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Coherent Equalization versus Direct Detection for 111-Gb/s Ethernet Transport

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***Abstract*—We discuss coherent equalization to realize robust 111-Gb/s transmission. For 111-Gb/s POLMUX-RZ-DQPSK we experimentally show the advantage of coherent equalization over direction detection for compensation of both chromatic dispersion and differential group delay.**

I. Introduction

Optical transmission networks designed for Ethernet traffic are becoming more and more important due to an increasing dominance of data over voice services. This has fuelled the need for an 100-Gb/s Ethernet transport solution that can handle the capacity requirements of wavelength division multiplexed (WDM) core network transport. A number of different alternatives have been proposed in recent years for single-wavelength 100-Gbit/s Ethernet transport (111 Gb/s including forward error correction and Ethernet overhead). Ultra-high frequency electronics has enabled generation and detection of on-off keyed signals using electrical time-division multiplexing (ETDM) [1]. Alternatively, return to zero differential quadrature phase shift keying (RZ-DQPSK) encodes 2 bits/symbol, which allows 107-Gb/s transmission with a 53.5-Gb/s symbol rate [2]. Polarization multiplexing combined with RZ-DQPSK [3] can be used to further reduce the symbol rate to ~27-Gb/s. A ~27-Gb/s symbol rate has the advantage that it enables the use of digital signal processing techniques [4, 5] using high-speed analog-digital converters (ADCs). This enables 111-Gb/s POLMUX-RZ-DQPSK as a robust solution for next-generation core network 100-Gb/s Ethernet transport.

In this paper we compare direction detection and coherent detection combined with equalization for 111-Gb/s POLMUX-RZ-DQPSK. We show that using coherent equalization linear transmission impairments can be compensated, enabling robust 111-Gb/s transmission.

II. Experimental Setup

The experimental setup is shown in figure 1. In the transmitter (figure 1a) an external cavity laser (ECL) at 193.4 THz is used. The 111-Gb/s POLMUX-RZ-DQPSK transmitter consists of an integrated DQPSK modulator for the data and a pulse carver for RZ modulation. The DQPSK modulator is driven by a 27.75-Gb/s 2^{16} pattern, where I and Q data are de-correlated by an 8 bit delay. Note that this de-correlation precisely results in a 4^8 bits long pseudo-random quaternary sequence for proper modeling of the RZ-DQPSK modulation format. A 50-GHz interleaver after the transmitter ensures that the spectral width of the signal is compatible with a 50-GHz WDM grid. Finally, a polarization multiplexed signal is generated by dividing and recombining the signal with orthogonal polarizations and a 353 symbol delay.

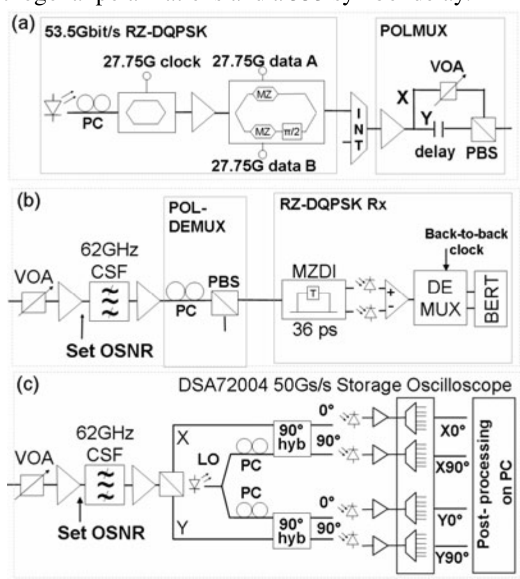

Figure 1. Experimental setup; (a) transmitter, (b) direct detection receiver and (c) coherent receiver.

At the receiver, the OSNR is set using a variable optical attenuator (VOA) followed by an Erbium doped fiber amplifier (EDFA) and a 62-GHz channel selection filter (CSF). The direct detection receiver (figure 1b) consists of manual polarization de-multiplexing using a polarization controller (PC) followed by a polarization beam splitter (PBS). Afterwards, the signal is fed to a one-bit (36 ps) Mach-Zehnder delay interferometer (MZDI) followed by a balanced detector. The transmitter clock is used as input for the de-multiplexer as no 27.75-Ghz clock recovery was available. The signal is evaluated using a BER-tester (BERT) programmed for the expected bit sequence.

The coherent receiver (figure 1c) consisted of a local oscillator (LO), polarization beam splitter (PBS), two fiber based 90° hybrids and 4 single-ended Pin/TIA modules. The 90° hybrids consist of 3x3 couplers with a 2:2:1 output ratio. The input polarization state is not controlled, and an arbitrary mix of each transmitted polarization tributary is incident on the photodiodes. The LO is a tunable laser source (100 kHz linewidth), aligned to within 400 MHz of the transmitter laser. The LO to signal ratio is ~18 dB. Using a digital storage oscilloscope with 20 GHz electrical bandwidth (DSA72004, generously provided by Tektronix) data was sampled at 50 Gs/s and subsequently post-processed on a desktop PC. The post-processing (see [7] for more details) consists of a clock recovery using a digital filtering and square timing recovery algorithm to resample the signal to 2 samples/symbol (55.5 Gs/s). Equalization is performed by a bank of 4 complex T/2-spaced finite impulse response (FIR) filters arranged in a butterfly structure and optimized using a least-mean square (LMS) algorithm. The frequency and phase offset between the LO and signal is compensated by using a Viterbi-and-Viterbi carrier recovery stage. Differential decoding is used to prevent cycle-slips followed by error-counting with 524,288 symbols ($2{\cdot}10^6$ bits).

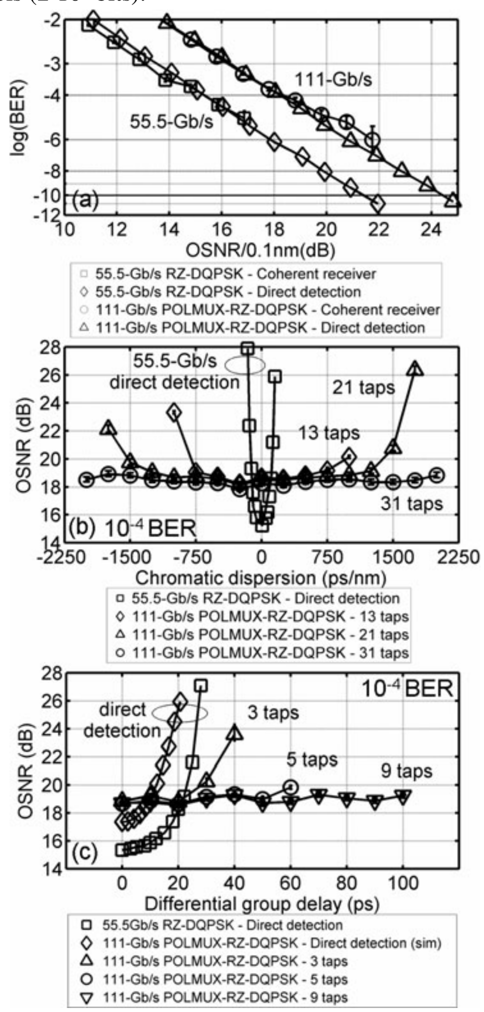

Figure 2. Comparison between direct detection and coherent equalization for (a) back-to-back sensitivity, (b) chromatic dispersion tolerance and (c) differential group delay tolerance.

III. EXPERIMENTAL RESULTS

Figure 2 compares the receiver sensitivity and impact of chromatic dispersion (CD) and differential group delay (DGD) between direct detection and a coherent equalization receiver. Figure 2a shows the back-to-back sensitivity for 55.5-Gb/s RZ-DQPSK and 111-Gbit/s POLMUX-RZ-DQPSK for both receiver types. The difference in required OSNR between POLMUX and non-POLMUX is as expected 3 dB. For a 10^{-4} BER the required optical signal-to-noise ratio (OSNR, 0.1 nm res.) is 15.3 dB and 18.3 dB for non-POLMUX and POLMUX modulation, respectively. Theoretically, coherent detection has an 1.5 dB advantage in OSNR requirement over direct detection (at 10^{-3} BER, [6]). The measured performance of coherent equalization and direct detection is however similar. Among other impairments in the receiver this could be the result of using single-ended photodiodes instead of balanced detection. The CD tolerance is shown in figure 2b. For direct detection the CD tolerance of 55.5-Gb/s RZ-DQPSK is shown, which has a dispersion tolerance of +/-80 ps/nm for a 2-dB OSNR penalty. Note that the dispersion tolerance of 111-Gbit/s POLMUX-RZ-DQPSK is equal to the tolerance of 55.5-Gb/s RZ-DQPSK, with the exception of a 3-dB OSNR difference. When 111-Gb/s POLMUX-RZ-DQPSK is combined with coherent detection and subsequent electronic equalization the CD tolerance is solely determined by the number of FIR taps used in the equalizer. For 31 taps no significant penalty is evident for a dispersion window ranging from -2000 ps/nm to +2000 ps/nm. This indicates the for a sufficient large number of FIR taps an arbitrary amount of CD can be compensated. Reducing the number of FIR taps results in a decreased CD tolerance. However, even for 13 taps the CD tolerance is in excess of +/-800 ps/nm, a factor of 10 above the direct detection CD tolerance.

Figure 2c depicts the DGD tolerance. POLMUX modulation has a smaller DGD tolerance in comparison to non-POLMUX modulation at the same symbol rate. The DGD is reduced by about a factor of two, assuming both polarization tributaries are bit-aligned [3]. The direct detection DGD tolerance of 55.5-Gb/s RZ-DQPSK (2-dB OSNR penalty) is approximately 18 ps. For 111-Gbit/s POLMUX-RZ-DQPSK modulation (simulated curve) this is reduced to 10.5 ps. Despite the use of POLMUX modulation DGD impairments can be compensated with a coherent receiver and subsequent electronic equalization For 3 FIR taps the DGD tolerance of 111-Gb/s POLMUX-RZ-DQPSK is larger than the DGD tolerance of 55.5-Gb/s RZ-DQPSK. When the number of FIR taps is enlarged to 9 taps the DGD tolerance is in excess of 100 ps, the equivalent of 2.75 bits lengths. Although direct detection and electronic equalization can also be combined, the compensation DGD impairments in POLMUX modulation would be difficult to realize.

IV. CONCLUSIONS

POLMUX-RZ-DQPSK modulation in combination with coherent detection and electronic equalization results in a robust solution for 111-Gb/s Ethernet transport. We showed that coherent equalization can compensate for almost arbitrary amounts of chromatic dispersion and differential group delay.

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