Layered Antisymmetry-Constructed Clipped Optical OFDM for IM/DD Systems

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***Abstract*—In this paper, antisymmetry-constructed clipped optical OFDM (AC-OFDM) is proposed for intensity modulation with direct detection (IM/DD) systems, in which an antisymmetry property is imposed directly in time domain. AC-OFDM has the same spectral efficiency as traditional asymmetrically clipped optical OFDM (ACO-OFDM) but is less complex to implement. Layered AC-OFDM (LAC-OFDM) is then proposed as an extension to further improve spectral efficiency, where different layers of AC-OFDM signals are added in the time domain and transmitted simultaneously. Computational complexity analysis and numerical results show that LAC-OFDM has the same spectral efficiency as layered asymmetrically clipped optical OFDM (LACO-OFDM) and enhanced unipolar OFDM (eU-OFDM) but is less complex in terms of both the number of real multiplications and real additions required. Specifically, LAC-OFDM requires less than half the multiplication and addition operations compared to the comparable LACO-OFDM scheme. Monte Carlo simulation results show that LAC-OFDM has the same bit error rate (BER) performance as LACO- and eU-OFDM.**

***Index Terms*—visible light communications, intensity modulation with direct detection (IM/DD), OFDM, LACO-OFDM, eU-OFDM.**

I. Introduction

Visible light communications (VLC) is enjoying intense interest in both industrial and academic research communities due to the ubiquity of solid-state illumination [1], [2]. In VLC, data are modulated onto the instantaneous optical intensity emitted by a light-emitting diode (LED), i.e., intensity modulation (IM), and are detected by a photodiode (PD), i.e., direct detection (DD). Thus, all signalling for VLC channels must be real, non-negative and have a bounded mean value [1]–[3].

The use of orthogonal frequency division multiplexing (OFDM) in VLC channels has been considered by many others to extract maximum spectral efficiencies from illumination LEDs which are typically lowpass in nature. In order to make OFDM compatible with the amplitude constraints of VLC channels, direct current (DC) biased optical OFDM (DCO-OFDM) adds a DC bias to a conventional OFDM signal, consuming optical power while conveying no information. [4]. To improve optical power efficiency, asymmetrically clipped optical OFDM (ACO-OFDM) [5] and unipolar OFDM (U-OFDM) [6] were proposed, however, at a cost of half of the spectral efficiency. Enhanced U-OFDM (eU-OFDM) [6], and layered ACO-OFDM (LACO-OFDM) [7]–[12] where developed to retain the power efficiency of early approaches (i.e., no DC bias) while improving spectral efficiency. Both of these approaches work by combining different streams or layers of non-negative time-domain signals at the transmitter and successively detecting the modulated symbols at the receiver [6], [7]. Although the spectral efficiency can be enhanced theoretically up to two times, both eU- and LACO-OFDM suffer from potentially high computational complexity with a large number of layers which may limit their application in simple and energy efficient luminaires.

In this paper, we propose *antisymmetry-constructed clipped optical OFDM* (AC-OFDM) for IM/DD systems. In this approach, an antisymmetric time domain signal is constructed, as in ACO-OFDM, however, all processing is done in time domain. It is shown that AC-OFDM has the same spectral efficiency as traditional ACO-OFDM however requires far fewer computations. Using a similar approach as in [7], a layered AC-OFDM (LAC-OFDM) is proposed to further improve the spectral efficiency by sending information in different layers of AC-OFDM signals that are superimposed and detected successively. The computational complexity analysis and numerical results show that LAC-OFDM requires less multiplication operations and addition operations than LACO- and eU-OFDM. Specifically, LAC-OFDM requires less than half multiplication operations and addition operations compared to the traditional LACO-OFDM, and has the same spectral efficiency and bit error rate (BER) performance as LACO- and eU-OFDM. Though LAC-OFDM is similar in philosophy to LACO-OFDM, it is shown to have a much simpler implementation which is amenable to low cost, energy efficient, luminaires employed in VLC.

The balance of the paper is organized as follows. Section II introduces AC-OFDM and LAC-OFDM and makes connections to existing ACO- and LACO-OFDM techniques. The computational complexity and spectral efficiency of LAC-OFDM are analyzed in Section III while numerical results of the complexity and BER performance are presented in Section IV. Finally, conclusions are drawn in Section V.

II. Layered Antisymmetry-Constructed Clipped Optical OFDM

A. Background

In an ACO-OFDM system with N subcarriers, data symbols are only modulated onto the odd subcarriers, while the even subcarriers are set to zero [5]. Considering the Hermitian symmetry necessary to have a real-valued output, the input

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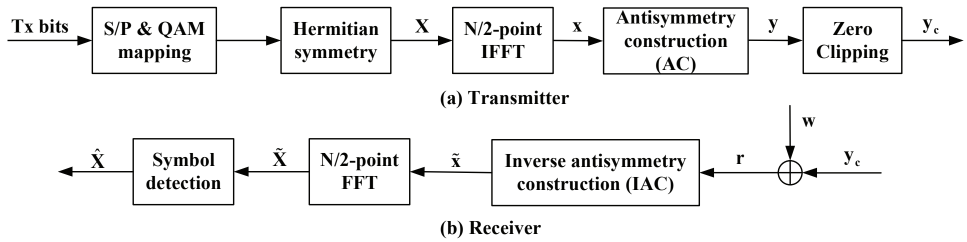

Fig. 1. Transceiver design block diagram for AC-OFDM.

symbol vector to the inverse fast Fourier transform (IFFT) is

$$\mathbf{X}_{\text{ACO}} = [0, X_1, 0, X_3, 0, \cdots, 0, X_3^*, 0, X_1^*]^T \tag{1}$$

where $X_k, 1 \leq k \leq N-1$, is a complex symbol chosen from a quadrature amplitude modulation (QAM) constellation and $(\cdot)^T$ denotes the transpose operation. A consequence of using odd carriers only is that the output ACO-OFDM signal vector $\mathbf{x}$ of the IFFT is antisymmetric [5], i.e.,

$$x_n = -x_{n+N/2}, \ 0 \leq n \leq N/2-1. \tag{2}$$

It has been shown that the non-negativity constraint can be satisfied by clipping the negative part of $\mathbf{x}$ directly with no distortion to the data being transmitted. The clipping distortion consists only of components at even subcarriers in the frequency domain and hence at the receiver side, ACO-OFDM symbols can be detected directly on the odd subcarriers [5].

Although, ACO-OFDM is energy efficient, it has half of the spectral efficiency of traditional DCO-OFDM. To improve the spectral efficiency, LACO-OFDM was proposed where different layers of ACO-OFDM signals are added in time domain and transmitted simultaneously [7]. In the l-th layer, LACO-OFDM modulates data onto subcarriers with index $2^{l-1}(2k+1), (k = 0, 1, \ldots, N/2^{l+1}-1)$. Notice that for each layer, the set of subcarriers used is disjoint. The output signal vector of the IFFT of each layer shares the antisymmetric property of ACO-OFDM and thus zero clipping is used to make the signal nonnegative. The clipping distortion for a given layer distorts all high layers and hence, the LACO-OFDM receiver demodulates low layer ACO-OFDM symbols before higher layers.

B. Antisymmetry-Constructed Clipped Optical OFDM

For an N-subcarrier AC-OFDM system, the transceiver block diagram is shown in Fig. 1.

At the transmitter, bits are mapped to QAM constellation symbols after serial-to-parallel (S/P) conversion. After Hermitian symmetry, the input symbol vector to the $N/2$-point IFFT is given by

$$\mathbf{X} = \left[0, X_1, X_2 \cdots, X_{N/4-1}, 0, X_{N/4-1}^*, \cdots, X_2^*, X_1^*\right]^T. \tag{3}$$

Notice that the AC-OFDM frame is of length $N/2$, rather than N for ACO-OFDM in (1), and that there is no requirement to use only odd subcarriers. The output of $N/2$-point IFFT is given as

$$x_n = \frac{1}{\sqrt{N/2}} \sum_{k=0}^{N/2-1} X_k \exp\left(j\frac{2\pi}{N/2}nk\right), \ 0 \leq n \leq \frac{N}{2}-1. \tag{4}$$

Prior to zero clipping, consider constructing the time-domain signal vector $\mathbf{y}$ using a process termed here as *antisymmetry construction* (AC) as

$$\mathbf{y} = [\mathbf{x}^T, -\mathbf{x}^T]^T. \tag{5}$$

Notice that $\mathbf{y}$ is antisymmetric, as in ACO-OFDM, i.e.,

$$y_n = -y_{n+N/2}, \ 0 \leq n \leq N/2-1. \tag{6}$$

Similar to ACO-OFDM, the negative part of $\mathbf{y}$ can be clipped without any loss of information. Hence, applying zero clipping to $\mathbf{y}$ leads to the AC-OFDM signal

$$y_{c,n} = \frac{1}{2}(y_n + d_n), \ 0 \leq n \leq N-1 \tag{7}$$

where $d_n = |y_n|$ is the clipping distortion and $|\cdot|$ denotes absolute value operation. Using (5) and (7), $\mathbf{y}_c$ can be written as

$$\mathbf{y}_c = \left[\frac{1}{2}\mathbf{x}^T + \frac{1}{2}|\mathbf{x}|^T, -\frac{1}{2}\mathbf{x}^T + \frac{1}{2}|\mathbf{x}|^T\right]^T. \tag{8}$$

Notice that $\mathbf{x}$ can be retrieved from $\mathbf{y}_c$ though the an *inverse antisymmetry construction* (IAC) operation

$$x_n = y_{c,n} - y_{c,n+N/2}, 0 \leq n \leq N/2-1. \tag{9}$$

At the receiver, shot noise and thermal noise are present and well modelled as additive white Gaussian noise (AWGN) [5], [7]. Without loss of generality, a flat channel with unit channel gain is assumed to aid in comparison with earlier work [5]. The received signal is therefore given by

$$r_n = y_{c,n} + w_n, \ 0 \leq n \leq N-1 \tag{10}$$

where w_n is a sample of AWGN with standard deviation σ_w. Based on (9), an estimate of x_n can be obtained through the IAC operation as

$$\tilde{x}_n = r_n - r_{n+N/2}, 0 \leq n \leq N/2-1. \tag{11}$$

Define $\tilde{\mathbf{X}}$ as the $N/2$ point FFT of the received vector $\tilde{\mathbf{x}}$.

Finally, AC-OFDM can be detected symbol-by-symbol, i.e.,

$$\widehat{X}_k = \arg\min_{X \in \Omega_X} \left\|X - \widetilde{X}_k\right\|^2, \ k = 1, 2, \cdots, N/4-1 \tag{12}$$

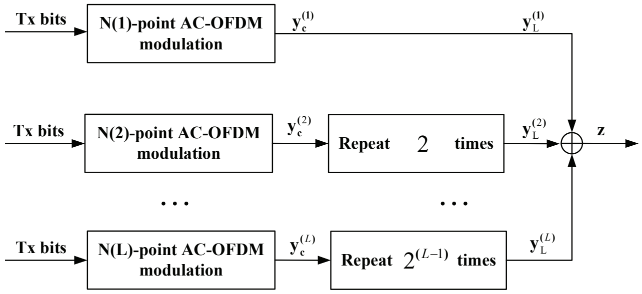

Fig. 2. Transmitter design block diagram for LAC-OFDM.

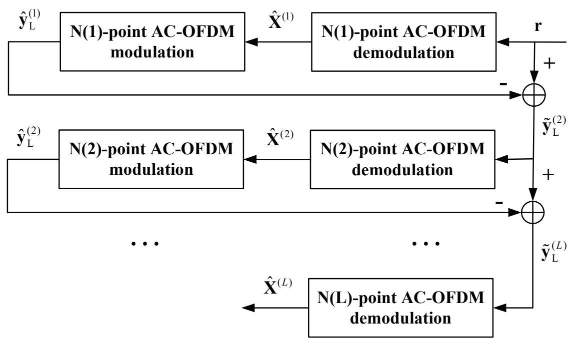

Fig. 3. Receiver design block diagram for LAC-OFDM.

where Ω_X denotes the constellation and $\|\cdot\|$ denotes the magnitude of a complex value.

C. Layered AC-OFDM

The transmitter block diagram for the proposed LAC-OFDM is shown in Fig. 2. Similar to traditional LACO-OFDM [7], different layers of AC-OFDM signals are added in the time domain and transmitted simultaneously.

In the l-th layer AC-OFDM, an $N_{\text{AC}}(l)$-point IFFT is utilized where

$$N_{\text{AC}}(l) = \frac{N}{2^l}. \tag{13}$$

In contrast, a $2N_{\text{AC}}(l)$-point IFFT is used at layer l in the traditional LACO-OFDM. At each layer, AC-OFDM modulation is performed including an $N_{\text{AC}}(l)$-point IFFT (4), antisymmetry construction (5) and zero clipping (7), resulting in the signal, $\mathbf{y}_c^{(l)}$, with length $2N_{\text{AC}}(l)$. Similar to traditional LACO-OFDM [7], repeating $\mathbf{y}_c^{(l)}$ for 2^{l-1} times gives the l-th layer signal in LAC-OFDM

$$\mathbf{y}_L^{(l)} = [\underbrace{{\mathbf{y}_c^{(l)}}^T, \cdots, {\mathbf{y}_c^{(l)}}^T}_{\text{repeated } 2^{l-1} \text{ times}}]^T. \tag{14}$$

The LAC-OFDM signal vector, $\mathbf{z}$ is the summation of the L layers,

$$\mathbf{z} = \sum_{l=1}^{L} \alpha_l \mathbf{y}_L^{(l)} \tag{15}$$

where α_l is power allocation factor for each layer. Though not explicitly shown in the figure, this scaling is done to ensure that each layer of LAC-OFDM has the same BER performance as discussed in Sec. IV.

At the receiver, LAC-OFDM is demodulated layer-by-layer in an analogous fashion to LACO-OFDM. Since the clipping distortion of l-th layer only affects layers higher than l, symbols in lower layers are detected first. Specifically, symbols $\widehat{\mathbf{X}}^{(1)}$ in the first layer are detected first through an $N/2$-point AC-OFDM demodulation including inverse antisymmetry construction (11), $N/2$-point FFT and symbol detection (12). Then the first layer AC-OFDM signal $\hat{\mathbf{y}}_L^{(1)}$ is reconstructed through $N/2$-point AC-OFDM modulation including $N/2$-point IFFT (4), antisymmetry construction (5) and zero clipping (7). The signal $\hat{\mathbf{y}}_L^{(1)}$ is subtracted from $\mathbf{r}$ leading to $\tilde{\mathbf{y}}_L^{(2)}$, which is used to demodulate the symbols $\widehat{\mathbf{X}}^{(2)}$ in the second layer.

For $l \geq 2$, as seen in Fig. 2, notice that $\mathbf{y}_c^{(l)}$ is repeated 2^{l-1} times in each frame. Taking advantage of this inherent repetition code in the frame of the LAC-OFDM signal, an estimate of the AC-OFDM signal $\tilde{\mathbf{y}}_c^{(l)}$ can be found by averaging over the repetitions in the frame as

$$\tilde{y}_{c,n}^{(l)} = \frac{1}{2^{l-1}} \sum_{q=0}^{2^{l-1}-1} \tilde{y}_{c,n+q}^{(l)}, 0 \leq n \leq \frac{N}{2^{l-1}} - 1. \tag{16}$$

This repetition in the structure of the AC-OFDM signal is also exploited in LACO-OFDM through the use of the N-point FFT operation. The remaining detection process is similar to the case for layer 1 described earlier with the signals reconstructed at each layer and subtracted from the received signal.

It is interesting to note that this receiver structure combines the layered approach of LACO-OFDM [7] with the time-domain processing of the receiver from eU-OFDM [6].

III. Analysis

A. Computational Complexity Assumptions

In this section, the computational complexity of LAC-OFDM is quantified by counting the number of real-valued multiplication and addition operations required and comparing them to the requirements for LACO- and eU-OFDM.

According to [13], for an N-point IFFT or FFT module using Cooley-Tukey decomposition and N a power of 2, $M(N)$ real-valued multiplications and $A(N)$ real-valued addition operations are required where

$$M(N) = 2N\log_2(N) - 4N + 4 \tag{17}$$

and

$$A(N) = 3N\log_2(N) - 2N + 2. \tag{18}$$

In the subsequent analysis, our underlying assumption is that operations such as clipping or antisymmetry construction (5) do not require any arithmetic operations as they can be efficiently implemented via switching logic. Additionally, the complexity of detecting individual symbols on carriers is not included in this analysis and will be the same for all schemes considered.

B. Computational Complexity: Transmitter

At the LAC-OFDM transmitter, each layer requires an FFT of length $\frac{N}{2^l}$. Hence, the number of operations required for an N-subcarrier LAC-OFDM system with L layers is

$$\begin{aligned} M_{\text{LAC}}^{(t)}(L,N) &= \sum_{l=1}^{L} M\left(\frac{N}{2^l}\right) \\ &= \left(1-\frac{1}{2^L}\right) 2N\log_2(N) - \left(8-\frac{L+4}{2^{L-1}}\right)N + 4L \end{aligned} \tag{19}$$

and

$$\begin{aligned} A_{\text{LAC}}^{(t)}(L,N) &= \sum_{l=1}^{L} A\left(\frac{N}{2^l}\right) \\ &= \left(1-\frac{1}{2^L}\right) 3N\log_2(N) - \left(8-\frac{3L+8}{2^{L}}\right)N + 2L. \end{aligned} \tag{20}$$

Using a similar analysis, for traditional LACO-OFDM with N subcarriers and L layers, the number of real-valued multiplication and additions are

$$\begin{aligned} M_{\text{LACO}}^{(t)}(L,N) &= \sum_{l=1}^{L} M\left(\frac{N}{2^{l-1}}\right) \\ &= \left(1-\frac{1}{2^L}\right) 4N\log_2(N) - \left(12-\frac{2L+6}{2^{L-1}}\right)N + 4L \end{aligned} \tag{21}$$

and

$$\begin{aligned} A_{\text{LACO}}^{(t)}(L,N) &= \sum_{l=1}^{L} A\left(\frac{N}{2^{l-1}}\right) \\ &= \left(1-\frac{1}{2^L}\right) 6N\log_2(N) - \left(10-\frac{3L+5}{2^{L-1}}\right)N + 2L. \end{aligned} \tag{22}$$

For eU-OFDM with N subcarriers and L streams, the total number of real-value multiplications and additions required averaged over an OFDM super frame is

$$\begin{aligned} M_{\text{eU}}^{(t)}(L,N) &= \frac{1}{2^L}\sum_{l=1}^{L} 2^{L-l} M(N) \\ &= \left(1-\frac{1}{2^L}\right)\left(2N\log_2(N) - 4N + 4\right) \end{aligned} \tag{23}$$

and

$$\begin{aligned} A_{\text{eU}}^{(t)}(L,N) &= \frac{1}{2^L}\sum_{l=1}^{L} 2^{L-l} A(N) \\ &= \left(1-\frac{1}{2^L}\right)\left(3N\log_2(N) - 2N + 2\right). \end{aligned} \tag{24}$$

Comparing $M_{\text{LAC}}^{(t)}(L,N)$ and $A_{\text{LAC}}^{(t)}(L,N)$ to $M_{\text{LACO}}^{(t)}(L,N)$ and $A_{\text{LACO}}^{(t)}(L,N)$, LAC-OFDM requires only half real-valued multiplication and half real-valued addition operations as traditional LACO-OFDM. Hence LAC-OFDM is less complex compared to LACO-OFDM. The complexity of LAC-OFDM and the averaged complexity eU-OFDM are similar, however, LAC-OFDM has the advantage of lower latency since each symbol can be decoded from N received samples.

C. Computational Complexity: Receiver

To detect the l-th layer of the AC-OFDM signal ($1 \le l \le L-1$), an $N_{\text{AC}}(l)$ point FFT is required followed by an $N_{\text{AC}}(l)$ point IFFT. For the last layer, i.e., $l = L$, a single $N_{\text{AC}}(L)$ point FFT is required for demodulation as signal reconstruction is not necessary. Thus, LAC-OFDM requires $M_{\text{LAC}}^{(r)}(L,N)$ real-valued multiplication operations where

$$\begin{aligned} M_{\text{LAC}}^{(r)}(L,N) &= 2\sum_{l=1}^{L-1} M\left(\frac{N}{2^l}\right) + M\left(\frac{N}{2^L}\right) \\ &= \left(1-\frac{3/2}{2^L}\right) 4N\log_2(N) - \left(16-\frac{3L+10}{2^{L-1}}\right)N + 8L - 4. \end{aligned} \tag{25}$$

Similarly, the number of real additions for LAC-OFDM can be computed, however, three additional steps are required. Averaging of the received samples is done in each layer following (16) to take advantage of the structure of each layer followed by the IAC operation, defined in (9). Also, the interference of lower layers must be removed from upper layers. The resulting number of real additions required is

$$\begin{aligned} A_{\text{LAC}}^{(r)}(L,N) &= 2\sum_{l=1}^{L-1} A\left(\frac{N}{2^l}\right) + A\left(\frac{N}{2^L}\right) \\ &\quad + \underbrace{\sum_{l=1}^{L}\left(1-\frac{1}{2^{l-1}}\right)N}_{\text{Averaging (16)}} + \underbrace{\sum_{l=1}^{L}\frac{N}{2^l}}_{\text{IAC (9)}} + \underbrace{N(L-1)}_{\text{Subtraction of lower layers}} \\ &= \left(1-\frac{3/2}{2^L}\right) 6N\log_2(N) - \left(18-2L-\frac{9L+19}{2^{L}}\right)N \\ &\quad + 4L - 2. \end{aligned} \tag{26}$$

For traditional LACO-OFDM [7], in a similar way, the total number of real arithmetic operation is

$$\begin{aligned} M_{\text{LACO}}^{(r)}(L,N) &= 2\sum_{l=1}^{L-1} M\left(\frac{N}{2^{l-1}}\right) + M(N) \\ &= \left(\frac{2^L-\frac{8}{5}}{2^L}\right) 10N\log_2(N) - \left(28-\frac{8L+16}{2^{L-1}}\right)N + 8L - 4 \end{aligned} \tag{27}$$

and

$$\begin{aligned} A_{\text{LACO}}^{(r)}(L,N) &= 2\sum_{l=1}^{L-1} A\left(\frac{N}{2^{l-1}}\right) + A(N) + \sum_{l=1}^{L-1}\frac{N}{2^l} \\ &= \left(\frac{2^L-\frac{8}{5}}{2^L}\right) 15N\log_2(N) - \left(21-\frac{12L+7}{2^{L-1}}\right)N + 4L - 2. \end{aligned} \tag{28}$$

For eU-OFDM, the number of real-valued addition operations on average over a super OFDM frame is

$$\begin{aligned} M_{\text{eU}}^{(r)}(L,N) &= \frac{1}{2^L}\left(2\sum_{l=1}^{L-1} 2^{L-l} M(N) + M(N)\right) \\ &= \left(1-\frac{3/2}{2^L}\right)\left(4N\log_2(N) - 8N + 8\right) \end{aligned} \tag{29}$$

and

$$A_{\text{eU}}^{(r)}(L,N) = \frac{1}{2^L}\left(2\sum_{l=1}^{L-1} 2^{L-l}A(N) + A(N)\right.$$
$$\left. + \sum_{l=1}^{L}\left(2^{l-1}-1\right)\frac{2^L N}{2^{l-1}} + \sum_{l=1}^{L} 2^{L-l}N + 2^L(L-1)N\right)$$
$$= \left(1-\frac{3/2}{2^L}\right)6N\log_2(N) - \left(6-2L-\frac{7}{2^L}\right)N + 4 - \frac{6}{2^L}. \tag{30}$$

Comparing $M_{\text{LAC}}^{(r)}(L,N)$ and $A_{\text{LAC}}^{(r)}(L,N)$ with $M_{\text{LACO}}^{(r)}(L,N)$ and $A_{\text{LACO}}^{(r)}(L,N)$, we can conclude that the proposed receiver for LAC-OFDM requires less than half complexity than the traditional LACO-OFDM. In addition, as was the case with the transmitter, the receiver of LAC-OFDM requires nearly the same complexity as eU-OFDM on average but with much less latency.

D. Spectral Efficiency Analysis

In LAC-OFDM, different layers of AC-OFDM signals are added together in the time domain and transmitted simultaneously. Its spectral efficiency can be calculated by

$$\Upsilon_{\text{LAC}} = \frac{\sum_{l=1}^{L}(\frac{N}{2^{l+1}}-1)\log M_l}{N} \tag{31}$$

where M_l is constellation size of QAM utilized in l-th layer. If the constellation size for each layer is set to be the same, $M_l = M$, (31) can be rewritten as

$$\Upsilon_{\text{LAC}} = \frac{1}{2}\left(1-\frac{1}{2^L}\right)\log_2(M) - \frac{L}{N}\log_2(M) \quad \text{bit/s/Hz}. \tag{32}$$

In LACO-OFDM, the spectral efficiency is given by [7]

$$\Upsilon_{\text{LACO}} = \frac{1}{2}\left(1-\frac{1}{2^L}\right)\log_2(M) \quad \text{bit/s/Hz}. \tag{33}$$

For eU-OFDM with N subcarriers and L streams, the spectral efficiency is [6]

$$\Upsilon_{\text{eU}} = \left(\frac{1}{2}-\frac{1}{N}\right)\left(1-\frac{1}{2^L}\right)\log_2(M) \quad \text{bit/s/Hz}. \tag{34}$$

For a given N and L, LACO-OFDM has the biggest spectral efficiency while LAC-OFDM has the smallest efficiency. However, in the case when N is large

$$\lim_{N\longrightarrow\infty}\frac{L}{N}\log_2(M) = 0 \tag{35}$$

and $\Upsilon_{\text{LAC}} \rightarrow \Upsilon_{\text{LACO}}$. Hence, for large N

$$\Upsilon_{\text{LAC}} \approx \Upsilon_{\text{eU}} \approx \Upsilon_{\text{LACO}} = \frac{1}{2}\left(1-\frac{1}{2^L}\right)\log_2(M) \text{ bit/s/Hz}. \tag{36}$$

IV. Numerical Results

A. Computational Complexity Results

Computational complexity comparison among transmitters of LAC- and LACO- and eU-OFDM with different subcarrier number N and layer number L is shown in Fig. 4 and are plotted using the expressions derived in Sec. III-B. In Fig. 4 (a) and (b), the layer number $L = 4$ and in Fig. 4 (c) and (d), $N = 1024$. It is evident the transmitter of traditional LACO-OFDM requires the most real-valued multiplication operations as well as addition operations, which is more than twice as the proposed LAC-OFDM. Notice also that the transmitter of eU-OFDM requires slightly more operations than LAC-OFDM.

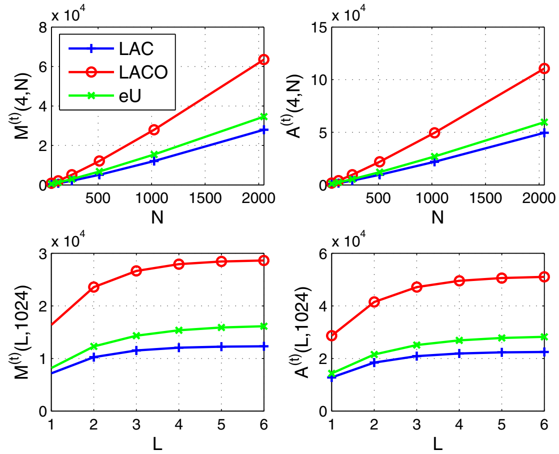

Fig. 4. Computational complexity comparison among transmitters of LAC- and LACO- and eU-OFDM with different N and L. For (a) and (b) $L = 4$ while for (c) and (d) $N = 1024$.

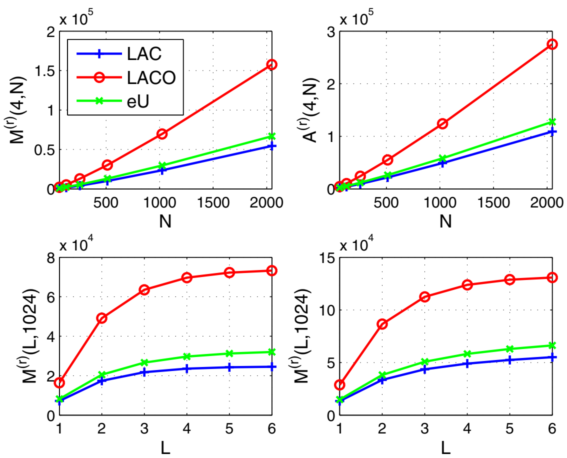

Fig. 5. Computational complexity comparison among receivers of LAC- and LACO- and eU-OFDM with different N and L. For (a) and (b) $L = 4$ while for (c) and (d) $N = 1024$.

Computational complexity comparison among receivers is computed using the expressions in Sec. III-C and is shown in Fig. 5. In Fig. 5 (a) and (b), L is set to 4, while in Fig. 5 (c) and (d), N is set to 1024. As is the case in the transmitter, the relative complexity of LAC-OFDM is the least amongst the techniques considered. Notice also that the complexity of all receivers is sensitive to N as the dominant term in the complexity analysis arises due to the size of the FFT/IFFT operations. Since LAC-OFDM uses a smaller FFT size, it benefits from reduced complexity. In addition, the complexity

TABLE I
COMPLEXITY COMPARISON OF LAC-, LACO- AND EU-OFDM ($N = 1024$ AND $L = 4$)

	$M^{(t)}$	$A^{(t)}$	$M^{(r)}$	$A^{(r)}$
LAC	12048	21896	23580	48974
LACO	27920	49544	69660	123790
eU	15364	26882	29703	58180

saturates with increasing L since the number of degrees of freedom, either in frequency (e.g., LAC- or LACO-OFDM) or in time (e.g., eU-OFDM), in all IM/DD OFDM techniques considered here reduces by half with each increase in layer number. Thus, the incremental increase in complexity must saturate for increasing L.

Consider the case of $N = 1024$ and $L = 4$ for example. Table I provides a summary of the number of addition and multiplication operations required for each IM/DD OFDM approach. Clearly, LACO-OFDM requires the most operations while LAC-OFDM requires the smallest number. Notice that the transmitter for LACO-OFDM requires more than twice the number of real-valued multiplications as LAC-OFDM while for the recieiver LAC-OFDM requires a third of the number of multiplications as LACO-ODFM.

B. BER Performance

The BER performance of LAC- and LACO- and eU-OFDM are compared in terms of optical signal-to-noise ratio $\mathrm{OSNR} = 10\log_{10}(P_o/\sigma_w)$ (dB) where P_o is signal optical power [14]. A flat channel with AWGN is assumed in the simulation [5], [6] and QAM constellations normalized to unit average energy with Gray labeling are utilized. Following [6] and [7], the power allocation factor in each layer of LAC-OFDM (15) and eU-OFDM is set so that

$$\alpha_1 : \alpha_2 : \ \cdots \ : \alpha_L = 1 : 2^{-\frac{1}{2}} : \ \cdots \ : 2^{-\frac{L-1}{2}}. \quad (37)$$

The BER performance comparison among LAC-, LACO- and eU-OFDM is shown for each layer in Fig. 6 where $N = 1024$, $L = 4$ and 16-QAM are utilized. It can be seen that all schemes have nearly the same performance. As discussed in Sec.III-D, the spectral efficiency of these three techniques are also nearly identical. Thus, LAC-OFDM provides the same BER performance as LACO- and eU-OFMD while remaining less complex.

V. CONCLUSION

In this paper, a new approach for the construction of IM/DD OFDM signalling is given. Low-complexity AC-OFDM is proposed where antisymmetry is imposed in time-domain to make satisfying the non-negatively constraint straightforward. To improve spectral efficiency, LAC-OFDM is then proposed, which consists of L superimposed layers of AC-OFDM much like traditional LACO- and eU-OFDM.

Our analysis shows that LAC-OFDM is less complex than existing LACO- or eU-OFDM methods both for the transmitter and the receiver while preserving the same BER performance.

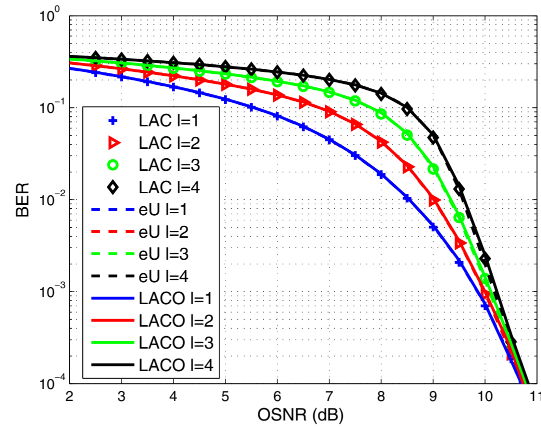

Fig. 6. BER performance for each layer for LAC- and LACO- and eU-OFDM with $N = 1024$ and $L = 4$.

The development of low complexity OFDM signalling is especially important in VLC due to the requirement to maintain energy efficient illumination from the luminaire.

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