Long-haul Transmission of 1 Tb/s Data Rate Channel with Inline Filtering based on 145 GBd Dual Polarization 16QAM

S. Almonacil, Y. Hong, H. Mardoyan, X. Ye, A. Ghazisaeidi and J. Renaudier
Nokia Bell Labs, Paris-Saclay, France
sylvain.almonacil@nokia-bell-labs.com

Abstract: We demonstrate Tb-class long-haul experiment based on 145-GBd signal occupying one 150-GHz slot. We achieve 1.0-Tb/s/λ over 3630-km distance with a spectral efficiency of 6.67-b/s/Hz while accounting for inline filtering from ROADM in transport networks.

1. Introduction

To sustain ceaseless traffic growth in optical fiber communications, the development of higher speed coherent optical interfaces is required to scale with the next generation of client signals [1] and further reduce the cost per bit. 1-Tb/s-class transmission has been widely investigated over the past decade. Multi-wavelengths approaches (also termed as superchannels), have first been proposed for the transport of 1-Tb/s data rates to overcome the limitations of high-speed optoelectronics components [2-4], which however are less cost-effective for optical transport networks as compared with single-wavelength solutions. Later, 1-Tb/s/λ systems with high spectral efficiencies were demonstrated using high cardinality constellations, but their reach did not meet long distance requirements (>1,000-km) for cost-effective transport networks since the corresponding required signal-to-noise ratio (SNR) must be relatively high [5-10]. Recently, the use of analog bandwidth multiplexing technique combined with optical equalization at the transmitter has been proposed to boost the symbol rate per wavelength up to 168-GBd [11]. Packing the signal within a 175-GHz spacing grid, the long-haul transmission of 1-Tb/s/λ has been demonstrated over 3840-km with a spectral efficiency of 5.7-b/s/Hz. However, this was achieved by the adoption of backward Raman amplification and filtering effects that may arise from ROADMs in meshed networks were not considered.

In this paper, we demonstrate the long-haul transmission of a 1-Tb/s single-wavelength dual-polarization (DP) signal at 145-GBd modulated with 16QAM inserted into a 150-GHz slot which corresponds to a spectral efficiency of 6.67-b/s/Hz. The Tb-class channel is successfully transmitted over up to 4235-km using a recirculating loop made of pure silica core fiber spans separated by erbium-doped fiber amplifiers (EDFAs). We then compare the impact of inline filtering when operating at 145-GBd and 48.33-GBd into 150-GHz and 50-GHz slots respectively, namely at the same spectral efficiency, and experimentally show better bandwidth efficiency of the 145-GBd channel. With inline filtering the 1-Tb/s channel is transmitted over up to 3630-km distance when operating over a 150-GHz slot.

2. Experimental setup

Fig. 1 depicts the experimental setup used for the long-haul transmission. The transmitted signal is made of a WDM comb composed of 49 C-band DFB lasers spaced at 50-GHz plus one channel under test (CUT). The loading channels are modulated with 48.33-GBd PDM 16QAM signals generated by DACs operating at 120-GS/s. The CUT is made of a low linewidth tunable laser source (TLS) set at 1550.52-nm, independently modulated with 145-GBd PDM-16QAM signals, generated by DACs from a commercially available arbitrary waveform generator operating at 256-

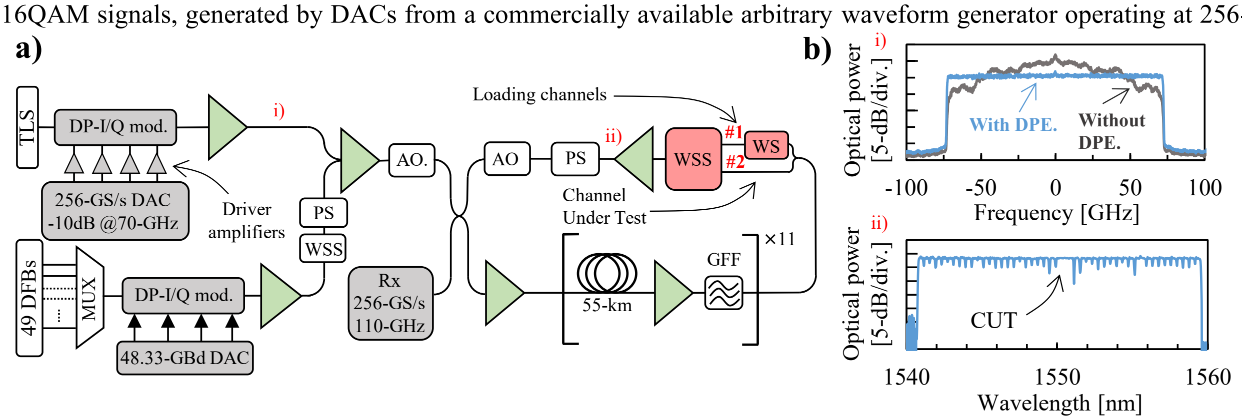

Fig. 1. a) Experimental setup; b) Optical spectrum of i) the channel under test (CUT) at the transmitter output; ii) the WDM channel comb after 1 loop. WSS: wavelength selective switch; WS: waveshaper; PS: polarization scrambler; AO: acousto-optics switch.

GS/s with a -10-dB bandwidth of 70-GHz. The digital signal is Nyquist shaped (root-raised-cosine, roll-off 0.01) and its spectrum is shown in part i) of Fig. 1-1b), with and without digital pre-emphasis (DPE). No optical equalization of the CUT has been used in this experiment. The loading comb passed through a polarization scrambler (PS) before being multiplexed with the test channel. The 50-GHz-grid-resolution WSS at the transmitter is used to flatten the power profile of the loading channel comb and programmed as a 150-GHz stopband notch filter centered at the wavelength of 1550.52-nm. The CUT and the loading WDM comb are then multiplexed together and launched into the recirculating loop as shown in the inset ii) to Fig. 1. The loop consists of 11 spans of 55-km Corning EX3000 fibers, with 0.157-dB/km loss coefficient, 20.5-ps/nm/km dispersion coefficient at 1550-nm, and 150-µm^2 effective area. Each loop thus corresponds to transmission over 605-km. The span loss is compensated at the end of each span by a C-band EDFA followed by a gain flattening filter (GFF). A 50 GHz-grid-resolution WSS is placed after the last span of the loop to equalize channels powers across the WDM comb. Moreover, a 3-dB optical coupler is used at the input of the WSS to possibly emulate filtering that may arise from ROADM in transport networks [12]. The 3-dB coupler duplicates the WDM comb to enter the WSS through two distinct input ports, denoted as #1 and #2. In the first scenario, referred to as the "filtering" scenario, the CUT is passed through port #2 of the WSS. On this port, the WSS is configured to reject the loading channels by programming a 150-GHz passband transfer function centered at 1550.52-nm, as depicted in Fig. 2-a). The loading channels are passed through the waveshaper (WS) and port #1 of the WSS, both with a stopband filter of 150-GHz width centered at 1550.52-nm, as depicted in Fig. 2-a). This ensures that no residual crosstalk effects may add to filtering effects in this experiment. For analysis at 48.33-GBd, the width of the transfer functions is reduced to 50-GHz. In the "no-filtering" scenario, regardless of the symbol rate, the passband transfer function of port #2 of the WSS is enlarged to 250-GHz, as well as the stopband function of port #1 of the WSS and that of the WS. The WDM signal at the loop output, as illustrated in Fig. 2-b), is then received by a standard coherent receiver front-end and sampled at 256-GS/s using a 100-GHz real-time sampling scope. The offline DSP is applied to the recorded sampled waveforms. The standard DSP suite [13] includes chromatic dispersion compensation, complex MIMO 2x2 constant modulus algorithm, frequency offset compensation, blind phase search carrier phase recovery, and least-mean square equalizer to mitigate for transmitter impairments. Finally, the SNR and achievable information rate (AIR) of the received CUT are computed.

3. Transmission results

We first perform back-to-back transmission experiments to assess the performance of the 145 GBd DP-16QAM signal. Fig. 2-c) shows the performance in terms of SNR as a function of the optical SNR (OSNR) measured in 0.1 nm. The graph shows that the 145-GBd DP-16QAM signal exhibits a SNR floor above 16-dB, which results from the limited bandwidth and imperfect response of the transmitter and receiver. A 1-Tb/s AIR, corresponding to a normalized generalized mutual information of 0.865, can be achieved at the target SNR of 11.5-dB, where the system exhibits a 1.4-dB penalty with respect to ideal expectations. Next, we perform long-haul transmission experiments by inserting our 145-GBd channel into a 150-GHz slot, surrounded by loading channels. The resulting WDM comb signals are launched into the recirculating loop. The WSS and the WS are first configured for the "no filtering" scenario while keeping the transmission distance to 3025-km, which corresponds to 5 loops. We vary the launched power of the EDFAs in each span and measure the performance evolution of our CUT. Fig. 2-d) shows the measured SNR versus the launched power, indicating an optimum channel launched power of -1-dBm per 50-GHz bandwidth at 3025-km for the 145-GBd transmission. We then measure the CUT performance at the optimum launched power in the "filtering" scenario by sweeping the carrier frequency of the CUT between 1550.56-nm (193,344-GHz) and 1550.47-nm (193,356-GHz). The results are shown in Fig. 3-a). As expected, the best performance is obtained with the CUT carrier at 1550.52-nm (193,350-GHz). With 1-GHz detuning, we measure a SNR penalty below 0.3-dB.

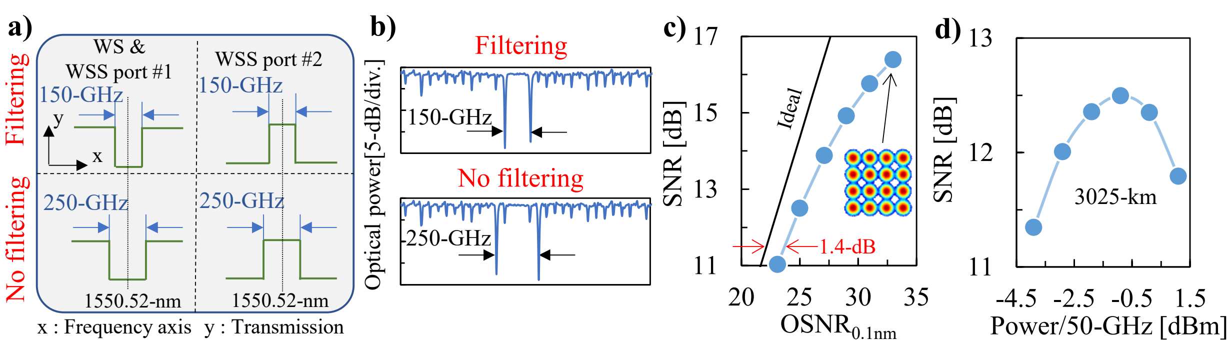

Fig. 2. a) Schematic of the "filtering" and "no filtering" scenarios. b) Optical spectrum of the CUT and nearest loading channels with "filtering" and with "no filtering". c) Back-to-back sensitivity to noise of the 145-GBd DP-16QAM. d) SNR versus launched power.

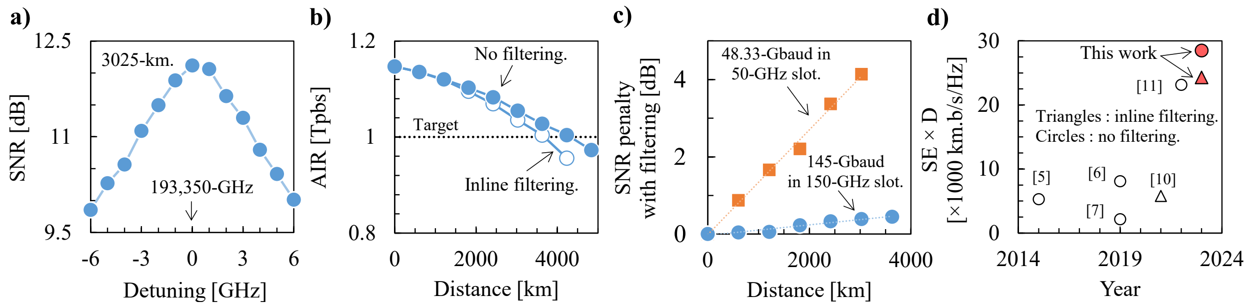

Fig. 3. a) SNR versus detuning frequency of the CUT after 3025-km. b) Achievable information rate (AIR) for the 145-GBd DP 16-QAM versus distance. c) SNR penalty from inline filtering versus distance. d) Overview of achieved spectral efficiency times distance products for 1-Tbps (AIR) class experiments.

We then measure the performance of the CUT versus distance up to 4840-km in both the "filtering" and "no filtering" scenarios, at the optimum launched power and with a CUT carrier at 1550.52-nm (193,350-GHz). Fig. 3-b) shows the measured AIR versus distance for the 145-GBd DP-16QAM channel. Without filtering, 1-Tbps AIR is successfully achieved over up to 4235-km (7 loops). With 150-GHz "filtering", the reach is reduced to 3630-km (6 loops) while maintaining the 1-Tbps AIR. For comparison, we repeat these measurements when modulating the CUT at 48.33-GBd and inserting it into a 50-GHz slot. We present in Fig. 3-c) the comparison of SNR penalty between the "filtering" and the "no filtering" scenarios for both configurations {symbol rate, grid spacing}. This figure clearly shows that the impact of filtering is rapidly growing at 48.33-GBd in 50-GHz, while the penalty observed at 145-GBd in 150-GHz is slightly below ~0.5-dB at 3630-km after passing through 6 filtering functions. This result highlights the potential of optimizing the bandwidth efficiency of WDM channels when moving to wide WDM slots from 50-GHz to 150-GHz [14]. To the best of our knowledge, the improved bandwidth efficiency (i.e., 6.67-b/s/Hz) of our 1-Tb/s 145-GBd DP-16QAM channel yields the highest spectral efficiency times distance products reported to date for single-wavelength Tb-class experiments, which correspond to 24,321-(b/s/Hz)·km and 28,375-(b/s/Hz)·km for "filtering" and "no filtering" scenarios, respectively, as depicted in Fig. 3-d).

4. Conclusion

We have successfully demonstrated 1.0-Tb/s/λ transmission with 145-GBd DP 16-QAM signals over a maximum distance of 4235-km using ultra low loss fibers and EDFAs only. Inserted into a 150-GHz slot, our result corresponds to an achievable spectral efficiency of 6.67-b/s/Hz. We have also analyzed the impact of inline filtering stemming from ROADM cascade in transport mesh networks. We showed that the reduced filtering impairments from improved bandwidth occupancy enables the 1-Tb/s data to reach up to 3630-km. These results show that the reach of 1-Tb/s/λ-class transmission can be extended using high symbol rates and DP-16QAM to accommodate with future optical transport networks.

References

[1] Ethernet Alliance, "The 2020 Ethernet Roadmap," [online] Available: https://ethernetalliance.org/technology/2020-roadmap.
[2] Y.-K. Huang et al, "Terabit/s optical superchannel with flexible modulation format for dynamic distance/route transmission," in OFC'12 Proceedings, OM3H.4, Los Angeles (2012).
[3] X. Liu et al, "1.5-Tb/s Guard-Banded Superchannel Transmission over 56x100-km ULAF Using 30-GBaud Pilot-Free OFDM-16QAM Signals with 5.75-b/s/Hz Net Spectral Efficiency,", in ECOC'12 Proceedings, paper Th3C5, Amsterdam (2012).
[4] J. Renaudier, et al, "1-Tb/s PDM-32QAM Superchannel Transmission at 6.7-b/s/Hz over SSMF and 150-GHz-Grid ROADMs," in Proceedings of ECOC'14, paper Tu3.3.4, Cannes (2014).
[5] R. Rios-Müller, et al, "1-Terabit/s net data-rate transceiver based on single-carrier Nyquist-shaped 124 GBaud PDM-32QAM," In proceedings of Optical Fiber Communication Conference 2015, paper Th5B-1, Los Angeles, USA (2015).
[6] T. Kobayashi et al., "35-Tb/s C-band transmission over 800 km employing 1-Tb/s PS-64QAM signals enhanced by complex 8 × 2 MIMO equalizer," in Proc. Opt. Fiber Commun. Conf. (OFC), Mar. 2019, Paper Th4B.2.
[7] M. Nakamura et al., "1.04 Tbps/carrier probabilistically shaped PDM-64QAM WDM transmission over 240 km based on electrical spectrum synthesis," in Proc. Opt. Fiber Commun. Conf. (OFC), Mar. 2019, Paper M4I.4.
[8] K. Schuh et al., "Single carrier 1.2 Tbit/s over 300 km with PM-64 QAM at 100 GBaud," in Proc. OFC'17, Th5B.5, LA, CA, 2017.
[9] F. Buchali et al., "1.52 Tb/s single carrier transmission supported by a 128 GSa/s sige DAC," in Proc. OFC', Th4C.2, San Diego, CA, 2020.
[10] F. Pittalà et al., "Single-carrier coherent 930 G, 1.28 T and 1.60 T field trial," in Proc. of ECOC'21, Sep. 2021, pp. 1–4.
[11] N. Nakamura, et al, "1.0-Tb/s/λ 3840-km and 1.2-Tb/s/λ 1280-km Transmissions with 168-GBaud PCS-QAM Signals Based on AMUX Integrated Frontend Module," in proceedings of OFC'22, paper W3C.1, San Diego, USA (2022).
[12] A. Morea, et al, "Throughput comparison between 50-GHz and 37.5-GHz grid transparent networks", JOCN, 7(2), A293-A300, 2015.
[13] A. Ghazisaeidi et al., "Advanced C+L-band trans-oceanic transmission systems based on probabilistically shaped PDM-64QAM," J. Lightw. Technol., vol. 35, no. 7, pp. 1291–1299, Apr. 2017.
[14] F. Buchali, et al., "DCI field trial demonstrating 1.3-Tb/s single-channel and 50.8-Tb/s WDM transmission capacity," *JLT,* 38.9, pp. 2710-2718, 2020.