Leveraging Raman Amplification to Improve and Equalize the Performance of a 20-THz Multi-band Optical System

André Souza[(1,3)], Bruno Correia[(2)] Nelson Costa[(1)],Vittorio Curri[(2)], João Pedro[(1,3)], João Pires[(3)]

[(1)] Infinera Unipessoal Lda, Carnaxide, Portugal, anunes@infinera.com
[(2)] Politecnico di Torino, Torino, Italy.
[(3)] Instituto de Telecomunicações, Instituto Superior Técnico, Lisboa, Portugal.

Abstract *We compare deploying additional optical amplification sites with deploying Raman pumps in existing sites to increase the capacity of 20-THz optical systems. Results show that deploying Raman pumps is a cost-effective solution to increase system capacity while equalizing the optical performance of transmitted bands.*

Introduction

Increasing the bandwidth utilization of the currently deployed optical fibre infrastructure by deploying multi-band transmission (MBT) systems is an effective strategy to improve network capacity and postpone costly fibre deployment[1]. However, one should perform a careful techno-economic analysis to determine the viability of the additional transmission bands since they typically have higher fibre loss and key enabling components usually show worse characteristics not only but also due to the use of less mature technologies. Despite the worse optical performance, enabling the S-band in a C+L-band system can be more cost-effective than deploying additional optical fibers[2]. Moreover, the cost per transmitted bit on an S+C+L MBT system can be further reduced by using properly optimized Raman amplification[3] or optimizing the amplifier placement[4]. The former is potentially easier to deploy since the latter requires setting up additional amplification sites.

In this work, we numerically compare the network capacity using two different strategies to improve the optical performance of MBT systems comprising the C-, L- and S-bands, i.e., a total transmission bandwidth of 20 THz. The proposed approaches are to deploy Raman amplification on existing sites or to expand the set of in-line amplification sites, i.e., to deploy new optical amplification sites. These approaches are mostly mutually exclusive since Raman amplification is not an interesting solution in short spans.

Simulation Scenarios and Launch Power Optimization

The generalized signal-to-noise ratio (GSNR)[5] is used as the quality of transmission (QoT) metric of a lightpath (LP). The GSNR includes the effect of the additive Gaussian disturbances introduced by the optical amplifiers, i.e., amplified spontaneous emission (ASE) noise, and the nonlinear interference due to the self- and cross-channel nonlinear crosstalk resulting from optical fibre propagation. The stimulated Raman scattering (SRS) effect is calculated by solving the numerical ordinary differential equation system with the numerical solver available on GNPy[6],[7]. The different transmission bands are demultiplexed after each fibre span. The resulting optical signals are then delivered to optical amplifiers that perfectly compensate for the link losses and the SRS-induced power tilt in each band. The total insertion loss of the band demultiplexer and multiplexer (used to combine all bands after optical amplification) is assumed to be 3 dB. We assume the transmission of 64-GBd signals with a 0.15 roll-off within a 75-GHz frequency grid. The S-band is split into two sub-bands (denoted as S1 for the lower and S2 for the higher frequencies) to guarantee that the requirements for the S-band amplifier are not too stringent. Each (sub) band accommodates 64 channels and a guard band of 500 GHz is considered between adjacent bands. We additionally consider input and output connector losses of 0.25 dB. The amplifiers' noise figures are set to $[4.7, 4.3, 6.5]$ dB for L, C and S bands, respectively. These are the average NFs obtained through experimental characterization of commercially available Erbium-doped fibre amplifiers (EDFA)s for the C- and L-bands[2] and from a benchtop Thulium-doped fibre amplifier (TDFA) for the S-band[8]. The fibre characteristics are the same as in[3].

The launch power is optimised to maximise the average GSNR and minimise the GSNR ripple of each band considering full spectral load following

Tab. 1: Required OSNR for each mode of operation of transceiver.

Mod. Format	QPSK	8QAM	16QAM
Bit rate [Gb/s]	200	300	400
OSNR$_{req}$ [dB]	16	21	24

the same approach as in[3]. In the case of using Raman amplification, and to simplify the optimization process, a total optical power of 1 W resulting from the use of one, two or four pumps with equal frequency spacing between the pumps is considered. Thus, the launch power needs to be optimized considering different numbers of pumps, pump power profiles, pump frequency separations, and pump comb central frequency. For the MBT scenario with two Raman pumps, frequency separations of 4, 5 and 6 THz, and pump power profiles where the optical power of the highest frequency pump is 1, 2, 3 and 4 times higher than the lowest one have been considered. In the case of using four Raman pumps, frequency separations of 1 and 2 THz, and pump power profiles where the optical power of the 2 higher frequency pumps is 1, 2, 3 and 4 times higher than the power of the 2 lower frequency pumps, were considered. In the case of the in-line amplifier expansion, the launch power is optimized taking into account that each span is divided into two spans where the length of each span is half of the original one.

Network Simulation Framework

We use the statistical network assessment process (SNAP)[9] framework to calculate the capacity of the Italian reference network[10]. This network is composed of 21 nodes and 36 fibres links, with an average node degree of 3.4 and an average link length of 209 km. The SNAP runs several iterations in order to retrieve the statistical dynamic metrics of the network, such as allocated capacity for a given blocking probability. In total, SNAP runs 1500 iterations with 400-Gbps connections, incrementally added and uniformly distributed among the network nodes. The routing and spectrum assignment relies on the shortest path and last-fit (LF) algorithms, respectively. The LF spectrum assignment strategy deploys the most spectrally-efficient modulation format at the highest feasible frequency. The SNAP uses a physical layer abstraction of the network topology to compute the GSNR of each lightpath. If the computed GSNR is higher than the required SNR plus an additional 3-dB system margin, the lightpath is considered feasible. The transceiver

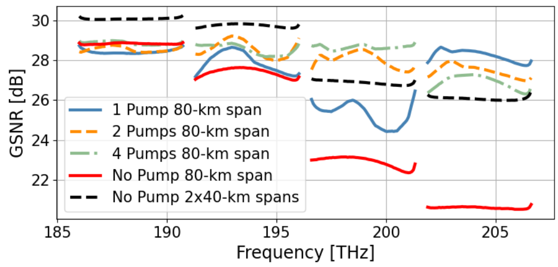

Fig. 1: Optimized GSNR profiles for different system configurations.

Tab. 2: Optimized Raman pump comb characteristics.

Number of Pumps	Central Frequency [THz]	Frequency Separation [THz]	Pump Powers [W]
1	217.0	—	1.00
2	214.0	6	[0.30, 0.70]
4	214.5	2	[0.17, 0.17, 0.33, 0.33]

modes of operation and corresponding required OSNR values are depicted in Table 1. These values are extracted from the Open ROADM Multi-Source Agreement (MSA)[11]. The OSNR$_{req}$ is converted to required SNR as indicated in[12]

Results

Fig.1 shows the GSNR in a C+L+S MBT system after transmission along 80 km of optical fibre considering the different network upgrade strategies proposed in this work. The baseline scenario (no Raman amplification and 80-km span) is shown also for benchmarking purposes. As expected, by splitting the span in half and transmitting along two spans, the performance of all transmission bands is improved, with the minimum GSNR of the [L, C, S1, S2]-bands increasing by about [1.2, 2.5, 4.3, 5.4] dB, respectively. This is a very relevant optical performance improvement but comes at the expense of requiring the deployment of a completely new optical amplification site, with the high cost of all the involved logistics. Alternatively, Raman pumps can be deployed in the 80-km span link with the optimized configuration indicated in Table 2. Using a single high-output power pump, the minimum GSNR of the C, S1 and S2-band is improved, with the performance of the S2-band becoming similar to the one of the C and L-bands. However, the S1-band performance is still $\approx$ 3 dB lower than the one of the remaining bands. This is a consequence of having a Raman pump configuration that focuses mainly on the improvement of the S2-band. Other pump power and frequency configurations focusing on the improvement of the S1-band could have been selected, but that would come at the trade-off of losing performance in the remaining transmission bands. Alternatively, Fig.1 shows that this limitation can be mitigated by using a two-pump system. In-

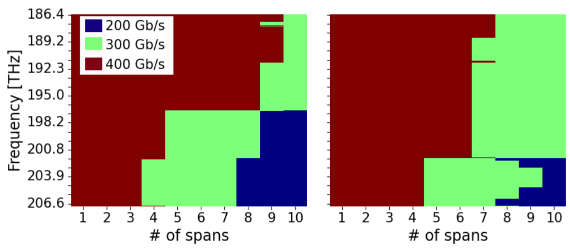

Fig. 2: Channel capacity as a function of the number of 80-km spans when increasing the number of in-line amplifier sites (left) or adding Raman amplification (right).

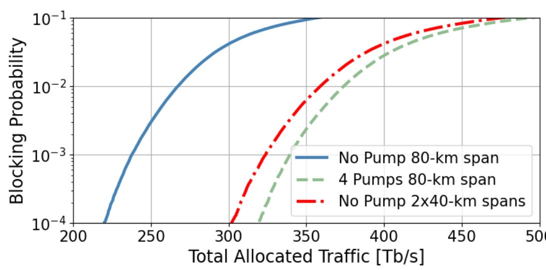

Fig. 3: Total allocated traffic for different system upgrades.

deed, when using two pumps separated by 6 THz and a somewhat optimized pump configuration, the optical performance of both S1- and S2-bands can be significantly improved in comparison to the original scenario, with similar optical performance being achieved in all bands of the C+L+S MBT system. This feature is very important because it may simplify considerably the network management (optical performance becomes approximately wavelength independent over a very wide transmission bandwidth). To further improve the average GSNR and minimize the GSNR ripple, a four-pump solution can be explored. However, only minor optical performance improvement has been observed in this case with respect to the two-pump configuration.

To highlight the potential of Raman amplification to equalize optical performance, Fig. 2 depicts the channel capacity as a function of the number of traversed 80-km spans when the MBT system is upgraded by increasing the number of in-line amplifier sites (left-hand side) or by deploying four Raman pumps in each existing amplification site (right-hand side). The transceivers are modelled as indicated in Table 1. Note that splitting each span into two effectively doubles the span count but, to ease the comparison, we neglect this effect in this study. The analysis of Fig. 2 shows that, when using Raman amplification, most of the frequencies typically support the same modulation format after transmission along a given distance e.g., 400 Gb/s signals are still supported in all frequencies after transmission along 4 spans whereas some of the channels only support 300 Gb/s signals in the case of increasing the number of in-line amplification sites. Nevertheless, increasing the number of amplification sites enables transmitting 400 Gb/s signals up to 9x80km distance (in a few channels) whereas only 7x80km can be traversed by the same 400 Gb/s signals when Raman amplification is used instead. Interestingly, for a lightpath with 6 spans, the MBT system with Raman amplification supports 75% of the channels with 400 Gb/s while the system where the number of amplification sites is increased supports only 50% of channels with 400 Gb/s.

To better evaluate the benefits of each upgrade solution, Fig. 3 depicts the total allocated traffic versus blocking probability for the non-upgraded system, the optimized system with four Raman pumps and the case with amplifier site expansion (40-km spans). The analysis of Fig. 3 shows that the upgrade solution that leads to the highest capacity improvement is deploying Raman amplification. As an example, at a blocking probability of 1%, the total allocated traffic for the network with Raman amplifiers is 374 Tb/s, which is 40% higher than the non-upgraded system (267 Tb/s) and 4% higher than the one that achieved by reducing the span length to half of the original value (359 Tb/s). This result further stresses the potential of Raman amplification for MBT system upgrades.

Conclusions

Increasing the number of amplification sites or deploying Raman amplification have been proposed as solutions to improve the capacity of S+C+L MBT systems occupying 20 THz. We show that increasing the number of amplification sites is an effective solution to improve optical performance in all transmission bands. However, it is not a cost-effective solution (due to the required logistics). On the other hand, deploying Raman amplification in each of the existing amplification sites leads to a much more equalized optical performance across all bands. Using the Italian reference network as test-case, we have shown that Raman amplification enables increasing the total allocated traffic at a blocking probability of 1% by 40% and 4% with respect to the non-upgraded system and the system where additional amplification sites are considered, respectively.

Acknowledgements

This work was partially funded by the EU H2020 within the ETN WON, grant agreement 814276, and Horizon Europe SEASON, grant agreement 101096120.

References

[1] A. Ferrari, A. Napoli, J. K. Fischer, *et al.*, “Assessment on the achievable throughput of multi-band itu-t g.652.d fiber transmission systems”, *Journal of Lightwave Technology*, vol. 38, no. 16, pp. 4279–4291, 2020. DOI: 10.1109/JLT.2020.2989620.

[2] B. Correia, R. Sadeghi, E. Virgillito, *et al.*, “Power control strategies and network performance assessment for C+L+S multiband optical transport”, *IEEE/OSA Journal of Optical Communications and Networking*, vol. 13, no. 7, pp. 147–157, 2021. DOI: 10.1364/JOCN.419293.

[3] A. Souza, N. Costa, J. Pedro, and J. Pires, “Benefits of counterpropagating Raman amplification for multi-band optical networks”, *J. Opt. Commun. Netw.*, vol. 14, no. 7, pp. 562–571, Jul. 2022. DOI: 10.1364/JOCN.456582. [Online]. Available: https://opg.optica.org/jocn/abstract.cfm?URI=jocn-14-7-562.

[4] J. L. Vizcaíno, Y. Ye, F. Jiménez, A. Macho, and P. M. Krummrich, “Optimized amplifier placements for improved energy and spectral efficiency in protected mixed-line-rate networks”, in *Optical Fiber Communication Conference*, Washington, D.C.: OSA, 2014, Th1E.5, ISBN: 978-1-55752-993-0. DOI: 10.1364/OFC.2014.Th1E.5. [Online]. Available: https://opg.optica.org/abstract.cfm?URI=OFC-2014-Th1E.5.

[5] A. Pilipetskii, D. Kovsh, E. Mateo, *et al.*, “The subsea fiber as a shannon channel”, in *SubOptic 2019*, 2019.

[6] OOPT-PSE team within the Telecom Infra Project, *Github repository of GNPy*, [Online]. Available:https://github.com/Telecominfraproject/oopt-gnpy.

[7] A. Ferrari, M. Filer, K. Balasubramanian, *et al.*, “GNPy: An open source application for physical layer aware open optical networks”, *IEEE/OSA Journal of Optical Communications and Networking*, vol. 12, no. 6, pp. C31–C40, 2020. DOI: 10.1364/JOCN.382906.

[8] FiberLabs Inc., *AMP-FL8221-SB-16 Amplifier Datasheet.*

[9] V. Curri, M. Cantono, and R. Gaudino, “Elastic all-optical networks: A new paradigm enabled by the physical layer. How to optimize network performances?”, *Journal of Lightwave Technology*, vol. 35, no. 6, pp. 1211–1221, Mar. 2017, ISSN: 0733-8724. DOI: 10.1109/JLT.2017.2657231. [Online]. Available: http://ieeexplore.ieee.org/document/7829312/.

[10] B. G. Bathula and J. M. H. Elmirghani, “Constraint-based anycasting over optical burst switched networks”, *Journal of Optical Communications and Networking*, vol. 1, no. 2, A35–A43, 2009. DOI: 10.1364/JOCN.1.000A35.

[11] Open ROADM MSA, *Open ROADM MSA Specification ver 5.0.* [Online]. Available: http://openroadm.org/download.html.

[12] R.-J. Essiambre and R. W. Tkach, “Capacity trends and limits of optical communication networks”, *Proceedings of the IEEE*, vol. 100, no. 5, pp. 1035–1055, 2012. DOI: 10.1109/JPROC.2012.2182970.