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Color Multiplexing Based Unipolar OFDM for Indoor RGB LED Visible Light Communication

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Abstract

In this paper, a novel unipolar orthogonal frequency-division multiplexing (OFDM) scheme is proposed for indoor intensity modulation/direct detection (IM/DD) visible light communication (VLC) using red-green-blue (RGB) light emitting diode (LED). The positive and negative parts of a bipolar OFDM signal are transmitted separately on two colors of a RGB LED through color multiplexing. Compared with conventional DC biased optical OFDM (DCO-OFDM) or asymmetrically clipped optical OFDM (ACO-OFDM), the proposed color multiplexed optical OFDM (CMO-OFDM) can greatly improve the overall power efficiency of indoor VLC systems without reducing the total transmission capacity. Two types of receivers are designed and their performances are examined for CMO-OFDM based indoor VLC systems. By utilizing a practical RGB LED model, performance comparisons between CMO-OFDM and conventional unipolar OFDM schemes have also been conducted. The obtained results show that, to achieve the same bit rate, CMO-OFDM based indoor VLC system requires the least average optical power.
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Keywords: orthogonal frequency-division multiplexing (OFDM); visible light communication (VLC); color multiplexing

1. Introduction

Indoor visible light communication (VLC) or optical wireless communication (OWC) using white light emitting diodes (LEDs) has been attracting increasing attention recently, due to many inherent advantages of LEDs such as

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low power consumption, long lifetime, cost effectiveness and small size [1]. In an LED-based indoor VLC system, LEDs are not only used for indoor illumination, but also for indoor optical wireless communication. There are two typical methods to generate human-comfortable white light for illumination, one is to mix red, green, and blue colors via a RGB LED [2] and the other is to combine a blue LED chip with a yellow phosphor layer [3]. Compared with the phosphorescent LED, RGB LED has many advantages such as higher modulation bandwidth, effective color control ability and possibility of wavelength division multiplexing (WDM).

Orthogonal frequency-division multiplexing (OFDM) has been extensively studied in fiber-based optical access networks [4-6] and outdoor free-space optical (FSO) links [7,8], due to its high spectral efficiency. OFDM has also been applied in indoor VLC systems, in order to improve the data rate and mitigate multipath induced inter-symbol interference (ISI) [9]. The light from LEDs is not coherent, thus intensity modulation/direct detection (IM/DD) is generally used and only real and unipolar signals can be transmitted. A real but bipolar OFDM signal can be generated by using Hermitian symmetry and the bipolar signal can be converted to unipolar by adding a DC bias, as in DC biased optical OFDM (DCO-OFDM) [9]. However, the required DC bias could be very large due to the high PAPR of the OFDM signal, which would greatly reduce the power efficiency of indoor VLC systems. So far, several power efficient unipolar OFDM schemes have been proposed, such as asymmetrically clipped optical OFDM (ACO-OFDM) which clips all the negative part of a bipolar OFDM signal [9] and so on. Since ACO-OFDM sacrifices half of the spectral efficiency to eliminate the use of a large DC bias, the total capacity of indoor VLC system using ACO-OFDM is halved compared with the system using DCO-OFDM.

In this paper, we propose a novel unipolar OFDM scheme based on color multiplexing in a RGB LED for indoor VLC systems. By utilizing the proposed color multiplexed optical OFDM (CMO-OFDM) which requires relatively small DC biases, power efficient indoor VLC can be achieved without sacrificing the total capacity. Two types of receivers are designed for CMO-OFDM based indoor VLC systems. In order to evaluate the system performance, a practical RGB LED model is adopted and the impact of LED nonlinearities is also investigated. We further compare the performance of the proposed CMO-OFDM with other existing unipolar OFDM schemes in indoor VLC systems, in terms of BER and required average optical power.

2. RGB LED model

In our analysis, a practical RGB LED (Cree Xlamp MC-E) model is considered. The relations between the forward voltages (V) across the each chip of the RGB LED and the corresponding current (I) through each chip can be effectively modeled through polynomials by using the least-square curve fitting technique.

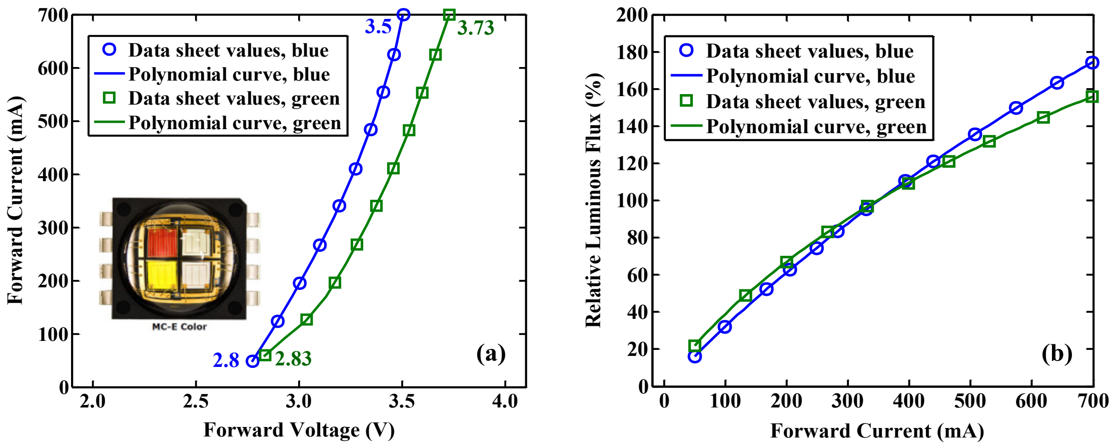

Fig. 1. (a) I-V characteristics; (b) L-I characteristics.

The I-V characteristics of the blue and green chips of the RGB LED are shown in Fig. 1(a). According to the data sheet, two polynomial curves of the sixth order are obtained to model the I-V characteristics of the blue and green chips of the RGB LED. It is observed that the turn-on voltages (TOVs) of the blue and green chips are 2.8 and 2.83 V, respectively. The maximum forward voltages (MFVs) of the blue and green chips are 3.5 and 3.73 V, respectively. Similarly, the relations between the luminous flux (L) and the forward current (I) through each chip can also be effectively modeled through polynomials according to the corresponding data sheet. Fig. 1(b) shows the L-I characteristics of the blue and green chips of the RGB LED.

3. CMO-OFDM based indoor VLC system

The schematic diagram of an indoor VLC system based on CMO-OFDM with a polarity combining (PC) receiver is shown in Fig. 2(a). In the CMO transmitter (Tx), input data are fed into an OFDM modulator (mod.) to generate a real but bipolar OFDM signal $x(k)$. In order to obtain a unipolar OFDM signal, a polarity separator (sep.) is used to separate the positive and negative parts of the bipolar signal and then the negative half is inverted to positive in a polarity invertor (PI). After cyclic prefix (CP) addition and digital-to-analog conversion (D/A), the positive half $x_1(k)$ and the inverted negative half $x_2(k)$ are used to modulate the green and blue chips of a RGB LED, respectively. In order to maintain white color illumination, a DC bias is applied to drive the red chip of the RGB LED. Note that the red channel here can also be exploited to transmit other signals, such as the signal for indoor localization, so as to fully exploit the total capacity of the proposed indoor VLC system. After free-space transmission, two lenses are used to collect the green light and the blue light onto two photodiodes (PDs), respectively. Then, a pair of green and blue filters is followed to separate the signals on the green and blue channels. As a result, the positive half and the inverted negative half of the bipolar OFDM signal are received parallelly. Since nearly half of the zero-valued data and part of the positive data will be made negative by the additive noise, the positive half and the inverted negative half of the bipolar OFDM signal are clipped at zero to reduce the noise. After receiver negative clipping (RNC), the obtained analog signals are converted to digital signals via analog-to-digital conversion (A/D) and the CP is removed. Then, the inverted negative part of the bipolar OFDM signal is inverted back to negative via another PI. To recover the bipolar OFDM signal, a polarity combiner is utilized to combine the obtained positive and negative signals together. Finally, an OFDM demodulator (demod.) is used to demodulate the received signal.

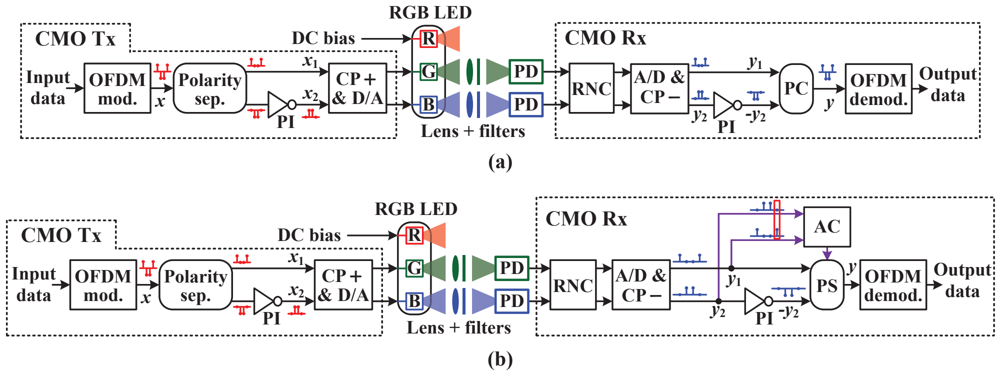

Fig. 2. CMO-OFDM based indoor VLC system using (a) a polarity combining (PC) receiver; (b) a polarity selecting (PS) receiver.

To reduce the additive noise, a modified CMO-OFDM receiver with polarity selecting (PS) is designed, as shown in Fig. 2(b). Considering that $x_1(k)$ and $x_2(k)$ are generated from one bipolar OFDM signal, for any given k, only one of them contains the signal component. Thus, only one of the two received signals, $y_1(k)$ or $y_2(k)$, contains the signal component and the other one must only contain the noise component. Therefore, we can reconstruct the bipolar OFDM signal by utilizing a novel amplitude comparing (AC) based polarity selecting technique. Since $y_1(k)$ and $y_2(k)$ are both non-negative due to RNC, it is easy to identify which of them contains the signal component. If $y_1(k)$

$> y_2(k)$, then we know that $y(k)=y_1(k)$, otherwise $y(k)=-y_2(k)$. By selecting the signal component from two obtained signals using a polarity selector, the proposed polarity selecting technique can further reduce the additive noise of the reconstructed bipolar OFDM signal. Finally, a bipolar OFDM demodulator is followed to obtain the output data.

4. Results and discussions

Fig. 3(a) compares the BER performance of PC and PS based CMO-OFDM for an indoor RGB LED based VLC system using 64QAM mapping. It is observed that CMO-OFDM using a PS based receiver has a signal power improvement of more than 1 dB at the BER benchmark of 10^{-3}, compared with that using a PC based receiver. This improvement is obtained by selecting the only signal component from the two parallel signals and thus reduce the additive noise. The performance of CMO-OFDM with a PS receiver for different orders of QAM mapping is depicted in Fig. 3(b). When the average electrical signal power P_s is relatively low, the BER performance is mainly affected by thermal noise and shot noise in the receiver and the BER decreases with the increase of P_s. However, when P_s gets higher than a certain value, the clipping noise becomes dominant and the BER increases with P_s. It can be seen that there is an optimal P_s for all QAM orders which is around 17.5 dBm. The discontinuity in BER curves of 4QAM and 16QAM indicates that the BER is less than 10^{-6}. Furthermore, the BER of 256QAM is always above 10^{-3}, regardless of the value of P_s. To achieve a BER benchmark of 10^{-3}, lower order QAM mappings should be employed.

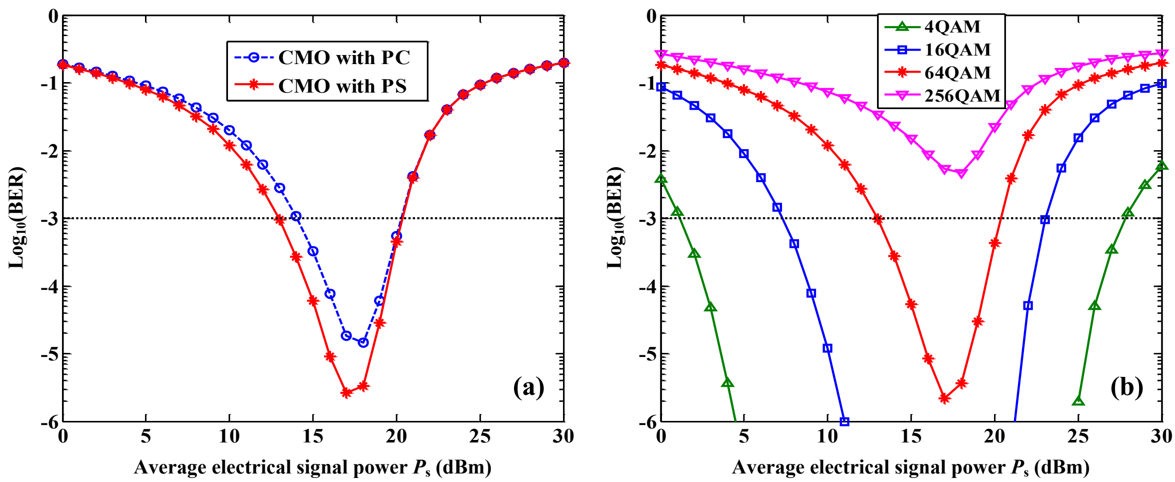

Fig. 3. (a) BER comparison between PC and PS based CMO-OFDM with 64QAM; (b) BER of CMO-OFDM with a PS receiver.

We compare the performance of PS based CMO-OFDM with other reported unipolar OFDM schemes, such as DCO-OFDM and ACO-OFDM, in indoor VLC systems. In order to conduct a fair comparison, three different cases are considered. In Case I, as shown in Fig. 4(a), the green and blue chips of a RGB LED are independently used to transmit two different OFDM signals. The two independent OFDM channels are then detected by two PDs and demodulated separately. In Case II, as shown in Fig. 4(b), two white LEDs are used to transmit the same signal. The transmitted signal is collected by a lens and then detected by a PD. For both Case I and Case II, either DCO or ACO-OFDM can be used. The PS based CMO-OFDM scheme is given in Case III, as shown in Fig. 4(c). When the number of subcarriers is relatively large, the overall achievable bit rate for M-QAM based DCO-OFDM channel is about $B\log_2 M/2$, where B is the channel bandwidth. In contrast, the achievable bit rate for M-QAM based ACO-OFDM channel is around $B\log_2 M/4$, which is halved compared with DCO-OFDM. In the comparison, the channel bandwidth B is set to 100 MHz for all three cases. Two practical white LEDs (Cree Xlamp XM-L) are adopted in Case II. In Case I with ACO-OFDM, two chips of the RGB LED are biased at their TOVs, while they are biased at middle points of their dynamic ranges when DCO-OFDM is used. Similarly, two white LEDs are biased at their TOVs for ACO-OFDM in Case II while for DCO-OFDM, they are biased at middle points of their dynamic ranges. In Case III with the proposed CMO-OFDM, two chips of the RGB LED are also biased at their TOVs.

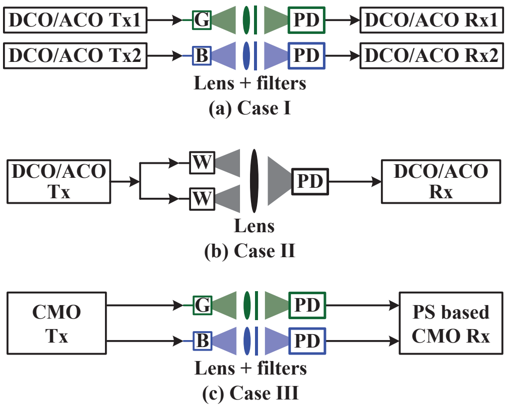

Fig. 4. Different schemes for performance comparison with the same average electrical signal power: (a) Case I with DCO-OFDM or ACO-OFDM; (b) Case II with DCO-OFDM or ACO-OFDM; (c) Case III with PS based CMO-OFDM.

Fig. 5 compares the BER performances of different schemes for the same bit rate of 300 Mb/s. It can be observed that, to achieve the BER of 10^{-3}, Case I and Case II with DCO-OFDM require smaller average electrical signal powers than other schemes. For Case I with ACO-OFDM, the required P_s to reach the BER benchmark is about 15.5 dBm. However, the BERs of ACO-OFDM based Case II are always above 10^{-3}, since a QAM order of 4096 is utilized to achieve a bit rate of 300 Mb/s in this case. For Case III with our proposed CMO-OFDM, a P_s of about 13 dBm is required, which shows a 2.5 dB improvement compared with Case I with ACO-OFDM. Even though Case I and Case II with DCO-OFDM require much less powers than other schemes, as can be seen in Fig. 5, they need much higher DC biases which are not counted in the required average electrical signal power.

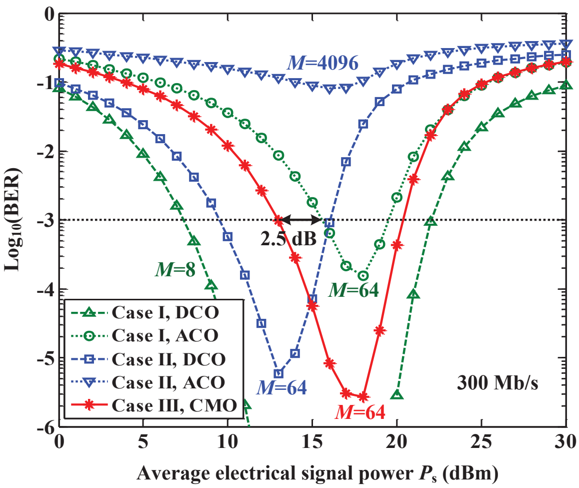

Fig. 5. BER performance comparison of different schemes for the same bit rate of 300 Mb/s.

In practical indoor VLC systems, the LEDs must perform dual function of illumination and wireless data communication. Therefore, we compare the required average optical power P_o of different schemes to achieve the bit rate of 300 Mb/s. A luminous efficacy of 300 lm/W is adopted to convert luminous flux to average optical power. Fig. 6 shows the comparison of the required average optical power P_o of different OFDM schemes. It is found out that DCO-OFDM based Case I and Case II require nearly constant average optical powers. It is also clear to see that ACO-OFDM based Case I and Case II and CMO-OFDM based Case III require much less optical powers compared with the cases using DCO-OFDM. Moreover, Case I with ACO-OFDM and Case III with CMO-OFDM require the same average optical powers for a same average electrical signal power P_s.

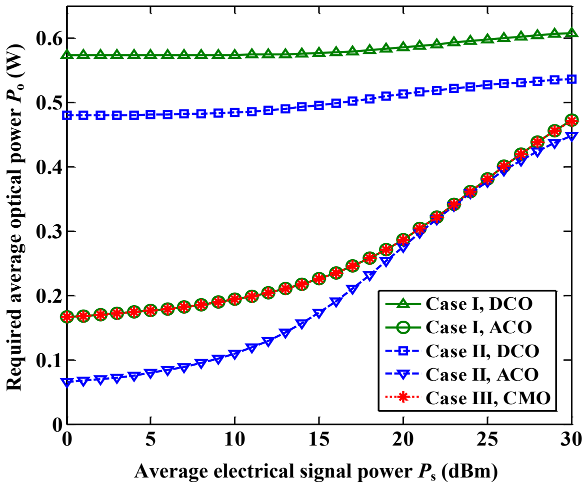

Fig. 6. Required average optical power vs. average electrical signal power for different OFDM schemes.

A detailed comparison regarding the QAM order M, average electrical signal power P_s and average optical power P_o is given in Table 1. It can be seen that Case III with CMO-OFDM consumes the least optical power to achieve the bit rate of 300 Mb/s. Compared with DCO-OFDM based Case I and Case II, the power reductions of Case III are 363.3 and 273.6 mW, respectively. A power reduction of 19.7 mW is also obtained when compared with Case I with ACO-OFDM. For Case II with ACO-OFDM, it cannot achieve the bit rate of 300 Mb/s since 4096QAM is required which is impractical.

Table 1. Performance comparison of different schemes.

Scheme	M	P_s (dBm)	P_o (mW)
Case I, DCO	8	7.3	573.6
Case I, ACO	64	15.5	230
Case II, DCO	64	9.6	483.9
Case II, ACO	4096	-	-
Case III, CMO	64	13	210.3

5. Conclusion

We have proposed and analyzed a CMO-OFDM scheme for IM/DD based indoor VLC systems, which can improve system power efficiency without sacrificing the total transmission capacity. Based on a practical RGB LED model, we show that CMO-OFDM requires the least average optical power when compared with other schemes for achieving the same bit rate. In conclusion, CMO-OFDM is a promising candidate for future indoor VLC systems.

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