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Abstract: We experimentally demonstrate the best known 16-ary 4-d modulation format at 24.8 Gb/s using coherent optical OFDM, achieving 0.58 dB OSNR gain over PDM-QPSK at a SER of 10^{-2}. With 7% overhead optimal codes, a 0.38 dB gain is theoretically achievable.

OCIS codes: (060.1660) Coherent communications; (060.5060) Phase modulation; (060.2330) Fiber optics communications.

1. Introduction

Coherent optical communication, which gives access to both quadratures and polarizations of the electromagnetic field for data transmission, has motivated the design of four-dimensional modulation formats to provide a good trade-off between power and spectral efficiency [1–4]. Therefore, at a fixed spectral efficiency, designing more power-efficient formats allows to operate at lower powers, thereby mitigating the effect of nonlinear fiber transmission impairments.

Polarization-division multiplexed quadrature phase-shift keying (PDM-QPSK) has been extensively studied due to its ease of implementation [5]. In signal space, the constellation set of PDM-QPSK consists of 16-points which lie on the vertices of a 4-d cube, thus providing a spectral efficiency of 4 bits/s/Hz. Since the optical channel can be modeled as an additive white Gaussian noise (AWGN) channel in the absence of fiber nonlinearity, the problem of optimizing constellations can be formulated as a 4-d sphere packing problem [3]. The minimum distance between the spheres, i.e., the sphere diameter, governs the error rate performance at high signal-to-noise ratio (SNR). The 4-d spheres with centers lying on the vertices of a 4-d cube do not provide the best packing in 4-d Euclidean space. Consequently, there exist constellations providing a better power efficiency compared to PDM-QPSK while achieving the same error rate performance. In [4], a 16-ary 4-d constellation denoted as $\mathscr{C}_{4,16}$ was presented as the best known packing of sixteen 4-d spheres in 4-d space. This constellation is described as a single point, six points lying on the vertices of a 3-d octahedron, eight points lying on the vertices of a 3-d cube, and another single point layered along one coordinate [4]. Its coordinate representation is $\mathscr{C}_{4,16} = \{(a+\sqrt{2},0,0,0),(a,\pm\sqrt{2},0,0),(a,0,\pm\sqrt{2},0),(a,0,0,\pm\sqrt{2}),(a-c,\pm1,\pm1,\pm1),(a-c-1,0,0,0)\}$ with all combinations of signs, where $a=(1-\sqrt{2}+9c)/16$ and $c=\sqrt{2\sqrt{2}-1}$. This constellation provides a 1.11 dB asymptotic average optical power gain over PDM-QPSK for the same spectral efficiency.

In this work, we experimentally demonstrate the advantage of $\mathscr{C}_{4,16}$ at 24.8 Gb/s using coherent optical OFDM. We also evaluate its theoretical performance in the presence of optimal coding and compare it with that of PDM-QPSK.

2. Experimental Setup

Figure 1 shows the schematic of the experimental setup. At the transmitter, an external cavity laser (ECL) at 1550 nm with a linewidth of ∼30 kHz was used as the laser source, followed by a dual-polarization I/Q modulator. The four drive signals for the modulator, accessing the real and imaginary parts of each of the two polarizations, were stored in two synchronized arbitrary waveform generators (AWGs), each equipped with two 10 GS/s digital-to-analog converters (DACs). To generate the drive signals, pseudo-random bit sequences (PRBS) of length $2^{15}-1$ were first encoded and mapped to $\mathscr{C}_{4,16}$ and PDM-QPSK (as a reference) symbols. The encoded symbols were modulated on the subcarriers of a reduced-guard-interval (RGI) coherent optical orthogonal frequency-division-multiplexing (CO-OFDM) signal [6]. The IFFT size was 128, and the guard-interval (GI) was 2 samples, resulting in a small GI-overhead of 1.56%. Each

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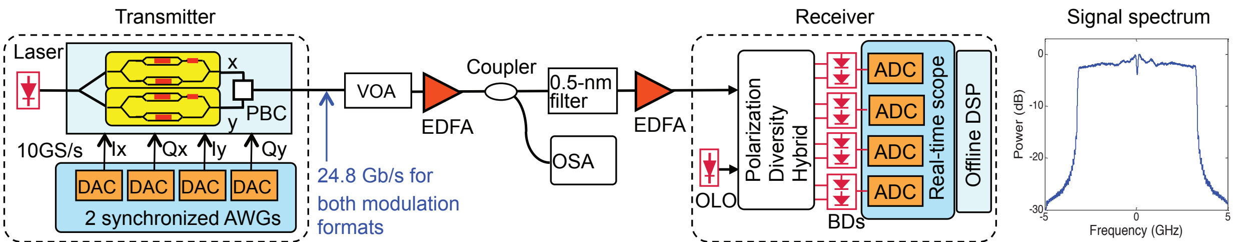

Fig. 1: Schematic of the experimental setup for comparing the OSNR performances of $\mathscr{C}_{4,16}$ and PDM-QPSK.

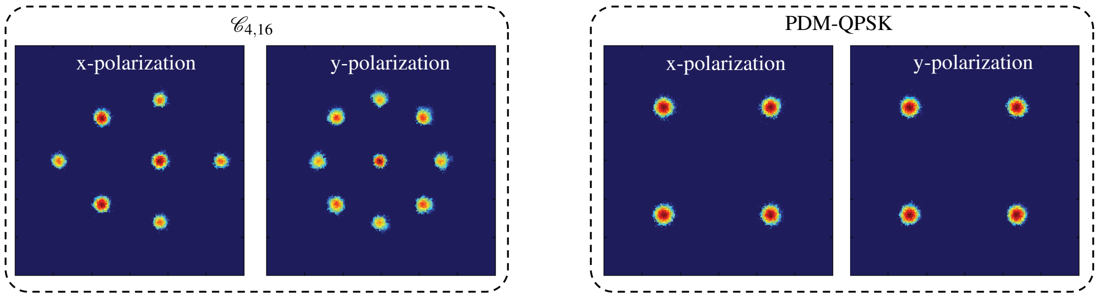

Fig. 2: Recovered signal constellations (projected on x- and y-polarizations) for the $\mathscr{C}_{4,16}$ signal (left) and the PDM-QPSK signal (right) in the back-to-back configuration with OSNR= 37 dB.

polarization component of an OFDM symbol contained 81 data subcarriers (SCs), one pilot SC, one unfilled center SC, and 45 unfilled edge SCs. The 3-dB bandwidth of the RGI-CO-OFDM signal was $\sim$6.48 GHz (=83/128 $\times$ 10 GHz), as shown in Fig. 1. Three correlated training symbols were used for every 509 payload OFDM symbols. The raw data rate of the signal is 25.6 Gb/s, and the payload data rate is 24.8 Gb/s. The generated signal was attenuated by a variable optical attenuator (VOA) before being amplified by an Erbium-doped fiber amplifier (EDFA). The optical signal-to-noise ratio (OSNR) of the amplified signal was measured by an optical spectrum analyzer (OSA). Note that OSNR is related to the electrical SNR using Eq. (36) in [7]. The optically pre-amplified signal was then filtered by a 0.5 nm optical filter before being received by a digital coherent receiver. The digital coherent receiver frontend consisted of another 30-kHz-linewidth ECL serving as the optical local oscillator (OLO), a polarization-diversity optical hybrid, four balanced detectors, and four 50-GS/s analog-to-digital converters (ADCs) in a real-time sampling scope. The four sampled waveforms were stored and down-sampled to 10 GS/s before being processed offline. After receive-side OFDM processing [6], the payload symbols were recovered. After demodulation, symbol error rate (SER) was obtained using maximum likelihood decoding by comparing the recovered signal points with the original constellation (see Fig. 2). Note that for $\mathscr{C}_{4,16}$, the information in both polarizations is required in the detection process.

3. Performance Analysis

Figure 3 depicts the SER of the modulation formats under study versus OSNR in the absence of coding. For PDM-QPSK, we use the exact SER formula in [3, Eq. (14)], and for $\mathscr{C}_{4,16}$, we use the standard union bound in [8, Eq. (4.81)] together with the simulated SER. The simulated SER is accurate at low SNR and the union bound is tight at high SNR. We also include the experimental results of both modulation formats. In theory, and at asymptotically high SNR, the $\mathscr{C}_{4,16}$ offers a 1.11 dB average optical power gain over PDM-QPSK to achieve the same SER. At SER of 10^{-3}, $\mathscr{C}_{4,16}$ offers a 0.71 dB gain over PDM-QPSK. However, the experimental results are somehow different from the theoretical ones due to the implementation penalties (e.g., digitization noise) accompanied with the experimental setup. At SER of 10^{-3}, $\mathscr{C}_{4,16}$ has a 1.19 dB penalty compared to the theoretical results whereas PDM-QPSK has a 1 dB penalty. Thus, $\mathscr{C}_{4,16}$ has an average optical power gain of 0.52 dB over PDM-QPSK at a SER of 10^{-3}, which is 0.19 dB less than the theoretical gain. It is interesting that the gain is higher (0.58 dB) at a SER of 10^{-2}, which infers that $\mathscr{C}_{4,16}$ is more robust to implementation penalties in comparison to PDM-QPSK at this SER.

In Fig. 4, we evaluate the modulation formats in terms of their mutual information to predict their performance for AWGN channels in the presence of capacity-achieving error-correcting codes. We also include the capacity of 4-d AWGN channels. The spectral efficiencies obtained give a lower bound on the rate in bits/s/Hz that can be achieved by a modulation format since we consider all symbols in a constellation to be equally likely. Higher spectral efficiencies can be obtained if we allow the input distribution to have a nonuniform probability, however, this is outside the scope

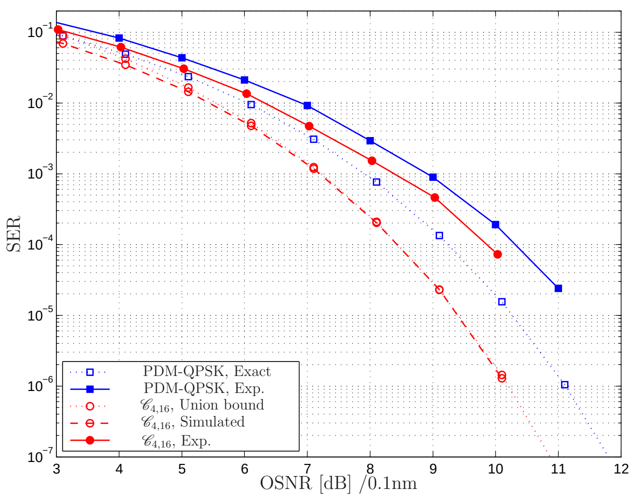

Fig. 3: Symbol error rate versus OSNR at a raw bit rate of 25.6 Gb/s. (Dotted line: union bound for $\mathscr{C}_{4,16}$ (circle) and exact SER for PDM-QPSK (square). Dashed line: simulated SER of $\mathscr{C}_{4,16}$. Solid line: experimental results.)

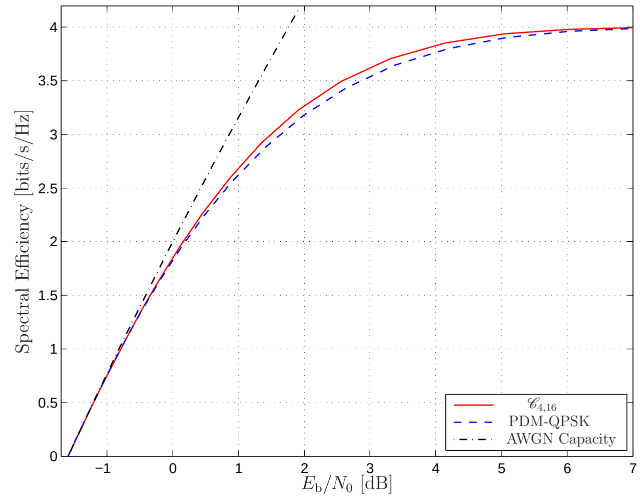

Fig. 4: Constrained capacity of both modulation formats versus SNR per bit. The minimum SNR per bit for spectral efficiencies > 0 bit/s/Hz is -1.59 dB.

of this work. The two modulation formats under study perform the same in terms of SNR per bit (E_b/N_0) for a spectral efficiency less than 1.5 bits/s/Hz. For higher spectral efficiencies, $\mathscr{C}_{4,16}$ offers a better performance in the presence of coding. For example, at a spectral efficiency of 3.5 bits/s/Hz, $\mathscr{C}_{4,16}$ has 0.29 dB gain in SNR per bit compared to PDM-QPSK. At a spectral efficiency of 3.74 bits/s/Hz (corresponding to 7% overhead codes), the gain is 0.38 dB. At high SNR, both constellations approach 4 bits/s/Hz.

4. Conclusion

We experimentally demonstrated the best known constellation in 4-d Euclidean space using optical OFDM. In the absence of coding, it has an average optical power gain of 0.58 (0.52) dB over PDM-QPSK at a SER of 10^{-2} (10^{-3}), which improves system performance, especially by reducing the effect of nonlinear fiber transmission impairments. However, this comes at the expense of a higher modulator/demodulator complexity. This new format can achieve higher spectral efficiencies than PDM-QPSK in the presence of optimal coding at moderate SNRs.

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