Experimental Demonstration of an OCT-based Precoding Scheme for Visible Light Communications

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Abstract: We propose an orthogonal circulant matrix transform (OCT) based precoding scheme for VLC and experimentally demonstrate 400-Mb/s transmission over 1-m. The scheme outperforms conventional DFT-precoding and exhibits significantly reduced complexity than the adaptive loading scheme.
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1. Introduction

Visible light communication (VLC) is emerging as an alternative solution for the conventional radio frequency communication because of its advantages such as free license and enhanced physical security. However, it is challenging to achieve high data rate transmission for VLC systems because of the limited modulation bandwidth of LED, typically several megahertz [1-2]. RGB type LED has been widely used in recent works to improve the overall capacity of VLC systems since the three color LED chips can be used to enable wavelength division multiplexing (WDM) [3]. Besides, techniques like using multiple resonant circuits for pre-distortion [1] or for post-equalization [2] are also proposed to enhance the achievable 3-dB modulation bandwidth. Furthermore, the spectrally efficient techniques such as discrete multi-tone modulation (DMT) with bit and power loading can be used to boost the capacity of bandwidth-limited VLC systems [3]. However, precise channel state information (CSI) is needed for the electrical circuit-based equalization schemes in order to determine the parameters in the equalizer circuit design. The adaptive bit and power loading scheme, despite its optimum system performance, also requires accurate CSI at the transmitter, meaning that an additional reliable uplink is required.

In this paper, we propose and experimentally demonstrate a channel independent orthogonal circulant matrix transform (OCT) based precoding scheme for the VLC systems. An orthogonal circulant matrix and its inverse matrix are used to pre-code and de-code the data at the transmitter and receiver, respectively. We show that a BER of 3.75×10^{-4} can be achieved for 400 Mbit/s transmission over 1-m distance by utilizing the proposed scheme. The BER performance outperforms that of conventional discrete Fourier transform (DFT) precoding scheme [4] and is comparable with that of the adaptive bit and power loading scheme [5]. Furthermore, the proposed scheme offers reduced implementation complexity and cost, and thus is more favorable for practical VLC systems.

2. Principles

Before performing Hermitian symmetry, OCT precoding is applied, i.e., the mapped signal [X_1, X_2, …, X_N] is multiplied by an orthogonal circulant matrix given by $\boldsymbol{F}=(1/\sqrt{N})\times[c_1,c_2,\ \ldots,c_N;c_N,c_1,\ \ldots,c_{N-1};\ \ldots;c_2,c_3,\ \ldots,c_1]$, where each entry c_i ($1 \le i \le N$) of $\boldsymbol{F}$ is the corresponding element of the Zadoff-Chu (ZC) sequence [6] with sequence index of 1 and length of N. ZC sequence is utilized in this paper 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. At the receiver, the original transmitted signal can be recovered by multiplying the received signal after data subcarrier extraction by the inverse of $\boldsymbol{F}$. In this paper, to investigate the performances of the proposed scheme, we compare it with another similar approach known as DFT precoding or single carrier frequency division multiple access (SC-FDMA), which is specified for the uplink of 3GPP-LTE standard for next-generation cellular wireless systems [4].

3. Experimental setup

Fig.1 shows the block diagram of the OCT-based VLC system. At the transmitter, after serial-to-parallel (S/P) conversion and quadrature amplitude modulation (QAM) mapping, the signal is multiplied by the orthogonal circulant matrix $\boldsymbol{F}$ given in Section 2. In order to obtain the real-valued OFDM signal, 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, cyclic prefix (CP) insertion, and pilot insertion are performed. Subsequently, the generated signal is feed into an arbitrary waveform generator (AWG). After amplified by a tunable electrical amplifier (EA), the resulting signal coupled with the DC signal by the bias-tee is then applied to a white LED (OSRAM LUW W5AM). A bi-convex lens is fixed in front of the LED for collimating the light at the transmitter.

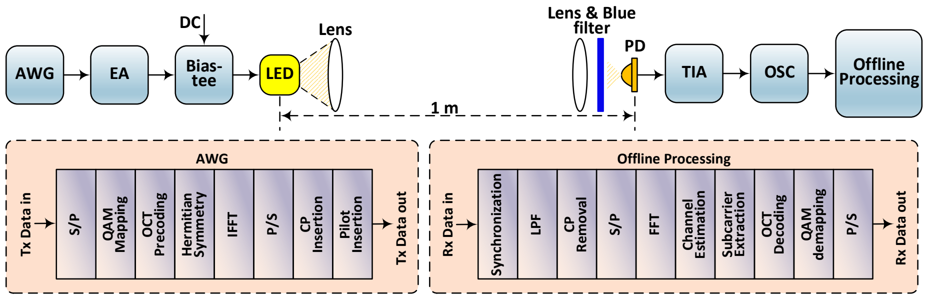

Fig. 1. Block diagram of the OCT-based VLC system. (DC: direct current; LPF: low pass filter; PD: photodiode)

After 1-m free space transmission, the same lens is utilized to focus the visible light at the receiver. A blue filter is mounted in front of the PIN photodiode (HAMAMATU S10784) to suppress the phosphorescent component of the incident light. The detected current signal is amplified by a transimpedance amplifier (TIA) circuit and then recorded by a real-time oscilloscope for further offline processing.

The block FFT size is 256, the CP length is 1/32 of the OFDM symbol length, and the sampling rates of the AWG and the OSC are 200 MS/s and 500 MS/s, respectively. The OFDM signal consists of 127 data subcarriers with a net electrical bandwidth of 99.23 MHz. In this paper, the data rate is varied from 198.44 Mb/s to 396.88 Mb/s by adopting different order QAM formats. The experiments are conducted under normal illumination (~400 lux).

4. Experimental results

We first investigate the influence of different levels of bias voltage and driving signal intensity to the VLC system without precoding, with DFT precoding and with the proposed OCT precoding, respectively. The BER performances versus bias voltages at ~200 Mb/s are shown in Fig. 2(a). According to the result, the optimal bias voltage for the LED is 2.9 V. When the RMS voltage of driving signal is 100 mV, the BER performances of the system without precoding, with DFT precoding and with the proposed OCT precoding are 5.91×10^{-5}, 6.30×10^{-6}, and lower than 10^{-6}, respectively. With the optimum bias voltage, we change the RMS voltage of driving signal to find the optimum driving signal intensity. Fig. 2(b) shows the BER performances versus RMS of driving signal. The optimum RMS voltage of driving signal is 300 mV, where the minimum SNRs for the three schemes are 10.54 dB, 12.10 dB and 16.67 dB, respectively, and the BERs are all lower than 10^{-6}, as shown in the insets of Fig. 2(b). It is seen that the performance of DFT precoding outperforms that of the system without precoding. The best BER performance is achieved by the proposed OCT precoding scheme. The optimum RMS voltage lies in the medium level because a lower driving signal will result in a lower signal to noise ratio (SNR) while a larger driving signal will suffer from transmitter nonlinearity.

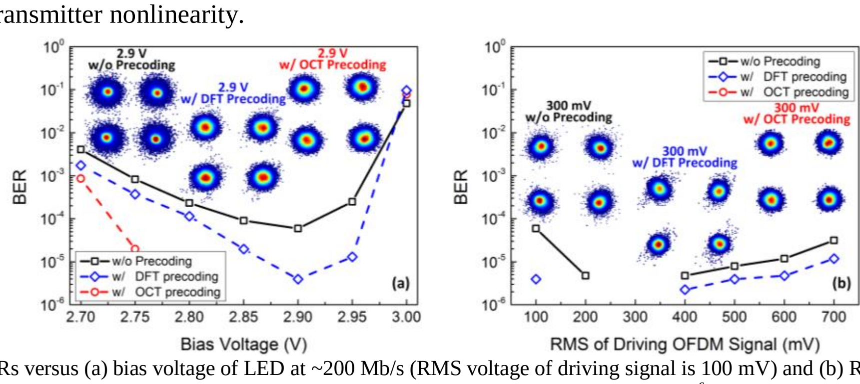

Fig. 2. Measured BERs versus (a) bias voltage of LED at ~200 Mb/s (RMS voltage of driving signal is 100 mV) and (b) RMS voltage of driving signal (bias voltage is 2.9V). Note that the measured BER of OCT precoding scheme is below 10^{-6}, and thus is not shown in Fig. 2(b).

We further investigate performances of the VLC system for the three schemes at data rates of ~300 Mb/s (8-QAM) and ~400 Mb/s (16-QAM), and the results are shown in Fig. 3. It is seen that when the data rate is around 300 Mb/s, the BER performances of the system without precoding, with DFT precoding and with the proposed OCT precoding are 1.28×10^{-4}, 1.10×10^{-4}, and lower than 10^{-6}, respectively. When the data rate is increased to ~400 Mb/s, the BER performances are 1.93×10^{-3}, 6.57×10^{-4}, and 3.75×10^{-4}, respectively, confirming the performance benefits of the proposed scheme.

We then compare the proposed scheme with the adaptive bit and power loading scheme at the same total data rates. The bits and power are allocated to each subcarrier according to the corresponding SNR obtained by channel estimation. Fig. 4 shows the SNR of each data subcarrier, which is estimated by error vector magnitude (EVM) of the received signal. The corresponding signal constellation diagrams are also shown in Fig. 4. With the adaptive loading scheme, a BER lower than 10^{-6} can be realized for 300-Mb/s transmission, as shown in Fig. 4(a), and a BER of 2.57×10^{-4} is achieved for 400 Mb/s transmission, as shown in Fig. 4(b).

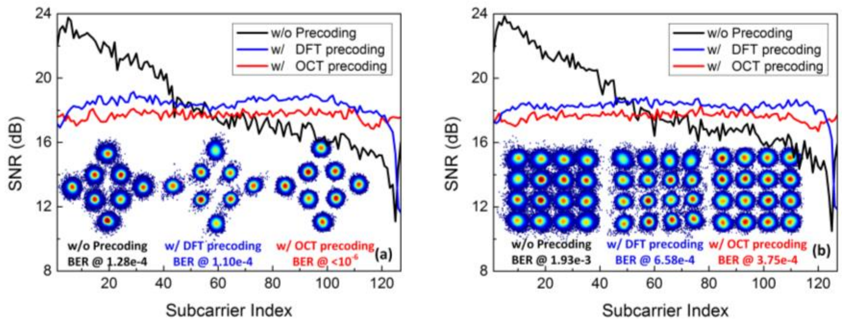

Fig. 3. Estimated SNRs and corresponding signal constellation diagrams for the system without precoding, with DFT precoding and with OCT precoding when data rate is: (a) 300 Mb/s; (b) 400 Mb/s

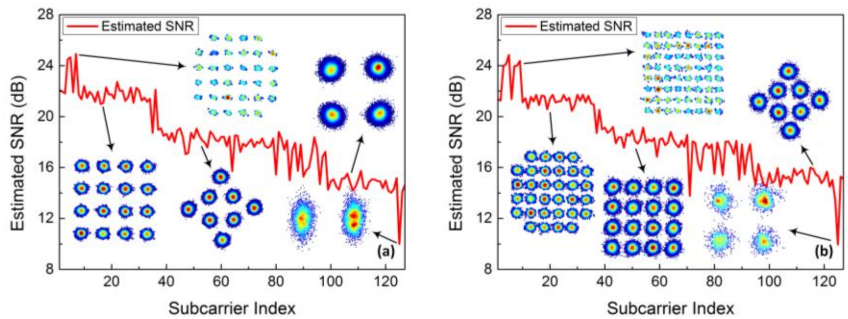

Fig. 4. Estimated SNRs and corresponding signal constellation diagrams for adaptive loading when data rate is: (a) 300 Mb/s; (b) 400 Mb/s

The detailed comparison of BER performances and additional requirements that will affect the complexity of the schemes is listed in Table 1. It is clear that the proposed OCT-based precoding scheme has comparable performance with the adaptive bit and power loading scheme, while significantly reducing the implementation complexity. This makes the proposed scheme more desirable for practical VLC applications.

Table 1. BER and implementation complexity comparison

Scheme	BER		Additional requirements
	300 Mb/s	400Mb/s	
w/o Precoding and adaptive loading	1.28×10^{-4}	1.93×10^{-3}	Nil
w/ DFT precoding	1.10×10^{-4}	6.57×10^{-4}	I
w/ OCT precoding	lower than 10^{-6}	3.75×10^{-4}	I
w/ Adaptive loading	lower than 10^{-6}	2.57×10^{-4}	II, III, IV, V

Note: I: Two linear transformations; II: Support for multiple modulation formats; III: Knowledge of real-time channel state information at transmitter; IV: Knowledge of real-time information of allocation results at receiver; V: Additional uplink

5. Conclusion

We have proposed a channel independent OCT-based precoding scheme, and experimentally shown that the performance of the proposed scheme outperforms that of conventional DFT precoding scheme and is comparable to that of the optimal adaptive bit and power loading scheme. By utilizing the proposed scheme, a BER of 3.75×10^{-4} can be achieved for ~400 Mbit/s-transmission over 1-m distance. The proposed scheme also offers reduced implementation complexity and cost, and thus is more favorable for practical VLC systems. This work was supported by HKSAR RGC grant (GRF 14200914) and Science Foundation Ireland grant 11/SIRG/I2124.

6. References

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