Coherent 40 Gb/s Transmission with High Spectral Efficiency Over Transpacific Distance

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Abstract: We experimentally study the reach of coherent 40 Gb/s PDM RZ QPSK transmission at several spectral efficiencies. Transpacific transmission distance at 3.2 bits/s/Hz and record SE-distance product at 2.4 bits/s/Hz are demonstrated.

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1. Introduction

Improving spectral efficiency (SE) is an attractive way to increase available fiber capacity and meet the challenges of increasing bandwidth demand. 40 Gb/s line rates are now being deployed in terrestrial networks making it necessary to find optimal technical solutions for transporting this data rate over transoceanic routes. 40 Gb/s transpacific reach (>9,000 km) has been demonstrated at 0.8 bits/s/Hz SE using polarization division multiplexed (PDM) binary phase shift keying (BPSK) with coherent detection and offline digital signal processing (DSP) [1].

In this work we target spectral efficiencies greater than unity for transoceanic length propagation. We use 40 Gb/s coherent PDM return-to-zero quaternary phase shift keying (RZ-QPSK) for its ability to provide both high SE and good nonlinear tolerance. Moreover, massive dispersion compensation in DSP is feasible for this modulation format due to its relatively low baud rate. We achieve transpacific reach for spectral efficiencies up to 3.2 bits/s/Hz with ~1.7 dB FEC margin. These results are close to the current state of the art at 100 Gb/s (3.6 bits/s/Hz SE [2]). However, we achieve even higher FEC margin and/or transmission distance for spectral efficiencies lower than 3.2 bits/s/Hz. This margin could be traded for increased repeater spacing or relaxed requirements for fiber parameters such as loss and effective area. At 2.4 bits/s/Hz SE we achieve 17,900 km transmission distance for a record SE-distance product of 42,960 km·bits/s/Hz.

2. Experimental Setup

Figure 1 shows a schematic of our experimental setup. Our transmitter uses 8 tunable external cavity lasers (ECL) that are arranged in two independent rails (odd and even channels). The 40 Gb/s channels are generated by splitting the wavelengths of each rail into two paths that are modulated separately at a symbol rate of 11.56 Gbaud with the RZ-QPSK format using data and inverted data patterns with quarter word shift in the 2^{23}-1 pseudo random binary sequence (PRBS). The two paths are then recombined with orthogonal polarization using a polarization beam combiner (PBC) to create the final PDM RZ QPSK-signals. We pre-filter and combine both generated rails using an optical interleaver filter (OIF) at the appropriate channel spacing for each investigated SE. We have also experimentally confirmed that a de-correlated 4-rail transmitter described in [3] performs similarly to the 2-rail setup shown in Fig. 1 at 12.5 GHz channel spacing.

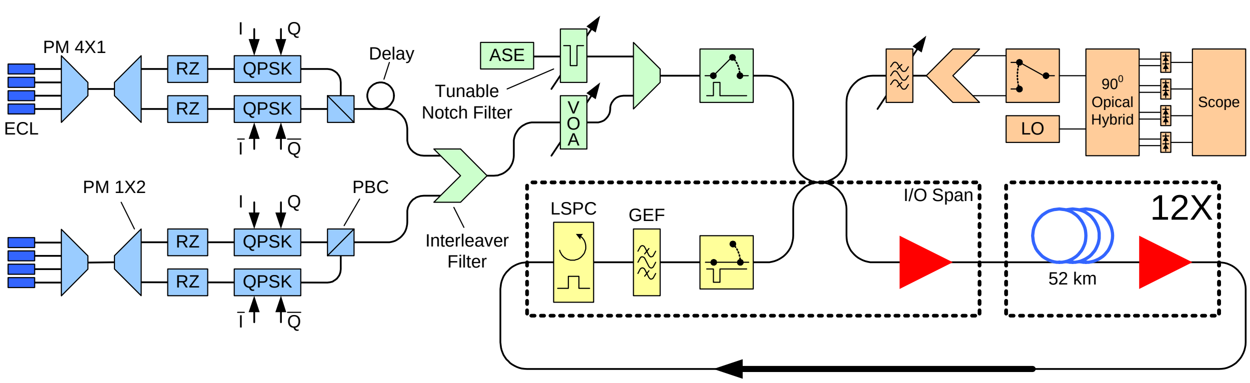

Figure 1: Block diagram of the experimental setup.

To properly load the 26 nm pass-band of the amplifier chain we combine the eight modulated data channels with broad-band amplified spontaneous emission (ASE) noise. For this purpose we use a broadband ASE source and a tunable notch filter where the notch is tuned in position and bandwidth to match the position and bandwidth of the combined data channels.

The circulating loop test bed is constructed using twelve 52 km spans of large effective area fiber with Aeff ~150 μm^2. The mid-band chromatic dispersion of this fiber is ~20.6 ps/nm/km and attenuation is ~0.183 dB/km. The loss of each span is compensated with a single stage EDFA that is gain equalized to 26 nm bandwidth and running at 17 dBm output power. The loop-specific section contains a loop-synchronous polarization controller (LSPC) to randomize the polarization evolution and an additional gain equalization filter to compensate residual gain error. The total loop length is 624 km and average DGD of the loop is 1.7 ps.

Our coherent detection receiver (Fig. 1) consists of OIFs combined with an optical tunable filter to demultiplex the measurement channels, followed by a polarization diversity 90° optical hybrid and four balanced detectors. The electrical signals from the detectors are recorded using a digital sampling scope with 16 GHz analog bandwidth and 50 GS/s sampling rate. No pre-, post- or inline optical dispersion compensation is used in this experiment. The recorded electrical signals are digitally processed offline. Each data point corresponds to at least 1 million samples. After waveform recovery and alignment, dispersion compensation is performed digitally in the Fourier domain. The resulting waveform is then re-sampled with the recovered clock. A constant modulus algorithm is used for polarization tracking and PMD compensation. Carrier-phase estimation is subsequently applied using the Viterbi-Viterbi algorithm [4]. We do not use differential coding. At very high SE, pre-filtering can induce significant intra-channel inter-symbol interference (ISI) [2, 5] and we use a MAP detection algorithm [6, 7] to mitigate the penalty.

3. Transmission Results

In our transmission experiments we use 4 different channel spacings which result in spectral efficiencies between 1.2 bits/s/Hz and 3.2 bits/s/Hz (Table 1). Note that in the spectral efficiency calculation we use 40 Gb/s information rate. The actual experiment uses a baud rate of 11.56 GBd; thus, the equivalent FEC overhead is ~15%.

Table 1: Channel spacing and corresponding SE.

Channel Spacing (GHz)	33	25	16.67	12.5
Corresponding SE (bits/s/Hz)	1.2	1.6	2.4	3.2

Figure 2 (a) shows the transmission results at 2.4 bits/s/Hz SE as a function of received OSNR for several transmission distances from 8,000 km to 17,900 km. To change the received OSNR at a fixed distance we vary the ratio of noise power to total channel power using a variable optical attenuator (VOA) at the transmitter. The received OSNR among the group of data channels is equalized to within +/-0.5 dB. All curves nearly coincide in the linear portion of the graph at low received OSNR. Note that at 2.4 bits/s/Hz SE and at a transmission distance of 10,500 km the achieved FEC margin is 3.9 dB relative to the 7.6 dB FEC threshold of a commercially available hard-decision FEC with 15% overhead.

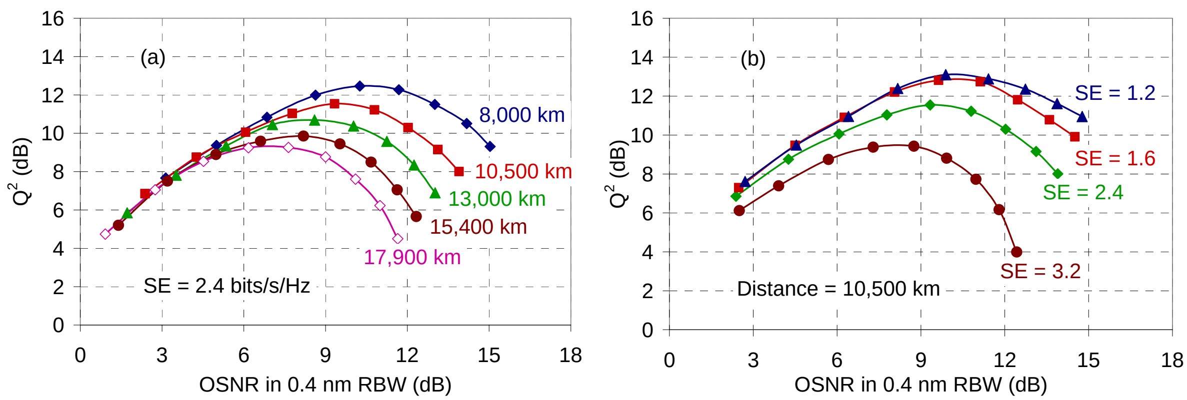

Figure 2: Channel performance at 1550 nm on the test bed at 2.4 bits/s/Hz SE for several distances (a) and at 10,500 km transmission distance for several SE (b).

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We also measure the transmission performance using all four channel spacings at a fixed distance of 10,500 km (Fig. 2 (b)). We observe at the lowest OSNR increased linear crosstalk and inter-symbol interference at 12.5 GHz channel spacing (or the highest spectral efficiency). The optimum received OSNR in 0.4nm RBW also decreases as the channel spacing is reduced.

To assess the reach of the 40G PDM RZ-QPSK transmission format, we repeat the measurements shown in Fig.2 (a) for all four SE from Table 1. For each SE and distance we extract the maximum Q-factor at the optimum received OSNR. The results are plotted in Fig. 3 (a). At 10,500 km transmission distance and 3.2 bits/s/Hz SE approximately 1.7 dB of margin above the FEC threshold are still available.

To evaluate the transmission performance as a function of wavelength, we tune the ASE filter notch and group of eight data channels across the available bandwidth of our test bed. The results are shown in Fig. 3 (b). Average and minimum performance are 9.5 dB and 9.3 dB Q-factor, respectively, corresponding to >1.7 dB margin above the 7.6 dB FEC threshold.

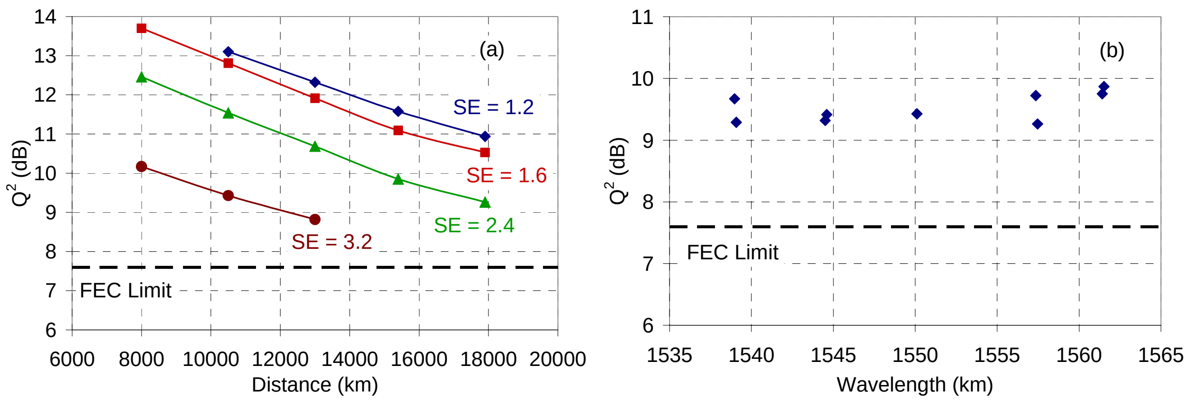

Figure 3: Reach of PDM RZ-QPSK (a) and performance across the band at 3.2 bits/s/Hz and 10,500 km transmission distance (b).

4. Discussion

Margin above the FEC limit increases for decreasing SE at a fixed distance as shown in Fig. 3(a). For example, at 10,000 km transmission distance, decreasing the SE from 3.2 bits/s/Hz to 2.4 bits/s/Hz or 1.6 bits/s/Hz increases the available margin by ~2 dB or ~3 dB, respectively. This increased margin can be traded for increased repeater spacing maintaining the same FEC margin as available at 3.2 bits/s/Hz.

For a fixed number of gates the dispersion compensation capability of DSP is higher for the QPSK format compared to a binary format such as BPSK due to its lower baud rate. For equivalent bit rate and overhead the BPSK baud rate is twice the QPSK baud rate translating into four times higher DSP dispersion compensation capability at a fixed number of gates for the QPSK format.

4. Conclusions

We have experimentally studied the reach of 40 Gb/s coherent PDM RZ-QPSK at high spectral efficiency on a transmission path made up of large effective area fiber with no optical dispersion compensation and simple single stage EDFAs. We demonstrated >10,000 km reach at 3.2 bits/s/Hz spectral efficiency. We also demonstrated that at lower spectral efficiency 40 Gb/s PDM RZ QPSK has significant performance margin. We believe that these results significantly increase the state-of-the-art spectral efficiency- distance product using 40 Gb/s channels.

5. References

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