Experimental assessment of multi-dimensional modulation formats at high Baudrate for unrepeatered WDM systems

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Abstract *We experimentally assess a series of four multi-dimensional modulation formats for 100 Gbaud single-span unrepeatered multi-rate applications. We show the variation of maximum acceptable span loss for entropies between 1 and 2 b/S/pol, with a granularity of 0.25 b/S/pol.*

Introduction

In the context of repeatereless single span transmission systems, modulation formats such as Binary Phase Shift Keying (BPSK) and Quadrature Phase Shift Keying (QPSK) are commonly used when the span loss becomes very large. In recent years, higher power-efficient multi-dimensional modulation formats such as Polarization-Switched (PS) QPSK was proposed[1], adding an intermediate entropy between BPSK and QPSK. On the other hand, increasing the multi-rate capability of transmission systems was done using Probabilistic Constellation Shaping (PCS)[2]. However, reaching spectral efficiencies between BPSK and QPSK remains challenging for such formats, and solutions as modulation formats coded in multi-dimensions constituted a good alternative[3]. It was numerically and experimentally demonstrated that such 8D formats have high power-efficiency, multi-rate capabilities as well as fiber nonlinearity tolerance[6,7]. Although some implementation complexity has to be expected, previous work showed that low-complexity algorithms can be used to reduce it, and make these solutions usable in coherent transmission systems[4,5].

In this paper, we will experimentally assess the performance of these modulation formats at high Baudrate, and experimentally validate the multi-rate capabilities and the SNR sensitivity in the context of 100 Gbaud unrepeatereless single span applications.

Multi-Dimensional Set-Partitionning of PDM-QPSK

Multi-dimensional modulation formats are designed by set-partitioning a standard constellation. As such, a Polarization-Division-Multiplexed (PDM) QPSK is considered in 8 dimensions: In-phase and Quadrature-phase in both orthogonal polarizations and in two consecutive time slots. The selection of symbols is then constrained by the State-Of-Polarization (SOP), where in two consecutive time slots, symbols with orthogonal SOPs are preferred. This 8D set partitioning results on four modulations formats: Polarization-Balanced 4 Bits in 8 Dimensions (PB-4B8D), PB-5B8D, PB-6B8D and Polarization-Alternating (PA) 7B8D, with entropies of 1, 1.25, 1.5 and 1.75 bits/Symbol/polarization, respectively. The full set-partitioning operation is done by coding using Boolean equations[4,5,7]. In this study, these four modulation formats are considered along with PDM-QPSK.

Experimental Transmission System Setup

The experimental setup is shown in Fig. 1. The generated signals include random payload data at which one pilot is inserted every 32 symbols. For each modulation format, a Root Raised Cosine (RRC) pulse shaping is considered with a roll-off factor of 0.01. A digital pre-emphasis is applied to the spectrum in order to have flat-spectrum channels at the output of the modulator. The data is loaded into the memory of the Digital-to-Analog-Converter (DAC) operating at 120 Gsamples/s, and then modulated with a Baudrate of 100 Gbaud. Five Tunable Laser Sources (TLS) are combined through an 8x1 Polarization Maintaining (PM) coupler and injected into the modulator. The set of TLS is tuned to a central frequency of 193 THz, and within a grid of 112.5 GHz. It is important to note that, due to experimental constraints, channels at the output of the modulator were not decorrelated. For this experimental setup, the central channel is decorrelated from the two adjacent channels by one symbol after only 0.55 km of fiber, which is much lower than the effective length. In addition, a simulation study was carried out in order to assess

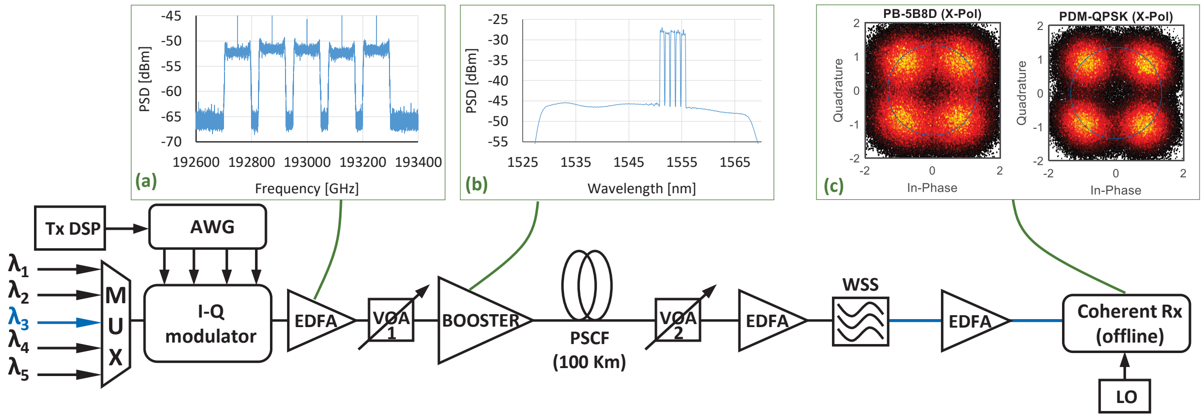

Fig. 1: Experimental transmission system setup. Insets (a) and (b) are WDM spectrums acquired with resolutions of 140 MHz and 0.1 nm, respectively. Inset (c) shows constellations at the optimum launch power of PB-5B8D (3.98 dB SNR and 55.1 dB span loss) and PDM-QPSK (5.92 dB SNR and 52.1 dB span loss).

the effect of decorrelation, and results show a difference smaller than 0.15 dB in Q^2 factor between correlated and decorrelated channels for all modulation formats, which is low. At the output of the modulator, the five Wavelength-Division-Multiplexed (WDM) channels (Fig. 1 - inset a), are amplified using an Erbium-Doped-Fiber-Amplifier (EDFA) module. At the output of the latter, a Variable-Optical-Attenuator (VOA) is used along with a fixed-gain high power EDFA, in order to vary the total launch power into the fiber, and work at high power. A single span Pure-Silica-Core Fiber (PSCF) of 100 km with $125\,\mu m^2$ effective area and 0.17 dB/km attenuation is considered, which allows to emulate 98% of nonlinearities of 300 km or more. At the output of the fiber, a VOA is used with an adjusted attenuation to emulate longer fiber length and capture the Amplified Spontaneous Emission (ASE) noise from the receiver EDFA. The signal is then amplified by and EDFA and then filtered using a Wavelength-Selective-Switch (WSS) to select the channel of interest (the central channel). Another EDFA is used to further amplify the signal and send it to a coherent receiver, which includes a coherent mixer, four high-speed balanced receivers with 70GHz bandwidth, a local oscillator and an Analog-to-Digital-Converter (ADC) working at a rate of 256 Gsamples/s. Finally, the resulting signals are processed offline. The DSP consists of digital chromatic dispersion compensation, polarization demultiplexing using a 51-tap Constant Modulus Algorithm (CMA), carrier frequency estimation, synchronization and a Pilot-Aided Carrier-Phase-Recovery (PA-CPR) algorithm. The pilots here avoid cycle slips at low Signal-to-Noise-Ratio (SNR) values. An example of offline processed PB-5B8D and PDM-QPSK

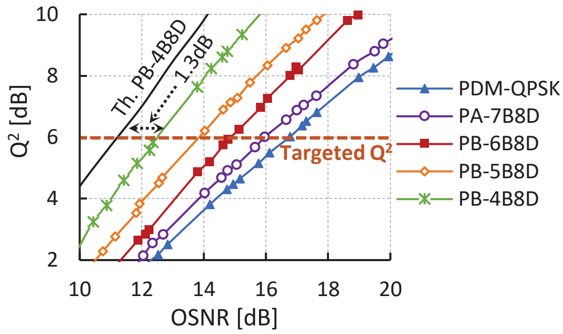

Fig. 2: Optical Back-to-Back with a highlight on the targeted Q^2 factor value.

constellations is showed in Fig. 1 - inset c, highlighting the fact that PB-5B8D is working at a much lower SNR than PDM-QPSK. Finally, the Bit Error Rate (BER) is counted over 1×10^6 symbols and converted to Q^2 factor. The results are then assessed at a Q^2 $=6$ dB, as we consider a Forward Error Correction (FEC) code of 25.5% overhead (Q^2 ≈ 5 dB)[8] with around 1 dB margin.

Experimental results

The optical Back-to-Back (BtB) shows the linear performance of each modulation format (Fig. 2). It is important to note that the comparison between the studied formats can change according to the targeted Q^2 factor value, because each format has a different slope of the curve Q^2 factor versus Optical Signal-to-Noise Ratio (OSNR). The difference between PDM-QPSK and PB-4B8D in terms of required OSNR (ROSNR) is 4.25 dB at Q^2 $=$ 6dB. Besides a lower ROSNR for PB-4B8D due to a lower spectral efficiency than PDM-QPSK, the additional gain comes from a coding gain due to an increased Euclidean distance between symbols on multi-dimensions[6], and a slightly lower Tx/Rx penalty than for PDM-QPSK. Specifically, the SNR for this experimental setup saturates at

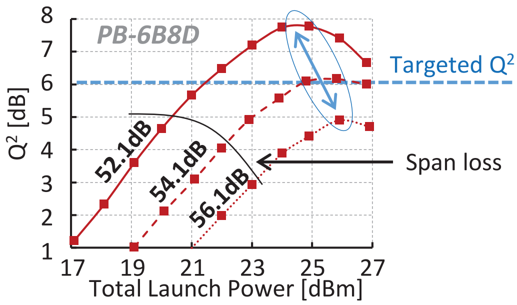

Fig. 3: Bell curve for PB-6B8D for three span loss values with a highlight on the targeted Q^2 factor value and the interpolation method.

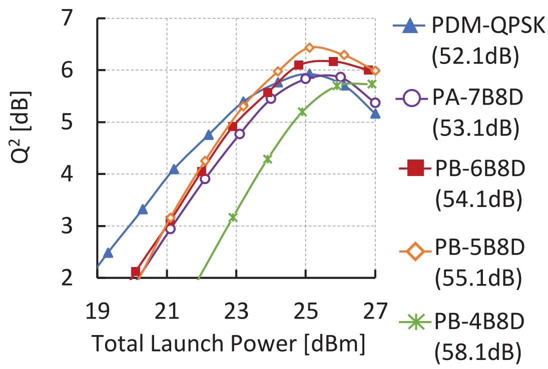

Fig. 4: Bell curve of the single-span transmission. The span loss for each modulation format is showed in the legend.

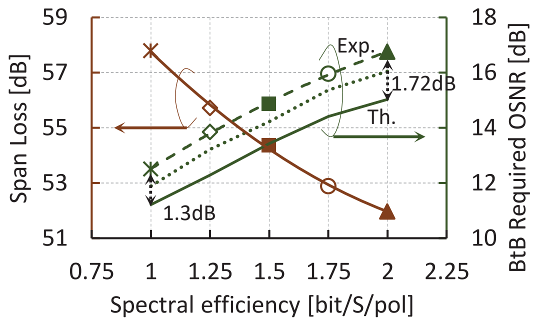

Fig. 5: Theoretical ROSNR (green line), simulated ROSNR assuming a SNR floor (dotted green line) and measured ROSNR (dashed green line with markers) at the targeted Q^2. Interpolated maximum span loss for Q^2 factor at the optimal launch power.

14 dB, while the theoretical SNR working points at $Q^2 = 6$ dB of PB-4B8D and PDM-QPSK are 2.3 dB and 6 dB, respectively. The theoretical ROSNR is shown on Fig. 5 with a green line, simulation results while considering the experimental SNR floor in dotted green line and experimental BtB in dashed green line with markers. It can be observed that the dependency of the ROSNR penalty on modulation formats comes from the SNR floor, because the gap is constant between the simulated ROSNR with SNR floor and the experimental BtB ROSNR.

For the transmission experiment, three span loss values were assumed for each modulation format. In order to estimate the span loss on a Bell curve where $Q^2 = 6$ dB at the optimal launch power, an interpolation method was used on the three measured bell-curves. An example of the obtained bell-curves for PB-6B8D is shown on Fig. 3, highlighting the interpolation method. The Q^2 factor is plotted as a function of the total launch power, for three different span loss. Fig. 4 shows bell-curves for each modulation format. The curves that had Q^2 the closest to 6 dB at the optimal launch power are picked. It is important to note that the optimal launch power of PDM-QPSK is 25 dBm, and increases as the format SE decreases, to end-up with a value of 26.5 dBm for PB-4B8D, while the maximum output power of the EDFA booster is 27 dBm. This is the reason why only five WDM channels are considered in this experiment.

The final results on span loss values are shown on Fig. 5 in brown line with markers. For instance, a total gain of 5.8 dB in span loss is found for PB-4B8D over PDM-QPSK, which corresponds to the 4.25 dB gain in BtB (on Fig. 5 in dashed green line) plus an additional 1.55 dB gain due to a better tolerance to nonlinear noise. Considering the rest of the modulation formats, intermediate values of span loss are obtained. This allows to achieve the rate flexibility for single-span unrepeatered systems, while for different transmission distances, the transmission capacity can be maximized.

Conclusions

We experimentally assessed a series of multi-dimensional modulation formats for 100 Gbaud single-span unrepeatered applications. We showed that these PDM-QPSK based modulation formats can be a solution for multi-rate applications at entropies lower than 2 b/S/pol. As we are targeting a system configuration at a Baudrate of 100 Gbaud at 112.5 GHz channel spacing with an FEC overhead of 25.5%, the throughput (including pilots) with PDM-QPSK is 320 Gbit/s at a spectral efficiency of 2.84 b/S/Hz. We therefore demonstrated a multi-rate capability with data-rates between 160 Gbit/s (SE $= 1.42$ b/S/Hz) and 320 Gbit/s (SE $= 2.84$ b/S/Hz) with a granularity of 40 Gbit/s (ΔSE ≈ 0.36 b/S/Hz). We showed that multiple transmission distances can be reached while maximizing the transmission capacity. Finally, it is important to note that the same DSP algorithms required by PDM-QPSK are used for all other formats, while only a low-complexity mapping and demapping parts are added.

References

[1] M. Karlsson et al., “Which is the most power-efficient modulation format in optical links?,” Opt. Express, **17**, pp 10814-10819, (2009).

[2] F. Buchali et al., “Rate Adaptation and Reach Increase by Probabilistically Shaped 64-QAM: An Experimental Demonstration,” J. Lightwave Technol., Vol. **34**, no. 7, pp. 1599-1609, (2016).

[3] M. Reimer et al., “Optimized 4 and 8 dimensional modulation formats for variable capacity in optical networks,” Proc. OFC, M3A.4, (2016).

[4] D. F. Bendimerad et al., “Ultra-Low Complexity and High Performance Soft-Demapper for 8D Set-Partitioned PDM-QPSK Modulation Formats,” Proc. ECOC, Mo4F.1, (2018).

[5] D. F. Bendimerad et al., “Partially Ordered Statistics Demapping for Multi-Dimensional Modulation Formats,” Proc. OFC, W3H.5 (2019).

[6] A. D. Shiner et al., “Demonstration of an 8-dimensional modulation format with reduced inter-channel nonlinearities in a polarization multiplexed coherent system,” Opt. Express, Vol. **22**, p. 20366-20374 (2014).

[7] D. F. Bendimerad et al., “Nonlinearity-tolerant 8D modulation formats by set-partitioning PDM-QPSK,” Proc. OFC, M1G.5 (2018).

[8] K. Sugihara et al., ”A spatially-coupled type LDPC Code with an NCG of 12 dB for optical transmission beyond 100 Gb/s,” Proc. OFC/NFOEC, OM2B.4 (2013).