0.87 Tbit/s 160 Gbaud Dual-Polarization D8PSK OTDM Transmission over 110 km

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Abstract *The feasibility of transmitting 0.87 Tbit/s dual polarization D8PSK-OTDM over 110 km is, for the first time, demonstrated along with 0.44 Tbit/s single polarization D8PSK-OTDM over 220 km in conventional 55-km span SMF+DCF link.*

Introduction

Over the last years there has been a significant interest in identifying schemes capable of increasing the data capacity in optical transmission by employing more sophisticated modulation formats than the conventional binary modulation. To further increase the capacity of individual wavelength channels it has been suggested to use optical time division multiplexing (OTDM) to increase the achievable symbol rate[1]. The use of differential quadrature phase shift keying (DQPSK) in conjunction with OTDM has been demonstrated several times reaching transmission distances of several hundred km and data rates exceeding 1 Tbit/s[2,3]. Applying more complex modulation formats to OTDM signals such as 8-level phase shift keying (D8PSK) and 16-level quadrature amplitude modulation (16-QAM) has so far only been demonstrated in back-to-back configuration. These demonstrations have, however, emphasized the great capacity potential of such signals where generation and detection of several Tbit/s in a single wavelength channel has been shown[4].

In this paper, we present the first demonstration of the transmission of a D8PSK OTDM signal. In contrast with previous work[4], our system does not rely on a digital coherent receiver with offline processing, but make use of real time interferometric detection after time demultiplexing in an all-optical gate. We demonstrate 220 km transmission of a 0.44 Tbit/s D8PSK OTDM signal, and 110 km transmission of 0.87 Tbit/s using polarization multiplexing. The signals have total bit-rate of 0.48 Tbit/s and 0.96 Tbit/s, respectively, and both achieve a BER better than the 10^{-3} required for error free detection with 10% forward error correction (FEC) overhead. The transmission demonstrated here is carried out over standard single mode fiber (SMF) using 55 km spans compensated by dispersion compensating fibers (DCF) making the system fully compatible with existing fiber infrastructure. We believe this is a major step towards increasing channel capacity in optical transmission systems far beyond what is currently available. The demonstrated data signal has sufficient capacity to carry two 400 Gbit/s channels making the signal format highly relevant for the anticipated 400 Gbit/s Ethernet standard.

Experimental Setup

The experimental setup of the 160 Gbaud DP-D8PSK OTDM system is illustrated in Fig. 1. At the transmitter, a highly chirped 40 GHz pulse (1553 nm) with 33% duty cycle was created by two cascaded Mach-Zehnder (MZ) modulators followed by a phase modulator. The chirped pulse was subsequently compressed to 2.7 ps through 20 m of a DCF and, thereafter, was launched into the 40 Gbaud D8PSK modulator. The I/Q modulator was driven by two 40 Gb/s

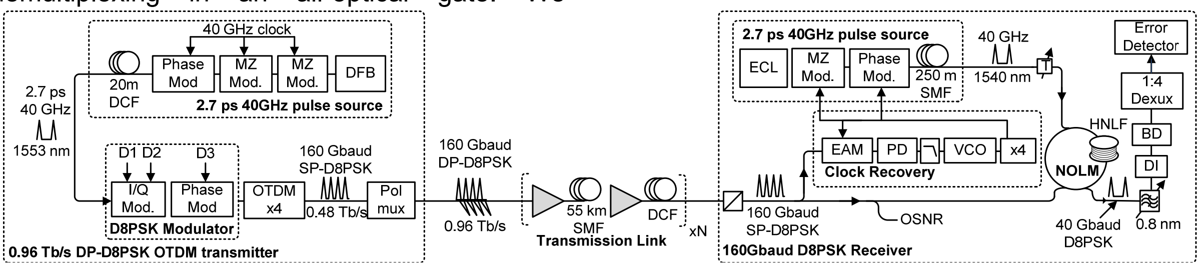

Fig. 1: Experimental Setup of the 160 Gbaud D8PSK OTDM system

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binary data streams, providing a DQPSK signal at the output. The following phase modulator was driven by a third 40 Gb/s binary data stream creating a π/4 phase shift to generate the D8PSK signal. All data streams were decorrelated Pseudo Random Bit Streams (PRBS) with a length of 2^7-1, which was chosen to preserve pseudo-noise characteristic of the signal after the OTDM. The phase-modulated signal was, subsequently, optical time division multiplexed (x4) to generate 160 Gbaud single polarization (SP) D8PSK corresponding to the total bit-rate of 0.48 Tbit/s and it was then polarization multiplexed yielding 0.96 Tbit/s for dual polarization (DP) signal. The polarization multiplexing was realized using a polarization controller, a polarization maintaining 3-dB coupler, and a polarization beam splitter (PBS).

The transmission link used to reach 220 km consisted of four spans of a 55 km SMF and double-stage Erbium-doped fiber amplifiers (EDFAs) with a DCF in between. The average loss of SMFs and DCFs in each span was 11.5 dB and 8 dB, respectively. The chromatic dispersion of the link was compensated within ± 0.5 ps/nm accuracy. At 220 km, the higher-order dispersion and the differential group delay were estimated to be 12 ps/nm^2 and 0.8 ps.

At the receiver, a PBS was used to select one of the orthogonal polarizations of the 160 Gbaud signal. This single polarization signal was then split into two branches, one going to the clock recovery and the second going to the OTDM demultiplexer. A phase-locked loop based on a pre-scaled clock recovery was used to extract the necessary clock signals from the transmitted data signal to synchronize the receiver. The clock recovery sampled the signal by a 40 GHz electro absorption modulator (EAM) driven by a voltage controlled oscillator (VCO). The error signal generated by this sampling process was then used in a feedback configuration to lock the frequency and phase of the VCO to the data signal. A second short pulse source similar to the one described in the transmitter was used to generate optical clock pulses of ~2.7 ps FWHM for demultiplexing in the receiver. The OTDM demultiplexer was based on a non-linear optical loop mirror (NOLM) exploiting the cross-phase-modulation (XPM) effect between the 160 Gbaud data and the 40 GHz clock in a 65m highly-nonlinear fiber (HNLF). The short HNLF length resulted in less than 1 ps walk-off delay thus maximizing XPM between the data and the clock pulses and the switching window width was 2.8 ps allowing efficient demultiplexing of the 160 Gbaud signal. At the output port of the NOLM the 40 Gbaud demultiplexed signal was spectrally isolated and moderately broadened using a 0.8 nm tunable bandpass filter and was then fed into the delay interferometer (DI) with 43 GHz (non-ideal) free-spectral-range (FSR). The differentially demodulated signal was detected by a balanced detector and, later, electronically demultiplexed by a 1:4 demultiplexer before entering the error detector, which was programmed with the expected differentially demodulated bit patterns

Measurement results

Fig. 2a shows the 160 Gbaud SP-D8PSK intensity waveform captured by an all-optical sampling scope after the transmitter illustrating the four OTDM channels having proper temporal alignment and negligible power variation. The amplitude noise found in the waveform is mainly caused by an imperfect modulation of the I/Q modulator and possibly by slight interference between pulse pedestals and neighboring channels. Nevertheless, the differential eye diagrams of the four OTDM channels shown in fig. 2b, as captured with an all-optical balanced detection system[5], are visually identical, suggesting that all channels should have similar performances. Fig. 3 depicts the 0.44 Tbit/s SP-D8PSK signal spectrum measured with 0.1 nm resolution bandwidth. The signal OSNR after the transmitter was measured to be 48 dB. The 20 dB bandwidth of the signal was found equal to 435 GHz, potentially leading to a spectral efficiency of 1 bit/s/Hz for the single polarization signal, and 2 bit/s/Hz for DP-D8PSK.

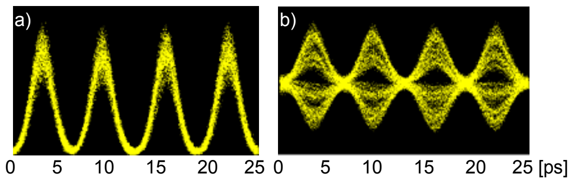

Fig. 2: a) The intensity waveforms and b) differential eye diagrams of 160 Gbaud SP-D8PSK captured after the transmitter

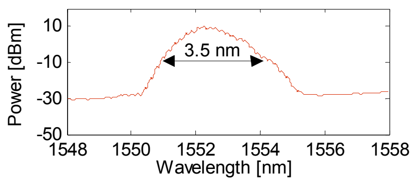

Fig. 3: 160 Gbaud SP-D8PSK spectrum after the transmitter measured with 0.1 nm resolution bandwidth

Fig. 4 presents the back-to-back BER performance as a function of the signal OSNR for the four 40 Gbaud D8PSK channels demultiplexed from 160 Gbaud. Each tributary of the four OTDM channels was measured individually by applying appropriate phase offsets to one arm of the 43 GHz DI (±π/8 and ±3π/8), resulting in 16 curves for single polarization system. The plot shows similar BER performance among the four OTDM channels, confirming the observations on the differential eyes illustrated in Fig. 2b. The required OSNR for BER = 10^{-3} (FEC threshold) was found to be 32 dB, which is in agreement with[6] assuming that 6 dB penalty is expected from quadrupling the baud-rate to 160 Gbaud. The 2 dB excess penalty is likely caused by transfer of intensity noise to phase noise in the optical demultiplexer, induced by interference between OTDM channels. No attempt to launch the signal into the principal states of polarizations were made and since the polarization was varying in the system while no significant BER variation occurred, we conclude that PMD had a small impact on the performance.

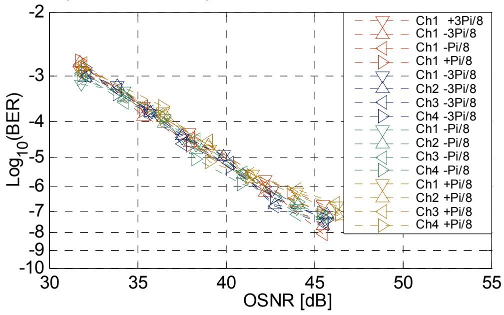

Fig. 4: BER versus OSNR of 160 Gbaud SP-D8PSK. 16 curves illustrates 4 tributaris from all 4 OTDM channel.

Fig. 5 presents the BER performance of 0.44 Tbit/s SP-D8PSK transmission as a function of the optical launch power into the SMFs over various transmission distances (up to 220 km). The input power into the DCFs was kept 5 dB lower than that into the SMFs. For each of the transmission distances we can identify degraded BER performance at lower launch powers due to reduced OSNR as well as at high launch powers, due to nonlinear degradation of the signal during transmission. The curves thus show an interval of optimal launch powers for each transmission distance. At 220 km, accumulated higher-order dispersion gives rise to measureable pulse broadening and ripples in the pulse tails. This causes coherent interference with adjacent channels, which consequently degrades the signal quality. Nevertheless, BER for all distances at the optimal launch power are below 10^{-3}, sufficient for error free detection with FEC overhead. Although single channel-tributary was depicted in fig. 5, several of the others were evaluated, all of which confirmed to have similar performance.

In fig. 6, we compare the performance of the 0.44 Tbit/s SP-D8PSK to the 0.87 Tbit/s DP-D8PSK over 110 km. The 0.87 Tbit/s signal has significant range of launch power where the BER is better than 10^{-3}. Compared to the single polarization case, the BER degradation is partly caused by the OSNR reduction due to the polarization multiplexing but also by the polarization crosstalk between the two orthogonal polarizations. Yet, the BER performance is below the FEC threshold at the whole range of optimal launch powers. In addition, we have verified that BER performances are comparable for both orthogonal polarizations.

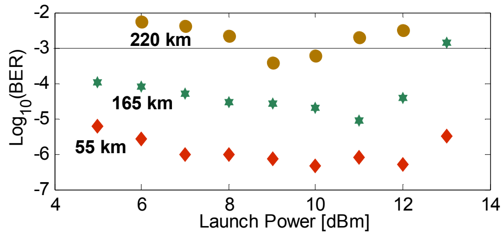

Fig. 5: 0.44 Tbit/s SP-D8PSK BER performances as a function of launch power over 55, 165, and 220 km.

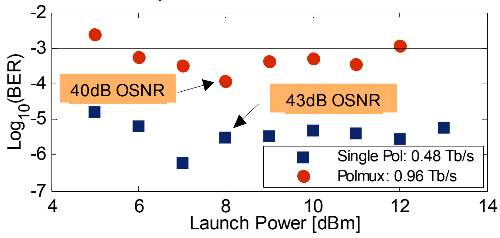

Fig. 6: 0.44 and 0.87 Tbit/s D8PSK BER performances as a function of launch power over 110 km.

Conclusion

We experimentally demonstrated, for the first time, the feasibility of transmitting 0.44 Tbit/s SP-D8PSK OTDM over 220 km enabling 400 Gbit/s Ethernet solution and over 110 km for 0.87 Tbit/s without auxiliary clock transmission. We have clearly shown the potential in using the spectrally efficient D8PSK format together with a high signal base rate of 40 Gbaud to allow single channel transmission of Tbit/s signals over a conventional transmission link using SMF and DCF without coherent detection.

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References

1 M. Nakazawa et al, Electronics Letters, 1998, 34, (9), pp. 907-908
2 C. Schmidt-Langhorst et al, OTuN5, OFC'09
3 C. Zhang et al, PD2.8, ECOC'09
4 C. Schmidt-Langhorst et al, PDPC6, OFC'09
5 H. Sunnerud et al, OThF4, OFC'09
6 E. Tipsuwannakul et al, OMJ2, OFC'10