Novel Visible Light Communication Approach Based on Hybrid OOK and ACO-OFDM

Fang Yang, *Senior Member, IEEE*, Junnan Gao, and Sicong Liu, *Student Member, IEEE*

***Abstract*— In this letter, we present a novel hybrid intensity modulation and direct detection communication system, which integrates asymmetrically clipped optical orthogonal frequency division multiplexing (ACO-OFDM) and on–off keying (OOK) modulation schemes. First, the negative ACO-OFDM is proposed based on the conventional ACO-OFDM system to accommodate the on case with direct current in the OOK modulation, while the ACO-OFDM can match the off case in the OOK modulation. Therefore, the novel hybrid system combines the ACO-OFDM and OOK modulation schemes, while the signals can be recovered at the receiver to support the different qualities of service with high spectral efficiency and can be adapted to various receivers with different complexities. Simulation results are reported for the visible light channel and show that both the ACO-OFDM and OOK signals can be well recovered.**

***Index Terms*— On-off keying (OOK), asymmetrically clipped optical OFDM (ACO-OFDM), visible light communication (VLC).**

I. Introduction

UTILIZING the light emitting diodes (LEDs) for illumination and data transmission at the same time brings many distinctive advantages to visible light communication (VLC), such as wide modulation bandwidth, inherent security, localization capability, etc [1]. These features enrich VLC with enormous and acknowledged potentials for future wireless communications, and capture plenty of attention from both academia and industry. On-off keying (OOK) [2] as a single carrier pulsed modulation has been simply utilized in VLC systems with low complexity and cost. Meanwhile, orthogonal frequency division multiplexing (OFDM) [3] as a multicarrier modulation technique has been recently widely adopted to achieve high spectral efficiency and mitigate inter-symbol interference.

In VLC systems, where the actual signal is transmitted using intensity modulation and direct detection (IM/DD), time-domain signals have to be real-valued and non-negative [4]. Direct current (DC) biased optical OFDM (DCO-OFDM) [5] is proposed to meet the requirements of real and non-negative value by means of Hermitian symmetry [6] and DC bias. However, DCO-OFDM is energy inefficient since the DC bias does not carry any information, which degrades the system performance. Therefore, asymmetrically clipped optical OFDM (ACO-OFDM) [7] is investigated to solve the problem, where only odd sub-carriers are occupied in the frequency domain and the negative signal is clipped in the time domain. However, due to only half utilization of the subcarriers, the ACO-OFDM scheme suffers from a loss of spectral efficiency.

As a result, the hybrid systems, which combine multiple modulation schemes, are a trend in achieving high spectral efficiency [8]–[10]. One approach is the integration of ACO-OFDM and DCO-OFDM characteristics by simultaneously transmitting the ACO-OFDM signal on the odd subcarriers and the DCO-OFDM signal on the even subcarriers [9]. Another technique is the recently proposed hybrid ACO-OFDM (HACO-OFDM) [10] scheme, where ACO-OFDM signal occupying odd subcarriers and pulse-amplitude-modulated discrete multitone modulation (PAM-DMT) signal using even subcarriers are combined in the time domain for simultaneous transmission. These hybrid schemes have superior power and spectral efficiency compared with the conventional ACO-OFDM. However, these hybrid systems consume high computational complexity [4] and can hardly support multiple services with different qualities of service (QoS).

In this letter, a novel negative ACO-OFDM (NACO-OFDM) is firstly investigated, where the positive part of the signal in the time domain is clipped while the negative part is retained. The NACO-OFDM signal with an add-on DC bias, where the DC bias can be provided by the "on" signal of the OOK modulation, could ensure the transmitted signal to be recovered as accurately and completely as in the conventional ACO-OFDM. Meanwhile, the ACO-OFDM signal combined with the "off" signal of the OOK modulation can also be processed as the original ACO-OFDM signal in the same way. Therefore, the ACO-OFDM is combined with the OOK modulation according to different OOK signal scenarios. Thus, the proposed scheme enjoys the advantages of different modulation schemes with high spectral efficiency and can accommodate to various receivers with different complexities.

The remainder of this letter is organized as follows. Section II presents a system model of the convenient OOK and ACO-OFDM, while the proposed NACO-OFDM is also addressed. Then, the proposed hybrid scheme is introduced in Section III. In Section IV, the simulation results are presented. Finally, conclusions are drawn in Section V.

II. System Model

In this section, we will give a brief introduction of the OOK and ACO-OFDM modulation, and then the novel proposed NACO-OFDM is investigated.

A. OOK and ACO-OFDM Modulation

OOK modulation, which uses the presence of a carrier wave to deliver information, is the simplest amplitude shift keying. For VLC systems, there are normally two fixed bias currents in LED transmitters to represent "on" and "off" signals. The symbol "on" is represented by transmitting a fixed-amplitude

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The authors are with the Tsinghua National Laboratory for Information Science and Technology, Research Institute Information Technology, Tsinghua University, Beijing 100084, China (e-mail: fangyang@tsinghua.edu.cn; gaojunnan93@126.com; liu-sc12@mails.tsinghua.edu.cn).

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carrier wave for a bit duration of T, and the symbol "off" means the absence of wave.

In the ACO-OFDM communication system, the transmitted symbol $\mathbf{X}$ [6], which is usually modulated by QAM, can be represented as

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

where N is the number of OFDM subcarriers. The time-domain signal is obtained by the inverse fast Fourier transform (IFFT) process, and can be given by

$$x_n = \frac{1}{N}\sum_{k=0}^{N-1} X_k \exp\left(\frac{j2\pi kn}{N}\right), \quad 0 \le n < N. \tag{2}$$

To guarantee a non-negative transmitted signal, a clipping operation is performed, and the time-domain signal after the clipping operation can be represented as

$$x_{\mathrm{ACO},n} = \lfloor x_n \rfloor = \begin{cases} x_n, & x_n \ge 0, \\ 0, & x_n < 0. \end{cases} \tag{3}$$

Without considering the channel noise at the receiver for simplicity, the received signal $y_n = x_{\mathrm{ACO},n}$ is transformed to the frequency domain by fast Fourier transform (FFT) operation and obtained $Y_k,\ 0 \le k < N$. Researches have verified that the distortion due to the clipping operation only falls on the even subcarriers at the receiver [7], so that the transmitted signal can be recovered as

$$\hat{X}_k = 2Y_k, \quad \text{if } k \text{ is odd.} \tag{4}$$

B. NACO-OFDM Modulation

For the NACO-OFDM system, the data pattern is the same with that of ACO-OFDM in the frequency domain. However, after the IFFT operation, there is an opposite clipping operation compared with ACO-OFDM, which generates the negative signal, i.e.,

$$x_{\mathrm{NACO},n} = \lceil x_n \rceil = \begin{cases} x_n, & x_n \le 0, \\ 0, & x_n > 0. \end{cases} \tag{5}$$

Considering when k is odd, where $\exp(-j\pi k) = -1$, and combined with the half-wave symmetry property $x_n = -x_{n+N/2}, 0 \le n < N/2$, the transmitted frequency-domain signal can be rewritten as

$$\begin{aligned} X_k &= \frac{1}{N}\sum_{n=0}^{N/2-1}\left[x_n \exp\left(\frac{-j2\pi kn}{N}\right) + x_{n+\frac{N}{2}} \exp\left(\frac{-j2\pi k(n+\frac{N}{2})}{N}\right)\right] \\ &= \frac{1}{N}\sum_{n=0}^{N/2-1}\left[x_n \exp\left(\frac{-j2\pi kn}{N}\right) - x_{n+\frac{N}{2}} \exp\left(\frac{-j2\pi kn}{N}\right)\right]_{x_n \le 0} \\ &\quad + \frac{1}{N}\sum_{n=0}^{N/2-1}\left[x_n \exp\left(\frac{-j2\pi kn}{N}\right) - x_{n+\frac{N}{2}} \exp\left(\frac{-j2\pi kn}{N}\right)\right]_{x_n > 0} \\ &= \frac{2}{N}\sum_{n=0}^{N/2-1}\left\{\left[x_n \exp\left(\frac{-j2\pi kn}{N}\right)\right]_{x_n \le 0} - \left[x_{n+\frac{N}{2}} \exp\left(\frac{-j2\pi kn}{N}\right)\right]_{x_n > 0}\right\}. \end{aligned} \tag{6}$$

The received signal in the odd subcarriers is decoded using FFT operation as

$$\begin{aligned} Y_k &= \frac{1}{N}\sum_{n=0}^{N/2-1}\left[x_{\mathrm{NACO},n} \exp\left(\frac{-j2\pi kn}{N}\right) + x_{\mathrm{NACO},n+\frac{N}{2}} \exp\left(\frac{-j2\pi k(n+\frac{N}{2})}{N}\right)\right] \\ &= \frac{1}{N}\sum_{n=0}^{N/2-1}\left[x_{\mathrm{NACO},n} \exp\left(\frac{-j2\pi kn}{N}\right) - x_{\mathrm{NACO},n+\frac{N}{2}} \exp\left(\frac{-j2\pi kn}{N}\right)\right]_{x_n \le 0} \\ &\quad + \frac{1}{N}\sum_{n=0}^{N/2-1}\left[x_{\mathrm{NACO},n} \exp\left(\frac{-j2\pi kn}{N}\right) - x_{\mathrm{NACO},n+\frac{N}{2}} \exp\left(\frac{-j2\pi kn}{N}\right)\right]_{x_n > 0} \\ &= \frac{1}{N}\sum_{n=0}^{N/2-1}\left\{\left[x_n \exp\left(\frac{-j2\pi kn}{N}\right)\right]_{x_n \le 0} - \left[x_{n+\frac{N}{2}} \exp\left(\frac{-j2\pi kn}{N}\right)\right]_{x_n > 0}\right\}. \end{aligned} \tag{7}$$

It is obvious that $Y_k = X_k/2$ from (6) and (7) when k is odd. Therefore, the NACO-OFDM signal on odd subcarriers has the same property of ACO-OFDM, and can also be detected as that in the ACO-OFDM scheme, which is the crucial point in our proposed scheme.

III. Proposed Hybrid OOK and ACO-OFDM Scheme

In this section, a detailed description for the proposed hybrid OOK and ACO-OFDM (HOOK-ACO-OFDM) system is introduced, including both the transmitter and receiver.

A. Proposed Transmitter

Fig. 1 shows a block diagram of the transmitter and receiver for the proposed HOOK-ACO-OFDM system. The input data bits of OFDM branch are modulated according to the conventional ACO-OFDM approach. After a cyclic prefix (CP) is added, the positive or negative part of the time-domain signal is clipped depending on the input data bits of the OOK branch, which is decided by the OOK control unit in Fig.1. Finally, an asymmetrically clipped OFDM signal with duration of T is generated, which is the same as that of the OOK signal. Furthermore, it should be ensured for the hybrid system that the OOK and ACO-OFDM signals are synchronized in the time domain.

The mathematical expression of OOK signal is given by

$$x_{\mathrm{OOK},n} = \begin{cases} I_{\mathrm{bias}}, & \text{OOK is "on"}, \\ 0, & \text{OOK is "off"}, \end{cases} \tag{8}$$

where I_{bias} is a constant value representing the amplitude of the biased DC. According to the OOK signal, the ACO-OFDM

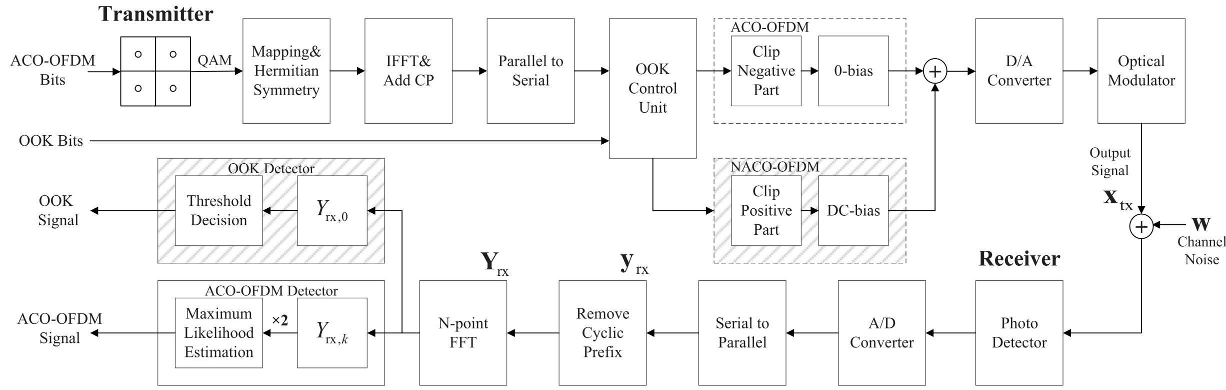

Fig. 1. The block diagram of the transmitter and receiver for the proposed HOOK-ACO-OFDM system.

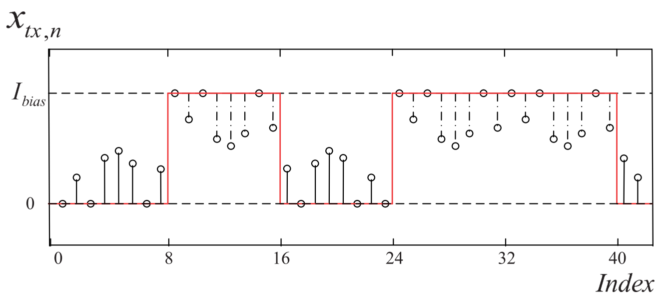

Fig. 2. The diagrammatic sketch of transmitted signal in the time domain.

or NACO-OFDM signal is chosen as

$$x_{\mathrm{M},n} = \begin{cases} x_{\mathrm{NACO},n}, & \text{OOK is "on"}, \\ x_{\mathrm{ACO},n}, & \text{OOK is "off"}, \end{cases} \tag{9}$$

where $x_{\mathrm{M},n}$ represents the mixed ACO-OFDM and NACO-OFDM signal. The clipping operation should be adopted to ensure the finally transmitted signal is non-negative. Therefore, the combined transmitted signal of the HOOK-ACO-OFDM system in the time domain is given by

$$x_{\mathrm{tx},n} = \lfloor x_{\mathrm{M},n} + x_{\mathrm{OOK},n} \rfloor. \tag{10}$$

Finally, $\mathbf{x}_{\mathrm{tx}}$ is passed through a D/A converter to generate a continuous time signal that modulates the intensity of the optical modulator. Fig. 2 shows a diagrammatic sketch of the transmitted signal in the time domain.

B. Proposed Hybrid ACO-OFDM and OOK Receiver

As shown in Fig.1, at the receiver, the signal is detected by a photodetector and passed through an A/D converter firstly, then the received signal in the time domain is given by

$$y_{\mathrm{rx},n} = x_{\mathrm{tx},n} + w_n, \tag{11}$$

where w_n represents the discrete time samples of the channel noise. Assuming the timing and frequency-domain equalization are perfect at the receiver, the received signal is fed into the FFT operation block after removing the CP, to obtain the frequency-domain OFDM symbols,

$$Y_{\mathrm{rx},k} = X_{\mathrm{tx},k} + W_k, \tag{12}$$

where $Y_{\mathrm{rx},k}$, $X_{\mathrm{tx},k}$, and W_k represent the corresponding values for the received signal $y_{\mathrm{rx},n}$, transmitted signal $x_{\mathrm{tx},n}$, and noise signal w_n at subcarriers with index k, respectively.

It is noted that a constant OOK signal in the time domain only affects the zero subcarrier at the receiver. Therefore, whatever the signal of the OOK modulation is, the signal of ACO-OFDM in odd subcarriers at the receiver is simply multiplied by 2 to scale the signal for the subsequent recovery, and is given by

$$\hat{X}_{\mathrm{ACO},k} = 2Y_{\mathrm{rx},k} = 2(X_{\mathrm{tx},k} + W_k), \quad \text{if } k \text{ is odd}. \tag{13}$$

As mentioned above, the OOK signal could be detected by the value of the zero subcarrier. Omitting the noise for simplicity, the value of the zero subcarrier is given by

$$Y_{\mathrm{rx},0} = \begin{cases} \mathrm{E}\{x_{\mathrm{ACO},n}\}, & \text{OOK is "off"}, \\ I_{\mathrm{bias}} + \mathrm{E}\{x_{\mathrm{NACO},n}\}, & \text{OOK is "on"}, \end{cases} \tag{14}$$

where $\mathrm{E}\{x_{\mathrm{ACO},n}\}$ and $\mathrm{E}\{x_{\mathrm{NACO},n}\}$ are the expectation of the ACO-OFDM and NACO-OFDM signals in the time domain, respectively, and satisfy $\mathrm{E}\{x_{\mathrm{ACO},n}\} = -\mathrm{E}\{x_{\mathrm{NACO},n}\}$.

However, when the noise is considered, a decision threshold A defined as the average value when the OOK signal is "on" and "off", should be adopted as

$$A = \frac{\mathrm{E}\{x_{\mathrm{ACO},n}\} + (I_{\mathrm{bias}} + \mathrm{E}\{x_{\mathrm{NACO},n}\})}{2} = \frac{I_{\mathrm{bias}}}{2}. \tag{15}$$

Then, the received OOK signal $\hat{y}_{\mathrm{OOK},n}$ is estimated by

$$\hat{y}_{\mathrm{OOK},n} = \begin{cases} I_{\mathrm{bias}}, & Y_{\mathrm{rx},0} \geq A, \\ 0, & Y_{\mathrm{rx},0} < A. \end{cases} \tag{16}$$

C. Proposed OOK-Only Receiver

For the low cost and low data rate receiver that only detects the OOK signal, there is no need to perform FFT operation and decode OFDM symbols, and thus, a simplified OOK-only receiver is proposed in this subsection.

Firstly, an auto-correlation of the received signal is performed in the time domain. For the conventional ACO-OFDM signal, the expectation of the received signal power is calculated as

$$\mathrm{E}\{y_{\mathrm{rx},n}^2\}_{\mathrm{ACO}} = P + \sigma^2, \tag{17}$$

where P and σ^2 are the powers of the ACO-OFDM signal and noise, respectively. Similarly, for the NACO-OFDM signal, the expectation of the received signal power can be given by

$$\mathrm{E}\{y_{\mathrm{rx},n}^2\}_{\mathrm{NACO}} = I_{\mathrm{bias}}^2 - P + \sigma^2. \tag{18}$$

Then, the OOK signal can be directly detected by

$$\hat{y}_{\mathrm{OOK},n} = \begin{cases} I_{\mathrm{bias}}, & \mathrm{E}\{y_{\mathrm{rx},n}^2\} \geq B, \\ 0, & \mathrm{E}\{y_{\mathrm{rx},n}^2\} < B, \end{cases} \tag{19}$$

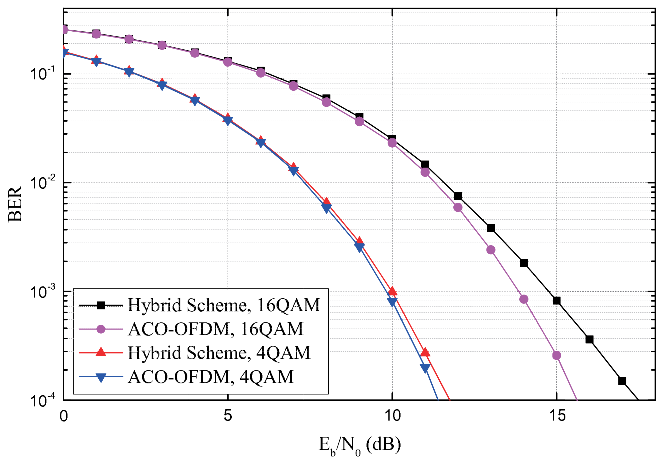

Fig. 3. The BER performance versus E_b/N_0 for HOOK-ACO-OFDM and conventional ACO-OFDM systems.

where B is a decision threshold given by

$$B = \frac{(P+\sigma^2) + (I_{\text{bias}}^2 - P + \sigma^2)}{2} = \frac{I_{\text{bias}}^2}{2} + \sigma^2. \quad (20)$$

Moreover, compared to the reverse polarity optical (RPO)-OFDM scheme in [11], which combines pulse-width modulation (PWM) and VLC, the proposed system is focusing on simultaneously transmitting the ACO-OFDM and OOK signals to support multiple services with higher capacity and accommodate to various receivers with different complexities. Furthermore, the demodulations of the ACO-OFDM and OOK signals in the proposed hybrid system are independent with each other as presented above. However, in a RPO-OFDM system the PWM signal should be firstly detected in order to determine whether the received signal is reversed.

IV. Simulation Results

The performance of the proposed scheme is evaluated by means of simulations. The number of subcarriers is 64, and the constellation for ACO-OFDM or NACO-OFDM is 4-QAM and 16-QAM. The bandwidth of the hybrid system is 20 MHz, while the bit rates of the OFDM and OOK systems are 40 and 0.625 Mbps for 4-QAM constellation, 80 and 0.625 Mbps for 16-QAM constellation, respectively. The bit error rate (BER) of the proposed hybrid system is computed, while the conventional ACO-OFDM and OOK schemes are also investigated for comparison.

Fig. 3 shows the BER performance of the HOOK-ACO-OFDM and conventional ACO-OFDM. The amplitude of the biased DC in the OOK modulation for the hybrid scheme is $I_{\text{bias}} = \sqrt{3}$ for the normalized OFDM signal. The energy per bit to the noise power spectral density ratio (E_b/N_0) is adopted, which is more suitable than the signal-to-noise ratio (SNR) for fair performance evaluation [5]. From Fig. 3, it is observed that the performance of the proposed hybrid scheme is degraded by about 0.3 dB and 0.5 dB compared to the conventional ACO-OFDM system at the target BER of 10^{-3} for 4-QAM and 16-QAM, respectively, due to the clipping noise in the NACO-OFDM signal and the power allocation between ACO-OFDM and OOK schemes.

Fig. 4 illustrates the BER performance versus the SNR with different I_{bias}, while the power of ACO-OFDM is fixed, to find the optimal value of the biased DC. From Fig. 4, it is clearly

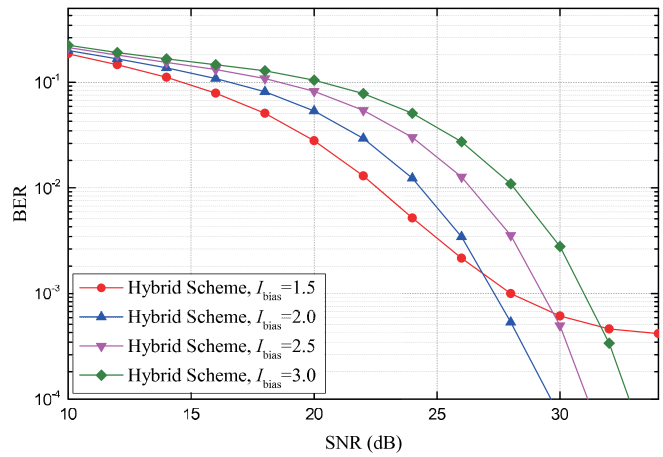

Fig. 4. The BER performance versus the SNR with various I_{bias}.

shown that if I_{bias} is not large enough, e.g. $I_{\text{bias}} = 1.5$, the BER will converge to a bit error floor due to the clipping operation. On the other hand, the BER performance of the hybrid system is degraded with the increase of the I_{bias} value since more power is allocated to the OOK scheme. Therefore, the value of I_{bias} should be rationally selected to achieve a trade-off between the clipping noise and power allocation.

V. Conclusions

In this letter, a novel hybrid scheme that is able to transmit ACO-OFDM and OOK signals simultaneously is presented. The proposed approach forms a novel framework for various receivers with different complexities, where the OOK and ACO-OFDM schemes can be two physical layer pipes to support multiple services. Furthermore, the proposed novel HOOK-ACO-OFDM modulation is promising to be applied in future optical wireless communication systems with good flexibility, high spectral efficiency, and low complexity as well.

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