Real-time transmission of 34.9 Tb/s with 1-Tb/s channels over 4800 GHz-wide C-band along 1000 km of G654E fiber

B. Lavigne[1], M. Le Monnier[1], T. Zami[1], J. David[1],
(1) ASN/Nokia, 1 Avenue du Canada, 91940 Les Ulis, France
S. Weisser[2], L. Raddatz[2], F. Pulka[3]
(2) Nokia Germany, Thurn-und-Taxis-Strasse 10, 90411 Nuremberg, Germany; (3) Nokia France, Route de Villejust, 91620, Nozay, France
Bruno.lavigne@asn.com

Abstract: We transmit 34.9 Tb/s over the 4800 GHz-wide C-band through ten 100km-long G654E fiber spans. This is a record spectral efficiency with real-time 1-Tb/s 128-GBaud transponder and pure Erbium-doped-fiber-based amplification along 1000km core/regional distance. © Nokia 2024

1. Introduction.

The growth of WDM channel symbol rate recently entered its 6th generation with the advent of 130/140 GBaud Optical Transponders (OT), capable of up to 1.2 Tb/s single channel data rate [1]. This evolution better streamlines cost, power and footprint per Gb/s in the WDM transparent networks [2]. In that respect, this paper outlines a laboratory experiment transmitting 34.9 Tb/s total throughput over 1000 km via 35 WDM channels occupying 4800 GHz. The multiplexed WDM comb corresponds to thirty-four 1-Tb/s 128-GBaud channels spaced by 11x12.5=137.5 GHz, and one 900-Gb/s 116-GBaud channel within one 10x12.5=125 GHz-wide slot. Unlike emblematic prior arts reporting WDM transmissions with OT enabling at least 800 Gb/s channel data rate and 64QAM-based probabilistic shaped constellation channels as listed in Table 1, this paper reports the performance of 35 carriers traversing ten 100km-long G654E fiber spans, only with Erbium Doped Fiber Amplifier (EDFA)-based amplification and under fully loaded conditions. We also examine how the wide 128-GBaud channels are affected by the Intra-Channel Tilt (ICT) possibly cumulated in a resonant way [3] throughout the suite of crossed EDFAs.

Table 1: Recently published transmission experiments with real-time PCS-64QAM carriers (ULL=Ultra Low Loss)

Symbol rate	Spectral efficiency	Amplification	Fiber type, distance	All channels tested	Reference
100.4 GBaud	800/112.5 = 7.11 bit/s/Hz	EDFA+Raman	G654E, 16x100 = 1600 km	No (2 Ch)	[5]
90.5 GBaud	800/100 = 8 bit/s/Hz	EDFA+Raman	ULL fiber, 1122 km	No (12 Ch)	[6]
91.6 GBaud	800/100 = 8 bit/s/Hz	C+L EDFA	SSMF, 4x75 = 300 km	No (30 Ch)	[7]
138 GBaud	1000/150 = 6.67 bit/s/Hz	EDFA+Raman	SSMF+ELEAF, 869 km (field trial)	No (1 Ch)	[2]
95 GBaud	800/112.5 = 7.11 bit/s/Hz	EDFA+Raman	ULL fiber, 20x100.9 = 2018 km	No (10 Ch)	[8]
128 GBaud	1000/137.5 = 7.27 bit/s/Hz	EDFA	G654E, 10x100 = 1000 km	Yes (35 Ch)	this paper

2. Transmission set-up description.

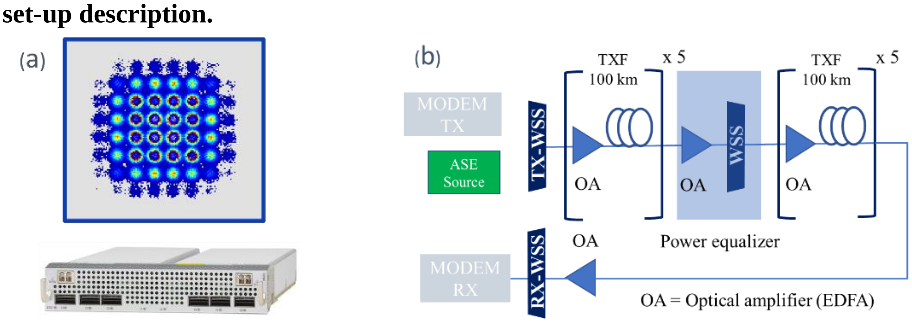

Fig. 1. (a) Constellation recorded at 1 Tb/s, using PCS-64QAM modulation format at 128 GBaud and DMAT6^{TM} Nokia dual transponder, (b) Transmission testbed description.

The WDM system under study is composed of 2 key elements. Firstly, the real-time OT shown in Fig.1a. It incorporates a Nokia PSE-6s 5-nm CMOS reconfigurable coherent ASIC handling multi-rate WDM channels, with a soft-decision FEC corresponding to 16% overhead, using standard Quaternary Amplitude Modulation (QAM) constellations and probabilistic constellation shaping. We display in Fig.1a back-to-back constellation recorded on a 1-Tb/s 128-Gbaud channel, using 64QAM-based Probabilistic Constellation Shaping (PCS-64QAM), and corresponding to ~ 5 bits/symbol/polarization. The delivered signal at the TX output is shaped using root-raised-cosine shaping with a roll-off factor of 0.1. Secondly, we use G.654.E compliant Corning® TXF® fiber. This fiber provides the benefits of an effective area of 125 µm², of a local chromatic dispersion of 21.1 ps/(nm.km) and of a loss coefficient of 0.17 dB/km. The combination of these features enables a Raman-free transmission over long distances.

The transmission test-bench (see Fig.1b) comprises two optical multiplexing sections (OMS) respectively made of five 100 km-long spans of TXF fiber, with a span-loss of 17.5 dB-18 dB, the loss of each span being compensated by one EDFA. Additional losses of 0.5 dB to 1 dB are due to connector losses at the amplifier inputs and outputs and the quality of solders in between the fiber spools. OMS's are separated by one Wavelength Selective Switch (WSS)-based power equalizer, compensating for the gain ripple of EDFA and the Stimulated Raman Scattering (SRS). Standard channel power equalizers, like in this experiment, only apply a constant attenuation over each individual channel spectral slot, without rebalancing spectral distortion inside this slot. Hence, this distortion can significantly grow in the slot, particularly across the long series of in-line optical amplifiers. Prior arts [3][4] have drawn the attention to this effect for relatively high symbol rate signals (up to 95 GBaud). We analyze this issue in the last part of this paper for even larger 128-GBaud channel symbol rate.

At the transmitter side, the spectrum is loaded by 34 channels spaced by 137.5 GHz and 1 channel within a 125 GHz-wide spectral slot, to occupy the entire C-band (4800GHz). The loading channels consist of Amplified Spontaneous Emission power (ASE), generated by one EDFA, and steered into a WSS (TX-WSS) multiplexing loading channels and the channel of interest (COI). COI is surrounded by the ASE-based stream: ASE loading method has been shown to be valid to assess WDM systems in [9]. Fig.2a shows a reconstruction of the spectrum at the input of the first span, using the 35 positions of COI (and 35 spectra) over the entire band: we apply a pre-tilt of 2dB to compensate for SRS generated along the transmission. At the Egress terminal, RX-WSS demultiplexes the WDM comb and sends COI to the receiver.

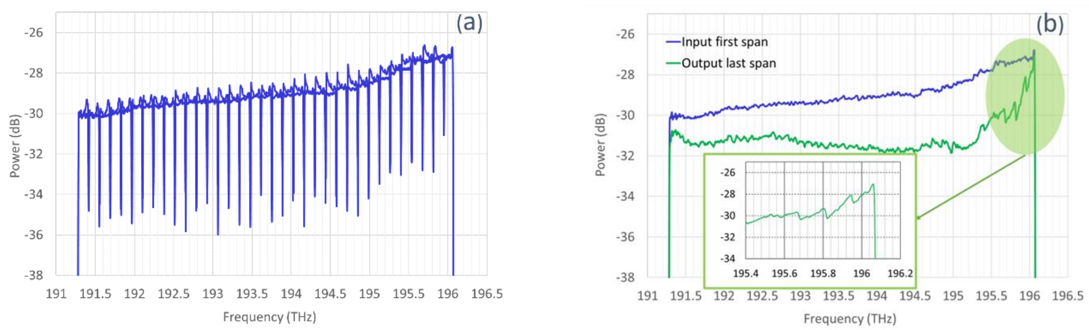

Fig.2. (a) Spectrum reconstruction at the input of the first span combining the 35 spectrum positions of COI. (b) Spectrum recorded at the input of the first span and the output of the last span only with ASE loading, showing the spectrum distortion inside the channel grid (see curve in inset).

3. Point-to-point transmission over 1000 km of G654E fiber.

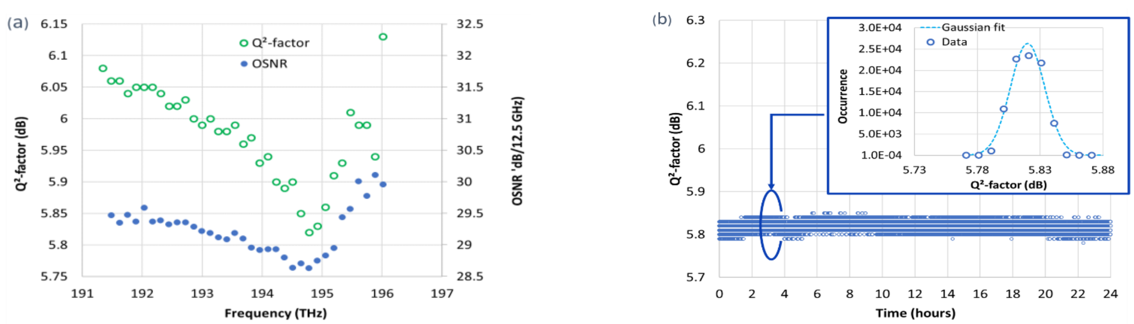

Fig.3. (a) Q²-factor and OSNR recorded after 1000 km. (b) Stability measurement performed on the worst-case channel over 24 hours

The assessment of the performance over the full band consists in scanning the 35-positions by replacing each ASE channel by COI, while keeping the same channel power. The result of the power tuning may be checked in Fig.2a using the reconstructed spectrum: the continuous line that appears over the entire spectrum of Fig.3a corresponds to the blue spectrum of Fig.2b. The performance recorded for each channel after 1000 km is reported in Fig.3a, showing the evolution of Q²-factor and OSNR, expressed in a reference optical bandwidth of 12.5 GHz. Q²-factor spreads over 0.2 dB, with respective minimum and maximum values of 5.8 dB and 6.13 dB. We note that Q²-factor follows OSNR evolution in the spectral region in between 194 THz to 196 THz. In the spectral region 194-191 THz, Q²-factor slightly improves while OSNR remains almost constant, showing lower perturbations from nonlinear effects due to the pre-tilt applied at each optical amplifier to mitigate SRS. Finally, we recorded Q²-factor over 24 hours (see Fig.3.b), considering the worst-case channel (at 194.78125 THz, see Fig3.a), fully assessing the transmission and thus demonstrating the total throughput of 34.9 Tb/s.

4. Impact of intra-channel tilt (ICT).

As mentioned in section 3, publications stressed the impact of ICT on high symbol rate signals (≥ 90GBaud). An example of ICT is shown in inset in Fig.2b. Whatever the type of carriers, single carrier [3] or multiple electrical subcarriers [4], the presence of ICT generates an extra OSNR penalty that grows along with the number of cascaded amplifiers. However, it remains to check if the co-existence of ICT and nonlinear propagation effects (NL-effects) amplifies this penalty. Because it is not possible to simply suppress ICT, except mitigating it with sophisticated techniques based on WSS out of the scope of this experiment, we rather focus on a spectral region where this effect is missing. In that respect, we selected the channel in the middle of the C-band (193.57 THz). Our intent is to generate a given ICT at the emission side, computed in the channel grid (the real tilt experienced by the channel is ~80% of so defined ICT), using TX-WSS, and detecting a possible interaction of ICT with NL effects through the measurements of Q^2-factor vs channel power. To get more Q^2-factor operation margins, we reduce the channel count to 15 channels. This method emulates a worst-case situation in the sense that the signal is tilted while the cumulated ASE is remaining flat over the transmission (unlike in a real system). We consider 3 cases: case 1 (Fig.4a) as reference case with no ICT, case 2 (Fig.4b) with ICT of 2 dB/137.5 GHz, corresponding to the worst ICT value observed in our set-up (see inset in Fig.2b), and case 3 (Fig.4c) with ICT of 4.5 dB/137.5 GHz. As may be seen in Fig.4d, adding ICT at the emission side induces Q^2-factor penalty, but Q^2-factor maximum value remains aligned to 0 dB (normalized optimal power for the reference case). Therefore, there is no obvious interactions between ICT and NL-effects, at least up to 1000 km. In addition, we record that Q^2-factor penalty remains relatively small and does not significantly impact the performance, owing to the largest ICT of 2 dB/137.5 GHz recorded in this experiment.

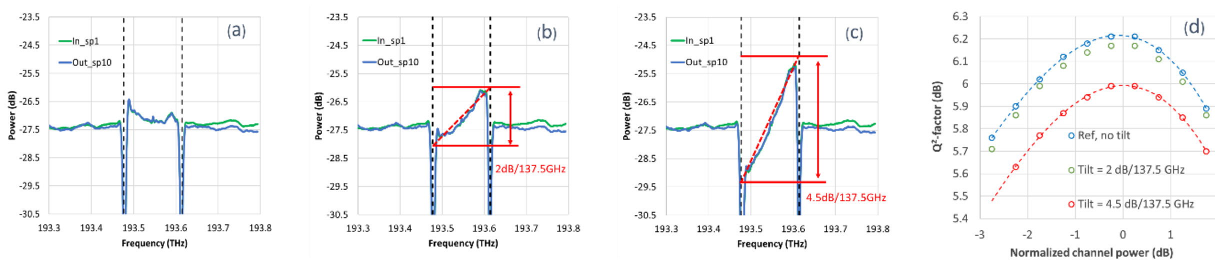

Fig. 4. Spectrum evolution vs applied tilt applied on 128-GBaud channel with (a):0 dB, (b): 2 dB/137.5GHz, (c): 4.5 dB/137.5 GHz. (d) Corresponding Q^2-factor penalty vs the normalized channel power at the power given maximum Q^2-factor and for different applied tilts.

5. Conclusions.

In this paper we demonstrate 137.5 GHz channel spacing is viable to transport 34.9 Tb/s (i.e. 87x400 GbE services) with 1 Tb/s WDM carriers in point-to-point WDM systems only equipped with C-band EDFAs over several hundreds of km. The product total-throughput-x-distance could be further improved by adding Raman amplification and/or with C+L amplification. In addition, we show ICT has no visible interaction with nonlinear propagation effects and a negligible impact on the performance with 2dB/137.5GHz ICT.

6. References.

[1] https://www.nokia.com/about-us/news/releases/2023/09/25/nokia-and-lyntia-demonstrate-power-of-pse-6s-coherent-optics-in-live-commercial-network-in-spain/

[2] T. Richter et al., "*1Tb/s and 800 Gb/s real-time transmission at 138 GBd over a deployed ROADM network with live traffic*", Paper Th4C.1, OFC'2023, March 2023, https://doi.org/10.1364/OFC.2023.Th4C.1

[3] Z. Jiang et al., "*Machine Learning Based EDFA Channel In-band Gain Ripple Modeling*", Paper W4I.2, OFC'2022, San Diego USA, March 2022, https://doi.org/10.1364/OFC.2022.W4I.2

[4] J. Rahn et al., "*High Baud Rate Modulation: Applications for Next-Generation Backbone Networks*", Paper F4G.1, June 2021, https://doi.org/10.1364/OFC.2021.F4G.1

[5] R. Maher et al., "*Real-time 100.4GBd PCS-64QAM transmission of a 1.6 Tb/s super-channel over 1600 km of G.654. E fiber*", Paper Tu6D.2, OFC'2021, https://doi.org/10.1364/OFC.2021.Tu6D.2

[6] H. Li et al., "*Real-time demonstration of 12-λ × 800-Gb/s single-carrier 90.5-GBd DP PCS-64QAM coherent transmission over 1122-km ultralow-loss G.654. E fiber*", Paper We3C1.5, ECOC'2021, September 2021, DOI: 10.1109/ECOC52684.2021.9606039

[7] Z. Feng et al., "*88 Tb/s Extended C P lus L B and Transmission over 300-km SMF Using 800G Realtime Transponders and Commercial EDFAs and WSSs*", Paper # ID 4192, ACP'2022, November 2022, DOI: 10.1109/ACP55869.2022.10088699

[8] D. Zhang et al., "*Technological Prospection and Requirements of 800G Transmission Systems for Ultra-Long-Haul All-Optical Terrestrial Backbone Networks*", Journal of Lightwave Technology, Page 3774, Vol. 41, n°12, June 2023, DOI: 10.1109/JLT.2023.3267241

[9] D. J. Elson et al., "*Investigation of bandwidth loading in optical fibre transmission using amplified spontaneous emission noise*", Optics Express, Vol. 25, n°16, Page 19529–19537, August 2017, https://doi.org/10.1364/OE.25.019529