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# Set-Partitioned QAM Fast-OFDM with Real-Valued Orthogonal Circulant Matrix Transform Pre-Coding

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**Abstract:** We propose SP-QAM based Fast-OFDM with a novel real-valued OCT pre-coding scheme for IM/DD systems. For 19.76-Gbit/s 20-km transmission, the proposed scheme achieves 3.5-dB sensitivity improvement and higher filtering tolerance over conventional PAM Fast-OFDM. 
**OCIS codes:** (060.2330) Fiber optics communications; (060.4080) Modulation

## 1. Introduction

Recently, set-partitioned coded quadrature amplitude modulation (SP-QAM) formats were implemented in intensity modulation/direct detection (IM/DD) optical systems to achieve improved transmission performance [1, 2]. In view of lower computational complexity, fast orthogonal frequency division multiplexing (Fast-OFDM) is one of the promising technologies for IM/DD systems [3], because only real-valued operation is required in this scenario.

In this paper, we investigate SP-QAM based Fast-OFDM and validate its performance advantage over conventional PAM based Fast-OFDM for IM/DD systems. We propose a real-valued orthogonal circulant matrix transform (OCT) pre-coding scheme to mitigate the joint subcarrier-dependent error (JSDE). Experiments show the proposed scheme achieves a 3.5-dB performance improvement and a higher tolerance to narrow bandwidth optical filtering and fiber nonlinearity, compared to the conventional PAM-4 Fast OFDM at the same data rate.

## 2. Principles and experimental setup

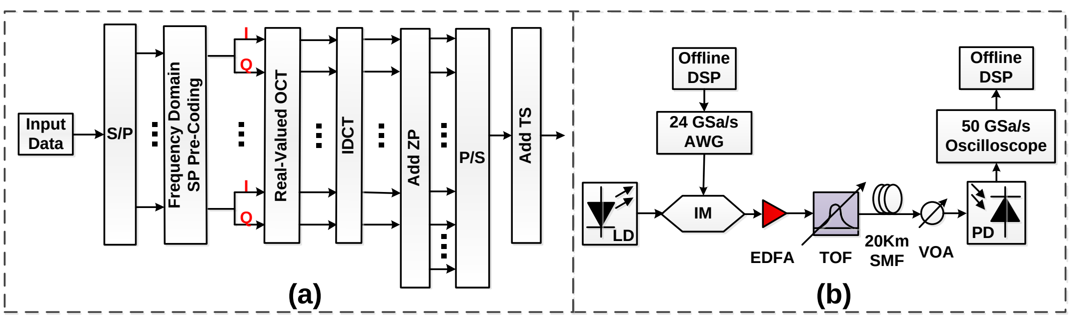


Fig. 1. (a) Block diagram of the proposed scheme; (b) Experimental setup.

As shown in Fig. 1 (a), since the inverse discrete cosine transform (IDCT) used in Fast-OFDM is a real-valued transform, each SP-128-QAM symbol, consisting of two jointly encoded 16-QAM symbols, is allocated to four subcarriers to implement the IM/DD optical system. To reduce the JSDE, which is induced by the differences in the signal-to-noise ratios (SNRs) of subcarriers, these four subcarriers should be adjacent in order to have similar SNR. It should be noted that this scheme is also applicable to time domain implementation but induces a larger latency as well as a higher sensitivity to synchronization errors. After the I/Q separation, a real-valued OCT is employed to further mitigate the JSDE, which was modified from our recent work [4].

Fig. 1 (b) illustrates the schematic diagram of the experiment. At the transmitter side, 32 SP-128QAM symbols were encoded and allocated to 128 subcarriers in Fast-OFDM. The point size of IDCT for subcarrier multiplexing was 256. PAM-4 based Fast-OFDM was also implemented for comparison. Because the spectrum efficiency of SP-128-QAM is only 7/8 of that of the conventional PAM4, only 128×7/8=112 subcarriers at the positive frequency were modulated with PAM4 symbols. The zero padding (ZP) was set to 1/16 of the length of a Fast-OFDM symbol to combat dispersion. After the digital signal processing (DSP), the signal was converted to an analog signal by using a 24-GSa/s arbitrary waveform generator (AWG). Hence, the net bit rates of both formats were about 19.76 Gb/s. Then, the signal was used to drive an optical intensity modulator (IM). Before launching into a 20-km single-mode fiber (SMF), an erbium-doped optical fiber amplifier (EDFA) and a tunable optical filter (TOF) were employed to vary the launched power and the optical bandwidth, respectively. At the receiver side, a variable optical attenuator (VOA) was used to emulate different received optical power (ROP) values. After detection by a photodiode (PD), the electrical signal was sampled by using a real-time oscilloscope at a sampling rate of 50 GSa/s for offline DSP.

## 3. Results and discussions

Fig. 2 depicts the experimental results. In this work, we have also investigated discrete cosine transform (DCT) pre-coding to illustrate the advantage of the proposed scheme. Fig. 2 (a) shows the back-to-back (B2B) BER of different schemes. It is seen that only using the SP-QAM formats can achieve 1.5 dB improvement at the KP4-FEC threshold of $2.2\times10^{-4}$. SP-QAM Fast-OFDM with OCT pre-coding further improves the performance significantly. Despite of its relatively higher peak to average power ratio (PAPR), OCT pre-coding outperforms DCT pre-coding when ROP is above -6 dBm. From Fig. 2(b), the improvements of both SP and DCT pre-coding markedly reduce after 20-km SMF transmission. This can be attributed to its increased JSDE as shown in Fig. 2(c), where the SP-128-QAM without pre-coding and with DCT pre-coding show a large fluctuation of SNR distribution over subcarriers. On the other hand, around 3.5-dB sensitivity improvement can be achieved over the conventional PAM4 at KP4-FEC limit by employing the proposed scheme. It is because a relatively small fluctuation within 2 dB can still be achieved in this case (see Fig. 2 (c)), resulting in significant reduction in JSDE and restoration of the performance improvement with SP-QAM encoding. Figs. 2 (d) and (e) show the BER versus optical bandwidth for the cases of B2B and after 20-km SMF transmission, respectively. We can observe that the proposed scheme has the best performance in the bandwidth-limited region compared to the other schemes. Finally, we have also investigated the fiber nonlinear tolerance as depicted in Fig. 2 (f). Due to the improvement from a relatively uniform SNR distribution, the scheme with real-valued OCT pre-coding also shows the best performance in the nonlinear region.

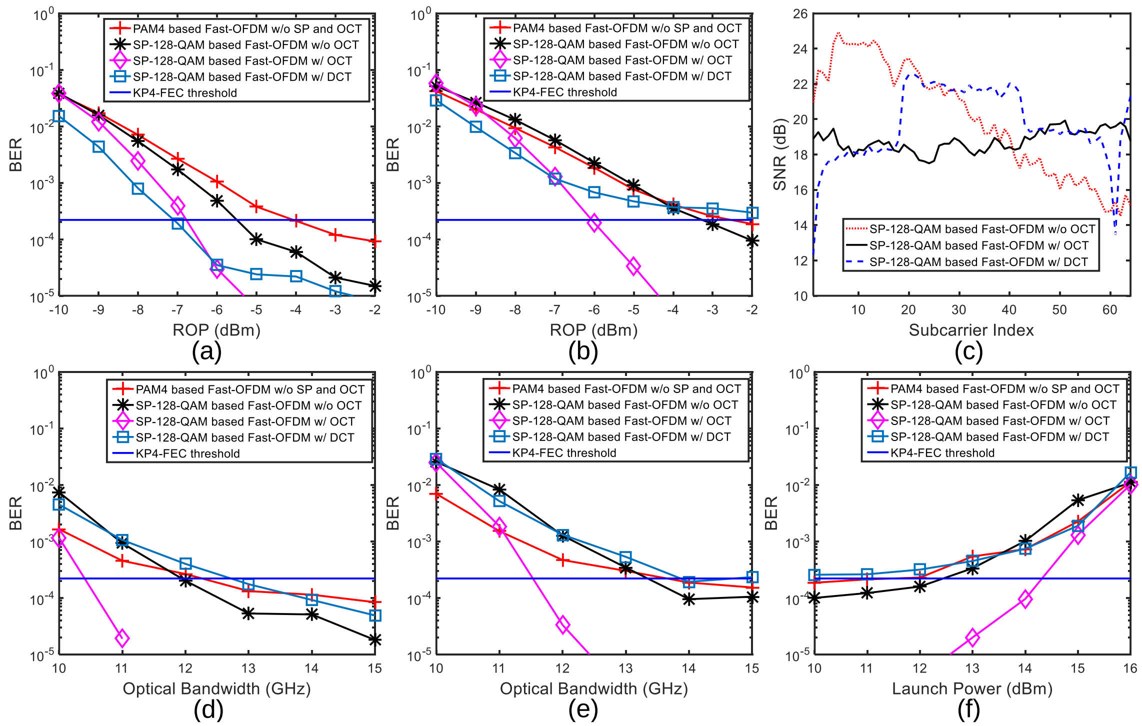


Fig. 2. BER versus ROP after transmission of (a) B2B and (b) 20-km SMF; (c) Estimated SNR after 20-km SMF transmission; BER versus optical bandwidth for (d) B2B and (e) 20-km SMF; (f) BER versus the launch power after 20-km SMF transmission. (In Figs. 2 (b), (c) and (e), the signal launch power is 7 dBm. In Figs. 2 (c)-(f), the ROP is -2 dBm. In Figs. 2 (b), (c) and (f), the optical bandwidth is 14 GHz.)

## 4. Summary

We have proposed and experimentally demonstrated SP-QAM based Fast-OFDM with real-valued OCT precoding over IM/DD optical transmission. A 19.76-Gbit/s pre-coded Fast-OFDM signal has been successfully implemented over 20-km SMF. The experimental results have indicated that the proposed scheme achieves around 3.5-dB ROP margin improvement at the BER of $2.2\times10^{-4}$ compared to the conventional PAM4 based Fast-OFDM without pre-coding. The proposed scheme also shows a higher tolerance to narrow-bandwidth filtering and fiber nonlinearity. *This work was supported in part by Science Foundation Ireland (SFI) grant 15/CDA/3652, and HKSAR RGC grant (GRF 14204015).*

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