Transmission of 800 Gbps Net Bit Rate per Wavelength over Transoceanic Distance Using 148-GBaud PCS-16QAM

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Abstract *We demonstrate 800-Gbps net long-haul experiment based on single-carrier 148-GBaud signal occupying one 150-GHz slot. With dual-polarization PCS-16QAM, we achieve 800-Gbps/λ over 7865-km at the spectral efficiency of 5.33-b/s/Hz. We also demonstrate 400-Gbps/λ over 22990-km with dual-polarization QPSK. ©2023 The Author(s)*

Introduction

With no cease in sight for traffic growth in optical fiber communication systems, the deployment 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. In that context, the development of 800-Gbps per wavelength class interfaces have focused massive efforts in the past few years. A first wave of demonstrations using coherent transceivers operating around 100-GBaud have been reported. However, due to the limited symbol rate, high cardinality signals such as 64QAM [2] or even 256QAM [3] needed to be generated and reliably transmitted while transceiver induced penalties as well as high optical signal-to-noise ratio (OSNR) requirements of this modulation formats fundamentally limited the propagation distance. For instance, authors in [4] achieved 800-Gbps net transmission over 605-km with 99.5-GBaud 64QAM. By using probabilistic constellation shaping (PCS) the propagation distance has been increased and a reach of 2000-km has been exceeded with 100-GBaud PCS-64QAM yet resorting on Raman amplification [5, 6]. By pushing the symbol rate to 120-GBaud, authors in [7] reported the transmission of 800-Gbps over 3250-km based on PCS-36QAM. With the introduction of the latest generation of coherent transceivers, symbol rate has been pushed in the range of 130-140-GBaud. This enables 800-Gbps per wavelength to be generated with 16QAM. Recently, a field trial demonstration of 800-Gbps transmission above 2000-km of terrestrial fiber network has been reported by using 138-GBaud PCS-16QAM and relying on hybrid Raman/EDFA amplification [8]. Thus, the increase in symbol rate has enabled to extend the reach of 800-Gbs transmissions yet, to the best of our knowledge, without overpassing 4000-km. In that context, achieving 800-Gbps per wavelength over transoceanic distances would be also appealing for the next generation of submarine cables to further reduce the cost per bit of transcontinental communication systems.

In this work, we demonstrate the transmission of 800-Gbps net bit rate per wavelength at transoceanic distance up to 7865-km based on a dual-polarization (DP) 148-GBaud PCS-16QAM signal without resorting to Raman amplification. To maximize the spectral efficiency while increasing the symbol rate, the signal is packed into a single 150-GHz slot. This result is obtained by propagating the 148-GBaud signal into a submarine-class recirculating loop made of EX3000 fiber spans separated by Erbium-doped fiber amplifiers (EDFA). With a net spectral efficiency of 5.33-b/s/Hz, we improve the transmission distance by more than a factor of 2 with respect to previous achievements, as depicted in Fig. 1. We further demonstrate the benefits of high symbol rates for ultra-long-haul propagation by transmitting a 400-Gbps DP-QPSK signal at the distance of 22990-km.

Experimental set-up

Fig. 2 depicts the experimental set-up used for ultra-long-haul transmissions. The transmitted signal is made of a WDM comb composed of 44 C-band DFB lasers spaced at 50-GHz plus one channel under test (CUT). The CUT is made of a tunable laser source (TLS) set at 1550.52-nm, modulated with DP-PCS-16QAM signal at a symbol rate of 148-GBaud. The digital waveforms are generated by digital-to-analog converters (DACs) from a commercially available arbitrary

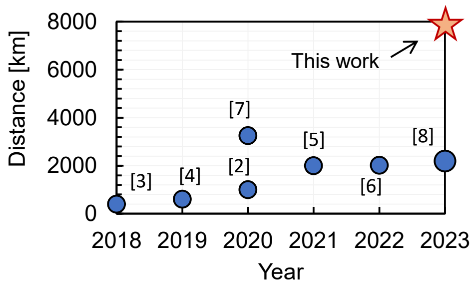

Fig. 1. Achieved transmission reaches for 800-Gbps per wavelength transmissions.

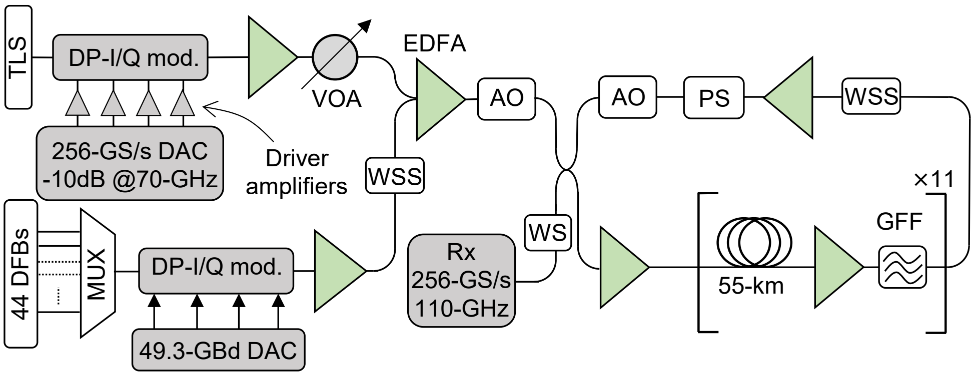

Fig. 2. a) Experimental setup. WSS: wavelength selective switch; WS: Wave Shaper; PS: polarization scrambler; AO: acousto-optics switch. VOA: Variable Optical Attenuator. EDFA: Erbium doped fiber amplifier. GFF: Gain flattening filter.

waveform generator operating at 256-GS/s having 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 Fig. 3a with and without digital pre-emphasis (DPE). No optical equalization of the CUT has been used in this experiment. The loading channels, occupying each 50-GHz, are independently modulated at 49.3-GBaud to keep the same power spectral density as the CUT. A 50-GHz-grid resolution WSS at the transmitter is used to flatten the power profile of the loading channels comb and the power level of the CUT is manually adjusted by mean of a variable optical attenuator (VOA). The loading comb and the CUT are then multiplexed with an optical coupler and launched into the recirculating loop. The submarine recirculating loop consists of 11 spans of 55-km Corning EX3000 fibers, with 0.157-dB/km loss coefficient, 20.5-ps/nm/km at 1550-nm, and 150-μm^2 effective area. Each loop thus corresponds to transmission over 605-km. Fiber attenuation is compensated at the end of each span of the loop 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

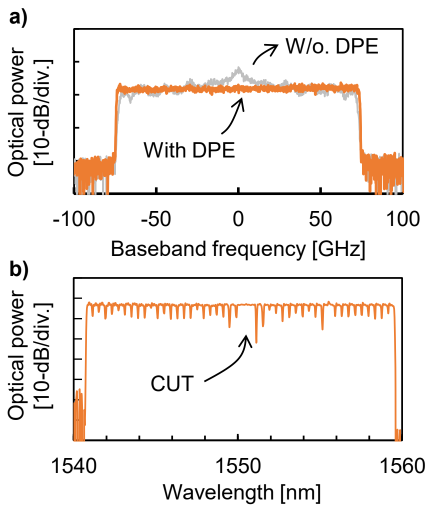

Fig. 3. Optical spectrum of a) the channel under test (CUT) at the transmitter output; b) the WDM channel comb after 1 loop (605-km).

channel powers across the WDM comb. Finally, a loop synchronous polarization scrambler (PS) enables to randomly distribute the state of polarization of the signals over the Poincaré sphere at the end of each loop trip. The WDM spectrum at the end of the first loop (605-km) is shown in Fig. 3b. At the receiver side, the CUT is extracted from the WDM comb with a Wave Shaper configured as a bandpass filter. The CUT is then received by a standard coherent receiver front-end and sampled at 256-GS/s using a 110-GHz bandwidth real-time oscilloscope. Each recorded waveform consists of 2 million samples which are processed offline. The standard DSP suite consists of matched filter, chromatic dispersion compensation, complex 2x2 MIMO adaptive equalization, frequency offset compensation, blind phase search carrier phase recovery, and least-mean square equalizer to mitigate for transmitter I/Q imbalances. Adaptive equalization is done using periodically distributed QPSK pilots with a rate of 2% [9]. No digital back propagation for nonlinear effects compensation is applied. Finally, we independently measure, on the demodulated signal, the signal-to-noise ratio (SNR), the normalized generalized mutual information (NGMI) as well as the net bit rate by applying a family of SC-LDPC codes with rates varying between 0.5 and 0.9 to achieve error-free decoding [9].

Transmission results

We first perform back-to-back experiments to assess the performance of our transmitter with 148-GBaud DP-PCS-16QAM. The signal entropy is set at 3.8-bits/symbol/polarization (optimized for propagation, as shown later). Fig. 4a shows the back-to-back sensitivity to noise as a function of the optical signal-to-noise ratio (OSNR) measured in 0.1-nm bandwidth. This graph shows that the 148-GBd DP-PCS-16QAM signal exhibits a SNR floor slightly above 15-dB, which results from the imperfect response and limited bandwidth of the transmitter and receiver. An example of recovered constellation diagram is

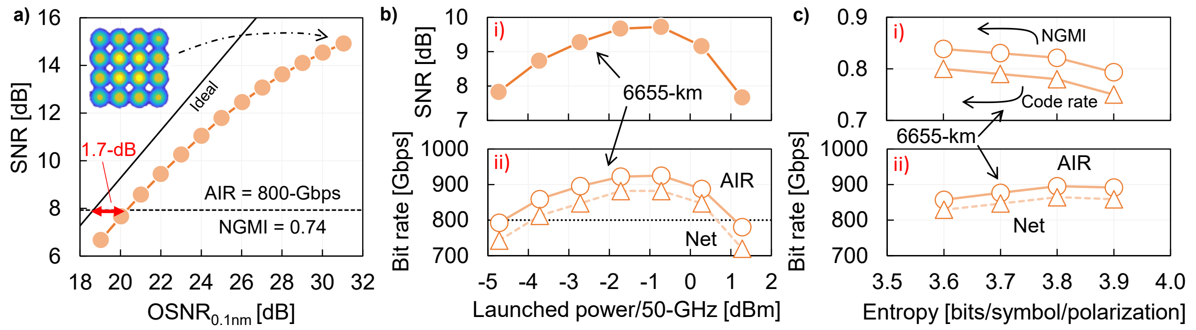

Fig. 4. Experimental results. a) Back-to-back sensitivity to noise of the 148-GBaud DP-PCS-16QAM signal. b) SNR and bit rate versus launched power. c) Entropy optimization : code rate, NGMI and bit rate at the optimum launched power.

shown for the best SNR value. At 800-Gbps achievable information rate (AIR), obtained for the NGMI (which corresponds to the ideal code rate) of 0.74, the measured SNR is equal to 7.9-dB and the transceiver exhibits a 1.7-dB OSNR penalty with respect to ideal expectations. Next, we perform submarine transmission experiments by inserting the 148-GBd channel into the 150-GHz slot centered at 1550.52-nm, surrounded by the loading channels. We first calibrate the launch power of the EDFAs in each span by measuring the performance of our CUT at the target transoceanic distance of 6655-km (11-loops). Fig. 4b inset i) shows the measured SNR as a function of launched power, indicating an optimum launched power of -0.7-dBm per 50-GHz bandwidth (16-dBm total launched power). We also show in inset ii) of Fig. 4b the measured net bit rate after SC-LDPC decoding. To determine the maximum usable code rate r_c we apply SC-LDPC decoding to the recorded traces, following the procedure described in [9]. From the code rate r_c the net bit rate is given by:

$$Net\ bit\ rate = 2 \cdot R \cdot R_p \cdot (H - (1 - r_c) \cdot m) \quad (1)$$

With R the symbol rate, Rp = 0.98 the 2% pilot overhead correction, H the PCS signal entropy and m the native constellation (16QAM) cardinality (4-bits/symbol/polarization). At the optimum launched power and after 6655-km, the AIR reaches 925-Gbps, and the net bit rate 882-Gbps. We also report in insets i) and ii) of Fig. 4c the results of the entropy optimization between 3.6 and 3.9-bits/symbol/polarization. At the transmission distance of 6655-km, the net bit rate is maximum with an entropy of 3.8-bits/symbol/polarization. We then push the transmission distance up to 10890-km by keeping constant launched power and signal entropy. Fig. 5a shows the performance evolution as a function of distance. An AIR of 800-Gbps is achieved at up to 9075-km (NGMI = 0.75) while 800-Gbps net bit rate is obtained at up to 7865-km with a code rate r_c = 0.74.

We then switch to DP-QPSK modulation with the goal of pushing the transmission distance of a 400-Gbps channel to its maximum extent. Recently, transmission distances of 20570-km have been achieved at net bit rate of ~300-Gbps with 99-GBaud DP-QPSK [10] and 20631-km at net bit rate of 400-Gbps with 128-GBaud DP-QPSK [11]. Fig. 5b shows the measured net bit rate and AIR with propagation distance in this experiment. At 24200-km (40-loops) the AIR of the DP-QPSK signal is 407-Gbps. After FEC decoding, a net bit rate of 400-Gbps (r_c = 0.72) can be achieved at up to 22990-km, corresponding, to the best of our knowledge, to the longest transmission distance reported so far for 400-Gbps data per wavelength.

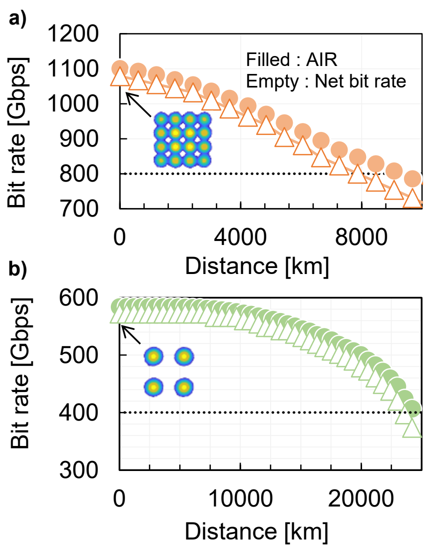

Fig. 5. Bit rate versus transmission distance. a) DP-PCS-16QAM at 148-GBaud. b) DP-QPSK.

Conclusion

We demonstrate 800-Gbps net bit rate transmission at up to 7865-km in a submarine recirculating loop with a single wavelength dual-polarization 148-GBaud PCS-16QAM signal inserted into a 150-GHz WDM slot and resorting to EDFA amplification only. This result opens the door for the future deployment of single wavelength 800-Gbps coherent transceivers over transoceanic submarine cables. We also demonstrate 400-Gbps net bit rate with DP-QPSK at the distance of 22990-km.

References

[1] Ethernet Alliance, “The 2020 Ethernet Roadmap,” [online] Available: https://ethernetalliance.org/technology/2020-roadmap.

[2] H. Sun, M. Torbatian, M. Karimi, R. Maher, S. Thomson, M. Tehrani, Y. Gao, A. Kumpera, G. Soliman, A. Kakkar, M. Osman, Z. A. El-Sahn, C. Doggart, W. Hou, S. Sutarwala, Y. Wu, M. R. Chitgarha, V. Lal, H. Tsai, S. Corzine, J. Zhang, J. Osenbach, S. Buggaveeti, Z. Morbi, M. I. Olmedo, I. Leung, X. Xu, P. Samra, V. Dominic, S. Sanders, M. Ziari, A. Napoli, B. Spinnler, K. Wu and P. Kandappan, “800G DSP ASIC Design Using Probabilistic Shaping and Digital Sub-Carrier Multiplexing,” in *Journal of Lightwave Technology*, vol. 38, no. 17, pp. 4744-4756, 2020, DOI: 10.1109/JLT.2020.2996188

[3] M. Nakamura, A. Matsushita, S. Okamoto, F. Hamakoa and Y. Kisaka, “Spectrally Efficient 800 Gbps/carrier WDM Transmission with 100-GHz Spacing Using Probabilistically Shaped PDM-256QAM,” presented at *European Conference on Optical Communication (ECOC)*, Roma, Italy, 2018. DOI: 10.1109/ECOC.2018.8535182

[4] A. Arnould, A. Ghazisaeidi, D. Le Gac, E. Awwad, P. Brindel and J. Renaudier, “Net 800 Gbit/s Transmission over 605 km Using 99.5 GBaud PDM-64QAM with CMOS Digital-to-Analog Converters,” presented at *European Conference on Optical Communication (ECOC)*, Dublin, Ireland, 2019. DOI: 10.1049/cp.2019.0842

[5] M. Kong, C. Liu, B. Sang, K. Wang, J. Ding, J. Shi, L. Zhao, W. Zhou, X. Xin, B. Ye, W. Chen and J. Yu, “Demonstration of 800-Gbit/s/carrier TPS-64QAM WDM Transmission over 2,000 km Using MIMO Volterra Equalization,” presented at *Optical Fiber Communication Conference (OFC)*, San Francisco, USA, 2021.

[6] D. Ge, H. Zhang, C. Yu, D. Wang, D. Zhang, R. Wang, Y. Li, S. Liu, S. Cao, L. Mei, H. Zhou, L. Han, H. Li, L. Gu, J. Zhu, X. Duan and H. Li, “Real-time 10-λ×800-Gb/s Sub-carrier-multiplexing 95-GBd DP-64QAM-PCS Transmission over 2018-km G.654.E Fibre with Pure Backward Distributed Raman Amplification,” presented at *European Conference on Optical Communication (ECOC)*, Basel, Switzerland, 2022.

[7] M. Nakamura, T. Kobayashi, H. Yamazaki, F. Hamakoa, M. Nagatani, H. Wakita, H. Nosaka and Y. Miyamoto, “Entropy and Symbol-rate Optimized 120 GBaud PS-36QAM Signal Transmission over 2400 km at Net-rate of 800 Gbps/λ,” presented at *Optical Fiber Communication Conference (OFC)*, San Diego, USA, 2020.

[8] T. Richter, S. Searcy, P. Jennevé, D. Giannakopoulos, B. Owens, M. A. Mestre, A. Awadalla and S. Tibuleac, “1 Tb/s and 800 Gb/s real-time transmission at 138 GBd over a deployed ROADM network with live traffic,” presented at *Optical Fiber Communication Conference (OFC)*, San Diego, USA, 2023.

[9] A. Ghazisaeidi, I.F. de Jauregui Ruiz, R. Rios-Müller, L. Schmalen, P. Tran, P. Brindel, A. Carbo Meseguer, Q. Hu, F. Buchali, G. Charlet and Jérémie Renaudier, "Advanced C+L-Band Transoceanic Transmission Systems Based on Probabilistically Shaped PDM-64QAM," in *Journal of Lightwave Technology*, vol. 35, no. 7, pp. 1291-1299, 2017, DOI: 10.1109/JLT.2017.2657329.

[10] A. Arnould, A. Ghazisaeidi, D. Le Gac, M. Ionescu, P. Brindel and J. Renaudier, “Record 300 Gb/s per Channel 99 GBd PDM-QPSK Full C-Band Transmission over 20570 km Using CMOS DACs,” presented at Optical Fiber Communication Conference (OFC), San Diego, USA, 2020.

[11] J. Esparza, H. Pavani, A. Quintana, R. Garuz, S. Dupont and S. Ruggeri, “128GBd record QPSK transmission over 20 631 km and PCS16QAM transmission over 12 558 km using InP technology Platform,” presented at *Optical Fiber Communication Conference (OFC)*, San Diego, USA, 2023.