Performance enhancement for visible light communication based ADO-OFDM

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Abstract
The increasing demand for bandwidth through modern applications and multimedia services has led to high-speed wireless communications. Optical wireless communications (OWC) encourages solutions that provide a higher data rate due to the large bandwidth available. In this paper, performance enhancement approaches are studied and simulated for visible light communication (VLC) as a case study. The orthogonal frequency division multiplexing (OFDM) systems are used to investigate Intensity modulation/direct detection (IM/DD) to improve the performance of VLC. The IM/DD in OWC requires positive real OFDM symbols, so there are many approaches to satisfy this requirement. This paper proposes a model of Asymmetrically Clipped DC-Biased Optical (ADO-OFDM) to use in OWC/VLC environment. The proposed system has avoided the use of the noise cancellation technology that is used in traditional ADO-OFDM. The results show that the ADO-OFDM has the best spectral efficiency than DC-biased optical (DCO-OFDM) and Asymmetrically clipped optical (ACO-OFDM). Also, it has better optical efficiency than DCO-OFDM with the equally overall bit error rate (BER) at the same signal-to-noise ratio. Hamming channel coding/decoding with different code lengths is applied in various optical OFDM schemes for BER improvements. Furthermore, we simulate and analyze these optical OFDM systems with many modulation orders.

Keywords ADO-OFDM · Visible light communication (VLC) · DCO-OFDM · ACO-OFDM · Hamming coding

1 Introduction

Wireless communication can be categorized into two different types, radio frequency (RF) and optical wireless communication (OWC). Higher data rates increasing demands are growing as users requirement causes congestion in the RF existing spectrum (Chowdhury et al. 2018).
Today, the Internet of Things (IoT) networks have gained almost importance due to connecting and exchanging data between an enormous number of embedded sensors and devices over the internet. OWC has received significant interest from researchers for its excellent features (Pham et al. 2014; Anandkumar and Sangeetha 2021; Jha et al. 2018; Amphawan et al. 2020; Singh and Malhotra 2019; Algamal et al. 2020). However, it can take an essential rule for satisfying the IoT requirement for high data rate and a real-time communication system for future communication networks, including Fifth- and Sixth-Generation (5G and 6G, respectively) communication systems (Jihad and Abdul Satar 2020; Calvanese Strinati et al. 2019; Chowdhury et al. 2019). Free Space Optical (FSO) is an outdoor version of OWC that can be used for high data rates and long-distance transmission with an inherent secure link (Jha et al. 2018; Lei et al. 2018; Abaza et al. 2015; Yousif et al. 2019; Elsayed and Yousif 2020a). FSO uses a narrow high directional link, and it can apply in satellite applications, military communication, and fiber optic backup emergency system (Jha et al. 2018; Abaza et al. 2015; Yousif et al. 2019; Uysal et al. 2014; Yaseen et al. 2020). The OWC based visible light communication (VLC) has been of tremendous interest for indoor communication due to high data rate, low cost, and security (Saadi et al. 2019; Huang et al. 2019a; Kumar and Ghorai 2018). The VLC uses the Light Emitting Diode (LED) as a light source, satisfying both communication and illuminations simultaneously (Saadi et al. 2019). VLC can be applied in local area wireless networks or personal network and vehicular communications (Uysal et al. 2014). In most OWC systems, the intensity modulation with direct detection (IM/DD) is preferred for simplicity in the modulation/demodulation process and can obtain high bandwidth (Anandkumar and Sangeetha 2021; Rahman et al. 2020; Elsayed and Yousif 2020b; Farid and Hranilovic 2007). Orthogonal Frequency Division Multiplexing (OFDM) has been commonly used in VLC systems in recent years (Sobhy et al. 2020; Sharan and Ghorai 2020; Wang et al. 2017), due to its high spectral efficiency and the Intersymbol Interference (ISI) resistance. The OFDM symbols can be represented as intensity for optical wireless communication, which means the modulated signals are both real and positive; however, the baseband OFDM signals usually are complex and bipolar (Armstrong 2009). The (IM/DD) is easy and straightforward to apply with OFDM (Zhang et al. 2014). Hermitian symmetry conversion is appropriate for the inverse fast fourier transform (IFFT) for producing real signals (Sharan and Ghorai 2020; Zhang et al. 2014). In IM/DD, different unipolar OFDM methods can be used, such as DC-Offset (DCO-OFDM) (Abdulkafi et al. 2015), asymmetrically clipped optical (ACO-OFDM), and asymmetrically clipped DC biased optical (ADO-OFDM), which is a hybrid of both ACO-OFDM and DCO-OFDM (Dissanayake et al. 2013; Mohamed et al. 2018). In this paper, an enhancement model for ADO-OFDM is proposed first, which reduces the complexity of the traditional ADO-OFDM receiver. Then DCO-OFDM, ACO-OFDM, and the proposed model of ADO-OFDM systems are tested in the VLC environment, a comparison between these systems is achieved. Hamming channel coding/decoding is used with the proposed model and other optical OFDM schemes. Simulation results show the enhanced ADO-OFDM gives the best performance in the OWC / VLC environment. The rest of the paper is organized as Sect. 2 system model, Sect. 3 proposed enhancement model, Sect. 4 simulation results, and Sect. 5 conclusions.
2 System model

The performance of OWC depends on the type of system used, the transmitter used, the laser or LED, and propagation via channel line of sight (LOS) or diffused. We can reach high data rates in VLC based LOS, but the receiver is susceptible to shadowing effect, and it must be aligned with the transmitter. In diffuse VLC, there are many light paths in a system from source to receiver, making the system resilient to block/shadow (Mesleh et al. 2011). Optical OFDM increases optical power efficiency and decreases the ISI with minimum acceptable bit error rate (BER) compared to typical optical modulation systems (Mesleh et al. 2011; Chen et al. 2017; Godwin et al. 2016). This section describes the features of different optical OFDM such as DCO-OFDM, ACO-OFDM, and ADO-OFDM. Furthermore, the indoor VLC model features and characteristics are presented.

2.1 Optical OFDM

At the optical OFDM transmitter, digital signals are modulated using either different orders of M-ary quadrature amplitude modulation (MQAM) or M-ary phase shift keying (MPSK) and mapped to symbols with complex values represented by \([X_1, X_2, \ldots X_N]\). The data is converted from serial to parallel at OFDM framing and Hermitian symmetry block, as shown in Fig. 1. The input symbols to the IFFT block after applying as Hermitian symmetry can be written as (Armstrong 2009; Dissanayake et al. 2013):

\[ X_{N-m} = X_m^* \quad m = 0, 1, \ldots, \frac{N}{2} \]  

(1)

\[ X_0 = X_{N/2} = 0 \]  

(2)

where \(X_m^*\) is complex conjugate, by taking IFFT into OFDM symbols and applying (1) and (2), the output time domain is determined as (Jativa et al. 2020; Kareem et al. 2018):

\[ X_n = \frac{1}{N} \sum_{m=0}^{N-1} X_m e^{\frac{j2\pi mn}{N}} \quad \text{for} \quad 0 \leq n \leq N - 1 \]  

(3)

where \(N\) is the number of IFFT points, the OFDM symbols \((X_n)\) are real values after Hermitian symmetry, but the signals are bipolar. Only positive signals with real values can transmit in IM/DD or OWC systems (Dissanayake et al. 2013; Mohamed et al. 2018). There are two methods for converting bipolar signals to unipolar, DC-biased in DCO-OFDM and zero clipping in ACO-OFDM (Armstrong 2009).

The Cyclic Prefix (CP) is very important to prevent the ISI; the CP is appended at the beginning of each OFDM frame as a guard interval. The output sequence can be described by adding CP as a copy of the OFDM symbol’s last portion (Armstrong 2009):

\[ X_{CP} = [X_{N-G} \ldots X_{N-1}, X_0 \ldots X_{N-1}] \]  

(4)

where \(G\) is the CP length and is chosen longer than the delay spread of the channel (Abdulkafi et al. 2015). The sequence at (4) is converted to a continuous signal by a Digital to Analog Converter (DAC). The OFDM signal becomes ready for transmission by LED, which satisfies IM/DD requirements. The optical intensity signal is transmitted through the
OWC channel, and the photodetector detected the optical signal. It converted it into an electrical signal on the receiver side, as shown in Fig. 1. The non-distorted received signal with existing Additive white Gaussian noise (AWGN) is given as Mesleh et al. (2011):

\[
y(t) = h(t) * x(t) + w(t)
\]  

where \( w(t) \) is AWGN, \( h(t) \) impulse response of the optical channel, and \( x(t) \) is the transmitted signal. The electrical signal is prepared for OFDM demodulation processing using the Analog-to-Digital conversion (ADC) and serial-to-parallel conversion. The CP is removed, and a Fast Fourier Transform (FFT) is applied to extract the original modulated symbols.
(Mesleh et al. 2011; Jativa et al. 2020). The FFT of N point is given by Armstrong (2009; Abdulkafi et al. 2015):

\[
Y_m = \sum_{n=0}^{N-1} X_n e^{-\frac{2\pi inm}{N}} + W_m \quad \text{for } 0 \leq m \leq N - 1
\]  

(6)

where \( W \) is the noise component at the receiver after FFT operation and is written as (Armstrong 2009; Abdulkafi et al. 2015):

\[
W_m = \sum_{n=0}^{N-1} w_n e^{-\frac{2\pi inm}{N}} \quad \text{for } 0 \leq m \leq N - 1
\]  

(7)

The output from (6) is deframing by converting complex symbols from parallel to serial and extract the information by demodulating process.

### 2.2 VLC model

It is necessary to study the received power and the path loss in typical environments due to the indoor OWC/VLC channel (Abdulkafi et al. 2015). There are two link types inside the room: dominant direct link LOS and non-dominant diffuse links arise due to light reflection through the walls, floor, and ceiling (Céspedes et al. 2021). The received power at any point \((x, y, z)\) inside the room and neglecting the diffuse links is given by Abdulkafi et al. (2015):

\[
P_r = H(0)P_t
\]  

(8)

where \( P_t \) is the transmitted power by LEDs for the transmitted OFDM signal, and \( H(0) \) is the DC gain of the indoor OWC/VLC channel impulse response. The Lambertian distribution represents the radiated intensity by Kumar and Ghorai (2018); Communications 2019):

\[
R(\Phi) = \frac{(ml + 1)}{2\pi} \cos^{ml}(\Phi) \quad \text{for } -\frac{\pi}{2} \leq \Phi \leq \frac{\pi}{2}
\]  

(9)

where \( \Phi \) is the irradiance angle, and \( ml \) is the Lambertian index is given as:

\[
ml = -\ln(2) \ln(\cos(\Phi_{1/2}))
\]  

(10)

where \( \Phi_{1/2} \) is half illumination angle and also is called (Radiation semi-angle) (Céspedes et al. 2021).

Thus, the LOS channel impulse response for indoor OWC/VLC is modeled as (Communications, 2019; Céspedes et al. 2021):

\[
H(t) = \frac{A(ml + 1)}{2\pi d^2} \cos^{ml}(\Phi)T(\Psi)g(\Psi)\cos(\Psi)
\]  

(11)

where \( d \) is the distance between the transmitter and the receiver, and \( A \) is the photodetector physical area. The photodetector is collecting the light at an incidence angle \( \Psi \), and \( \Psi_c \) is the Field of View (FOV) angle for the receiver, which is \( \Psi_c \leq \Phi_{1/2} \) (Mohamed et al. 2018).
\( T(\Psi) \) is the transmission filter, and \( g(\Psi) \) is the receiver concentrator filter that is characterize by lens refractive index of photodetector \( (n_{\text{len}}) \) as follow (Jativa et al. 2020):

\[
g(\Psi) = \frac{n_{\text{len}}^2}{\sin\Psi_c^2} \quad \text{for} \quad 0 \leq \Psi \leq \Psi_c
\]  

Substituting (11) in (8), and let \( T(\Psi) \) the transmission filter gain is unity, the power at the detector is written as:

\[
P_r = P_t \cdot \frac{A(ml + 1)}{2\pi d^2} \cos^m(\Phi) \cos(\Psi) g(\Psi)
\]  

Thus, from (5) and using (11), the received signal by photodetector can be re-written as:

\[
y(t) = \frac{A(ml + 1)}{2\pi d^2} \cos^m(\Phi) T(\Psi) g(\Psi) \cos(\Psi) \star x(t) + w(t)
\]  

where \( x(t) \) is the emitted signal by LEDs, and \( w(t) \) is the AWGN that is added in the electrical domain.

### 2.3 DCO-OFDM

At the DCO-OFDM transmitter, the modulated complex symbols \([X_1, X_2, \ldots, X_N]\) are assigned to the IFFT after applying Hermitian symmetry. The number of subcarriers available for data is \((N/2 - 1)\), so the spectral efficiency is reduced by about 50\% from traditional OFDM due to Hermitian symmetry (Zhang et al. 2014). The DC bias is used in DCO-OFDM to convert the bipolar signal to unipolar, as shown in Fig. 2. The added DC bias is responsible for shifting the OFDM symbols before clipping. The output DCO-OFDM is written by change (3), and it becomes (Sobhy et al. 2020):

\[
X_{DCO} = \frac{1}{N} \sum_{m=0}^{N-1} X_m e^{\frac{i\pi m}{N}} + \beta_{dc} \quad \text{for} \quad 0 \leq m \leq N - 1
\]  

where \( \beta_{dc} \) is DC bias could be added and selected concerning the standard deviation of the DCO-OFDM signal (Huang et al. 2019a). The performance of DCO-OFDM is strongly affected by the DC bias, as the optical power efficiency of the system decreases (Sobhy et al. 2020; Zhang et al. 2014; Dissanayake et al. 2013).

### 2.4 ACO-OFDM

In ACO-OFDM, data symbols are transmitted by the only odd subcarriers, and the modulated symbols are distributed over \((N/4)\) subcarriers. The spectral efficiency of ACO-OFDM is reduced by 25\% of traditional OFDM and 50\% of DCO-OFDM spectral efficiency (Dissanayake et al. 2013). The input symbols to IFFT are mapped across only odd subcarriers and the even subcarriers represented by zero as:

\[
[0, X_1, 0, X_3, \ldots, X_{N/2-1}]
\]
The output of IFFT becomes real after applying Hermitian symmetry in (1) and (2). The clipping at zero technique is used at bipolar to unipolar block in Fig. 3. As in (15), The ACO-OFDM output can be written as:

$$X_{ACO} = \begin{cases} X_n \text{ if } X_n \geq 0 \\ 0 \text{ if } X_n < 0 \end{cases}$$

(17)

where $X_n$ is obtained from (3), due to the anti-symmetry property, there is no data loss in the clipping process (Godwin et al. 2016). The Optical power efficiency of ACO-OFDM is better than DCO-OFDM because it doesn’t need DC bias (Mohamed et al. 2018). To compensate for the bitrate loss gap, we can increase the modulation order of MQAM or MPSK, which means an increase in the number of bits ($\log_2 M$) per OFDM symbol (Calvanese Strinati et al. 2019).

### 2.5 ADO-OFDM

ADO-OFDM is a technology that imposes the performance of spectral efficiency; it is a combination of both DCO-OFDM and ACO-OFDM (Zhang et al. 2014; Dissanayake et al. 2013; Chen et al. 2017; Jativa et al. 2020). The odd subcarriers are transmitted using ACO-OFDM, where DCO-OFDM sends even subcarriers (Dissanayake et al. 2013). The generated ADO-OFDM is given by Jativa et al. (2020):
On the receiver side, the odd subcarriers are demodulated as ACO-OFDM, wherein even subcarriers are demodulated after the noise cancellation process (Zhang et al. 2014; Dissanayake et al. 2013; Chen, et al. 2017; Jativa et al. 2020). The optical power efficiency of ADO-OFDM is better than ACO-OFDM because it relies on DC bias only for even subcarriers (Dissanayake et al. 2013; Wang et al. 2017).

\[ X_{ADO} = X_{ACO} + X_{DCO} \quad (18) \]

Fig. 3 ACO-OFDM generation system

3 Proposed enhancement model

Many authors suggested several techniques to enhance the spectral efficiency based on optical OFDM (Sobhy et al. 2020; Mohamed et al. 2018; Zhang et al. 2017; Huang et al. 2019b). This section describes the proposed model of ADO-OFDM features and the details for the system design. The proposed system reduces the complexity of the traditional ADO-OFDM receiver. We introduce a scheme by transmitting constellation sizes unequally with even and odd subcarriers in the proposed approach to increase the data rates. Furthermore, the Hamming channel coding is utilizing in BER enhancement for our proposed system and OFDM optical systems.
3.1 The proposed model of ADO-OFDM system

The proposed ADO-OFDM transmitter consists of a Hamming channel encoder and MQAM modulator. The encoded/modulated symbols $X$ are divided into odd and even variables, $X_{\text{odd}}$ and $X_{\text{even}}$, respectively. The odd subcarriers in ADO-OFDM are transmitted using ACO-OFDM, where even subcarriers are sending via DCO-OFDM, as shown in Fig. 4. The Hermitian symmetry applies for both ACO-OFDM and DCO-OFDM components (Chen, et al. 2017; Jativa et al. 2020), where:

$$X_{\text{odd}} = [0, X_1, 0, X_3, 0, \ldots, X_{N-1}]$$  \hspace{1cm} (19)

$$X_{\text{even}} = [X_0, 0, X_2, 0, \ldots, X_{N-2}, 0]$$  \hspace{1cm} (20)

The ACO-OFDM symbols in the time-domain are generated after the IFFT process to $X_{\text{odd}}$. The output symbols have real values due to Hermitian symmetry but bipolar. They are converted to unipolar by clipping the negative values by setting them to zero. Also, the DCO-OFDM signals are created after IFFT and are converted to unipolar by adding $\beta_{dc}$ to get non-negative output. We propose a variable DC bias by taking the minimum value of each OFDM symbol, then taking the absolute value, and adding it to the signal to get a non-negative output. The resulting ADO-OFDM signal is $(X_{\text{ACO}} + X_{\text{DCO}})$, then adding CP and converted to analog by (DAC) and transformed to LED’s intensity light.

On the receiver side, firstly, the optical signal transformed to an electrical signal by the photodetector, converted to digital, removing CP, and then passes to IFFT, as shown in Fig. 5. Our proposed ADO-OFDM receiver has two paths, the direct path that we call ACO-OFDM demodulation and the other called DCO-OFDM reconstruction. The ACO-OFDM symbols in the odd subcarriers are straightly recovered and demodulated in a direct path. The demodulated bits are then re-modulated again using ACO-OFDM to recover the DCO-OFDM symbols and subtract from the overall received signal. Now, The information on the even subcarriers is ready for the demodulation process. Then the odd and even data are rearranged, and the original data extracted after the demodulation and decoding process. The proposed receiver reduces the design complexity by overcoming the uses of the ACO-OFDM noise estimation block as mentioned in references (Zhang et al. 2014; Dissanayake et al. 2013; Jativa et al. 2020). Also, the
noise estimation can work only in a flat channel (Dissanayake et al. 2013). We can use (N/2−1) of subcarriers in ADO-OFDM for data transmission as in DCO-OFDM. We can increase our proposed system’s spectral efficiency and data rate higher than DCO-OFDM by using different modulation consultation sizes for odd and even subcarriers, respectively, M_{ACO} and M_{DCO}.

In Wang et al. (2017), the authors provide a comparative study among various VLC OFDM schemes. Consider the following example for spectral efficiency comparison as in Table 1 based the formulas in Wang et al. (2017) by assuming N = 1024. It can be seen that the proposed model can increase the spectral efficiency if using M_{ACO} = 8 and M_{DCO} = 4. Furthermore, the ADO-OFDM is medium power efficiency, but it is better than the DCO-OFDM. The detection complexity of ACO-OFDM and DCO-OFDM is less than that of ADO-OFDM, but the proposed model reduces detection complexity by eliminating the stage of noise estimation.

![Fig. 5 The enhanced ADO-OFDM receiver system](image)

| Optical OFDM | Spectral efficiency formulas (Wang et al. 2017) | Spectral efficiency (bit/s/Hz) |
|--------------|-----------------------------------------------|-------------------------------|
| ACO-OFDM (M = 4) | \( \frac{\log_2 M}{4} \) | 0.5 |
| DCO-OFDM (M = 4) | \( \frac{(N-2) \log_2 M}{N} \) | 0.998 |
| ADO-OFDM (M = 4 for odd and even subcarriers) | \( 1 - \frac{2N}{\log_2 M} \) | 0.998 |
| ADO-OFDM (M_{ACO} = 8, M_{DCO} = 4) | \( \frac{(\log_2 N + \log_2 M_{ACO})}{4} - \frac{\log_2 M_{DCO}}{N} \) | 1.248 |
3.2 Hamming channel coding/decoding

Channel coding techniques can be used with optical OFDM to improve system performance by reducing noise effects resulting through transmission, detection, or channel non-linearity (Mohamed et al. 2018; Mesleh et al. 2012). In Kumar et al. (2018), channel coding was used to reduce the influence of high-peak to average power in an OFDM system. We can use channel coding with error corrections before the data modulation to compensate for the BER during the data transmission, especially when higher modulation constellation order is used (Fleah and Al-Doori 2019). In this paper, we use Hamming code as one type of linear channel coding in forwarding error correction, and it can be applied with DCO-OFDM, ACO-OFDM, and DCO-OFDM. Hamming code is the right choice for a single error bit correction with simple parity codes (Mohamed et al. 2018). The Hamming codes notation can be written as Kumar et al. (2018):

\[(2^r - 1, 2^r - r - 1)\]  \hspace{1cm} (21)

where \(r\) number of parity digits and \(r \geq 2\), \(2^r - 1\) is the length of the Hamming code and \(2^r - r - 1\) is the message length. So if \(r = 2\), the code is (3,1), and for \(r = 3\), the code (7,4) and so on. The generator matrix \(G\) and parity check matrix for (7,4) Hamming code example respectively are:

\[
G = \begin{bmatrix}
1 & 0 & 0 & 0 & 1 & 1 & 0 \\
0 & 1 & 0 & 0 & 1 & 0 & 1 \\
0 & 0 & 1 & 0 & 0 & 1 & 1 \\
0 & 0 & 0 & 1 & 1 & 1 & 1
\end{bmatrix}
\]  \hspace{1cm} (22)

\[
H = \begin{bmatrix}
1 & 1 & 0 & 1 & 1 & 0 & 0 \\
1 & 0 & 1 & 1 & 0 & 1 & 0 \\
0 & 1 & 1 & 1 & 0 & 0 & 1
\end{bmatrix}
\]  \hspace{1cm} (23)

4 Simulation result

In this section, the BER simulations for DCO-OFDM, ACO-OFDM, and the proposed model of ADO OFDM systems are accomplished using a different modulation constellation size of QAM. Matlab software version R2019b is employed in the simulation, and BER comparison curves are produced using 5000 OFDM symbols, \(N=1024\), and \(G=N/16\), the number of CP is 64. The actual number of subcarriers for data transmission is (256 for ACO-OFDM, 511 subcarriers for both DCO-OFDM and enhanced ADO-OFDM. All these systems are tested with different Signal-to-Noise Ratios (SNR) in the LOS OWC/VLC channel. Figure 6 shows a DCO-OFDM BER simulation case for \(M=2,4,5,7,\) and 10 with of \(\beta_{dc} 0.2\) V is used in this scheme.

Figure 7 shows the BER performance of ACO-OFDM, which was tested for \(M=2,4,5,7,10,\) and 12. ACO-OFDM achieves a better BER response than DCO-OFDM, because it does not require bias, while the spectral efficiency is low.

The proposed model of the ADO-OFDM system mixes both ACO-OFDM for odd subcarriers transmission and DCO-OFDM for even subcarriers. In the simulation, odd
subcarriers’ size is equal to 256, while even subcarriers are set to 255. Figure 8 demonstrates the simulation results for the proposed ADO-OFDM performance for different states, equally constellation order for both odd and even subcarriers such as (QAM DCO-OFDM + QAM ACO-OFDM) and unequally M-order such as (QAM DCO-OFDM + 16 QAM ACO-OFDM). The $\beta_{dc}$ values are reduced in the ADO-OFDM and

Fig. 6 DCO-OFDM BER performance

Fig. 7 ACO-OFDM BER performance
are approximately adaptively in the range $0.09 \leq \beta_{dc} \leq 0.115$. Reduction of $\beta_{dc}$ due to only 50% subcarriers with DC biasing is used and leads to the enhanced ADO-OFDM system’s power utilization.

Simulation results show that the BER performance for ACO-OFDM is better than ADO-OFDM and DCO-OFDM since only half of the subcarriers are used in this scheme. However, the BER curves of ADO-OFDM are close to that of DCO-OFDM in some cases. The proposed system enhances the BER performance over the traditional ADO-OFDM systems because it does not need ACO path noise estimation. Table 2 presents a BER comparison between ADO-OFDM for the proposed and the traditional form for different modulation orders based on the result obtained for the LOS channel in Jativa et al. (2020).

To make an exact comparison between the different OFDM optical systems concerning efficient power, we calculate the transmitted optical signal as given in Mohammed et al. (2017):

### Table 2 BER Performance comparison between proposed ADO-OFDM versus traditional ADO-OFDM at SNR = 30 dB

| Modulation | Proposed ADO-OFDM |
|------------|-------------------|
| BER        | Traditional ADO-OFDM |
| BER (Jativa et al. 2020) | |
| QAM        | $4 \times 10^{-6}$ | $10^{-5}$ |
| 8QAM       | $10^{-4}$ | $5 \times 10^{-4}$ |
| 16QAM      | $10^{-3}$ | $9 \times 10^{-3}$ |
| 32QAM      | $3 \times 10^{-3}$ | $10^{-2}$ |
| 64QAM      | 0.015 | 0.08 |
where $X_{OFDM}$ is N-point transmitted OFDM (either DCO-OFDM, ACO-OFDM, or ADO-OFDM). Figure 9 presents a comparison of optical power concerning the number of transmitted subcarriers N. The simulation is carried out for $M=4$ for both ADO-OFDM and DCO-OFDM, where $M=8$ is adjusted for ACO-OFDM to investigate the nearest spectral efficiency approximately.

We can see from Fig. 9 the proposed ADO-OFDM optical power efficiency is better than DCO-OFDM, while the ACO-OFDM is the best response because it does not need DC biasing. Also, we tested the proposed system for unequal constellation size for odd and even subcarriers; it gives better power efficiency than equally constellation size about 1dBm. Hamming coding/decoding is used with our proposed system and other schemes to compensate for the BER performance.

Figure 10 presents Hamming coding/decoding advantages for performance enhancement for different optical OFDM. To achieve a BER comparison, we use various lengths of message and code such as (3,1), (7,4), and (15,11). We can see that the Hamming codes improve performance by correcting the bit errors due to AWGN and channel response. Although (3,1) coding gives the best result, it reduces the spectral efficiency by the rate (1/3), while (7,4) and (15,11) coding scheme reduces the spectral efficiency by (4/7) and (11/15), respectively. Table 3 summarizes the BER comparisons between the systems, using $M=4$ for both DCO-OFDM and enhanced ADO-OFDM and $M=8$ for ACO-OFDM.

Finally, the coverage of VLC inside indoor OWC simulated concerning LOS channel and the simulation parameters as in Table 4. We consider physical room space dimensions (6 m, 5 m, 3 m); four LED sources are distributed in different room ceiling locations. We simulate each transmitter source with a grid (30×30) of LEDs to optimize illumination and receiving power. The Matlab R2019b software is used to plot the optical power hologram at the receiver for study the power distribution inside the room. The optical distribution range differs as the values of $\Phi_{\frac{1}{2}}$ variations. Figure 11a shows that the hologram appears as a uniform distribution at $\Phi_{\frac{1}{2}}=70^\circ$, the optical received power is concentrated in the center while it is reduced in the corners of the room. Figure 11b presents the distribution at $\Phi_{\frac{1}{2}}=30^\circ$, the hologram is changed from the prior case, and several dead regions appear with a considerable variation between the maximum and

\[
P_{optical} = E[X_{OFDM}] = \sqrt{\frac{E[|X_{OFDM}|^2]}{\pi}}
\]
minimum receiving power. The received power range in dBm for \( \Phi_{1/2} = 70^\circ \) and \( \Phi_{1/2} = 30^\circ \) is \(-9.5 \leq P_r \leq -3.8 \) and \(-11 \leq P_r \leq 0.4 \) respectively.

5 Conclusions

In this paper, we have simulated and tested the LOS channel of OWC based VLC. Various effecting parameters can characterize the optical distribution in an indoor environment, such as transmit power, room dimensions, half illumination angle, FOV angle, and physical area of the photodetector. We have performed IM/DD based on different optical OFDM to study the performance of OWC/VLC in LOS channels. We proposed an ADO-OFDM system model that reduces the complexity of traditional ADO-OFDM and enhances the VLC performance. The Proposed system gives the best spectral efficiency than ACO-OFDM and the same as DCO-OFDM if it uses the same number of subcarriers. When we use higher constellation modulation with an odd subcarrier, the ADO-OFDM spectral efficiency exceeds the DCO-OFDM. The spectral efficiency of the proposed system for \( M_{ACO} = 8, \)
M_{DCO} = 4) is 1.248 bit/s/Hz while 0.998 bit/s/Hz for DCO-OFDM and traditional ADO-OFDM modulation for 16QAM modulation. The proposed ADO-OFDM has better optical power efficiency than DCO-OFDM, and ACO-OFDM is the best because it does not use a DC bias. The BER performances are evaluated for OFDM systems; the BER increases if the M order constellation modulation of QAM increases. Different lengths of Hamming channel coding are tested with the optical OFDM systems, and the BER decreases and marking (7,4) as an excellent choice to use in VLC system-based OFDM. The simulation results show that the proposed model BER performance is better than traditional ADO-OFDM. It can enhance BER from 9 × 10^{-3} for 16QAM modulation to 10^{-3} at SNR = 30 dB and reach BER = 10^{-5} at SNR = 33 dB. Furthermore, the SNR can be decreased to 28 dB by using Hamming encoder/decoder with the OFDM system. As future work, The proposed model will be implemented and tested using a hardware model on Field Programmable

| Scheme                                | (SNR) in dB at BER = 10^{-4} | (SNR) in dB at BER = 10^{-5} | Spectral efficiency (bit/s/Hz) |
|---------------------------------------|-----------------------------|-----------------------------|-----------------------------|
| DCO-OFDM (without coding)             | 32                          | 33                          | 0.998                       |
| Hamming coding (3,1)                  | 27                          | 28                          | 0.331                       |
| Hamming coding (7,4)                  | 28                          | 29                          | 0.57                        |
| Hamming coding (15,11)                | 29                          | 30                          | 0.732                       |
| ACO-OFDM (without coding)             | 28.5                        | 31                          | 0.75                        |
| Hamming coding (3,1)                  | 18                          | 22                          | 0.25                        |
| Hamming coding (7,4)                  | 21.5                        | 22.5                        | 0.429                       |
| Hamming coding (15,11)                | 21.7                        | 22.7                        | 0.55                        |
| Enhanced ADO-OFDM (without coding)    | 32                          | 33                          | 0.998                       |
| Hamming coding (3,1)                  | 27                          | 28                          | 0.331                       |
| Hamming coding (7,4)                  | 28.5                        | 30                          | 0.57                        |
| Hamming coding (15,11)                | 29                          | 30.2                        | 0.732                       |

Table 4 System parameter for VLC-OWC

| Parameter                                | Value                                |
|------------------------------------------|--------------------------------------|
| LED locations in the ceiling of the room | (1.5, 1.25, 3); (1.5, 3.75, 3); (4.5, 1.25, 3); (4.5, 3.75, 3) |
| Transmit Power                           | 20 mw                                |
| Total power per grid (30 x 30)           | 30 x 30 x 20 mw = 18w                |
| Half illumination angle                  | 70°; 30°                             |
| The physical area of the photodetector   | 1 cm²                                |
| FOV                                      | 60°                                  |
| Distance between a transmitter to receiver | 2 m                                 |
| Lens refractive index                    | 1.5                                  |
Gate Array (FPGA). Also, we will investigate the performance of the model in the diffuse channel and study and apply different coding schemes.

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