Performance Evaluation of DHT Based Optical OFDM for IM/DD Transmission Over Diffused Multipath Optical Wireless Channel

Hussein A. Leftah,
Basrah Engineering Technical College (BETC),
Southern Technical University (STU), Basrah, Iraq
Email: h.a.leftah@stu.edu.iq

***Abstract*—Optical OFDM based on discrete Hartley transform (DHT-O-OFDM) has been proposed for large-size data mapping intensity modulation direct detection (IM/DD) scheme as an alternative to the conventional optical OFDM. This paper presents a performance analysis and evaluation of IM/DD optical DC-biased DHT-O-OFDM over diffused multipath optical wireless channels. Zero-padding guard interval along with minimum mean-square error (MMSE) equalizer are used in electrical domain after the direct detection to remove the intersymbol interference (ISI) and eliminate the deleterious effects of the multipath channels. Simulation results show that the ZP-MMSE can effectively reduce the effects of multipath channels. The results also show that the effects of optical wireless multipath channel become more serious as the data signaling order increases.**

***Index Terms*—Multipath optical wireless channel (OWC), Intensity modulation-direct detection (IM/DD), Orthogonal frequency division multiplexing (OFDM).**

I. Introduction

OPTICAL transmission based on multicarrier modulation (MCM) has received an intensive research attention. It has been adopted in several applications such as interconnects in data centres, high-speed optical local area networks (LANs), 100 Gbs Ethernet using multimode fiber (MMF) and high-performance computing [1] and [2]. Multicarrier modulation (MCM) is an effective technique in mitigating intersymbol interference (ISI) and channel dispersion in optical communications. Therefore, its combining with high order data mapping represents a promising low cost, high speed intensity modulation-direct detection (IM/DD) scheme. Optical MCM represented by the orthogonal frequency division multiplexing (O-OFDM) is more flexible to higher order signal mapping than single carrier optical systems as the latter requires costly coherent technique [3]. The cost effective implementation part of the conventional optical OFDM that is based on discrete Fourier transform (DFT) is the Hermitian symmetry (HS) constraint. The signal at the laser diode must be positive real signal whereas the output of the DFT is complex even though when its input is real. To make the output of the DFT real, its input must obey the Hermitian symmetry (HS) constraint. The HS constraint means half of the input data does not carry information and they are used only for HS purpose, hence reduce the spectral efficiency to half.

Recently, several research have been conducted on using discrete Hartley transform (DHT) as an alternative to the classic DFT for optical multicarrier transmission applications [4], [5] and [6]. It has been shown that the DHT based optical OFDM could achieve exact performance of the conventional optical OFDM that is based on the DFT without any loss in spectral efficiency and do not require the HS constraint. The DHT-O-OFDM transmission accomplished with using real data mapping such as binary phase shift keying (BPSK) or 4-32 pulse amplitude modulation (PAM) which is equivalent to DHT-O-OFDM when complex constellation 4-1024 quadrature amplitude modulation (QAM) is used. However, the DFT-O-OFDM requires HS constraint, hence reducing the spectral efficiency to half. It has been also shown that the DHT-O-OFDM is a promising alternative technique for IM/DD optical communication with direct bias optical (DCO) and asymmetrically clipped optical (ACO) schemes.

All previous works on using the DHT instead of the DFT in optical communications were over additive white Gaussian noise (AWGN) channel. However, the popularity of OFDM comes from its effectiveness in mitigating the deleterious effects of intersymbol interference (ISI) which is caused by the dispersive multipath channels. Therefore, to prove the validity of any proposed OFDM system, its performance should be analyzed and evaluated over multipath channels. Consequently, motivated by this popular characteristics of the DHT transform, we study, analyze and evaluate the performance of the DHT-O-OFDM over indoor multipath optical wireless channels.

The contribution of this paper is using ZP-MMSE equalizer to cancel the ISI and eliminate the effects of optical wireless multipath channels. It is also analyze and evaluate the bit-error-rate (BER) performance of IM/DD DHT-O-OFDM scheme over diffused multipath optical wireless channel with a large range of real data mapping (BPSK, 4-PAM, 8-PAM, 16-PAM and 32-PAM). The performance over multipath channels is different than that over AWGN channel and has serious challenges to be dealt with. Unlike the performance over AWGN channels, the performance over multipath channels required channel equalization and intersymbol interference (ISI) cancelation techniques. This channel equalization is different than that of the conventional DFT based optical OFDM where single-tap equalizer is used to eliminate the channel effects. Single-tap equalizer is only applicable in the case of DFT-O-OFDM due to the circular convolution/ direct multiplication

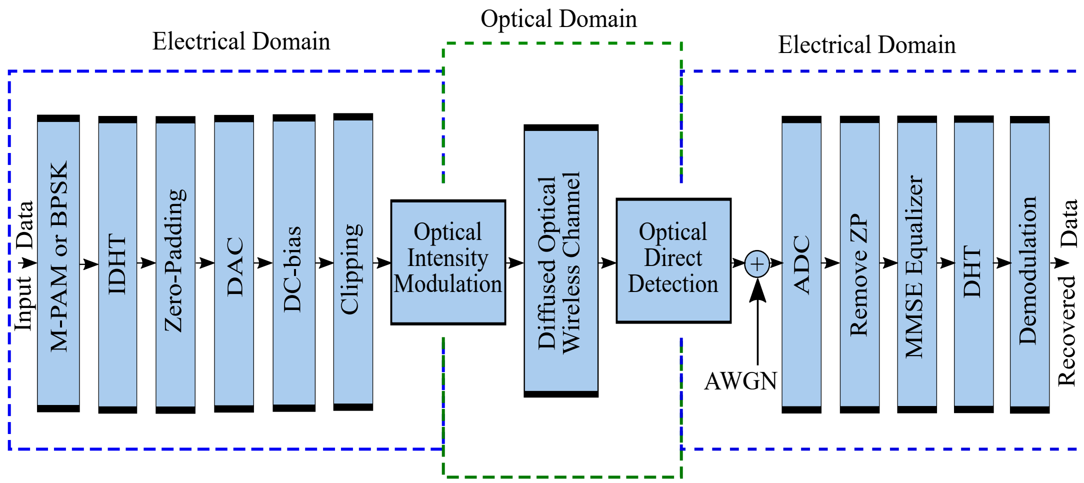

Fig. 1. Schematic diagram of optical OFDM based on DHT over diffused optical wireless channel

property of the DFT transform. This is not the case in the presented paper, where single tap equalizer cannot work with DHT based optical OFDM. Therefore we used a zero-padding along with time domain equalizer [7] and [8] to cancel the ISI and compensate for the channel gain. A direct current biased (DC-biased) optical scheme is used with DC-biased =7dB and 13 dB to study the effects of clipping noise and power efficiency on the transmission performance.

The rest of this paper is organized as follows: section II presents the DC-biased IM/DD technology. System model and mathematical transmission model is presented in section III. Section IV presents simulation results and discussion, and finally our conclusions is presented in section V.

II. DC-biased IM/DD

To make the signal suitable for IM/DD scheme, the signal must be positive real unipolar signal to avoid the clipping. Direct current DC-biased optical (DCO) and asymmetrical clipped optical (ACO) schemes are the most accepted technology to provide an unipolar positive signal [9]. DCO is a power inefficient technique as it added DC bias at least twice the standard deviation of the transmitted signal, which is unfortunately, this DC bias does not carry any information signal. On the other hand, ACO could generate a positive unipolar signal without a DC-bias, however, it is a spectral inefficient as it transmit signal only on the odd subcarriers

III. System Model

The IM/DD DHT-O-OFDM transmission system block diagram is shown in Fig. 1 for the baseband transmission over diffused optical wireless channel with MMSE equalizer. The signal is generated in electrical domain using BPSK or large-size real constellation M-array PAM. This real data symbol is then processed with the DHT to produce a multicarrier OFDM symbols as follows.

$$\mathbf{x} = \mathbf{H}\mathbf{d}, \tag{1}$$

where $\mathbf{H}$ is the $(N \times N)$ DHT matrix, and $\mathbf{d}$ is $(N \times 1)$ information data vector that are drawn from real constellation.

In order to prevent the ISI between the successive symbols, the produced symbol is zero padded with $N/4$ zeros. It is worth mentioning here that ZP technique is used in this work instead of the conventional cyclic prefix (CP) to mitigate the dispersion effects of optical multipath channel. It has been proved in [10] that the ZP based OFDM system achieves better transmission performance than the conventional CP based OFDM system. This was justified as, unlike the CP scheme, for the case of ZP scheme, the data symbols recovered regardless of the channel deep notches or zeros. Regarding the receiver complexity, both the CP and ZP based DHT-OFDM has the same equalizer degree of complexity.

The zero padded signal $\mathbf{x}_{zp}$ of length $(N_{zp} = N + \frac{N}{4})$ is expressed as

$$\mathbf{x}_{zp} = \mathbf{Z}\mathbf{x} \tag{2}$$

where $\mathbf{Z} = \left[\mathbf{I}_N \ \mathbf{0}_{N\times\frac{N}{4}}\right]^T$, $\mathbf{I}_N$ is identity matrix of length N and $(\mathbf{I}_N \ \mathbf{0}_{N\times\frac{N}{4}})$ is $(N \times \frac{N}{4})$ zero matrix and $[.]^T$ is the matrix transpose.
This signal is then used to modulate the intensity modulator to produce the optical domain signal. The clipping at laser diode intensity modulator due to the high negative picks of the $\mathbf{x}_{zp}$ could have a severe performance degradation. Therefore, the signal is the DC-biased with at least twice of its standard deviation to produce positive unipolar positive signal

$$\mathbf{s} = \mathbf{x}_{zp} + \mathbf{B}_{DC} \tag{3}$$

where $\mathbf{B}_{DC} = K\sqrt{E\left[\mathbf{x}_{zp}^2\right]}$ is the DC-biased level; its value in dB is $10\log_{10}^{K^2+1}$, and $E\left[\mathbf{x}_{zp}^2\right]$ is the variance of the electrical signal. If $\mathbf{B}_{DC}$ is not high enough and the remaining negative picks with be clipped producing extra clipping noise.

$$\mathbf{s} = \begin{cases} \mathbf{s}, & \text{if } \mathbf{s} \geq 0 \\ 0, & \text{if } \mathbf{s} < 0 \end{cases}$$

This optical signal is passed through the optical wireless channel (OWC). The OWC channel impulse response (CIR) is modeled using ceiling bounce model [11] and [12]. The CIR of diffused indoor OWC is given as

$$g(t) = G(0)\frac{6a^6}{(t+a)^7}u(t) \quad (4)$$

where $G(0)$ is the DC optical channel gain, $u(t)$ is a unit step function, $a = 12\sqrt{\frac{11}{13}}D_{rms}$ and D_{rms} is the delay spread of the multipath channel.

The received signal

$$\mathbf{y} = \mathbf{s} * \mathbf{g} + \mathbf{n}_c + \mathbf{w} \quad (5)$$

where $\mathbf{g} = [g_0, g_1, g_2, \cdots, g_L]$ is a vector whose elements are the discrete form of $g(t)$, $*$ is the convolution operation, and $\mathbf{w}$ is the additive white Gaussian noise (AWGN) and $\mathbf{n}_c$ is the clipping noise due to clipping of residual negative picks at zero level. It is obvious that the value of $\mathbf{n}_c$ is a function of $\mathbf{B}_{DC}$. It means that the clipping noise $\mathbf{n}_c$ decreases as the DC-biased level $\mathbf{B}_{DC}$ increases. In matrix form, (5) can be written as

$$\mathbf{y} = \mathbf{G}\mathbf{s} + \mathbf{n}_c + \mathbf{w}, \quad (6)$$

where $\mathbf{s}*\mathbf{g} = \mathbf{G}\mathbf{s}$. In (6), $\mathbf{G}$ is $N_{zp} \times N_{zp}$ channel convolution Toeplitz matrix [8]. its elements i_{th}, $0 \leq i \leq N_{zp}-1$, row and k_{th}, $0 \leq k \leq N_{zp}-1$, column are given as $G(i,k) = g(i-k)$ for $0 \leq (i-k) \leq L$ and $G(i,k) = 0$ otherwise.

Direct detection is then used to detect data from optical to electrical domain. To compensate for the OWC channel gain, channel equalization must be used. In this paper, an MMSE equalizer used before the DHT processing as follows:

$$\mathbf{r}^{MMSE} = \mathbf{Z}^T\mathbf{\Phi}\mathbf{y} \quad (7)$$

where $\mathbf{Z}^T$ is used to discard the last $\frac{N}{4}$ zero padded length and $\mathbf{\Phi}$ is the MMSE equalization matrix which is given as [7]:

$$\mathbf{\Phi} = \sigma_s^2(\sigma_s^2\mathbf{G}^T\mathbf{G} + \sigma_n^2\mathbf{I}_{N_{zp}})^{-1}\mathbf{G}^T. \quad (8)$$

In (8), $\sigma_s^2 = E\left[\mathbf{s}^2\right]$ and σ_n^2 is the signal and noise standard deviation respectively.

The equalized signal is then processed by the forward DHT to detect the information symbols as

$$\widehat{\mathbf{d}} = \mathbf{H}\mathbf{r}^{MMSE} \quad (9)$$

IV. Simulation Results

Simulation results and performance analysis of intensity modulation/ direct detection (IM/DD) DC-biased optical DHT-OFDM system is presented in this section. Large-size data mapping, BPSK, 4-PAM 8-PAM. 16-PAM and 32-PAM, are used in this section. Two types of DC-biased level ($\mathbf{B}_{DC}$ =7 dB and $\mathbf{B}_{DC}$ =13 dB) are used to demostrate the effects of clipping noise and power efficiency on the system performance. It is worth mentioning here that for, the sake of compatibility, we used the same DHT-O-OFDM system parameters of [4] and [5]. The simulation is run and averaged over 10000 transmission frames to achieve the simulation reliability. The BER performance is evaluated based on signal bit electrical power normalized to noise power.

A. Performance over AWGN channel

The BER performance of DC-biased IM/DD optical DHT-OFDM system over AWGN channel is shown in Fig. 2. As the channel is AWGN, guard interval represented by ZP and channel equalization are not used in this section. This results are in a good agreement with that in [4] and [5] as the simulation is run over AWGN channel.

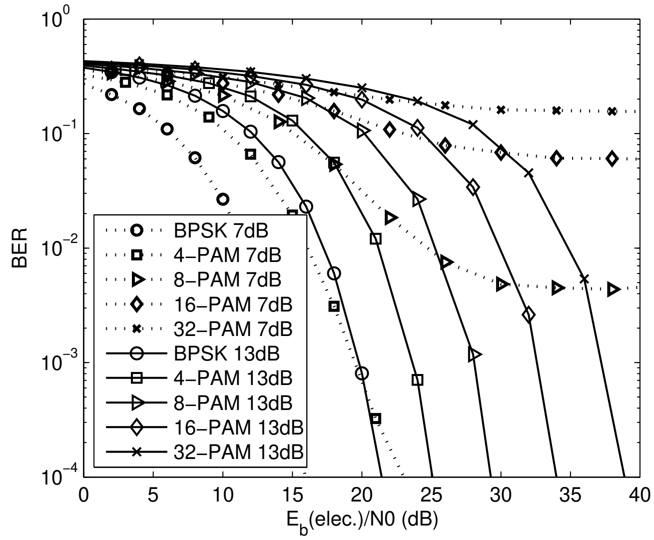

Fig. 2. BER performance of DC-biased IM/DD optical DHT-OFDM system over AWGN channel.

It is clear from Fig. 2 that for DC-bias=7 dB and small size constellations (BPSK and 4-PAM), the power efficiency is more important than clipping noise. Hence systems with DC-bias level =7dB superiors to systems with DC-bias level =13 dB. However, for large size constellations, such as 8-PAM, the clipping noise dominated the transmission performance and effected the overall BER performance, where error-flooring with BER=5×10^{-2} occurs at 30 dB $E_b(elect.)/N0$. Furthermore, this BER performance reduction will become even worse and the system lose its reliability for larger size constellation (16-PAM and 32-PAM).

When DC-bias level increases to 13 dB, the clipping noise of high negative picks at zero-level will not noticeably effect the BER, however at the cost of power efficiency.

For the case of BPSK, at 10^{-4} BER, the system with DC-bias=7 dB achieves 6 dB $E_b(elect.)/N0$ gain in comparison to BPSK system of DC-bias=13 dB. This $E_b(elect.)/N0$ gain was reduced to about 3 dB as the constellation size increased to 4-PAM. However, for 8-PAM and above, the DHT-O-OFDM with DC-bias=13 dB superior to that with DC-bias=7 dB and the BER continue to decrease as the signal power per noise ratio increased even for 32-PAM signal mapping.

B. Performance over diffused multipath OWC

In this section, indoor optical wireless multipath channel is used in our simulation to evaluate the transmission and BER performance of our proposed system. The channel impulse response (CIR) is normalized with maximum delay spread

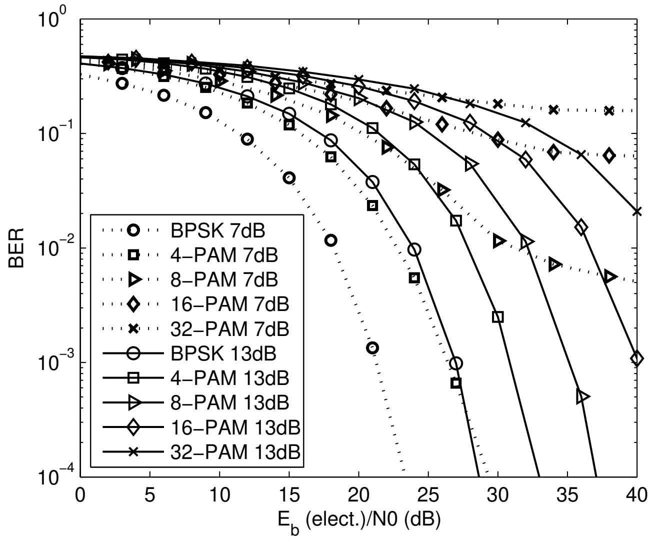

Fig. 3. BER performance of DC-biased IM/DD optical DHT-OFDM system over diffused multipath wireless optical channel.

($D_{rms} = 20ns$). The sampling frequency, $f_s = 100MHz$, is considered in simulation of discrete time domain channel impulse response. We assume that all the reflected light signal are arrived to the receiver side without being blocked by furniture or objects inside the room. We also assume that the furniture and objects in the room are not displaced so that the channel is quasi-static among the whole simulation transmission. This discrete time channel impulse response is having 32 samples. Hence, 32 guard interval is enough to cancel the intersymbol interference (ISI). However, in this simulation we used guard interval, represented by zero-padding, of $N/4 = 64$ samples to adhere to standards. BPSK, 4-PAM, 8-PAM, 16-PAM and 32-PAM data mapping with 80 Mbs, 160 Mbs, 2.4 Mbs, 320 Mbs and 400 Mbs data rate were used in our simulation.

It is clear from Fig. 3 that, unlike the single-tap equalizer, the ZP-MMSE time domain equalizer can effectively detect the useful signal out of the multipath channels. It is also obvious that at 10^{-4} BER and BPSK signaling, the $E_b(elect.)/N0$=24 and 28 dB for DC-bias= 7 dB and 13 dB respectively. In comparison with the case of AWGN channel, this BER was achieved at $E_b(elect.)/N0$=16 and 22 dB for DC-bias= 7 dB and 13 dB respectively. This means that the multipath channel imposes a reduction in SNR about 8 dB and 6 dB for DC-bias= 7 dB and 13 dB respectively. For larger-size constellation, the effects of optical multipath channel become more serious. For 32-PAM, and DC-bias=13 dB, the SNR penalty due to the multipath optical channel is about 10 dB at 10^{-4} BER. This can be attributed to the fact that as the constellation size increased, the distance between the signaling points become shorter and the modulation will be more susceptible to error than small size constellation.

V. Conclusion

A zero-padding time domain minimum mean-square-error (ZP-MMSE) equalizer was used with the DHT-based optical OFDM to eliminate the deleterious effects of the optical multipath wireless channels. A performance analysis and evaluation of IM/DD DC-biased optical DHT-O-OFDM over diffused multipath optical wireless channel was presented using wide-range of real data mapping (BPSK, 4-PAM, 8-PAM, 16-PAM and 32-PAM). The results showed that the ZP-MMSE equalizer can effectively compensate for the multipath channel effects. It was also shown that as the constellation size move to higher, the effects of the multipath optical wireless channel become more serious. This was clarified as the high order constellations have shorter euclidean distances and hence easily affected by the multipath channels.

References

[1] N. Naas and H. Mouftah, "On determining the cost-effective optical transport network architecture for next generation data center interconnectivity," 2016 IEEE Canadian Conference on Electrical and Computer Engineering (CCECE), Vancouver, BC, 2016, pp. 1-6.
[2] J. Krause Perin, M. Sharif and J. M. Kahn, "Modulation Schemes for Single-Laser 100 Gb/s Links: Multicarrier," in Journal of Lightwave Technology, vol. 33, no. 24, pp. 5122-5132, Dec.15, 15 2015.
[3] W. Shieh and I. Djordjevic.: "OFDM for Optical Communications". Elsevier, 2010.
[4] M. Svaluto Moreolo, R. Munoz and G. Junyent,: "Novel Power Efficient Optical OFDM Based on Hartley Transform for Intensity-Modulated Direct-Detection Systems," in Journal of Lightwave Technology, vol. 28, no. 5, pp. 798-805, March1, 2010.
[5] M. Svaluto Moreolo: "Performance Analysis of DHT-Based Optical OFDM Using Large-Size Constellations in AWGN" IEEE Comm. Letter, , vol.15, no.5, pp.572,574 2011
[6] Y. Cao, X. Zhou, J. Sun, W. Zhang and C. X. Wang, "Optical spatial modulation with DHT-based OFDM in visible light communication systems," 2017 9th International Conference on Wireless Communications and Signal Processing (WCSP), Nanjing, 2017, pp. 1-5.
[7] H. Leftah and S. Boussakta, "Efficient modulation scheme for OFDM system with ZP and MMSE equalizer," 2013 IEEE International Conference on Communications (ICC), Budapest, 2013, pp. 4703-4707.
[8] H. Leftah and S. Boussakta, "Novel OFDM Based on C-Transform for Improving Multipath Transmission," in IEEE Transactions on Signal Processing, vol. 62, no. 23, pp. 6158-6170, Dec.1, 2014.
[9] J. Armstrong and B. J. C. Schmidt, "Comparison of Asymmetrically Clipped Optical OFDM and DC-Biased Optical OFDM in AWGN," in IEEE Communications Letters, vol. 12, no. 5, pp. 343-345, May 2008.
[10] B. Muquet, W. Zhengdao, G. B. Giannakis, M. de Courville, and P. Duhamel, "Cyclic prefixing or zero padding for wireless multicarrier transmissions?," IEEE Transactions on Communications, vol. 50, pp. 2136-2148, 2002.
[11] Z. Ghassemlooy, W. Popoola, S. Rajbhandari, "Optical Wireless Communications: System and Channel Modelling with MATLAB" CRC press 2013.
[12] H. G. Zelalem, K. L. Philip and M. Ciira: "BER Performance of Stratified ACO-OFDM for Optical Wireless Communications over Multipath Channel". Journal of Computer, Networks and Communications, Volume 2018, Article ID 9575281, 14 pages.