Enhanced DC-biased optical OFDM for intensity-modulated optical OFDM access systems

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ABSTRACT

In this paper, an enhanced DC-biased optical orthogonal frequency division multiplexing (EDCO-OFDM), compatible with intensity-modulation optical access systems is proposed. Compared to conventional dc-biased optical OFDM (DCO-OFDM), EDCO-OFDM overcomes the performance limitation pertinent to high peak-to-average power ratio (PAPR) and provides better power and spectral efficiency over the state-of-the-art DCO-OFDM at the expense of increased computational complexity. High PAPR of the optical OFDM signal is counteracted using clipping and the clipping distortion instigated due to the clipping process, is eliminated at the receiver by reconstructing the affected samples iteratively. The fundamental parameters such as bit-error rate (BER) performance, spectral efficiency, and complexity, are analysed for EDCO-OFDM and compared with DCO-OFDM. Simulation results are provided to demonstrate the superiority of EDCO-OFDM over conventional DCO-OFDM.

Keywords: Peak-to-average power ratio, optical orthogonal frequency division multiplexing, clipping distortion.

1. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is used in optical systems because of inherent robustness against inter-symbol interferences, high spectral and power efficiency and immunity to florescent noise near the DC region [1]. In optical systems, intensity-modulation and direct-detection (IM/DD) is particularly attractive because of low cost and ease of implementation. IM/DD systems use signal envelop to modulate the optical carrier using an electrical to optical (E/O) transceiver (light emitting diode (LED) or laser). The intensity waveform (signal envelop) in IM/DD is restricted to be positive and real. OFDM techniques (tailored for IM/DD) which guarantee real and positive intensity waveform for IM are: dc-biased optical OFDM (DCO-OFDM) [2] and asymmetrically-clipped optical OFDM (ACO-OFDM) [3]. In DCO-OFDM, DC bias is added to bipolar signal to attain a unipolar signal, which results in increased transmitted power. In ACO-OFDM, only the odd sub-carriers are modulated (sacrificing the even sub-carriers) to obtain an asymmetric time-domain signal, even though this technique is power efficient but suffers with low spectral efficiency compared to DCO-OFDM. Also, conventional optical OFDM techniques are generally associated with high peak-to-average power ratio (PAPR), which results in degraded performance because of restricted E/O transceiver's dynamic range (DR) and limited resolution of digital-to-analog converter (DAC) [4].

In this paper, we have proposed enhanced DCO-OFDM (EDCO-OFDM), which overcomes the drawbacks/limitations of conventional DCO-OFDM, such as, high PAPR and low power/spectral efficiency. Deliberate clipping is applied at the transmitter to counteract the high PAPR, and thereby, reducing the required DC bias and consequently resulting in better power efficiency. The effected (or lost) samples due to clipping process are identified and reconstructed at the receiver (in time-domain) in an iterative manner. The iterative reconstruction of affected samples is inspired from [5]. Simulation results are provided to demonstrate the superiority of EDCO-OFDM over conventional DCO-OFDM.

2. ENHANCED DC-BIASED OPTICAL OFDM (EDCO-OFDM)

Consider an optical OFDM transmission with N sub-carriers, for which frequency-domain data-symbol sequence, $X_k,\ \forall\ k = 0,1,\cdots,N-1$, is mapped according to M-ary QAM alphabet $\{Q_0,Q_1,\cdots,Q_{M-1}\}$. The frame structure of data-symbol sequence, X_k, is such that first $N/2$ sub-carriers, $X_l,\ \forall\ l = 1,\cdots,N/2-1$, are modulated, setting the first sub-carrier equal to zero, i.e., $X_0 = 0$. Hermitian symmetry is imposed on the remaining $N/2$ sub-carriers, $X_m,\ \forall\ m = N/2+1,\cdots,N-1$, and setting $X_{N/2} = 0$ to ensure a real time-domain counterpart. X_k is converted to time-domain sequence, x_n, using IFFT. The N point IFFT output sequence is $x_n = \sum_{k=0}^{N-1} X_k e^{j2\pi kn/N},\ \forall\ n = 0,1,\cdots,N-1$.

The time-domain sequence x_n has high PAPR, which is counteracted by subjecting the signal to amplitude limiter prior to DAC stage. Following [1], the clipping model for time-domain sequence, x_n, resulting in clipped sequence, c_n, with amplitudes constrained by upper and lower limits, $A_{\rm ul}$ and $A_{\rm ll}$, respectively, is given by

$$c_n = \begin{cases} A_{\rm ul}, & x_n > A_{\rm ul} \\ x_n, & A_{\rm ll} \le x_n \le A_{\rm ul} \\ A_{\rm ll}, & x_n < A_{\rm ll} \end{cases}, \quad 0 \le n \le N-1. \tag{1}$$

For symmetric clipping i.e., $A_{ll} = -A_{ul}$, the clipping ratio, γ, and the clipping limits (A_{ul}, A_{ll}) are related as $\gamma \triangleq A_{ul}/\Omega$; where Ω is the root mean square power of OFDM signal. Upper and lower clipping limits (A_{ul}, A_{ll}) are defined by DR of the E/O transceiver as $D \triangleq A_{ul} - A_{ll}$. Observe that the model considered here, assumes that the clipped time-domain sequence, c_n, corresponds to the DR of E/O transceiver and input limits of DAC, and can be applied to both, optical wireless and optical fiber transmission systems, assuming that channel distortions are compensated using cyclic prefix at the transmitter and equalization at the receiver [6]. Furthermore, linear response of the transmitter and perfect synchronization is assumed [1].

Note that, the sequence, c_n, can be statistically modeled as a sum of two uncorrelated parts, $c_n = x_n + d_n \ \forall \ n = 0, 1, \cdots, N-1$, where d_n is the clipping distortion statistically uncorrelated to x_n [7]. The clipped sequence c_n is then impinged upon DAC to obtain a data-carrying intensity waveform, $x(t)$. Due to clipping, the required DC bias, β_{dc}, now becomes $\beta_{dc} = |\min[x(t)]|$ and can be prescribed in terms of clipping ratio γ, as $\beta_{dc} = \gamma\Omega$. Note that we have used DC bias, $\beta_{dc} = |\min[x(t)]|$, therefore, no clipping is performed after DC bias addition, since there are no residual negative samples left. The DC-biased signal is given by, $x_{\text{EDCO}}(t) = x(t) + \beta_{dc}$ for $\beta_{dc} > 0$. The transmitter of EDCO-OFDM is presented in Fig. 1. Assuming an additive white Gaussian noise (AWGN) channel [8], light

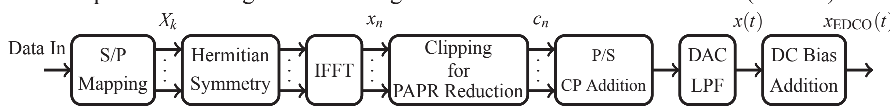


Figure 1. Proposed Enhanced DCO-OFDM Receiver.

intensity is photo-detected at the receiver and is transferred to an electrical signal. The received sequence, y_n, is given as

$$y_n = c_n + w_n, \ \ 0 \leq n \leq N-1. \tag{2}$$

where the noise w_n is IID (independent and identically distributed) with zero mean and variance of σ^2. The receiver of EDCO-OFDM is presented in Fig. 2. Performing FFT on y_n in equation (2) gives

$$Y_k = C_k + W_k = X_k + D_k + W_k = X_k + Z_k \ \forall \ k = 0, 1, \cdots, N-1 \tag{3}$$

where X_k and D_k are frequency-domain counterparts of x_n and d_n, respectively, and Z_k is combined clipping distortion and additive noise. Note that the naive DCO-OFDM receiver will disregard the presence of distortions, D_k, instigated due to the clipping process in (3) to obtain the estimated transmitted signal, thus, leading to significant performance degradation.

In EDCO-OFDM, time-domain samples (affected or lost by clipping) are reconstructed at the receiver with prior knowledge about the clipping ratio. The clipped samples are identified (using defined decision sets) and are reconstructed in an iterative fashion. It is worth mentioning that the reconstruction of the affected samples is similar in its logic to DAR algorithm proposed by Kim and Stüber in [5], but the uniqueness comes from the fact how it handles the real time-domain optical signal and deals with the DC bias. The affected samples can be reconstructed as follows

1. Time-domain signal, $\hat{y}_n$=IFFT$\{\hat{Y}_k\} - \beta_{dc}$ is evaluated and stored in memory. The step is performed only once.
2. Decisions on the transmitted symbols, $\hat{X}_k^{(i)}$, are made in frequency-domain by decoding and detecting the channel observations, $\hat{Y}_k^{(i)}$. For the first iteration, $i = 1$, which seeds the algorithm, we have $\hat{Y}_k^{(1)}$=FFT$\{\hat{y}_n\}$.
3. The decoded symbols are converted to time-domain, $\hat{x}_n^{(i)}$ = IFFT$\{\hat{X}_k^{(i)}\}$.
4. The clipped samples are identified based on decision sets defined as $S_1 : \hat{x}_n^{(i)} > A_{ul}$, $S_2 : A_{ll} \leq \hat{x}_n^{(i)} \leq A_{ul}$ and $S_3 : \hat{x}_n^{(i)} < A_{ll}$.
5. A set of indexes is evaluated such that $I \triangleq \{n_m, m = 0, 1, \cdots, N-1\}$ where $n_m = m$ for decision sets S_1 and S_3.
6. The clipped samples are reconstructed by replacing the samples in decision sets S_1 and S_3 by the ones which are issued from the encoder $\hat{x}_n^{(i)}$, as follows

$$\hat{y}_n^{(i)} = \begin{cases} \hat{x}_n^{(i)}, & n \in I \\ \hat{y}_n, & n \in \overline{I} \end{cases} \tag{4}$$

   where $\overline{I}$ is the complementary set of I, i.e., $\overline{I} \cap I = \varnothing$ and $\overline{I} \cup I = \{0, 1, \cdots, N-1\}$. The sequence $\hat{y}_n$ in (4) is the same which is obtained in step 1.
7. The reconstructed signal, $\hat{y}_n^{(i)}$, is converted to frequency-domain as $\hat{Y}_k^{(i)}$ = FFT$\{\hat{y}_n^{(i)}\}$.
8. Iteration counter is incremented $i = i+1$ and $\hat{Y}_k^{(i)}$ is updated as $\hat{Y}_k^{(i)} = \hat{Y}_k^{(i-1)}$.
9. Using $\hat{Y}_k^{(i)}$, $\hat{X}_k^{(i)}$ is estimated for the next iteration.

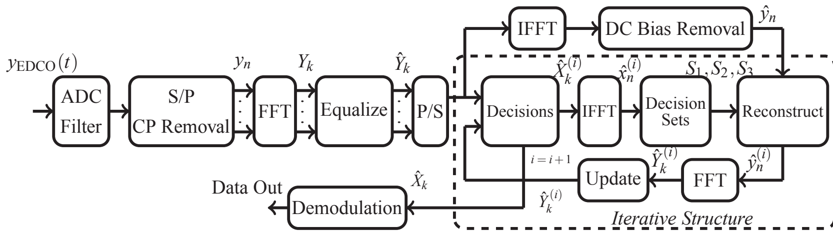


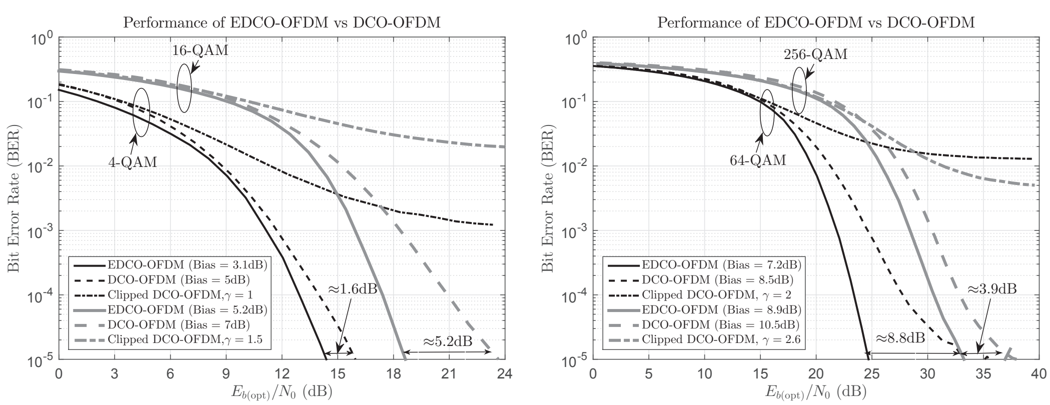
Figure 2. Proposed Enhanced DCO-OFDM Receiver.

3. SIMULATION RESULTS

In this section, simulation results are provided to demonstrate the performance of EDCO-OFDM considering 4-, 16-, 64- and 256-QAM and 3 iterations for iterative structure. EDCO- and DCO-OFDM with 1024 sub-carriers are simulated. The BER performance of clipped OFDM without reconstruction (at the receiver) is also evaluated, to demonstrate the capability of iterative reconstruction in EDCO-OFDM. Complementary cumulative distribution function (CCDF) curves are presented to illustrate the reduced PAPR of EDCO-OFDM. 3000 realizations are evaluated, unless mentioned otherwise.

3.1. Bit Error Rate Performance

Figure 3 depicts the BER performance of EDCO-OFDM for 4-, 16-, 64- and 256-QAM and γ of 1, 1.5, 2 and 2.6, respectively against $E_{b(\mathrm{opt})}/N_0$ (refer to [10] for definition of $E_{b(\mathrm{opt})}/N_0$ and DC bias). Non-clipped DCO-OFDM with 4-, 16-, 64- and 256-QAM with a DC bias of 5dB, 7dB, 8.5dB and 10.5dB, respectively, is used as a benchmark. Note that EDCO-OFDM provides a significant gain over an ideal case of non-clipped DCO-OFDM with 3 iterations. This is expected as due to clipping process, the required DC bias is reduced from 5dB to 3dB, 7dB to 5.1dB, 8.5dB to 7dB, and from 10.5dB to 8.9dB using 4-, 16-, 64- and 256-QAM, respectively, thus, resulting in better performance in terms of optical power consumption. $E_{b(\mathrm{opt})}/N_0$ gain is approximately 1.6dB, 5.2dB, 8.8dB and 3.9dB for clipping ratio γ of 1, 1.5, 2 and 2.6 using 4-, 16-, 64- and 256-QAM, respectively. The power consumption improvement is due to PAPR reduction as seen from CCDF curves presented Fig. 4(a). Achieved gain is significant when upper clipping is induced by the E/O transceiver (as for any current limited device) and no distortion compensation is done at the receiver. Further, it can be observed from CCDF curves, EDCO-OFDM using 4-, 16-, 64-, and 256-QAM exhibits reduced PAPR by approximately 8dB, 6.3dB, 4.3dB and 2.9dB for 4-, 16-, 64-, and 256-QAM respectively as compared to conventional DCO-OFDM.

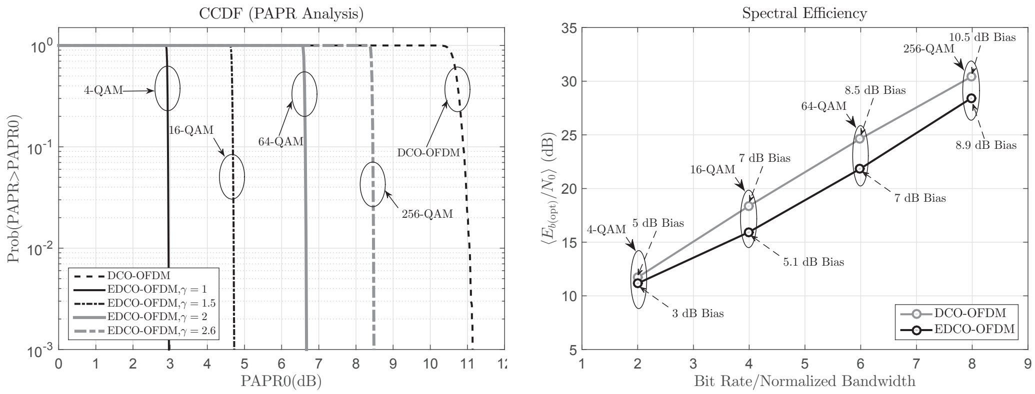


(a) (b)

Figure 3. BER versus $E_{b(\mathrm{opt})}/N_0$ for EDCO-OFDM.

3.2. Spectral Efficiency Performance

This experiment depicts how $\langle E_{b(\mathrm{opt})}/N_0 \rangle$ (the required $E_{b(\mathrm{opt})}/N_0$ for BER of 10^{-3}) varies with spectral efficiency defined as the ratio of bit rate to the normalized bandwidth. Fig. 4(b) has been achieved by fixing the BER equal to 10^{-3} and number of iterations equal to 3. The clipping ratio γ for EDCO-OFDM and DC bias for both EDCO- and DCO-OFDM are same as used in the BER performance analysis. Note that EDCO-OFDM provides better spectral efficiency as compared to conventional DCO-OFDM for each evaluated value of bit rate/normalized bandwidth.



(a) (b)

Figure 4. (a) CCDF curves (b) $\langle E_{b(\mathrm{opt})}/N_0 \rangle$ versus Bit Rate/Normalized Bandwidth.

3.3. Computational Complexity

FFT/IFFT of size N requires approximately $4N\log_2(N)$ real operations [11], therefore, the total number of real operations needed per second for FFT/IFFT are $4N\log_2(N)/\mathrm{T_{OFDM}}$, where $\mathrm{T_{OFDM}}$ is an OFDM symbol period defined as $\mathrm{T_{OFDM}} = (N+N_{CP})/R_s$, where N_{CP} is the size of cyclic prefix samples and R_s is the symbol rate. At the receiver, considering single tap equalization, 4 real multiplications and 2 real additions are required [11]. Therefore, the overall complexity order in real operations per bit for DCO-OFDM and EDCO-OFDM is

$$O_{\mathrm{DCO}}^{Tx+Rx} = \frac{[8N\log_2(N)+6N]\,T_bR_s}{(N+N_{CP})} \qquad O_{\mathrm{EDCO}}^{Tx+Rx} = \frac{[(2+i)8N\log_2(N)+6N]\,T_bR_s}{(N+N_{CP})} \tag{5}$$

where i is the number of iterations and $T_b = 1/(R_s\log_2(M))$ for modulation index M.

4. CONCLUSION

In this work, enhanced version of DCO-OFDM for IM optical access systems is proposed, which exhibits low PAPR and provide better power and spectral efficiency as compared to state-of-the-art DCO-OFDM. The PAPR is reduced by deliberate clipping of an optical OFDM signal and affected samples due to clipping are reconstructed in time-domain at the receiver. It has been demonstrated that the performance of the optical OFDM systems can be enhanced by using the proposed scheme. Further, it can be concluded that with a moderate number of iterations and additional complexity, EDCO-OFDM can be of interest for future optical IM/DD OFDM systems.

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