscope visualizer receiver helps to know the output sampled signal after the photodetector. The input sampled signals are bipolar in nature but the received sampled signals are uni-polar in nature can be easily observed from both the oscilloscope visualizer respectively. The optical signal noise ratio (OSNR) component is used to add a defined noise floor level to an optical signal, which is defines as the ratio of total signal power within the signal bandwidth and noise power measured within the window. Figure 10 represents the result of BER vrs OSNR from the simulation output, which express as the OSNR increases BER reduces, which validates the accuracy of output. The BER rate is high as compared to wireless communication but it is considerable in VLC for high data rate communication (Barrami et al. 2014). VLC communication is more sensitive towards the distance of transceiver and that can be explained in the Fig. 11. As the distance increases the rate of BER increases is observed. Figures 10 and 11 are the output plot from the optisystem, shows the BER response for OSNR and distance respectively.

5 Conclusions

The work is mainly devoted to the performance analysis of VLC in an indoor multiuser LOS and NLOS scenarios. A multi-carrier modulation and multiple access are proposed using ACO-OFDM NOMA to achieve higher data rate and spectral efficient for multiuser

Fig. 10 BER of OFDM-NOMA VLC from optisystem
scenario. Analytical results are compared with simulation results to validate the proposed system. A 4-QAM ACO-OFDM NOMA VLC system performs better in a multiuser scenario at lowest SNR (20 dB) than the conventional techniques. The performance of the proposed method exhibits a lower BER (9 dB) than the OOK NOMA. Also, the proposed system is validated using a hardware simulation of VLC system for two user scenario in Optisystem with a data rate of 10 Gbps. The proposed method gives a flexible platform for multi-user VLC system with higher data rate and spectral efficiency.

**Code Availability** Not applicable

**Declaration**

**Conflict of interest** All the authors declare that none of us have no conflict of interests.

**References**

Al-Ahmadi, S., Maraqa, O., Uysal, M., et al.: Multi-user visible light communications: State-of-the-art and future directions. IEEE Access 6, 70555–70571 (2018)

Armstrong, J., Lowery, A.J.: Power efficient optical ofdm. Electron. Lett. 42(6), 370–372 (2006)

Armstrong, J., Schmidt, B.J.: Comparison of asymmetrically clipped optical ofdm and dc-biased optical ofdm in awgn. IEEE Commun. Lett. 12(5), 343–345 (2008)

Barrani, F., Le Guennec, Y., Novakov, E., et al.: An optical power efficient asymmetrically companded dco-
ofdm for im/dd systems. In: 2014 23rd Wireless and Optical Communication Conference (WOCC), IEEE, pp 1–6 (2014)
Performance analysis of ACO-OFDM NOMA for VLC communication

Benjebbour, A., Saito, Y., Kishiyama, Y., et al.: Concept and practical considerations of non-orthogonal multiple access (noma) for future radio access. In: 2013 International Symposium on Intelligent Signal Processing and Communication Systems, IEEE, pp 770–774 (2013)

Chen, C., Zhong, W.D., Yang, H., et al.: On the performance of MIMO-NOMA-based visible light communication systems. IEEE Photonics. Technol. Lett. 30(4), 307–310 (2017)

Deepthi, S., Visalakshi, P.: Enhanced optical ofdm: a novel approach for SISO and MIMO visible light communication system in indoor environment. Opt. Quantum Electron. 53(9), 1–24 (2021)

Dissanayake, S.D., Armstrong, J.: Comparison of ACO-OFDM, DCO-OFDM and ADO-OFDM in IM/DD systems. J. Lightwave Technol. 31(7), 1063–1072 (2013)

Fu, Y., Hong, Y., Chen, L.K., et al.: Enhanced power allocation for sum rate maximization in OFDM-NOMA VLC systems. IEEE Photonics Technol. Lett. 30(13), 1218–1221 (2018)

Ghassemlooy, Z., Popoola, W., Rajbandari, S.: Optical wireless communications: system and channel modelling with Matlab®. CRC Press (2019)

Hameed, S.M., Abdulsatar, S.M., Sabri, A.A. Performance enhancement for visible light communication based ADO-OFDM. (2021)

Hao, L., Wang, D., Cheng, W., et al.: Performance enhancement of aco-ofdm-basedvlc systems using a hybrid autoencoder scheme. Opt. Commun. 442, 110–116 (2019)

Jiang, R., Sun, C., Tang, X., et al.: Joint user-subcarrier pairing and power allocation for uplink ACO-OFDM-NOMA underwater visible light communication systems. J. Lightwave Technol. 39(7), 1997–2007 (2020)

Komine, T., Nakagawa, M.: Fundamental analysis for visible-light communication system using LED lights. IEEE Trans. Consum. Electron. 50(1), 100–107 (2004)

Lee, D., Choi, K., Kim, K.D., et al.: Visible light wireless communications based on predistorted OFDM. Opt. Commun. 285(7), 1767–1770 (2012)

Lian, J., Brandt-Pearce, M.: Multiuser visible light communications using OFDMA. In: 45th European Conference on Optical Communication (ECOC 2019), IET, pp 1–4 (2019)

Lian, J., Brandt-Pearce, M.: Multiuser visible light communication systems using OFDMA. J. Lightwave Technol. 38(21), 6015–6023 (2020)

Lin, B., Ye, W., Tang, X., et al.: Experimental demonstration of bidirectional NOMA-OFDMA visible light communications. Opt. Expr. 25(4), 4348–4355 (2017)

Liu, X., Wang, Y., Na, Z.: Cooperative NOMA-based dco-ofdm vlc system. In: International Conference on Green Communications and Networking, Springer, pp 14–24 (2019)

Ma, S., Yang, R., Deng, X., et al.: Spectral and energy efficiency of aco-ofdm in visible light communication systems. IEEE Trans. Wirel. Commun. 21(4), 2147–2161 (2021)

Marshoud, H., Kapinas, V.M., Karagiannidis, G.K., et al.: Non-orthogonal multiple access for visible light communications. IEEE Photonics Technol. Lett. 28(1), 51–54 (2015)

Marshoud, H., Sofotasios, P.C., Muhaidat, S., et al.: On the performance of visible light communication systems with non-orthogonal multiple access. IEEE Trans. Wirel. Communications 16(10), 6350–6364 (2017)

Mohtash, S.A.H., Amjad, H.: A comprehensive survey on hybrid wireless networks: practical considerations, challenges, applications and research directions. Opt. Q. Electron. 53(9), 1–56 (2021)

Ren, H., Wang, Z., Han, S., et al.: Performance improvement of M-QAM OFDM-NOMA visible light communication systems. In: 2018 IEEE Global Communications Conference (GLOBECOM), IEEE, pp 1–6 (2018)

Rodoplu, V., Hocaoglu, K., Adar, A., et al.: Characterization of line-of-sight link availability in indoor visible light communication networks based on the behavior of human users. IEEE Access 8, 39336–39348 (2020)

Saju, S.C., George, A.J., Koovapally-Kerala, K.K.: Comparison of ACO-OFDM and DCO-OFDM in IM/DD systems. Int. J. Eng. Res. Technol. (IJERT) 4(04), 1315–1318 (2015)

Selvendran, S., Raju, A.S., Muthu, K.E., et al.: Certain investigation on visible light communication with OFDM modulated white LED using optisystem simulation. Wirel. Pers. Commun. 109(2), 1377–1394 (2019)

Shi, J., Hong, Y., Deng, R., et al.: Demonstration of real-time software reconfigurable dynamic power-and-subcarrier allocation scheme for OFDM-NOMA-based multi-user visible light communications. J. Lightwave Technol. 37(17), 4401–4409 (2019)

Verma, C., Selwal, C.: 4QAM OFDM visible light communication using laser. In: 2018 7th International Conference on Reliability, pp 618–622. Infocom Technologies and Optimization (Trends and Future Directions)(ICRITO), IEEE (2018)

Wang, J.Y., Wang, J.B., Wang, Y.: Fundamental analysis for visible light communication with input-dependent noise. Optical Fiber and Wireless Communications pp 143–157 (2017)
Ye, W., Chen, J., Lin, B., et al.: Experimental demonstration of NOMA visible light communications based on SCFDM. In: 2017 16th International Conference on Optical Communications and Networks (ICOCN), IEEE, pp 1–3 (2017)

Yeh, C.H., Chen, H.Y., Chow, C.W., et al.: Utilization of multi-band OFDM modulation to increase traffic rate of phosphor-led wireless VLC. Opt. Exp. 23(2), 1133–1138 (2015)

Zhang, X., Wang, Q., Zhang, R., et al.: Performance analysis of layered aco-ofdm. IEEE Access 5, 18366–18381 (2017)

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.