8×256 Gb/s WDM Transmission Over 2880 km of SSMF with 64 Gbaud DP-QPSK Signals

Qunbi Zhuge*, Xian Xu, Mohammad E. Mousa-Pasandi, Mohamed Morsy-Osman, Ziad A. El-Sahn, Mathieu Chagnon, and David V. Plant
Department of Electrical and Computer Engineering, McGill University, Montreal, QC, H3A 2A7, Canada
**qunbi.zhuge@mail.mcgill.ca*

Abstract: We demonstrate a transmission of 8×256 Gb/s WDM 64 Gbaud QPSK signals over 2880 km of standard single mode fiber (SSMF) with erbium doped fiber amplifier (EDFA)-only amplification and coherent detection.
OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications; (060.4080) Modulation.

1. Introduction

As the 100G optical transports have been commercialized, the research interests and activities are moving to next generation optical transmission systems with higher spectral efficiency [1]. Nevertheless, the transmission of high symbol rate signal still attracts many attentions, since for a given bandwidth it reduces the hardware complexities such as the number of lasers and photodiodes. 56 Gbaud dual-polarization (DP) quadrature phase shift keying (QPSK) transmissions have been demonstrated by some groups [2-4]. More recently, 80 Gbaud DP-QPSK transmission with coherent detection was reported in [5]. With such a high baud rate signal, an eight-channel wavelength-division multiplexing (WDM) transmission with a data rate of 8×320 Gb/s over 5600 km of ultra-large area fiber with Raman amplification was demonstrated.

In this work, we report a coherent transmission of electrically generated 64 Gbaud QPSK signals. A 8×256 Gb/s WDM (100 GHz channel spacing) transmission over 2880 km of standard single mode fiber (SSMF) is realized with erbium doped fiber amplifier (EDFA)-only amplification. In back-to-back transmission, an approximately 3 dB optical signal-to-noise ratio (OSNR) penalty is observed compared to the theoretical limit. Then we show that using the data-aided phase recovery algorithm proposed in our previous work [6] the transmission distance can be increased by approximately 21% compared to the Viterbi and Viterbi algorithm. Finally, we demonstrate that the bit error rates (BERs) of all the eight channels after 2880 km transmission are below 3.8×10^{-3}, which corresponds to the 7% overhead forward error correction (FEC) threshold.

2. Experimental setup

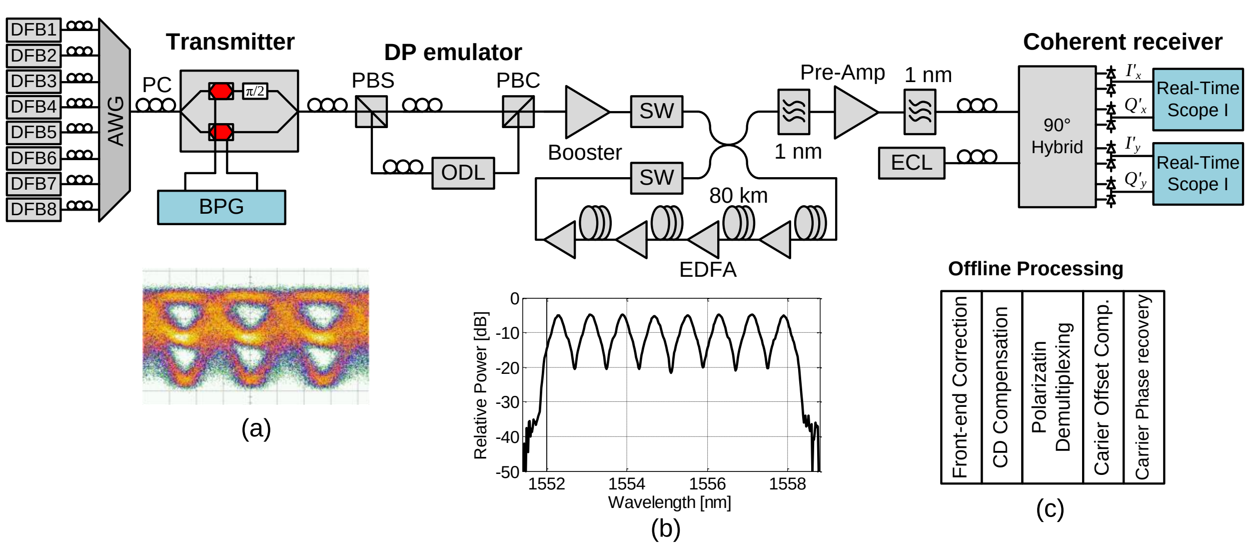


Fig. 1. Experimental setup. ODL: optical delay line, PBS/PBC: polarization beam splitter/combiner, PC: polarization controller, SW: switch. Insets: (a) single-polarization optical QPSK eye diagram; (b) optical spectrum of the eight WDM channels; (c) the offline processing procedures.

Fig. 1 shows the schematic of the experimental setup. 64 Gbaud two-level non-return-to-zero (NRZ) signals were generated using a big pattern generator (BPG). A radio frequency (RF) delay line was used to skew the inphase and quadrature signals, which then drove an IQ modulator for the electrical-to-optical conversion. The single-polarization optical QPSK eye diagram is shown in the inset (a) of Fig. 1. For WDM transmission, eight distributed feedback (DFB) lasers spaced by 100 GHz were combined using an arrayed waveguide grating (AWG), before being bulk modulated. Although the eight channels were not de-correlated at the transmitter, the performance of the WDM transmission system with the same data on all channels should be close to that with different data on different channels. This is because that the large channel spacing reduces the impact of cross phase modulation (XPM) and all channels were quickly de-correlated by chromatic dispersion (CD) after a short transmission distance. The modulated optical signal with eight wavelengths was then split to two orthogonal polarizations, one of which was delayed by 742 symbols. By recombining them, the DP signal was formed. The optical spectrum of the eight DP-QPSK channels is shown in the inset (b) of Fig.1. The signal was boosted by a booster EDFA before being launched into the re-circulating fiber loop, which consisted of 4 spans of 80 km standard single mode fiber (SMF-28e+). An erbium doped fiber amplifier (EDFA) with a noise figure of 5 dB was used in each span to compensate the loss which is 0.18 dB/km. The signal out of the loop was filtered by a 1 nm optical filter to remove the out-of-band noise accumulated during transmission. It was then filtered again to remove the out-of-band noise from the pre-amplifier. An external cavity laser (ECL) laser with a linewdith of ~100 kHz was employed as the local oscillator (LO), and its wavelength was tuned to select the channel for measurement. Along with the LO light, the signal was fed into a 90° hybrid followed by 4 balanced photodiodes with a bandwidth of 40 GHz for coherent detection. Two real-time scopes with a bandwidth of 33 GHz and a sampling rate of 80 GS/s were used to digitize the four electrical signals. The inset (c) of Fig. 1 shows the offline processing procedures. The IQ imbalance was first compensated, followed by a frequency domain equalizer for CD compensation. Afterwards, the constant modulus algorithm (CMA) was used for the adaption of a time-domain filter for polarization de-multiplexing and compensation of residual inter-symbol interference. Since the spectrum of the signal was severely narrowed by the scopes which have a very sharp transition at 33 GHz, we used 51 taps, which is a relatively large number, for the time domain filter to compensate for such a narrow filtering effect. Carrier frequency offset was compensated using the method based on the periodogram of the 4th power of the symbols [7]. The data-aided superscalar phase-locked loop combined with the maximum-likelihood (ML) algorithm proposed in our previous work [6] was used for phase recovery. In this algorithm, the differential coding can be removed to improve the performance, which will be evaluated later, at the expense of approximately 1% overhead.

3. Experimental results

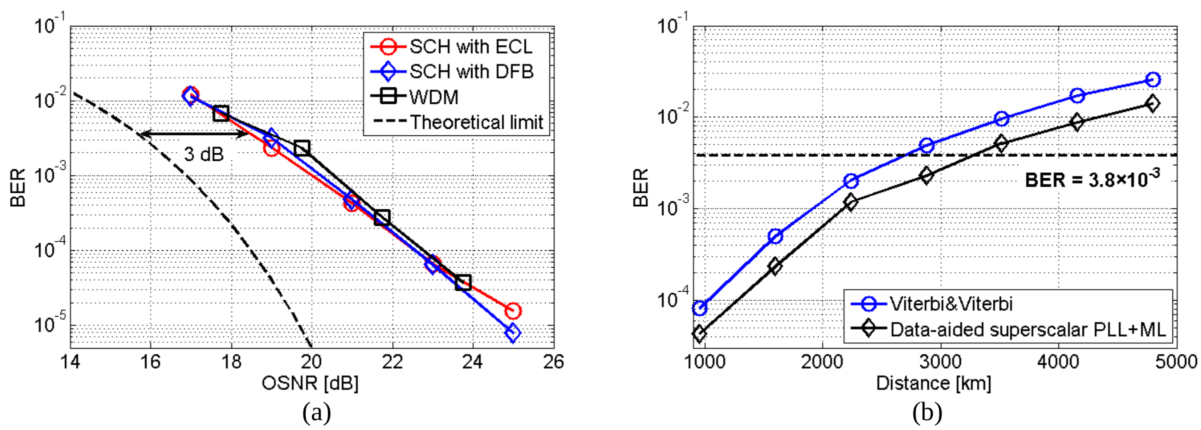
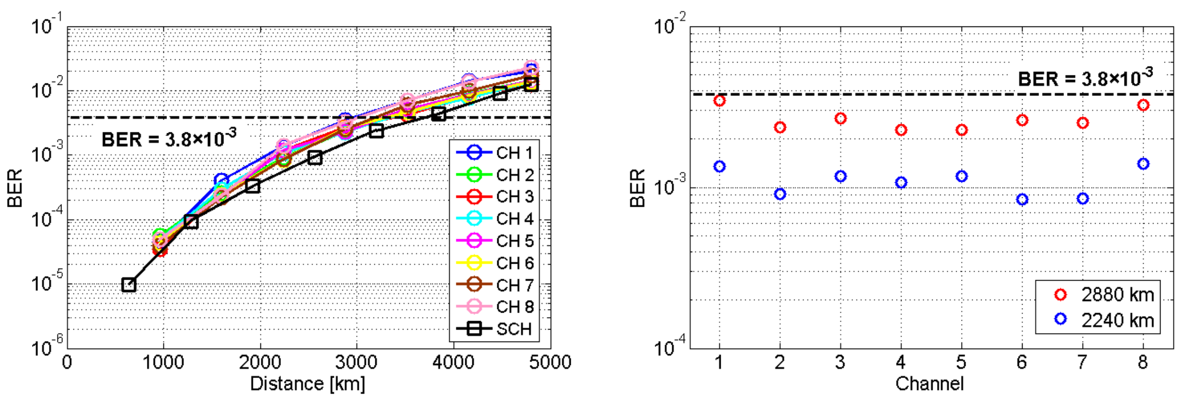


Fig. 2. (a) BER versus OSNR in back-to-back transmission. SCH: single channel. (b) Comparison of the transmission performance with different phase recovery.

Fig. 2(a) shows the BER as a function of OSNR in back-to-back transmission. The single channel system achieves a similar performance with an ECL or a DFB laser at the transmitter, since QPSK is very tolerant to laser phase noise. For the WDM system, only a very slight degradation is observed with respect to the single channel case. This is because the spectrum of each channel is well confined within the 100 GHz spacing due to the limited bandwidth of the transmitter, leading to a low crosstalk between channels. For all systems shown in Fig. 2(a), there is an approximately 3 dB OSNR penalty around the 3.8×10^{-3} BER compared to the theoretical limit.

In Fig. 2(b), we show the performance improvement using our phase recovery algorithm. As a comparison, the well known Viterbi and Viterbi (also referred to as the 4th power scheme) algorithm is also evaluated [8]. It can be seen that our algorithm reduces the BER for all the distances and increases the transmission distance by 21.5% at the BER threshold. Such an improvement is mainly attributed to the removal of differential coding/decoding, since pilot symbols are used to remove the phase ambiguity and prevent the cycle slip induced failure. In addition, our algorithm achieves very high laser linewidth tolerance for an arbitrary QAM format as demonstrated in [6]. In the following WDM transmission, it will be shown that our algorithm is able to tolerate the linewidths from hundreds of kHz to several MHz of the different DFB lasers employed for the different channels.

The WDM transmission performance is shown in Fig. 3. Different channels achieve similar BER performances versus the transmission distance. The difference of the achieved transmission distances at BER=3.8×10^{-3} is smaller than 400 km. Without inter-channel crosstalk and XPM, the single channel system is able to transmit 340-740 km longer distance. It should be noted that in our experimental setup, the gain of the EDFAs was not flattened, whereas a gain equalizing filter was instead employed to adjust the power of each channel in the loop in order to have a similar OSNR for all the channels in other works [2, 3, 5]. Therefore, it is interesting that in our experiments the performances of the eight channels are so close even with a very uneven power profile of the spectrum after transmission. In particular, as shown in Fig. 3(b), a relatively flat BER is observed for both 2240 km and 2280 km distances. Moreover, the BERs are all below the BER threshold at the 2880km distance, demonstrating error-free transmission of 8×256 Gb/s WDM 64 Gbaud DP-QPSK signals. However, it is expected that with a gain equalizing filter the performance of our system should be improved.



(a) (b)

Fig. 3. (a) BER versus distance for the single channel (SCH) transmission and the eight channels in the WDM transmission. (b) The BERs of all channels after 2880 km and 2240 km WDM transmissions.

4. Conclusion

A 8×256 Gb/s WDM transmission of 64 Gbaud QPSK signals over the standard single mode fiber (SSMF) with erbium doped fiber amplifier (EDFA)-only amplification and coherent detection was reported. By employing the data-aided carrier phase recovery algorithm, the transmission distance reaches 2880 km.

5. References

[1] P. Winzer, "Beyond 100G Ethernet," *IEEE Commun. Mag.*, vol. 48, pp. 26-30, 2010.

[2] A. H. Gnauck, P. J. Winzer, G. Raybon, M. Schnecker, and P. J. Pupalaikis, "10×224-Gb/s WDM Transmission of 56-Gbaud PDM-QPSK Signals Over 1890 km of Fiber," *IEEE Photon. Technol. Lett.*, vol. 22, pp. 954-956, 2010.

[3] M. Salsi, O. Bertran-Pardo, J. Renaudier, W. Idler, H. Mardoyan, P. Tran, G. Charlet, and S. Bigo, "WDM 200Gb/s single-carrier PDM-QPSK transmission over 12,000km," in *Proc. ECOC'11*, Paper. Th.13.C.5.

[4] Q. Zhuge, X. Xu, Z. A. El-Sahn, M. E. Mousa-Pasandi, M. Morsy-Osman, M. Chagnon, M. Qiu, and D. V. Plant, "Experimental investigation of the equalization-enhanced phase noise in long haul 56 Gbaud DP-QPSK systems," *Opt. Exp.*, vol. 20, pp. 13841-13846, 2012.

[5] G. Raybon, P. J. Winzer, A. A. Adamiecki, A. H. Gnauck, A. Konczykowska, F. Jorge, J. Y. Dupuy, A. Sureka, C. Scholz, R. Delbue, P. J. Pupalaikis, L. L. Buhl, C. R. Doerr, S. Chandrasekhar, B. Zhu, and D. W. Peckham, "8x320-Gb/s transmission over 5600 km using all-ETDM 80-Gbaud polarization multiplexed QPSK transmitter and coherent receiver," in *Proc. OFC'12*, Paper. OTu2A.

[6] Q. Zhuge, M. E. Pasandi, X. Xu, B. Châtelain, Z. Pan, M. Osman, and D. V. Plant, "Linewidth-tolerant low complexity pilot-aided carrier phase recovery for M-QAM using superscalar parallelization," in *Proc. OFC'12*, Paper. OTu2G.2.

[7] T. Nakagawa, M. Matsui, T. Kobayashi, K. Ishihara, R. Kudo, M. Mizoguchi, and Y. Miyamoto, "Non-data-aided wide-range frequency offset estimator for QAM optical coherent receivers," in *Proc. OFC'11*, Paper. OMJ1.

[8] M. G. Taylor, "Phase estimation methods for optical coherent detection using digital signal processing," *J. Lightw. Technol.*, vol. 27, pp. 901-914, 2009.