Novel Unipolar Optical Modulation Techniques for Enhancing Visible Light Communication Systems Performance

SARA M. FARID,1,2 (Member, IEEE), MONA Z. SALEH,2 (Member, IEEE), HESHAM M. ELBADAWY,3 (Senior Member, IEEE), AND SALWA H. ELRAMLY2, (Life Senior Member, IEEE)

1Department of Electronics and Communications, Faculty of Engineering, Modern Academy for Engineering and Technology, Cairo 11585, Egypt
2Department of Electronics and Communications, Faculty of Engineering, Ain Shams University, Cairo 11517, Egypt
3Department of Network Planning, National Telecommunications Institute, Cairo 11768, Egypt

Corresponding author: Sara M. Farid (1901894@eng.asu.edu.eg)

ABSTRACT  Visible Light Communications (VLC) are receiving increased attention in the wireless communications research community. VLC is secured, power efficient, and operates in the visible light range, thus RF communication bandwidth limitation is overcome. In this article, the authors enhance the data rate, system complexity, power efficiency, and spectrum efficiency in VLC systems. An innovative unipolar transceiver system is proposed, mathematically analyzed, and compared with other existing techniques and it demonstrates to have a very high data rate ratio (43.75%) with a good system bit energy to noise ratio \(E_b/N_0\) compared to other existing techniques. Development for the traditional asymmetrically and symmetrically clipping optical (ASCO-OFDM) system is also proposed, which involves combining a modified receiver with the ASCO-OFDM system traditional transmitter. The proposed receiver reduces the system complexity by \(O(N \log_2 N)\) with better \(E_b/N_0\) than the conventional ASCO-OFDM. Detailed analysis, simulation results, and comparison of the proposed systems with the existing systems are presented beside a brief assessment of existing techniques.

INDEX TERMS  ACO-OFDM, ADO-OFDM, ASCO-OFDM, DCO-OFDM, E-ASCO OFDM, spectral efficiency, VLC.

I. INTRODUCTION  The demand for wireless communications are growing day by day and currently, most researchers are looking for a new spectrum for wireless communication systems instead of the radio frequency (RF) spectrum as it will be fully occupied by 2035 [1]. Therefore, Visible Light Communications (VLC) research attracts more attention over the last ten years [2], as the visible light spectrum ranges from \((4 \times 10^{14})\) to \((8 \times 10^{14})\) Hz [3], that is ten times wider than the RF spectrum. In VLC, data is transmitted using non-coherent sources at the transmitter such as Light Emitting Diode (LED) due to its high efficiency, low-cost, and easy implementation for front-end devices [4]–[6]. Meanwhile, LEDs are used for making their conventional job as a lighting source. Intensity modulation with direct detection (IM/DD) technique is applied in VLC applications [7] as data is transmitted by modulating the input current intensity of the LED. Based on this idea, different optical modulation techniques were introduced for optical wireless communication (OWC) [8]. At the receiver, direct detection is accomplished using a photodiode (PD) to generate current proportional to the received optical power. VLC systems require modulation techniques that restrict the data to be transmitted as real and in a unipolar form [9]. Moreover, those techniques must take into consideration the required high data rate. Single subcarrier techniques such as pulse position modulation (PPM), on-off keying (OOK), and binary phase shift keying (BPSK) satisfy both the real-valued and unipolar criteria but unfortunately, they imply low data rates because of its low modulation order (\(M = 2\)) [10]. On the other hand, higher-order modulation techniques such as M-ary pulse amplitude modulation (M-PAM), M-ary phase shift keying (M-PSK), and M-ary quadrature amplitude modulation (M-QAM) achieve high...
data rates but cannot be directly used in VLC systems as they output complex data. Consequently, optical orthogonal frequency division multiplexing (OFDM) was proposed to be utilized in VLC systems [9]. OFDM systems achieve high spectral efficiency (SE) and high data rate transmission for multiple users by transmitting spectrally efficient OFDM signals with minimal inter symbol interference (ISI). However, employing OFDM and those high-order modulation techniques in the VLC systems needs some adaptations to be applied to achieve high data rates with real and unipolar data form [11]. One of these adaptations is applying the Hermitian symmetry on the transmitted data at the input of the IFFT [12], [13], which results in converting the data into real form at the cost of reducing the data rate to half compared to the rate of the traditional OFDM (real and imaginary).

The issue of converting the bipolar signal into a unipolar one was the main motivation for many researchers [5], [8]–[11]. So, different modified OFDM systems were under investigation taking into consideration SE, power efficiency (PE), bit error rate (BER), and nonlinearity distortion. Previous studies introduced different techniques like DC-biased optical-OFDM (DCO-OFDM) [14], [15], which main merit is achieving the maximum data rate ratio (DRR) of (50%) in the VLC systems at the cost of adding a DC bias that leads to power inefficiency and degrading the system BER performance [16]. Asymmetrically clipped optical (ACO)-OFDM [17], [18], FLIP-OFDM [19], [20], and unipolar OFDM (U-OFDM) [11], [21], schemes have a low DRR of (25%), but better BER system performance compared to DCO-OFDM system. Asymmetrically clipped DC biased optical (ADO)-OFDM [9], is considered as a hybrid technique of ACO-OFDM and DCO-OFDM. ADO-OFDM also has a high DRR of (50%) same as DCO-OFDM but with worse BER system performance than DCO-OFDM, ACO-OFDM, FLIP-OFDM, and U-OFDM. Asymmetrically and symmetrically clipping optical (ASCO)-OFDM scheme achieved a compromise between data rate and BER performance. It has a moderate DRR of (37.5%) with better BER system performance than other existing schemes [22]. According to the massive development in the VLC system applications, the transmitted data rate, BER system performance, and SE are traditional metrics for measuring the improvement of the VLC systems performance. The tradeoff between those metrics imposes a challenge for the researchers to guarantee a high data rate and SE, at low system complexity, and minimal BER.

Two new innovative optical modulation schemes are introduced in this paper. The first proposed scheme is the special symmetric and asymmetric clipping optical (SSACO)-OFDM system which has a higher DRR than ACO-OFDM, FLIP-OFDM, U-OFDM, and ASCO-OFDM while achieving almost the same BER performance, with lower DRR than DCO-OFDM and ADO-OFDM but with much better BER system performance than these two schemes. The second proposed scheme is the enhanced ASCO (EASCO)-OFDM system. It improves the traditional ASCO-OFDM system complexity by reducing the processing latency and the computational complexity by $O(N \log_{2} N)$ with better BER system performance than the conventional ASCO-OFDM scheme by at least 0.2 dB at BER of $10^{-4}$, where $N$ is the FFT size.

The rest of the paper is organized as follows: Section II illustrates four different optical OFDM modulation schemes which are ACO-OFDM, DCO-OFDM, ADO-OFDM, ASCO-OFDM, and FLIP-OFDM. The proposed systems, SSACO-OFDM and EASCO-OFDM are explained and mathematically analyzed in Section III. The SE of the proposed and existing schemes are discussed in Section IV. Section V shows the simulation results and analysis of the proposed SSACO and E-ASCO OFDM techniques. Finally, the paper is concluded in Section VI.

II. VLC SYSTEMS BASED ON OFDM TECHNIQUES

In this section different optical modulation schemes such as DCO-OFDM, ACO-OFDM, FLIP-OFDM, ADO-OFDM, and ASCO-OFDM are illustrated and analyzed.

A. DCO-OFDM

In this system, a DC-biasing level is applied to shift up the signal to achieve a unipolar signal form [14]. This biasing level is selected taking into consideration the LED power rating and linear operating range. It is practically impossible to convert all the signal samples into positive ones by adding a high DC-bias value since, the peak to average power ratio (PAPR) will be very high and some of the signal samples will lie out of the LED linear operation range. Thus, a clipping at zero level after the addition of the DC-biasing level should take place. The main advantage of this technique is the high data rate since half of the subcarriers carry information symbols data $(N/2)$ where $N$ is the FFT size [14]. On the other hand, its main disadvantage is the degradation of the system BER because the addition of a DC-biasing level may force the system to work in a nonlinear region causing non-linearity distortion. Also, the distortion resulting from clipping the signal at the transmitter with the difficulty to restore the original data at the receiver. The optimization of the DC bias point was studied in [23]. The DCO-OFDM system block diagram is represented as in Fig. 1.
In the DCO-OFDM transmitter, the input serial data is first mapped using one of the modulation techniques (e.g., M-QAM, QPSK, or BPSK), then a serial-to-parallel conversion is applied to output complex data symbols \( X(s) \) with length \( (N^2 - 1) \). The \( X(s) \) signal is then arranged as in (1) [14], and Fig. 2 to apply the Hermitian symmetry property form.

\[
X(N - k) = X^*(k) \tag{1}
\]

where, \( 1 \leq k \leq \frac{N}{2} - 1 \) and \( X(0) = X(N/2) = 0 \)

**FIGURE 2.** The hermitian symmetry arrangement for \( (N^2 - 1) \) DCO data symbols.

where \( k \) is the sample index, \( X(k) \) is the complex data symbol after applying Hermitian symmetry property on \( X(s) \), and \( ( )^* \) indicates a conjugate operation. The output from the Hermitian symmetry block is applied to the IFFT block with size \( N \) to get real-valued time-domain data symbols \( x(n) \), then converting them into serial form through the (P/S) block.

In this technique, a shifted signal \( x_{DC}(n) \) is produced through adding a DC biasing level \( B_{DC} \) [24]. Then a zero clipping is applied to get the unipolar real data \( x_{DC}(n) \) and a Cyclic Prefix (CP) is added before signal transmission.

An inverse operation takes place at the receiver, first by removing the CP and the DC-level that were added at the transmitter side. Second, converting the received time-domain samples \( y(n) \) into the frequency domain symbols \( Y(k) \). Finally, inverting the process of Hermitian symmetry is realized at the receiver to get \( Y(s) \) signal which subcarriers carry the original symbols. Demodulation is applied through De-Mapper to extract the originally transmitted data.

**B. ACO-OFDM**

In this technique, there is no need for adding a DC-level. The input data are arranged in a specific manner that differs from the DCO such that only the odd subcarriers carry data and the even ones carry zero value [25], as illustrated in Fig. 3.

**FIGURE 3.** Hermitian symmetry arrangement for \( (N/4) \) ACO-OFDM data symbols.

In this arrangement, the second half of the odd subcarriers carry the conjugate of the symbols carried on the first half - in reversed order – to attain Hermitian symmetry criterion. So, effectively only \( (N/4) \) of the subcarriers are utilized, and accordingly, the data rate is reduced by half compared to the DCO-OFDM technique. However, the system BER performance is improved as will be explained shortly. The ACO-OFDM system block diagram is shown in Fig. 4.

**FIGURE 4.** The ACO OFDM system block diagram.

The only difference here from the DCO-OFDM block diagram illustrated in Fig. 1 is removing the DC-level and the way of arranging the data. This arrangement results in asymmetric output samples from the IFFT block, as represented in (2). Derivation for (2), is found in [26].

\[
x(n) = -x\left(\frac{N}{2} + n\right), \quad 0 \leq n \leq \frac{N}{2} - 1 \tag{2}
\]

The data output from the IFFT is repeated after \( (N/2) \) samples with opposite sample signs. So, each clipped sample has its positive counterpart as shown in Fig. 5, which facilitates the reconstruction of the data at the receiver. A zero bias level clipper is then applied on the signal to clip negative samples to be ready for transmission through the channel. The clipping process causes a clipping noise to appear at the even subcarriers indices only as shown in Fig. 6 and proved in [26]. So, the original data carried on the odd subcarriers
will not be affected by the clipping distortion which explains the BER improvement. The reverse operations are applied at the receiver side to extract the original data from the received clipped signal \( y(n) \). An FFT block is used to get the frequency domain signal \( Y(k) \). Then, the resulting output is arranged in such a manner to get only the odd subcarriers symbols that carry the original data and by demodulating these symbols through a De-mapper block, the original data can be extracted.

**C. FLIP-OFDM**

In FLIP-OFDM [20], contrary to ACO-OFDM and DCO-OFDM, there is no need for adding any DC-biasing level or using any clipping techniques. It utilizes a different way to convert the data into unipolar by separating the signal into two parts: positive part \( x^+(n) \) and negative part \( x^-(n) \). Then, \( x^-(n) \) is multiplied by \(-1\), so it can be transmitted using the VLC technology. Afterwards, the two parts are transmitted sequentially through the channel. Data information samples frame of length \( N \) is transmitted on two frames each of length \( N \). So, the data rate is the same as in the ACO-OFDM but reduced to half compared to the DCO-OFDM system.

At the receiver, two subframes \( y^+(n) \) and \( y^-(n) \) are received through the LED. The received signal \( y^+(n) \) represents the positive samples of the signal and \( y^-(n) \) represents the absolute value of the negative samples. So, by subtracting \( y^-(n) \) from \( y^+(n) \), the bipolar received signal \( y(n) \) can be extracted as in,

\[
y(n) = y^+(n) - y^-(n)
\]

Then after passing \( y(n) \) through the FFT block the frequency domain \( Y(k) \) samples are detected. Data information samples with length \( N \) are transmitted on two frames each of length \( N \). So, the data rate is the same as in the ACO-OFDM but reduced to half compared to the DCO-OFDM data rate. The FLIP-OFDM (also known as Unipolar-OFDM (U-OFDM)) and ACO-OFDM systems have comparable BER system performance since both are not affected by the clipping noise. However, for FLIP-OFDM system, the channel noise added is doubled due to transmitting the data over two frames. The FLIP-OFDM transmitter and receiver block diagrams are shown in Fig. 7.

**D. ADO-OFDM**

This system is considered as a hybrid technique that combines ACO-OFDM and DCO-OFDM to double the data rate compared to (ACO-OFDM, U-OFDM, and FLIP OFDM) [27]. It has the same data rate as the DCO-OFDM system.

Figure (8), and (9), show the ADO-OFDM system block diagram and subcarriers structure, respectively. Which is considered the maximum data rate in VLC systems so far.

At the transmitter side, the input data are carried on the odd subcarriers in the same manner as the ACO-OFDM shown in
Fig. 3. This system increases the utilization ratio by carrying data symbols on the \((N/4 - 1)\) even subcarriers as well instead of being nulled. These data symbols are transmitted using the DCO-OFDM technique shown in Fig. 1, where, \(x_{\text{odd}}(n)\) is the data carried on the odd subcarriers and \(x_{\text{even}}(n)\) is the data carried on the even subcarriers.

On the receiver side, first to regenerate the transmitted data carried on the odd subcarriers, \(Y_{\text{odd}}(k)\) is extracted from the total received data \(Y_{\text{ADO}}(k)\) directly in the frequency domain. Second, to regenerate the data carried on the even subcarriers, a reference signal \(Y_{\text{odd} \text{ Ref}}(k)\) is generated to be subtracted from the received signal \(Y_{\text{ADO}}(k)\) to remove the clipping noise applied on the even subcarriers as derived in [26], and shown in Fig. 6. then \(Y_{\text{even}}(k)\) can be extracted.

E. ASCO-OFDM

The objective behind the ASCO-OFDM system was to promote the data rate to be better than FLIP-OFDM and ACO-OFDM systems. But, unfortunately, ASCO still has a data rate below the data rate of DCO-OFDM. On the other hand, it has better system BER performance than ACO-OFDM, FLIP-OFDM, and DCO-OFDM systems [29].

ASCO-OFDM system enhances the data rate by using \((3N/4)\) subcarriers carrying actual data but, as the samples are separated into two frames, the data rate spectrum efficiency ratio is degraded to be 37.5%. ASCO-OFDM transmitter and receiver block diagram are illustrated in Fig. 10.

In Fig. 10, the transmitted data is divided into four parts \([x_{\text{odd} i}, x_{\text{odd} j}, x_{\text{even} \text{ PC}}(n), x_{\text{even} \text{ NC}}(n)]\) where, \(x_{\text{odd} i}\) and \(x_{\text{odd} j}\) are two data vectors with only odd-indexed data symbols from the original data stream, i.e., both vectors have zeros at all even indices. Those vectors are transmitted on two consecutive frames.

![FIGURE 10. The ASCO-OFDM system block diagram.](image)

Also, the even data vector is divided into two vectors one for the positive even data signal \(x_{\text{even} \text{ PC}}(n)\) and the other is for the negative one \(x_{\text{even} \text{ NC}}(n)\).

From Fig. 10, three frames are generated from two IFFT blocks. The first and second frames \([x_{\text{odd} i}(n), x_{\text{odd} j}(n)]\) are generated from the first IFFT block where the first part of the input data symbols \([x_{\text{odd} i}(k)\text{ and } x_{\text{odd} j}(k)]\) with size \((N/4)\) are carried on the odd subcarriers only, and the even ones are set to zero as in the ACO-OFDM. These two frames are then clipped at the zero-bias level to convert the transmitted bipolar asymmetric samples into positive clipped ones \([x_{\text{odd} i}(n), x_{\text{odd} j}(n)]\).

The third frame is generated from the second IFFT block by carrying the last part of the input data symbols \(x_{\text{even}}(k)\) with size \((N/4 - 1)\) on the even subcarriers only and setting the odd ones to zero. Then, the third frame is separated into two parts with equally sized \((N)\) samples, \(x_{\text{even} \text{ PC}}(n)\) and \(x_{\text{even} \text{ NC}}(n)\). Where, \(x_{\text{even} \text{ PC}}(n)\) is the absolute value of the negative frame which results from clipping all the positive samples of \(x_{\text{even}}(n)\), and \(x_{\text{even} \text{ NC}}(n)\) is the positive frame which results from clipping all the negative samples of \(x_{\text{even}}(n)\). The data carried on the even subcarriers will be symmetric bipolar frame \(x_{\text{even}}(n)\) as illustrated in [29], and shown in Fig. 11. The transmitted two OFDM symbols are \(x_{\text{i sum}}(n)\) and \(x_{\text{j sum}}(n)\) as shown in (4), and (5), then a CP is applied to both symbols.

\[
x_{\text{i sum}}(n) = x_{\text{odd} i}(n) + x_{\text{even} \text{ PC}}(n) \tag{4}
\]

\[
x_{\text{j sum}}(n) = x_{\text{odd} j}(n) + x_{\text{even} \text{ NC}}(n) \tag{5}
\]

At the receiver, the received signal \(Y_{\text{i,j} \text{ sum}}(k)\) is FFT transformed to \(Y_{\text{i,j} \text{ sum}}(k)\). Then, the original data is processed in two steps. Firstly, detecting the odd data symbols from the received signal \(Y_{\text{i,j} \text{ sum}}(k)\). Secondly, generating a reference signal \(Y_{\text{i,j} \text{ odd} \text{ Ref}}(k)\) by converting the odd symbols into time-domain samples \(Y_{\text{i,j} \text{ odd}}(n)\) then clipping it. This reference signal will be next subtracted from the received signal, \(Y_{\text{i,j} \text{ sum}}(k)\) to get the data carried on the even subcarriers. \(Y_{\text{even}}(k)\) then demodulating the symbols to extract the originally transmitted data.

![FIGURE 11. Even subcarriers data signal represented in a symmetric time-domain signal \((N = 16)\).](image)

The reference signal is generated to remove the clipping distortion that falls into the even subcarriers due to the clipping that occurs at the odd transmitted data samples, this is illustrated in [26].

III. THE PROPOSED SCHEMES

This section shows two unprecedented modulation schemes in VLC systems. The first one is SSACO OFDM system that enhances the SE than other existing systems, except for the DCO-OFDM system which has high SE but, worse system
BER performance, and power inefficient system compared to the proposed SSACO-OFDM system.

The second proposed system is E-ASCO OFDM system that has main advantage in reducing the system complexity with better system BER performance than the traditional ASCO-OFDM system.

A. THE SPECIAL SYMMETRIC AND ASYMMETRIC CLIPPING OPTICAL (SSACO-OFDM) SCHEME

In this scheme, ((7N/8) – 1) data symbols are transmitted over two different OFDM symbols each has (N) available subcarriers without any need for DC-biassing, i.e., more power-efficient system. The SSACO scheme also has the merit of high SE equal to 43.75% which is higher than ACO-OFDM, FLIP-OFDM, and U-OFDM by 18.75% and higher than ASCO-OFDM by 6.25%. Moreover, it enhances the transmitted data rate by a factor of (N/8) data symbols compared to the ACO-OFDM, FLIP-OFDM, and U-OFDM systems, and by a factor of (N/16) data symbols compared to the ASCO-OFDM. In comparison to the DCO-OFDM and ADO-OFDM systems, the SSACO-OFDM system has less SE ratio and data rate by only 6.25% and (N/16) data symbols, respectively, with much better (E_b/N_0) system performance by at least 6 dB at BER of 10^-4.

1) THE SSACO-OFDM TRANSMITTER

The SSACO-OFDM transmitter block diagram is shown in Fig. 12. The input transmitted data is applied to a mapper then S/P block that outputs parallel data symbols X (k), then X (k), is divided into 3 vectors X_A(k), X_B(k), and X_C(k) as represented in (6), and (7). Those 3 vectors are applied to the Hermitian symmetry and data arrangement block that outputs the parallel data vectors X_{odd}(k), X_{even}(k), and X_{even special}(k) respectively. The symbols of those vectors are arranged as illustrated in (8)-(10). The data symbols are sorted, such that the output of the IFFT blocks are real bipolar signals.

\[ X(k) = [X_A(k), X_B(k), X_C(k)] \]

(6)

where k is the symbol index that ranges as,

\[
\begin{align*}
X_A(k), & \quad 1 \leq k \leq \left( \frac{N}{2} \right) \\
X_B(k), & \quad \left( \frac{N}{2} + 1 \right) \leq k \leq \left( \frac{5N}{8} \right) \\
X_C(k), & \quad \left( \frac{5N}{8} + 1 \right) \leq k \leq \left( \frac{7N}{8} - 1 \right)
\end{align*}
\]

(7)

\[ X(k) = \left[ X(1), X(2), X(3), \ldots, X \left( \frac{7N}{8} - 2 \right), X \left( \frac{7N}{8} - 1 \right) \right], \]

\[ 1 \leq k \leq \frac{7N}{8} - 1 \]

(8)

\[ X_{oddj}(k) = \begin{cases} 
0, X(1), 0, X(2), 0, X(3), 0, \ldots, 0, X \left( \frac{N}{4} - 1 \right), 0, \\
X \left( \frac{N}{4} + 1 \right), 0, X \left( \frac{N}{4} + 2 \right), 0, \ldots, 0, X \left( \frac{N}{2} - 1 \right), \\
0, X \left( \frac{N}{2} \right), 0, X \left( \frac{N}{2} \right), 0, \ldots, 0, X \left( \frac{N}{4} + 1 \right) 
\end{cases} \]

(9)

The second proposed system is E-ASCO OFDM system which only the odd subcarriers carry data and the second IFFT block are arranged in a special manner in which the positions of the even subcarriers are set to zeros so the resultant output will be asymmetric bipolar signal X_{oddj}(k). Then, X_{oddj}(n) signal is applied to a splitter to output x_{odd}(n) and x_{jodd}(n) signals. After that a zero clipping is applied to get unipolar asymmetric signals x_{odd}(n) and x_{jodd}(n).

\[ x_{odd}(n) = \frac{x_{odd}(n) + |x_{odd}(n)|}{2} \]

(10)

Secondly, the data symbols of X_{even special}(k) applied to the second IFFT block are arranged in a special manner in which a set of the even subcarriers carry data while all other subcarriers are set to zeros as illustrated in (9), This arrangement leads to a symmetric-asymmetric bipolar signal x_{special}(n) at the output of the IFFT as shown in Fig. 13. Thus, the proposed technique is named as special symmetric and asymmetric clipping optical technique. Moreover, a zero clipping process takes place to convert x_{special}(n) into a unipolar real signal x_{special}(n) as in,

\[ x_{special}(n) = \frac{x_{special}(n) + |x_{special}(n)|}{2} \]

(11)
Thirdly, the data symbols of $X_{even}(k)$ applied to the third IFFT block are applied to some even subcarriers in an order as illustrated in (10), this arrangement leads the output of the IFFT to be symmetric bipolar signal $x_{even}(n)$ as discussed in [29], and shown in Fig. 11. Afterwards, negative and positive clipping processes takes place to generate the negative clipping signal $x_{evenNC}(n)$, and the positive clipping signal $x_{evenPC}(n)$, respectively, where, $x_{evenNC}(n)$ is the exact replica of $x_{evenPC}(n)$. $x_{evenPC}(n)$ is multiplied by $(-1)$, so it can be transmitted using the VLC technology. After that the two parts are transmitted sequentially through the channel as in,

$$x_{evenNC}(n) = \begin{cases} x_{even}(n), & \text{if } x(n) \geq 0 \\ 0, & \text{otherwise} \end{cases} \quad (14)$$

$$x_{evenPC}(n) = \begin{cases} -x_{even}(n), & \text{if } x(n) < 0 \\ 0, & \text{otherwise} \end{cases} \quad (15)$$

The two transmitted OFDM symbols $x_{i \text{ SSACO}(n)}$ and $x_{j \text{ SSACO}(n)}$ are represented in (16), and (17).

$$x_{i \text{ SSACO}(n)} = x_{i \text{ odd}(n)} + x_{evenNC}(n) + x_{special}(n) \quad (16)$$

$$x_{j \text{ SSACO}(n)} = x_{j \text{ odd}(n)} + x_{evenPC}(n) + x_{special}(n) \quad (17)$$

The SSACO-OFDM receiver block diagram is shown in Fig. 14. It improves the system BER performance by overcoming all the clipping noise resulting from clipping the transmitted data carried on both the odd and even subcarriers through using the following data receiving algorithm.

1. The data carried on the odd subcarriers are reconstructed via dividing the received signal $y_{SSACO,i,j}(n)$ into two parts each of size $(N/2)$ samples. The first part is $y_{A,i,j}(n)$ and the second part is $y_{B,i,j}(n)$ as in,

$$y_{SSACO,i,j}(n) = \frac{y_{odd}(n)}{2} + \frac{y_{even}(n)}{2} + y_{special}(n) \quad (19)$$

$$y_{A,i,j}(n) = \begin{cases} y_{A,i,j}(n), & \text{if } y_{A,i,j}(n) \end{cases} \quad (20)$$

$$y_{B,i,j}(n) = \begin{cases} y_{B,i,j}(n), & \text{if } y_{B,i,j}(n) \end{cases} \quad (21)$$

where the received time domain signals $y_{odd}(n)$ and $y_{even}(n)$ are the first $(N/2)$ samples of the received signal $y_{odd}(n)$ and $y_{even}(n)$ which are corresponding to the data carried on the odd subcarriers (odd symbols) which indices as in equation (8), and the data carried on the even subcarriers (special even, and even symbols) which indices as in equation (9), and (10), respectively.

2) THE SSACO-OFDM RECEIVER

The received data which is mathematically represented in (18), and (19), are reconstructed through three steps.

$$y_{SSACO,i,j}(n) = \frac{y_{odd}(n)}{2} + \frac{y_{even}(n)}{2} + y_{special}(n) \quad (18)$$

$$y_{A,i,j}(n) = \begin{cases} y_{A,i,j}(n), & \text{if } y_{A,i,j}(n) \end{cases} \quad (20)$$

$$y_{B,i,j}(n) = \begin{cases} y_{B,i,j}(n), & \text{if } y_{B,i,j}(n) \end{cases} \quad (21)$$

where, the received time domain signals $y_{odd}(n)$ and $y_{even}(n)$ are the last $(N/2)$ samples of the received signal
FIGURE 14. The SSACO-OFDM receiver block diagram.

\( y_{A_{i,j}}(n) \) which are corresponding to the data carried on the odd subcarriers (odd symbols) which indices as in equation (8), and even subcarriers (special even, and even symbols) which indices as in equation (9), and (10), respectively.

Assuming the signal is transmitted through an AWGN channel, then

\[
y_{A_{i,j}}(n) = \left[ x_{odd\ A_{i,j}}(n) + x_{Even\ A_{i,j}}(n) \right] + n_o
\]  
(23)

\[
y_{B_{i,j}}(n) = \left[ x_{odd\ B_{i,j}}(n) + x_{Even\ B_{i,j}}(n) \right] + n_o
\]  
(24)

where, \( x_{odd\ A_{i,j}}(n) \), and \( x_{Even\ A_{i,j}}(n) \) are the first \((N/2)\) samples of the transmitted \( x_{odd\ i,j}(n) \) signal which are corresponding to the data carried on the odd subcarriers (odd symbols) that indices as in equation (8), and even subcarriers (special even, and even symbols) that indices as in equation (9), and (10), respectively.

Also, \( x_{odd\ B_{i,j}}(n) \) and \( x_{Even\ B_{i,j}}(n) \) are the last \((N/2)\) samples of the transmitted \( x_{odd\ i,j}(n) \) signal which are corresponding to the data carried on the odd subcarriers (odd symbols) that indices as in equation (8), and even subcarriers (special even, and even symbols) that indices as in equation (9), and (10), respectively. Moreover, \( n_o \) is the added channel noise, and \( \overline{x} \) is the clipped version of \( x \).

Using the symmetry property mentioned in [29], and represented in Fig. 11, then:

\[
x_{Even\ A_{i,j}}(n) = x_{Even\ B_{i,j}}(n)
\]  
(25)

Accordingly, the data carried on the odd subcarriers can be reconstructed as follows,

\[
y_{odd\ A_{i,j}}(n) = y_{A_{i,j}}(n) - y_{B_{i,j}}(n)
\]  
(26)

\[
y_{odd\ B_{i,j}}(n) = y_{B_{i,j}}(n) - y_{A_{i,j}}(n)
\]  
(27)

\[
y_{i,j}(n) = \left[ y_{odd\ A_{i,j}}(n), y_{odd\ B_{i,j}}(n) \right]
\]  
(28)

where \( y_{i,j}(n) \) is the received data carried on the odd subcarriers represented in time domain. At this stage, the data carried on the even subcarriers cancel each other after subtracting \( y_{A_{i,j}}(n) \) from \( y_{B_{i,j}}(n) \) due to the symmetry property of the even subcarriers. Then, after passing \( y_{i,j}(n) \) through the FFT block, the odd data symbols \( y_{odd\ odd_{i,j}}(k) \) can be reconstructed.

By substituting equations (23) and (24) in (26), assuming perfect channel estimation and very low noise level that can be ignored, the proof goes as follows,

\[
y_{odd\ A_{i,j}}(n) = \left[ x_{odd\ A_{i,j}}(n) + x_{Even\ A_{i,j}}(n) \right] - \left[ x_{odd\ B_{i,j}}(n) + x_{Even\ B_{i,j}}(n) \right]
\]  
(29)

Then substituting (26), in (30),

\[
y_{odd\ A_{i,j}}(n) = \left[ x_{odd\ A_{i,j}}(n) - x_{odd\ B_{i,j}}(n) \right] + \frac{1}{2} \left[ x_{odd\ B_{i,j}}(n) + x_{Even\ B_{i,j}}(n) \right]
\]  
(30)

Using the asymmetric property mentioned in [26],

\[
x_{odd\ A_{i,j}}(n) = -x_{odd\ B_{i,j}}(n) \quad \text{and} \quad x_{odd\ A_{i,j}}(n) = \left| x_{odd\ B_{i,j}}(n) \right|
\]  
(31)

\[
y_{odd\ A_{i,j}}(n) = \left[ x_{odd\ A_{i,j}}(n) - x_{odd\ B_{i,j}}(n) \right] + \frac{1}{2} \left[ x_{odd\ B_{i,j}}(n) - x_{Even\ B_{i,j}}(n) \right]
\]  
(32)

Similarly, \( y_{odd\ B_{i,j}}(n) \) can be reconstructed in the same manner,

\[
y_{odd\ B_{i,j}}(n) = \left[ y_{B_{i,j}}(n) - y_{A_{i,j}}(n) \right] = x_{odd\ B_{i,j}}(n)
\]  
(33)

Thus, (32), and (33), show that the data carried on the odd subcarriers can be completely reconstructed.

2. The data carried on the even subcarriers are reconstructed from two different signals \( y_{even\ n} \) and \( y_{p,nc\ n} \).
Where $y_{even}(n)$ is the received data carried on a set of even subcarriers which indices are defined in (10), and $y_{sp,nc}(n)$ is the received signal carried on the special even subcarriers which indices are defined in (9), after applying the noise cancellation technique, respectively.

So, the even subcarriers data will be extracted in two stages. The first stage is to extract $y_{even}(n)$ from the received signals represented in (18), and (19) taking into consideration $y_{even \, NC}(n)$, and $y_{even \, PC}(n)$ are the received signals for $x_{even \, NC}(n)$ illustrated in (14), and $x_{even \, PC}(n)$ illustrated in (15), respectively.

Therefore $y_{even}(n)$ can be obtained through subtracting $y_{even \, PC}(n)$ from $y_{even \, NC}(n)$ as shown in (34),

$$y_{even}(n) = y_{even \, NC}(n) - y_{even \, PC}(n) \quad (34)$$

This will be accomplished by first splitting the received odd signal $y_{i,j}(n)$ into $y_{odd}(n)$, and $y_{odd}(n)$ signals then clipping them to generate the reference signals $y_{odd}(n)$, and $y_{odd}(n)$, respectively. Then, subtracting $y_{odd}(n)$ and $y_{odd}(n)$ from the total received signals $y_{SSACO}(n)$, and $y_{SSACO}(n)$, respectively. This step eliminates the clipping distortion resulting from the clipping process that occurred on the odd data samples at the transmitter and removes the data carried on the odd subcarriers. Thus, the output from the first stage can be represented as in (35) and (36),

$$y_{even \, i}(n) = y_{even \, NC}(n) + y_{special}(n) \quad (35)$$
$$y_{even \, j}(n) = y_{even \, PC}(n) + y_{special}(n) \quad (36)$$

Finally, $y_{even}(n)$ can be extracted by subtracting (36), from (35).

The second stage is to extract $y_{special}(n)$ by subtracting $y_{even \, NC}(n)$ signal from $y_{even \, i}(n)$ signal as in,

$$y_{special}(n) = y_{even \, i}(n) - y_{even \, NC}(n) \quad (37)$$

Where $y_{special}(n)$ is applied to a clipping noise cancellation block at the receiver that outputs $y_{sp,nc}(n)$ signal. The noise cancellation block is used not only to enhance the system performance by minimizing the system clipping distortion noise but also to restore the original transmitted special even data from the clipped samples. Figure (15), shows the noise cancellation technique is based on three stages, the first stage is splitting the received $y_{special}(n)$ into four parts each of size $(N/4)$ and storing them as represented in (38),

$$y_{special}(n) = \begin{cases} 
  y_A(n), & 1 \leq n \leq \left( \frac{N}{4} \right) \\
  y_B(n), & \left( \frac{N}{4} + 1 \right) \leq n \leq \left( \frac{N}{2} \right) \\
  y_C(n), & \left( \frac{N}{2} + 1 \right) \leq n \leq \left( \frac{3N}{4} \right) \\
  y_D(n), & \left( \frac{3N}{4} + 1 \right) \leq n \leq (N) 
\end{cases} \quad (38)$$

Since for special even subcarriers the data is symmetric-asymmetric as shown in Fig. 13 and discussed in Section III-A, then the inverse of $y_A(n)$ is $y_B(n)$ and the inverse of $y_C(n)$ is $y_D(n)$. So, each negative clipped sample has its positive counterpart. For this reason, in the second stage two comparisons between the four signals take place. One comparison is between $y_A(n)$ and $y_B(n)$ and the other comparison is between $y_C(n)$ and $y_D(n)$. Finally, $y_{sp,nc}(n)$ is extracted after some subtraction processes as in the third stage represented in Fig.15.

Also, Fig. 16 shows that the transmitted data is mainly the same as the received data after the noise cancellation technique. So, the proposed noise cancellation technique has a great enhancement in improving the system BER performance. Taking the second sample as an example to show the noise cancellation technique ability in restoring the data.
FIGURE 16. SSACO-OFDM special even data transmitted and received signals. (a) Transmitted data on special even subcarriers. (b) Received data before noise cancellation technique. (c) Received data after noise cancellation technique.

The second sample has an original value of $-0.175$ at the transmitter as shown in Fig. 16-a, then the sample is clipped to be transmitted through VLC system, so the transmitted sample value is forced to zero. Then the received sample value is a little value above zero value as shown in Fig. 16-b, due to channel noise effect but after applying the noise cancellation technique, the received sample value almost becomes $-0.175$ as shown in Fig. 16-c, as its original value so, the noise cancellation technique can almost restores all the clipped samples and removes the channel noise. Finally, the data is applied to an FFT block then a data arrangement, and de-mapper blocks to extract the originally transmitted data.

B. THE ENHANCED-ASCO (E-ASCO) OFDM SYSTEM

The EASCO-OFDM is proposed to reduce the receiver complexity and the processing latency with better system BER performance than the conventional ASCO-OFDM system explained in Section II-E. This is accomplished by introducing an innovative receiver as shown in Fig. 17.

1) THE E-ASCO OFDM TRANSMITTER

E-ASCO OFDM has the same transmitter as the traditional ASCO-OFDM illustrated in Fig. 10. The transmitted odd, and even data vectors are represented as in (39), (40), and (41), also Fig. 18 shows an example for the data arrangement in E-ASCO OFDM transmitter using $N = 16$ subcarriers.

\[
\begin{align*}
X_{\text{oddi}}(k) &= \left[0, X \left(\frac{N}{4}\right), 0, X \left(\frac{N}{4}+1\right), 0, X \left(\frac{N}{4}+2\right), 0, \ldots, 0, X \left(\frac{N}{2}-1\right)\right], \\
X_{\text{oddj}}(k) &= \left[0, X \left(\frac{N}{4}\right), 0, X \left(\frac{N}{4}+1\right), 0, X \left(\frac{N}{4}+2\right), 0, \ldots, 0, X \left(\frac{N}{2}-1\right)\right], \\
X_{\text{even}}(k) &= \left[0, 0, X \left(\frac{N}{4}\right), 0, X \left(\frac{N}{4}+1\right), 0, X \left(\frac{N}{4}+2\right), 0, \ldots, 0, X \left(\frac{N}{2}-1\right)\right].
\end{align*}
\]

\[\text{Symbols: } s_0, s_1, s_2, s_3, s_4, s_5, s_6, s_7, s_8, s_9, s_{10}, s_{11}, s_{12}, s_{13}, s_{14}, s_{15}\]

FIGURE 17. EASCO-OFDM receiver block diagram.

FIGURE 18. E-ASCO OFDM data arrangement example ($N = 16$).
2) THE E-ASCO OFDM RECEIVER

The main difference in the proposed modified receiver structure compared to the original one is the methodology used to extract the information from the received signal. The proposed E-ASCO receiver process the received data in time domain to extract the information by applying a subtraction process after splitting the received signals. while, the traditional ASCO receiver process the received signal in frequency domain to extract the information data.

So, for the proposed EASCO-OFDM receiver, the received data is extracted through two stages:

1. Extract the data carried on the odd subcarriers by the same criteria represented in Section III-A, and mathematically analyzed in (20), - (33).

2. Extract the data carried on the even subcarriers by generating the reference signal \( y_{i,j} (n) \) which represents the received clipped odd signal. Then, subtract \( y_{i,j} (n) \) from the total received signal \( y(n) \) to eliminate the clipping distortion resulting from clipping the odd data samples at the transmitter as shown in Fig. 6. Moreover, a splitter is used after the FFT block to separate the even negative clipping data symbols \( Y_{Even}^N (k) \) and even positive clipping data symbols \( Y_{Even}^P (k) \). Afterwards, a subtraction process takes place as in (42), to extract the received data \( Y_{Even} (k) \) on the even subcarriers.

\[
Y_{Even} (k) = Y_{Even}^N (k) - Y_{Even}^P (k)
\]  

(42)

The odd \( Y_{i,j}^o (k) \) and the even \( Y_{Even} (k) \) data symbols are then arranged using a data arrangement block before passing through a de-mapper block to restore the originally transmitted data.

3) THE COMPLEXITY ANALYSIS OF THE EASCO-OFDM AND ASCO-OFDM SYSTEMS

For the EASCO-OFDM system, there are two N-point IFFT blocks and two N-point FFT blocks at the transmitter and the receiver, respectively. Firstly, the subtraction and addition operations complexity at both transmitter and receiver can be neglected as it is a very small value compared to the IFFT and FFT operations complexity [30]. So, the EASCO-OFDM system computational complexity is approximately 2O (\( N \log_2 N \)) for the transmitter and 2O (\( N \log_2 N \)) for the receiver. Also, since ASCO-OFDM transmitter is identical to EASCO-OFDM transmitter, therefore, the transmitter computational complexity is 2O (\( N \log_2 N \)), whereas the receiver complexity for the ASCO-OFDM system is approximately 3O (\( N \log_2 N \)). Because at the receiver, there are two N-point FFT and one N-point IFFT blocks with computational complexity 2O (\( N \log_2 N \)) and O (\( N \log_2 N \)) respectively. Thus, the EASCO-OFDM has a great reduction in the computational complexity than the ASCO-OFDM by O (\( N \log_2 N \)).

IV. DATA RATE AND SPECTRAL EFFICIENCY

In this section, the transmitted data rate \( R \) for \( x \) technique (\( R_x \) like \( R_{DCO}, R_{ADO}, R_{ACO}, R_{FLIP}, R_{ASCO}, R_{SSACO} \), and \( R_{E-ASCO} \)) are calculated and compared. The data rate for the DCO-OFDM system \( R_{DCO} \) is \( (N/2) \) due to applying a Hermitian symmetry property on the subcarriers. Since applying this property requires only half of the available subcarriers to be loaded by the data, so \( R_{DCO} \) ratio is 50%. The ACO-OFDM system data rate \( R_{ACO} \) is \( (N/4) \) as it also follows Hermitian symmetry and only odd subcarriers are loaded by the data, so the DRR is 25%. For the FLIP-OFDM system, the \( R_{FLIP} \) is \( (N/2) \) for each transmitted OFDM symbol but since the \( (N/2) \) symbols are to be transmitted over two OFDM symbols, then the actual data rate for the system will be reduced to half to be \( (N/4) \) with a DRR of 25%. In the ASCO-OFDM system, for transmitting \( (3N/4) \) data symbols, three OFDM symbols are produced at the transmitter. For the first and second ones, the data is carried on the odd subcarriers only. So, for the first 2 OFDM Symbols each have only \( (N/4) \) of the subcarriers carrying data symbols. For the third OFDM symbol, the data is carried only on the even subcarriers, accordingly only \( (N/4) \) of the subcarriers are carrying data symbols. Hence, the total transmitted data rate for the ASCO-OFDM system is \( (3N/4) \) but since the three frames are summated and transmitted through the channel in two frames only, thus the actual data rate \( R_{ASCO} \) will be \( (3N/8) \) that has a DRR of 37.5%.

For the proposed SSACO-OFDM system the \( R_{SSACO} \) is \( (7N/16) \) as two generated OFDM symbols are transmitted through the channel. The odd subcarriers of the two OFDM symbols are loaded by data arranged in the same manner as in the ACO-OFDM system. For the even subcarriers a certain arrangement is used for loading the data as discussed in section III-A, taking into consideration that the data carried on special even subcarriers are transmitted twice on the channel as represented in (16), and (17), which causes a reduction in the DR by a factor of \( (N/16) \).

For the proposed E-ASCO OFDM system, it has the same data rate as ASCO-OFDM \( R_{ASCO} \) of \( (3N/8) \) since the modification proposed was only in the system receiver. Table 1, summarizes the transmitted data rate, DRR, complexity, and the system power efficiency for the previously mentioned techniques. VLC systems have different SE at different modulation orders. So, for a fair comparison, simulations and analysis were performed at certain SE. For example, 8-QAM DCO, 8-QAM ADO, 16-QAM E-ASCO, 16-QAM ASCO, 64-QAM ACO, and 64-QAM FLIP; OFDM systems have the same SE of 2.9942 as will be discussed later in Fig. 19 and Table 4.

SE is defined as data bit rate divided by normalized bandwidth.
TABLE 1. Comparison between the transmitted data rate for the previously mentioned techniques.

| Technique      | Transmitted data rate | Transmitted DRR | Power efficiency | complexity |
|----------------|-----------------------|-----------------|------------------|------------|
| DCO-OFDM       | (N/2)                 | 50%             | Inefficient      | 20(Nlog₂ N) |
| ADO-OFDM       | (N/2)                 | 50%             | Inefficient      | 50(Nlog₂ N) |
| ACO-OFDM       | (N/4)                 | 25%             | Efficient        | 20(Nlog₂ N) |
| FLIP-OFDM      | (N/4)                 | 25%             | Efficient        | 20(Nlog₂ N) |
| ASCO-OFDM      | (3N/8)                | 37.5%           | Efficient        | 50(Nlog₂ N) |
| SSACO-OFDM     | (7N/16)               | 43.75%          | Efficient        | 60(Nlog₂ N) |
| E-ASCO-OFDM    | (3N/8)                | 37.5%           | Efficient        | 40(Nlog₂ N) |

The SE of DCO, ACO, ADO, FLIP, ASCO, SSACO, and E-ASCO OFDM systems can be calculated as in (43), (44), (45), (46), (47), (48), and (49), respectively.

\[
SE_{DCO} = \frac{(\log_2 M_{DCO})}{(1 + \frac{2}{N})} \quad (43)
\]

\[
SE_{ACO} = \frac{(\log_2 M_{ACO})}{(1 + \frac{2}{N})} \quad (44)
\]

\[
SE_{ADO} = \frac{(\log_2 M_{ADO})}{(1 + \frac{2}{N})} \quad (45)
\]

\[
SE_{FLIP} = \frac{(\log_2 M_{FLIP})}{(1 + \frac{2}{N})} \quad (46)
\]

\[
SE_{ASCO} = \frac{(\log_2 M_{ASCO,odd})}{2} + \frac{(\log_2 M_{ASCO,even})}{4} \quad (47)
\]

\[
SE_{SSACO} = \frac{(\log_2 M_{odd})}{2} + \frac{(\log_2 M_{even})}{4} + \frac{(\log_2 M_{special,even})}{8} \quad (48)
\]

\[
SE_{E-ASCO} = \frac{(\log_2 M_{odd})}{2} + \frac{(\log_2 M_{even})}{4} \quad (49)
\]

where \(M_{xx}\) is the modulation order \(M\) used with VLC technique \(xx\). Moreover \(M_{odd}, M_{even}, \) and \(M_{special,even}\) is the used modulation order for the odd subcarriers, the even subcarriers, and the special even subcarriers used in the system respectively, where \(N = 1024\) is the used IFFT size in the analysis.

V. SIMULATION RESULTS

The simulation results of the proposed techniques compared to the published systems in [9], and [17] are introduced and simulated using MATLAB. The simulation results were studied for different modulation techniques to analyze the effect of modulation on the system performance. The simulated channel is additive white Gaussian noise (AWGN) channel and Table 2, summarized the simulation parameters.

For the DCO and ADO OFDM systems, the biasing DC-level used in the simulation is 13 dB to reach BER of \(10^{-4}\) at high modulation order. The performance of E-ASCO, DCO, ACO, FLIP, ADO, and ASCO OFDM systems at SE of 2.9942 is illustrated in Fig.19. The E-ASCO OFDM system outperforms the other compared techniques with \(E_b/N_0 = 17.35\) dB at BER of \(10^{-4}\), which is better than the other existing techniques by values illustrated in Table 3.

| PARAMETER       | VALUE       |
|-----------------|-------------|
| Number of OFDM Symbols | 1000        |
| Modulation techniques | QPSK,16-QAM,...,4096-QAM |
| FFT size (N)   | 1024        |
| Cyclic prefix length | N/4         |
| DC-Level       | 13 dB       |
| Channel model  | AWGN channel|

Also, the E-ASCO OFDM system has a higher system data rate performance by 12.5% than ACO-OFDM and FLIP-OFDM, and the same DRR of 37.5% as ASCO-OFDM but with lower system complexity at the receiver side. However, it has a lower DRR of 12.5% than DCO-OFDM, and ADO-OFDM.

TABLE 3. E-ASCO BER system enhancement compared to other existing techniques.

| Technique | ASCO OFDM | ACO OFDM | FLIP OFDM | DCO OFDM | ADO OFDM |
|-----------|-----------|----------|-----------|-----------|----------|
| Difference Value (dB) | 0.2 | 2.1 | 2.25 | 6.95 | 10.25 |

For the SSACO-OFDM system, by changing the modulation order there is no common suitable SE between the existing techniques, so a comparison is applied under the same modulation order of 16-QAM with \(N = 1024\) as shown in Fig. 20. The SSACO OFDM system at BER of \(10^{-4}\) outperforms the DCO, and ADO OFDM systems by 6 dB, and 9.5 dB, respectively. Also, it has higher BER than ASCO and E-ASCO OFDM systems by just 1.4 dB, and 1.6 dB respectively, with the benefit of improving the system data rate by 6.25% than ASCO and E-ASCO OFDM systems.
Figure (21), shows that the E-ASCO, SSACO, ACO, and DCO OFDM techniques have almost the same rate of increase of required \( Eb/No \) by increasing the constellation sizes. At a certain BER of \( 10^{-4} \), the DCO has the highest required \( Eb/No \) values for all the constellation sizes due to the added dc level. Whereas, ACO has the lowest required \( Eb/No \) as it has the lowest SE compared to the other systems, so minimum energy is required. Moreover, the proposed E-ASCO OFDM has a moderate value between the compared techniques that is because E-ASCO has a SE higher than ACO and lower than DCO, thus moderate energy is required. Also, SSACO requires a higher energy than ACO, ASCO, and E-ASCO but lower than DCO that is because SSACO has a SE higher than ACO, ASCO, and E-ASCO but lower than DCO.

Figure (22), shows the relation between different optical modulation techniques SE against the \( Eb/No \) at different constellation sizes. It’s noticed that the rate of increase of \( Eb/No \) against the SE for the ACO-OFDM curve is very high that results in a spectrally inefficient technique.

So, they are the most spectrally efficient techniques among the compared techniques. The different rates of increase of \( Eb/No \) from one technique to another causes intersection points between the curves. Data extracted from Fig. 22 are represented in Table 4.

| \( M \) (QAM) | DCO OFDM | ADO OFDM | ACO & FLIP | ASCO OFDM | SSACO OFDM | E-ASCO OFDM |
|--------------|-----------|-----------|-----------|-----------|-----------|------------|
| 8            | 2.9942    | 3.9922    | 1.9961    | 2.9442    | 3.49317   | 2.9942     |
| 16           | 5.9883    | 5.9883    | 2.9942    | 4.4912    | 5.23976   | 4.4912     |
| 256          | 7.9844    | 7.9844    | 3.9922    | 5.9883    | 6.98655   | 5.9883     |
| 512          | 8.9825    | 8.9825    | 4.4912    | 6.7368    | 7.85964   | 6.7368     |

VI. CONCLUSION

In this paper, two new optical modulation techniques were presented; the SSACO-OFDM and the E-ASCO OFDM systems. The proposed systems were evaluated, analyzed, and compared with other existing techniques as ACO, DCO,
AD0, FLIP, and ASC0 OFDM according to system complexity, SE, and BER system performance through simulation verification and mathematical analysis. The proposed SSAC0-OFDM system demonstrates to be a compromise choice between having a low system complexity by introducing a special receiver with mathematical analysis and enhancing the system BER performance by introducing a noise cancellation technique also, increasing the transmitted data rate which results in a spectrally efficient technique. SSAC0-OFDM system has a spectral efficiency enhancement by a ratio of 75%, 75%, and 16.666% compared to ACO, FLIP, and ASC0-OFDM systems respectively, but with a spectral efficiency less than both DCO OFDM and ADO OFDM by 12.5%. Also, it has an enhancement in the system performance at BER of $10^{-4}$ by 6 dB, and 9.5 dB compared to DCO-OFDM, and ADO-OFDM respectively, and worse than ASC0-OFDM by just 1.4 dB. The proposed E-ASC0 OFDM system has the same spectrum efficiency as ASC0-OFDM but with lower complexity and better BER system performance by at least 0.2 dB at BER of $10^{-4}$. Also, E-ASC0 outperforms the existing techniques for enhancing the system BER performance by 6.95 dB, 10.25 dB, 2.1 dB, and 2.2 dB than DCO, ADO, ACO, and FLIP respectively at the same spectral efficiency of 2.9942.

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Mona Z. Saleh (Member, IEEE) received the B.Sc. (Hons.), M.Sc., and Ph.D. degrees in the electrical engineering field from the Faculty of Engineering, Ain Shams University, in 2002, 2008, and 2013, respectively. In 2002, she joined the Electronics and Communications Engineering Department, Ain Shams University, as a Teaching Assistant, in 2008, she became a Teaching Associate, in 2014, she was promoted to an Assistant Professor, and since 2019, she has been working as an Associate Professor. Her current research interests include but are not limited to signal processing and wireless communication systems. She participated in many research projects and has many conference and journal publications in these areas. She has been an Organizing Committee Member in several scientific conferences, e.g., MMS’03, NRSC’07, and ESOLE, since 2009. She has been also an Executive Office Member of the ESOLE journal, since April 2014.

Hesham M. Elbadawy (Senior Member, IEEE) received the B.Sc., M.Sc., and Ph.D. degrees from the Faculty of Engineering, Ain Shams University, Egypt, in 1993, 1997, and 2003, respectively. He is currently a Professor with the Network Planning, National Telecommunication Institute, Cairo, Egypt. He has authored over 120 journals and conference papers supervising over 100 Ph.D. and M.Sc. students. His research interests include networking, performance evaluation techniques, teletraffic modeling, MIMO systems, and energy efficient HetNets, queueing networks, and broadband wireless communication systems, such as 4G/5G and beyond. He is also a Recognized Instructor and an Academia Member of the International Telecommunication Union (ITU). Since May 2014, he has been elevated to be the IEEE Senior Member in both of Vehicular Technology Society and the Communications Society. He has been also a Senior Member of the International Union of Radio Science (URSI), since June 2017. In addition, he is the Egyptian Representative in the Electromagnetic Environment and Interference, URSI Scientific Commissions.

Salwa H. ElRamly (Life Senior Member, IEEE) received the B.Sc. and M.Sc. degrees from the Faculty of Engineering, Ain Shams University, Egypt, in 1967 and 1972, respectively, and the Ph.D. degree from Nancy University, France, in 1976. She is currently a Professor Emeritus with the Electronics and Communications Engineering Department, Faculty of Engineering, Ain Shams University, where she was the Head of the Department, from 2004 to 2006. She has published over 200 scientific papers and supervised over 100 M.Sc. and Ph.D. theses. Her research interests include wireless communication systems and signal processing, language engineering, coding, encryption, and radars. She received the Ain Shams Award of Appreciation in Engineering Sciences, in 2010, the Award of Excellence from the Society of Communications Engineers, in 2009, and the Award of Excellence from the Egyptian Society of Language Engineering, in 2009, the Award of Appreciation from the National Radio Science Committee, and the Academy of Science Research and Technology, Cairo, Egypt, in 2018. She has been the IEEE Signal Processing Chapter Chair in Egypt, since 2003. She shared in the establishment of the Egyptian Society of Language Engineering, in 1996, where she is currently the President.

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