# Comparative Assessment of S+C+L-band and E+C+L-band Systems with Hybrid Amplification

**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,*
*[2] Instituto de Telecomunicações, Instituto Superior Técnico, 1049-001 Lisboa, Portugal*
*anunes@infinera.com*

**Abstract:** We compare the potential of four multi-band transmission systems leveraging optimized Raman amplification. Simulation results highlight that complementing a SuperC+L-band system with the S-band outperforms using the E-band or interleaving data channels and Raman pumps. 

## 1. Introduction

Multi-band transmission systems offer a promising means to enhance the data-carrying capacity of optical networks. While spatial-division multiplexing (SDM) is often considered the most future-proof solution for augmenting optical network capacity [1], there are valuable alternatives in broadening the available transmission spectrum, particularly by encompassing the longer (L) and shorter (S) wavelength bands alongside the traditional (C) band. It is essential to emphasize that multi-band transmission (MBT) and SDM are not mutually exclusive approaches [2]. In future optical networks, MBT will likely be used to optimize the transmission capacity per fiber, core, or mode, seamlessly complementing SDM in the task of supporting the ever-increasing demand for capacity.

Contemporary commercial systems already integrate the L-band, resulting in a twofold increase in capacity. The deployment of systems with even more bandwidth is now a subject of increased discussion, with research endeavors dedicated to developing devices compatible with transmission bands beyond the C and L bands, as well as evaluating their techno-economic prospects. Exploiting the S-band, which has fiber characteristics still similar to those of the C and L bands, is a promising option. Several studies have demonstrated the additional capacity achieved by incorporating the S-band into a C+L-band system [3]. Nevertheless, the S-band still features a lower performance when compared to the other two bands. This reduced performance is primarily influenced by power transfer to the C and L bands, a phenomenon driven by stimulated Raman scattering (SRS). Additionally, slightly higher fiber losses and a potentially higher noise figure (NF) for S-band amplifiers can further contribute to the optical performance imbalance among transmission bands. Recent research has shown that selective Raman amplification can be employed to enhance S-band performance, up to a level close to that of C and L bands, thereby simplifying service provisioning in optical networks exploiting MBT [4].

Since introducing the S-band comes with the additional challenge that existing services can be impacted by the power interactions caused by SRS, an alternative proposition is to bypass the S-band and instead utilize the E-band. Particularly, by keeping a guard band of 14 THz between the E-band and the already operational C and L bands, it is possible to avoid power transfer between the newly added and existing bands [5]. However, previous works do not take into account the impact of using Raman amplifiers to enhance the performance of the C+L-band. In this scenario, the power loss in the E-band becomes significant due to the presence of high-power Raman pumps at lower frequencies. In this study, we conduct a network performance comparison among three configurations: C+L, S+C+L, and E+C+L bands, all employing hybrid amplification techniques, including fiber-doped lumped amplification and backward-propagating Raman distributed amplification, with each band occupying 6 THz of spectrum. The optimization of channel and pump powers is carried out using a multi-objective genetic algorithm with dual objectives of maximizing system capacity and equalizing the performance across the bands.

## 2. Simulation Setup and Framework Description

The performance of the different transmission systems is evaluated in the Spanish national reference network, as defined by Telefónica in the IDEALIST project [6] (Fig. 1a) and considering, for simplicity, that all spans have 80 km and a fully-loaded spectrum. The quality of transmission estimation used is the per-channel generalized signal-to-noise ratio (GSNR) and the optical fiber characteristics are the same as in [6]. After each fiber span, a band demultiplexer (with a 1 dB or 2 dB insertion loss for 2 or 3 bands, respectively) separates the transmitted bands and delivers them to the respective optical amplifier. The amplifiers' noise figure is 5 dB for the C and L and 6 dB for the S and E bands. Their gain compensates for the exact loss of each channel considering the SRS and the gain already provided by the Raman amplifiers. The power evolution of the signals and pumps across the fiber is calculated by numerically solving the Raman differential equations. Subsequently, an optical coupler (with a 0.5 dB or 1 dB insertion loss for 2 or 3 bands, respectively) recombines the transmitted bands.

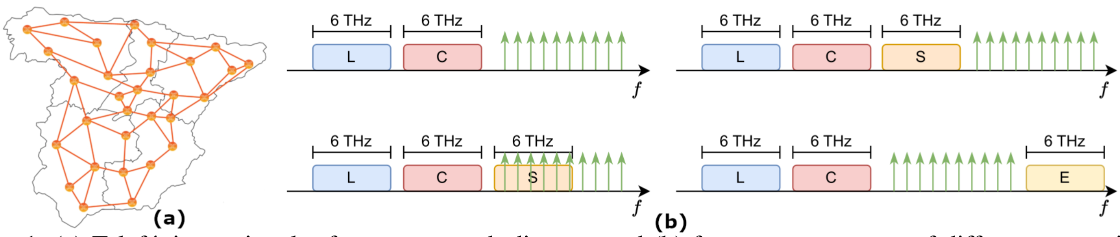

Fig. 1: (a) Telefónica national reference network diagram and (b) frequency spectrum of different transmission system configurations.

We consider the transmission of 120-GBd ($R_S$) signals in a 150-GHz spectral grid (40 channels per band). Fig. 1b shows the four MBT system configurations considered in this work. All systems employ up to 10 Raman pumps with 1 THz spacing and a minimum guard band of 500 GHz between adjacent bands. First, as a reference scenario, we consider a C+L-band system with channels from 184.5 THz to 197 THz and pumps from 199 THz to 208 THz. Then we have two versions of the S+C+L-band with channels from 184.5 THz to 203.5 THz and pumps (i) from 205 THz to 214 THz and (ii) from 199 THz to 208 THz. The first system is referred to as S+C+L-band system and the second as Int-S+C+L-band system in the remainder of this work. In Int-S+C+L, there is an interleaving of Raman pumps and channels of the S-band. We considered a guard band of 500 GHz around the pumps to avoid signal degradation [7], reducing the number of channels on the S-band from 40 to 21. Lastly, we consider an E+C+L-band system by adding the E-band, from 211 THz to 217 THz, to the reference scenario.

A multi-objective genetic algorithm (NSGA-II) is used to optimize the power of the channels and the pumps. The algorithm has two objectives: (i) maximizing the sum of the Shannon capacity of the channels, calculated as $2 \cdot R_S \cdot log_2(1+\mathrm{GSNR})$ and (ii) minimizing the GSNR variation of the entire system. Notice that these objectives are concurrent since some system capacity must be sacrificed to equalize the GSNR of all channels. The power per channel was varied between $-10$ dBm and 10 dBm and the sum of the pump powers was set to 1 W.

After optimization, we evaluate the number of feasible lightpaths in the network using different signal configurations (from 400 Gb/s to 800 Gb/s in steps of 100 Gb/s [6]) and transmission schemes. For each channel, the GSNR at the end of a lightpath with $N$ spans is given by $\mathrm{GSNR}_N = GSNR - 10\log_{10}(N) - M$, where $GSNR$ is the optimized per-channel and per-span GSNR and $M$ is the system margin defined as $M = 2 + 0.05(N_{OLAs} + N_{ROADMs})$. This 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 if the required SNR is smaller than $\mathrm{GSNR}_N$.

## 3. Results and Discussion

The key advantage of employing multi-objective optimization algorithms, as opposed to single-objective ones, lies in their ability to generate a range of solutions, each of which satisfies the specified objectives to an acceptable degree without being dominated by any other solution. In the context of this study, these solutions represent the trade-off between maximizing capacity and minimizing GSNR variation.

Figure 2a illustrates the non-dominated solutions achieved by the optimization algorithm upon convergence for each transmission scenario. Among these solutions, the S+C+L-band system stands out as the top performer. It attains the highest capacity of 141 Tb/s while maintaining a GSNR variation of 7 dB. It is worth noting that the GSNR variation can be reduced to 0.5 dB with a 6% reduction in total capacity (down to 132 Tb/s). This upgrade results in an approximately 40% capacity boost for the C+L-band system while preserving the same GSNR variation. Conversely, the E-band upgrade ranks as the least favorable solution. It can provide 15% more capacity than the C+L system at the expense of a high GSNR variation. This is due to the lack of Raman amplification to improve the E-band's performance, as well as the adverse impact of deployed Raman pumps, which, while enhancing the C and L bands, deplete the power of the E-band channels. Lastly, the Int-S+C+L-band transmission scheme demonstrates intermediate performance between the C+L and S+C+L-band systems. This can be attributed to the smaller number of channels in the additional band.

Figure 2b presents the power levels of the Raman pumps for the eight optimized solutions identified in Fig.2a, each representing the best outcome in one of the two objectives for each transmission configuration. Notably, it is evident across all these solutions that some of the Raman pumps have a negligible effect due to their low power. Only 4 or 5 out of the 10 pumps exhibit power levels exceeding 50 mW, suggesting the potential for simplifying the implementation of these systems. Interestingly, very little power is allocated to pumps operating at the same frequencies as the S-band. Consequently, in the case of the Int-S+C+L-band system, it becomes feasible to enhance performance by eliminating specific pumps and utilizing the available bandwidth for data transmission. Furthermore, in the E+C+L-band system, the algorithm appears to have avoided using the lower frequency pumps, likely as a strategy to mitigate power depletion in the E-band. This precaution comes from the fact that power transfer via SRS is more pronounced for frequency offsets of around 13 THz. Nevertheless, the

E-band's performance remains significantly affected by the remaining pumps, resulting in a considerable GSNR variation that the algorithm could not reduce below 10 dB within the prescribed power constraints.

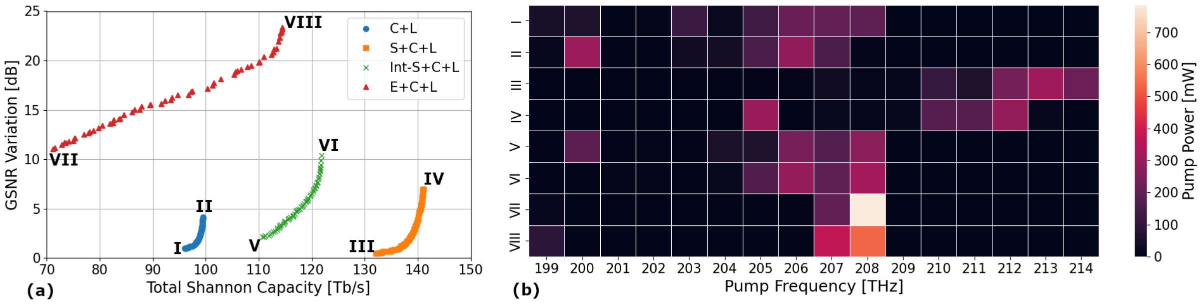


Fig. 2: (a) Optimal non-dominated solutions and (b) Raman pump power distribution for selected solutions.

Lastly, we compare the network performance of the selected solutions on the reference network. Fig. 3a details the per band average and variation of the channels' GSNR after one 80-km span. These values are used to obtain the per-channel GSNR at the end of the lightpaths. Fig. 3b shows the number of lightpaths working at a given data rate for each transmission scheme, averaged for all channels. The number of shortest paths in the network is $\sum_{i=1}^{30-1} i = 435$, but the bars of the E+C+L-band scenario do not reach this value because lightpaths are not feasible in some channels due to the low GSNR, especially in scenario VII. The most spectrally efficient system is the C+L-band, confirming that adding more bands with worse fiber and amplifier characteristics is detrimental to the spectral efficiency of the system. Both S+C+L solutions have similar spectral efficiency but scenario VI has more 400 Gb/s lightpaths than scenario IV because of the lower GSNR on the S-band (1.5 dB reduction) and more 800 Gb/s lightpaths because of the higher GSNR on the L-band (2.4 dB improvement).

| | I | II | III | IV | V | VI | VII | VIII |
|---|---|---|---|---|---|---|---|---|
| L | 30.2±0.5 | 32.1±1.2 | 27.5±0.4 | 29.8±2.2 | 27.5±1.5 | 32.2±1.6 | 17.5±0.7 | 28.5±0.8 |
| C | 30.0±0.5 | 30.2±1.6 | 27.7±0.5 | 31.3±1.1 | 27.7±1.0 | 30.7±1.5 | 17.7±1.9 | 30.5±1.4 |
| S | - | - | 27.7±0.5 | 27.3±2.2 | 27.3±1.0 | 25.7±2.6 | - | - |
| E | - | - | - | - | - | - | 8.8±1.4 | 12.5±3.7 |

(a)

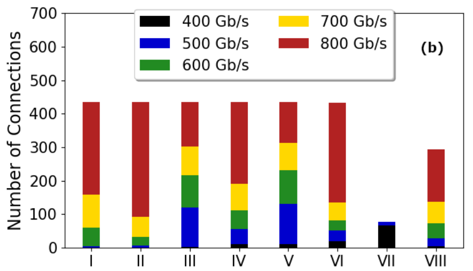


Fig. 3: (a) Per band average and variation of the GSNR in dB for transmission in one 80-km span and (b) number of lightpaths working at a given bitrate for different solutions.

## 4. Conclusion

We reported a network performance comparison involving three systems: C+L-band, S+C+L-band, and E+C+L-band, each utilizing hybrid amplification. Our findings indicate that the S-band upgrade for a C+L-band system is the most favorable choice when considering Raman amplification. This preference arises because Raman pumps, while enhancing the C+L-band, deplete power and thereby diminish the performance of the E-band. Although it is shown that, due to less favorable fiber and amplifier characteristics, the introduction of additional bands reduces spectral efficiency, the cost overhead of deploying new fibers may still make these solutions competitive. Furthermore, the analysis revealed that interleaving Raman pumps with data channels in the S-band is disadvantageous for the system's capacity. This is primarily because it reduces the number of available channels in the S-band without a significant gain in spectral efficiency.

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