

Ultra-long-haul transmission of 7×42.9 Gbit/s PS-QPSK and PM-BPSK

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Abstract: We report on ultra-long haul transmission of polarization-switched QPSK (PS-QPSK) and polarization-multiplexed BPSK (PM-BPSK) at 42.9Gbit/s per WDM channel. Although achieving similar transmission distances in excess of 13,600km, PS-QPSK offers a significant reduction in receiver complexity due to a lower symbol-rate.

OCIS codes: (060.2330) Fiber optics communication; (060.4080) Modulation.

1. Introduction

To date, transmission over ultra-long haul transmission links has been carried out using conventional polarization-multiplexed signal formats, e.g. polarization-multiplexed binary phase shift keying (PM-BPSK) [1] and quadrature phase shift keying (PM-QPSK) [2]. However, these modulation formats are tailored to a 2-dimensional channel with circularly-symmetric Gaussian noise despite the fact that an optical wave offers 4 degrees of freedom (2 quadratures in 2 polarizations). Recently, work to determine the optimum modulation format for this higher dimensional channel by solving a 4-dimensional sphere packing problem has been carried out[3, 4]. In this work, polarization-switched QPSK has been proposed as the modulation format with the highest asymptotic power efficiency and an asymptotic sensitivity gain of 1.76dB over BPSK, which is currently the only commercially available option for transpacific transmission at 40Gb/s[5].

In this paper we present, for the first time, a comparison of PS-QPSK and PM-BPSK on an ultra-long-haul transmission link, extending the recent work experimentally demonstrating PS-QPSK and its comparison with PM-QPSK [6]. Wavelength-division-multiplexed (WDM) transmission is carried out on a 50GHz grid with a line rate of 42.9Gbit/s per WDM channel demonstrating similar transmission distances for both modulation formats. However, due to its lower symbol-rate PS-QPSK offers significantly lower DSP complexity by allowing for a more than 50% reduction in length of the FIR-filter for chromatic dispersion compensation.

2. Experimental Setup

To compare the transmission performance of PM-BPSK and PS-QPSK we used an external cavity laser (ECL) at 1553nm with a linewidth of 100kHz surrounded by 6 DFB-lasers on 50GHz frequency grid. BPSK was generated by driving two arms of an IQ-modulator with 21.45Gbit/s $2^{15}-1$ long pseudo-random binary sequences (PRBS) using DATA and $\overline{\text{DATA}}$ outputs of a pulse pattern generator. The IQ-modulator was followed by a polarization multiplexing stage with a relative delay of 48 symbols yielding PM-BPSK (Figure 1 (a)). In the case of PS-QPSK, the IQ-modulator was driven with two decorrelated 14.3Gbit/s PRBS-15 patterns to obtain QPSK, which was

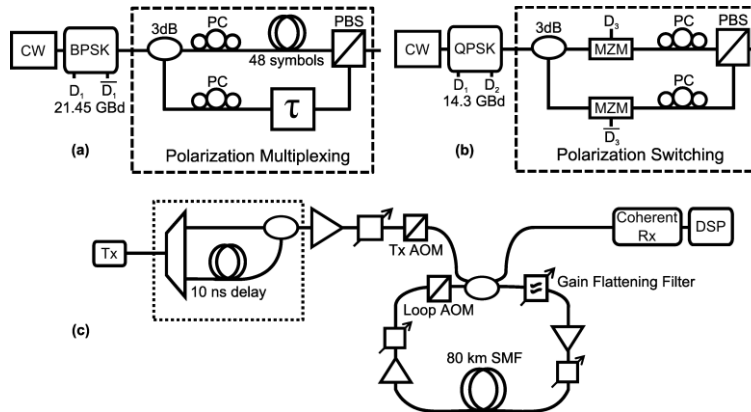


Figure 1: Schematic of (a) the PM-BPSK transmitter, (b) the PS-QPSK transmitter, and (c) the single span recirculating loop with coherent receiver used to investigate transmission performance.

followed by a polarization switching stage consisting of two parallel Mach-Zehnder modulators (MZMs) (Figure 1 (b)). The MZMs were driven with inverse data patterns to block one or the other polarization to generate the PS-QPSK. Even and odd channels were subsequently separated with a 50GHz interleaver and recombined with a relative delay of 10ns to decorrelate neighbouring channels. The WDM-signal was then launched into a single-span recirculating loop with 80.24km of standard single mode fiber (SMF). The accumulated chromatic dispersion per recirculation was 1347ps/nm and the span loss was 15.4dB [7]. Two EDFAs with noise figures of 4.5dB and a fixed output power of 17dBm were used to amplify the signal while variable optical attenuators were used to set the launch power and balance the loop. A Mach-Zehnder filter was used to equalize the wavelength-dependent gain of the EDFAs.

The signal was detected with a phase and polarization-diverse coherent receiver using a pair of balanced PINs to receive each quadrature. The local oscillator was an ECL with 100kHz linewidth whose frequency was tuned to ensure that the frequency offset did not exceed 1GHz. The signal was digitized with a digital sampling oscilloscope (DSO) with an electrical bandwidth of 16GHz and processed offline. After the signal had been deskewed, normalized and resampled, chromatic dispersion was compensated digitally. For PS-QPSK, a polarization-switched constant modulus algorithm (PS-CMA) equalizer with least-mean squares (LMS) updating followed by a modified Viterbi & Viterbi phase recovery was used [7, 8]. In the case of PM-BPSK, joint equalization and phase-recovery was performed in a similar manner to that described in [9] for PM-QPSK.

3. Transmission results at 42.9Gbit/s

Figure 2 shows back-to-back measurements of the receiver sensitivity for (a) PM-BPSK and (b) PS-QPSK. The results are plotted on a double-log scale and fitted linearly to ease comparison between the formats as well as against theoretical sensitivity limits. Single channel PM-BPSK shows an implementation penalty of 0.4dB at $\text{BER}=3.8 \times 10^{-3}$ as opposed to 0.8dB for PS-QPSK. Adding more WDM channels to the signal resulted in an additional penalty of 0.2dB in both cases, which is due to coherent crosstalk induced by neighbouring channels. Taking this into account it is worth noting that, at a BER of 3.8×10^{-3} , PS-QPSK preserves 0.4dB of the theoretical sensitivity advantage of 0.75dB over PM-BPSK.

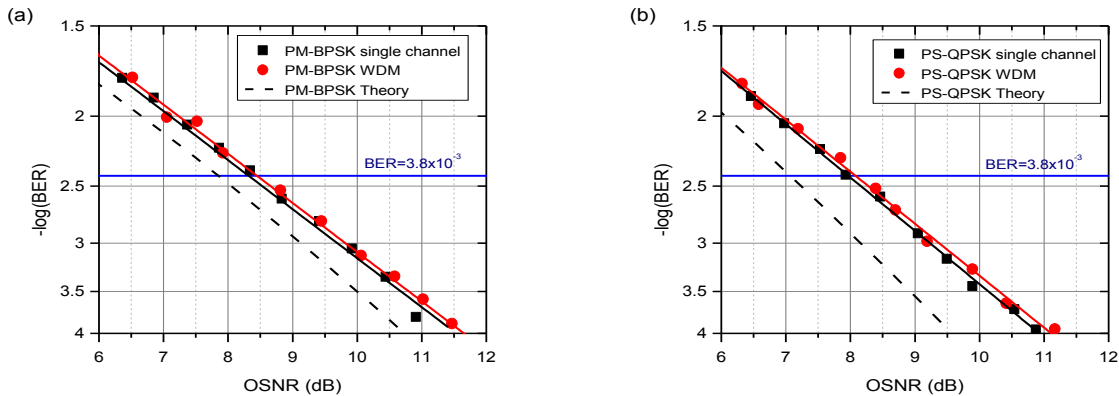


Figure 2: Back to back measurement of OSNR sensitivity for single channel and WDM configuration of (a) PM-BPSK and (b) PS-QPSK

To characterize the transmission performance of both modulation formats, 7 WDM channels were launched into a recirculating loop and the launch power per channel was varied between -14 and 4dBm to determine the maximum transmission distance at $\text{BER}=3.8 \times 10^{-3}$. Figure 3 shows the experimental results which have been fitted with a polynomial fit [10] to emphasize the trend in the linear and nonlinear transmission regimes.

The improved sensitivity of PS-QPSK with respect to PM-BPSK observed in the back-to-back measurements translates directly into a 0.4dB improvement in the linear region of the reach curve. However, on the nonlinear part of the reach curve, PM-BPSK is up to 2dB more resilient towards nonlinearities than PS-QPSK, which we attribute to a higher phase-margin between adjacent constellation points. The higher susceptibility of PS-QPSK to nonlinear distortions leads to a 1dB lower optimum launch power of -3.5dBm compared to -2.5dBm for PM-BPSK.

However, Figure 3 indicates that this only translates into a less than 3% higher transmission distance for PM-BPSK (14,000km for PM-BPSK versus 13,600km for PS-QPSK). Additionally, PM-BPSK requires an approximately 56% longer FIR-filter for chromatic dispersion compensation since the number of taps scale with the square of the symbol-rate. For transmission over 170 spans this corresponds to 1498 taps as opposed to 3371 taps [11], which translate into 2048 and 4096 taps when ceiled to the nearest power of two for implementation with the

overlap and save technique. Furthermore, the lower symbol-rate of PS-QPSK leads to 33% lower electrical bandwidth requirements for transmitter and receiver-side electronics compared to PM-BPSK.

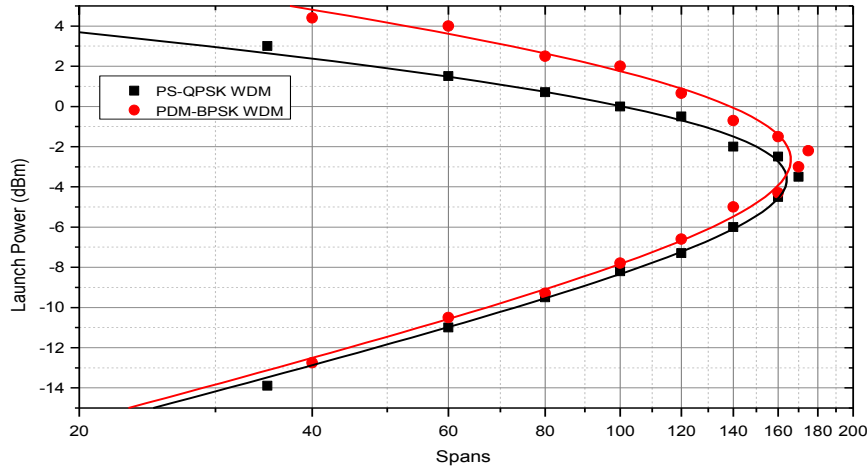


Figure 3: Achievable transmission distance of 42.9Gbit/s PM-BPSK and PS-QPSK at $BER=3.8 \times 10^{-3}$. 7 WDM channels were transmitted on a 50GHz grid achieving maximum transmission distances in excess of 13,600km with a span-length of 80km.

4. Conclusions

We compared, for the first time, ultra-long haul transmission of PS-QPSK and PM-BPSK at 42.9Gbit/s. WDM-transmission over an uncompensated SMF link employing 80km spans with EDFA-only amplification and phase and polarization-diverse coherent detection was investigated experimentally. Due to its reduced resilience to nonlinearities, PS-QPSK yielded a marginally lower transmission distance of 13,600km as opposed to 14,000km for PM-BPSK. However, due to its reduced symbol-rate PS-QPSK offers the benefits of reduced receiver complexity and lower bandwidth requirements for transmitter and receiver electronics which makes it attractive for ultra-long haul transmission.

5. Acknowledgements

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