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Experimental investigation of multi-band OCT precoding for OFDM-based visible light communications

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Abstract: In this paper, we propose and experimentally demonstrate a channel-independent multi-band orthogonal circulant matrix transform (MB-OCT) precoding, to efficiently combat the severe frequency-selective fading of visible light communications (VLC). The proposed MB-OCT precoding exhibits an attractive ladder-like signal-to-noise-ratio (SNR) profile, thus can significantly reduce system BER by applying different quadrature amplitude modulation (QAM) level to different sub-bands. The impacts of sub-band number, signal bandwidth, and length of cyclic prefix (CP) on bit error rate (BER) of the VLC system are investigated. We experimentally compare BER performance of the proposed MB-OCT precoding with that of the conventional MB discrete Fourier transform (MB-DFT) precoding and the adaptive-loaded discrete multitone (DMT). The results show that the MB-OCT precoding outperforms the MB-DFT precoding and the single-band case for different data rates. Furthermore, it exhibits reduced implementation complexity and comparable BER performance with the adaptive-loaded DMT. For ~700-Mb/s VLC system with 2-m transmission distance, the BER is reduced from 1.53×10^{-2} to 1.17×10^{-4} by using the proposed MB-OCT precoding.

OCIS codes: (060.2605) Free-space optical communication; (060.4510) Optical communications.

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1. Introduction

Visible light communication (VLC), a promising solution for future high-speed wireless access, has attracted increasing interests from both academia and industry in recent years [1, 2]. By modulating light-emitting diodes or laser diodes that are widely deployed, potential ubiquitous and seamless connectivity can be facilitated for users in various environments, including cubicle offices, shopping malls, and future smart homes [2]. Currently, the key issue that limits the achievable capacity of VLC systems is the severe low-pass-like fading, induced by the limited bandwidth of the overall system [3]. To avoid the fading of the VLC system, a multi-band orthogonal frequency division multiplexing (OFDM) scheme was proposed by applying different bands of the OFDM signal to different light transmitters [4]. For the single light transmitter scenarios, to combat the bandwidth limitation of VLC systems, most of the prior works focus on digital/analog equalization to achieve relatively uniform spectrum over the signal bandwidth. By compensating the high-frequency band, system bit error rate (BER) can be reduced. Based on electronic circuits or digital processing, both pre-emphasis [5] and post-equalization [6] schemes have been proposed and experimentally demonstrated for VLC. Generally, these electrical circuits or digital equalization approaches are based on precise prior knowledge of channel state information (CSI) of the overall VLC system, and need to adjust the corresponding parameters when the system configuration is changed. In addition to equalizing the spectrum/signal-to-noise-ratio (SNR) to a uniform level, it is also possible to use discrete multi-tone (DMT) with adaptive bit and power loading [7] for VLC to boost the system capacity. Based on the prior estimated SNR condition, bits and power are allocated to subcarriers accordingly, such that a ladder-like spectrum/SNR is achieved [7,8].

However, the equalization schemes and the adaptive-loaded DMT are all channel-dependent and require precise prior knowledge of CSI, which considerably restricts their application for scenarios that have time-varying channel. For robust VLC implementation, channel-independent solutions are preferred, as the system can achieve reliable data transmission for diverse physical channel scenarios. We have proposed and experimentally demonstrated a channel-independent single-band orthogonal circulant matrix transform (OCT) precoding for both single-input single-output (SISO) [9] and multiple-input multiple-output (MIMO) VLC systems [10]. Results show that the proposed single-band OCT precoding scheme exhibits a uniform SNR profile, resulting in significantly reduced system BER. The robustness of the single-band OCT precoding in the system with time-varying channel has also been verified in a mobile VLC system in [11].

In this paper, we propose a bit-loaded multi-band OCT (MB-OCT) precoding for OFDM-based VLC. The impacts of sub-band number, signal bandwidth and length of cyclic prefix (CP) on the system BER and SNR performance are studied. The results show that the proposed MB-OCT precoding can offer an attractive ladder-like SNR profile. By applying different level of quadrature amplitude modulation (QAM) to the MB-OCT precoding, significant BER performance improvement can be achieved. We also experimentally compare BER performance of the proposed MB-OCT precoding with that of the conventional MB discrete Fourier transform (MB-DFT) precoding [12,13] and the adaptive-loaded DMT [7]. Experimental results show that the MB-OCT precoding outperforms the MB-DFT precoding and the single-band OCT precoding for different data rates. It offers reduced implementation complexity and comparable BER performance with the adaptive-loaded DMT. It is shown that for a 700-Mb/s transmission link at a distance of 2 m, the BER can be reduced from 1.53 × 10^{-2} to 3.58 × 10^{-3} with the help of single-band OCT precoding, and can be further reduced to 1.17 × 10^{-4} by utilizing the proposed MB-OCT precoding.

2. Principles and system setup

Figure 1 shows the block diagram of the MB-OCT precoding for OFDM-based systems. After serial to parallel (S/P) conversion and mapping, the mapped complex signal is allocated to K sub-bands, i.e., $\boldsymbol{S} = [\boldsymbol{S}_1, \boldsymbol{S}_2, \ldots, \boldsymbol{S}_K]^{\mathrm{T}} = [X_1, \ldots, X_m; X_{m+1}, \ldots, X_{2m}; \ldots; X_{(K\text{-}1)m+1}, \ldots, X_{Km}]^{\mathrm{T}}$, where $(\cdot)^{\mathrm{T}}$ denotes the transpose operation. The mapped signal of each sub-band is then pre-coded with an orthogonal circulant matrix $\boldsymbol{F}$, which can be expressed as

$$\boldsymbol{Z} = [\boldsymbol{Z}_1, \boldsymbol{Z}_2, \ldots, \boldsymbol{Z}_K]^{\mathrm{T}} = [\boldsymbol{F} \cdot \boldsymbol{S}_1^{\mathrm{T}}; \boldsymbol{F} \cdot \boldsymbol{S}_2^{\mathrm{T}}; \ldots; \boldsymbol{F} \cdot \boldsymbol{S}_K^{\mathrm{T}}], \tag{1}$$

where the precoding matrix $\boldsymbol{F} = \boldsymbol{circ}\{f_1, f_2, \ldots, f_m\}$ is a $m \times m$ circulant matrix. The entry f_l ($1 \leq l \leq m$) of the precoding matrix is the corresponding element of Zadoff-Chu sequence [14]. The detailed principles to construct the precoding matrix is given in [9]. It was demonstrated that with the single-band OCT precoding, the equivalent channel gains of all subcarriers approximately equal to the average of the original channel gains, resulting in a uniform channel gain/SNR profile over the signal bandwidth that alleviates significant BER degradation at high frequency carriers. In this work, as given in Eq. (1), the matrix $\boldsymbol{F}$ is used to precode multiple frequency bands over the OFDM signal bandwidth, such that a ladder-like SNR profile is obtained for the multi-band case, i.e., the SNR condition within each sub-band is equalized by using the advantage offered by the OCT precoding. For an MB-OCT precoded OFDM signal with K sub-bands, the number of modulated data subcarrier for each sub-band is m, thus the total number of modulated subcarrier equals to $K \cdot m$. To ensure a real-value time-domain OFDM signal, Hermitian symmetry operation is applied before implementing inverse fast Fourier transform (IFFT). The rest of the DSP at transmitter are the same as the conventional OFDM scheme. To evaluate the performance of the MB-OCT precoding, experimental comparisons among the proposed MB-OCT precoding, the conventional MB-DFT, and the adaptive-loaded DMT, are also conducted in the following.

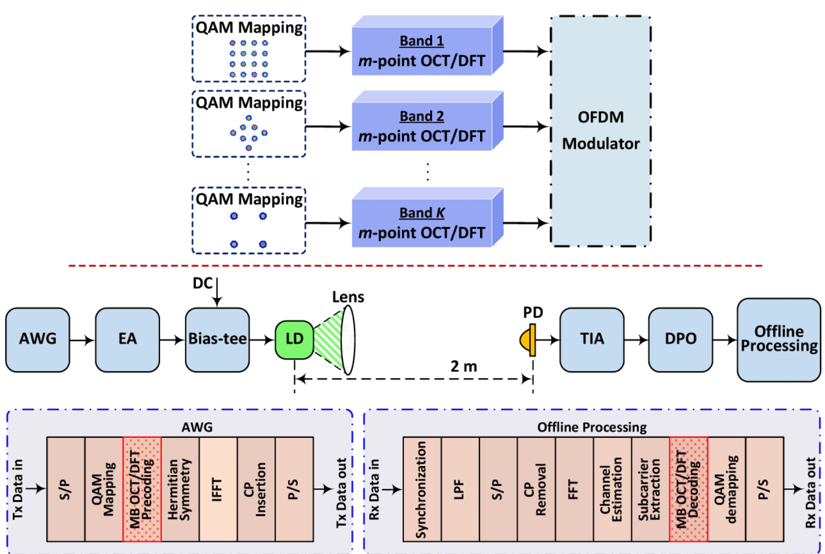

Fig. 1. Illustration of the MB-OCT/DFT precoding (upper) and block diagrams of OFDM-based VLC system using MB-OCT/DFT precoding (lower).

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The experimental setup of the MB-OCT precoding based VLC system and the corresponding digital signal processing (DSP) are shown in Fig. 1. After offline signal processing at the transmitter, the generated signal was feed into an arbitrary waveform generator (AWG) to generate the analog OFDM signal. Subsequently, the output signal was amplified by an electrical amplifier (EA). The resulting signal coupled with a DC bias via a bias-tee was then used to drive a single green laser diode (LD, Osram PL520). The laser's modulation bandwidth is roughly larger than 100 MHz, as stated in the datasheet. A bi-convex lens was fixed in front of the laser for collimating the light. After 2-m free space transmission, the light was detected by a receiver module, which consists of a PIN photodiode (Hamamatsu S10784) and a trans-impedance amplifier (TIA) circuit. The output of the receiver module was then recorded by a digital phosphor oscilloscope (DPO) for offline DSP. Symmetrically, after data subcarrier extraction, MB-OCT decoding was performed for signal reconstruction, i.e., the extracted signal at each sub-band was multiplied by the inverse matrix of $\boldsymbol{F}$, to recover the original transmitted signal.

In the experiments, the block size of IFFT/FFT was 256. Each OFDM symbol carries 120 (out of 256) data-modulated subcarriers, and these data subcarriers were allocated to K sub-bands, $K = \{1, 2, 3, 4\}$. The bias voltage and amplification gain for the laser diode were optimized to be 6.7 V and 9 dB, respectively. The sampling rate of AWG varied from 300 MS/s to 500 MS/s, to emulate the different OFDM signal bandwidths (equals to around half of the AWG sampling rate). The detected signal were recorded by a DPO at a sampling rate of 1.25 GS/s. For the system without precoding or with single-band OCT/DFT precoding, all the OFDM data subcarriers were modulated with 8QAM signal. Considering the low-pass property of the VLC system response, bit allocations for the MB scenarios just follow a decreasing trend for different sub-bands. Hence, to ensure the same data rate, 16QAM and 4QAM formats were used for the 2-band case, 16QAM, 8QAM and 4QAM formats were used for the 3-band case, and 16QAM, 16QAM, 8QAM and 2QAM formats were used for the 4-band case, respectively.

3. Experimental results

We first investigate the BER performance improvement of the VLC system under different AWG sampling rates using the proposed bit-loaded MB-OCT precoding. The conventional MB-DFT precoding is also implemented for performance comparison.

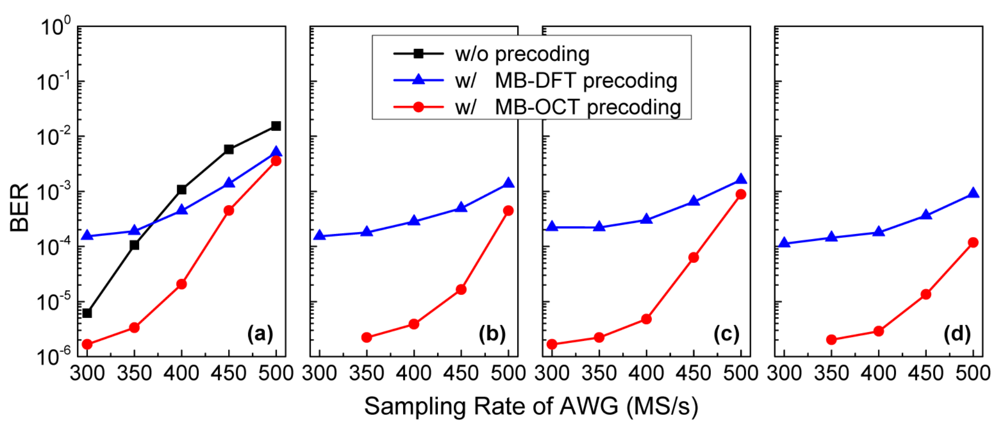

Fig. 2. BER of the system without precoding, with MB-DFT precoding and with MB-OCT precoding versus sampling rate of AWG: (a) 1-band, (b) 2-band, (c) 3-band and (d) 4-band. The length of CP equals to 1/32 of one OFDM symbol.

Figure 2 shows the BER comparison of system (i) without precoding, (ii) with MB-DFT precoding and (iii) with the proposed MB-OCT precoding, for different number of sub-bands.

It is seen that for the larger sampling rate cases, the MB-DFT precoding provides enhanced BER performance compared to the system without precoding. For all cases, the proposed MB-OCT precoding further reduces the system BER. Consequently, significant BER performance improvement is achieved by using the MB-OCT precoding for the VLC system. Besides, for both MB-DFT precoding and MB-OCT precoding, the bit-loaded multi-band cases exhibit lower BER than the single-band case [9]. The best BER performance is achieved by the four-band OCT precoding. For 500-MS/s, i.e., the net data rate is around 700 Mb/s, the system BER can be reduced from 1.53×10^{-2} to 5.07×10^{-3} and 3.58×10^{-3} by using single-band DFT precoding and single-band OCT precoding, respectively. The BER can be further reduced to 9.03×10^{-4} and 1.17×10^{-4} with the help of four-band DFT precoding and four-band OCT precoding, respectively.

The SNR profiles of the system without precoding, with MB-DFT precoding and with MB-OCT precoding, for the single-band case and the four-band case, are depicted in Fig. 3. Similar to the single-band case, the BER reduction offered by the MB-OCT precoding is attributed to its robustness to frequency-selective fading, resulting in the relatively uniform SNR profile. The difference is that the uniform SNR profile is achieved for each sub-band. Therefore, a ladder-like SNR profile is enabled. By applying different QAM level to different sub-bands, significant BER reduction is achieved. As depicted in Fig. 3, the MB-DFT precoding can also equalize the SNR profile at each sub-band. However, the DFT precoding suffers from significant SNR degradation in fringe subcarriers. This is because that the DFT precoding in essence is a block transmitted single-carrier-like scheme, where symbols at the edge of the blocks are more sensitive to the interference from adjacent blocks if the length of CP is insufficient. The inter-symbol interference (ISI) will result in significantly degraded SNR at fringe subcarriers, which imposes BER performance degradation for the DFT precoded system [15,16].

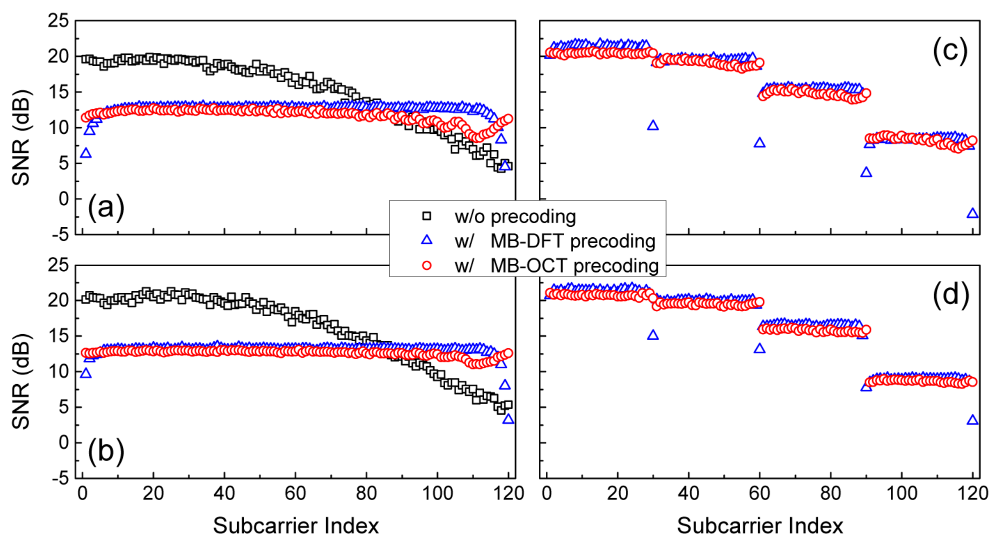

Fig. 3. SNR profiles of the system without precoding, with MB-DFT precoding and MB-OCT precoding when the AWG sampling rate is 500 MS/s: (a) single-band case with 1/64 CP length; (b) single-band case with 1/32 CP length; (c) four-band case with 1/64 CP length and (d) four-band case with 1/32 CP length.

Note that the edge effect of the MB-DFT precoding can be mitigated by using a longer length of CP. As shown in Fig. 3, when the length of CP is increased from 1/64 of one OFDM symbol to 1/32 of one OFDM symbol, the SNR dropping can be reduced, resulting in system BER performance enhancement. However, the spectral efficiency is sacrificed when using a longer length of CP, leading to system capacity reduction. To further investigate the influence

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of the CP length on the BER performance of the three schemes, we experimentally investigate BERs versus difference length of CP and the results are shown in Fig. 4. It is seen that for all cases, the BER is reduced with the increase in the length of CP, and the MB-OCT precoding always exhibit better performance than the MB-DFT precoding.

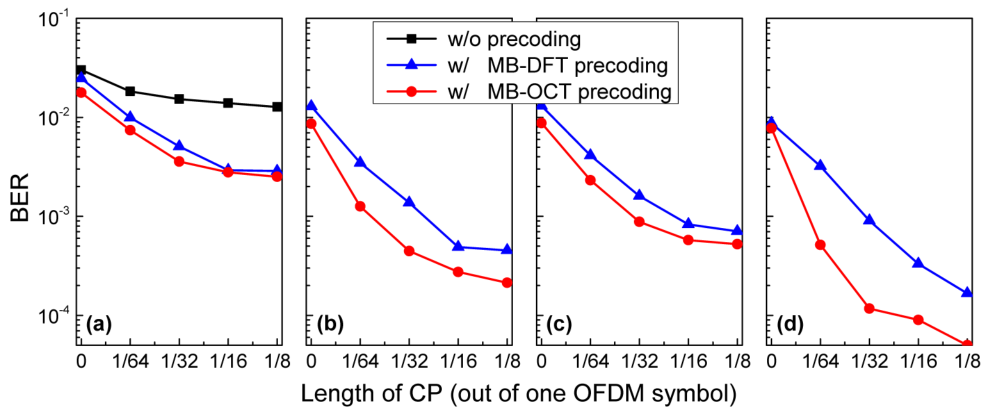

Fig. 4. BERs versus the length of CP for the system without precoding, with MB-DFT precoding and with MB-OCT precoding when the AWG sampling rate is 500 MS/s: (a) 1-band, (b) 2-band, (c) 3-band and (d) 4-band.

Finally, we compare the performance of the MB-OCT precoding with that of the adaptive-loaded DMT [7]. The main reasons that we include the comparison with the adaptively-loaded DMT are (1) the adaptively-loaded DMT is generally considered as the optimal scheme for the frequency-selective VLC systems since the resources can be optimally allocated to ensure a minimized BER; and (2) the adaptively-loaded DMT also exhibits a ladder-like SNR profile with the help of adaptive bit and power loading. The key idea of the adaptive-loaded DMT is to adaptively allocate bits and power to the data subcarriers according to the prior estimated CSI. It is generally considered as the optimal scheme for the frequency-selective VLC systems since the resources can be optimally allocated to ensure a minimized BER. Figure 5 shows the results of the adaptive-loaded DMT with 500-MS/s AWG sampling rate and 700-Mbit/s data rate.

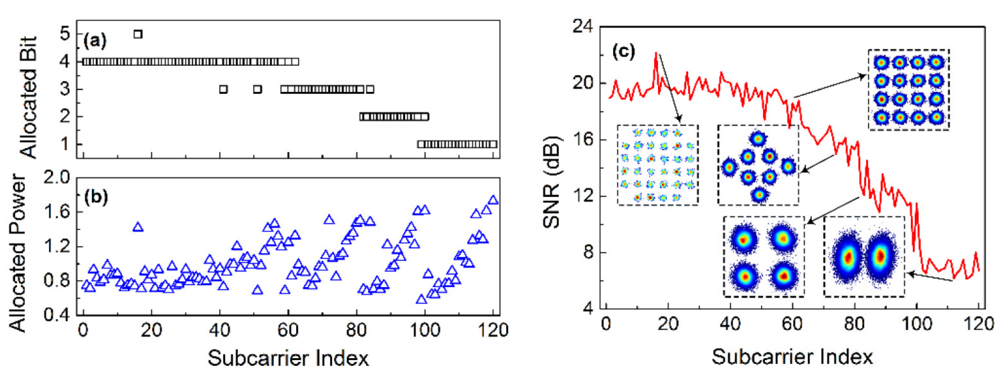

Fig. 5. Bits and power allocation results and the corresponding transmission performance with the adaptive-loaded DMT at a data rate of 700 Mbit/s: (a) bit allocation result; (b) power allocation result; (c) the estimated SNR profile after transmission. Insets: signal constellation of the corresponding QAM signals. The length of CP equals to 1/32 of one DMT symbol.

It is shown that with the adaptive bit and power loading, the bit distribution is proportional to the estimated CSI, i.e., less bits are allocated to the high frequencies because of lower SNR conditions. The power distribution exhibits a saw-tooth behavior, so as to maintain a similar

BER level for subcarriers with the same QAM order. However, the adaptive-loaded DMT requires (i) an additional uplink, (ii) prior knowledge of real-time CSI at the transmitter, and (iii) optimization for bits and power allocation. In contrast, the MB-OCT precoding only requires channel-independent linear transformations. To further evaluate the performance of the proposed MB-OCT precoding, we have also changed the sampling rate of AWG to investigate the BER of the proposed scheme under different system SNR conditions. The detailed BER comparison is given in Table 1. It is shown that for all the cases, similar BERs are achieved by the proposed MB-OCT precoding compared to that of the DMT. Note that the DMT is with the adaptive bit and power loading according to different SNR conditions in different AWG's sampling rate cases, whereas the MB-OCT's bit allocation remains unchanged for different scenarios. Therefore, considering the much lower implementation complexity, the MB-OCT precoding is more preferable for practical VLC systems with diverse channel conditions. The above comparison is for the system with static channel. For the system with time-varying channel, if real-time accurate CSI is available, the MB-OCT precoding may degrade more than the adaptively-loaded DMT. However, the performance of the adaptively-loaded DMT highly depends on the CSI estimation's accuracy and the dynamics of the time-varying channel. For time-varying channels, performance of the MB-OCT precoding can also be further improved by optimizing the bits allocation for different sub-bands according to the channel characteristics, and its complexity is still lower than that of the adaptively-loaded DMT.

Table 1. BER comparison of different schemes

Schemes \ Sampling Rate	300 MS/s	350 MS/s	400 MS/s	450 MS/s	500 MS/s
w/o Precoding	6.11×10^{-6}	1.06×10^{-4}	1.08×10^{-3}	5.78×10^{-3}	1.53×10^{-2}
w/ Four-band DFT	1.12×10^{-4}	1.44×10^{-4}	1.78×10^{-4}	3.61×10^{-4}	9.03×10^{-4}
w/ Four-band OCT	$< 1 \times 10^{-6}$	2.02×10^{-6}	2.89×10^{-6}	1.34×10^{-5}	1.17×10^{-4}
w/ Adaptive-loaded DMT	$< 1 \times 10^{-6}$	$< 1 \times 10^{-6}$	2.78×10^{-6}	1.17×10^{-5}	4.28×10^{-5}

4. Conclusions

In this paper, a bit-loaded MB-OCT precoding is proposed to combat the bandwidth limitation issue of VLC systems. While requiring no prior knowledge of CSI, the MB-OCT precoding offers a ladder-like SNR profile. Therefore, the proposed scheme can provide significantly reduced BER when applying different QAM level to different sub-bands. The results show that BER performance of the proposed MB-OCT precoding outperforms that of the conventional MB-DFT precoding and the single-band case. While reducing the implementation complexity, the MB-OCT precoding also offers similar BER performance with the adaptive-loaded DMT scheme, thus is more favorable for practical VLC implementations with diverse channel conditions. Experimental results show that for ~700-Mb/s at a distance of 2 m, system BER can be reduced from $\sim 10^{-2}$ to $\sim 10^{-4}$ with the bit-loaded MB-OCT precoding. Although demonstrated in the VLC system, the proposed scheme is applicable to other systems suffering from the frequency-selective fading, such as dual-sideband OFDM based direct-detection fiber systems.

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