OCT Precoding for OFDM-based Indoor Visible Light Communications

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Abstract: *An orthogonal circulant matrix transform (OCT) precoding scheme is proposed for indoor visible light communications. We show the proposed scheme has much reduced complexity but exhibits comparable performance with adaptive bit and power loading.*
Keywords: *Visible light communications; OFDM; OCT precoding*

I. INTRODUCTION

Visible light communications (VLC), emerging as an alternative solution for the RF communications, has gained interests from both academia and industry in recent years [1-2]. One of the main challenges for high-speed VLC is the limited LED's modulation bandwidth, typically several megahertz [2]. Blue filtering or RGB-type LED is commonly used in recent works to improve the 3-dB system bandwidth. The electrical circuit based compensation is another way to extend the system bandwidth, achieving a relatively flat spectrum or signal to noise ratio (SNR) over a larger signal bandwidth. Various design of multi-resonant electrical circuits are reported for pre-distortion [1] or for post equalization [2] to improve the performance of VLC systems. However, besides the requirement of pre-knowledge for channel state information (CSI), the designed circuits cannot achieve adaptive adjustment to the changes of system setup or channel properties without incurred high complexity. Alternatively, the SNR equalization can also be achieved by the discrete Fourier transform (DFT) precoding, which is also known as single carrier frequency division multiple access (SC-FDMA) [3]. The DFT precoding is channel independent and only requires one linear transformation at transmitter and receiver, respectively. However, the conventional DFT precoding is more sensitive to inter-symbol interference (ISI). Therefore, a large cyclic prefix (CP) length is needed to combat the ISI, leading to lower spectral efficiency.

The discrete multitoned modulation (DMT) with bit and power loading [4-5] is generally known an effective solution to boost system capacity, since the bits and power are allocated adaptively according to the pre-known channel state information (CSI). Despite of its optimal performance, the adaptive bit and power loading scheme requires the support of multiple modulation levels at both transmitter and receiver. The allocation results of bits and power also need to be transmitted to receiver accurately. All these issues increase the complexity and cost for the implementation of adaptive bit and power loading scheme in practical VLC systems. We have recently proposed a channel-independent OCT precoding scheme for VLC systems, with proof-of-concept point-to-point experiments demonstrated in [6]. The results show that with the same spectral efficiency, the performance of OCT precoding outperforms that of conventional DFT precoding. To apply OCT precoding to the emerging indoor VLC applications, it is essential to investigate the feasibility of the proposed OCT precoding in indoor environments.

In this paper, we focus on the performance investigation of OCT precoding with the consideration of multi-reflection effect, as well as location influence of the different indoor scenarios. We show that by utilizing the proposed OCT scheme, relatively flat SNR with ~1-dB fluctuation for different subcarriers can be obtained, resulting in significant bit error rate (BER) performance improvement of the system. Numerical simulation results show that the proposed OCT precoding have comparable BER performance with the adaptive bit and power loading, but exhibits significantly reduced implementation complexity, thus is more preferable for practical VLC applications.

II. SYSTEM MODEL

Fig. 1 shows schematic diagram of a VLC system with the proposed OCT precoding. After serial to parallel (S/P) conversion and mapping, OCT precoding is performed, i.e., the mapped signal $[X_1, X_2, \ldots, X_N]$ is multiplied by an orthogonal circulant matrix given by

$$\boldsymbol{F} = \tfrac{1}{\sqrt{N}} \times \left[c_1, c_2, \ \ldots, c_N; c_N, c_1, \ \ldots, c_{N-1}; \ \ldots; c_2, c_3, \ \ldots, c_1 \right], \tag{1}$$

where each entry c_i ($1 \le i \le N$) of $\boldsymbol{F}$ is the corresponding element of Zadoff-Chu (ZC) sequence with a length of N. We utilize the ZC sequence in this work because of its ideal periodic auto-correlation property, i.e., the periodic auto-correlation is zero for all time shifts other than zero. Therefore, the constructed circulant matrix $\boldsymbol{F}$ is orthogonal and $\boldsymbol{F}^*\boldsymbol{F} = \mathbf{I}$, where $(\cdot)^*$ denotes Hermitian transpose. In order to obtain real-valued OFDM signal, after the OCT precoding, subcarrier assignment is needed to constrain the input of the inverse fast Fourier transform (IFFT) operation to have Hermitian symmetry. Then, parallel to serial (P/S) conversion, CP insertion, pilot insertion and normalization are performed. Subsequently, the signal is fed into digital to analog converter (DAC). After DAC, the output is combined

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with DC-bias to drive four LEDs. The properties of LED transmitter are the same as that in [4].

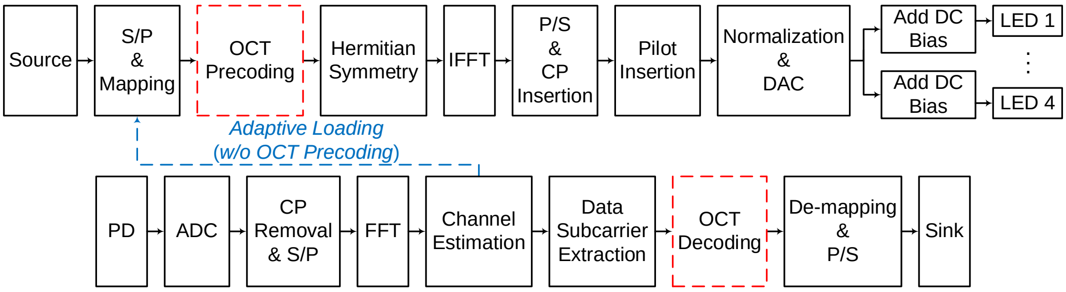

Fig. 1. Block diagram of indoor VLC system with (i) OCT precoding or (ii) adaptive loading.

Indoor VLC channel property from the i-th LED transmitter to the receiver can be characterized by the corresponding impulse response, which is described by

$$h_i(t) = h_i^{(0)}(t) + \sum_{k=1}^{\infty} h_i^{(k)}(t), \tag{2}$$

where the two terms on the right side of Eq. (2) represent the line-of-sight (LOS) contribution and the non-LOS contribution, respectively. Monte Carlo method used in [4] is utilized to model the indoor multi-reflection VLC channel, and the simulation parameters used are given in Table I.

TABLE I SIMULATION PARAMETERS

Parameter	Value	Parameter	Value
LED locations (in meter)	(3.5,3.5,3); (1.5,3.5,3); (3.5,1.5,3); (1.5,1.5,3)	Max. reflection order	5
Receiver location (Scenario A - center) (in meter)	(2.5,2.5,0.85)	Receiver field of view	60°
Receiver location (Scenario B - corner) (in meter)	(0.5,0.5,0.85)	LED power	3 W
Reflection coef. (walls, floor, ceiling)	0.83; 0.63; 0.4	Number of Rays	200,000

Assume that the output signal of LED is denoted by $x(t)$. The received signal $y(t)$ is

$$y(t) = \gamma \cdot \sum_{i=1}^{4} h_i(t) \otimes x(t) + n(t), \tag{3}$$

where γ is the photodiode responsivity and $n(t)$ denotes the noise with zero mean, with $n(t)$'s variance containing shot noise and thermal noise contributions. After data subcarrier extraction, OCT decoding is performed, i.e., the received signal is multiplied by the inverse matrix of $\boldsymbol{F}$, to recover the original complex signal. The error vector magnitude (EVM) of the recovered complex signal is then used to estimate each subcarrier's SNR.

III. SIMULATION RESULTS

The indoor configuration is set as follows. Four LEDs are mounted on the ceiling and the distance from ceiling to the receiving plane is 0.85 m. Two scenarios, as given in Table I, are considered in the performance investigation of the proposed scheme. Note that DCO-OFDM is utilized in the following simulations, with an IFFT/FFT size of 256 and a CP length of 8.

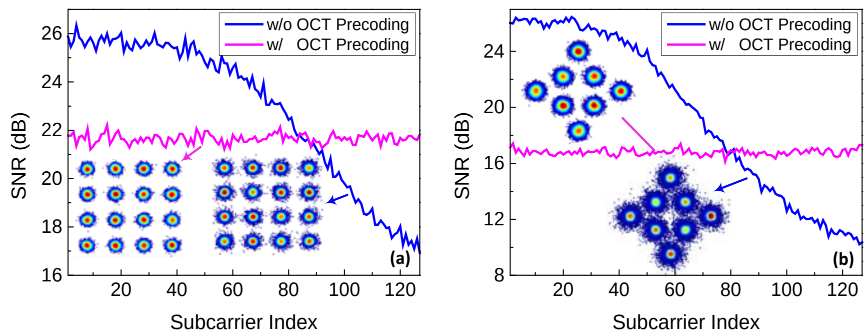

Fig. 2. SNR comparison of the VLC system with and without OCT precoding: (a) 16QAM-OFDM for scenario A, (b) 8QAM-OFDM for scenario B.

Fig. 2 shows the SNR performance comparison of the indoor VLC system with and without the proposed OCT precoding scheme in the two scenarios. The bandwidth of the DCO-OFDM signal is 60 MHz. Note that 16-QAM is used for all data subcarriers of DCO-OFDM symbols in scenario A, whereas 8-QAM is used for the data subcarriers of DCO-OFDM symbols in scenario B. The BER performance of scenario A and scenario B without the proposed OCT precoding scheme is 5.12×10^{-5} and 2.31×10^{-3}, respectively. As shown in Fig. 2, SNR can be equalized to around the median value with ~ 1dB fluctuation for different data subcarriers by using the OCT precoding scheme; and a BER of less than 10^{-5} can be achieved for both scenarios. Besides, it is clear that the performance improvement is related to SNR conditions of the system, therefore, it is desirable to investigate the proposed OCT precoding under the situation that data subcarriers are modulated with different order QAM signals. Fig. 3 shows the corresponding BER comparison.

The BER of scenario A is superior to that of scenario B because of larger received signal intensity and less multi-path influence. Generally, significant improvement in BER performance can be obtained for both scenarios when the signal bandwidth is lower than 100 MHz. The performance of the proposed scheme may be reduced for high-order QAM modulation format at larger bandwidth, where the BER is significantly above the 3.8×10^{-3} FEC limit.

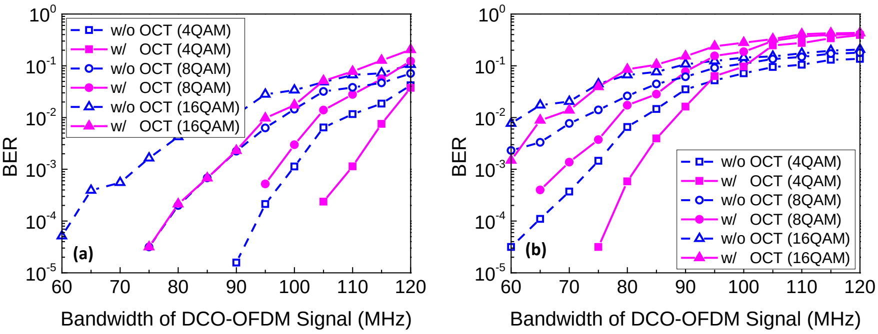

Fig. 3. BER comparison of the indoor OFDM-based VLC system with and without OCT precoding: (a) Scenario A, (b) Scenario B.

In order to further investigate the performance of the proposed scheme, we compare the BER of adaptive bit and power loading scheme with the results in Fig. 2. The main idea of bit and power loading scheme is to adaptively allocate the bits and power to different subcarriers according to CSI, which is estimated before data transmission with the help of training symbols. The estimated SNR of each subcarrier at the receiver along with the signal constellation diagrams are shown in Fig. 4. Basically, the estimated SNR from EVM over different subcarriers are positive correlated with the number of allocated bit. In both scenarios, a BER of less than 10^{-5}, similar to that of the proposed OCT precoding scheme, can be achieved. However, considering the complicated implementation of the adaptive bit and power loading scheme, the proposed OCT precoding, which offers significantly reduced complexity, is more robust for practical VLC applications.

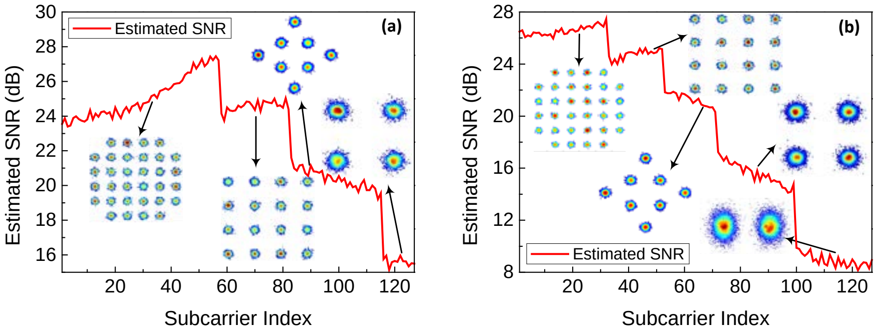

Fig. 4. SNR of the data subcarriers and corresponding signal constellations at the receiver: (a) Scenario A, (b) Scenario B.

IV. Conclusions

We propose and investigate an OCT precoding scheme to combat the bandwidth limitation issue in OFDM-based indoor VLC systems. Significant BER improvement compared to the conventional OFDM transmission, as well as a relatively flat SNR condition with ~1-dB fluctuation, can be achieved by using the proposed scheme. The robustness of the OCT precoding is verified by the BER performance improvements in both center and off-center of indoor coverage. In addition, simulation results show the proposed scheme's BER performance is comparable to that of the adaptive bit and power loading scheme. However, considering the implementation complexity, the proposed scheme is more suitable for practical VLC systems. It is worth noting that besides VLC applications, the proposed scheme is applicable to other bandwidth-limited OFDM transmission systems.

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