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First Real-Time 400G PAM-4 Demonstration for Inter-Data Center Transmission over 100 km of SSMF at 1550 nm

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Abstract: Real-time transmission of 400G (8x50G DWDM) PAM-4 signals for data center interconnects up to 100 km SSMF is successfully demonstrated. All channels stay well below the 802.3bj KR4 FEC limit, thus allowing error free transmission.

OCIS codes: (060.2330) Fiber optics communications; (060.4080) Modulation

1. Introduction

The continuous growth in bandwidth hungry applications such as high definition TV, online social networks, and cloud computing drives the need for high speed data center interconnects. The IEEE 802.3bs 400 Gb/s Ethernet Task Force has worked on industry standards for intra-data center interconnects with link distances of 500 m, 2 km, and 10 km over standard single mode fiber (SSMF). Intensity modulation and direct detection (IMDD) links are preferred for low cost. Experimental demonstrations of e.g. 4×100-Gb/s DMT signal transmission over 4 km SSMF [1] and 2×56 Gb/s PAM-4 signal over 10 km SSMF [2] have been performed using offline digital signal processing (DSP).

However, for inter-data center connections, there is the requirement to transport 100G or 400G data rates over longer distances up to 80 km or 100 km, which are beyond the limit for 400GbE. For such applications, optically amplified wavelength division multiplexed (WDM) systems are specified, using the 1550 nm window. It is a cost-effective approach to scale up from the short reach IMDD based intra-data center optics. The challenge resides in the optical signal to noise ratio (OSNR) performance and the chromatic dispersion tolerance. It has been shown that 56-Gb/s IMDD DMT on 8 channels can successfully bridge 240 km of SMF [3]. Single channel 112-Gb/s PAM-4 transmission was demonstrated over 80 km SMF [4] and a 100-km DWDM transmission of 3×56-Gb/s PAM-4 via tunable laser and 10-Gb/s InP MZM was shown [5], both using a dispersion compensating module in the transmission setup. However, all these demonstrations utilized offline DSP. Real-time PAM-4 transmission at 25 GBaud and at 56 GBaud has been demonstrated only for a single channel over up to 10 km and 2 km SMF, respectively and at high OSNR [6-7].

In this paper, the first known demonstration of real-time, 400G (eight channels, each at 25.78125 GBaud) PAM-4 signal transmission over 100 km and standard SMF at C-band is performed, using simple receiver equalization and a low-complexity in-band FEC with 2.7 % overhead only. The experiment clearly demonstrates an interesting option for a low-cost 400-G solution for inter-data center connections under practical OSNR and fiber dispersion conditions. Furthermore, the use of dense WDM systems represents a spectrally efficient way to scale up to multi-Tb/s DWDM links with > 4 Tb/s system capacity.

2. Experimental Setup

In Fig. 1 the experimental setup is shown. For the real-time generation and decoding of two 25.78125-GBaud PAM-4 signals, the *Inphi IN015025-CA0* PAM-4 transceiver PHY was used, which supports dual lambda 100G transceivers. At the transmit side, the PHY consisted of a forward error correction (FEC) block, a PRBS generator, a DSP unit, to map the bits into PAM-4 symbols, and a digital-to-analog converter (DAC). Additionally, the DSP unit provided a programmable 3-tap equalizer and a level shifting function to compensate for limited bandwidth and the nonlinear behavior of the modulator, respectively. The non-pre-equalized eye has a measured SNR of more than

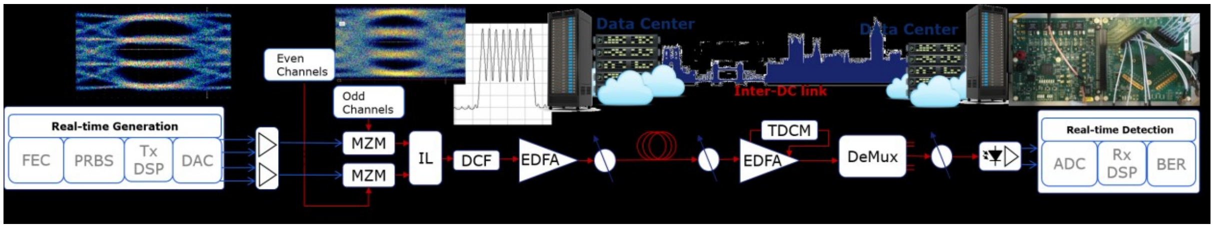

Fig. 1: Experimental setup for single channel and DWDM transmission (IL: Interleaver, EDFA: Erbium Doped Fiber Amplifier, TDCM: Tunable Dispersion Compensating Module, VOA: Variable Optical Attenuator).

28 dB. At the receive side, the PHY consisted of an integrated analog-to-digital converter (ADC) and an adaptive FFE-DFE equalizer with adaptive thresholds prior to the PRBS bit error checker and the FEC decoder.

The two generated electrical PAM-4 signals were amplified with a linear 35-GHz amplifier before driving two 27-GHz LiNbO3 Mach-Zehnder modulators (MZM). When transmitting 400G, each MZM modulated a group of four 100-GHz spaced wavelengths, with a relative offset of 50 GHz between the two groups. Both modulators were biased at quadrature point and driven at full Vπ, resulting in an extinction of approx. 12 dB. After the MZMs an in-line power meter was used to determine the operating point of the MZM, before a 50-GHz interleaver (IL) combined the two modulated four-channel groups leading to an eight-channel, 50-GHz spaced DWDM signal. A conventional 80 km or 100 km SSMF link, both pre-compensated with a dispersion compensating fiber (DCF) for 80 km was used for the experiment, representing typical transmission distances for data center interconnects. The input power into the DCF was set to -8 dBm per channel. Furthermore, the DCF ensures sufficient decorrelation of the jointly modulated channels before the WDM signal is launched into the SSMF. An Erbium-doped fiber amplifier (EDFA), followed by a variable optical attenuator (VOA) was used to set the launch power level into the fiber. After transmission, a VOA allowed the adjustment of the OSNR for single channel performance evaluation. For DWDM transmission, the OSNR was set to the maximum value of approx. 34 dB for 80 km and approx. 31.5 dB for 100 km transmission. As the transmission link exhibited a loss of approx. 18 dB and 22 dB, for 80 km and 100 km, respectively, the second EDFA was needed to ensure sufficient power into the receiver. In case of 100 km transmission, the tunable dispersion compensation module (TDCM) placed inside the second stage of this EDFA, was used to compensate the last 20 km. The DCF was not replaced, emulating a realistic system scenario. Finally, the channels were separated with a demultiplexer of approx. 39 GHz optical bandwidth, and a VOA controlled the power into a 23-GHz photodiode with transimpedance amplifier (PIN/TIA). As only one PIN/TIA was available in the lab, the different signals were measured consecutively.

In case of optical back-to-back transmission, only one EDFA was used in the transmission setup and amplified spontaneous emission (ASE) noise was added by means of a 3-dB coupler.

3. Results

The following bit-error rate (BER) results were achieved with the dedicated PRBS generators and checkers within the PHY circuit. A PRBS of order 31 was chosen, and for single-wavelength transmission the optical carrier frequency was set to 194.05 THz. For DWDM-transmission the wavelengths on the ITU grid between 194 THz and 194.35 THz were used.

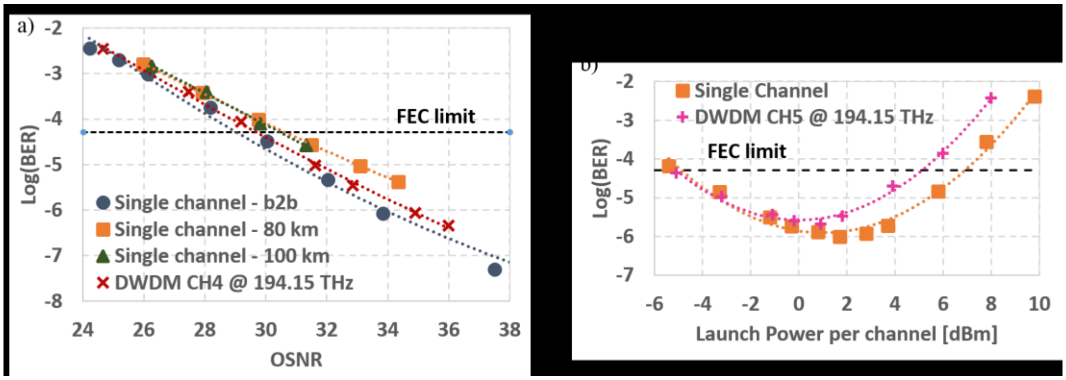

Fig. 2: a) BER vs. OSNR for single channel and DWDM transmission and b) BER vs. launch power into the fiber

Fig. 2a) shows the measured BER vs. OSNR performance of a single PAM-4 channel for optical b2b, for 80 km and for 100 km transmission as well as the b2b performance of channel 4 of the DWDM system. Additionally, at BER of $5.2 \cdot 10^{-5}$ the threshold for the KR4 FEC is shown, which guarantees a post-FEC error rate below 10^{-12}. A 64B/66B to 256B/257B transcoder allows to apply the KR4 FEC (RS(528,514)) in-band, without increasing the gross rate of the signal [8]. At this FEC threshold an OSNR penalty of approx. 1.5 dB between optical b2b and the transmission over 80 km and 100 km SSMF is observable; associated with fiber nonlinearities, as the launch power into the fiber was set to 2 dBm. No performance difference between 80 km and 100 km is noted. Furthermore, this graph reveals a negligible impact of linear crosstalk, as nearly no performance differences between single channel results and DWDM results for optical b2b is shown.

In Fig. 2b), the BER vs. launch power per channel into 80 km SSMF is displayed for DWDM transmission (+-marker) and for single wavelength transmission (squared-marker). At lower input power, the link is OSNR limited, while at higher input power nonlinearities cause significant distortions. Nonlinear cross phase modulation (XPM) distorts the DWDM transmission at higher input power and thus, a different optimum launch power as well as a different minimum BER between DWDM transmission and single channel transmission is observed. The optimum launch power for a single channel is approx. 2 dBm while for 8 channels it is approx. 1 dBm.

Fig. 3a) shows the impact of residual dispersion to DWDM PAM-4 transmission. Here, the residual dispersion was introduced with the TDCM while transmitting over the DCF compensated 80-km link. The TDCM has an operating bandwidth of up to 40 GHz and can be used for full C-band chromatic dispersion compensation. A residual dispersion up to ± 170 ps/nm is tolerable for the given FEC-limit.

Fig. 5 finally demonstrates the achievable BER for all eight channels, over 80 km and 100 km. Fig. 5a) shows the results, transmitting at quadrature point, while 5b) shows the minimum BER which was achieved by optimizing the bias point of the MZM. The difference between 80-km and 100-km results is due to the different achievable OSNR (~34 dB OSNR vs. ~31.5 dB).

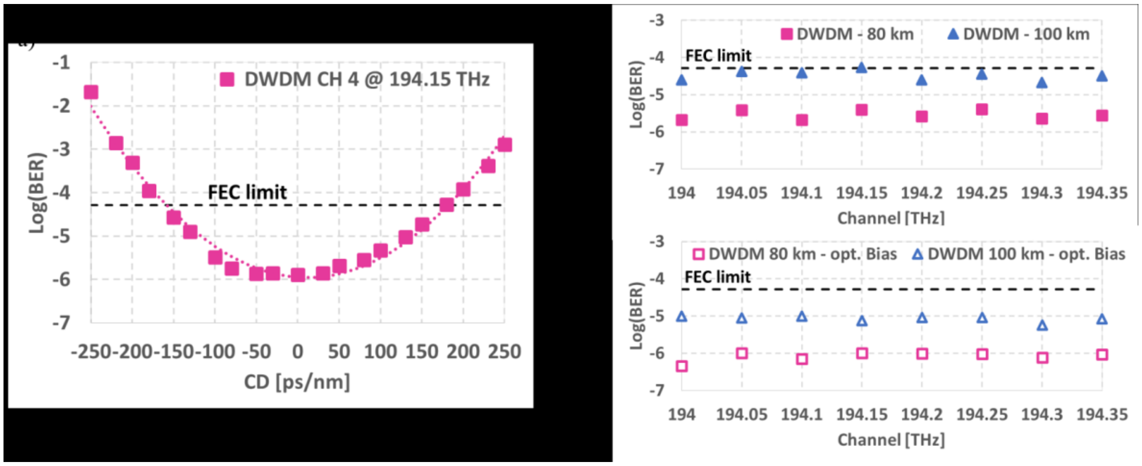

Fig. 3: a) Tolerance to residual dispersion, b) & c) DWDM transmission results over 80 km and 100 km at b) quadrature point and c) with optimized bias settings.

4. Conclusion

To our knowledge, for the first time 400G real-time PAM-4 with 25.78125 GBaud per channel was demonstrated over 80 km and 100 km SSMF in the 1550-nm transmission window. The system concept allows > 4-Tb/s links for next generation of data center interconnects. For all considered transmission scenarios a BER below the KR4-FEC threshold of $5.2 \cdot 10^{-5}$ was achieved, allowing error free transmission.

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