A Comparison of 43-Gb/s POLMUX-RZ-DPSK and POLMUX-RZ-DQPSK Modulation for Long-Haul Transmission Systems

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Abstract *We compare the suitability of 43-Gb/s POLMUX-RZ-DPSK and POLMUX-RZ-DQPSK modulation for long-haul optical transmission. We experimentally demonstrate that the higher robustness against nonlinear impairments of 43-Gb/s POLMUX-RZ-DPSK allows for a ~40% increase in feasible transmission distance.*

Introduction

Scaling optical transmission systems towards 40-Gb/s line rates has received significant attention over the past decade. With the continuous evolution of the technology, there has as well been a continuous shift in the modulation format considered to be the most suitable for 40-Gb/s long-haul transmission [1].
Recently, the use of digital coherent receivers has attracted much attention as it can enable compensation of linear transmission impairments by using relatively simple FIR equalizers. A number of different modulation formats has been demonstrated combined with digital coherent detection, this includes POLMUX-DQPSK [2], POLMUX-BPSK [3], POLMUX-8PSK [4], and POLMUX-16QAM [5]. Modulation formats such as POLMUX-8PSK and POLMUX-16QAM are best suited for transmission with very high spectral efficiency (i.e. in excess of 2 b/s/Hz), but do not scale well to long-haul transmission distances. 40-Gb/s POLMUX-DQPSK modulation is therefore currently the solution most widely used for commercial deployment, as it relies on optical and electrical components with ~10-GHz bandwidth, which makes it a very cost-effective approach. POLMUX-BPSK at first seems not the most obvious choice for 40-Gb/s line rates. It requires optical and electrical components with ~20-GHz bandwidth, which makes it difficult to enable a cost-effective solution compared to ~10-GBaud POLMUX-DQPSK modulation. However, as shown in [3], 40-Gb/s POLMUX-BPSK might be a suitable choice for ultra-long haul application where it might outperform POLMUX-DQPSK modulation.

In this paper, we compare 43-Gb/s POLMUX-RZ-DPSK and 43-Gb/s POLMUX-RZ-DQPSK modulation, using a digital coherent receiver, for use in long-haul transmission systems. We compare both modulation formats with respect to transmission performance, i.e. their robustness against nonlinear transmission impairments over a non-dispersion managed (NDM) transmission link and finally their feasibility to allow for an ultra long-haul transmission distance at 43-Gb/s line rates.

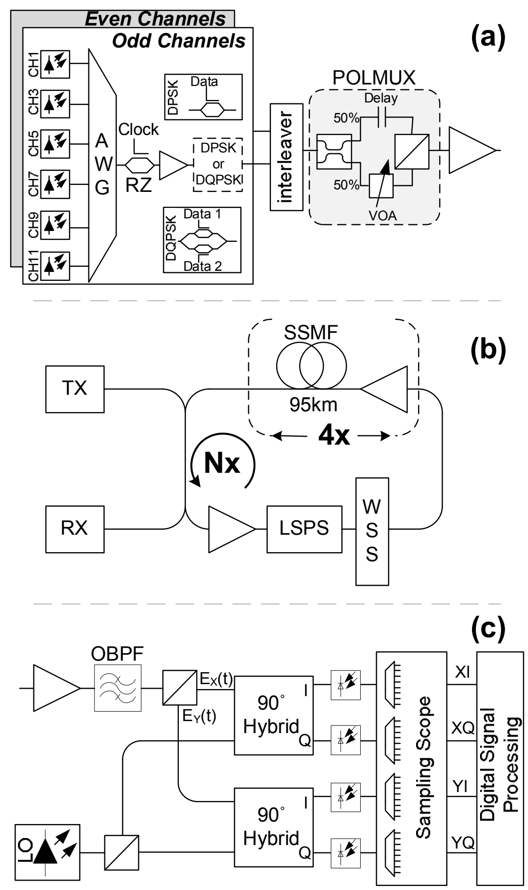

Fig. 1: Experimental Setup, (a) Transmitter, (b) Recirculating loop and (c) Coherent receiver

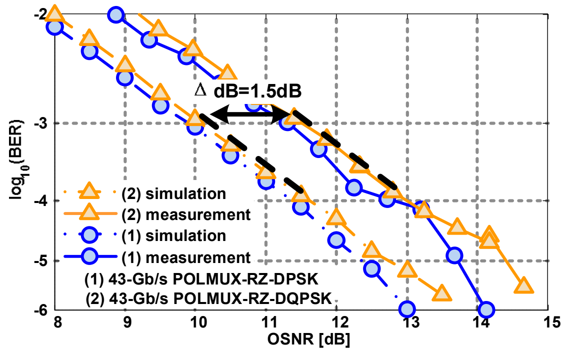

Fig. 2: Back-to-back results

Experimental System Setup

Fig. 1 shows the schematic of the experimental system setup. Two distinct transmitters are used to generate either a 43-Gb/s POLMUX-RZ-DPSK or a 43-Gb/s POLMUX-RZ-DQPSK modulated signal. In each configuration two separate modulator chains are used to modulate the wavelength channels, one for the 100-GHz spaced ITU grid and one for the offset ITU grid. After combining the output of the lasers with an AWG, the signal is first return-to-zero (RZ) pulse carved using a Mach-Zehnder modulator (MZM), driven at a clock frequency of 21.5 GHz for POLMUX-RZ-DPSK or 10.75 GHz for POLMUX-RZ-DQPSK. Afterwards the signal is modulated using a standard and complex IQ modulator for DPSK and DQPSK, respectively. The line rate of the data is equal to the clock frequency and consists of two 2^{16} PRBS sequences, one the inverted of the other, fed to the two distinct transmitters. For QPSK modulation, the data fed to the I- and Q-branch of the modulator are identical, but with a delay of 20 bits. The outputs of the two parallel transmitters are then interleaved by means of a 50-GHz interleaver, yielding 11 DWDM channels. Subsequently, the signal is polarization-multiplexed (POLMUX) by dividing it into two tributaries with equal power, delaying one tributary, and then recombining both tributaries on orthogonal polarizations using a polarization beam splitter (PBS). The delay between both tributaries is set such that the resulting signal is polarization interleaved.

The transmission link consists of a re-circulating loop with 4 spans of 95 km SSMF and EDFA-only amplification. The re-circulating loop contains as well a loop synchronized polarization scrambler (LSPS) in order to emulate the polarization evolution of a long-haul transmission link and a WSS to emulate optical add-drop nodes and to equalize the optical spectrum.

At the receiver, an optical bandpass filter (OBPF), with a 40 GHz bandwidth for POLMUX-RZ-DPSK or 25 GHz bandwidth for POLMUX-

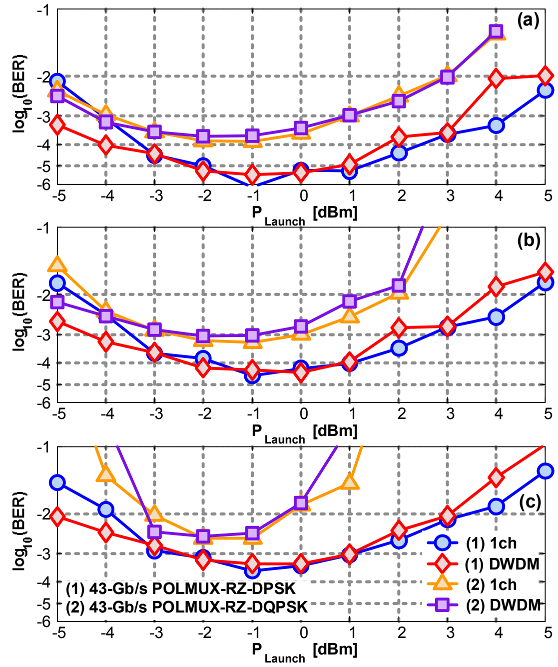

Fig. 3: Launch power vs. BER after (a) 3420km, (b) 4560km and (c) 5700km of SSMF (Experimental)

RZ-DQPSK, is used to extract the center channel at 1550.52 nm. Subsequently two polarization beam splitters and two 90° hybrids are used to mix the signal with a free-running LO-laser. The four outputs of 90° hybrids are detected using four single-ended PIN/TIA photodiodes (PDs).

After the PDs, a digital storage scope samples the four tributaries at a sampling rate of 50 Gsamples/s and stores samples from each tributary. Offline digital signal processing is used to demodulate the resulting samples as described in [6].

Transmission results

The back-to-back results are depicted in Fig. 2. It can be observed that for both modulation formats the difference between the simulated curve and measured curve is equal to ΔdB=1.5dB. The difference between POLMUX-RZ-DPSK and POLMUX-RZ-DQPSK is less than 0.2 dB, thus it can be concluded that the difference in performance after transmission is due to transmission impairments only.

Fig. 3 depicts the experimental results after transmission over (a) 3420 km, (b) 4560 km and (c) 5700 km of non-dispersion-managed SSMF transmission link (9, 12 and 15 loop re-circulations, respectively). It is evident that there is a significant difference in nonlinear tolerance between the two modulation formats. For 43-Gb/s POLMUX-RZ-DQPSK the optimum input power is approx. -2 dBm, whereas the optimum input power for 43-Gb/s POLMUX-RZ-

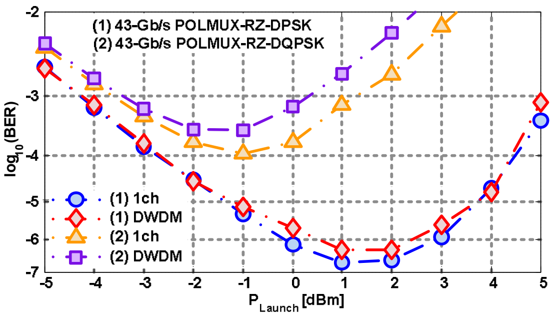

Fig. 4: Launch power vs. BER after 5700km of SSMF (Simulation)

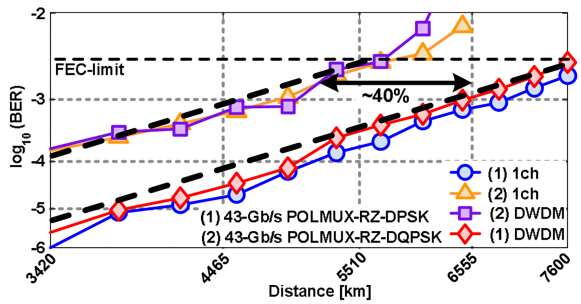

Fig. 5: Distance vs. BER with optimal launch power (Experimental)

DPSK is equal to 0 dBm. The main reason for the higher nonlinear tolerance of DPSK is the twice as large phase difference between the constellation points in comparison to DQPSK, which makes DPSK less vulnerable to nonlinear phase rotations.

Moreover, it is observed that when increasing the transmission distance the nonlinear penalties for 43-Gb/s POLMUX-RZ-DPSK increase only minimally, whereas a much stronger increase is observed for 43-Gb/s POLMUX-RZ-DQPSK. This indicates that the accumulation of nonlinear transmission penalties for 43-Gb/s POLMUX-RZ-DPSK is smaller in comparison to 43-Gb/s POLMUX-RZ-DQPSK. For dispersion uncompensated transmission the nonlinear transmission penalty does not scale only with the total accumulated nonlinear phase shift, but is as well dependent on the number of spans [7]. This effectively results in a slower increase of the nonlinear transmission penalty for increasing transmission distances, and this effect is evidently stronger for 43-Gb/s POLMUX-RZ-DPSK in comparison to 43-Gb/s POLMUX-RZ-DQPSK.

For both 43-Gb/s POLMUX-RZ-DPSK and POLMUX-RZ-DQPSK modulation the difference between single-channel and multi-channel transmission is negligible. The XPM penalty is low because the SSMF is a highly dispersive fiber, which results in a strong walk-off between neighbouring channels. It can therefore be concluded that transmission is mainly SPM limited.

Fig. 4 depicts the simulation results after transmission over 5700 km of NDM SSSMF transmission. When comparing the experimental results in Fig. 3 with the simulation results in Fig. 4 the same trend is observed. The optimum launch power for 43-Gb/s POLMUX-RZ-DPSK is +1 dBm whereas for 43-Gb/s POLMUX-RZ-DQPSK this is -1 dBm in for both measurements and simulations, which confirms that 43-Gb/s POLMUX-RZ-DPSK modulation is significantly more tolerant to nonlinear transmission impairments. The advantage of POLMUX-RZ-DPSK over POLMUX-RZ-DQPSK is significantly larger in the simulation when compared with measurements. We conjecture that this is the result of transmission impairments that are not reflected in the simulations, such as nonlinear phase noise.

Fig. 5 shows the measured BER versus transmission distance at a launch power of -1 dBm and -2 dBm for 43-Gb/s POLMUX-RZ-DPSK and 43-Gb/s POLMUX-RZ-DQPSK, respectively. The results show that transmission of multi-channel 43-Gb/s POLMUX-RZ-DPSK over SSMF can reach up to 7600 km while staying below the FEC-limit (3.8e-3 for a 7% FEC overhead), whereas 43-Gb/s POLMUX-RZ-DQPSK is limited to a maximum transmission distance of 5600 km. The performance difference between the modulation formats is constant over distance, which indicates that the feasible transmission distance can be increased by ~40% when using 43-Gb/s POLMUX-RZ-DPSK instead of 43-Gb/s POLMUX-RZ-DQPSK modulation.

Conclusions

In this paper we have shown by means of experiments that 43-Gb/s POLMUX-RZ-DPSK is more tolerant to nonlinear transmission impairments than 43-Gb/s POLMUX-RZ-DQPSK. Although a more complex solution, the feasible transmission distance can be increased by ~40% when employing 43-Gb/s POLMUX-RZ-DPSK, clearly indicating it's benefit for ultra long-haul transmission systems.

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