LETTER

An Adaptively Biased OFDM Based on Hartley Transform for Visible Light Communication Systems

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SUMMARY Direct-current biased optical orthogonal frequency division multiplexing (DCO-OFDM) converts bipolar OFDM signals into unipolar non-negative signals by introducing a high DC bias, which satisfies the requirement that the signal transmitted by intensity modulated/direct detection (IM/DD) must be positive. However, the high DC bias results in low power efficiency of DCO-OFDM. An adaptively biased optical OFDM was proposed, which could be designed with different biases according to the signal amplitude to improve power efficiency in this letter. The adaptive bias does not need to be taken off deliberately at the receiver, and the interference caused by the adaptive bias will only be placed on the reserved subcarriers, which will not affect the effective information. Moreover, the proposed OFDM uses Hartley transform instead of Fourier transform used in conventional optical OFDM, which makes this OFDM have low computational complexity and high spectral efficiency. The simulation results show that the normalized optical bit energy to noise power ratio ($E_{b(opt)}/N_0$) required by the proposed OFDM at the bit error rate (BER) of 10^{-3} is, on average, 7.5 dB and 3.4 dB lower than that of DCO-OFDM and superimposed asymmetrically clipped optical OFDM (ACO-OFDM), respectively.

key words: *visible light communication, optical orthogonal frequency division multiplexing, Hartley transform, power efficiency*

1. Introduction

Visible light communication (VLC) is widely used in communications due to its advantages, such as unlimited bandwidth, low cost, and immunity to electromagnetic radiation interference. Orthogonal frequency division multiplexing (OFDM) technology, which offers resistance to inter-symbol interference (ISI) and high spectral efficiency, is extensively employed in VLC systems [1].

The signal transmitted using intensity modulated/direct detection (IM/DD) technique in VLC systems must be positive. To achieve non-negative signals, the initial solution was DCO-OFDM [2], which transformed the bipolar OFDM signal into a non-negative signal by introducing a DC bias, but the high DC bias led to low the power efficiency.

To improve power efficiency, asymmetrically clipped Optical OFDM (ACO-OFDM) was proposed, a solution in which the negative part of the signal was directly clipped to obtain a non-negative signal but this method would induce suboptimal spectral efficiency [3]. In recent years, superimposed OFDM schemes have emerged to increase power efficiency, such as hybrid ACO-OFDM (HACO-OFDM) [4] and layered ACO-OFDM (LACO-OFDM) [5]. The spectral and power efficiency of both superimposed OFDM is higher than that of ACO-OFDM. However, the transmitter side of both schemes consists of multiple OFDM modulation blocks superimposed, and the receiver requires an iterative receiver to detect the superimposed components, which results in a very high computational complexity of the whole system. To reduce complexity, the DHT-LACO-OFDM proposed in [6] utilizes discrete Hartley transform (DHT) instead of fast Fourier transform (FFT) and presents a layered signal reception method based on time-domain reconstruction. This method reduces the computational complexity to half that of traditional iterative receivers, and DHT compensates for the lower spectral efficiency of FFT. While HACO-OFDM and LACO-OFDM achieve high spectral and power efficiency, the computational complexity remains high, posing challenges for hardware implementations.

An OFDM scheme was proposed in this letter that incorporated adaptive bias in Hartley transform-based OFDM, with the aim of achieving high power efficiency and low computational complexity for O-OFDM. Since the DC bias of DCO-OFDM is a fixed and high value, it leads to DCO-OFDM having low power efficiency. The proposed OFDM uses an adaptive bias that can be changed according to the amplitude of the signal to improve the power efficiency, and this bias does not need to be taken off intentionally at the receiver without affecting the useful information. Our OFDM uses Hartley transform instead of the Fourier transform, which makes the computational complexity significantly lower than that of superimposed ACO-OFDM, and reduces the difficulty of hardware implementation while doubling the spectral efficiency. Simulation data show that the proposed OFDM has high power efficiency.

2. Adaptively Biased OFDM Based on Hartley Transform

As shown in Fig. 1, the proposed scheme uses Hartley transform instead of Fourier transform. Since Hartley transform is a real number transform, one-dimensional real number constellation mappings, such as binary phase shift keying (BPSK) and multi-order pulse amplitude modulation (M-PAM), must be used [7]. As shown in Fig. 2, $\{X_k\}_{k=0}^{N-1}$ is the frequency-domain signal on the subcarrier after constellation

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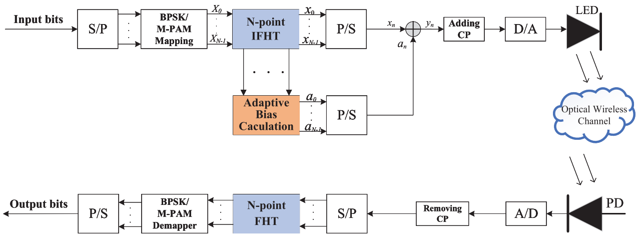
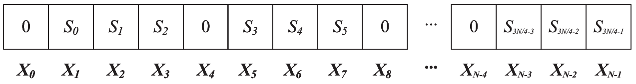


Fig. 1 System block diagram.



0	S_0	S_1	S_2	0	S_3	S_4	S_5	0	···	0	$S_{3N/4-3}$	$S_{3N/4-2}$	$S_{3N/4-1}$
X_0	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	···	X_{N-4}	X_{N-3}	X_{N-2}	X_{N-1}

Fig. 2 Corresponding positions of symbols in real-valued constellation mapping on subcarriers.

mapping,and $\{S_i\}_{i=0}^{\frac{3N}{4}-1}$ is the data symbol of constellation mapping. When $k = 4e, (e = 0, 1, \ldots, N/4 - 1)$, no information data symbol is carried on the 4e-th subcarrier, and these reserved empty subcarriers are for placing bias-induced interference at the receiver. Only 1/4 of the N subcarriers are empty with no data symbols placed, and the other 3/4 have information data symbols. Then doing the inverse fast Hartley transform (IFHT), the expression is

$$x(n) = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X(k) \operatorname{cas}\left(\frac{2\pi kn}{N}\right), n = 0, 1, \ldots, N-1 \tag{1}$$

where N is the sequence length of the IFHT, $X(k)$ is the frequency-domain signal of the k-th subcarrier after BPSK or M-PAM real number mapping, and $x(n)$ is the time-domain signal after the IFHT.

The time-domain signal after the IFHT is $\{x_n\}_{n=0}^{N-1}$. To obtain a unipolar non-negative OFDM signal, DCO-OFDM adds a DC bias. However, since adding DC bias can lead to low power efficiency, this letter introduces adaptive biasing, which can improve the power efficiency by adding different biases depending on the signal amplitude. This bias is an algorithm that does not add current, so it differs from the DC bias. The specific approach of the adaptive bias algorithm is to divide the fixed four time-domain information samples into a group; each group of information samples is $x_n, x_{n+N/4}, x_{n+N/2}, x_{n+3N/4}$, $(n = 0, 1, \ldots, N/4 - 1)$, and the opposite number of the minimum value of each group of information samples is the bias of this group. For example, if the information samples of a group are $0.1, -0.1, -0.2, 0.3$, then the bias of this group is 0.2, and the signal after adding this bias to this group is $0.3, 0.1, 0, 0.5$. Further, if a group of four signal samples is all positive, e.g., $0.1, 0.2, 0.3, 0.4$, then the bias of this group is -0.1, and the signal after adding this bias is $0, 0.1, 0.2, 0.3$. This operation reduces the amplitude of the signal to save power consumption. Adaptive bias is defined as:

$$\begin{aligned} a_n &= a_{n+\frac{N}{4}} = a_{n+\frac{N}{2}} = a_{n+\frac{3N}{4}} \\ &= -min\{x_n, x_{n+\frac{N}{4}}, x_{n+\frac{N}{2}}, x_{n+\frac{3N}{4}}\} \\ n &= 0, 1, \ldots, N/4 - 1 \end{aligned} \tag{2}$$

The biases at the corresponding positions of x_n, $x_{n+N/4}$, $x_{n+N/2}$, $x_{n+3N/4}$ are a_n, $a_{n+N/4}$, $a_{n+N/2}$, $a_{n+3N/4}$, respectively. The non-negative information obtained after adding the biases is as follows:

$$y(n) = x(n) + a(n), n = 0, 1, \ldots, N-1. \tag{3}$$

$x(n)$ represents the bipolar OFDM information, and $a(n)$ represents the bias.

Adaptive biasing is handled differently at the receiver than DC biasing in DCO-OFDM. DC bias must be intentionally taken off at the receiver side, but adaptive bias does not. The received signal will be directly operated by the FHT, and the expression is

$$\begin{aligned} Y(k) &= \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} y(n) \operatorname{cas}(2\pi kn/N) \\ &= \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} x(n) \operatorname{cas}(2\pi kn/N) + \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} a(n) \operatorname{cas}(2\pi kn/N) \\ &= X(k) + A(k), k = 0, 1, \ldots, N-1. \end{aligned} \tag{4}$$

The kernel function for the Hartley transform in Eqs. (1) and (4) is defined as follows:

$$\operatorname{cas}(2\pi kn/N) = \cos(2\pi kn/N) + \sin(2\pi kn/N) \tag{5}$$

$X(k)$ is the result of performing FHT on $x(n)$, while $A(k)$ is the result of performing FHT on $a(n)$. $A(k)$ is

$$A(x) = \begin{cases} 0 & k \neq 4e \\ \dfrac{4}{\sqrt{N}} \displaystyle\sum_{n=0}^{N/4-1} a_n \operatorname{cas}(8\pi en/N) & k = 4e \end{cases} \tag{6}$$

From (6), it can be seen that biasing the received information after doing an FHT operation will not affect the useful information, and the generated interference will only fall on $k = 4e, (e = 0, 1, \ldots, N/4 - 1)$ of subcarriers. And the 4e-th subcarrier has been reserved in advance at the transmitter without placing useful information, so there will be no interference to the useful information. Compared with HACO-OFDM and superimposed ACO-OFDM, the proposed OFDM receiver is simpler, greatly simplifying the system's complexity.

3. Complexity Analysis

In this section, a comparison of the complexity between the proposed scheme and existing methods will be conducted. In the proposed scheme, the adaptive bias requires the computation of the minimum value of the information, which has the same computational complexity as the amplitude clipping operation in ACO-OFDM since the clipping operation is equivalent to finding the minimum value between 0 and the

Table 1 Comparison of system complexity for different OFDM schemes.

Modulation	Transmitter	Receiver
the proposed OFDM	$N/2\log_2 N$	$N/2\log_2 N$
ACO-OFDM	$2N\log_2 N$	$N\log_2 N-3N+4$
HACO-OFDM	$3N\log_2 N-3N+4$	$4N\log_2 N-6N+8$
DHT-LACO-OFDM	$N\log_2 N-3N+6$	$3N\log_2 N-9N+18$

information. In this case, the complexity is calculated based on the number of multiplication operations for IFHT and IFFT [8]. ACO-OFDM and HACO-OFDM utilize IFFT for computation, where the number of multiplication operations for ACO-OFDM is $2N\log_2 N$, and HACO-OFDM requires separate N-point IFFT for real and imaginary parts, resulting in a complexity of $3N\log_2 N-3N+4$. DHT-LACO-OFDM and the proposed scheme employ IFHT, leading to lower computational complexity than IFFT. The complexity of the transmitter in DHT-LACO-OFDM is $N\log_2 N-3N+6$, while the proposed scheme only requires $N/2\log_2 N$ operations, significantly reducing the complexity compared to other OFDM schemes.

At the receiver, ACO-OFDM performs only one N-point FFT with a multiplication operation count of $N\log_2 N-3N+4$. HACO-OFDM requires two N-point real-valued FFT and one N-point complex-valued IFFT operation, resulting in a receiver complexity of $4N\log_2 N-6N+8$. DHT-LACO-OFDM receiver involves three N-point DHT computations, resulting in a complexity of $3N\log_2 N-9N+18$. In contrast, the proposed scheme requires only one N-point FHT computation, and the computational complexity of both FHT and IFHT is $N/2\log_2 N$. The computational complexities of different OFDM schemes are summarized in Table 1, and compared to other OFDM schemes, the proposed scheme exhibits a significant reduction in overall complexity.

4. Simulation Results

This section presents the simulation performance results of the proposed OFDM. The simulations are performed in the case of an indoor ideal additive Gaussian white noise (AWGN) visible light channel. The proposed OFDM uses 256 subcarriers and 10^4 OFDM symbols. Since the normalized optical bit energy to noise power ratio ($E_{b(opt)}/N_0$) is a key performance metric for assessing the performance in optical wireless communication (OWC), it is used to evaluate the performance of the proposed scheme in the following simulation analysis.

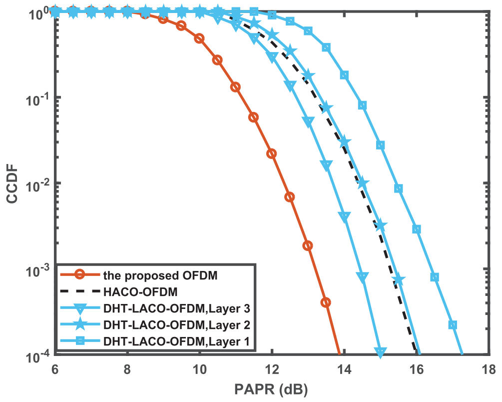


Fig. 3 The CCDF of PAPR for the proposed new scheme, HACO-OFDM, and DHT-LACO-OFDM.

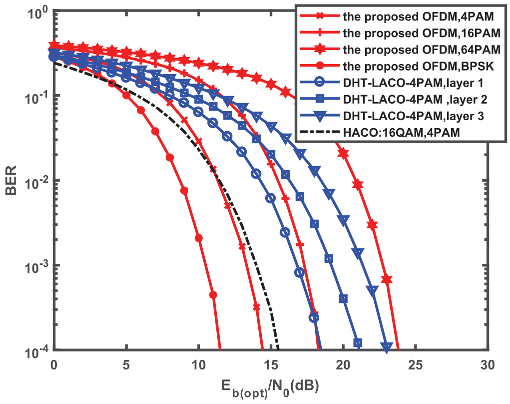


Fig. 4 The comparison of the bit error rates between the proposed OFDM, DHT-LACO-OFDM, and HACO-OFDM at different $E_{b(opt)}/N_0$ values.

As shown in Fig. 3, the PAPR comparison is presented for the proposed OFDM, HACO-OFDM, and DHT-LACO-OFDM. From the figure, it can be observed that when the CCDF is 10^{-4}, the PAPR of the proposed OFDM is 13.8 dB, and HACO-OFDM is 16 dB. The PAPR of the three-layer DHT-LACO-OFDM is lower than HACO-OFDM, but the two-layer and one-layer are higher than HACO-OFDM. The decrease in PAPR with an increase in the number of layers in DHT-LACO-OFDM is due to the faster growth of the average power compared to the peak power as the layers increase, resulting in a reduction in PAPR [9]. Both superimposed OFDM schemes have higher PAPR than the proposed OFDM due to the increased peaks caused by multiple layers. Compared to HACO-OFDM and DHT-LACO-OFDM, the proposed scheme achieves the lowest PAPR, indicating a good ability to resist nonlinearity.

Figure 4 compares bit error rates between the proposed OFDM, DHT-LACO-OFDM, and HACO-OFDM. The proposed OFDM uses 4-PAM modulation, DHT-LACO-OFDM uses 4-PAM modulation, and HACO-OFDM uses 16-QAM and 4-PAM modulations. At this point, these three OFDM schemes have the same spectral efficiency. However, to convert the bipolar OFDM signal of the two superimposed OFDM schemes into non-negative signals, asymmetric clipping is employed, which leads to a loss in bit error rate performance. The proposed OFDM achieves lower bit error rates at the same spectral efficiency. In summary, The proposed OFDM can significantly improve the BER performance because of its low BER and good resistance to nonlinearity.

In Fig. 5, the relationship between the required $E_{b(opt)}/N_0$ and the bit rate/normalized bandwidth is depicted when the BER of various OFDMs is 10^{-3}. ACO-OFDM, DCO-OFDM, and HACO-OFDM employ QAM modulation

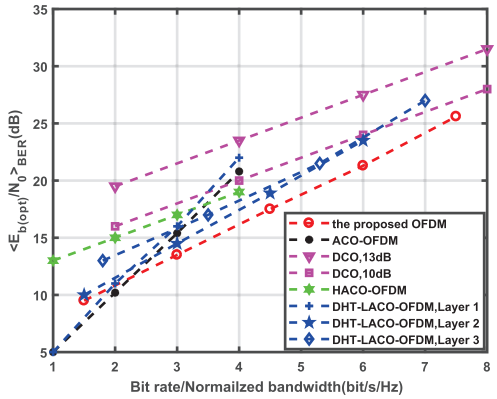


Fig. 5 Relationship between $E_{b(opt)}/N_0$ and bit rate/normalized bandwidth when the BER of various OFDM is 10^{-3}.

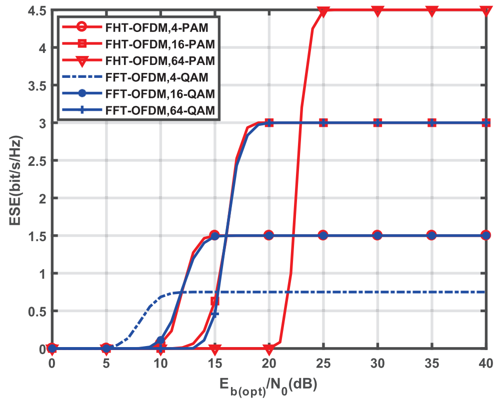


Fig. 6 Comparing the spectral efficiency when applying the adaptive bias method to FFT-OFDM and FHT-OFDM.

with modulation orders of 4, 16, 64, and 256. Since the spectral efficiency of FHT is twice that of FFT, when the transmission rate is the same, the constellation size of FFT is M, and the constellation size of FHT is $\sqrt{M}$. Thus The proposed scheme and DHT-LACO-OFDM use BPSK and PAM modulation orders of 16, 64, and 256. The $E_{b(opt)}/N_0$ required when the BER of each OFDM is 10^{-3} is used to evaluate the power efficiency. In Fig. 5, DCO-OFDM requires the highest $E_{b(opt)}/N_0$ due to the addition of a high DC bias, so the power efficiency is the lowest. In contrast, ACO-OFDM, HACO-OFDM, and DHT-LACO-OFDM use the cropping operation to become non-negative signals and do not use DC bias, so the power efficiency of these three OFDM is higher than that of DCO-OFDM. Compared with the above OFDM, the proposed OFDM requires the lowest $E_{b(opt)}/N_0$, which is about 7.5 dB lower than DCO-OFDM, and about 3.4 dB lower than the two superimposed OFDM, so the proposed OFDM can significantly improve the power efficiency.

Figure 6 shows a comparison of the spectral efficiency when applying the adaptive bias method to FFT-OFDM and FHT-OFDM [10]. As can be seen from the figure, when the modulation orders are the same, FHT-OFDM saves half of the spectrum resources compared to FFT-OFDM because it does not use conjugate symmetry to generate real number signals. Therefore, the spectral efficiency of FHT-OFDM is twice that of FFT-OFDM. This demonstrates that the application of the adaptive bias method in FHT-OFDM achieves higher spectral efficiency compared to FFT-OFDM.

5. Conclusion

An OFDM scheme with high power efficiency was proposed for visible light communication systems in this letter. The proposed OFDM uses an adaptive biasing technique to turn the bipolar OFDM signal into a non-negative unipolar signal without interfering with the effective signal and also significantly improves power efficiency. In addition, the proposed OFDM uses Hartley transform to make the system have low computational complexity and high spectral efficiency. The required $E_{b(opt)}/N_0$ of the proposed OFDM at a BER of 10^{-3} is approximately 38.1% lower than that of the DCO-OFDM, and approximately 19.5% lower than that of the superimposed ACO-OFDM. The proposed OFDM demonstrates superior power efficiency compared to DCO-OFDM and superimposed ACO-OFDM, and it also outperforms superimposed ACO-OFDM in terms of error rate performance.

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