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Quasi Real-Time 230-Gbit/s Coherent Transmission Field Trial over 820 km SSMF Using 57.5-Gbaud Dual-Polarization QPSK

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Abstract: We demonstrate 230-Gbit/s (57.5-Gbaud) polarization-multiplexed QPSK coherent transmission over 820 km field-installed SSMF with quasi real-time DSP, without resorting to ETDM. BER performance well below FEC error-free threshold (2×10^{-3}) at 2^{31}-1 PRBS length was achieved.

OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications

1. Introduction

Coherent detection employing digital signal processing (DSP) allows multi-level modulation formats in optical transmission systems that increase the spectral efficiency and enhance the transmission capacity. Meanwhile, impairments such as chromatic dispersion (CD), polarization mode dispersion (PMD), laser phase noise (PN), and fiber nonlinearities (FNLs) can also be compensated or mitigated by using DSP in the electrical domain [1]. Coherent detection has become one of the most promising solutions for high speed optical transmission systems. Indeed, with the commercialization of the first generation 100G coherent transmission systems, research has now moved to investigate various solutions to enhance the transmission capacity beyond 100-Gbit/s. One track is to use phase-locked optical sub-carriers to form the so-called 'super-channel' [2]. However, this requires multiple transmitter and receiver setups in real systems and may not be energy efficient. Compared to multi-carrier solutions, single carrier coherent systems allow simpler structures of transmitter, receiver and DSP hardware [3]. For the single carrier systems, the bit rate can be increased by either raising the signal symbol rate or by employing higher-order modulation formats. The latter method is more dispersion tolerant but requires higher optical signal-to-noise ratio (OSNR) and is therefore more susceptible to fiber nonlinearities. Hence, increasing the symbol rate may be a better alternative since faster analog-to-digital converters (ADCs) and DSP processors makes it more straightforward to compensate chromatic dispersion at high baud rate than to compensate for fiber nonlinearities.

Coherent systems using polarization division multiplexed quadrature phase shift keying (PDM-QPSK) at 56-Gbaud had been demonstrated by lab recirculating loop experiment [4,5]. PDM-QPSK system experiment at 80-Gbaud was also demonstrated by transmission over a lab recirculating loop using ultra-large area fiber (ULAF) with Raman amplification [6]. The 80-Gbaud PDM-QPSK system was implemented by using electrical time division multiplexing (ETDM) technique, where bit-error-rate (BER) was actually measured at the original pseudo random bit sequence (PRBS) tributary data rate of 40-Gbit/s [6]. Moreover, in these experiments, signal equalization and BER measurement were carried out using off-line DSP, and the PRBS pattern length was limited to 2^{15}-1 [4-6].

In this paper, we report, to the best of our knowledge, the first time quasi real-time PDM-QPSK coherent transmission at up to 57.5-Gbaud symbol rate over a 820 km field-installed standard single mode fiber (SSMF) link with only in-line Erbium doped fiber amplifiers (EDFAs), without using ETDM technique. The tributary PRBS data at 57.5-Gbit/s had a pattern length of 2^{31}-1, amounting to a single channel bit rate of 230-Gbit/s. Transmitted signal data recovery and BER measurement in the receiver were carried out using quasi real-time DSP. BER performance well below standard forward error correction (FEC) error-free threshold (2×10^{-3}) was achieved.

2. Experimental setup and field link overview

The experimental setup for 57.5-Gbaud PDM-QPSK coherent transmission over the 820 km dispersion unmanaged field link (FL) is shown in Fig. 1. The setup mainly comprised the PDM-QPSK transmitter, the coherent receiver and the field-deployed 820 km SSMF with in-line EDFAs.

In the transmitter, a tunable external-cavity laser (ECL) at 1552.5 nm with ~100 kHz linewidth was used as the signal light source. The tributary 57.5-Gbit/s PRBS data was generated from a pattern generator with a PRBS pattern length of 2^{31}-1, which was then input to an integrated quadrature amplitude modulation (QAM) transmitter module to generate the 57.5-Gbaud QPSK signal. Polarization multiplexing was realized by using an optical polarization multiplexer, where the single polarization QPSK signal from the QAM transmitter was split equally first by a polarization beam splitter (PBS), delayed in one polarization branch, and then recombined by another polarization beam combiner (PBC).

At the receiver, an optical modulation analyzer (OMA) using a 4-channel 33 GHz & 80-GSa/s real-time sampling oscilloscope was used to recover and analyze the received signal. The incorporated local oscillator (LO) in the OMA was a tunable ECL with ~100 kHz linewidth, and the balanced detection had a bandwidth of 40 GHz. Main DSP programs for signal recovery and impairments compensation were as the following: clock recovery was implemented using digital re-sampling; CD compensation was realized using overlap-save based frequency domain equalizer [7], polarization equalization was realized using constant modulus algorithm [1], and carrier phase estimation was achieved using Viterbi-Viterbi algorithm [8]. No PMD equalization and FNLs mitigation were carried out in the DSP. The DSP and BER measurement were run in a quasi real-time manner, meaning that the received data in the processing block were updated continually with the counting of BER being accumulated.

The 820 km field link comprised a series of G.652 SSMFs deployed in eastern coastal area in Sweden, which interconnected seven nodes at Kista, Råsunda, Norrtälje, Östhammar, Gävle, Söderhamn and Hudiksvall, as shown in Fig. 1. The PDM-QPSK signal was transmitted from and received in the transmission laboratory at Kista, while it was looped back in the farthest node at Hudiksvall. Traditional EDFAs are deployed in each node to control the launched signal optical power and to balance the losses of fibers. The OMA measured CD of the installed 820 km SSMF was 14400 ps/nm. The measured PMD of the field link based on Jones matrix analysis was at ~4 ps, giving a PMD coefficient of ~0.14 $ps/\sqrt{km}$. No optical dispersion compensation was employed in the experiment.

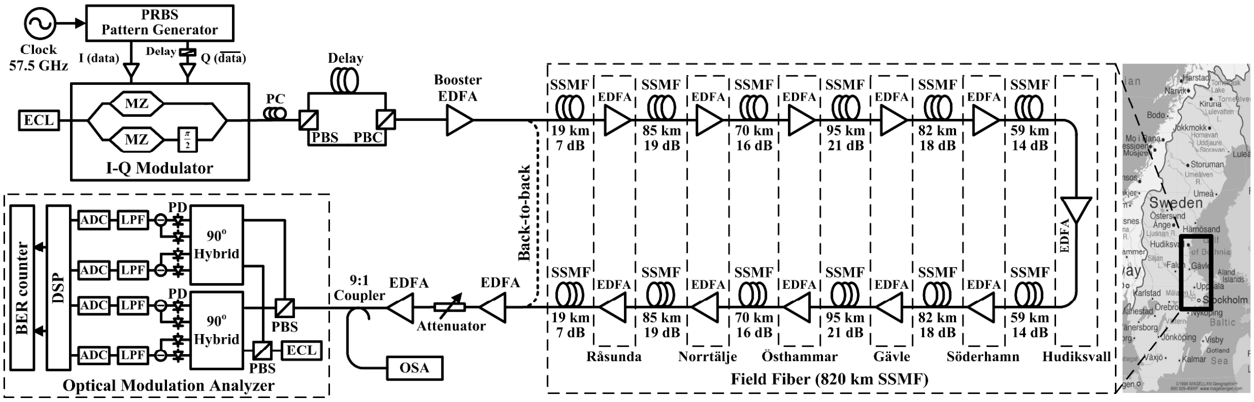
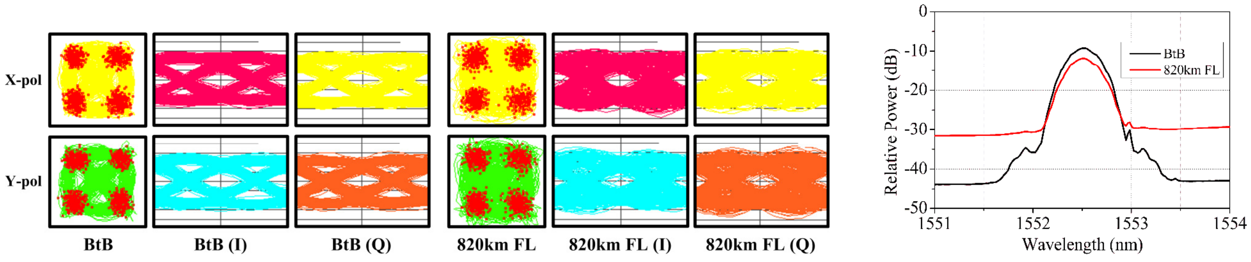


Fig. 1. Experimental setup and field overview of 57.5-Gbaud PDM-QPSK coherent transmission over 820 km installed SSMF in Sweden

3. Experimental results and discussion

As an illustration, Fig. 2(a) shows the I-Q constellations and the demodulated I/Q tributary data eye-diagrams of the 57.5-Gbaud PDM-QPSK signal before and after 820 km FL transmission. Their corresponding optical spectra are shown in Fig. 2(b). The error vector magnitude (EVM) of the QPSK signal generated at this baud rate was relatively large at ~20-22% root-mean-square (RMS). This was mainly due to the amplitude variations of the original PRBS data generated by the pattern generator at such high bit rate.



(a) (b)

Fig. 2. Constellations and spectra of the 57.5-Gbaud PDM-QPSK signal before and after 820 km field link, (a) I-Q constellations and tributary (I&Q) eye-diagrams, (b) optical spectra (0.07 nm resolution)

Fig. 3(a) shows the best achievable BER performance after transmission through 820 km field link with different launched optical power in each SSMF span. For comparison, the same results for the signal at 56-Gbaud are also shown. We can see that when the launched optical power was in the range of 0.9 - 7.5 dBm, BER below the standard FEC error-free threshold can be achieved. The optimum launched power was at 4 dBm. When input power was less than 4 dBm, BER behavior improved with the increment of launched optical power. When input power exceeded 4 dBm, BER behavior would degrade with the increment of launched power due to the increasing effect of fiber nonlinearities. Nevertheless, the 57.5-Gbaud PDM-QPSK signal had a robust (6.6 dB) tolerance to channel noise and fiber nonlinearities, when the launched optical power deviated from the optimum value.

Fig. 3(b) shows the measured BER versus signal OSNR at the optimum launch power (4 dBm) in each SSMF span. For comparison, the BtB as well as the corresponding measurement results at 56-Gbaud are also shown. We can see that little degradation can be observed as compared to the BER performance at 56-Gbaud. The BER can reach well below standard FEC error-free threshold (2×10^{-3}) after transmission over the 820 km field-installed SSMF link. The penalty between BtB and 820 km field transmission at FEC error-free threshold (2×10^{-3}) was ~3 dB. This penalty is attributed mainly to equalization enhanced phase noise (EEPN) and the effect of fiber nonlinearities that the DSP algorithms in the OMA did not compensate [9].

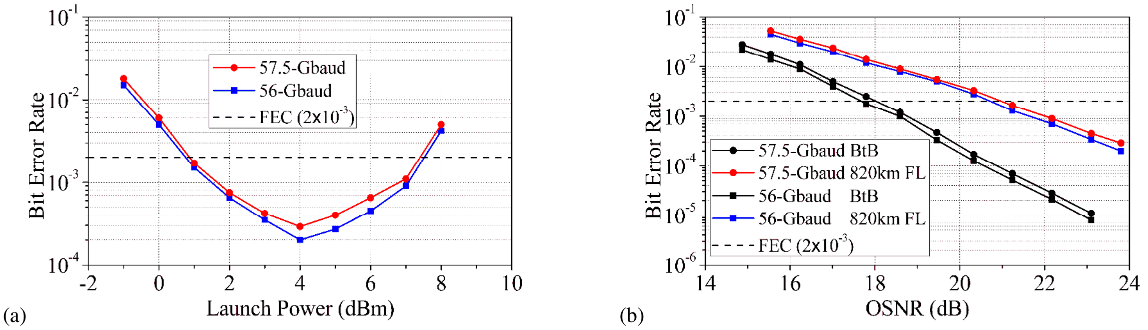


Fig. 3. BER performance in the 57.5-Gbaud PDM-QPSK system, (a) BER versus signal launch power in each SSMF span in the field link, (b) BER versus OSNR at the optimum signal launch power (4 dBm)

4. Conclusions

We demonstrated coherent transmission over 820 km field-installed SSMF of PDM-QPSK signal at 57.5-Gbaud, corresponding to a total signal bit rate of 230-Gbit/s, where the quasi real-time DSP and BER measurement were applied. BER performance well below standard FEC error-free threshold (2×10^{-3}) at the signal tributary PRBS pattern length of 2^{31}-1 was achieved. The 57.5-Gbaud PDM-QPSK signal was generated without using ETDM technique. Our work verifies the feasibility for upgrading the capacity of the commercial 100-Gbit/s PDM-QPSK coherent transmission system directly to 200-Gbit/s and beyond.

5. Acknowledgements

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