Real-time measurements of a 40 Gb/s coherent system

Han Sun, Kuang-Tsan Wu, and Kim Roberts

Nortel Networks, 3500 Carling Ave. Ottawa, Canada, K2H 8E9
hsun1@nortel.com, ktwu@nortel.com, krob@nortel.com

Abstract: Continuous real-time measurements are shown from a coherent 40 Gb/s transmission system that uses Dual-Polarization Quadrature Phase Shift Keying (DP-QPSK) modulation. Digital compensation is used for dispersion and polarization effects, with little performance degradation created by 150 ps of rapidly varying 1st-order PMD.

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

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1. Introduction

Coherent 40 Gb/s DP-QPSK has approximately the same noise performance as 10 Gb/s intensity modulation direct detection, and so provides four times the capacity on an overbuild

#88003 - $15.00 USD Received 28 Sep 2007; revised 20 Nov 2007; accepted 20 Nov 2007; published 9 Jan 2008

of existing 10 Gb/s routes, still without the need for any optical dispersion compensation [1]. With coherent detection, linear digital filters in the receiver are effective to combat dispersion, PDL and PMD [2-7].

2. Measurements

Figure 1 shows the block diagram of the DP-QPSK transmitter (Tx), where only the circuit of Xpol QPSK is shown. The Ypol circuit is identical to that of the Xpol, with its own I and Q channel data. The polarization combiner accepts these two optical signals and adds them to produce the transmitted signal.

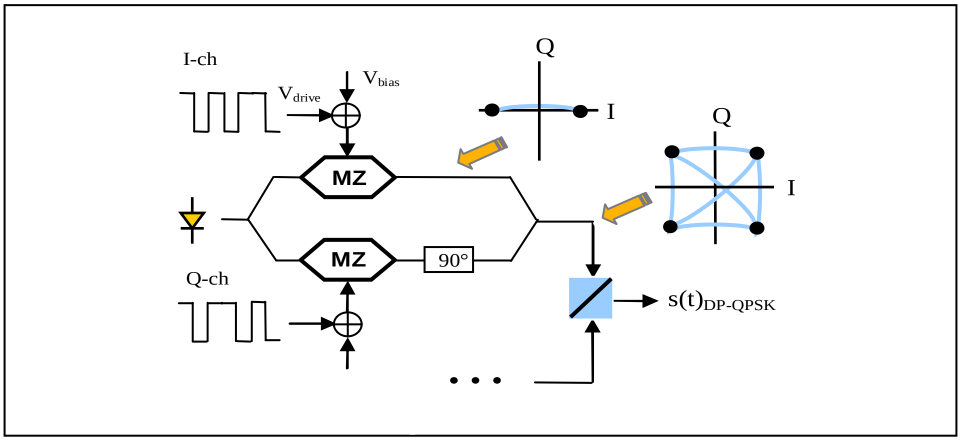

Fig. 1. DP-QPSK transmitter block diagram

The coherent detection of DP-QPSK is shown in Fig. 2(a), where the receive signal is passed through a polarization beam splitter and decomposed into two orthogonal signals. Each orthogonal signal is fed into an optical hybrid together with the output of the local oscillator (a commercial tunable laser) that is provisioned to select the WDM channel used by the transmitter and then controlled to be within a few hundred MHz of the carrier frequency. The four resulting polarization & phase orthogonal signals are fed into individual PINs for detection and electrical amplification/filtering before digitization using four A/D's with 6-bit resolution. The A/D's and the overall receive electrical circuits have a net 3dB bandwidth of ~6GHz. This helps to reject aliasing noise. Coherent optical detection has been described in many papers, for example in [2-7]. Clock recovery, carrier recovery, polarization & PMD tracking, and dispersion compensation are all done digitally, requiring 12 trillion ($12\text{x}10^{12}$) integer operations per second. Digital clock phase detection is described in [9] and electrical polarization control is described in [5]. The equalization and carrier recovery methods are shown in [10]. Multiple stages of linear and nonlinear processing are used, as introduced in [8], with the overall linear FIR response having 152 effective taps. This matches the dispersion tolerance of a 10 Gb/s precompensating system [1] with negligible degradation at 50,000 ps/nm, and with ~2 dB penalty at 80,000 ps/nm. The fast hardware control loops track a joint laser linewidth of up to 2 MHz, and polarization rotations of 50,000 Hz. Embedded firmware provides supervision and reports the measured dispersion and PMD values.

The 4 A/D's, all the digital signal processing circuits, and the supervisory processor are implemented in a custom mixed-signal 20 million gate ASIC, shown in Fig. 2(b). This ASIC has been manufactured using 90 nm CMOS technology and dissipates 21 Watts. The systems being tested use only factory production cards. The 40 Gb/s modem, containing a Tx and an Rx, dissipates 140 Watts. A photo of the 40G coherent transceiver card is shown in Fig. 3.

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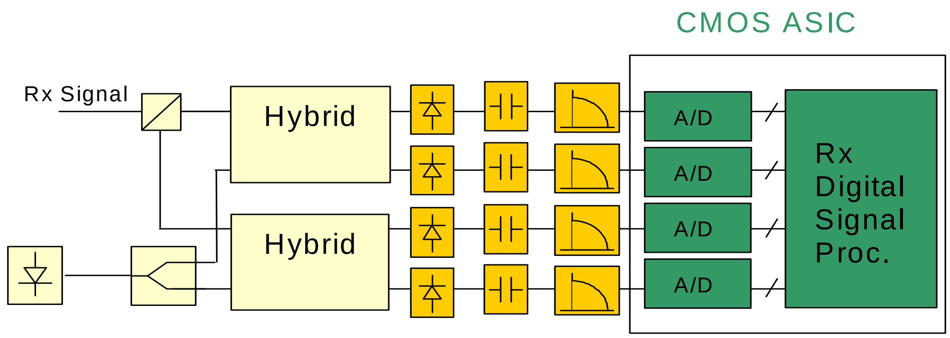

Fig. 2. (a) DP-QPSK receiver block diagram

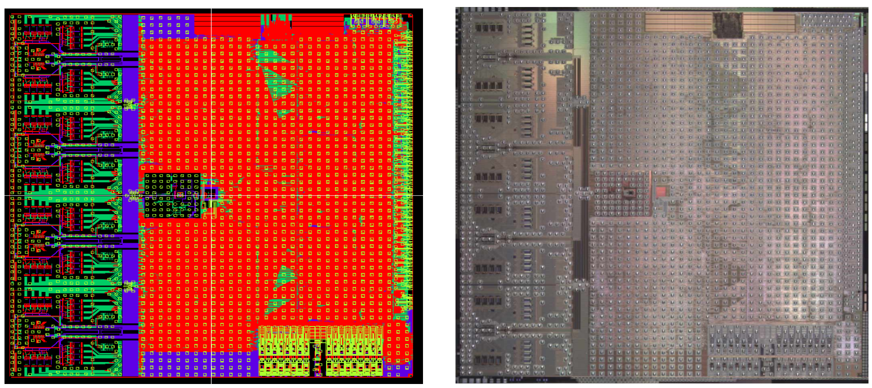

Fig. 2. (b) CMOS Rx ASIC with four 20 Gs/s A/Ds and 12 trillion ($12x10^{12}$) operations per second

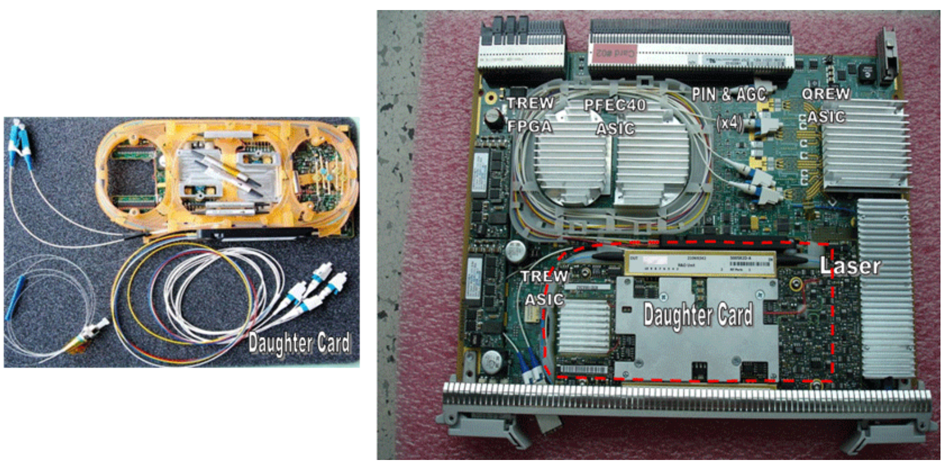

Fig. 3. The 40G coherent transceiver card

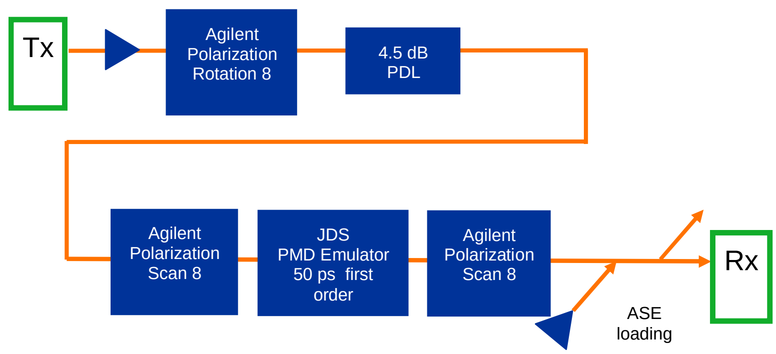

Fig. 4. PDL and PMD test configuration

Figure 4 shows the PMD/PDL test configuration for the 40 Gb/s DP-QPSK modem with a combination of 4.5 dB peak PDL and 50 ps of peak DGD (differential group delay). The objective of the test is to make sure the DP-QPSK signal goes through enough random polarization states and the coherent receiver is able to track the effect of PMD and PDL. The Agilent polarization rotators (11896A) perform random polarization rotations. The rate of change of polarization rotation at scan setting '8' is characterized using a CW source illuminating the input port of the rotator, and a polarization beam splitter (PBS) connected at the output port of the rotator. The PBS output is connected to a photo-detector. The electrical signal is connected to a sampling scope sampling at 500 Hz. Two minutes worth of data is sampled and transferred into the computer. The power spectral density (PSD) of the electrical waveform is a measure of the statistical rate of change of the power exchange between the two polarization modes and is shown in Fig. 5. The '+'curve shows the maximum rate of polarization variation for a single device is 10 Hz (at 20dB down). The 'x' curve shows the maximum rate for two devices connected in series is about 14 Hz. Thus we expect three devices concatenated as shown in Fig. 4 would produce a maximum rate of change of PMD/PDL state at 17Hz (=10*sqrt(3)).

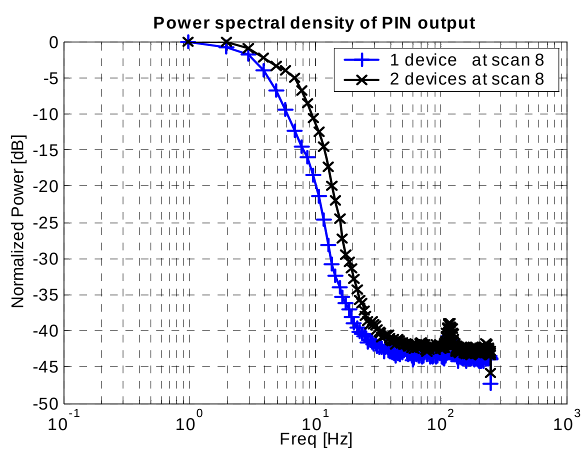

Fig. 5. PSD of the electrical waveform after characterizing the Agilent 11896A polarization rotator

The baud rate is 11.502 GHz giving a line rate of 46 Gb/s including 7% OTN and FEC overhead. A 2^{31}-1 PRBS binary pattern is used in the transmitter and detected in the receiver. White ASE is loaded before the receiver and the total ASE noise is measured across 0.1 nm to

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determine the final OSNR. The BER is continuously measured in real-time and averaged over a period of one minute at 46 Gbit/s for each OSNR level. That is, the measured BER is averaged over 2.76×10^{12} raw bits. At the 17 Hz scan rate, one minute is long enough to thoroughly explore the polarization states. Any state that significantly degrades the bit error rate would dominate this average.

In Fig. 6, the green dotted line is the FEC threshold at BER=3.84×10^{-3}. Although the FEC ASIC has not yet been integrated into the testing, this is the raw rate that the FEC will correct to an error rate of 10^{-20}. Compared to the ideal DP-QPSK theory, shown as the pink curve, the implementation degradation is 2.7 dB (taken as the difference between pink and blue at the FEC threshold). The orange line is the theoretic value including the noise enhancement from 4.5 dB of PDL. The measured BER curve at back-to-back (B-B) with nominally zero PMD and PDL is the blue line, with 10.8 dB at the FEC threshold. The brown line is the measured BER with the PMD emulator set to 50 ps and the PDL at 4.5 dB.

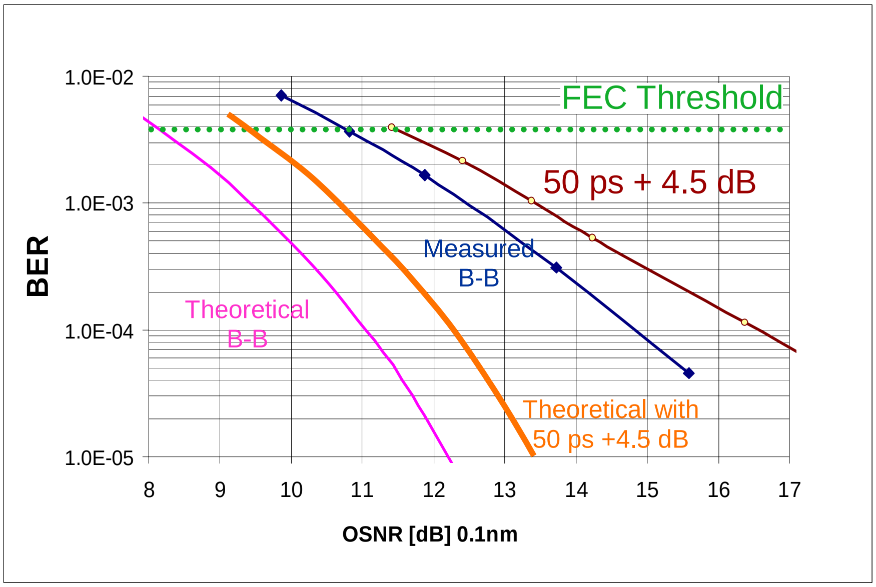

Fig. 6. Real-time 40Gb/s modem performance

Figure 7 describes the measurement setup for testing the joint PMD and dispersion tolerance of the modem. The 46 Gb/s Tx signal is passed through a link consisting of 900 km of NDSF, then followed by PMD emulation. The link does not have any dispersion compensating fiber. The net dispersion of ~15,000 ps/nm is entirely compensated in the receiver ASIC. In order to, initially, verify the purely linear performance of the coherent receiver, the launch power is kept below -6 dBm at each amplifier, for a single optical channel (1550.92nm) within the 50 GHz ITU grid. Longer links, higher powers, and 88 channel configurations will be tested in due course, as this test configuration is not a limit case.

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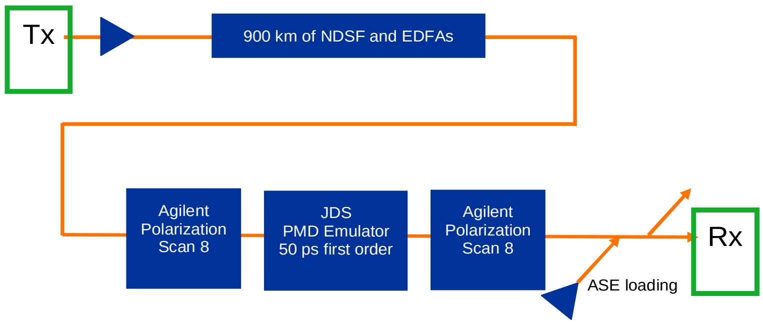

Fig. 7. PMD test setup with a 900 km NDSF link

Figure 8 shows the measured BER of this link, with added 1st-order PMD (peak DGD) of 0 and 50 ps. The fiber and amplifier PMD is negligible. The required OSNR is once again 10.8 dB at threshold. The modem is robust to 50 ps of rapidly varying 1st-order PMD as the diamond (0 ps) and square (50 ps) curves are identical, within the experimental error. The receiver simultaneously compensates for the polarization effects and the 15,000 ps/nm of dispersion.

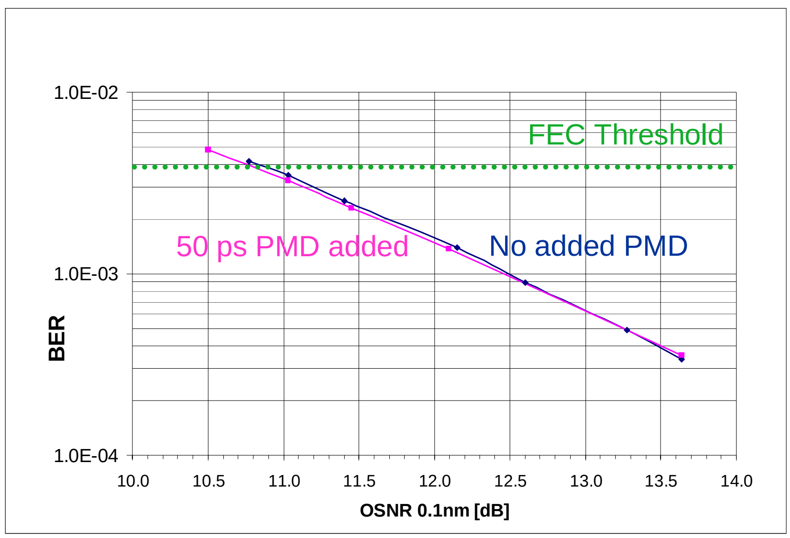

Fig. 8. Measured BER with single channel in a link of 900 km NDSF without DCM's

Figure 9 shows the OSNR values at the FEC threshold for a range of peak DGD values. This was measured with the configuration of Fig. 7, but without the fiber and associated line amplifiers. In this case, the receive ASIC does not need to compensate for any dispersion. Note however that this was measured with specific receiver control loop conditions, and so is not guaranteed worst-case performance. With this unit, the performance is better with large amounts of net dispersion than without dispersion (comparing 10.8dB of OSNR in Fig. 8 against 11.1dB of OSNR in Fig. 9 at zero DGD). Another observation from Fig. 9 is that with 50ps DGD the performance is improved relative to 0ps DGD. The two observations are consistent, in the sense that large amounts of intersymbol interference input to the receiver improve performance. This effect is counter intuitive and not yet fully understood, but we suspect that pulse broadening allows improved T/2 sampling. The equipment used to obtain

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the results shown in Fig. 6 did not show this effect, although the measured penalty for combined PMD & PDL is lower than theoretical, at least at low OSNR.

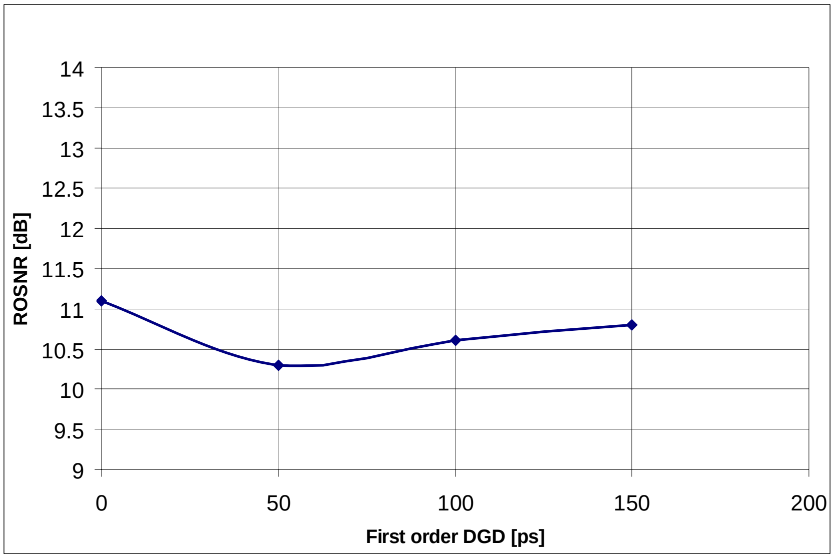

Fig. 9. Measured ROSNR at FEC Threshold vs. Peak DGD

3. Conclusion

Continuous measurement results have been shown for a coherent 40 Gb/s DP-QPSK system. A 10.8 dB OSNR is tolerated after real-time digital compensation for extensive dispersion, PDL, and PMD. Rapid polarization and PMD variations are tracked without measurable signal degradation. Optical dispersion compensation remains obsolete!

Acknowledgments

We would like to thank the 107 Nortel engineers that were also essential to achieving these measurements.

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