

Efficient Optical OFDM System Resilience to Indoor Wireless Multipath Channels

Hussein A. Leftah

Dept. of Electrical Engineering Techniques, BETC, Southern Technical University, Basrah, Iraq

Correspondance
Hussein A. Leftah
Dept. of Electrical Engineering Techniques,
BETC, Southern Technical University,
Basrah, 42001, Iraq
Email: h.a.leftah@stu.edu.iq

Abstract

This article presents a developed intensity modulation/direct detection (IM/DD) optical orthogonal frequency division multiplexing (O-OFDM). More precisely, the presented C-O-OFDM is based on the C-transform as a unitary orthogonal transform instead of the state-of-the-art discrete Fourier transform (DFT). Due to the properties of the real C-transform, Hermitian symmetry (HS) is not required to produce real OFDM samples. Therefore, the proposed scheme supports twice the input symbols compared to conventional DFT-based OFDM system. Real data mapping and DC bias technology is considered to evaluate the performance of the presented scheme over optical wireless multipath. The simulation results shows that the proposed C-O-OFDM is more resilience to multipath phenomena than the competitive DFT-O-OFDM and DHT-O-OFDM schemes for similar bit rate. The proposed scheme achieves about 22 dB signal-to-noise ratio (SNR) gain in comparison with the DFT-O-OFDM and about 2.5dB SNR gain in comparison with the DHT-O-OFDM scheme.

Keywords

Intensity modulation-direct detection, bit error rate, signal-to-noise ratio, Orthogonal frequency division multiplexing (OFDM), wireless optical communications.

I. INTRODUCTION

Due to the continuous demands for high speed and large capacity optical networks, developed modulation schemes and algorithms are firmly being proposed for optical communications [1]. Orthogonal frequency division multiplexing (OFDM) is a modulation technology that is exported from broadband communication to optical networking for its popular characteristics in spectral efficiency and immunity against severe channel conditions [2]. The OFDM is a special case of multicarrier modulation that is efficient in eliminating the intersymbol interference (ISI) between the followed symbols due to the multipath phenomena [3]. It also converts the multipath frequency selective fading channel into several parallel flat fading subchannels [4].

The OFDM system exploits the discrete Fourier transform (DFT) or its fast algorithm (FFT) as an efficient algorithm in

modulation/demodulation technique in its transmitter/ receiver structure. The use of FFT in OFDM for optical communication enables the use of mature digital signal processing. However, the output of the FFT is bipolar and complex signal which considers as a challenge for certain optical communication techniques.

Direct detection (DD) and coherent detection have been proposed as a trade-of between simplicity and sensitivity that could meet with OFDM requirements in optical communications [5–7]. Direct detection is a simple and cheap technology as it used only photodiode without local oscillator or any laser diode to recover the optical signal. However, this technique required real unipolar optical signal. To ensure real output of the OFDM system, the input data symbol must be set to be complex conjugate with Hermitian symmetry (HS). Therefore, fifty percent of subcarriers do not carry information and reserved for HS purpose. Coherent detection does not



This is an open-access article under the terms of the Creative Commons Attribution License, which permits use, distribution, and reproduction in any medium, provided the original work is properly cited.
©2023 The Authors.

Published by Iraqi Journal for Electrical and Electronic Engineering | College of Engineering, University of Basrah.

require real data transmission, so, direct implementation of conventional OFDM system is applicable. However, it is more expensive compared to DD. Additionally, because the laser diode and local oscillator at the receiver, coherent detection is more sensitive to frequency offset and phase noise than the DD

Recently, OFDM based on discrete Hartley transform (DHT) along with real data constellations has been proposed for optical communications to avoid the HS constraint [8,9]. It has been evidenced that when the DFT is replaced by the DHT, both systems will have identical BER performance for same bit rate. In other words, BPSK to 32 pulse amplitude modulation (PAM) DHT-O-OFDM has the same BER performance as 4-1024 quadrature amplitude modulation (QAM) when conventional optical OFDM over . These approaches, however, considered the transmission over additive white Gaussian noise (AWGN) channel and falls short of addressing the transmission over multipath fading channels.

Therefore, in this paper, we propose the C-transform [10] based optical OFDM for wireless communication to effectively reduce the impairment of optical wireless channels and hence, improve the optical transmission. The C-transform based OFDM has been proposed for wireless communications and showed a very promising technique resilience to multipath transmission [10] and [11]. Therefore, in this paper we will borrow this promising technology from broadband to wireless optical networking which has twofold achievements. Firstly, utilizing the C-OFDM in optical wireless communications can significantly improve the BER performance of optical communications. Secondly, as the kernel of C-transform is a real, then, when real data mapping is used, there is no Hermitian symmetry constraint on the input data to produce real samples. Thus The main goal of the proposed optical scheme is to avoid the Hermitian constraint (HS) and increase the system robustness to multipath environments.

The remainder of this article is organized as follows: section II. presents a mathematical structure of C-transform. The mathematical model of the proposed optical OFDM system is provided in section III. Section IV. shows the numerical results and discussion. Finally, our conclusion is presented in section V.

Notation: $(\cdot)^T$ is the transpose operation. $\mathbb{R}^{n \times m}$ refers to the real space of $n \times m$ matrix. $\mathbb{E}[\cdot]$ is the expected value of a random variable and $(\cdot)^{-1}$ is the inverse of a matrix. \mathbf{I}_n is an identity matrix of size n .

II. C-TRANSFORM

C-transform is a real unitary transform, it can be considered as a Walsh-Hadamard transform (WHT) followed by a discrete cosine transform (DCT). It is formatted in a low complexity block diagonal structure (BDS) using the subsequent proce-

dures. Let $\mathbf{P} \in \mathbb{R}^{N \times N}$ be the permutation matrix that would rearrange the rows of WHT matrix (\mathbf{W}) and the rows of DCT matrix (\mathbf{D}) in a bit-reverse order (BRO). Where $\mathbf{W} \in \mathbb{R}^{N \times N}$ and $\mathbf{D} \in \mathbb{R}^{N \times N}$ are the WHT and DCT matrices of size N respectively. The \mathbf{P} of size N is given in (1).

$$\mathbf{P} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}. \quad (1)$$

Thus, the C-transform can be written as

$$\mathbf{C} = \mathbf{PDW}^T\mathbf{P}^T. \quad (2)$$

where $(\cdot)^T$ is the transpose operation. For more illustration, the C-transform of size $N = 8$ will be formed as:

$$\mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0.9239 & 0.3827 & 0 & 0 & 0 & 0 \\ 0 & 0 & -0.3827 & 0.9239 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.9061 & -0.0747 & 0.3753 & 0.1802 \\ 0 & 0 & 0 & 0 & 0.2126 & 0.7682 & -0.5133 & 0.3182 \\ 0 & 0 & 0 & 0 & -0.3182 & 0.5133 & 0.7682 & 0.2126 \\ 0 & 0 & 0 & 0 & -0.1802 & -0.3753 & -0.0747 & 0.9061 \end{bmatrix} \quad (3)$$

The C-transform has been utilized in OFDM for broadband wireless communications systems, in our previous works [10] and [11], where it has been proved its superiority over the classic OFDM systems that are based on Fourier transform.

III. OPTICAL C-OFDM

It is clear from (3) that C-transform is a real transform, hence, when real data mapping such as BPSK or M-array PAM are used, the output of the C-transform is real. In other words, the HS restriction on the input vector is not required in the C-transform based optical OFDM which streamlined the process of transmission scheme. Therefore, the proposed C-O-OFDM achieves exactly the same spectral efficiency as the DHT-O-OFDM and twice the spectral efficiency of the classic optical OFDM.

The real data input symbols are first set in a vector form, each of length N before being processed by the inverse C-transform (ICT) as:

$$\mathbf{f} = \mathbf{C}^T\mathbf{d}, \quad (4)$$

where $\mathbf{d} \in \mathbb{R}^{N \times 1}$ is the BPSK or μ -PAM input data symbols vector. In the case of traditional DFT-based optical OFDM, the time domain OFDM signal is expressed as:

$$f_n^F = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} d_k^F e^{j(\frac{2\pi nk}{N})}. \quad (5)$$

the input data symbols must be complex and Hermitian conjugate to force the output of FFT to be real and suitable for direct detection (DD). In other words, only $N/2$ of the DFT-OFDM subcarriers are carrying information data whereas the others are reserved for the conjugate symmetry. Additionally, d_0^F and $d_{N/2}^F$ are set to zeros as shown in equation below:

$$\mathbf{d}^F = [0 \ d^{QAM} \ 0 \ d^{*QAM}]^T. \quad (6)$$

Therefore, as only half of the available DFT-based subcarriers are used to carry data, and to achieve the same data rate as the proposed C-O-OFDM, the bandwidth must be increased. As the available bandwidth is strict and cannot be enhanced, so to maintain the same spectral efficiency at the same bandwidth, the number of bits per subcarrier in constellation size will be doubled when the conventional DFT-O-OFDM is used. In other words, if μ is the PAM constellation size and M is the complex QAM constellation size, then

$$\mu = 2 \left(\frac{\log_2 M}{2} \right). \quad (7)$$

Due to the multipath phenomena of the channel, intersymbol interference (ISI) between successive OFDM symbols occurs. This deleterious effects of ISI can be completely mitigated by padding the OFDM samples with zeros vector N_g that is larger in length than the maximum path delay of the channel. The zero-padded signal is expressed as:

$$\mathbf{f}_p = [f_0 \ f_1 \ f_2 \ \dots \ f_{N-1} \ 0 \ 0 \ \dots \ 0]^T, \quad (8)$$

where $\mathbf{f}_p \in \mathbb{R}^{N_l \times 1}$ and $N_l = N + N_g$.

The signal \mathbf{f}_p must be unipolar and real. Therefore, to ensure that the C-OFDM signal is positive, several techniques has been proposed. In DC-biased technique, that is considered in this paper, a specific DC value is added to the output signal to turn it to positive signal. This DC-biased OFDM signal is still have several negative samples depending on the DC bias level. As the DC bias level increased, the negative notches decreased, however, high DC bias means low power efficiency. The produced signal after the DC-biased is given as:

$$\mathbf{x}_{DC} = \mathbf{f}_p + \mathbf{B}_{DC}. \quad (9)$$

In (9) \mathbf{B}_{DC} represents the level of DC bias. It's value is given as [12]

$$\mathbf{B}_{DC} = K \sqrt{\mathbb{E}[\mathbf{f}_p^2]}. \quad (10)$$

In dB, the value of DC-biased level is $10 \log_{10} K^{2+1}$, where $\mathbb{E}[\mathbf{f}_p^2]$ is the signal variance in electrical domain.

Intensity modulation (IM) is then used to convert the C-OFDM signal from electrical domain into optical domain. If \mathbf{B}_{DC} is not high enough, there is still some negative picks exist. Therefore, the IM modulator clips all the residual negative parts of the electrical domain signal at zero level producing what is called clipping noise (\mathbf{n}_c).

This optical intensity modulated OFDM signal is then transmitted through optical wireless channel. A ceiling bounce model [13] and [14] optical wireless channel (OWC) is used in this paper. The channel impulse response (CIR) of this channel is given as:

$$g(t) = G(0) \frac{6a^6}{(t+a)^7} u(t), \quad (11)$$

where $G(0)$ represents the DC gain of the channel, $u(t)$ is the heaviside step function which defined as $u(t) = 1$ for $t \geq 0$ and $u(t) = 0$ for $t < 0$, $a = 12 \sqrt{\frac{11}{13}} D_{rms}$ and D_{rms} is the root-mean-square delay of the optical multipath channel. In discrete form, let N_d is the maximum channel delay, then the arrived OFDM signal in optical domain at the receiver \mathbf{y} is given as:

$$\mathbf{y} = (\mathbf{x}_{DC} \circledast \mathbf{g}) + \mathbf{n}_c, \quad (12)$$

where \circledast , \mathbf{g} and \mathbf{n}_c represent the convolution operation, channel impulse response, and clipping noise respectively. The clipping noise, \mathbf{n}_c , is inversely proportional with the DC bias (\mathbf{B}_{DC}). In other words, when \mathbf{B}_{DC} increased, the \mathbf{n}_c will be reduced. In vector form, (12) could be expressed as

$$\mathbf{y} = \mathbf{\Pi} \mathbf{x}_{DC} + \mathbf{n}_c. \quad (13)$$

In (13), $\mathbf{\Pi} \in \mathbb{R}^{N_l \times N_l}$ is channel convolution Toeplitz matrix [10], its row elements i_{th} , $0 \leq i \leq N_l - 1$, and k_{th} column element, $0 \leq k \leq N_l - 1$, are expressed as $\mathbf{\Pi}(i, k) = g(i - k)$ for $0 \leq (i - k) \leq N_d$ and $\mathbf{\Pi}(i, k) = 0$ elsewhere.

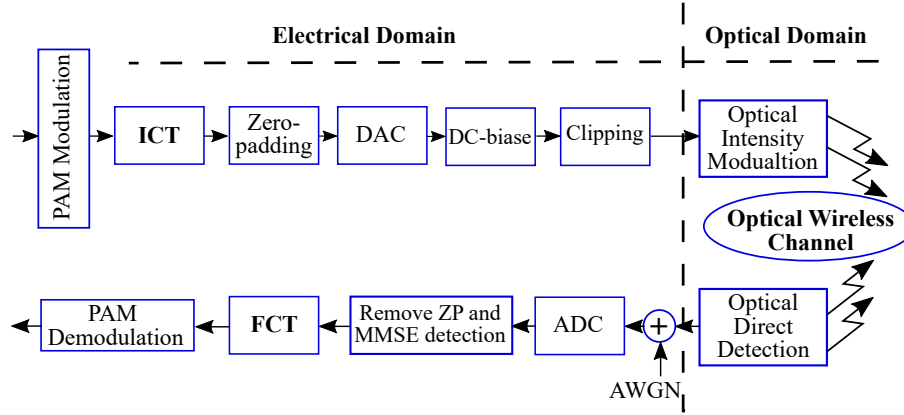


Fig. 1. Proposed Optical system over multipath channels

A single photodiode is utilized to perform the direct detection process to convert signal from optical to electrical domain. The received signal is expressed as

$$\mathbf{r} = \mathbf{y} + \mathbf{n}_w, \quad (14)$$

where \mathbf{n}_w is the additive white Gaussian noise (AWGN) noise.

To remove the channel effects from the desired signal, MMSE channel equalizer is employed before the forward C transform (FCT) processing as follows:

$$\mathbf{r}^{det} = \Phi \mathbf{y}, \quad (15)$$

where $\Phi \in \mathbb{R}^{N_t \times N_t}$ is a matrix that perform channel equalization. Mathematically, Φ is given as [15]:

$$\Phi = \gamma_s^2 (\gamma_s^2 \Pi^T \Pi + \gamma_n^2 \mathbf{I}_{N_t})^{-1} \Pi^T. \quad (16)$$

In (16), $\gamma_s^2 = \mathbb{E}[\mathbf{f}^2]$ is the desired signal standard deviation and γ_n^2 represents the noise signal standard deviation.

At the receiver side, to prevent the intersymbol interference (ISI), the last N_g samples, that were come from zero-padded, are discarded from the received signal before processing by the C-matrix. It folloes that, the signal in (15) is baseband processed by the forward C-transform (FCT) to recover the M -ary modulated symbols as

$$\hat{\mathbf{d}} = \mathbf{C} \mathbf{r}^{det}. \quad (17)$$

IV. NUMERICAL RESULTS

In this section, the validity of the presented intensity modulation direct detection (IM/DD) C-O-OFDM system over optical wireless communications is proved by computer simulation. Number of OFDM subcarriers $N = 256$ with zero-padding guard interval of length $N_g = N/4$ is used in our simulation.

To ensure unipolar signal transmission, DC-biased optical (DCO) technique with two DC bias level ($B_{DC} = 13dB$) is used. The system parameters and tools that was used in our simulation is given in Table I. It is beneficial mentioning here that the main comparison is with the traditional optical DFT based OFDM (DFT-O-OFDM) as a standard system, however, we also compare the results with the DHT-O-OFDM that is presented in [8, 9]. The scope of this work is to expose the advantages of the presented C-O-OFDM scheme in exploring the diversity of indoor diffused multipath channel. However, for more information, the transmission of the C-O-OFDM system over AWGN channel is also examined and compared with the both DFT-O-OFDM and DHT-O-OFDM. The data mapping considered in simulation for all OFDM system following equation (7) is shown in Table II.

A. Transmission over AWGN channel

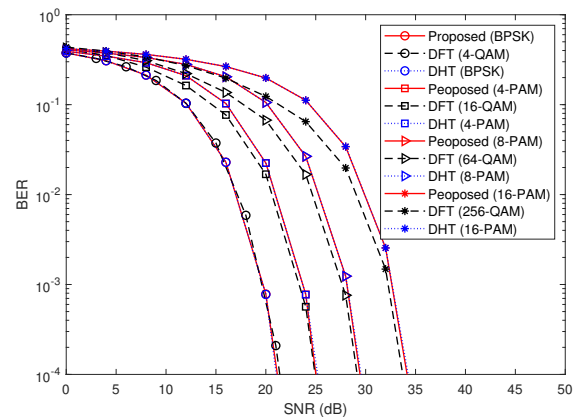


Fig. 2. BER performance of the proposed C-O-OFDM scheme in comparison with the conventional DFT-O-OFDM and DHT-O-OFDM schemes over AWGN channel.

TABLE I. Transmission parameters and software used for simulations.

System Item	Tools and Parameter
Software	Matlab R2019
Real Mapping	BPSK, 4-PAM, 8-PAM and 16-PAM
Complex Mapping	4-QAM, 16-QAM, 64-QAM and 256-QAM
Synchronisation	Perfect
Optical Channel	AWGN and Indoor diffused multipath channel
DC Bias	13 dB
Equalisation	MMSE
Number of Subcarriers (N)	256
Guard Interval	64
Bandwidth	6 MHz

TABLE II. Constellation size for DFT-O-OFDM, DHT-O-OFDM and the proposed C-O-OFDM.

Optical System	Constellation Size			
DFT-Based	4-QAM	16-QAM	64-QAM	256-QAM
DHT-Based	BPSK	4-PAM	8-PAM	16-PAM
Proposed C-Based	BPSK	4-PAM	8-PAM	16-PAM

In this section, the performance of the presented C-O-OFDM scheme is investigated in Fig. 2 and compared with the DFT-O-OFDM and DHT-O-OFDM over AWGN channel for $B_{DC} = 13dB$. It is clear from Fig. 2 that all aforementioned schemes have almost identical BER performance for all the modulation signalling (BPSK-16 PAM and 4-256 QAM). This is because the white noise nature that fairly distributes the noise power among the entire spectrum without fading. This results support our early claim that the proposed scheme can retain the orthogonality over AWGN exactly as the DFT - O-OFDM and DHT-O-OFDM. However, the advantages of the proposed scheme is in exploring the channel diversity of optical multipath wireless channels. It shows a significant superiority compared to other systems and achieves high immunity to multipath phenomena.

B. Transmission over optical multipath channel

The BER performance of the presented C-O-OFDM compared to that of the DFT-O-OFDM and DHT-O-OFDM schemes over diffused optical multipath channel for DC bias $B_{DC} = 13$ dB is presented in Fig. 3. It is obvious that the proposed optical scheme has the lowest error performance for all the data signalling. It is clear from Fig. 3 that, at 10^{-4} BER, the presented C-O-OFDM scheme outperforms the DFT-O-OFDM by about 22 dB SNR gain and achieves about 2.5 dB SNR gain in comparison with the DHT-O-OFDM. This superiority of our proposed scheme is owing to the exceptional characteristics of the C-transform that support incremental diversity and producing a robust multicarrier scheme to the

multipath channels.

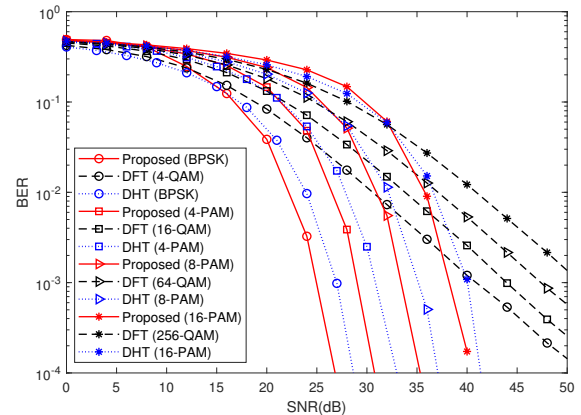


Fig. 3. BER performance of the proposed C-O-OFDM scheme in comparison to the conventional DFT-O-OFDM and DHT-O-OFDM schemes over indoor optical diffused wireless channel.

V. CONCLUSIONS

In this paper, a novel optical OFDM scheme based on real unitary C-transform suitable for indoor multipath transmission was presented. The proposed scheme has improved the BER performance over indoor multipath optical channel as well as enhanced the spectral efficiency as the real C modulation

transform does not require the Hermitian symmetry constraint on the input data. For DC bias $B_{DC} = 13$ dB and 10^{-4} BER, the developed scheme achieved about 22 dB SNR gain in comparison to the DFT-O-OFDM and about 2.5 dB SNR gain in comparison to the DHT-O-OFDM scheme among different signalling sizes (BPSK, 4-PAM, 8-PAM, 16-PAM and 32-PAM).

CONFLICT OF INTEREST

The author has no conflict of relevant interest to this article.

REFERENCES

- [1] J. K. Perin, M. Sharif, and J. M. Kahn, "Modulation schemes for single-laser 100 Gb/s links: Multicarrier," *J. lightwave technol.*, vol. 33, no. 24, pp. 5122–5132, 2015.
- [2] Z. A. H. Qasem, J. Wang, H. A. Leftah, H. Sun, S. Hong, J. Qi, and H. Esmail, "Real signal DHT-OFDM with index modulation for underwater acoustic communication," *IEEE J. Oceanic Engineering*, vol. 48, no. 1, pp. 246–259, Jan. 2023.
- [3] H. A. Leftah and S. Boussakta, "Precoded dct-ofdm system for baseband and wireless transmission: Performance analysis and evaluation," in *Wireless Telecommunications Symposium 2012*, pp. 1–6, 2012.
- [4] J. Armstrong, "OFDM for optical communications," *J. lightwave technol.*, vol. 27, no. 3, pp. 189–204, Feb. 2009.
- [5] B. J. C. Schmidt, A. J. Lowery, and J. Armstrong, "Experimental demonstrations of electronic dispersion compensation for Long-Haul transmission using direct-detection optical OFDM," *J. lightwave technol.*, vol. 26, no. 1, pp. 196–203, Jan. 2008.
- [6] Q. Yang, Y. Tang, Y. Ma, and W. Shieh, "Experimental demonstration and numerical simulation of 107-Gb/s high spectral efficiency coherent optical OFDM," *J. lightwave technol.*, vol. 27, no. 3, pp. 168–176, Feb. 2009.
- [7] W. Wang, D. Zou, X. Wang, Z. Li, X. Yi, L. Zhao-hui, and F. Li, "100 gbit/s/ λ DMT-PON system based on intensity modulation and heterodyne coherent detection," *IEEE Photonic Technol. Letters*, vol. 33, no. 18, pp. 1014–1017, Sep. 2021.
- [8] M. S. Moreolo, R. Munoz, and G. Junyent, "Novel power efficient optical OFDM based on hartley transform for intensity-modulated direct-detection systems," *J. lightwave technol.*, vol. 28, no. 5, pp. 798–805, March 2010.
- [9] M. S. Moreolo, "Performance analysis of DHT-Based optical OFDM using large-size constellations in AWGN," *IEEE comm. Letters*, vol. 15, no. 5, pp. 572–574, 2011.
- [10] H. A. Leftah and S. Boussakta, "Novel OFDM based on c-transform for improving multipath transmission," *IEEE Trans. Signal Process.*, vol. 62, no. 23, pp. 6158–6170, Dec. 2014.
- [11] H. A. Leftah and M. H. Al-Ali, "Index modulated spread spectrum OFDM with c-transform," *IEEE Commun. Lett.*, vol. 25, no. 9, pp. 3119–3123, Sep. 2021.
- [12] J. Armstrong and B. J. C. Schmidt, "Comparison of asymmetrically clipped optical OFDM and DC-Biased optical OFDM in AWGN," *IEEE Commun. Lett.*, vol. 12, no. 5, pp. 343–345, May 2008.
- [13] Z. Ghassemlooy, W. Popoola, and S. Rajbhandari, *Optical Wireless Communications: System and Channel Modelling with MATLAB*. CRC press, 2013.
- [14] H. G. Zelalem, K. L. Philip, and M. Ciira, "Ber performance of stratified aco-ofdm for optical wireless communications over multipath channel," *Journal of Comp., Networks and Comm.*, vol. 2018.
- [15] H. A. Leftah and S. Boussakta, "Efficient modulation scheme for OFDM system with ZP and MMSE equalizer," in *IEEE International Conference on Communications (ICC)*, June 2013.