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EXPERIMENTAL DEMONSTRATION OF EIGHT-DIMENSIONAL MODULATION FORMATS FOR LONG-HAUL OPTICAL TRANSMISSION

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Abstract

Two novel 5.5 bit/4D modulation formats are experimentally demonstrated to transmit over 9680 km of SSMF. A reach increase of 29.4 % over the 6 bit/4D PM-8QAM is shown. Furthermore, increased nonlinear tolerance with respect to PM-8QAM is shown.

1 Introduction

In optical transmission systems, the performance of a given modulation format is determined by its tolerance to both nonlinear interference arising from the Kerr effect, and linear accumulated amplified spontaneous emission (ASE) noise. Therefore, designing modulation formats which increase the achievable information rate (AIR) in the presence of linear and nonlinear impairments is crucial for designing future transmission systems.

Multidimensional constant modulus modulation formats have been shown to minimise the impact of nonlinear interference noise by minimising the signal power variations [1–4]. One example of this is the four-dimensional 64-ary polarisation-ring-switching (4D-64PRS) format we recently proposed in [4]. In [5], eight-dimensional (8D) formats were designed to further mitigate fibre nonlinear impairments via the polarisation-balancing concept.

Previous works were only able to construct nonlinearity-tolerant 8D modulation formats in the spectral efficiency (SE) range of 2-4 bit/4D. This was achieved by set-partitioning polarization-multiplexed binary phase-shift-keying (PM-BPSK) or polarization-multiplexed quaternary phase-shift-keying (PM-QPSK) [5–7]. Recently, two 8D formats with with an SE of 5.5 bit/4D were proposed in [8]. The design was based on the constant modulus and polarisation-balancing concepts. The formats were called eight-dimensional 2048-ary polarization-ring-switching (8D-2048PRS) and allow an increase in the sensitivity and nonlinearity tolerance. Two types were proposed: Type 1 (T1) and Type 2 (T2). The formats were compared using normalised generalised mutual information (NGMI) as performance metric, which represents the largest code rate of an ideal soft-decision forward error correction (FEC) in a coded modulation system with a bit-wise decoder.

In this work, the formats 8D-2048PRS-T1 and 8D-2048PRS-T2 are experimentally compared to 5.5 bit/4D time domain hybrid four-dimensional two-amplitude eight-phase shift keying (TH-4D-2A8PSK) [9] and 6 bit/4D polarization-multiplexed 8-ary quadrature amplitude modulation (PM-8QAM). A transmission distance of 9680 km is reported for both 8D-2048PRS modulation formats, showing a reach increase of 4.9 % (450 km) over TH-4D-2A8PSK and 29.4 % (2200 km) over PM-8QAM. Furthermore, 8D-2048PRS-T2 is shown to be more resilient against nonlinearities than PM-8QAM. The achieved performance is in agreement with simulation results and thus confirms the potential of these modulation formats in long-haul optical fibre transmission systems.

2 Time-slotted 8D Modulation Format

The 8 dimensions are obtained by using two consecutive time slots in two polarisations. 8D-2048PRS is based on two consecutive 4D-64PRS symbols and carries 11 bits per 8D symbol. To go from the 12 bits needed to index two consecutive 4D-64PRS formats ($b_1, b_2, \ldots, b_{12}$) to the 11 bits in 8D-2048PRS, the last bit is used as overhead (parity) bit [4]. In particular, $\overline{b}_{12} = b_1 \oplus b_2 \oplus b_3 \oplus b_4 \oplus b_5 \oplus b_6 \oplus b_7 \oplus b_8 \oplus b_9 \oplus b_{10} \oplus b_{11}$ for 8D-2048PRS-T1 and $\overline{b}_{12} = b_3 \oplus b_6 \oplus b_9$ for 8D-2048PRS-T2, where $\oplus$ and $\overline{b}$ denote modulo-2 addition and negation, respectively.

Both 8D-2048PRS formats are designed to avoid polarisation-identical symbols in both timeslots and therefore reduce the effects of cross-polarisation modulation. States of polarisation (SOP) and Eucledian distance (ED) are taken into account for the selection of 2048 8D symbols. 8D-2048PRS-T1 is designed to use the parity bit to protect all the information bits, and thus, it leads to a higher minimum ED and a better performance

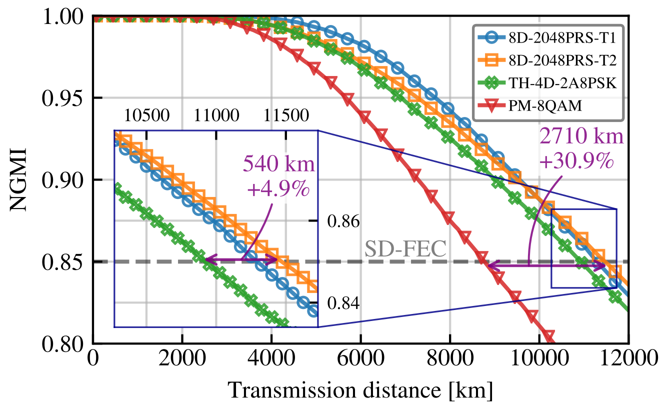

Fig. 1 Simulation results: NGMI as a function of transmission distance for the centre channel. Reach increases of 4.9% and 30.9% are observed for 8D-2048PRS with respect to TH-4D-2A8PSK and PM-8QAM, respectively.

Table 1 Simulation parameters.

Parameter name	Value
WDM Channels	11
Symbol rate	41.79 GBd
Root-raised-cosine roll-off factor	1 %
Channel frequency spacing	50 GHz
Center wavelength	1550 nm
Aggregate launch power	9.5 dBm
Attenuation	0.2 dB km^{-1}
Dispersion parameter	17 ps nm^{-1} km^{-1}
Nonlinearity parameter	1.3 W^{-1} km^{-1}
Fibre span length	75 km
EDFA noise figure	5 dB

at higher signal-to-noise ratio (SNR). On the other hand, 8D-2048PRS-T2 is designed to be better at the lower SNR regime since only the least significant bits are protected.

Split-step Fourier method (SSFM) simulations with a step-size of 0.1 km were performed to compare the modulation formats and predict system performance. The simulation parameters are given in Table 1 for the optical multi-span fibre link under consideration, which comprises multiple standard single-mode fibre (SSMF) spans, amplified at the end of each span by an erbium doped fibre amplifier (EDFA). The encoded bits are mapped according to four modulation formats: PM-8QAM (6 bit/4D), TH-4D-2A8PSK (5.5 bit/4D) and two 8D-2048PRS types (5.5 bit/4D). TH-4D-2A8PSK is generated by combining 5B4D-2A8PSK and 6B4D-2A8PSK from [9] with a 1:1 ratio in a time domain hybrid fashion, resulting in a time domain hybrid four-dimensional (TH-4D) modulation format. Each dense wavelength-division multiplexing (DWDM) channel carries independent data, where all of them are assumed to have the same transmitted power. At the receiver, an ideal receiver is used for detection and chromatic dispersion is digitally compensated for.

Fig. 1 shows NGMI [10] as a function of the transmission distance. The results show that the 8D-2048PRS formats offer large reach increases with respect to PM-8QAM. The inset in Fig. 1 shows that 8D-2048PRS-T2 offers a 4.9 % reach increase relative to TH-4D-2A8PSK.

Fig. 1 also shows that both 8D-2048PRS-T1 and 8D-2048PRS-T2 yield a 30.9 % reach increase relative to PM-8QAM at a NGMI of 0.85.

3 Experimental Setup

Fig. 2 depicts the experimental recirculating loop setup which approximates the simulation setup of Section 2. Sequences of 2^{16} 4D-symbols are used for PM-8QAM. For the 8D and TH-4D modulation formats, sequences of 2^{15} 8D-symbols are time-multiplexed into a four-dimensional sequence of length 2^{16}. The generated sequence is pulse-shaped using a root-raised-cosine (RRC) filter with 1% roll-off at 41.79 GBd and uploaded to a 100 GSa/s digital-to-analog converter (DAC).

The 1550.116 nm channel under test (CUT) is modulated using an optical-multi-format transmitter (OMFT), which consists of a external cavity laser (ECL), a dual-polarisation IQ-modulator (DP-IQM), an automatic bias controller (ABC) and RF-amplifiers. The multiplexed outputs of 10 ECLs are modulated using a DP-IQM, amplified, split into odd and even, decorrelated by 10,200 symbols (50 m) and 40,800 symbols (200 m) with respect to the CUT, respectively. The CUT, odd, and even channels are combined onto the 50 GHz spaced DWDM grid using an optical tunable filter (OTF). Using acoustic optical modulators (AOMs), the signal is circulated in a loop consisting of a loop-synchronised polarisation scrambler (LSPS), a 75 km span of SSMF, an EDFA, and an OTF used for gain equalisation. The launch power into the fibre is carefully controlled and the power per 50 GHz channel is equalised.

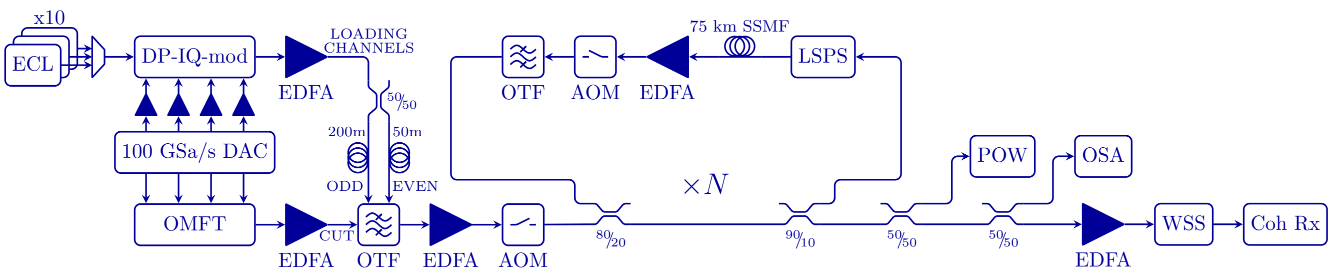

Fig. 2. Experimental optical recirculating loop setup.

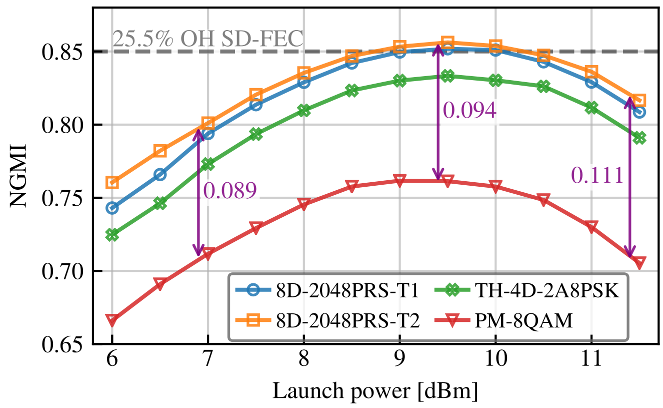

Fig. 3 Experimental results: NGMI versus total launch power after 9435 km. Larger NGMI gains at higher launch powers indicate better nonlinearity tolerance of 8D-2048PRS.

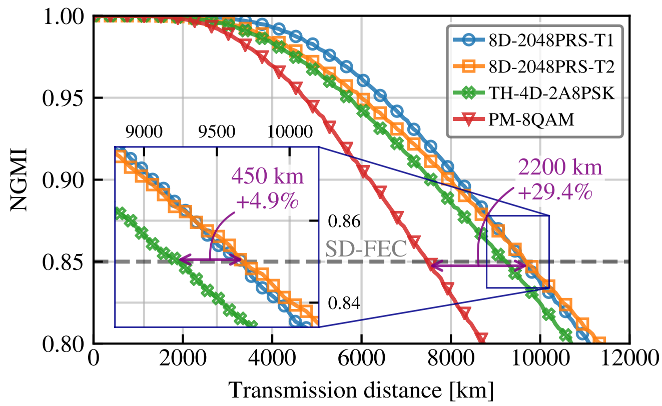

Fig. 4 Experimental results: NGMI versus transmission distance for the centre channel at a launch power of 9.5 dBm. Both 8D-2048PRS reach 9680 km and show a reach increase of 4.9 % and 29.4 % over TH-4D-2A8PSK [9] and PM-8QAM, respectively.

The aggregate launch power of the 11 channels is denoted as 'launch power' throughout this work.

After transmission, the signal is amplified, the CUT selected using a wavelength selective switch (WSS), detected using an intradyne coherent receiver, and digitised by an 80 GSa/s real-time oscilloscope. Receiver DSP consisting of front-end compensation, chromatic dispersion (CD) compensation, frequency-offset compensation, and decision-directed equalisation with in-loop phase search is performed offline. When an 8D modulation format is used, the four-dimensional sequence is time demultiplexed into 8D again. NGMI is evaluated for the CUT over approximately 3.5 million 8D-symbols (8D and TH-4D formats) or 7 million 4D-symbols (PM-8QAM).

4 Experimental Results

Fig. 3 shows NGMI versus launch power and indicates that the optimum launch power is 9.5 dBm. This optimum value is used in subsequent measurements. A NGMI gain of 0.094 for 8D-2048PRS-T2 over PM-8QAM is achieved at the optimum launch power. In the linear (low launch power) regime, a similar NGMI gain (0.089) is shown. At powers above the optimum launch power, a larger NGMI gain of 0.111 is shown. This confirms the observation in [8] that the 8D-2048PRS-T2 format is more resilient against nonlinearities than PM-8QAM.

Fig. 4 shows the measured NGMI for various transmission distances. As expected from the simulations, all 5.5 bit/4D formats perform much better than PM-8QAM. Throughout this work a 25.5 % overhead FEC is assumed with a threshold of 0.85 NGMI. The assumed FEC is based on a spatially-coupled low-density parity-check (LDPC) [11] and the threshold is derived in [3]. 8D-2048PRS-T1 and 8D-2048PRS-T2, similar modulation formats but optimised for different SNR regimes, cross at this FEC threshold of NGMI 0.85. This observed crossing in the experimental result is in good agreement with the simulation results of Fig. 1. Both 8D-2048PRS formats are able to be transmitted over 9680 km, a 4.9 % (450 km) reach increase over TH-4D-2A8PSK. The reach increase of both 8D-2048PRS formats over PM-8QAM is 29.4 % (2200 km), which is very well matched to the simulation prediction of 30.9 %. These experimental results confirm the performance of the novel eight-dimensional modulation formats obtained in simulation.

5 Conclusions

We experimentally demonstrate the transmission of two novel 5.5 bit/4D eight-dimensional modulation formats over 9680 km of SSMF. A reach increase of 29.4 % over the 6 bit/4D PM-8QAM is shown, which gives a system designer the interesting trade-off between 8.3 % rate loss and 29.4 % reach increase. Furthermore, compared to the TH-4D-2A8PSK format, which has the same SE of 5.5 bit/4D, 4.9 % reach increase is shown. Note that 8D-2048PRS is shown to be more resilient against nonlinearities with respect to PM-8QAM. Experimental results are in good agreement with simulation and thus confirms the potential benefits in employing these novel modulation formats in long-haul optical fibre transmission.

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