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LETTER

Selectively biased optical orthogonal frequency division multiplexing for visible light communication systems

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Abstract Traditional direct-current biased optical orthogonal frequency division multiplexing (DCO-OFDM) achieves unipolar signaling by adding a direct current (DC) bias and performing clipping. To suppress signal nonlinearity distortion caused by clipping, the DC bias needs to be set at a higher level, which results in low power efficiency of the DCO-OFDM. A scheme named Selectively Biased Optical OFDM (SBO-OFDM) was proposed in this letter. SBO-OFDM multiplies the OFDM signals with random phase sequences, selects the signal that requires the least amount of bias for transmission, and dynamically adds the bias based on signal variations to improve power efficiency. The experimental results demonstrate that the proposed SBO-OFDM exhibits a significant decrease in requirement of the normalized optical bit energy to noise power ratio $[E_{b(opt)}/N_o]$ compared to DCO-OFDM, ACO-OFDM, and PAM-DMT at a BER of 10^{-3}. The results indicate that SBO-OFDM outperforms traditional optical OFDM (O-OFDM) in terms of power efficiency and have better BER performance than traditional DCO-OFDM.

Keywords: visible light communication, selectively biased OFDM, power efficiency

Classification: Wireless communication technologies

1. Introduction

In the face of increasing data-traffic demand, it is increasingly difficult for wireless communication to meet the capacity, efficiency, security and other needs. The emergence of visible light communication (VLC) technology may be able to alleviate the problem of spectrum resource scarcity [1, 2].

Unlike conventional RF communication that transmits bipolar complex signals, VLC generally uses intensity modulation and direct detection (IM/DD) techniques. The modulation signal of the LEDs has to be a unipolar real signal, since the light intensity cannot be negative and a single transmitter does not transmit complex signals. In order to make the signal suitable for visible light communication transmission, many OFDM schemes have been proposed for VLC systems. Among them, there are several well-known methods: DC biased O-OFDM (DCO-OFDM) [3], asymmetric limiting O-OFDM (ACO-OFDM) [4, 5, 6] and also Pulse Amplitude Modulated Discrete Multi Tone (PAM-DMT) [7]. In DCO-OFDM, a constant DC bias needs to be added to convert the signal to a unipolar real signal that can be transmitted by the LEDs. Due to the high peak-to-average power ratio (PAPR) of OFDM, the DC bias should be set to a high level to mitigate clipping distortions, which lead to power inefficiency. ACO-OFDM only modulates the information on the odd subcarriers, and clips the negative part of the signal directly to obtain a unipolar real signal. This method does not cause any signal distortion from clipping, but it wastes half of the spectral resources, resulting in spectral inefficiency. PAM-DMT uses pulse amplitude modulation of the subcarrier and the resulting PAM-DMT time signal can be asymmetrically clipped to achieve unipolar signal transmission. But this method has disadvantages in terms of BER performance compared to QAM modulation.

Recently, researchers have made improvements to the original unipolar schemes and proposed hybrid O-OFDM modulation schemes. Hybrid modulation utilizes two or more unipolar optical OFDM schemes to modulate the signals and obtains better spectral efficiency or power efficiency. Some examples of hybrid modulation schemes include Asymmetrically Clipped Direct Current-biased Optical OFDM (ADO-OFDM) [8], Hybrid Asymmetrically Clipped Optical OFDM (HACO-OFDM) [9], and Enhanced Hybrid Asymmetrically Clipped Optical OFDM (EHACO-OFDM) [10]. Compared to traditional O-OFDM schemes, these hybrid modulation schemes offer improvement in spectral efficiency and power efficiency. However, the stacked O-OFDM schemes consist of two or more modulation modules. Consequently, compared to traditional O-OFDM schemes, hybrid O-OFDM introduces additional complexity in the receiver implementation due to delay processing at the receiver end. This increases the complexity of receiver implementation.

A novel O-OFDM named Selectively biased Optical Orthogonal Frequency Division Multiplexing (SBO-OFDM) is proposed in this letter. Since DCO-OFDM requires higher DC bias to reduce clipping distortion, it leads to power inefficiency. SBO-OFDM multiplies the frequency domain signals with U paths random phase sequences, calculates the total bias required for each of the U paths signals, selects a signal sequences with the smallest total bias and adds adaptive bias to make the signals positive. Compared to DCO-OFDM, this approach increases power efficiency, while avoiding information loss caused by amplitude limiting, and reduces BER. Compared to ACO-OFDM, SBO-OFDM uses more subcarriers to transmit information, significantly increasing the system's spectral efficiency. Additionally, the SBO-OFDM in this letter employs QAM modulation, which has better BER performance compared to PAM-DMT. Moreover, unlike the recently proposed hy-

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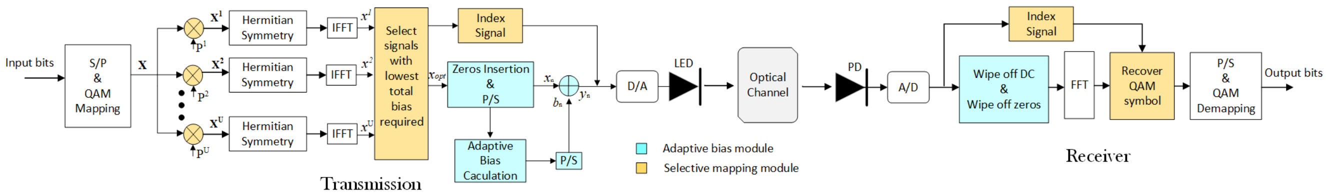

Fig. 1 Block diagram of SBO-OFDM

brid O-OFDM schemes, the receiver design of SBO-OFDM is the same as that of traditional O-OFDM, avoiding additional delay processing and reducing the complexity of receiver implementation.

2. Selectively biased OFDM

The system block diagram of SBO-OFDM is shown in Fig. 1. The traditional DCO-OFDM has low power efficiency due to the addition of high DC bias, unlike the traditional DCO-OFDM system, SBO-OFDM adds a selective mapping module and an adaptive bias module to reduce the amount of bias. The role of the adaptive bias module is to add different biases in groups according to the amplitude variation of the signal, so that the bipolar OFDM signal becomes a unipolar positive real signal and improves the power efficiency. Selective mapping (SLM) [11] was originally designed to reduce the PAPR, and this letter changes the part of the SLM algorithm to screen for the lowest total bias required by the adaptive bias module, instead of the lowest PAPR. The selective mapping module complements the adaptive bias module to further improve the power efficiency of the system. The selective mapping module and the adaptive biasing module are described in detail below.

The selective mapping module consists of three steps, the first step is to dot-multiply the frequency domain signal with a random phase matrix, the second step is to filter the signal and the third step is to send the index signal. At the transmitter side of the system, a frequency domain signal of length N, $X = [X(0), X(1), \ldots, X(N-1)]$ is copied into the same U paths, then a random phase sequence of U paths all of length N is generated $p^u = [p^u(0), p^u(1), \ldots, p^u(N-1)](u = 1, 2, \ldots, U)$, and subsequently dot-multiply X with P to obtain X^u $(1 \le u \le U)$. In order to ensure that the time-domain signals are real numbers, the input signals need to be processed with Euclidean conjugate symmetry and IFFT to obtain the time-domain signal sequence x^u. In the time-domain signal sequence x^u, we select the group of signals that necessitates the least total adaptive bias as the transmission sequence, denoted x_{opt}. The selection method for x_{opt} is as follows: put the four time domain signals in each path into one group, min_k denote the minimum value of each group (where $k = 0, 1, 2, \ldots, N/4-1$). The bias amount a_k required for each group is determined such that if min_k is greater than zero, then a_k is set to zero; if min_k is less than or equal to zero, then a_k is set to -min_k. Summing all a_k yields the total adaptive bias required for that signal, denoted as sum. Among the U path signals x^u, the one with the smallest sum is chosen as the transmission sequence x_{opt}. The formula for sum can be represented as:

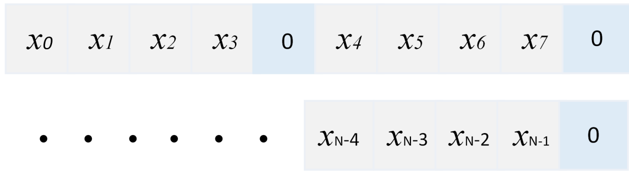

Fig. 2 Time-domain signal demonstration of SBO-OFDM.

$$
\begin{aligned}
&min_k = \min\{x_{4k}, x_{4k+1}, x_{4k+2}, x_{4k+3}\} \\
&\begin{cases} a_k = -min_k, min_k \leqslant 0 \\ a_k = 0, min_k > 0 \end{cases} \\
&sum = \sum_{k=0}^{\frac{N}{4}-1} a_k, k = 0, 1, 2, \ldots, \frac{N}{4} - 1
\end{aligned} \tag{1}
$$

To ensure the correct recovery of the transmitted signal at the receiver, it is imperative to identify which sequence in x^u is the transmitted sequence x_{opt}. Therefore, it is necessary to append $\log_2 U$ bits of index information to each signal group before transmission; these bits correspond to the identification number of the random phase sequences in the U paths. At the receiver, by extracting this index information, it is possible to determine with which random phase sequence the frequency domain signal was multiplied at the transmitter. Finally, by dividing the received signal by this particular random phase sequence, the transmitted signal can be restored.

At this time, the time domain signal x_{opt} is still a bipolar signal, which needs to be added with bias to change it into a positive real signal. Unlike the traditional DCO-OFDM, the bias added by SBO-OFDM is adaptive bias. As illustrated in Fig. 2, we insert a zero after every fourth bit of x_{opt} to obtain the time-domain signal x_n(where $n = 0, 1, 2, \ldots, 5N/4-1$). The fifth bit of each such group of signals is the bias added to the group, and the signal at that position is extracted at the receiver side to solve the adaptive bias. Every five such signals are considered as a group, after adding the same bias b_n for each group of signals to make them positive, b_n can be expressed as:

$$
\begin{aligned}
&min_k = \min(x_{5k}, x_{5k+1}, x_{5k+2}, x_{5k+3}, x_{5k+4}) \\
&\begin{cases} b_{5k} = b_{5k+1} = b_{5k+2} = b_{5k+3} = b_{5k+4} = -min_k, \\ min_k <= 0 \\ b_{5k} = b_{5k+1} = b_{5k+2} = b_{5k+3} = b_{5k+4} = 0, \\ min_k > 0 \end{cases} \\
&k = 0, 1, 2, \ldots, \frac{N}{4} - 1
\end{aligned} \tag{2}
$$

where min_k is the smallest value in each group of five signals, and b_n is the bias that needs to be added to the nth position of the signal.

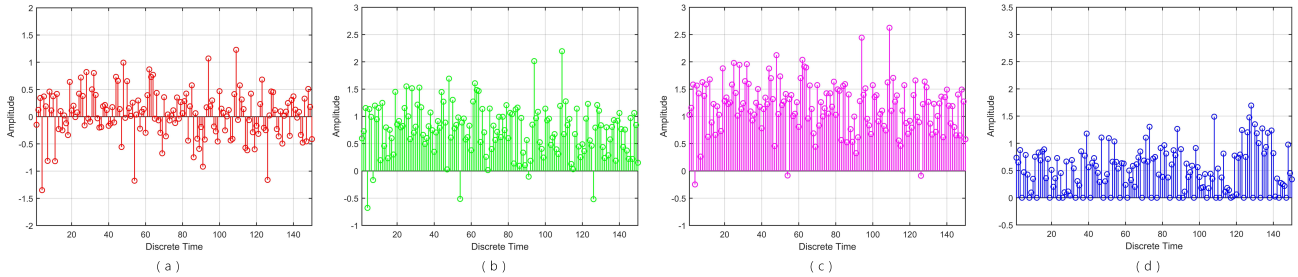

Fig. 3 Time-domain signal amplitude for each scheme. (a) Dipolar OFDM time-domain signal (b) time-domain signal of DCO-OFDM with a 7dB bias added (c) time-domain signal of DCO-OFDM with a 10dB bias added (d) time-domain signal of the SBO-OFDM

The signal y_n after adding the bias can be expressed as:

$$y_n = x_n + b_n, n = 0, 1, 2, \ldots, \frac{5N}{4} - 1 \qquad (3)$$

Compared to DCO-OFDM, SBO-OFDM greatly reduces the overall bias of the system, improves the power efficiency and eliminates the need to limit the signal, reducing the BER of the system.

3. Experimental result

The SBO-OFDM will be compared with traditional ACO-OFDM, DCO-OFDM, PAM-DMT, and the recently proposed hybrid modulation scheme HACO-OFDM. The modulation scheme used in this simulation is QAM and the size of the IFFT used is N=256, the number of random phase sequences is U=32. In the subsequent experimental analysis, we employ $E_{b(opt)}/N_0$ to evaluate the performance. $E_{b(opt)}/N_0$ represents the ratio of the energy required to transmit each bit of information to the noise power spectral density, which is directly associated with the information bits, independent of the transmission rate and bandwidth, and is suitable for comparing the performance of different modulation schemes in order to assess the system performance more accurately. In addition, $E_{b(opt)}/N_0$ is an important evaluation metric of power efficiency, can intuitively assess the power efficiency level of the system.

Figure 3 displays the time-domain OFDM signals processed in four different ways and records the amplitudes of 150 time-domain signals after performing IFFT on QAM symbols with a modulation factor of 64. In Fig. 3(a), the untreated bipolar time-domain signal of OFDM is shown. Since LEDs cannot transmit negative signals, a bias must be added to bring the signal up. Figure 3(b) represents the DCO-OFDM time-domain signal with a 7 dB bias. Compared to Fig. 3(a), it can be observed that a 7 dB bias raises the majority of the signals above zero. However, there are still negative signals present, and since LEDs cannot transmit negative signals, these signals are clipped. This results in distortion and significantly affects the BER. Next, the bias is increased to 10 dB. Figure 3(c) shows that although negative signals still exist, their number has noticeably decreased. To achieve distortion-free transmission, a higher DC bias would be required, but this would result in a loss of power efficiency. Figure 3(d) displays the time-domain signal of the proposed SBO-OFDM system. It can be observed that all the signals are positive real numbers, eliminating the need for signal clipping and avoiding signal distortion. Additionally, different group of signals has different bias based on its requirements. From the figure, it is evident that the overall bias of SBO-OFDM is much smaller than DCO-OFDM with the DC bias level of 7 dB and 10 dB.

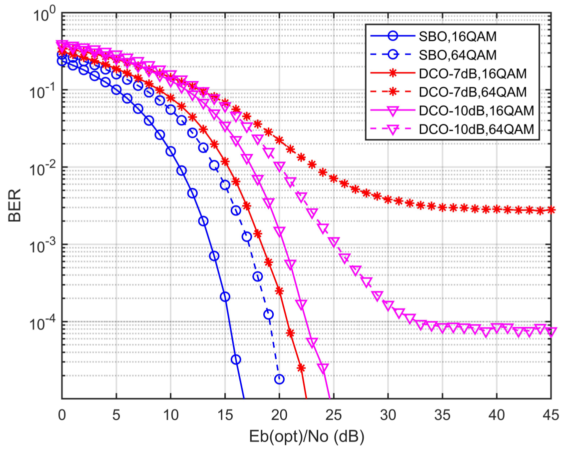

Fig. 4 BER performance comparison of the proposed SBO-OFDM and the conventional DCO-OFDM at various values of $E_{b(opt)}/N_0$.

Figure 4 shows the BER performance of SBO-OFDM and DCO-OFDM with different levels of bias. We evaluate their BER performance using the normalized optical bit energy to noise power ratio $E_{b(opt)}/N_0$. In this experiment, the BER performance of SBO-OFDM and DCO-OFDM with the DC bias level of 7 dB and 10 dB are tested under 16QAM and 64QAM conditions, respectively. In both low and high modulation order scenarios, SBO-OFDM consistently exhibits the best bit error rate performance. Particularly, in high modulation order scenarios, the advantage of SBO-OFDM's bit error rate performance becomes even more pronounced. DCO-OFDM with an additional 7dB bias even fails to meet communication standards at high modulation conditions. This is because the distortion introduced by clipping has a more significant impact at higher modulation conditions. SBO-OFDM does not require signal clipping, thus leading to better BER performance.

In Fig. 5, power efficiency is evaluated based on the required $E_{b(opt)}/N_0$ for a BER of 10^{-3}. We provides the experimental data for SBO-OFDM, DCO-OFDM with the DC bias level of 10 dB, DCO-OFDM with the DC bias level of 13 dB, ACO-OFDM, and PAM-DMT. It can be observed that within a wide range of bit rates/normalized bandwidths, SBO-OFDM requires significantly lower $E_{b(opt)}/N_0$ com-

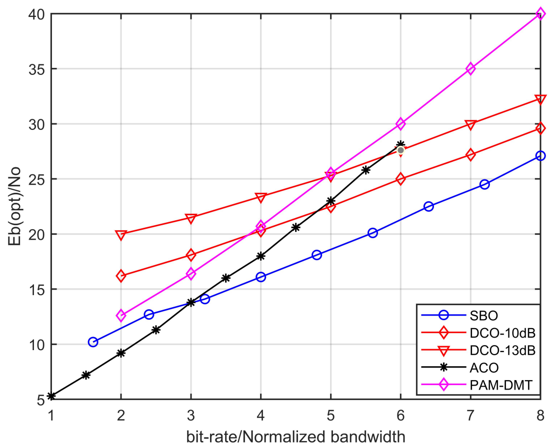

Fig. 5 $E_{b(opt)}/N_0$ required for the BER target of 10^{-3} versus bit rate/normalized bandwidth.

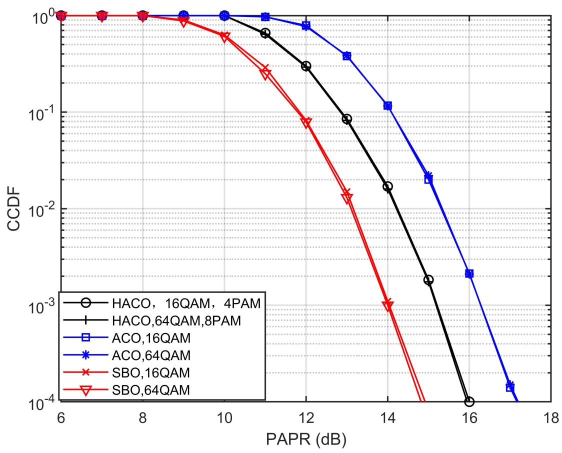

Fig. 6 Complementary cumulative distribution function of PAPR for the Proposed SBO-OFDM, ACO-OFDM, and HACO-OFDM.

pared to other traditional O-OFDM schemes. This indicates that our proposed SBO-OFDM achieves higher power efficiency.

Figure 6 displays the PAPR and Complementary Cumulative Distribution Function (CCDF) curves for three different schemes: SBO-OFDM, ACO-OFDM, and HACO-OFDM,ACO-OFDM and HACO-OFDM do not require the addition of bias. 16QAM and 64QAM are used in SBO-OFDM and ACO-OFDM, while 16QAM associated with 4-PAM and 64-QAM associated with 8-PAM are used in HACO-OFDM,to ensure that both schemes provide the same spectral efficiency. From the figure, it can be observed that the PAPR of the proposed SBO-OFDM is significantly lower than that of ACO-OFDM and HACO-OFDM, which indicates that SBO-OFDM has a better resistance to nonlinearities, and therefore reduces the linearity requirement of the optical front-end.

4. Conclusion

The proposed SBO-OFDM differs from the traditional DCO-OFDM by incorporating a selective mapping module and an adaptive bias module. By employing these two methods, It changes the static direct current bias in DCO-OFDM to a dynamic bias that depends on the signal's amplitude. With the assistance of the SLM algorithm, it further reduces the amount of bias needed for the signal, thus improving the power efficiency of the system. Experimental results demonstrate that the proposed SBO-OFDM scheme achieves higher power efficiency compared to traditional approaches such as DCO-OFDM, ACO-OFDM, and PAM-DMT. SBO-OFDM outperforms DCO-OFDM in terms of BER performance. Compared to the recently proposed hybrid modulation scheme HACO-OFDM, SBO-OFDM exhibits better nonlinearity resistance capability.

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