C-band Unrepeated Transmission System over 291-km at Net Throughput of 41.3-Tbps without ROPA

Sylvain Almonacil(1), Hans Bissessur(2), Haïk Mardoyan(1), Alexis Busson(2), Amirhossein Ghazisaeidi(1), Daryna Kravchenko(2) and Jérémie Renaudier(1)

(1) Nokia Bell Labs, Paris-Saclay, 91620 Nozay, France. *sylvain.almonacil@nokia-bell-labs.com*
(2) Alcatel Submarine Networks, Paris-Saclay, 91620 Nozay, France.

Abstract *We demonstrate 41.3-Tbps net unrepeated transmission in C-band with 37 channels, each carrying >1-Tbps net over 291-km of low-loss high effective-area optical fiber, applying co-Raman amplification, third-order counter-Raman amplification and using 135-GBaud PCS-64QAM signals. ©2023 The Author(s)*

Introduction

Unrepeated optical links provide an economical solution to connect areas such as remote islands or hardly accessible terrestrial regions. One of the main benefits of single-span over multiple-span (repeated) systems is that they do not require any in-line active component (i.e., optical amplifiers), thus reducing both the cost, system complexity and eliminating points of failure. In this context, the key objective of system designers is to simultaneously increase the link throughput and the transmission distance, which scale inversely because of fiber attenuation. To compensate for span attenuation and increase transmission distance, high-power boosters at the transmitter associated with low-loss high-effective area fibers can be used. In addition, Remote Optically Pumped Amplifiers (ROPA) and/or forward and backward Raman pumps enable to increase the transmission distance up to several hundreds of km [1, 2]. Simultaneously, increasing the transmission bandwidth [3-5] and/or the spectral efficiency allows to maximize the link throughput. For instance, authors in [3] reported the transmission of 99-Tbps in a 257-km unrepeated link by pushing the transmission bandwidth up to 100-nm by mean of semiconductor optical amplification (SOA). By constraining the transmission bandwidth to the C-band, the highest reported net throughput was 35.5-Tbps over 291-km, enabled by symbol rate above 100-GBaud and 16QAM signals [6]. Considering spectral efficiency, the highest demonstrated *spectral efficiency times distance* product of 275-(Tbps/nm).km was achieved in 2018 [7]. Table I summarizes recent achievements of unrepeated transmissions above 200-km obtained without the implementation of a ROPA and over single-mode-fiber (SMF).

In this work, we demonstrate the first C-band (41.1-nm bandwidth) unrepeated transmission with net throughput above 40-Tbps without ROPA and over SMF. This result is obtained by pushing the symbol rate up to 135-GBaud and the modulation order to 64QAM, with probabilistic constellation shaping (PCS) and optimized entropy. By leveraging wide electro-optics bandwidth transmitter and receiver, we can generate and transmit all the 37 channels with net bit rate above 1-Tbps after 291-km. We achieved a *spectral efficiency times distance* product of 292-(Tbps/nm).km while halving the number of transponders with respect to [7] and increasing the net C-band throughput for unrepeated transmission by 5.8-Tbps.

Experimental set-up

The experimental set-up built around the 291-km unrepeated link is shown in Fig. 1. At the transmitter side, the channel under test (CUT) is made of a tunable laser source (TLS) modulated with a dual-polarization (DP) 135-GBaud PCS-64QAM signal generated by digital-to-analog converters (DACs) from a commercially available

	Year	Throughput [Tpbs]	Distance [km]	Bandwidth [nm]	Transceivers count	(Tbps/nm).km
[3]	2022	99.35	257	100 *(S+C+L)*	247	256
[5]	2022	90	235	87 *(C+L)*	424	243
[4]	2022	59.2	202	102 *(C+L)*	158	117
[7]	2018	29.2	295	31.3 *(C)*	79	275
[2]	2021	25.6	320	38.4 *(C)*	64	214
[6]	2023	35.46	291	41.1 *(C)*	39	251
This work	**2023**	**41.3**	**291**	**41.1 *(C)***	**37**	**292**

Table 1. Recent >200-km unrepeated transmission achievements without ROPA over SMF.

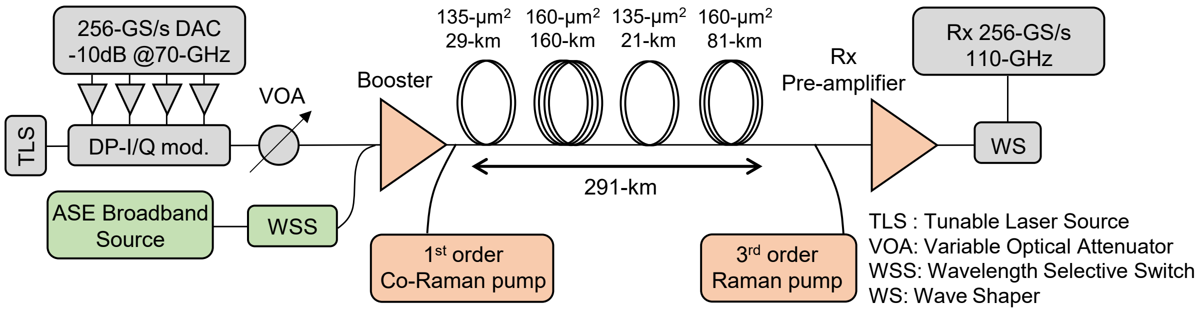

Fig. 1. 291-km unrepeated transmission link.

arbitrary waveform generator operating at 256-GS/s with 10-dB bandwidth up to 70-GHz. The digital waveforms are Nyquist shaped (root-raised-cosine, roll-off 0.01) and we apply digital pre-emphasis (DPE) to compensate for the imperfect response and the limited bandwidth of the transmitter's electro-optics chain. Fig. 2a shows the optical spectrum at the output of the transmitter without and with DPE. The 139.05-GHz DWDM comb is emulated with the association of a broadband source using Amplified Spontaneous Emission (ASE) followed by a Wavelength Selective Switch like in [6]. The ASE shaping is implemented such that the spectral shape of actual data channel is replicated. The CUT and the DWDM comb are combined with an optical coupler before being amplified by an EDFA booster and launched into the link. Power equalization across channels is achieved both with adjustment of the WSS slots attenuation and by mean of a variable optical attenuator (VOA) acting on the CUT, as shown in Fig. 1. An example of DWDM channels after the booster amplifier is shown in Fig. 2b. The 291-km link [6] consists of two different G.654.D pure silica core fibers having an effective area of 135

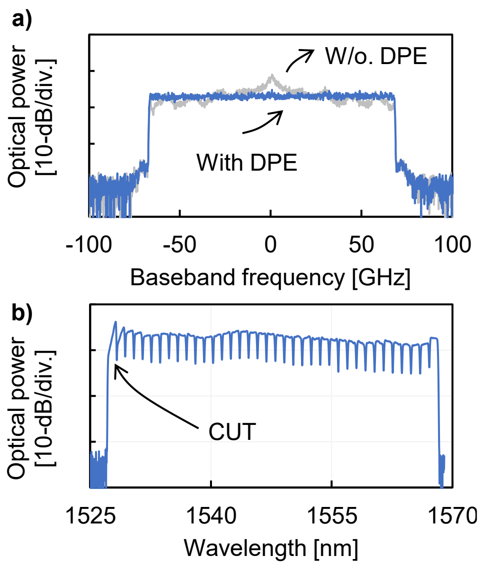

Fig. 2. a) Optical spectrum of the 135-GBaud DP-PCS-64QAM signal at the transmitter output. b) DWDM spectrum with the channel under test at 1527.66-nm.

and 160-μm² and ultra-low attenuation of 0.151-dB/km at 1550-nm. In addition to the booster, amplification through Raman effect both in Co- and Counter-propagated directions is employed. The co-Raman amplifier is optimized to give more gain at the lower wavelengths. At the receiver side, an optical amplifier (Rx pre-amplifier in Fig. 1) is used to increase the receiver input power and the CUT is extracted from the DWDM comb by means of a Wave Shaper configured to emulate a 150-GHz tunable filter. The received signal passes through a standard coherent receiver frontend and is sampled at 256-GS/s by means of a 110-GHz bandwidth real-time oscilloscope. Each acquisition is made of 2 million samples which are processed offline. The 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 equalization to mitigate residual transmitter I/Q imbalances. Adaptive equalization is done using periodically distributed QPSK pilots with a rate of 2% [8]. 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 0.67 and 0.9 to achieve error-free decoding [8].

Results

We first perform back-to-back experiments to assess the performance of the DP-135-GBaud PCS-64QAM signal. The signal entropy is fixed at 5.4-bits/symbol/polarization. Fig. 3a shows the measured SNR as a function of the optical signal-to-noise ratio (OSNR) measured in 0.1-nm bandwidth. This curve shows that the signal exhibits a SNR floor around 17-dB which results from the imperfect response and the limited bandwidth of the transmitter and receiver. An example of recovered constellation diagram is shown at the best SNR. For each SNR value of

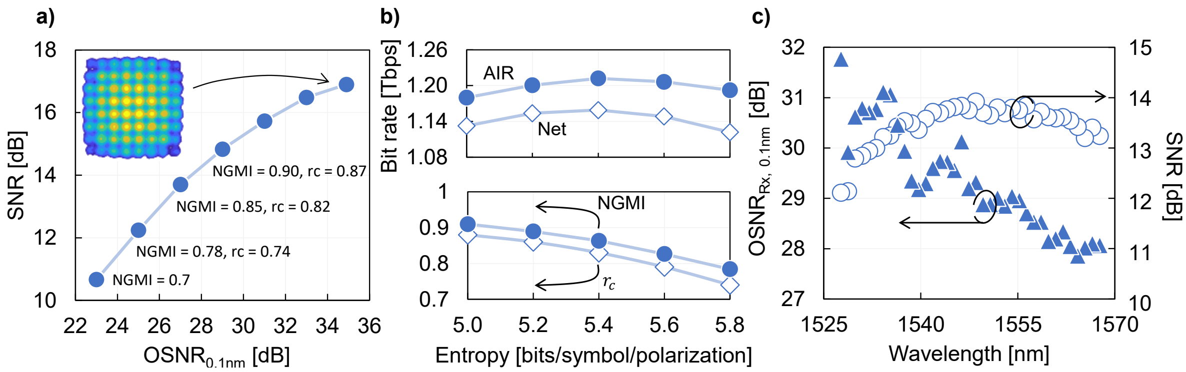

Fig. 3. Experimental results. a) Back-to-back: sensitivity to noise of the 135-GBaud DP-PCS-64QAM signal. b) Transmission: PCS-64QAM entropy optimization with the channel under test at 1554.09-nm. c) Optical signal to noise ratio and signal-to-noise ratio after transmission.

interest after 291-km propagation (12 to 14-dB as shown later) we also report in Fig.3a the measured code rate r_c and the measured NGMI (which corresponds to the ideal code rate). To determine the maximum usable code rate r_c we apply SC-LDPC decoding to the recorded traces, following the procedure described in [8]. Note that for a NGMI = 0.7 (OSNR = 23dB) error free operation is not possible at the minimum allowable code rate of 2/3 for PCS-64QAM [8]. For net throughput maximization, we optimize the PCS-64QAM entropy by measuring the performance after transmission with the CUT centered at 1554.09-nm. Fig. 3b shows the net bit rate and achievable information rate (AIR) together with the maximum usable code rate r_c and corresponding NGMI with varying entropy. For each entropy value, we compute the net rate as a function of code rate r_c with the formula:

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

Where R is the symbol rate, R_p = 0.98 the 2% pilot overhead correction, H the PCS signal entropy and m the native constellation (64QAM) cardinality (6-bits/symbol/polarization). This optimization results in an optimum value of H = 5.4-bits/symbol/polarization, which is used for all the channels in what follows. We then measure the transmission performance of the 37 channels one-by-one by sweeping the CUT central

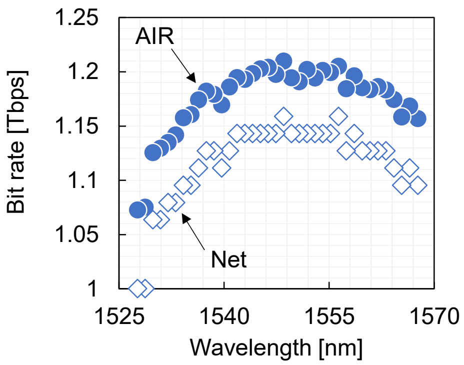

Fig. 4. Bit rate measured as a function of wavelength after 291-km.

frequency between 1527.66-nm and 1567.65-nm by step of 139.05-GHz. We also measure the OSNR after the receiver pre-amplifier ($OSNR_{Rx}$). For signal performance measurement, the corresponding wavelength λ_n of the noise loading comb is removed and replaced by the CUT. Once the traces have been recorded with the oscilloscope, the CUT is shifted to the next wavelength λ_{n+1} and the noise power at wavelength λ_n is measured, allowing computation of $OSNR_{Rx}$. Fig. 3c shows the measured $OSNR_{Rx}$ and measured SNR after data demodulation of the 37 channels. The $OSNR_{Rx}$ continuously decreases as channel wavelength increases while for wavelengths below 1550-nm, the measured SNR does not follow this trend. We attribute this discrepancy for the lowest wavelengths to higher non-linear effects as the channels around 1530-nm have the highest (equivalent) launch power. Also, we attribute the gap in SNR of the two channels with the lowest wavelengths with respect to their nearest neighbors (~1-dB) to the fact that the EDFAs gains are strongly tilted below 1528-nm at the edge of the C-band, as observed in Fig. 2b. Fig. 4 shows the measured net bit rate and AIR per wavelength of the 37 channels. With a minimum net bit rate of 1013-Gbps (1527.66-nm, r_c = 0.74) and a maximum of 1164-Gbps (1548.51-nm, r_c = 0.83), the total net throughput is 41.3-Tbps.

Conclusions

We report, to the best of our knowledge, the highest net throughput of 41.3-Tbps for an unrepeated link above 290-km using C-band technologies and without resorting to remote optically pumped amplification. This is achieved by transmitting 37x(135-GBaud PCS-64QAM) channels with 139.05-GHz spacing, resulting in a spectral efficiency of 8-b/s/Hz. This result shows the benefit of operating above 130-GBaud with highly spectrally efficient modulation formats to increase the link throughput while reducing the number of transceivers.

References

[1] J. Li, A Zhang, K. Lv, Y. Yang, H. Wang, F. Yan, Y. Tian, P. Lu, Z. Zhang, D. Pan, J. Chen, Y. Yu and L. Li, “16 Tb/s Real-time Unrepeated Transmission over 420 km G.654E fiber,” presented at *European Conference on Optical Communication (ECOC)*, Brussels, Belgium, 2020. DOI: 10.1109/ECOC48923.2020.9333042

[2] B. Zhu, T. Geisler, P.I. Borel, R. Jensen, M. Stegmaier, B. Palsdottir, R. Lingle Jr and D.J. DiGiovanni, “25.6 Tbit/s (64x400Gb/s) Real-time Unrepeatered Transmission over 320 km SCUBA Fibres by 400ZR+ Pluggable Modules,” presented at *European Conference on Optical Communication (ECOC)*, Bordeaux, France, 2021. DOI: 10.1109/ECOC52684.2021.9606127

[3] A. Ghazisaeidi, A. Arnould M. Ionescu, V. Aref, H. Mardoyan, S. Etienne, M. Duval, C. Bastide, H. Bissessur and J. Renaudier, “99.35 Tb/s Ultra-wideband Unrepeated Transmission Over 257 km Using Semiconductor Optical Amplifiers and Distributed Raman Amplification”, in *Journal of Lightwave Technology*, vol. 40, n°21, pp. 7014-7019, 2022. DOI: 10.1109/JLT.2022.3198518

[4] X. Zhao, D. Le Gac, S. Escobar Landero, I. Demirtzioglou, A. Lorences-Riesgo, L. Godard, N. El Dahdah, G. Gao, Ro. Brenot, Y. Frignac and G. Charlet, “Real-time 59.2 Tb/s Unrepeated Transmission over 201.6-km Using Ultra-wideband SOA as High Power Booster,” presented at *European Conference on Optical Communication (ECOC)*, Basel, Switzerland, 2022.

[5] R. S. Luis, B. J. Puttnam, G. Rademacher, Y. Awaji and H. Furukawa, “Demonstration of a 90 Tb/s, 234.8 km, C+L band unrepeatered SSMF link with bidirectional Raman amplification”, in *Optics Express,* vol. 30, n°8, pp. 13114-13120, 2022. DOI : 10.1364/OE.451948

[6] A. Busson, H. Bissessur, D. Kravchenko, F. Hedaraly and J. Esparza, “Unrepeated C-Band Transmission of 35.5 Tb/s Capacity over 291 km using 128 GBd DP-16-QAM” presented at *Optical Fiber Communication Conference (OFC)*, San Diego, USA, 2023.

[7] H. Bissesur, C. Bastide, S. Dubost, A. Calsat, F. Heradaly, P. Plantady and A. Ghazisaeidi, ‘Unrepeated transmission of 29.2 Tb/s over 295 km with Probabilistically Shaped 64 QAM,” presented at *European Conference on Optical Communication (ECOC)*, Roma, Italy, 2018. DOI: 10.1109/ECOC.2018.8535502

[8] 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.