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Iterative receiver for ADO-OFDM with near-optimal optical power allocation

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ABSTRACT

Visible light communication (VLC) systems using orthogonal frequency division multiplexing (OFDM) are attracting increasing interests due to its inherent benefits such as high spectral efficiency, resistance to frequency-selective channels and so on. In this paper, a novel iterative receiver is proposed for asymmetrically clipped DC biased optical OFDM (ADO-OFDM), where asymmetrically clipped optical OFDM (ACO-OFDM) and DC biased OFDM (DCO-OFDM) signals are transmitted simultaneously. In our proposed iterative receiver, ACO-OFDM and DCO-OFDM time-domain signals are distinguished firstly. Then pairwise clipping, negative clipping and pairwise averaging are utilized in the iterative receiver to reduce the effect of noise and interference. In addition, an optimal solution to the optical power allocation factor for ACO-OFDM and DCO-OFDM signals is derived. Furthermore, to reduce the computational complexity, an approximation of the optimal solution is obtained. Both theoretical analysis and simulation results indicate that the approximate solution is near-optimal, and only a few detection iterations are required for the iterative receiver.

1. Introduction

Recently, visible light communication (VLC) has drawn great interests, which has tremendous advantages such as hundreds of terahertz of license-free bandwidth, resistance to electromagnetic interference, low power consumption and communication security. It is regarded as a complement to the radio frequency (RF) communication [1,2]. In consideration of simple implementation and low cost, intensity modulation with direct detection (IM/DD) is commonly applied, in which the transmitted electrical signal is modulated onto the instantaneous power of the optical emitter [3,4]. Thus, the time-domain signals should be real-valued and non-negative.

To avoid inter-symbol interference (ISI) and enhance the data rate, orthogonal frequency division multiplexing (OFDM) is commonly utilized in VLC systems [5,6]. There are several forms of OFDM for IM/DD VLC systems, such as DC biased optical OFDM (DCO-OFDM) [7], asymmetrically clipped optical OFDM (ACO-OFDM) [8] and asymmetrically clipped DC biased optical OFDM (ADO-OFDM) [9], whereby Hermitian symmetry is imposed on the subcarriers to make the time-domain signals real-valued [10]. A DC bias is added to force the DCO-OFDM time-domain signals non-negative, which is inefficient in terms of optical power. In ACO-OFDM, only the odd subcarriers carry the transmitted data symbols, which is inefficient in terms of bandwidth [11]. In [9], ADO-OFDM is proposed, where ACO-OFDM signals are modulated on the odd subcarriers and DCO-OFDM signals are modulated on the even subcarriers. ADO-OFDM combines the advantages of ACO-OFDM and DCO-OFDM [9,11].

However, the conventional receiver employed in [11] suffers from noise and interference, which restricts the performance of ADO-OFDM. Therefore, to enhance the performance, a novel iterative receiver for ADO-OFDM is proposed in our work. In the iterative receiver, ACO-OFDM and DCO-OFDM time-domain signals are distinguished firstly. After that, pairwise clipping, negative clipping and pairwise averaging are imposed to reduce the effect of the noise and interference. In addition, to further improve the overall performance, unbalanced optical power allocation is investigated, which is merely based on simulation results in [11]. In this paper, an optimal solution to the optical power allocation factor for ACO-OFDM and DCO-OFDM signals is derived. Furthermore, to reduce the computational complexity, an approximation of the solution is obtained, and simulations are conducted to validate its near-optimal performance. Theoretical analysis and simulation results demonstrate that only a few detection iterations are required to achieve near-optimal performance. And, the computational complexity increment and signal delay can be

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acceptable considering the significant performance gains.

The rest of this work is organized as follows. In Section 2, a brief review of ACO-OFDM, DCO-OFDM and ADO-OFDM is presented. Then our proposed iterative receiver is represented in Section 3. In Section 4, the performances of the proposed iterative receiver are compared to that of conventional receiver via simulations. Finally, the conclusions are drawn in Section 5.

2. Overview of ACO-OFDM, DCO-OFDM and ADO-OFDM

In this section, a brief review of ACO-OFDM, DCO-OFDM and ADO-OFDM will be presented.

2.1. ACO-OFDM

In VLC ACO-OFDM systems, only odd subcarriers carry useful symbols, while the even subcarriers are all set to zeros. And in order to guarantee that the time-domain signals are real-valued, Hermitian symmetry is imposed on the subcarriers. Therefore, the frequency-domain signals of ACO-OFDM are given by [11,12]

$$\mathbf{X} = [0, X_1, 0, X_3, \ldots, X_{N/2-1}, 0, X^*_{N/2-1}, \ldots, X^*_1], \tag{1}$$

where N is the number of subcarriers and X_n $(0 < n < \frac{N}{2})$ is the complex-valued symbol on the nth subcarrier.

After the process of inverse fast Fourier transform (IFFT), the time-domain signal x_n is obtained, which is given by

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

As we know, $\{x_n\}$ have antisymmetry property as follows [12,13]

$$x_n = -x_{n+N/2} \quad \text{for } 0 \le n < N/2. \tag{3}$$

Therefore, we can clip the negative part of the time-domain signal without losing any information as follows

$$x_{aco,n} = x_n + c_{aco,n} \quad \text{for } 0 \le n \le N-1, \tag{4}$$

where $c_{aco,n}$ denotes the clipping noise of ACO-OFDM, given by

$$c_{aco,n} = \begin{cases} -x_n, & x_n < 0; \\ 0, & x_n \ge 0. \end{cases} \tag{5}$$

The probability density function (PDF) of ACO-OFDM has been derived in [14]. Then the optical power $P_{o,aco} = \delta_A/\sqrt{2\pi}$ and electrical power $P_{e,aco} = \delta_A^2/2$ are given by [11], where $\delta_A = \sqrt{E\{x_n^2\}}$ is the standard deviation of signal x_n. Thus, the relationship between the electrical and optical power could be obtained as

$$P_{e,aco} = \pi P_{o,aco}^2. \tag{6}$$

2.2. DCO-OFDM

In DCO-OFDM based VLC systems, the frequency-domain signals could be represented as

$$\mathbf{Y} = [0, Y_1, Y_2, \ldots, Y_{N/2-1}, 0, Y^*_{N/2-1} \ldots, Y^*_2, Y^*_1], \tag{7}$$

where Hermitian symmetry is constrained, and Y_0 and $Y_{N/2}$ are set to zero. After IFFT, the time-domain signals $\{y_n\}$ are obtained. Then a DC bias is added to the time-domain signals and all the remaining negative peaks are clipped, leading to positive signals $\{y_{dco,n}\}$. The DC bias level can be set according to the standard deviation of $\{y_n\}$, which is given by [11,15]

$$DC_B = k\delta_D, \tag{8}$$

where the standard deviation $\delta_D = \sqrt{E\{y_n^2\}}$ and k is a proportionality constant. Like in [15], the bias-index is defined as $\beta = 10\log_{10}(1 + k^2)$[dB]. And, we have

$$y_{dco,n} = y_n + DC_B + c_{dco,n} \quad \text{for } 0 \le n \le N-1, \tag{9}$$

where $c_{dco,n}$ is clipping noise of DCO-OFDM, given by

$$c_{dco,n} = \begin{cases} -(y_n + DC_B), & y_n < -DC_B; \\ 0, & y_n \ge -DC_B. \end{cases} \tag{10}$$

The PDF of $y_{dco,n}$ is studied in [14]. And the optical power is given by [11]

$$P_{o,dco} = \delta_D\left\{k[1 - Q(k)] + \frac{1}{\sqrt{2\pi}}\exp\left(-\frac{k^2}{2}\right)\right\}, \tag{11}$$

where $Q(k) = \frac{1}{\sqrt{2\pi}}\int_k^\infty \exp\left(\frac{-u^2}{2}\right)\mathrm{d}u$. The electrical power of DCO-OFDM is given by [11]

$$P_{e,dco} = \delta_D^2\left\{(1 + k^2)[1 - Q(k)] + \frac{k}{\sqrt{2\pi}}\exp\left(-\frac{k^2}{2}\right)\right\}. \tag{12}$$

2.3. ADO-OFDM

Since ACO-OFDM is inefficient in terms of bandwidth and DCO-OFDM is inefficient in terms of optical power, ADO-OFDM is proposed in [9], where ACO-OFDM is utilized on the odd subcarriers and DCO-OFDM is utilized on the even subcarriers. ADO-OFDM combines the advantages of ACO-OFDM and DCO-OFDM according to [9,11]. The ADO-OFDM time-domain signals are given by

$$z_{ado,n} = x_{aco,n} + y_{dco,n} \quad \text{for } 0 \le n \le N-1. \tag{13}$$

And the DCO-OFDM signals $\{y_{dco,n}\}$ in ADO-OFDM have symmetry property as follows [9,11]

$$y_{dco,n} = y_{dco,n+N/2} \quad \text{for } 0 \le n < N/2. \tag{14}$$

At the receiver, the thermal noise and shot noise are modeled as additive white Gaussian noise (AWGN) [12,16]. Therefore, the received signals are given by

$$r_{ado,n} = x_{aco,n} + y_{dco,n} + w_n = (x_n + c_{aco,n}) + (y_n + DC_B + c_{dco,n}) + w_n, \tag{15}$$

where w_n is the AWGN component with zero mean and the noise power spectral density of $N_0/2$. Taking the fast Fourier transform (FFT) of (15), the frequency-domain signal is obtained by [11,17]

$$R_{ado,k} = (X_k + C_{aco,k}) + (Y_k + DC_B + C_{dco,k}) + W_k = \frac{1}{2}X_{k_{odd}} + W_{k_{odd}} + C_{aco,k_{even}} + Y_{k_{even}} + DC_B + C_{dco,k_{even}} + W_{k_{even}}, \tag{16}$$

where k_{odd} and k_{even} denote the indices of the odd and even subcarriers respectively, and the factor $\frac{1}{2}$ is due to the half power loss in the clipping process.

For conventional receiver, the odd subcarriers are demodulated by conventional ACO-OFDM receiver and the even subcarriers are demodulated after interference removing process [11].

3. Proposed iterative receiver for ADO-OFDM

3.1. Proposed iterative receiver

In order to further improve the performance of ADO-OFDM, we propose a novel iterative receiver to reduce the effect of noise and estimation error. In the iterative receiver, ACO-OFDM and DCO-OFDM time-domain signals are distinguished first. Then pairwise clipping, negative clipping and pairwise averaging are utilized. The iterative receiver is illustrated as in Fig. 1.

More specifically, in the first iteration, ACO-OFDM signals are