Experimental Demonstration of Performance-enhanced MIMO-OFDM Visible Light Communications

Yang Hong[1], Lian-Kuan Chen[1] and Jian Zhao[2]
1 Department of Information Engineering, The Chinese University of Hong Kong, Hong Kong SAR, China
2 Tyndall National Institute and University College Cork, Lee Maltings, Cork, Ireland
yanghong@ie.cuhk.edu.hk; lkchen@ie.cuhk.edu.hk; jian.zhao@tyndall.ie

Abstract: We experimentally demonstrate individual OCT precoding and SVD-based adaptive loading to boost the capacity of MIMO-OFDM VLC systems. For 1.5-Gbit/s 1-m transmission, the average BER can be reduced from 1.7×10^{-2} to 4.1×10^{-3} and 4.7×10^{-4}, respectively.
OCIS codes: (060.2605) Free-space optical communication; (060.4510) Optical communications.

1. Introduction

Demands for data-intensive applications in next-generation 5G systems have driven visible light communication (VLC) as a promising solution for future indoor/outdoor wireless access [1]. The main challenge of VLC to provide high-speed transmission for a relatively large area is the limited system bandwidth as well as light intensity loss after free-space propagation. The availability of more than one lighting source has made multiple input and multiple output (MIMO) technique an attractive candidate to boost the system capacity and improve the coverage [2]. Conventional MIMO VLC using orthogonal frequency division multiplexing (OFDM) was experimentally demonstrated in [3]. In [4], schemes were proposed to estimate the channel matrix more accurately, thus improving the performance of the MIMO VLC system. However, the limited bandwidth of multiple equivalent channels is the key issue of MIMO VLC systems and the optimization to resolve this issue is yet to be investigated.

In this paper, we experimentally demonstrate two optimization schemes to enhance the performance of MIMO-OFDM VLC systems. The first scheme utilizes channel-independent orthogonal circulant matrix transform (OCT) to pre-code individual channels. It offers significant bit error rate (BER) performance enhancement over conventional MIMO-OFDM VLC with minor increment of implementation complexity. The second scheme requires prior knowledge of channel state information (CSI) so as to employ singular value decomposition (SVD) to decompose MIMO channels into orthogonal components, enabling joint bits and power loading of data subcarriers in all MIMO channels to achieve overall system optimization.

2. Principles

We consider a MIMO-OFDM VLC system with N_T transmitters and N_R receivers. After serial to parallel (S/P) conversion and mapping, the mapped complex signal in the frequency domain can be represented by $\boldsymbol{X} = [\boldsymbol{X_1}; \boldsymbol{X_2}; \ldots; \boldsymbol{X_{N_T}}]$, where $\boldsymbol{X_i} = [\boldsymbol{X_i}(1), \boldsymbol{X_i}(2), \ldots, \boldsymbol{X_i}(K)]$, $1 \le i \le N_T$; and K represents the number of modulated OFDM subcarriers.

For the system using individual OCT precoding, $\boldsymbol{X}_i$ in $\boldsymbol{X}$ are individually linearly pre-coded by a channel-independent matrix $\boldsymbol{F}$, i.e., $\boldsymbol{X}' = [\boldsymbol{F}\cdot\boldsymbol{X_1}; \boldsymbol{F}\cdot\boldsymbol{X_2}; \ldots; \boldsymbol{F}\cdot\boldsymbol{X_{N_T}}]$. The principle to construct the precoding matrix is the same as that of the OCT precoding for the single input and single output VLC system given in [5]. At the receivers, after MIMO equalization, the original transmitted signal streams can be recovered by multiplying the received signal by the inverse of $\boldsymbol{F}$ for each MIMO channel.

On the other hand, for the system with SVD-based adaptive loading, prior channel estimation is required to estimate the channel matrix $\boldsymbol{H}(k)$ at the k-th subcarrier, $1 \le k \le K$. With SVD, the channel matrix can be decomposed to $\boldsymbol{H}(k) = \boldsymbol{U}(k)\cdot\boldsymbol{D}(k)\cdot\boldsymbol{V}(k)^{*}$, where $(\cdot)^*$ denotes the conjugate transpose, $\boldsymbol{V}(k)$ is an $N_T \times N_T$ unitary matrix, $\boldsymbol{U}(k)$ is an $N_R \times N_R$ unitary matrix, and $\boldsymbol{D}(k)$ is an $N_R \times N_T$ diagonal matrix with nonnegative diagonal elements (singular values of matrix $\boldsymbol{H}$) λ_{mk}, where $m = 1, 2,\ldots, M$ and $M = min\ (N_T, N_R)$. In practical implementation, the signal $\boldsymbol{X}(k)$ at the transmitter are pre-coded by $\boldsymbol{V}(k)$. At the receiver, the received signals (in the frequency domain) are multiplied by $\boldsymbol{U}(k)^*$ to yield

$$\boldsymbol{U}(k)^*\cdot\boldsymbol{Y}(k) = \boldsymbol{U}(k)^*\cdot\left\{\boldsymbol{H}(k)\cdot\boldsymbol{V}(k)\cdot\boldsymbol{X}(k)+\boldsymbol{N}(k)\right\} = \boldsymbol{D}(k)\cdot\boldsymbol{X}(k)+\boldsymbol{U}(k)^*\cdot\boldsymbol{N}(k), \tag{1}$$

where $\boldsymbol{N}(k)$ represents the noise at the k-th subcarrier. Note that K data subcarriers in each OFDM signal are also orthogonal, therefore, the MIMO VLC are decomposed into $M \times K$ orthogonal components with equivalent gains as $\boldsymbol{G} = [\lambda_{11}, \ldots, \lambda_{1K}; \lambda_{21}, \ldots, \lambda_{2K}; \ldots; \lambda_{M1}, \ldots, \lambda_{MK}]$. By utilizing the equivalent channel information, joint inter-and intra-channel bits and power allocation for the MIMO-OFDM based VLC system can be realized. It is important to note that the precoding and decoding processes of both the individual OCT precoding and the SVD-based adaptive loading do not affect the signal/noise power since the precoding or decoding matrices are unitary matrices.

3. Experimental setup and results

Fig. 1 shows the block diagram of the 2 × 2 MIMO-OFDM based VLC system using individual OCT precoding or the SVD-based adaptive loading. At the transmitter, after OCT or SVD precoding, data subcarriers of each MIMO channel were extended under Hermitian symmetry to generate real-valued time-domain signals at the output of the inverse fast Fourier transform (IFFT). Then, parallel-to-serial (P/S) conversion and cyclic prefix (CP) insertion were performed. The resulting signals were fed into an arbitrary waveform generator (AWG). The two outputs of AWG were firstly amplified by two electrical amplifiers (EAs), and then were used to drive two green lasers (Osram PL520). The laser beam divergence was $\theta_{\parallel} \times \theta_{\perp}$ = 7 deg × 22 deg, and the total output power was 50 mW. Two bi-convex lenses were fixed in front of the lasers, respectively, to enhance the light intensity at the receivers. After about 1-m transmission, the signals were detected by two PIN photodiodes (Hamamatsu S10784). The detected signals were amplified by trans-impedance amplifiers (TIA) and then recorded by two channels of a real-time digital phosphor oscilloscope (DPO) for further offline signal processing. In the experiments, the block size of FFT was 256, and 127 of them were modulated with data in each OFDM symbol. The distance between the two TXs/RXs was 14 cm. As shown in Fig. 1, the offset between the centers of TXs and RXs was 3 cm to ensure that the channel matrix was of full rank. The bias voltages for laser 1 and laser 2 were optimized to 6.8V and 7.0V, and the corresponding amplification gains of EAs were optimized to 12 dB and 15 dB, respectively.

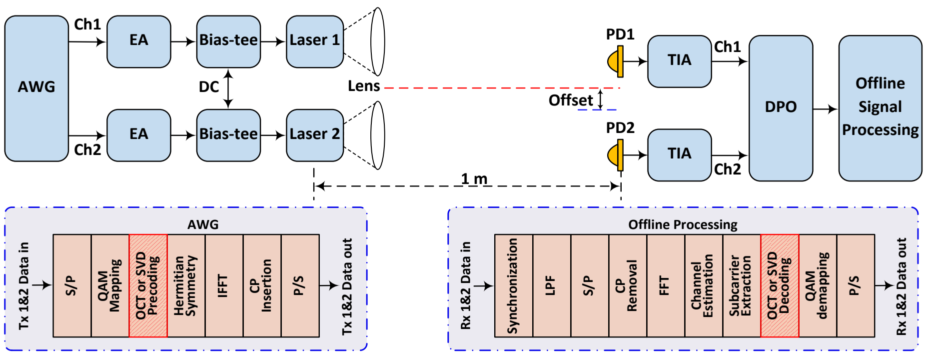

Fig. 1. Block diagram of the 2 × 2 MIMO-OFDM based VLC system.

We first investigate the BER and signal-to-noise ratio (SNR) performance of the conventional MIMO VLC system using 8QAM-OFDM. The CP length is 1/16 of one OFDM symbol and the sampling rate of AWG is 400 MS/s, i.e., the aggregate capacity of the system is 1.2 Gbit/s. Fig. 2 shows SNR profiles together with the signal constellations at the receivers (Rx1 and Rx2). The corresponding BER performance of Rx1 and Rx2 are 1.1×10^{-3} and 1.5×10^{-3}, respectively. Rx1 exhibits better BER performance because of higher received signal intensity.

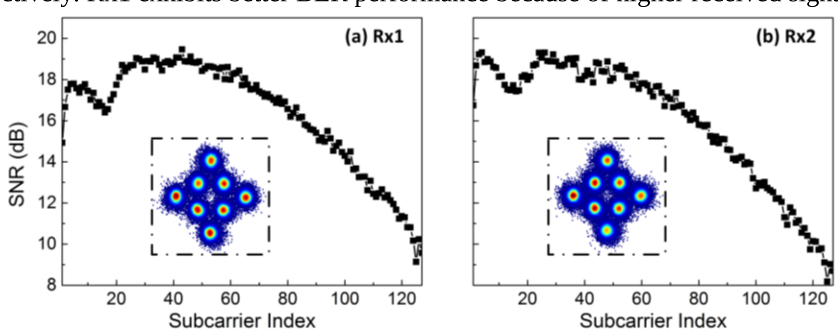

Fig. 2. SNR performance and the corresponding signal constellations of the conventional MIMO-OFDM VLC system: (a) Rx1 and (b) Rx2.

To combat the high-frequency roll-off shown in Fig. 2, we propose and investigate the individual OCT precoding scheme and the SVD-based adaptive loading scheme to enhance the BER performance. With the same CP length and aggregate data rate, the comparison of SNR profiles using the three schemes is depicted in Fig. 3. For 1.2-Gbit/s transmission, with the help of individual OCT precoding, the average BER performance of the MIMO-OFDM based VLC system can be improved from 1.3×10^{-3} to 6.6×10^{-5}. By utilizing the SVD-based adaptive loading, the average BER performance can be further enhanced to 3.0×10^{-5}.

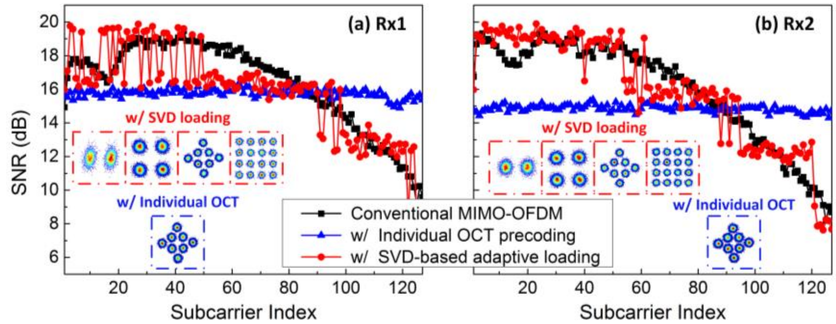

Fig. 3. SNR comparison and the corresponding signal constellations of the VLC system with conventional MIMO-OFDM, individual OCT precoding and SVD-based adaptive loading: (a) Rx1 and (b) Rx2.

Due to differential channel delays at receivers and the bandwidth limitation induced inter-symbol interference, the length of CP for the OFDM symbols would affect the performance of the MIMO VLC system. Hence, we compare the average BER performance of the system using the three schemes when the length of CP varies from 1/128 to 1/8 of one OFDM symbol. As shown in Fig. 4(a), increasing the length of CP can help enhance the average BER performance of the system, at the expense of reduced spectral efficiency. Generally, a CP length larger than 1/16 of one OFDM symbol is sufficient to achieve relatively good average BER performance.

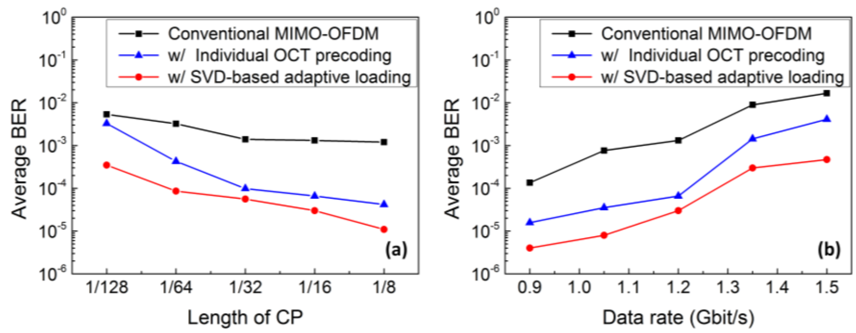

Fig. 4. Average BER performance of the MIMO-OFDM VLC system versus: (a) different length of CP and (b) different aggregate data rate.

In order to further investigate the performance enhancement of the individual OCT precoding and the SVD-based adaptive loading, we conduct experiments using the three schemes with different data rate when the length of CP is 1/16 of one OFDM symbol, and the results are shown in Fig. 4(b). For all the data rates, the BER performance of the individual OCT precoding and the SVD-based adaptive loading significantly outperform that of the conventional MIMO-OFDM scheme, confirming the performance benefits of the two proposed schemes. As shown in Fig. 4(b), for the 1.5-Gbit/s transmission, the average BER can be reduced from 1.7×10^{-2} to 4.1×10^{-3} and 4.7×10^{-4}, respectively. Furthermore, it can be seen that the SVD-based adaptive loading scheme exhibits better BER performance than the individual OCT precoding scheme since the bits and power can be jointly optimized in all subcarriers of all equivalent channels. However, the SVD-based adaptive loading scheme requires prior knowledge of CSI at the transceivers. In contrast, the individual OCT precoding is both signal and channel independent, and thus is more favorable for the application scenarios with time-varying channels.

4. Conclusion

We have experimentally demonstrated individual OCT precoding and SVD-based adaptive loading for a 2×2 MIMO-OFDM VLC system. The former offers significant performance improvement over conventional MIMO-OFDM without prior knowledge of CSI. The later requires CSI at transceivers but achieves overall system optimization. For 1.5-Gbit/s transmission, the BER can be reduced from 1.7×10^{-2} to 4.1×10^{-3} and 4.7×10^{-4} using these two schemes, respectively. This work was supported in part by HKSAR RGC grant (GRF 14204015) and Science Foundation Ireland 15/CDA/3652.

5. References

[1] A. Jovicic, J. Li, and T. Richardson, *IEEE Commun. Mag.*, **51**(12), 26-32 (2013).
[2] Y. Hong, T. Wu and L. K. Chen, *IEEE Photon. Technol. Lett.*, **28**(8), 907-910 (2016).
[3] A. H. Azhar, T. Tran, and D. O'Brien, *IEEE Photon. Technol. Lett.*, **25**(2), 171-174 (2013).
[4] Y. Wang and N. Chi, *J. Lightw. Technol.*, **32**(11), 2087-2093 (2014).
[5] Y. Hong, X. Guan, L. K. Chen and J. Zhao, in *Proc. of OFC*, paper M3A.6 (2016).