First Investigation of Set-Partition Format based IM/DD OFDM for Fiber Communications

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Abstract: We propose, for the first time, set-partition (SP) format based optical OFDM and experimentally show that SP-64QAM/SP-128QAM intensity-modulation direct-detection OFDM exhibits greatly improved performance over conventional 16QAM and 8QAM OFDM.

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1. Introduction
Set-partition (SP) modulation formats have attracted much interest recently in long-haul coherent systems due to their high power efficiency (PE) and fine spectral efficiency (SE) [1, 2]. However, very few works have been done to investigate this group of formats in intensity-modulation (IM) direct detection (DD) systems [3]. In particular, SP formats have not been reported in any optical OFDM systems. In this paper, we investigate, for the first time, SP format based optical OFDM, and evaluate its performance in IM/DD systems. We study SP-128QAM OFDM and further derive SP-64QAM OFDM with higher PE. It is shown that SP-128QAM/SP-64QAM OFDM significantly outperforms the conventional 16QAM and 8QAM OFDM.

2. Experimental setup and principle
![Experimental setup](image)

(a) Experimental setup

(b) Multi-dimensional OFDM

(c) Constellation points of SP-128QAM

(d) Constellation of SP-64QAM (a subset of SP-128QAM)

Fig. 1. (a) Experimental setup; (b) Principle of SP format based OFDM; (c) Constellation of SP-128QAM; (d) Design of different SP-64QAM.

Table 1. Normalized power per bit to achieve the same minimal Euclidean distance for different formats

<table>
<thead>
<tr>
<th></th>
<th>16QAM</th>
<th>8QAM</th>
<th>SP-128QAM</th>
<th>SP-64QAM-Type1</th>
<th>SP-64QAM-Type2</th>
<th>SP-64QAM-Type3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normalized power (dB)</td>
<td>4</td>
<td>2</td>
<td>1.55</td>
<td>0.67</td>
<td>1.25</td>
<td>3</td>
</tr>
</tbody>
</table>

Fig. 1 shows the experimental setup and the principle of SP format based OFDM. In SP-128QAM and SP-64QAM, every two OFDM symbols of the same subcarrier are jointly encoded. This principle can also be extended to jointly encode two subcarriers within each OFDM symbol. SP-128QAM (Fig. 1(c)), which increases the minimal Euclidean distance by $2^{1/2}$, has been investigated in coherent systems [2]. Based on the SP-128QAM constellation, we further derive SP-64QAM to improve the PE. Three types of constellation sets for SP-64QAM are investigated (see Fig. 1(d)). Table 1 gives the power per bit to evaluate the PE. It is seen that the proposed SP-64QAM-Type1 gives the best PE, and both SP-64QAM-Type1 and SP-128QAM have better PE than the conventional 16QAM and 8QAM. Note that the spectral efficiency (SE) of SP-64QAM is 3, the same as 8QAM, while that of SP-128QAM is 3.5, lower than that of 16QAM (SE=4). In the experiment, the FFT size was 256. The number of modulated data subcarriers was controlled to fix the data rate (including the cyclic prefix) at 30 Gbit/s. Consequently, 8QAM and SP-64QAM had a higher baud rate due to a lower SE. PAPR was set to be 11 dB by clipping for all formats.
OFDM signal was uploaded to a 24-GS/s arbitrary waveform generator (AWG) with 7-GHz bandwidth. A Mach-Zehnder modulator (MZM) was used for modulation and the input peak-to-peak voltage was ~V/2. The optical signal was amplified and transmitted over 26-km SMF. At the receiver, the signal was detected by a photodiode. A variable optical attenuator (VOA) was used to vary the received power. The detected signal was sampled by a 50-GS/s real-time oscilloscope. ~1M bits were measured and bit error rate (BER) was obtained by error counting.

3. Results and discussions

![Graphs](Image)

Fig. 2. (a) & (b) Back-to-back performance of (a) different SP-64QAM OFDM and (b) different formats at 30 Gbit/s (i.e. higher baud rate for 8QAM/SP-64QAM); (c) Performance versus the modulator bias at -8-dBm received power; (d) Performance after transmission at 30 Gbit/s; (e) BER versus signal launch power at -8-dBm received power; (f) BER versus the bias at -8-dBm received power and 8-dBm signal power.

Fig. 2(a) shows the back-to-back BERs of different types of SP-64QAM OFDM. It is verified that Type 1 has the best performance (see Table 1). Fig. 2(b) depicts the back-to-back performance of different formats. It is seen that both SP-64QAM and SP-128QAM OFDM exhibit greatly improved performance compared to the conventional 16QAM and 8QAM OFDM. SP-128QAM OFDM has a lower baud rate than SP-64QAM OFDM, and so is less distorted by the limited bandwidth. Consequently, it shows similar BER performance as SP-64QAM OFDM despite a lower PE (Table 1). In the experiment, the bias of the modulator might drift (<0.1 V over several days). We investigate the performance sensitivity to this bias, as shown in Fig. 2(c). It is seen that all formats have ~0.5-V tolerance range, which is within the variation range of the bias. Fig. 2(d) depicts the transmission performance of different formats. It is shown that SP-128QAM OFDM and the proposed SP-64QAM OFDM still exhibit the best performance and the transmission penalty (compared to Fig. 2(b)) is less than 1 dB at the BER of 10^-3. In Fig. 2(d), the signal power into the fiber is 8 dBm and the penalty is mainly from dispersion. In Fig. 2(e), we investigate the effect of fiber nonlinearity by varying the signal power into the fiber. It is shown that the influence of nonlinearity becomes prominent only for signal power >12 dBm. Finally, we study the tolerance range of the modulator bias after SMF, where the bias has been calibrated for comparison with Fig. 2(c). It is seen that the optimal bias changes slightly. Compared to Fig. 2(c), the optimal DC added to the signal is higher. A higher DC enhances the ratio of the DC-signal beating to the signal-signal beating, resulting in slightly better transmission performance.

4. Conclusion

We have investigated, for the first time, SP format based OFDM, and derived SP-64QAM that can be more power efficient than SP-128QAM and 8QAM. Experiments show that SP-128QAM OFDM and the proposed SP-64QAM OFDM exhibit greatly improved performance compared to conventional 16QAM/8QAM OFDM in the IM/DD system. Power-efficient SP formats with fine SE granularity can be very promising to combine with adaptive loading [4] to approach the capacity limit of OFDM systems. This work was supported by Science Foundation Ireland grants 11/SIRG/I2124 and 15/CDA/3652, and HK RGC grants (GRF14200914 and GRF14204015).

5. References