Experimental verification of performance improvement for a gigabit wavelength division multiplexing visible light communication system utilizing asymmetrically clipped optical orthogonal frequency division multiplexing

Yiguang Wang, Yuanquan Wang, and Nan Chi*

Department of Communication Science and Engineering, and Key Laboratory for Information Science of Electromagnetic Waves (MoE), Fudan University, Shanghai 200433, China
**Corresponding author: nanchi@fudan.edu.cn*

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Asymmetrically clipped optical orthogonal frequency division multiplexing (ACO-OFDM) has been a promising candidate in visible light communications (VLC) due to its improvement in power efficiency and reduction of nonlinearity based on previous simulation analysis. In this paper, for the first time as far as we know, we experimentally verify that ACO-OFDM would be an efficient scheme to improve the performance of a gigabit wavelength division multiplexing VLC system. Our theoretical investigations reveal that the advantages of ACO-OFDM can be attributed to the reduction of inter-carrier interference caused by signal–signal beating noise. An aggregate data rate of 1.05 Gb/s is successfully achieved over 30 cm transmission below the 7% forward-error-correction threshold of 3.8×10^{-3}. The experimental results show that ACO-OFDM can outperform DC-biased optical OFDM by BER performance of 1.5 dB at the same data rate and 4 dB at the same bandwidth, which clearly demonstrates the benefit and feasibility of ACO-OFDM.

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1. INTRODUCTION

In recent years, visible light communication (VLC) based on light emitting diodes (LEDs) has been garnering increasing attention for short-range wireless communication as LEDs are considered to be major candidates for future illumination [1]. Compared to traditional short-range wireless communication at radio frequency (RF), VLC offers several advantages, such as being such as cost effective, license-free, and immune to electromagnetic interference, and having high security. RGB LEDs, compared with white LEDs, have become better solutions to high-speed VLC systems as they offer the possibility of wavelength division multiplexing (WDM) technology.

In VLC systems, spectrally efficient modulation formats have been widely used to increase the transmission data rate. Due to the inherent robustness against multipath effects, high signal-to-noise ratio (SNR), and high spectral efficiency, orthogonal frequency division multiplexing (OFDM) modulation has become an excellent choice for high-speed VLC systems [2–4]. However, the time-domain OFDM signal envelope is utilized to modulate the intensity of the LED. For this purpose, the signal needs to be nonnegative in the intensity-modulated system. Therefore, a large DC bias has to be used to make OFDM signals non-negative, i.e., DC-biased OFDM (DCO-OFDM), which results in low power efficiency and low modulation depth. In order to overcome this disadvantage, asymmetrically clipped optical OFDM (ACO-OFDM) has been proposed. For ACO-OFDM, the time-domain signal is made unipolar by simply clipping the negative part, which does not need a large DC bias. Only odd subcarriers are modulated by signals, while even subcarriers are vacant, and all of the clipping distortion products fall on the even subcarriers. A number of investigations on ACO-OFDM-based VLC systems have been conducted recently [5–10]. In Ref. [5], the author makes a comparison between ACO- and DCO-OFDM in a simulated VLC system and attributes the performance improvement of ACO-OFDM to the increased modulation depth and power efficiency. In Refs. [6] and [7], the clipping noise and capacity of ACO-OFDM-based VLC systems are analyzed. Three different receiver designs are theoretically discussed in [8]. Reference [11] has proposed a novel modulation scheme called asymmetrically clipped DC-biased optical OFDM (ADO-OFDM), which transmits ACO-OFDM on the odd subcarriers and DCO-OFDM on the even subcarriers. Compared to ACO-OFDM, ADO-OFDM uses all the subcarriers to carry data, so the spectral efficiency is higher. However, this research is all based on theoretical analysis and simulations, and lacks experimental demonstration.

In this paper, for the first time as far as we know, we experimentally verify the performance improvement for a gigabit WDM VLC system using ACO-OFDM. We theoretically analyze ACO-OFDM at first. Our investigation reveals that, compared to DCO-OFDM, the advantages of ACO-OFDM are not only because of the increased power efficiency and modulation depth, as reported in Ref. [5], but also because of the reduction of inter-carrier interference (ICI) caused by signal–signal beating noise. In the experiment, a single RGB LED is used to for WDM. An aggregate data rate of 1.05 Gb/s is successfully achieved over 30 cm transmission below the 7% forward-error-correction (FEC) threshold of 3.8×10^{-3}. The BER results show that ACO-OFDM can outperform DCO-OFDM by 1.5 dB at the same data rate and 4 dB at the same bandwidth, which clearly demonstrates the benefit and feasibility of ACO-OFDM for high-speed VLC systems.

2. PRINCIPLE

In an ACO-OFDM system, the OFDM signal is made unipolar by clipping it at the zero level. Only odd subcarriers are modulated by signals, while even subcarriers are vacant, and all of the clipping distortion products fall on the even subcarriers. There is no need for a large DC bias at the cost of a half effective data rate.

Figure 1 illustrates the schematic diagram and experimental setup of the VLC system based on ACO-OFDM. A single RGB LED is used as the transmitter for WDM. In our ACO-OFDM-based system, the aggregate data rate is 1.05 Gb/s at 100 MHz modulation bandwidth. In each color chip, the original bit sequence is first fed to an encoder, which maps blocks of bits into complex symbols of 128 quadrature amplitude modulation (QAM). Then the QAM signals are modulated using ACO-OFDM. Here ACO-OFDM signals consist of 64 subcarriers, and only odd subcarriers are modulated by signals while even subcarriers are vacant. Pre-equalization is applied before inverse fast Fourier transform (IFFT) to compensate the frequency attenuation of the RGB LED. After adding cyclic prefix, complex-to-real-value conversion is achieved by upconverting the baseband OFDM signal to a RF subcarrier at the center frequency of 62.5 MHz. The upconversion processing can be expressed as

$$S(t) = I(t)\cos(2\pi f_{\mathrm{RF}}t) - Q(t)\sin(2\pi f_{\mathrm{RF}}t). \tag{1}$$

We choose upconversion to generate a real-value OFDM signal, because system performance will be affected by interference at the lower-frequency component, such as ambient light sources and the DC-wander effect. In our VLC system, the baseband OFDM signal is upconverted to a RF carrier, so that the spectrum at lower frequency is vacant to avoid the interference stemming from ambient light sources and the 4DC-wander effect.

ACO-OFDM signal is then obtained by clipping the negative part of the signal. The generated signal is filtered by a low-pass filter (LPF) and amplified by an electrical amplifier (EA). The electrical ACO-OFDM signals and DC-bias voltage are combined by a bias tee to driving different color chips. In free-space transmission, lens and RGB filters are used. At the receiver, direct detection is achieved by using a commercial avalanche photodiode (APD). The received signals are down-converted to baseband, and further processed offline, which is an inverse procedure of a QAM-OFDM encoder. Post-equalization based on training symbols is used for the compensation of the channel impairments.

In an intensity-modulation/direct-detection (IM/DD) system, OFDM always suffers from ICI caused by signal–signal beating noise [12]. In OFDM-based VLC systems, after being modulated to the LED the optical OFDM signal can be expressed as

$$s(t) = e^{j2\pi f_0 t}(1 + \alpha e^{j2\pi f_{\mathrm{RF}}t} \cdot s_B(t)), \tag{2}$$

where $s(t)$ is the optical OFDM signal, f_0 is the main optical carrier frequency, f_{RF} is the RF carrier frequency for upconversion, and α is the scaling coefficient describing the OFDM band strength related to the main carrier, and the value is set at 1. $s_B(t)$ is the baseband OFDM signal given by

$$s_B(t) = \sum_{k=0}^{N-1} c_k e^{j2\pi f_k t}. \tag{3}$$

At the receiver, the square-law photodetector works as an envelope detector and converts the light into the electrical signal. The photon current can be expressed as follows [12]:

$$\begin{aligned} I(t) &= \mu|s(t)|^2 = \mu|1 + 2\alpha e^{j2\pi f_{\mathrm{RF}}t} \cdot s_B(t) + (\alpha e^{j2\pi f_{\mathrm{RF}}t} \cdot s_B(t))^2| \\ &= \mu + 2\mu\alpha\,\mathrm{Re}\left\{ e^{j2\pi f_{\mathrm{RF}}t} \cdot \sum_{k=0}^{N-1} c_k e^{j2\pi f_k t} \right\} \\ &\quad + \mu\alpha^2 \cdot \sum_{k_1=0}^{N-1}\sum_{k_2=0}^{N-1} c_{k_1} c_{k_2}^{*} e^{j2\pi(f_{k_1} - f_{k_2})t}, \end{aligned} \tag{4}$$

where μ denotes the responsivity of the photon detector. It can be found that the first term of the equation is a DC component that can be easily filtered out. The second term is the fundamental term of OFDM signals that are to be retrieved,

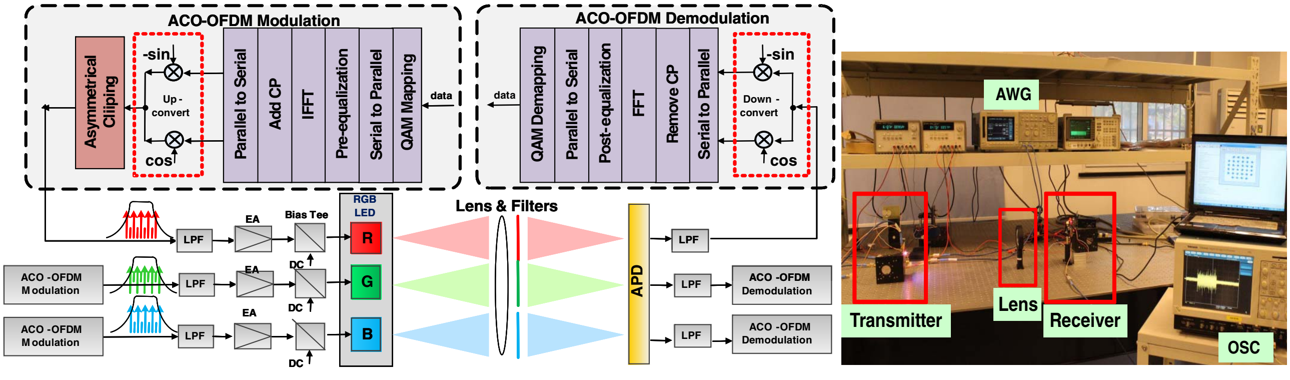

Fig. 1. Schematic diagram and experimental setup of the VLC system based on ACO-OFDM.

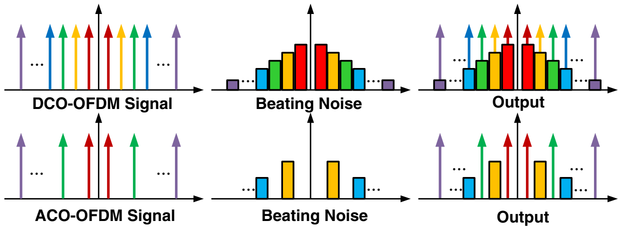

Fig. 2. ICIs of ACO- and DCO-OFDM.

while the third term is the signal–signal beating term that needs to be removed. In the third term, $f_{k_1}-f_{k_2}$ determines the frequency of beating noise. For DCO-OFDM, every subcarrier is modulated by signal. Therefore the beating noise will affect all the subcarriers and result in severe ICI. However, for ACO-OFDM, only odd subcarriers are modulated by signals, while even subcarriers are vacant. So the beating noise from odd subcarriers will fall on even subcarriers and not affect the OFDM signals, which lead to the reduction of ICI caused by signal–signal beating noise. Figure 2 clearly shows the difference of ICIs between ACO- and DCO-OFDM.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In this experiment, we utilize a RGB LED (Cree PLCC) as a transmitter. This type of RGB LED consists of four chips radiating in the wavelength regions of 620 nm (red), 520 nm (green), and 470 nm (blue). Each color chip of the RGB LED applied 128 QAM. An arbitrary waveform generator (AWG, Tektronix 710) is used to generate ACO-OFDM signals. At the receiver, an APD (Hamamatsu APD, 0.42 A/W at 620 nm and gain = 1) is used. The received signal is recorded by a commercial digital oscilloscope (Tektronix TDS 6604). Then the received signals are sent for offline processing.

At first, the frequency characteristics of all three color chips are investigated. The electrical spectra of the received signal of the red color chip are shown in Fig. 3(a). As we can observe, the RGB LED suffers from large attenuation at high frequencies. In order to compensate the frequency attenuation, pre-equalization is applied. Figure 3(b) depicts the electrical spectra of the received signal with pre-equalization, which demonstrates that by pre-equalization, the attenuation of the LED frequency response can be compensated. However, the pre-equalization is not an optimal method, because the attenuation of subcarriers at high frequency is compensated at the cost of the power reduction of subcarriers at lower frequency. A better solution for frequency precompensation is adaptive bit and energy loading, which ensures a constant SNR on all received subcarriers [4].

Then the influence of different bias voltages is studied to render the LED work at the optimal condition. We measure the BER performance versus bias voltages of the RGB LED for different color chips. The results of the red chip are shown in Fig. 4(a). According to the results, the optimal bias voltages of the RGB LED for red, green, and blue chips are 2.2, 4.0, and 3.8 V, respectively. It is noted that in our experiment, the utilized RGB LED is driven by a voltage. Therefore, nonlinearity of the LED is inevitable. The nonlinearity can be reduced when using a current drive.

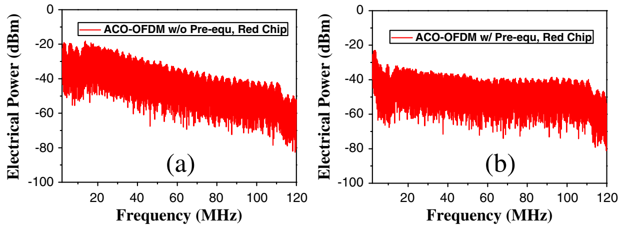

Fig. 3. Electrical spectra of the red chip (a) w/o pre-eq and (b) w/pre-eq.

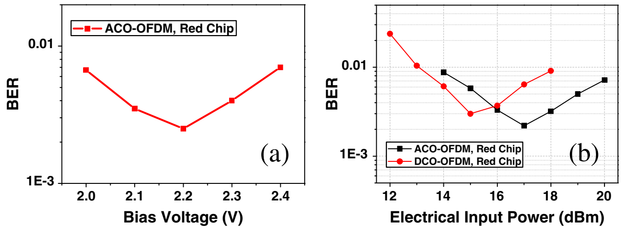

Fig. 4. (a) BER versus bias voltage of red chip. (b) BER versus input power of red chip.

At the optimum bias voltages, we change the electrical input signal power to investigate the nonlinearity of the RGB LED. A lower input power will result in lower SNR, while a higher one will cause nonlinearity and clipping. The BER performance versus different electrical input powers of all three color chips is measured. The BER results of the red chip with ACO-OFDM and DCO-OFDM are as presented in Fig. 4(b). We can observe that the optimal input power of the red chip using ACO-OFDM is 17 dBm, while the optimal input power using DCO-OFDM is 15 dBm. The optimum value of electrical input power for the ACO-OFDM system is 2 dBm larger than for the DCO-OFDM system. This can be explained by noting that the ACO-OFDM system benefits from a larger LED dynamic range and modulation depth, since it requires a lower DC-bias value and the negative part of the signal is clipped. According to the measured results, the optimal electrical input powers of the RGB LED for red, green, and blue chips are 17, 17, and 18 dBm, respectively.

We measure the BER performance of ACO-OFDM versus different subcarrier numbers. The results are shown in Fig. 5(a). It can be seen that when increasing the number of OFDM subcarriers, the BER performance will be worse. This is because when the number of subcarriers is large, the peak to average power ratio of OFDM signals and the interference between subcarriers will both be increased, which results in performance degradation.

We have also measured the BER performance versus different modulation orders of ACO- and DCO-OFDM in our experiment. The results are shown in the Fig. 5(b). It can be found that for lower modulation orders, ACO-OFDM has better BER performance than DCO-OFDM due to its power efficiency and reduction of ICI. Meanwhile, for higher modulation orders,

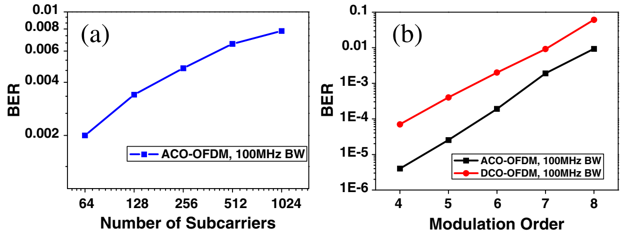

Fig. 5. (a) BER versus different numbers of subcarriers. (b) BER versus modulation orders.

DCO-OFDM outperforms ACO-OFDM because of spectral efficiency. The results match the theoretical analysis in [9].

The BER performance versus different distances of all the color chips is measured and presented in Figs. 6(a)–6(c). In the ACO-OFMD system, due to the expense of half data rate reduction, the effective data rate of the ACO-OFDM-based system is 1.05 Gb/s at 100 MHz modulation bandwidth. For a complete comparison between ACO- and DCO-OFDM, we respectively measure the performance of the DCO-OFDM-based VLC system at the same bandwidth and the same effective data rate. When at the same bandwidth of 100 MHz, the effective data rate of DCO-OFDM is 2.1 Gb/s, twice that of ACO-OFDM. In this case, the BER performance of ACO-OFDM is about 4 dB better than that of DCO-OFDM. When at the same data rate of 1.05 Gb/s, the bandwidth of DCO-OFDM is 50 MHz. In this case, ACO-OFDM outperforms DCO-OFDM by BER performance of 1.5 dB.

In our experiment, the three color chips of the RGB LED transmit signal simultaneously. To study the crosstalk between the three color chips, we also measure the BER performance of the color chips without the other two as shown in Fig. 6. It can be clearly seen that there is almost no interference between different color chips. This is because the wavelengths of the three color chips are different, and we use the RGB filters in front of the APD; therefore the crosstalk will be filtered out by the corresponding RGB filter. In addition, we measure the BER results at the aggregated rate of all three color chips, as shown in Fig. 7.

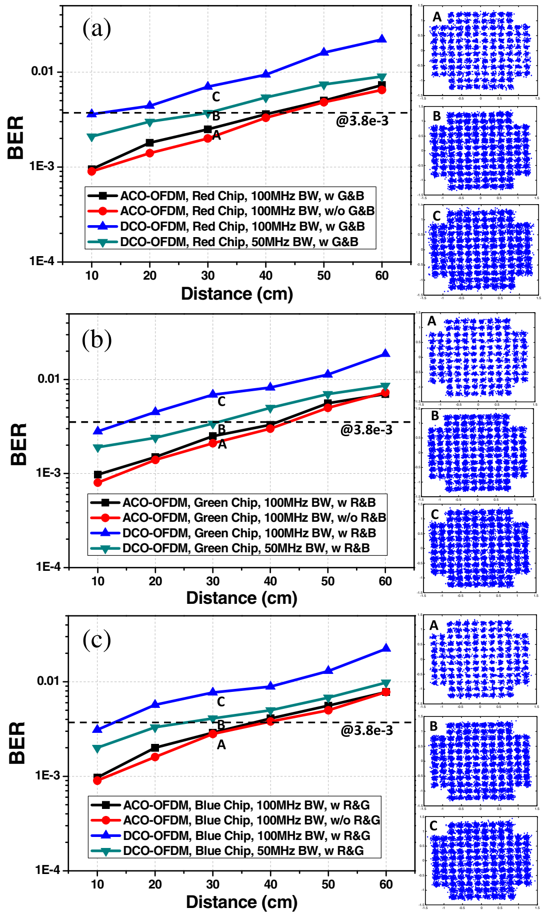

Fig. 6. BER versus transmission distance of (a) red chip, (b) green chip, and (c) blue chip.

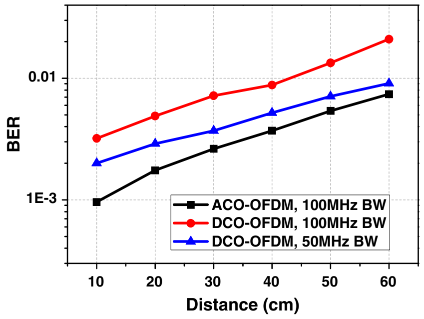

Fig. 7. BER versus transmission distance at the aggregated rate.

It should be noted that in the VLC system the luminance of the LED is the key factor that can limit the transmission distance. In our experiment, a single RGB LED with only 1 W output optical power is used, and the luminance of different color chips at 30 cm after the focusing lens is measured: red chip 50 lx, green chip 80 lx, and blue chip 10 lx. The luminance is below the standard value for brightness (500 lx). It is believed that distance can be easily improved by increasing the optical power of LEDs or deploying a LED array.

4. CONCLUSION

In this paper, for the first time as far as we know, we experimentally verify the performance improvement for a gigabit WDM VLC system based on ACO-OFDM. We theoretically analyze ACO-OFDM, and the investigation reveals that, compared to DCO-OFDM, the advantages of ACO-OFDM are not only because of the increased power efficiency and modulation depth, but also because of the reduction of ICI caused by signal–signal beating noise. In the experiment, a single RGB LED is used to for WDM. An aggregate data rate of 1.05 Gb/s is successfully achieved over 30 cm transmission below the 7% FEC threshold of 3.8×10^{-3}. The results show that ACO-OFDM can outperform DCO-OFDM by 1.5 dB at the same data rate and 4 dB at the same bandwidth, which clearly demonstrates the benefit and feasibility of ACO-OFDM for high-speed VLC systems.

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