Optimized Deployment of S-band and Raman Amplification to Cost-Effectively Upgrade Wideband Optical Networks

André Souza[(1,2)], Nelson Costa[(1)], João Pedro[(1,2)], João Pires[(2)]

[(1)] Infinera Unipessoal Lda, Rua da Garagem 1, 2790-078 Carnaxide, Portugal, anunes@infinera.com
[(2)] Instituto de Telecomunicações, Instituto Superior Técnico, 1049-001 Lisboa, Portugal

Abstract *The combined use of S-band and Raman amplification to cost-effectively increase the capacity of C+L-band transmission system is assessed. We show that Raman amplification improves and flattens the optical performance in the three bands, potentially reducing the complexity of routing and wavelength assignment algorithms.*

Introduction

The bandwidth demand in transport networks continues to increase. Recent drivers include the wider adoption of cloud computing and machine-to-machine communications, among others, whereas the introduction of new technologies such as 5G and 6G will reinforce the trend[1],[2]. To cope with this demand and avoid a capacity crunch, wideband transmission has received particular attention. Recent works show that using the already deployed fibre plant for wideband transmission is a more cost-effective solution than deploying additional fibre pairs[3].

Solutions for L-band data transmission are already commercially available[4]. However, solutions enabling even wider bandwidths are still not mature. The next natural step on the deployment of wideband systems is the enabling of the S-band since this is the transmission band where standard single mode fibers still show low loss and high chromatic dispersion and where optical amplification is still viable. Recent works have already analyzed the implications of using the S-band for data transmission and its effects on a network-wide scenario[3],[5], indicating an increase of up to 60% of throughput when adding the full S-band to a C+L-band system. However, the power transfer from the S- to the C- and L-bands caused by the stimulated Raman scatering (SRS) reduces the optical performance of the S-band, therefore restricting its utilization to shorter reach lightpaths and/or lower-order modulation formats. Noteworthy, the impact of this power transfer can be counteracted by deploying Raman amplification.

This work shows that with proper optimization, and even though only part of the S-band is used for data transmission, corresponding to an increase of the available bandwidth by only 50%, deploying Raman amplification leads to 65% growth of the network-wide capacity compared to the C+L-band system only. Without Raman amplification, adding the same part of the S-band would lead to an increase of capacity of only 33%.

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Methodology

Three transmission scenarios are evaluated in this work: C+L- and C+L+S-band transmission, the latter with and without counter-propagating Raman amplification. 64 channels with 64-GBd signals occupying a frequency slot of 75 GHz are transmitted in each band. Please note that only part of the S-band was used on this analysis to keep the amplifier's bandwidth similar to the ones used in the other two bands.Additionally, a guard-band of 500 GHz was considered between transmission bands.

The starting point of the analysis is to optimize the launch power profile per channel. For the optimization process, the per channel generalized signal-to-noise ratio (GSNR) after transmission through a 75 km fiber span followed by a lumped amplifier was used as the quality of transmission (QoT) indicator. The SRS is taken into account using the analytical SRS-GN model[6]. The model was further validated by comparing its results to the ones obtained using the generalized Gaussian noise (GGN) model available in the GNPy library[7], showing quite good agreement. The transmission fiber is characterized by a frequency-dependent attenuation with an average of 0.19 dB/km, 0.19 dB/km and 0.20 dB/km for the L-, C- and S-bands, respectively, a nonlinear coefficient of $1.27\ \mathrm{W}^{-1}$/km, a dispersion parameter of 16.7 ps/nm/km @ 1550 nm, a dispersion slope of 0.058 ps/nm^2/km and a Raman gain coefficient of 0.43 (W.km.Hz)$^{-1}$. The optical amplifier model considers a frequency dependent noise figure (NF) which is modeled as independent of the amplifier gain. A different amplifier was used for each band with an average NF of 4.69 dB, 4.25 dB and 6.41 dB for L-, C- and S-band, respectively. These values were obtained from commercially available Erbium-doped fiber amplifiers (EDFA)s for the C- and L-bands and from a benchtop Thulium-doped fiber amplifier (TDFA) for the S-band[3]. The gain of the amplifiers was set to compensate the loss of the most attenuated channel in each band. To take into account the effect of Raman amplification, the channel power profile after fiber transmission was obtained by numerically solving the Raman ordinary differential equations using the solver available in the GNPy library[7]. The noise added by the Raman amplifier is assumed to be equal on both polarizations. The impact of the counter-propagation of a Raman pump in the generation of nonlinear interference is usually negligible and, therefore, is not taken into account.

For simplicity, the optimization variables considered were the launch power of the central channel in each band and its tilt and the frequency and power of the Raman pump. The problem was solved by explicit enumeration and, in order to reduce the number of points evaluated, the multi-variable optimization problem was divided in a series of single-variable problems that were solved sequentially and iterativelly until convergence is achieved. The optical launch power in each band was optimized in order to maximize the average GSNR and reduce the average per band GSNR variation (ΔGSNR). When considering counter-propagating Raman amplification, the pump frequency and power were optimized simultaneously to reduce the difference between the average GSNR of the C- and S-bands and to have a small ΔGSNR.

The Telecom Italia (TI) reference network presented in the IDEALIST project[8] is considered in this work (see Fig. 1). We evaluate the number of feasible lightpaths using different modulation formats and transmission bands, and the network-wide spectral efficiency (SE) and capacity for each band following the same approach as in[9]. In this case, the shortest lightpaths interconnecting all ROADM nodes are considered. For each band, the GSNR at the end of a lightpath with N spans is given by $\mathrm{GSNR}_N = GSNR_{OPT} - 10\log_{10}(N) - M$, where $GSNR_{OPT}$ is the optimized GSNR of the worst channel in each band and M is the system margin defined as $M = 2 + 0.05(N_{OLAs} + N_{ROADMs})$. The system margin comprises a fixed 2 dB margin and a variable contribution that depends on the number of traversed optical amplifiers (N_{OLAs}) and ROADMs (N_{ROADMs}). A lightpath is considered feasible for a given modulation format and transmission band if the required OSNR (OSNR_{req}) is smaller than the GSNR_N. The characteristics of the considered modulation formats are presented in Fig. 1.

Modulation Format	OSNR_{req} [dB]	Bit Rate [Gb/s]
4QAM	14	200
8QAM	18	300
16QAM	21	400

Fig. 1: TI network topology (left) and modulation format characteristics[10] (right).

Results

The optimized launch power profile and the resulting per channel GSNR for the three considered transmission scenarios are presented in Figs. 2 and 3, respectively. The analysis of these two figures shows that data transmission in the S-band improves the average GSNR in the L-band due to the power transfer between bands caused by the SRS effect. However, and as a consequence, the average GSNR in the S-band is about 3 dB worse than in the other two bands. The higher NF of the benchtop amplifier also contributes to the worse optical performance. Moreover, the GSNR variation in the C- and L-bands is smaller than 0.4 dB whereas it reaches 0.7 dB in the S-band mainly due to the worse amplifier's noise figure profile[3].

In order to improve the optical performance of S-band, we deployed counter-propagating Raman amplification with an optimized frequency and optical power of the pump of 211.5 THz and 500 mW, respectively. In this case, the average GSNR of the S-band was greatly improved (from 27.1 dB to 31.2 dB) and the launch power of higher-frequency channels (> 194 THz) is decreased. Additionally, the average GSNR of all bands was improved when compared to the case without Raman amplification. However, a higher GSNR variation was also observed. Nevertheless, the worse channel in each band still shows better performance than in the case without Raman amplification. The objective function of the optimization approach may be changed to impose a smaller variation of GSNR. However, this strat-

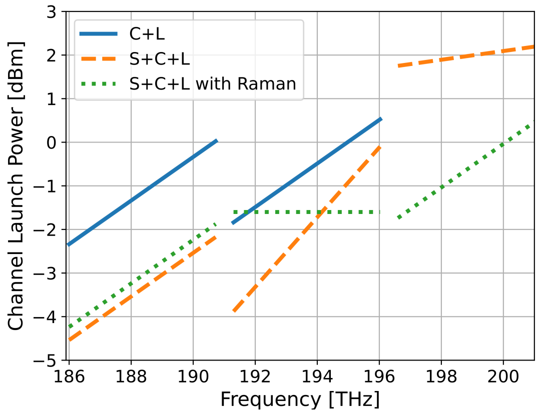

Fig. 2: Optimized channel launch power.

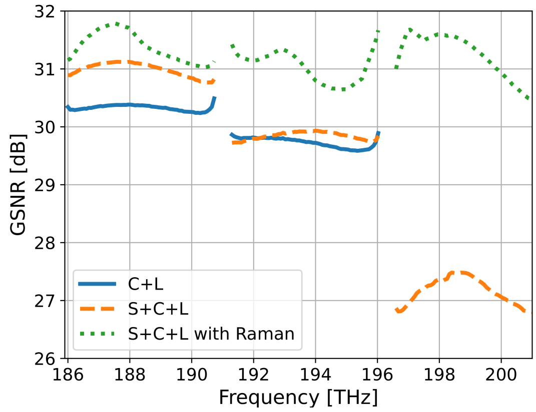

Fig. 3: Optimized per channel GSNR.

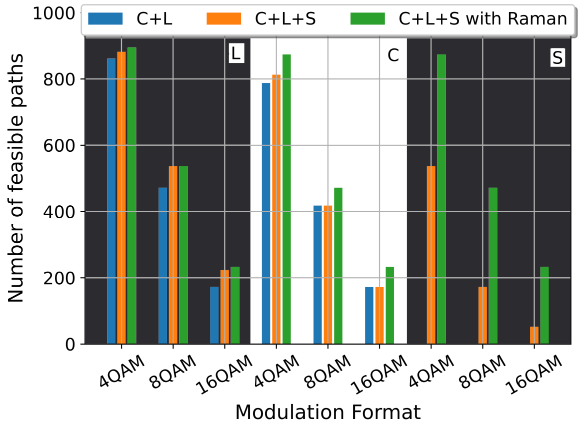

Fig. 4: Number of feasible lightpaths per band and modulation format.

egy will lead to a reduction of the mean GSNR as well. Using a second Raman pump can also be explored to flatten the received GSNR in each band, but with higher cost and complexity.

Fig. 4 depicts the number of feasible lightpaths by modulation format and transmission band, whereas Table 1 shows the network-wide spectral efficiency and capacity in each transmission band when considering the different transmission scenarios. The analysis of these results shows that simply adding the S-band to a C+L system leads to an enhancement of the average GSNR in the L-band, therefore increasing the number of feasible paths (for all modulation formats) and, consequently, improving the SE and capacity in L-band. However, the performance of the C-band remains almost unchanged in this case. Moreover, the performance of S-band is much worse than the one of the other two bands. When Raman amplification is added to this C+L+S-band transmission system, all performance measures are improved in all transmission bands (and specially in the S-band where the number of feasible lightpaths more than doubles for 8QAM and 16QAM modulation formats). Additionally, the performance of all three bands becomes very similar which can be further exploited to reduce the complexity of routing, modulation format and spectrum assignment algorithms. Compared to the C+L-band only transmission system, adding the S-band increases the total capacity per lightpath by 33% while the further deployment of Raman amplification enables increasing the capacity by up to 65%.

Conclusions

This work showed that deploying counter-propagating Raman amplification is a cost-effective approach to reduce the impact of the SRS power transfer from the S- to the C- and L-band in a C+L+S-band transmission system and to mitigate also for the worse performance of the optical amplifiers currently available for S-band amplification. As a consequence, Raman amplification greatly increases the offered capacity in such systems. Indeed, we show that by increasing the transmission bandwidth by just 50% and by deploying a single Raman pump, the network-wide lightpath capacity can be increased by 65% compared to transmission in C+L-band only. Moreover, the optimized performance of all three transmission bands was found to be very similar, which has added benefits in terms of simpler network planning and service provisioning.

Acknowledgements

This work was partially funded by the EU H2020 within the ETN WON, grant agreement 814276.

Tab. 1: Per band average network-wide spectral efficiency (SE) and channel capacity for the TI network.

Scenario	Band	SE [b/s/Hz]	Channel Capacity [Gb/s]
C + L only	L	3.3	250.1
	C	3.1	229.0
S+C+L	L	3.6	267.9
	C	3.1	234.3
	S	1.8	137.2
S+C+L with Raman	L	3.7	270.6
	C	3.6	259.3
	S	3.6	259.3

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