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Abstract: Using a novel geometrically-shaped four-dimensional modulation format, we transmitted 11×200 Gbit/s DWDM at 4.8 bit/4D-sym over 7,925 km and 11,700 km using EDFA-only and hybrid amplification, respectively. A reach increase of 16% is achieved over PM-8QAM.

Keywords: Advanced Modulation, Coding and Multiplexing. Transmission experiments for long haul, core and metro applications including data-center interconnect

1. Introduction

The non-linear Shannon limit for single-mode transmission systems remains despite the strong growth in traffic. In recent years, signal shaping via probabilistic shaping (PS) or geometric shaping (GS) have been demonstrated to close the gap to the non-linear Shannon limit by employing non-uniform probability or non-equidistant constellation points whilst maximising achievable information rate (AIR), respectively. Both techniques have been extensively demonstrated with PS shown to require complex coding techniques, whilst GS only requires straightforward modifications of the mapper and demapper.

Multidimensional constant modulus modulation formats have been shown to minimize the non-linear interference noise by minimizing the signal power variations [1, 2]. Recently, the four-dimensional 64-ary polarization-ring-switching (4D-64PRS) format was introduced in [3], where the 4D coordinates and labeling were jointly optimized. Numerical results in [3] show that 4D-64PRS outperforms other modulation formats with spectral efficiency (SE) of 6 bit/4D-sym, including polarization-multiplexed (PM)-8QAM, 4D-64SP-12QAM [4] and 4D-2A8PSK [2]. Results were presented in both linear and non-linear channel for a bit-interleaved coded modulation (BICM) system [3]. 4D-64PRS was reported to yield over 0.8 dB better sensitivity than PM-8QAM by maximizing generalized mutual information (GMI) [3].

In this work, we experimentally show a 16% reach increase over PM-8QAM, which is considered a viable candidate for beyond 200G per optical carrier ultra long-haul transmission [5–7]. Using a novel four-dimensional 4D-64PRS modulation format, both EDFA-only and hybrid EDFA plus Raman amplified long-haul transmission scenarios are evaluated. 4D-64PRS is shown to outperform both PM-8QAM and 6b4D-2A8PSK in an 11-channel dense wavelength division multiplexing (DWDM), net 200 Gbit/s/channel standard single-mode fiber (SSMF) recirculating loop transmission experiment. It is shown that pre-FEC reach gains are preserved for post-FEC.

2. Experimental transmission setup

Fig. 1 depicts the experimental transmission setup. The transmitted signal is modulated using eithr PM-8QAM, 6b4D-2A8PSK [2], or 4D-64PRS [3]. Fig. 1 inset (a) shows the Stokes representation of the 4D-64PRS format, which exhibits 16 distinct SOPs and consists of 64 4D-symbols. Each distinct SOP represents four 4D-symbols on the Poincaré sphere indicating constant modulus in 4D. Sequences containing 2^{16} symbols are shaped using a root-raised-cosine (RRC) filter with 1% roll-off at 41.79 GBd, generated offline and uploaded to a 100-GSa/s digital-to-analog converter (DAC). The positive ends of the differential DAC outputs are connected to the optical-multi-format transmitter (OMFT) which consists of an external cavity laser (ECL), a dual-polarization IQ-modulator (DP-IQM), an automatic bias controller (ABC) and RF-amplifiers. The CUT, which can be defined at any of the 11 tested C-band channels, is modulated by the OMFT and subsequently amplified. The loading channels are provided by the negative outputs of the DAC and modulated on the tones provided by 10 ECLs using a DP-IQM. These loading channels are amplified, split into even and odd, decorrelated by 10,200 (50 m) and 40,800 symbols (200 m), and multiplexed together with the CUT on a 50-GHz grid using an optical tunable filter (OTF). Bandwidth limitations due to transmitter electronics are compensated for partly through digital filters and partly using the OTF as proposed in [9].

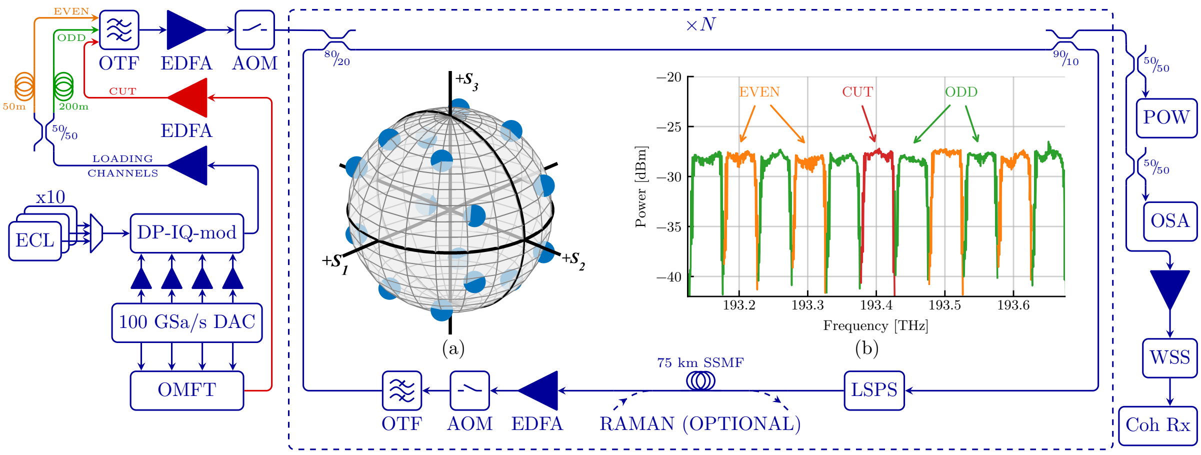

Fig. 1: Experimental setup. Inset **(a)** shows a Stokes-space representation of the 4D-64PRS modulation format, indicating 64 constant-modulus points in 16 distinct states-of-polarization (SOPs). Inset **(b)** shows the received spectrum after 106 circulations (8,000 km) of EDFA-only amplification. Note that the channel under test (CUT) is depicted in the center position but is tested in all 11 positions in the experiment.

The 11-channel 50-GHz-spaced DWDM signal is amplified and through an acousto-optical modulator (AOM) enters the recirculating loop which consists of a loop-synchronous polarization scrambler (LSPS), a 75-km span of SSMF, an erbium-doped fiber amplifier (EDFA), an AOM and an OTF used for gain flattening. Fig. 1 inset (b) shows the optical spectrum after 106 circulations, which corresponds to 8,000 km of transmission using only EDFA-amplification. Optionally, a hybrid amplification scheme can be used by adding a 750 mW 1480 nm Raman pump in a backward configuration. Part of the output of the recirculating loop is measured by a power meter, part is analyzed using an optical spectrum analyzer (OSA) and the rest is amplified, filtered by a wavelength selective switch (WSS) and digitized by a coherent receiver consisting of a local oscillator (LO), a 90-degree hybrid, four balanced photo-diodes and an 80-GSa/s analog-to-digital converter (ADC). Offline digital signal processing (DSP) includes front-end correction, frequency-offset compensation, chromatic dispersion compensation, multiple-input multiple-output (MIMO) equalization with in-loop blind phase search (BPS), error counting and GMI evaluation.

3. Results

Transmission scenarios using EDFA-only amplification (Fig. 2) and a hybrid of EDFA and Raman (Fig. 3) are evaluated. Fig. 2a shows that a total launch power of 9.5 dBm maximizes the average GMI per channel resulting in a 0.21 bit/4D increase for 4D-64PRS with respect to PM-8-QAM. At this optimal launch power, we demonstrate transmission below the pre-FEC-threshold of $4 \cdot 10^{-2}$ and above the GMI threshold of 5.1 bit/4D, thus enabling error-free 7,925 km transmission of net 200 Gbit/s per channel after 25.5% overhead and for all 11 channels. The GMI threshold 5.1 bit/4D (0.85 NGMI) is based on a spatially-coupled type LDPC code [8] and the corresponding BER threshold of $4 \cdot 10^{-2}$ is derived in [2].

A reach increase of 16% (+1,150 km), for 4D-64PRS compared to PM-8QAM is shown for a pre-FEC bit error rate (BER) of $4 \cdot 10^{-2}$ in Fig. 2c. Moreover, the 16% reach increase is preserved for the post-FEC gain using an

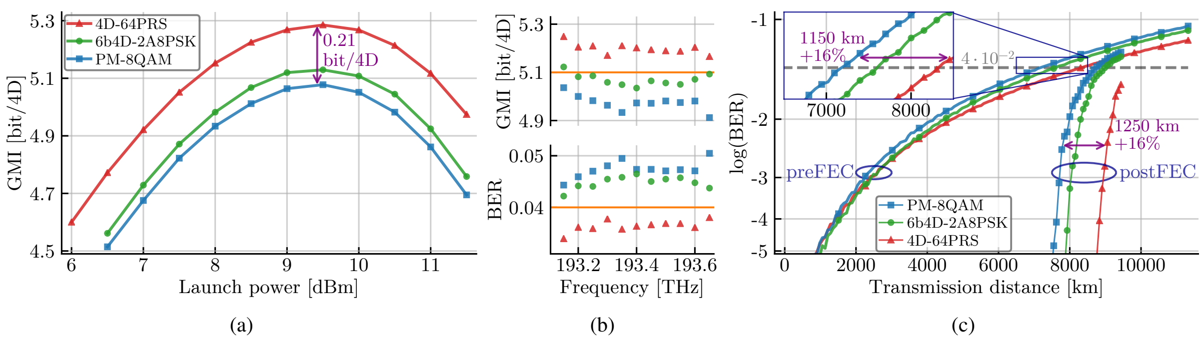

Fig. 2: Experimental results using EDFA-only amplification. **(a)** Average GMI per channel versus total launch power after 7,550 km. **(b)** Per-channel performance versus BERs (top) and GMIs (bottom) measured for all 11 channels individually after 7,925 km showing BERs below the FEC threshold $4 \cdot 10^{-2}$ [2] (top) and GMIs above 5.1 bit/4D [8] (bottom) for all 11 channels for 4D-64PRS. **(c)** BER versus transmission distance for the center channel at launch power of 9.5 dBm.

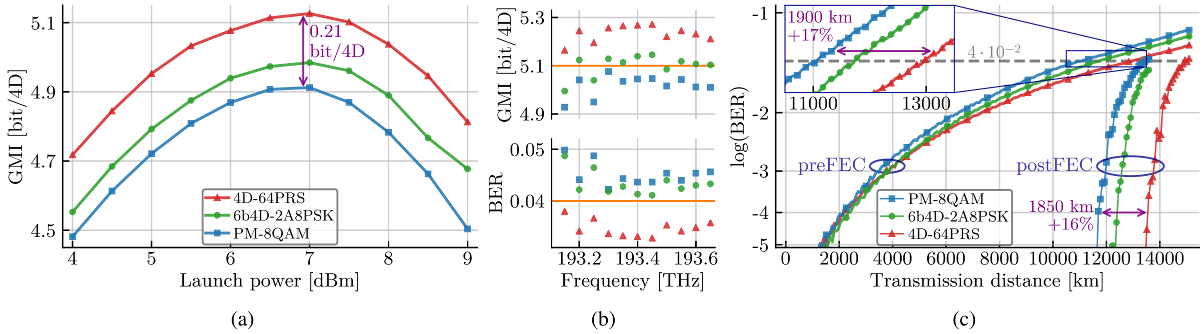

Fig. 3: Experimental results using a hybrid of EDFA and Raman amplification. **(a)** Average GMI per channel versus total launch power after 12,530 km. **(b)** Per-channel performance versus BERs (top) and GMIs (bottom) measured for all 11 channels individually after 11,700 km showing BERs below the FEC threshold $4 \cdot 10^{-2}$ [2] (top) and GMIs above 5.1 bit/4D [8]. **(c)** BER versus transmission distance for the center channel at launch power of 6.5 dBm.

off-the-shelf DVB-S2 low-density parity-check code (LDPC) with 25% overhead and code length $n = 64800$. In addition to the gains shown versus PM-8QAM, 4D-64PRS is also shown to outperform 6b4D-2A8PSK. BER and GMI calculations were done using over 42 million bits for all plotted data points. Note that 63 million bits were used for LDPC decoding.

For the hybrid amplification scenario, the relative gains are similar to the EDFA-only case as shown in Fig. 3. A GMI-increase of 0.21 bit/4D at 7 dBm launch power is observed in Fig. 3a. Further measurements were carried out at 6.5 dBm total launch power, near the optimal launch power. Fig. 3b shows all channels were able to transmit over 11,700 km successfully. Fig. 3c shows a pre-FEC reach increase of 17% and a post-FEC reach increase of 16%, which is consistent with the EDFA-only amplification scenario.

4. Conclusions

The novel geometrically-shaped 4D-64PRS modulation format is experimentally compared to other notable 6 bit/4D modulation formats such as PM-8QAM and 6b4D-2A8PSK, with 4D-64PRS outperforming both of them. Experimental results show a reach increase of 16% at 7,925 km for SSMF and EDFA-only amplification and 11,700 km of using hybrid of both EDFA and Raman amplification. LDPC decoding is performed on the experimental data to demonstrate a post-FEC 16% reach increase at a net SE of 4.8 bit/4D.

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