800ZR+ DWDM Demonstration over 600km G.654D Fiber Enabled by Adaptive Nonlinear TripleX Equalization

F. Pittalà, M. Schaedler, C. Bluemm, G. Goeger, S. Calabrò, M. Kuschnerov, C. Xie
Munich Research Center, Huawei Technologies Duesseldorf GmbH, Riesstrasse 25, D-80992 Munich, Germany;
fabio.pittala@huawei.com

Abstract: We demonstrate the feasibility of 800ZR+ by transmitting 32×96-GBaud DP-32QAM over 600km of G.654D fiber using a generic interoperability FEC. Superior performance is achieved by advanced nonlinear components compensation.
 OCIS codes: (060.1660) Coherent communications; (060.2330) Fiber optics communications.

1. Introduction

Since the introduction of the first 40Gb/s fixed line rate coherent optical modems in 2008, the industry evolved towards flexible rate transceivers supporting 100-600Gb/s per wavelength and integrating additional functionality in the DSP-ASIC such as SD-FEC, advanced modulation, transmitter (Tx) predistortion, and framing. At the same time, form factors evolved from line cards with discrete components towards more compact solutions as multi-source agreement (MSA) on-board modules and hot-pluggable modules like 100Gb/s CFP-DCO and 200Gb/s CFP2-DCO modules. These permitted a pay-as-you-grow model and the possibility to use grey and colored optics in the same slot of an OTN switch chassis. However, these pluggable form factors were not compatible with the QSFP28 grey optics used in data centers. Therefore, data center interconnect (DCI) applications using grey optics still required an additional demarcation from the core switch/router to the dense wavelength division multiplexing (DWDM) gear, which resulted in increased costs and operational complexity. OIF standardization and the introduction of 400ZR pluggable modules in QSFP-DD and OFSP formats defined a coherent colored interface, which could be directly put into a switch/router without compromising the density, and thus marked an important coming-of-age moment for coherent optics [1]. Currently, the industry is developing the first 800Gb/s single carrier transport products and the standardization effort of 800ZR+ extended reach future pluggable optics began in 2019.

In this paper, we demonstrate a proof-of-concept (PoC) of 800ZR+ DWDM transmission with a reach of 600km using 96GBaud dual polarization (DP)-32QAM and advanced component compensation and assuming a generic turbo product code (TPC) in line with the FEC under consideration for the 450km black-link 200G and 400G standards in ITU-T SG15 [2]. Compared to previous research experiments on 800Gb/s [3-7], our PoC shows superior reach, while using a simple modulation format and FEC, which are optimally suited for a potential future interoperability standard.

2. TripleX Equalization Architecture

As we move to 96GBaud, we place more emphasis on advanced and fully adaptive nonlinear component equalizers (EQs), targeting imperfections such as bandwidth limitations, frequency dependent I/Q gain, skew and phase ripple, I/Q crosstalk and high order nonlinearities at Tx and receiver (Rx). In contrast to previous publications [8], our methods do not require any time-consuming and resource-intensive factory calibration of the component compensation algorithms and run fully adaptively with limited *a priori* knowledge about the typical characteristics of the modem. We use a triple EQs (aka TripleX) architecture consisting of three parts – the compensation of Tx impairments, Rx impairments, as well as a partial-response whitening filter with maximum likelihood sequence estimation (MLSE) [9], as shown in Fig. 1.

The compensation of Tx impairments is done jointly on the Tx and Rx side. At the Tx, fully adaptive memory-based nonlinear digital predistortion (NL-DPD) with oversampling is implemented [10]. The DPD can be blindly adapted using the actual system payload over optical links with chromatic dispersion (CD), polarization mode dispersion (PMD), polarization-dependent loss (PDL), dynamic rotation of the state-of-polarization (SOP) and

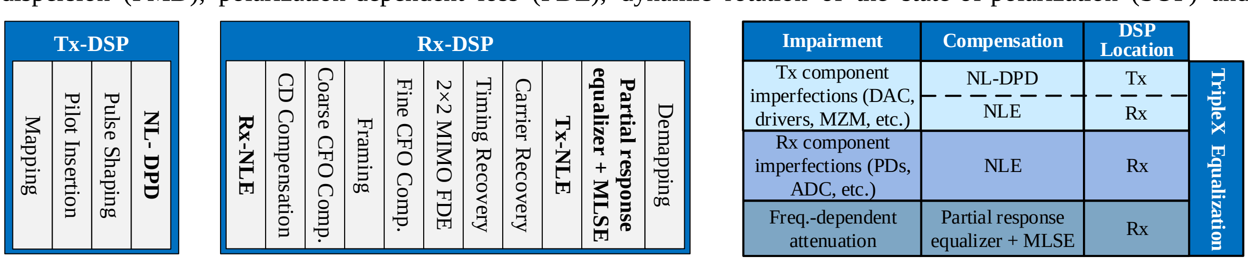

Figure 1. Schematic of the DSP architecture with TripleX equalization.

filtering effects in the wavelength selective switch (WSS). However, in our use case, we assume no dedicated feedback channel during operation and the DPD is defined only once at the link startup. Any time-dependent or wavelength-dependent changes at the Tx during operation are compensated by the adaptive Tx nonlinear equalizer (NLE) operating with 1 sample per symbol (sps) at the Rx. The Rx components are equalized in the oversampled Rx-NLE, which, similarly to the DPD and Tx-NLE, does not require any factory calibration and is adapted in pilot-aided and decision-directed mode during transmission. DPD/Tx-NLE and Rx-NLE are implemented as 4 real-valued filters. Finally, partial-response equalization with impulse response 1+αD is implemented after the Tx-NLE to whiten the noise, followed by 4 real-valued MLSEs with 1 memory tap used for sequence detection.

3. Experimental Setup

A schematic of the experimental setup is shown in Fig. 2. The channel under test (CUT) carries a 96GBaud dual polarization (DP) 32QAM with gross data rate of 960Gbit/s. Assuming 15% overhead for the FEC and 3.47% for pilot symbols, framing and other training sequences, the net bit rate is 800Gb/s. Four BiCMOS 6-bit digital-analog converters (DACs), with 40-GHz 3-dB analog bandwidth are operated at 100-GSa/s and generate a repeated pattern of 76800 samples. Four SHF S804A amplifiers with 60-GHz bandwidth drive the RF signals to a LiNbO3 DP-IQ modulator with 3-dB bandwidth of 32-GHz.

The receiver consists of a state-of-the-art optical 90°-hybrid and four 70-GHz balanced photodiodes (BPDs). The electrical signals are digitized using four 10-bit analog-digital converters (ADCs) operated at 256GSa/s with bandwidth limited to 59-GHz in order to reduce noise.

The WDM system is emulated by generating 31 noisy channels shaped with a 96-GHz root-raised cosine (RRC) filter with 0.2 roll-off factor having central frequencies ranging from 192.095-THz (1529.774 nm) to 195.970-THz (1560.633 nm) on a 125-GHz grid. The channels are multiplexed together with the CUT by using a 3dB coupler and then sent to an erbium-doped fiber amplifier (EDFA) acting as a booster. The DWDM signal is then launched into a transmission line consisting of six spans, each of 100km length. Pure-silica core fiber having ultra-low attenuation and compliant with ITU-T G.654D is used [11]. The seven C-band EDFAs are designed for terrestrial applications and allow 4dBm and 20dBm as input and output optical power, respectively, with an optical gain between 16 and 23dB. The noise figure is below 5.5dB and the gain flatness below 2dB. No optical gain equalizer is used in the link.

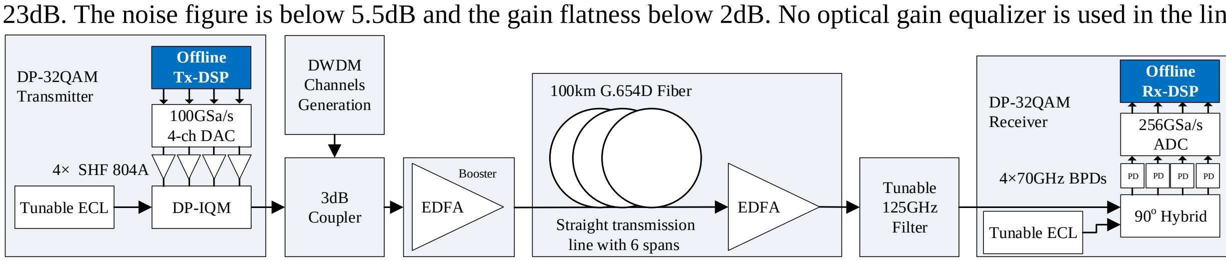

Figure 2. Schematic of the DWDM experimental setup.

3. Results and Discussion

The performance of the TripleX equalization is analyzed on the back-to-back (B2B) measurements and reported in Fig. 3. The pre-FEC BER is plotted against OSNR. The baseline plot refers to a system with NL-DPD (401/5/5 taps of order 1/2/3) and linear equalization at the Rx without I/Q imbalance compensation. This configuration leads to a required OSNR of 30.9dB at the considered FEC limit. By switching on the Tx-NLE (351/7/7 taps of order 1/2/3) a

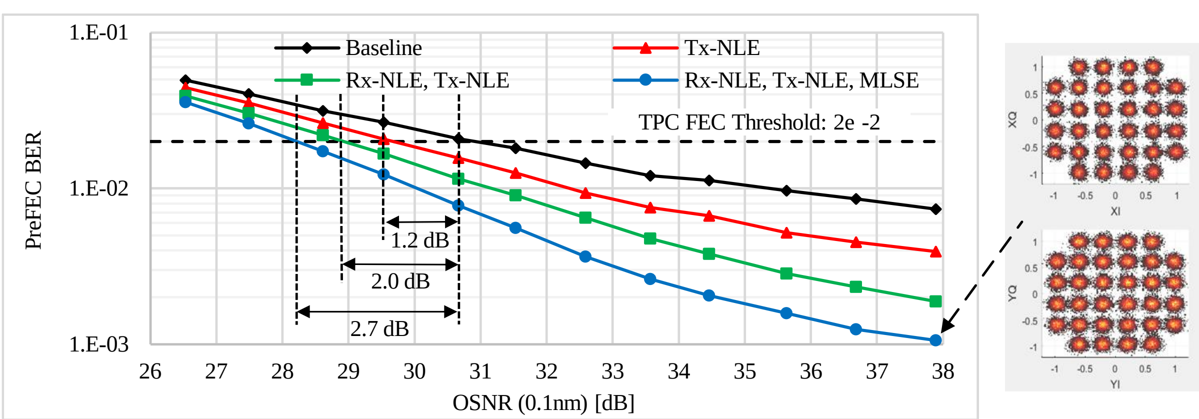

Figure 3. TripleX equalization analysis on B2B measurements.

gain of 1.2dB is observed. A further gain of 0.8dB is obtained when both Rx-NLE (161/7/7 taps of order 1/2/3) and Tx-NLE are used. Finally, using also the partial-response equalization and MLSE, the required OSNR is reduced to 28.2dB resulting in an overall gain of 2.7dB with respect to the baseline configuration. The large number of linear taps in the TripleX equalizer was chosen to cope with reflections in the setup assembly and avoid fine optimization, but it could be reduced with negligible impact on performance, especially in an integrated device.

Fig. 4-left shows the spectrum of a 96GBd DP-32QAM CUT having a central wavelength of 1531.74nm after being shaped by the NL-DPD. Fig. 4-center illustrates the DWDM spectra at the input and output of the 600km transmission line. It can be observed that although the spectrum at the output of the booster amplifier is fairly flat with a ripple below 0.5dB, after the transmission line, at pre-amplifier a ripple of 5dB is observed. The PoC of 800ZR+ DWDM transmission with a reach of 600km is shown in Fig. 4-right. It can be observed that using the TripleX equalization all 32 channels exhibit pre-FEC BER below the considered threshold of 2×10^{-2}.

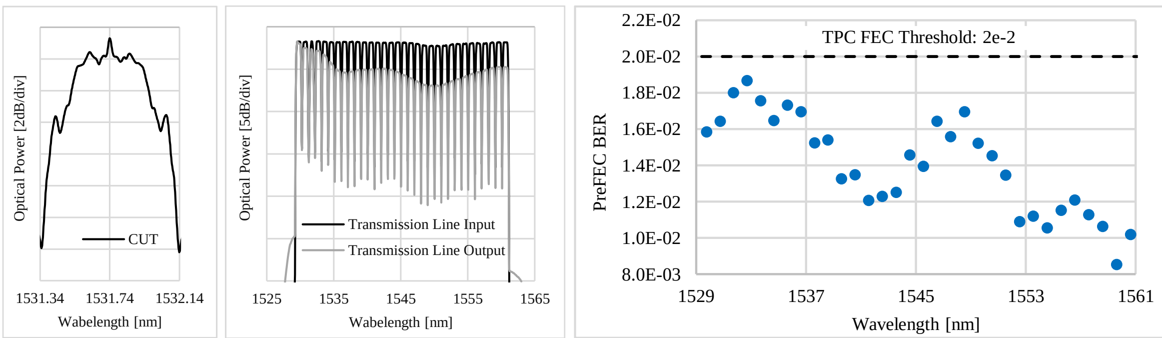

Figure 4. DWDM experiment: Spectrum of a 96GBd DP-32QAM CUT having central wavelength at 1531.74nm (left), DWDM spectra at the input and output of the 600km transmission line (center), pre-FEC BER for the 32-channel DWDM system transmission over a 600km G654D fiber link (right).

4. Conclusions

By means of an 800ZR+ DWDM proof of concept (PoC), we demonstrated the feasibility of extended metro transmission using a conventional modulation scheme and a generic TPC FEC, which are well suited for a potential standard. Despite the straight-forward coding and modulation scheme, the achieved performance outclasses previous demonstrations of single-lambda 800Gb/s due to the use of advanced equalization techniques. The PoC also proved the suitability of 96GBaud for an extended metro transmission, which indicates to the industry a lower-risk path towards small form-factor 800Gbit/s optics with respect to solutions based on 130GBaud DP-16QAM.

Future work includes the development of low-complexity implementations of the proposed TripleX architecture, possibly along the lines of [12]. We also expect that the introduction of new higher-bandwidth optical modulators, will both improve the system performance and reduce the complexity of the receiver by obviating the need for soft-output partial response equalization and MLSE.

5. References

[1] F. Pittalà, et al., "400Gbit/s DP-16QAM Transmission over 40km Unamplified SSMF with Low-Cost PON Lasers", in IEEE Photonics Technology Letters, vol. 31, no. 15, pp. 1229-1232, Aug.1, 2019.
[2] Y. Hirbawi, "Continuation & Results of FEC Proposals evaluation for ITU G.709.3 200-400G 450km Black Link", ITU-T SG15 - CD11-M10 https://www.itu.int/ifa/t/2017/sg15/exchange/wp3/q11/Ref_Mod_450kmFEC/CD11-M10-CICT-Updated%20_results_evaluation_of_FEC_Proposals.ppt
[3] F. Buchali, et al., "1.3-Tb/s Single-Channel and 50.8-Tb/s WDM Transmission over Field-Deployed Fiber", in Proc. Eur. Conf. Opt. Commun. (ECOC), Dublin, Ireland, Sep. 2019, PD.1.3.
[4] A. Matsushita, et al., "41-Tbps C-band transmission with 10-bps/Hz spectral efficiency using 1-Tbps 96-GBd PS-256QAM for DCI", in Proc. Eur. Conf. Opt. Commun. (ECOC), Dublin, Ireland, Sep. 2019, Tu.2.D.1.
[5] F. Buchali, et al., "Beyond 100 Gbaud Transmission Supported by a 120 GSa/s CMOS Digital to Analog Converter", in Proc. Eur. Conf. Opt. Commun. (ECOC), Dublin, Ireland, Sep. 2019, Tu.2.D.3.
[6] A. Ghazisaeidi, et al., "Power efficient transmission of 320 Gb/s over 17545 km,and 560 Gb/s over 6050 km using 98 GBd QPSK and 64QAM and CMOS technology", in Proc. Eur. Conf. Opt. Commun. (ECOC), Dublin, Ireland, Sep. 2019, Tu.2.D.4.
[7] S. Wolf, et al., "2-Channels ×100 GBd 32QAM Transmission over 500 km Enabled by InP PICs and SiGe ASICs", in Proc. Eur. Conf. Opt. Commun. (ECOC), Dublin, Ireland, Sep. 2019, Tu.1.E.2.
[8] M. Nakamura et al., "Spectrally Efficient 800 Gbps/carrier WDM Transmission with 100-GHz Spacing Using Probabilistically Shaped PDM-256QAM", in Proc. Eur. Conf. Opt. Commun. (ECOC), Rome, Italy, Sep. 2018, pp. 1-3.
[9] J. Li, et al., "Approaching Nyquist Limit in WDM Systems by Low-Complexity Receiver-Side Duobinary Shaping", in Journal of Lightwave Technology, vol. 30, no. 11, pp. 1664-1676, June1, 2012.
[10] C. Eun et al., "A New Volterra Predistorter Based on the Indirect Learning Architecture", in IEEE Transactions on Signal Processing, vol. 45, no. 1, pp. 223-227, Jan. 1997.
[11] "G.654 : Characteristics of a cut-off shifted single-mode optical fibre and cable", ITU-T Recommendation G.654, (Nov. 13, 2016).
[12] C. Bluemm, et al. "Equalizing Nonlinearities with Memory Effects: Volterra Series vs. Deep Neural Networks", in Proc. Eur. Conf. Opt. Commun. (ECOC), Dublin, Ireland, Sep. 2019, W.3.B.3.