Raman Amplification for Simplified Channel Provisioning in Wide-Band Optical Networks

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Abstract: This work provides evidence that jointly optimizing the signal launch power, and a counter-propagating Raman pump can both improve and equalize the capacity of an S+C+L-band network, enabling higher throughput and simpler optical channel provisioning.

1. Introduction

Current optical transmission systems mainly operate in the C-band. However, if limited to this band, the existing fibre infrastructure will not accommodate the future increase of IP traffic [1]. Using additional transmission bands is a viable option to postpone the costly deployment of new fibres by using a more significant portion of the bandwidth of the already deployed fibre infrastructure [2]. Beyond the C-band, devices for long-reach transmission on the L-band were the first to achieve commercial maturity [3]. The next band to be exploited will probably be the S-band, which still shows similar fiber parameters as the C- and L-bands, and can benefit from developments in ultra-wide-band amplification technologies such as thulium-doped fibre amplifiers (TDFA).

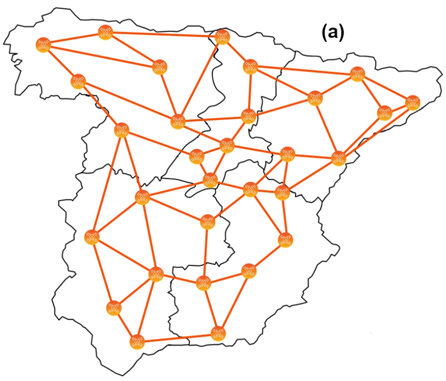
Transmission bands other than C and L require new amplification and switching technologies that are not yet mature enough for commercial utilization. In the meantime, analytical models that include the interchannel stimulated Raman scattering (ISRS) effect have been used to predict multi-band transmission systems' performance and benefits [4]. A recent work has shown that increasing three times the transmission bandwidth with respect to C-band only transmission (4.8 THz) (by deploying the L-band and part of the S-band) offers almost the same capacity as using three fibres and transmitting in the C-band only in all of them [5]. Notably, the performance of the S-band is highly impacted by the ISRS (assuming transmission in C- and L-bands also), the slightly higher fibre attenuation and the (expected) worse amplifier noise figure (NF). These reduce the overall capacity and result in a sharp performance unbalance between bands, which adds complexity to the routing and spectrum assignment (RSA) algorithms. Our previous work has provided early evidence that using a counter-propagating Raman pump effectively improve the optical performance of an S-C-L-band system [6]. This work extends that analysis, considering a more realistic system with band multiplexer and demultiplexer insertion losses, span lengths from 45 km to 90 km, and optimizing Raman amplification for each wide-band scenario. Results obtained in a reference network topology highlight that capacity can be increased 2.93 times while simultaneously simplifying the channel provisioning process by equalizing the performance of the different bands.

2. Optimization Framework

We consider wide-band systems with bandwidths of up to 15.5 THz using the C-, L- and part of the S-band with and without backward Raman amplification. We follow a disaggregated approach, and, therefore, the launch power is optimized span by span. In this case, the per band central channel optical power and power tilt are optimized in a line system composed by a transmitter and a receiver connected by a span of length L, as done in [5]. The quality of transmission estimation used is the per-channel generalized signal-to-noise ratio (GSNR), calculated using the GNPy library [7]. After each fibre span, a band demultiplexer (DEMUX) separates the transmitted bands and delivers them to the respective optical amplifier. Afterwards, an optical coupler recombines the transmitted bands. An equal amount of noise is assumed to be added by the Raman amplifier on both polarizations. The impact of the counter-propagating Raman pump in the generation of nonlinear interference is usually negligible and, therefore, is not considered [6].

The optical fibre characteristics, amplifier models and optical channel formats considered are the same as in [6]. The band DEMUX and coupler insertion losses are 2 dB and 1 dB, respectively. The amplifiers' gain is set to compensate for the loss of the most attenuated channel in each band and the losses of the band DEMUX and coupler. In the C-band only transmission scenario, the band DEMUX and coupler losses are not considered. The per band optical launch power and the frequency and power of the counter-propagating Raman pump were optimized to maximize the average GSNR and reduce the average per band GSNR variation (ΔGSNR).

In this work, we consider the Telefónica national reference network presented in the IDEALIST project [8] (see Fig. 1a). In this project's scope, this reference network is described in terms of a list of nodes and a list of links, each with its total fibre lengths and number of optical line amplifiers (OLA). We considered that each link is composed of spans of equal length. We evaluate the number of feasible lightpaths using different signal configurations (from 100 Gb/s to 400 Gb/s in steps of 100 Gb/s [9]) and transmission bands. We also evaluate each band's network-wide average spectral efficiency (SE) and channel capacity following the same approach as in [6]. For each band, the GSNR at the end of a lightpath with N spans of length L_n is given by $\mathrm{GSNR}_N = \sum_{n=1}^{N} GSNR_{OPT}^{L_n} - M$, where $GSNR_{OPT}^{L_n}$ 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 feasible for a given signal configuration and transmission band if the required OSNR is smaller than GSNR_N. The average system capacity is calculated by averaging the system capacity (the sum of the capacity of all transmitted channels) across all shortest routing paths.



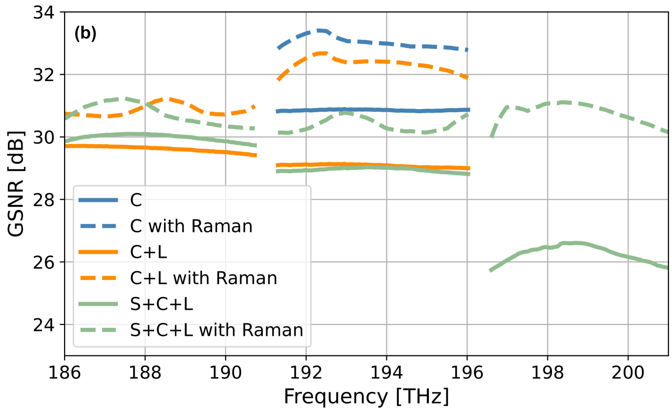


Fig. 1: (a) Telefónica national reference network diagram and (b) optimized GSNR profiles for a 70-km span.

3. Results and Discussion

The optimized GSNR profiles for a span of 70 km considering the use of C-, C+L-, and S+C+L-bands with and without Raman are shown in Fig. 1b. In addition, the optimal frequency and power of the Raman pump for this span length are presented in Table 1. These results show that adding the S-band to a C+L-band system improves the GSNR in the L-band due to the power transfer between bands (caused by the ISRS effect). Consequently, the average GSNR in the S-band is worse than in the other two bands. Most importantly, these results also show that adding a counter-propagating Raman pump to this transmission system is an effective way to compensate for the impact of ISRS, the worse NF of the S-band amplifier and the losses from the band DEMUX and coupler. This compensation leads to similar performance on all three bands, each comparable to the C-band-only transmission system.

Table 1: Raman pump optimized frequency and power for the 70-km span.

Scenario	Pump Frequency [THz]	Pump Power [mW]
C	207.0	450
C+L	207.0	500
S+C+L	211.5	500

Table 2: Per-band optimized average channel capacity.

Scenario	Raman	Average Channel Capacity [Gb/s] L	C	S
C	No	0	330	0
	Yes	0	375	0
C+L	No	299	280	0
	Yes	330	363	0
S+C+L	No	308	279	207
	Yes	328	319	320

Table 2 summarizes the average channel capacity for each transmission scenario. The results without Raman amplification confirm thatthe higher noise figure of the S-band amplifier and the ISRS effect reduce the performance of the S-band. Anyhow, deploying the S-band improves the C- and L-bands channel capacity because of the ISRS effect, leading to an average system capacity 140% and 37% higher than the C-band and the C+L-band system, respectively. Furthermore, the average system capacity of the S+C+L-band system is equal to 80% of a system with three fibres using C-band only transmission.

By deploying counter-propagating Raman amplification in all fibre spans, the average system capacity is improved by 13.5%, 19.5% and 21.8% for the C, C+L and C+L+S scenarios, respectively. In the case of the S+C+L system, the results show also that Raman amplification enables achieving 2.93 and 1.67 times the average system capacity of the C-band and C+L-band transmission systems without Raman amplification, respectively. Fig.2a

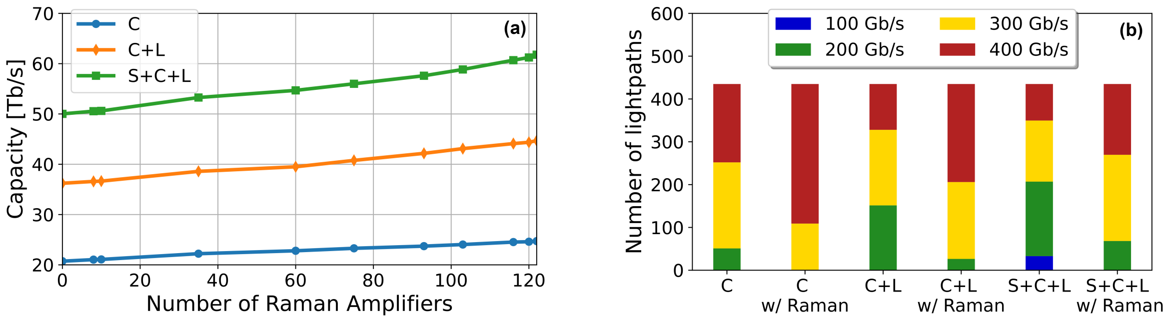


Fig. 2: (a) Average system capacity as a function of the number of deployed Raman amplifiers and (b) number of lightpaths working at a given bitrate.

depicts the average system capacity of the network as a function of the number of deployed Raman amplifiers for each transmission scenario. In this case, Raman amplifiers were firstly deployed in the longer fiber spans and afterwards in the shorter ones (amplifiers were simultaneously deployed on every span equal or above a certain length). The results confirm that the use of Raman amplification offers a smooth trade-off between cost and capacity. Using network-aware deployment strategies, such as the one presented in [10], could further reduce the number of Raman amplifiers required to achieve intermediate network capacities. Fig. 2b shows the average number of lightpaths transporting each considered bitrate (averaged across the transmission bands). As expected, the most spectral efficient solution is the C-band only transmission system using Raman amplification, whereas the only solution that uses 100 Gb/s optical channels is the S+C+L-band system without Raman amplification because of the worse optical performance of the S-band. The deployment of Raman amplification augments the usage of the more efficient modulation formats. This is particularly evident in the case of S+C+L-band transmission system with Raman amplification.

4. Conclusions

We presented the benefits of using counter-propagating Raman amplification in wide-band systems with bandwidths of up to 15.5 THz. Primarily, we showed that Raman amplification combined with S+C+L-band transmission is an efficient approach to compensate for the ISRS power transfer, the worse amplifiers' noise figure and band DEMUX and coupler insertion losses. Moreover, we showed that Raman amplification enables flattening the quality of transmission across all three bands, providing similar performance as in the case of C-band only transmission. Consequently, the complexity of routing and wavelength assignment algorithms may be reduced. Moreover, Raman amplification allows the S+C+L-band system to achieve 2.93 times the capacity of the C-band only transmission scenario, against a capacity of only 2.4 times without it.

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