Performance Investigation of OCT Precoding for MIMO-OFDM Based Indoor Visible Light Communications

Yang Hong, ***Student Member, IEEE*****, and Lian-Kuan Chen,** ***Senior Member, IEEE***
Department of Information Engineering, The Chinese University of Hong Kong, Shatin, N. T., Hong Kong
E-mail: yanghong@ie.cuhk.edu.hk; lkchen@ie.cuhk.edu.hk

ABSTRACT
In this paper, we propose a MIMO-OFDM indoor VLC system with orthogonal circulant matrix transform (OCT) precoding and angular receivers to significantly improve the achievable aggregate capacity of equivalent parallel channels. Compared with the conventional MIMO-OFDM based VLC systems, the data streams of LED transmitters in our proposed system are linearly pre-processed with the OCT precoding scheme and can be recovered by corresponding linear OCT decoding at receiver. Numerical results show that with 50-MHz modulation bandwidth, the BER performance can be improved to ~10^{-3} by the receiver module with angular diversity. With the help of OCT precoding, the BER can be further improved to ~10^{-5} for both center and off-center indoor coverage.
Keywords: visible light communications, optical MIMO-OFDM, OCT precoding.

1. INTRODUCTION

Due to the overcrowded spectrum of the conventional radio frequency communications, visible light communications (VLC) is emerging as an alternative solution for high-speed wireless access in recent years [1]. One of the main challenges for high-speed VLC is the limited modulation bandwidth of the transmitter, i.e., light emitting diode (LED), hence most of the current works focus on improving the achievable capacity of VLC systems. The combination of multiple input and multiple output (MIMO) and orthogonal frequency division multiplexing (OFDM) has been proved to be an efficient solution for VLC to improve spectral and spatial efficiency, thus boosting system capacity. The experimental demonstration of MIMO-OFDM with imaging receivers in VLC was reported in [2]. In [3], positive and negative coefficients separation (PNS) based scheme was proposed to reduce the implementation complexity for MIMO-OFDM VLC systems. Generally, the prior MIMO-OFDM based schemes for VLC systems only provide capacity improvement through parallel transmission over multiple parallel channels. The performance of the multiple equivalent parallel channels have not been optimized, meaning that inter-channel optimization can be exploited to further enhance the achievable aggregate capacity of the MIMO-based VLC systems. Recently, we have proposed and experimentally demonstrated the OCT precoding scheme for point-to-point VLC transmission in [4]. Results show that by using the proposed scheme, a relatively flat signal to noise ratio (SNR) condition with ~1-dB fluctuation over the OFDM signal bandwidth can be achieved, leading to significant BER performance improvement. Besides, we also show that BER performance of OCT precoding outperforms that of conventional discrete Fourier transform (DFT) precoding and is comparable with that of adaptive bit and power loading scheme.

In this paper, we propose utilizing OCT precoding for the MIMO-OFDM based indoor VLC system to boost system capacity. Both individual OCT precoding for each transmitter and joint OCT precoding for all transmitters are considered to investigate BER performance improvement of the system. Our previously proposed receiver module with angular diversity [5] is also used to reduce the channel correlation of the system. In the proposed system setup, the data stream of each LED transmitter is pre-processed by the individual/joint OCT precoding and can be recovered by corresponding OCT decoding at receiver after channel estimation. Based on a 4 × 4 indoor MIMO-OFDM VLC system, we investigate BER performance of the proposed system in both center and off-center indoor scenarios. Numerical simulation results show significant BER performance improvement and BERs of around 10^{-5} can be achieved for the two scenarios by utilizing the proposed scheme.

2. PRINCIPLES OF THE PROPOSED SYSTEM

We consider an indoor MIMO-OFDM VLC system with the number of LED transmitter and photodetector being N_T and N_R, respectively. The system block diagram is shown in Fig. 1.

2.1 Transmitters

After serial to parallel (S/P) conversion and mapping, individual OCT precoding is performed for each data streams, i.e., the mapped complex signal at each LED transmitter is linearly pre-coded by the precoding 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 [4, 6] with a length of N. Then, Hermitian symmetry is applied to enable real-valued output OFDM signal after inverse fast

Fourier transform (IFFT). After that, parallel to serial (P/S) conversion, cyclic prefix (CP) insertion and pilot insertion. Then, the OFDM signal is normalized before feeding into digital to analog converter (DAC). Subsequently, DC bias is added to the output signal of DAC to drive LED transmitters, with the same modulation bandwidth and nonlinearity as those in [5].

2.2 Indoor MIMO VLC Channel

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

$$h_{ji}(t) = h_{ji}^{(0)}(t) + \sum_{m=1}^{\infty} h_{ji}^{(m)}(t), \tag{2}$$

where the first term on the right-hand side of equation (2) represents the line-of-sight (LOS) contribution, and the other one represents the non-LOS contribution. In this work, multi-reflection effect of the system is taken into account by the Monte Carlo method [7], to model the channel characteristics within indoor coverage.

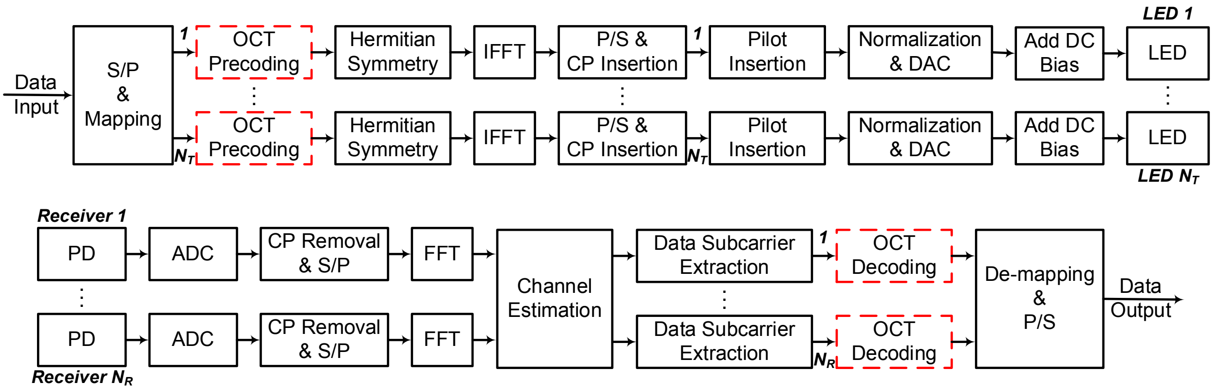

Figure 1. Block diagram of the indoor MIMO-OFDM VLC system with individual OCT precoding.

2.3 Receivers

Assume that the number of subcarriers in the OFDM symbol is K. Let $X_i(k)$ denote the transmitted signal on the k-th subcarrier at the i-th LED transmitter, $Y_j(k)$ denote the received signal on the k-th subcarrier at the j-th receiver, and $N_j(k)$ denote the noise on the k-th subcarrier at the j-th receiver. Then, $Y_j(k)$ is given by

$$Y_j(k) = \sum_{i=1}^{Nt} H_{ji}(k) X_i(k) + N_j(k), \quad k = 1, 2, \ldots, K \tag{3}$$

where $N_j(k)$ is the noise containing shot noise and thermal noise contributions [8]. $H_{ji}(k)$ is the frequency domain channel response corresponding to $h_{ji}(t)$ in equation (2). The overall system response of indoor MIMO-OFDM VLC system is estimated by least square (LS) scheme with the help of pilot symbols. Then, data subcarriers are extracted to perform individual OCT decoding, i.e., the signal is multiplied by the inverse matrix of the precoding matrix ***F***. Finally, the original input data can be recovered after de-mapping and P/S conversion.

3. NUMERICAL RESULTS

Based on a 4 × 4 MIMO-OFDM VLC system implemented in a typical 5 m × 5 m × 3 m room, two typical user terminal distribution scenarios are utilized to investigate robustness of the proposed scheme. The locations of LED transmitters and receivers in the two scenarios are given in Table 1.

Table 1. Locations of LED transmitters (Tx) and receivers (Rx).

Tx / Rx	Location (meter)
Tx-1 to Tx-4	(3.5,3.5,3); (1.5,3.5,3); (3.5,1.5,3); (1.5,1.5,3)
Rx-1 to Rx-4 (Scenario A - center)	(2.55,2.55,0.85); (2.45,2.55,0.85); (2.55,2.45,0.85); (2.45,2.45,0.85)
Rx-1 to Rx-4 (Scenario B - corner)	(0.5,0.5,0.85); (0.4,0.5,0.85); (0.5,0.4,0.85); (0.4,0.4,0.85)

The parameter values in simulations are set as follows: IFFT/FFT size and CP length of the OFDM symbol are 256 and 8, respectively; the responsivity, physical detection area and field of view of photodiode are 0.53 A/W, 1 cm^2 and 70°, respectively; bias voltage for LED is 3.2 V; LED power is 10 W; and the number of generated rays to simulate VLC channel is 100, 000. The polar angle of angular receivers is optimized to be 45°, while the values of azimuthal angles of the four receiver heads are 45°, 135°, 225° and 315°, respectively [5]. The bandwidth of DCO-OFDM signal in the following simulations is 50 MHz. Considering the larger received signal intensity and less multi-reflection influence in central region of indoor environment, 16QAM-OFDM modulation format is utilized for scenario A, whereas 8QAM-OFDM modulation format is utilized for scenario B.

3.1 Individual OCT Precoding

We first evaluate the performance of the MIMO-OFDM indoor VLC system (i) with conventional system setup, (ii) with angular receivers and (iii) with both individual OCT precoding and angular receivers. Table 2 gives the comparison of average BER at four receivers between the three schemes.

Table 2. Average BER Comparison for different schemes.

	w/ conventional system setup	w/ angular receivers	w/ individual OCT precoding & angular receivers
Scenario A	0.26	4.79×10^{-3}	9.20×10^{-5}
Scenario B	0.23	1.86×10^{-3}	1.72×10^{-4}

Due to the high correlation between the MIMO channels in indoor VLC system, the BER performance of conventional system setup is significantly degraded. As shown in Table 2, the BER can be improved to ~ 10^{-3} for both center and corner areas by using a receiver module with angular diversity. The best system performance is achieved by utilizing the combination of individual OCT precoding and angular receivers, confirming the benefits of the proposed scheme. BERs of 9.20×10^{-5} and 1.72×10^{-4} can be achieved for scenario A and scenario B, respectively. The corresponding SNRs over the subcarriers at four receivers are shown in Fig. 2. The SNR conditions at the each receiver can be significantly improved by utilizing angular receivers. However, the SNR profiles at the receivers are uneven, leading to BER degradation in high frequency band. By applying individual OCT precoding to the system, relatively flat SNRs with around 1-dB fluctuation over the subcarriers can be obtained for each receiver, resulting in significant BER improvements.

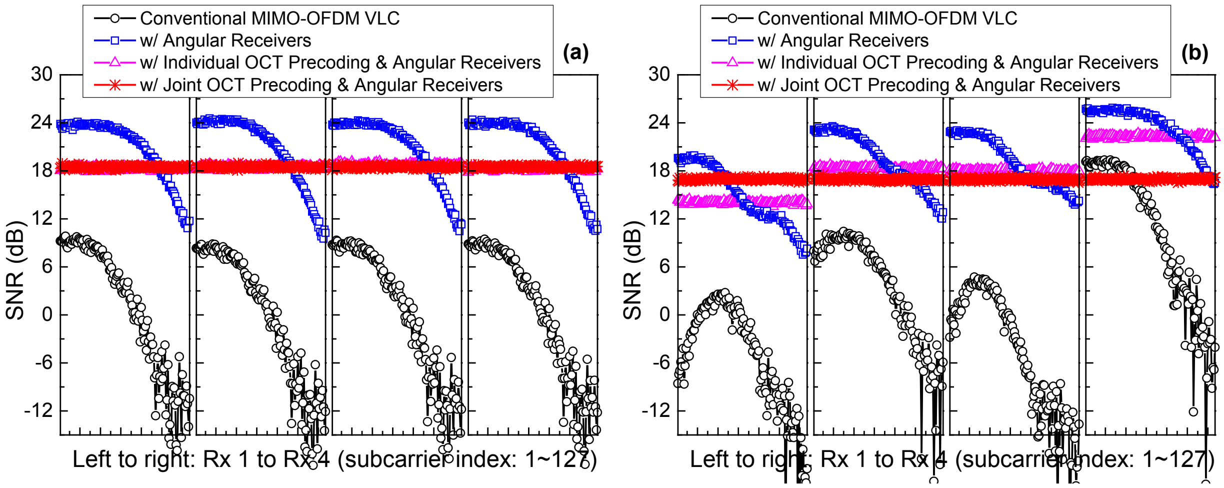

Figure 2. SNR performances over the subcarriers for (a) 16QAM-OFDM in scenario A and (b) 8QAM-OFDM in scenario B.

In addition, due to different received signal intensity at angular receivers in the corner of indoor coverage in scenario B, the SNR conditions with individual OCT precoding at different receivers differ from each other. One way to mitigate this issue is to apply different levels of modulation at different transmitters, e. g., the data stream at Tx-1 is modulated with 4QAM while the data stream at Tx-4 is modulated with 16QAM. The other two transmitters remain unchanged. However, this requires the support of multiple modulation formats at the transceivers and the prior knowledge of the level of QAM modulation utilized at different transmitters to demodulate the signal at the receivers.

3.2 Joint OCT Precoding

To further enhance the overall BER performance, we investigate the improvement by using joint OCT precoding for all transmitters, i.e., all the N_T parallel data streams are pre-coded with a $(N\cdot N_T)\times(N\cdot N_T)$ orthogonal circulant matrix. The decoding process at receivers is similar to that of individual OCT precoding. In this way, the SNR conditions at different receivers can be equalized to a similar level. The SNRs over different subcarriers at four receivers by using joint OCT precoding are also shown in Fig. 2. The average BER of scenario A is 8.67×10^{-5}, which is similar to that of OCT precoding for each individual LED transmitter. While in scenario B, the average BER can be further improved from 1.72×10^{-4} to 1.31×10^{-6}. The corresponding signal constellations and BERs at the four receivers with both joint OCT precoding and angular receivers are given in Fig. 3.

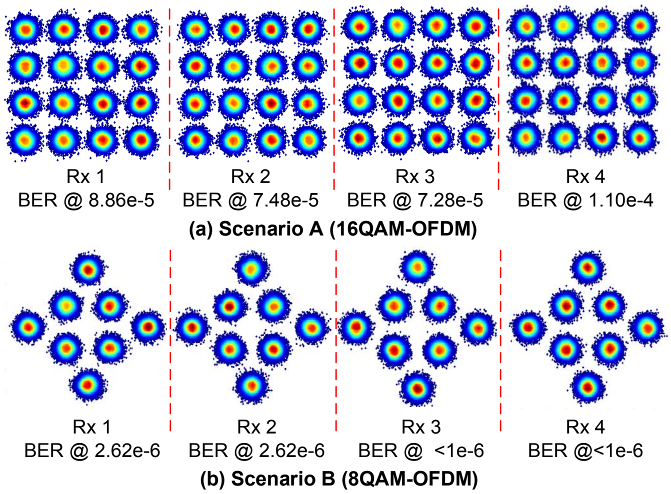

Figure 3. Signal constellations and corresponding BERs of the MIMO-OFDM indoor VLC system with both joint OCT precoding and angular receivers: (a) 16QAM-OFDM in scenario A and (b) 8QAM-OFDM in scenario B.

4. CONCLUSIONS

To enhance the achievable aggregate capacity of MIMO-based VLC systems, an indoor MIMO-OFDM system with individual/joint OCT precoding and angular receivers is proposed in this paper. The proposed scheme provides significant BER improvement with minor increment of implementation complexity. We show that both individual OCT precoding for each transmitter and joint OCT precoding for all transmitters are feasible to improve BER performance of the indoor MIMO-OFDM system. For both center and off-center of the indoor coverage, average BERs of the system can be significantly improved from $\sim 10^{-3}$ to around 10^{-5}, confirming the performance benefits and robustness of the proposed scheme.

ACKNOWLEDGEMENTS

This work was supported in part by RGC, Hong Kong SAR, under GRF 14204015.

REFERENCES

[1] P.H. Pathak, X. Feng, P. Hu, and P. Mohapatra: Visible light communication, networking, and sensing: A survey, potential and challenges, *IEEE Commun. Surv. & Tutorials*, vol. 17, no. 4, pp. 2047-2077, 2015.

[2] A. H. Azhar, T. Tran, and D. O'Brien: A gigabit/s indoor wireless transmission using MIMO-OFDM visible-light communications, *IEEE Photon. Technol. Lett.*, vol. 25, no. 2, pp. 171-174, 2013.

[3] L. Wu, Z. Zhang, and H. Liu: MIMO-OFDM visible light communications system with low complexity, in *Proc. IEEE ICC*, Budapest, Hungary, pp. 3933-3937, 2013.

[4] Y. Hong, X. Guan, L. K. Chen, and J. Zhao: Experimental demonstration of an OCT-based precoding scheme for visible light communications, in *Proc. of OFC*, Anaheim, CA, USA, 2016, paper M3A.6.

[5] Y. Hong, T. Wu, and L. K. Chen: On the performance of adaptive MIMO-OFDM indoor visible light communications, *IEEE Photon. Technol. Lett.*, vol. 28, no. 8, pp. 907-910, 2016.

[6] Z. Feng, M. Tang, S. Fu, *et al.*: Performance-enhanced direct detection optical OFDM transmission with CAZAC equalization, *IEEE Photon. Technol. Lett.*, vol. 27, no. 14, pp. 1507-1510, 2015.

[7] F. J. López-Hernández, R. Pérez-Jiménez, and A. Santamaría: Ray-tracing algorithms for fast calculation of the channel impulse response on diffuse IR wireless indoor channels, *Opt. Eng.*, vol. 39, no. 10, pp. 2775-2780, 2000.

[8] Z. Wang, C. Yu, W. D. Zhong, J. Chen, and W. Chen: Performance of a novel LED lamp arrangement to reduce SNR fluctuation for multi-user visible light communication systems, *Opt. Express*, vol. 20, no. 4, pp. 4564-4573, 2012.