Time domain diversity combining with delay-and-advanced operation in two layered asymmetrically clipped optical OFDM system

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Abstract
This paper demonstrates the advantage of application of time domain diversity combining (TDDC) at the transmitter over the time domain diversity combining receiver (TDDR) for a single layer of ACO-OFDM in terms of reduced complexity. The paper further demonstrates the implementation of time domain delay-and-advanced operation with TDDC at the transmitter for a two-layered LACO-OFDM system, where all the subcarriers are utilized and an improved BER performance is achieved. The new improved 2-LACO-OFDM system achieves 2.7 dB, 3.3 dB and 3.7 dB better optical signal to noise ratio (OSNR) than the ACO-TDDC, 2-LACO-TDDC, 3-LACO-TDDC respectively.

Keywords ACO-OFDM · LACO-OFDM · ACO-TDDC · LACO-TDDC
1 Introduction

Layered Asymmetrically Clipped Optical Orthogonal Frequency Division Multiplexing (LACO-OFDM) has been proposed in (Wang et al. 2015), with similar approaches in (Islim et al. 2015; Lam et al. 2015; Lowery 2016; Li et al. 2021), has gained lots of attention as the preferred modulated technique for intensity modulated/direct detection (IM/DD) OFDM system. LACO-OFDM increases the spectral efficiency of Asymmetrically Clipped Optical OFDM (ACO-OFDM) (Armstrong and Lowery 2006; Armstrong et al. 2006) by transmitting multiple layers of ACO-OFDM on its subcarriers and iteratively removing the clipping noise at the receiver. Two layers LACO-OFDM or simply referred to as 2-LACO-OFDM uses 75% of total of subcarriers and 3-LACO-OFDM uses 87.5% of total of subcarriers. Hence, to utilize all the available subcarriers, LACO-OFDM implements more than 6-layers of ACO-OFDM, at the expense of a very large complexity (Islim et al. 2015).

Recently, Dual stream Asymmetrically Clipped Optical OFDM (DSACO-OFDM) was successfully demonstrated in (Baig et al. 2018a, b), that uses delay-and-advance operations to combine two layers of ACO-OFDM signal without compromising the loss of information. DSACO-OFDM showed better BER than 2-LACO-OFDM and 3-LACO-OFDM while achieving high spectral efficiency (Baig et al. 2018a, b).

The clipping distortion occurring from conventional ACO-OFDM process, falls on even subcarriers that contains some valuable information of the transmitted ACO-OFDM signal. This information is utilized by the diversity combining (DC) technique (Chen et al. 2009) to improve the BER performance of ACO-OFDM signal. This technique is commonly applied to receiver known as Time-Domain Diversity Combining Receiver (TDDR) (Dang et al. 2015; Li et al. 2019). This was applied at each layer of LACO-OFDM to further enhance its BER performance as demonstrated in (Mohammed et al. 2017). In the above-mentioned techniques, the application of DC to the receiver required the additional use of IFFTs which adds to the overhead complexity.

The additional use of IFFT is reduced when DC is applied to the ACO-OFDM transmitter in (Baig et al. 2017), referred to as Time-Domain Diversity Combining (TDDC). As the DC frees the subcarriers from clipping distortion, the advantage of reusing more number of freed subcarriers with more modulated information can be witnessed in TDDC.

In this work, a novel transmitter scheme is proposed for a 2-LACO-OFDM system through the application of TDDC with delay-and-advanced operation. The transmitter operation of the improved LACO-OFDM can be described in two steps:

1. A TDDC block is applied to the first layer of the 2-LACO-OFDM on odd subcarriers.
2. In the second layer, the data on the even subcarriers is shifted on to odd-subcarriers using the delay block. The resulting ACO-OFDM data is then subjected to TDDC block. This data is then shifted to even subcarriers by advancing in time domain.

The two signals resulting from the two layers are then combined to yield an improved 2-LACO-OFDM signal.

At the receiver, the data on the odd subcarriers and even subcarriers are separately detected without any interference. The proposed system achieves improved BER performance, spectral efficiency and a lower computational complexity at the receiver.
Fig. 1 Block Diagram of (a) Conventional ACO-OFDM Transmitter (b) Conventional ACO-OFDM Receiver with TDDR (c) ACO-TDDC System
2 Comparison of LACO-OFDM with TDDR and TDDC

Fig. 1(a) shows the block diagram for conventional ACO-OFDM system. The unipolar ACO-OFDM signal is generated by clipping the bipolar OFDM signal at zero, represented as in (Armstrong and Schmidt 2008)

\[
x_{ACO,n} = \begin{cases} 
  x_n & x_n \geq 0 \\
  0 & x_n < 0 
\end{cases}
\]  

(1)

The clipping distortion that is resulted from clipping operation falls only on the even subcarriers, without affecting the data on the odd subcarriers. The ACO-OFDM signal in terms of modulated data and clipping distortion is represented as

\[
x_{ACO,n} = \frac{1}{2} (x_n + |x_n|)
\]  

(2)

\[
x_{ACO,n} = x_{D,n} + x_{C,n}
\]  

(3)

where \(x_{D,n} = \frac{1}{2} x_n\) is the modulated data and \(x_{C,n} = \frac{1}{2} |x_n|\) (\(|\cdot|\) denotes the absolute operator) is the clipping distortion falling on the even subcarriers. The clipping distortion does not affect the modulated data \(x_{D,n}\) present on the odd subcarriers as shown in (Chen et al. 2009; Armstrong and Schmidt 2008).

Multiple layers of ACO-OFDM represented by Eq. (3), are then combined and expressed in (Mohammed et al. 2017) as

\[
x_{LACO} (n) = \sum_{l=1}^{L} x_{lACO} (n)
\]  

(4)

where

\[
x_{lACO} = x_{lD,n} + x_{lC,n}
\]  

(5)

where ‘\(l\)’ represents the layers, \(x_{lD,n}\) and \(x_{lC,n}\) represents the data and the clipping distortion of ‘\(l\)’ layers.

2.1 LACO-OFDM with TDDR

The data and the clipping distortion are recovered at each layer of ACO-OFDM receiver, as shown in Fig. 1(b). The TDDR applied to each layer of LACO-OFDM in (Mohammed et al. 2017), is represented as

\[
x_{LACO-TDDR} (n) = (1 - \alpha) * x_{D} (n) + \alpha * (\text{sign}(x_{D} (n))) * x_{C} (n)
\]  

(6)
where ‘$\alpha$’ is the combination factor that defines the relation between modulated data $x_{D,n}$ and the non-linear processing of $\text{sign}(x_{D,n})^*|x_{D,n}|$.

### 2.2 LACO-OFDM with TDDC

The TDDC block is applied to each layer of ACO-OFDM transmitter as shown in Fig. 1(c), and the principle of operation remains the same as in ACO-TDDR. TDDC applied to each layer of LACO-OFDM transmitter, is represented as.

$$x_{\text{LACO-TDDC}}(n) = (1 - \alpha)^*x_{D}(n) + \alpha^*(\text{sign}(x_{D}(n))^*x_{C}(n))$$  \hspace{1cm} (7)

### 3 Comparison between TDDR and TDDC

This section analyzes the comparison between TDDR and TDDC in terms of BER and computational complexity. The BER comparison of TDDR and TDDC for ACO-OFDM is shown in Fig. 2.

The BER performance against $E_{b(\text{opt})}/N_0$ (dB) [optical signal-to-noise ratio (OSNR)] for the systems presented in Fig. 2 are evaluated for 16-QAM constellations. The average optical power is normalized to unity for all the models as in (Baig et al. 2018a, b). The simulations are carried for IFFT size $N=1024$ with 256 symbols. The OFDM symbol rate is 10 Gsamples/s and an oversampling of 4 is used to get accurate results as in (Baig et al. 2018a, b).

It is seen that for a BER of $10^{-3}$, the performance is the same for both TDDR and TDDC applied to each layer, and with both showing 3 dB improvement over ACO-OFDM for 64-QAM and 1024-QAM for a fixed $\alpha = 0.5$. ACO-TDDR OFDM and ACO-TDDC OFDM demonstrates a 3 dB improvement over conventional ACO-OFDM. Similarly, 2-LACO-TDDR OFDM and 2-LACO-TDDC OFDM demonstrate a 3 dB improvement over conven-

![Fig. 2 BER comparison curves for TDDR and TDDC applied to ACO-OFDM, 2-LACO-OFDM and 3-LACO-OFDM](image)
tional 2-LACO-OFDM. Likewise, 3-LACO-TDDR OFDM and 3-LACO-TDDC OFDM demonstrate a 3dB improvement over conventional 3-LACO-OFDM.

The complexity ‘Θ’ of a system is defined by the number of complex multiplications of IFFT/FFT operations (Dang et al. 2015; Niwareeba et al. 2021). The computational complexity comparison of ACO-TDDR and ACO-TDDC was analyzed for ACO-OFDM (single layer), as shown in Table 1. ACO-TDDR requires a single IFFT at the transmitter and its complexity is computed as Θ (Nlog₂N). The complexity of ACO-TDDR receiver is 4Θ (Nlog₂N) as it requires 4 FFTs.

The complexity of both ACO-TDDC transmitter and receiver is Θ (Nlog₂N), as it requires only a single IFFT and FFT at the transmitter and receiver respectively, as seen in Fig. 1(c). Therefore, it is evident that ACO-TDDC OFDM has a lower computational complexity when compared to ACO-TDDR OFDM.

This section has shown that TDDC has similar BER performance in comparison to TDDR. However, as TDDC has a lower computational complexity in comparison to TDDR, it is seen that is more advantageous.

4 Improved 2-LACO-OFDM system

This section presents the transceiver design of the improved 2-LACO-OFDM system.

4.1 Transmitter

The block diagram of the 2-LACO-OFDM system with TDDC transmitter is shown in Fig. 3(a).

The resulting signal \( x_{ACOTDDC}^o \) (first layer of improved 2-LACO-OFDM) generated from the combined application of ACO-OFDM modulation and TDDC block is given as

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Table 1 Complexity comparison of TDDR and TDDC for ACO-OFDM (single layer)

| Techniques       | Transmitter | Receiver |
|------------------|-------------|----------|
| ACO-TDDR         | Θ (Nlog₂N) | 4Θ (Nlog₂N) |
| ACO-TDDC         | Θ (Nlog₂N) | Θ (Nlog₂N) |

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Fig. 3 (a) Block diagram of improved 2-LACO-OFDM Transmitter

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\[ x^{\prime}_{ACOTDDC} = (1 - \alpha) \ast x^o + \alpha \ast (\text{sign}(x^o) \ast |x^o|) \] (8)

As stated earlier, this signal resulting from this process has only the processed data on the odd subcarriers, and it contains no data on the even subcarriers. The second layer, carrying the real valued data on the even subcarriers \( X^e \) are shifted onto the empty odd subcarriers by delaying in time, represented as \( x^e_{ACOTDDC} \). This signal is then fed into the ACO-OFDM modulation block (Abd Elkarim et al. 2021) that generates the ACO-OFDM signal represented as \( x^{\prime}_{ACO} \). The TDDC block generates the resulting ACO-TDDC OFDM signal on the odd subcarriers \( x^{ed}_{ACOTDDC} \) given as

\[ x^{ed}_{ACOTDDC} = (1 - \alpha) \ast x^e + \alpha \ast (\text{sign}(x^e) \ast |x^e|) \] (9)

This data signal present on the odd subcarriers, and is shifted to even subcarriers by advancing in time domain. This process generates the resulting signal represented as \( x^{ed}_{ACOTDDC} \). The two signals ACO-TDDC OFDM resulting from the two layers are now combined to yield the improved 2-LACO-OFDM signal given as

\[ x_{2-LACO} = x_{ACOTDDC}^o + x_{ACOTDDC}^e \] (10)

This signal is appended with Cyclic Prefix (CP), converted from parallel to serial (P/S), converted into analog signal using a digital to analog converter (D/A) and then sent to the optical modulator.

### 4.2 Receiver

The implementation of TDDC simplifies the receiver design as it only requires a single FFT to demodulate the received signals (on the odd and even subcarriers separately) as shown in Fig. 3(b).

The received signal detected by a photodetector is expressed in time domain as

\[ y_{i-2LACO,n} = x_{i-2LACO,n} \ast h_n + w_n \] (11)
for $n = 0, 1, \ldots, N - 1$, where $h_n$ represents the channel state information and $w_n$ represents the additive white Gaussian noise (AWGN). After the conversion of serial to parallel (S/P), analog to digital (A/D), removal of CP, the received signal is transformed into frequency domain by an $N$-point FFT. This signal is further equalized and represented as

$$Y_{i-2LACO,k} = X_{i-2LACO,k}H_k + W_k$$

(12)

for $k = 0, 1, \ldots, N - 1$. Considering a flat channel, Eq. (12) can be re-written as

$$Y_{i-2LACO,k} = X_{i-2LACO,k} + W_k$$

(13)

The enhanced ACO-OFDM signal, free from any distortion, is detected from the odd subcarriers using the maximum likelihood (ML) detection, given as

$$X_{ACOTDDC,k}^o = \arg \min_{X \in Q_M} |H_k X - Y_{ACOTDDC,k}^o|$$

(14)

where $k = 1, 3, \ldots, N/2 - 1$

Similarly, the enhanced ACO-OFDM signal, free from any distortion, is detected from the even subcarriers as

$$X_{ACOTDDC,k}^e = \arg \min_{X \in Q_M} |H_k X - Y_{ACOTDDC,k}^e|$$

(15)

where $k = 2, 4, \ldots, N/2 - 1$

5 Results and discussion

The BER curves for improved 2-LACO-OFDM shown in Fig. 4, are generated using Monte-Carlo simulations and are compared with the 2,3-LACO-OFDM as generated in
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(Mohammed et al. 2017). The BER performance of proposed system is also compared with conventional ACO-OFDM and applied TDDC. The simulations were carried out for 64-QAM. As seen in Fig. 4 for a BER of $10^{-3}$, improved 2-LACO-OFDM system has 2.7 dB, 3.3 dB and 3.7 dB better optical signal to noise ratio (OSNR) than ACO-TDDC, 2-LACO-TDDC and 3-LACO-TDDC respectively.

6 Conclusions

In this letter, an improved 2-LACO-OFDM with lower complexity is presented that uses all the available subcarriers without losing any information. It was shown that the improved 2-LACO-OFDM with the implementation of time domain delay-and-advanced operation and time domain diversity combining has a better OSNR performance.

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