CD-Aware OCT Precoding for C-Band 100-Gb/s IM/DD OFDM Transmission over 50-km SSMF

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Abstract: A CD-aware orthogonal-circulant-matrix-transform (OCT) precoding is proposed for C-band 100-Gb/s IM/DD-OFDM transmission over 50-km SSMF. The proposed scheme outperforms conventional schemes and improves the capacity by >20% (>12%) compared to CD-aware subcarrier loading (DFT precoding). © 2024 The Author(s)

1. Introduction

The continuous expansion of bandwidth-intensive services such as video streaming, artificial intelligence, and cloud computing has attracted significant attention in advancing high-speed inter-datacenter interconnects and metro/access networks [1, 2]. Intensity modulation/direct detection (IM/DD) based orthogonal frequency division multiplexing (OFDM) with quadrature amplitude modulation (QAM) is considered as a promising option for high-speed short-reach systems due to its high spectral efficiency (SE), flexible signal modulation, robustness against fiber chromatic dispersion (CD), and simple frequency-domain equalization (FDE) [3–5]. In an IM/DD OFDM system, the presence of CD induces frequency-selective power fading, resulting in spectral nulls and a non-flat frequency response. This CD-induced power fading is one of the dominant impairments that significantly degrades transmission performance, especially when employing long fiber distances and large signal bandwidths [3, 4]. To mitigate CD-induced power fading, a classical and widely studied approach is to employ adaptive bit and power loading technique in cost-effective IM/DD OFDM systems [3, 4]. However, an additional reverse link is required to realize precise feedback of channel state information (CSI), generally the signal-to-noise ratio (SNR), over all data-carrying subcarriers. Currently, channel-independent precoding techniques such as discrete Fourier transform (DFT) precoding and orthogonal circulant transform (OCT) precoding [5, 6] have been widely employed in IM/DD OFDM systems to equalize non-uniform SNR response. It has been observed that OCT precoding, which exhibits less sensitivity to inter-symbol interference (ISI), outperforms DFT precoding in bandwidth-limited IM/DD systems [6]. Nevertheless, to the best of our knowledge, these channel-independent precoding techniques have not yet been investigated in CD-constrained IM/DD systems experiencing severe CD-induced power fading.

In this paper, we propose and demonstrate a channel-independent CD-aware OCT precoding technique in a C-band 100-Gb/s IM/DD OFDM system over 50-km standard single-mode fiber (SSMF). Based on the theoretical frequency response of SSMF, an orthogonal circulant matrix is utilized for precoding the high-performance subcarriers at the transmitter, while its conjugate transpose is employed for decoding at the receiver. The experimental results validate that the proposed CD-aware OCT precoding scheme not only surpasses conventional OFDM, DFT precoding, and OCT precoding schemes in performance but also improves the capacity by more than 20% and 12%, respectively, compared to CD-aware subcarrier loading and CD-aware DFT precoding. These results highlight the potential of implementing CD-aware OCT precoding in high-speed optical IM/DD interconnects.

2. Principle of CD-aware OCT precoding

In an OCT-precoded OFDM transmitter, precoding is performed by multiplying the mapped QAM symbols, $\mathbf{x} = [x_1, x_2, \cdots, x_M]^T$, with an orthogonal circulant matrix, $\mathbf{P} = 1/\sqrt{M}[c_1, c_2, \cdots, c_M; c_M, c_1, \cdots, c_{M-1}; \cdots; c_2, c_3, \cdots, c_1]$, where $(\bullet)^T$ denotes the transpose operation and $c_m (1 \le m \le M)$ is the corresponding element of the Zadoff-Chu (ZC) sequence [5, 6] with a sequence index of 1 and a length of M. The OCT-precoded symbols can be expressed as $\mathbf{z} = [z_1, z_2, \cdots, z_M]^T = \mathbf{Px}$. Subsequently, subcarrier mapping (allocated to the 2$^{\text{nd}}$ – $(M+1)^{\text{th}}$ subcarriers) and Hermitian symmetry are applied before converting them into a real-valued OFDM symbol in the time domain using the N-point ($N \ge 2(M+1)$) inverse fast Fourier transform (IFFT). At the receiver, after data subcarrier extraction, the original transmitted symbols can be recovered by multiplying the received symbols over M data-carrying subcarriers with a matrix $\mathbf{P}^H$, where $(\bullet)^H$ denotes conjugate transpose. However, in the presence of severe CD-induced power fading in the transmission system, the precoding performance is degraded due to a significant number of spectral nulls within the signal bandwidth, rendering it ineffective. To address this limitation, here a CD-aware OCT precoding is proposed based on the normalized power response of the SSMF channel given by $P(f)=\cos^2(2\pi^2\beta_2 L f^2)$ [3, 4], where $\beta_2=-D\lambda^2/(2\pi c)$ is the group velocity dispersion (GVD) of SSMF, with λ, c, and D denoting the wavelength, speed of light, and dispersion coefficient, respectively. The CD-aware OCT precoding can be summarized as follows: 1) Initialize the number of active subcarriers M_1 $(M_1 < M)$ for precoding. 2) Calculate the power response $P(f_m)=P(mf_s/N)$ for each subcarrier, where f_s is the sampling rate. 3) Based on the pre-calculated power responses, only M_1 out of M subcarriers with higher power responses are utilized for OCT precoding and data transmission. By employing CD-aware OCT precoding, spectral nulls can be completely avoided during precoding, thereby significantly enhancing its performance. Note that the proposed CD-aware precoding scheme can be extended to other types of precoding approaches. In this paper, to evaluate the superior performance of the proposed scheme, we compare it with other schemes including conventional DFT precoding, OCT precoding, and CD-aware DFT precoding. Moreover, we also incorporate a CD-aware subcarrier loading scheme without precoding, which involves utilizing M_1 out of M subcarriers with higher power responses for data transmission.

3. Experimental setup and results

The performance of the proposed CD-aware OCT precoding scheme is evaluated in a C-band IM/DD OFDM transmission system as the experimental setup and DSP block diagram shown in Fig. 2. After QAM mapping and serial-to-parallel (S/P) conversion at the transmitter, the parallel symbols are multiplied by the orthogonal circulant matrix **P**. Subsequently, subcarrier mapping performed with effective payloads encoded at 2nd to 197th subcarriers. The real-valued OFDM signal is generated by employing a 512-point IFFT with a complex conjugate operation. After adding a 32-point cyclic prefix (CP), parallel-to-serial (P/S) conversion and hard clipping are carried out. The offline-generated signal is fed into an arbitrary waveform generator (AWG, Keysight M8194A) at 120-GSa/s. The electrical OFDM signal from the AWG is amplified by an electrical amplifier (EA, SHF M807) before driving a 32-GHz Mach-Zehnder modulator (MZM, Fujitsu FTM7938EZ) operating at the quadrature point. The optical carrier is generated by an external cavity laser (ECL) at a wavelength of 1550.12 nm. After 50-km SSMF transmission, an Erbium-doped fiber amplifier (EDFA) is utilized to boost the power up to 7 dBm. Finally, the optical signal is detected by a 70-GHz PD and captured by a real-time oscilloscope (OSC, Keysight UXR0804A) at 256 GSa/s. The offline DPS includes resampling to 120 GSa/s, S/P conversion, CP removal, FFT, data subcarrier extraction, one-tap FDE, OCT decoding, P/S conversion, QAM demapping, and bit error rates (BER) calculation. Except for one symbol dedicated to synchronization, each data frame consists of 900 OFDM symbols, in which the first 100 symbols are utilized for channel estimation while the remaining symbols serve as effective data symbols.

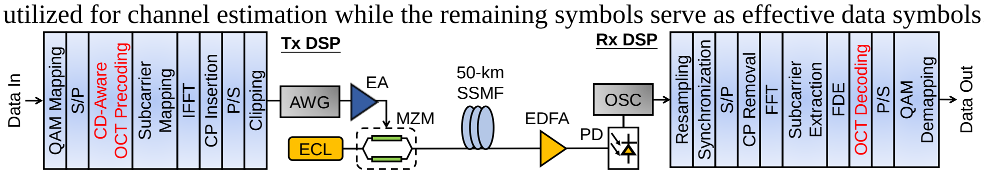

Fig. 1 Experimental setup and DSP block diagram.

We first investigate the frequency response characteristics of the SSMF channel, followed by a comparison of the SNR performance between conventional and proposed CD-aware precoding schemes. The frequency response of the back-to-back (BTB) system is presented in Fig. 2(a), showing that the overall system exhibits a -10-dB bandwidth of approximately 46 GHz, beyond which there is a sharp degradation. Consequently, we set a usable signal bandwidth of around 46 GHz in experiment. Fig. 2(b) illustrates the theoretical frequency response $P(f)$ calculated with D = 16.7 ps/ns/km as described in Section 2, along with the electrical spectrum of received OFDM signal after 50-km SSMF transmission. It can be observed that the received signal suffers from severe CD-induced power fading, which is consistent with the theoretical frequency response and validates the feasibility of the proposed CD-aware precoding scheme. Fig. 2(c) illustrates the subcarrier-SNR distributions of conventional OFDM and DFT/OCT-precoded OFDM signals after 50-km SSMF transmission at a received optical power (ROP) of 7 dBm. Due to severe CD-induced power fading, numerous dips in the subcarrier-SNR distribution degrade the performance of conventional OFDM. However, by implementing DFT or OCT precoding, subcarrier-SNR distribution can be equalized to a relatively flat level, albeit with all subcarrier-SNR values below 4 dB due to substantial noise introduced within SNR dips caused by CD. Constrained by CD-induced power fading over 50-km SSMF, the achievable BERs of conventional OFDM, DFT-precoded OFDM, and OCT-precoded OFDM signals with QPSK format are 4.24×10^{-2}, 1.85×10^{-1}, and 1.81×10^{-1} at 7-dBm ROP, respectively, much higher than 3.8×10^{-3} of 7% hard-decision forward error correction (HD-FEC) limit.

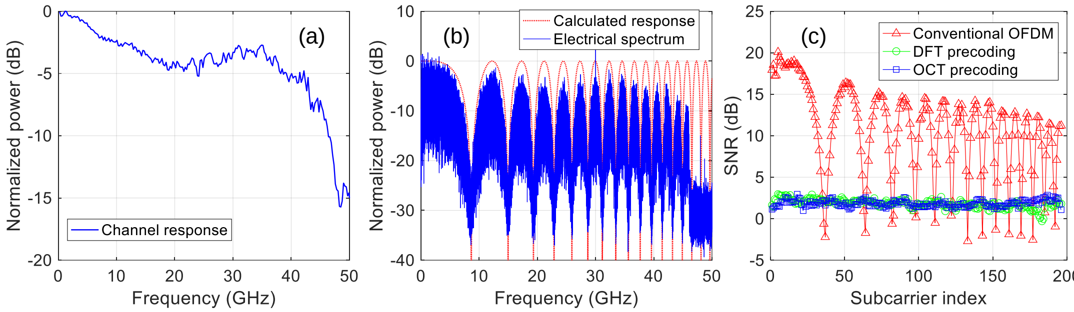

Fig. 2 (a) Normalized frequency response of the BTB system. (b) Calculated frequency response and electrical spectrum of received electrical OFDM signal after 50-km SSMF transmission. (c) Measured subcarrier-SNR distributions of 50-km SSMF system using conventional schemes.

By leveraging CD-aware subcarrier loading or precoding techniques, the transmission performance over 50-km SSMF can be significantly enhanced. The measured subcarrier-SNR distributions of the 50-km SSMF system employing CD-aware subcarrier loading and precoding schemes with 142 active subcarriers are illustrated in Fig. 3(a). It is evident that all data-subcarrier SNRs of the CD-aware subcarrier loading and precoding schemes exhibit improvements compared to conventional schemes depicted in Fig. 2(c). Moreover, when compared to CD-aware subcarrier loading and CD-aware DFT precoding, the proposed CD-aware OCT precoding demonstrates superior robustness against frequency-selective power fading, resulting in a more uniform subcarrier-SNR profile.

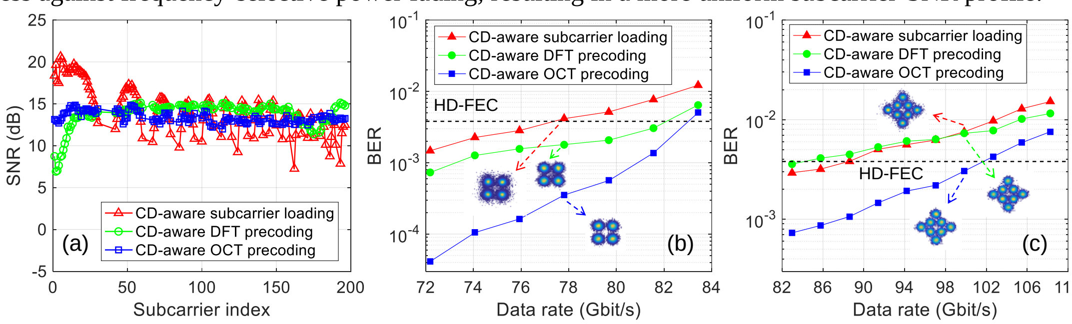

Fig. 3 (a) Measured subcarrier-SNR distributions of 50-km SSMF system using CD-aware subcarrier loading and precoding schemes. BER versus data rate using CD-aware OFDM signals with (b) QPSK and (c) 8QAM over 50-km SSMF at 7-dBm ROP.

Finally, we conduct a comparison of the transmission performance among different CD-aware schemes at varying data rates by adjusting the total number of active data subcarriers ranging from 154 to 178 and from 118 to 154 for QPSK and 8QAM, respectively. The BERs as a function of data rate over 50-km SSMF using CD-aware OFDM signals with QPSK and 8QAM are illustrated in Figs. 3(b) and 3(c), respectively. It can be seen that the BER can be reduced in QPSK transmission when switching form CD-aware subcarrier loading to CD-aware DFT precoding, but this improvement cannot be maintained for the case of 8QAM transmission. The reason is that 8QAM transmission exhibits higher sensitivity to SNR compared to QPSK transmission. Additionally, the DFT precoding experiences degradation in SNR on fringe subcarriers, as depicted in Fig. 3(a). Thanks to its relatively uniform subcarrier-SNR profile, the proposed CD-aware OCT precoding consistently outperforms the other two schemes regardless of modulation format and data rate, achieving more distinguishable recovered constellations as shown in the insets of Figs. 3(b) and 3(c). Compared with CD-aware subcarrier loading and CD-aware DFT precoding, the proposed CD-aware OCT precoding enables a data rate up to 100 Gb/s while improving transmission capacity by more than 20% and 12%, respectively, with the BER below the 7% HD-FEC limit of 3.8×10^{-3}. These results highlight the advantage of employing CD-aware OCT precoding for combating the CD-induced power fading.

4. Conclusion

We have proposed and experimentally demonstrated a CD-aware OCT precoding scheme for 100-Gb/s IM/DD OFDM transmission over 50-km SSMF in the C-band. The proposed scheme not only outperforms conventional OFDM and its conventional precoding schemes, but also improves the capacity by more than 20% and 12%, respectively, compared to CD-aware subcarrier loading and CD-aware DFT precoding.

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5. References

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