Performance Enhancement of Long-Haul C+L+S Systems by means of CFM-Assisted Optimization

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Abstract: We investigate C+L+S long-haul systems using a closed-form-model for launch power and Raman pump optimization. We show a potential 4x throughput increase over standard C-band systems in 1000km links, using moderate S-only Raman amplification.

1. Introduction

Many technologies are currently competing in the quest for increasing the throughput of optical links. They can be broadly classified as either "space-division-multiplexing" (SDM) or "ultra-wide-band" (UWB). All SDM and some UWB technologies require that new cables be deployed. A notable exception is UWB over existing standard single-mode fiber (SMF) cables, a potentially attractive alternative for carriers who do not wish to lay out new cables. UWB over SMF consists of extending the transmission bandwidth beyond the C band. The first step, the extension to L-band, is already commercially available. Research is now focusing on other bands, primarily S and O but also E and U. In the context of long-haul systems, which this paper focuses on, it is mostly the S-band that is being considered, because higher frequency bands such as E and O suffer from more serious propagation impairments, while the U-band appears problematic due to bend loss and non-mature amplification solutions.

The nominal bandwidth of the S-band is quite large, almost 10THz. Current efforts aim at exploiting the 5-6 THz adjacent to the C-band, about 196.5 to 202.5 THz, because propagation conditions are more favorable than at higher frequencies, and amplification is available as Thulium-doped fiber amplifiers (TDFAs) [1]. However, it is not inconceivable that in the future the upper limit can be pushed further. Many research experiments of C+L+S transmission have already been successfully carried out. For instance [1] where 18 THz (6 THz each for C, L, S) over 2x60km were transmitted. Also [2] where, remarkably, 12,345 km were reached, using about 3 THz of S-band (plus C and L band with 6 THz each) over special low-loss 4-core MCF and Raman amplification with 8 pumps.

To achieve commercial attractiveness of C+L+S systems in conventional terrestrial long-haul, some goals must conceivably be met: (a) the addition of the S-band must bring about a substantial throughput increase, such as 4x-5x vs. standard (4.5-THz) C-band-only systems; (b) the operating conditions in the three bands should be rather uniform (similar GSNRs); (c) if used, Raman amplification must need a small number of limited power pumps.

To pursue these goals, complex joint optimization needs to be carried out of link and system parameters, as well as WDM launch power profiles and Raman pump frequencies and powers. This requires fast and accurate physical layer models, capable of accounting for the broadband-dependence of all key fiber and system parameters, together with Inter-channel Raman Scattering (ISRS) and Raman amplification. UWB Closed-Form Models (CFMs) have been developed for this purpose: two groups, one at UCL, and one at PoliTo (in collaboration with CISCO), have independently obtained UWB CFMs based on approximations of the GN/EGN models, with similar foundations but with differences in features and final analytical form. For the UCL CFM see [3],[4], for the CISCO-PoliTo CFM see [5],[6]. An extensive experimental validation of the CISCO-PoliTo-CFM (henceforth called just "CFM") was recently presented at ECOC 2023 [7].

In this paper we focus on a long-haul SMF system, using 6+6+6 THz for C+L+S transmission, similar to [1]. Note that 6THz is already an extended bandwidth vs. standard C or L. We carry out multi-parameter optimization to achieve the goals (a)-(c) listed above. We look at transmission with and without Raman. We optimize WDM launch power per-channel and Raman pump power and frequency, aiming at maximizing throughput, subject to GSNR uniformity. We show that a greater than 4x throughput increase vs. standard (4.5 THz) C-band-only systems appears achievable in 1000 km links, within a ±0.5 dB GSNR uniformity across all 18 THz of spectrum, using only 3 Raman pumps and a total of less than 1Watt of pump power.

2. System description and results

The schematic is shown in Fig.1. It comprises 10 spans. The first five spans were characterized from the experimental set-up used for the CFM validation in [7]. Loss and dispersion were measured in C and L band and then extrapolated to the S-band (Fig.2a) using well-known formulas [7],[8]. The Raman gain spectrum $C_R(f, f_p)$ was experimentally characterized using a pump at f_p=206 THz (Fig.2b). It was shifted and scaled as a function of f and at f_p according to [7],[9]. The single-channel interference (SCI) coefficient γ is shown vs. frequency in Fig.2b. For both SCI and cross-channel interference (XCI) the general formula reported in [7],[10] was used. To evaluate both $C_R(f, f_p)$ and γ the mode effective area is needed and the expression in [11] was used.

To obtain a 10-span set-up from the 5-span experiment [7], the first five spans were replicated twice, with identical parameters. Also, in the [7] spans were 85km length. Here we stretched them to 100km so that the total span loss was about 22 dB per span at 190 THz, on average about 18.5dB from fiber loss and the rest accounting for various lumped loss (connectors, mux-demux, etc.).

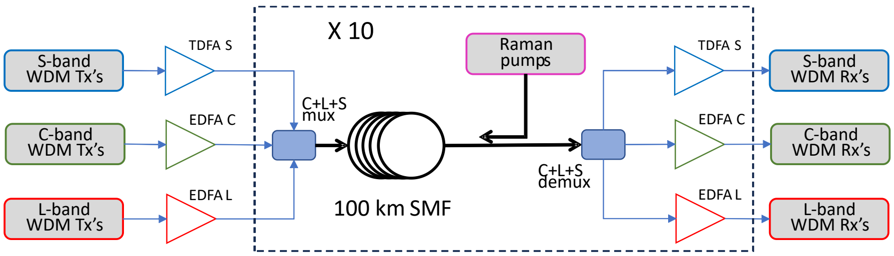

Fig.1: System schematic

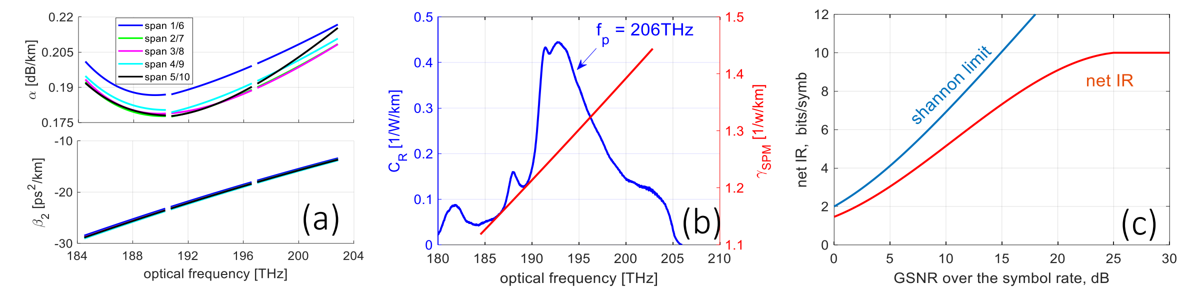

Fig.2: (a) loss and dispersion, measured in C and L band and extrapolated to S band; (b) Raman gain spectrum measured for a 206 THz pump (then translated and rescaled in the system calculations) and non-linearity coefficient γ; (c) transponder net user information rate.

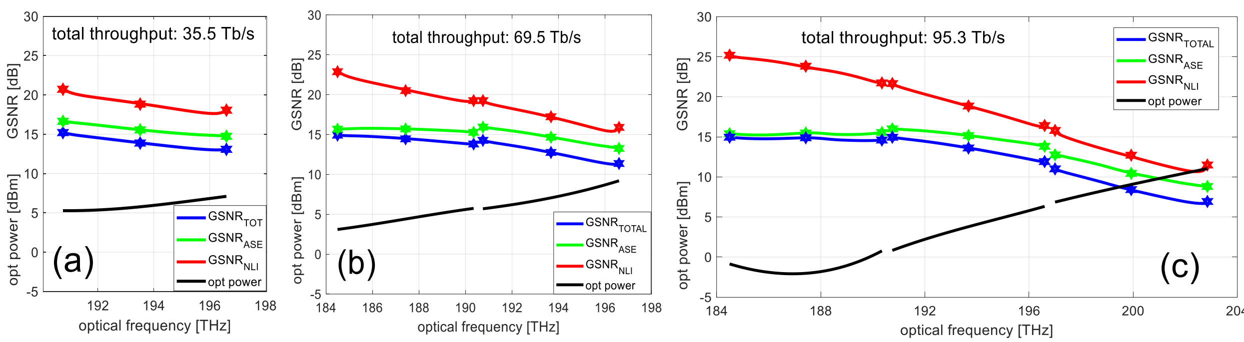

Fig.3: optimum launch power per channel and GSNR for (a) C, (b) C+L and (c) C+L+S 1000km SMF systems. GSNR is shown as due to ASE only, NLI only, and total (ASE+NLI). Star markers: CFM accuracy-check by numerical integration of the UWB EGN model.

The exact WDM band boundaries were similar to [1]: L-band 184.50 to 190.35; C-band 190.75 to 196.60; S-band 197.00 to 202.85. Doped-Fiber-Amplifiers (DFAs) were assumed with 6dB noise-figure in L and S-band and 5dB in C-band, according to the experimental values [1]. The WDM signal consisted of 50 channels in each band, with 100 GBaud symbol rate, roll-off 0.1 and spacing 118.75 GHz. Modulation was assumed Gaussian-shaped. The *net* user information rate of the transponders was assumed as shown in Fig.2c (FEC overhead is removed), representative of the expected next-generation transponder performance coming to market in 2024-2025.

In Fig.3 we show the system GSNR for C, C+L and C+L+S, with launch power optimized for *maximum throughput*. The markers are results obtained by numerically integrating the full EGN model, for CFM accuracy-check. When the S band is turned on, the optimum launch power goes down by 4 to 5 dB in the L-band, a clear sign that massive ISRS is taking place from the S-band to the L-band. Overall, adding the S-band adds only about 25 Tb/s to a system that is already capable of transmitting 70 Tb/s over C+L. Also, with S-band, the system GSNR has a peak-to-peak variation of more than 8dB. However, these GSNR results hint at Raman amplification potentially being of great help to the S-band and perhaps to re-balancing the whole system GSNR, by supplying power to a cascaded transfer from band to band. So, we turned on 3 Raman pumps and let the code free to optimize their frequencies, above a lower bound of 211.5 THz, and their power. We set max power constraints of 24 dBm for two pumps and 27 dBm for the third, to avoid exceeding 1Watt of total power. Note that the CFM duly takes into account both ASE and NLI due to backward Raman amplification, as well as pump depletion. As another key improvement, we decided to set as target not just the maximization of throughput alone, as done in Fig.3, but also its *flattening*, through the loss function:

$$f_{\text{cost}} = \max\left(\text{mean}\left(\text{IR}_{\text{Rx}}^{n}\right)\right) + \min\left(\text{IR}_{\text{Rx,max}} - \text{IR}_{\text{Rx,min}}\right)$$

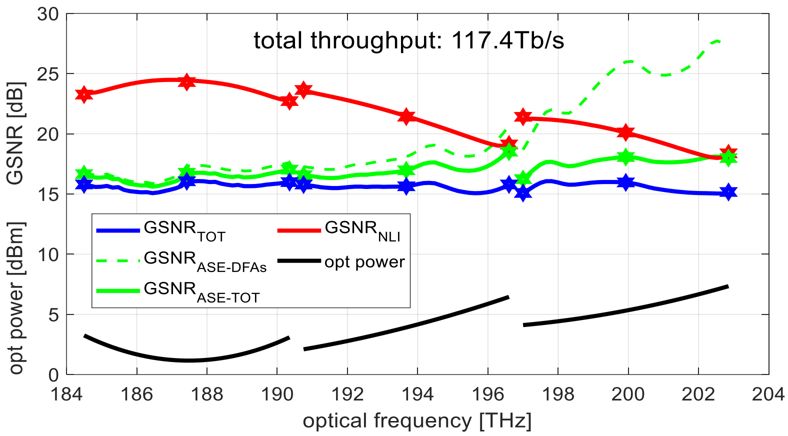

Fig.4: optimum launch power per channel and GSNR for a C+L+S 1000km SMF system with backward Raman amplification for the S-band. GSNR is shown as just due to ASE from DFAs, ASE from all amps, to NLI only, and total, to appreciate the impact of the different

where $\text{IR}_{\text{Rx}}^{n}$ is the information rate of the *n*-th channel.

The result of the optimization is shown in Fig.4. The three Raman pumps settled at:

1. 212.5 THz, 22.7 dBm
2. 214.8 THz, 22.9 dBm
3. 217.3 THz. 25.7 dBm

Quite remarkably, the total GSNR is equal or better than in any plot of Fig.3 and its flatness is within ±0.5 dB. Interestingly, the optimization leads to the L-band being in linearity, while both C and S-band have some channels in linearity and some in non-linear regime. Fig.4 also shows that most of the ASE noise in the S-band comes from Raman amplification, a sign that Raman amplification is prevalent. The tails of the Raman gain from the three pumps still amplify the C-band beneficially, given that the total GSNR in C-band is better and flatter than in Fig.3. Thanks to this excellent result, the overall throughput is now 117.4 Tb/s, 3.3x the result of 6THz C-band alone. As compared to standard 4.5THz C-band (28Tb/s), the result is better than 4x. Note that we also ran the optimization without the GSNR flatness term in the cost function. We obtained a slightly higher throughput (119.0 Tb/s) but GSNR flatness degraded to ±1.5dB. We are currently working towards extending the study, aiming to add another 6-THz beyond the low S-band, into the high-S/low-E band, using further limited and optimized Raman amplification.

3. Conclusion

The availability of tested CFMs allows to design and optimize possible multiband system solutions, accounting for frequency dependence of all parameters as well as ISRS and Raman amplification. The results obtained through such optimized design are quite encouraging for the potential of the addition of the S-band in future long-haul systems. Moderate Raman amplification focused on the S-band appears to provide a beneficial effect through all bands, allowing a potential 3x throughput increase with respect to super-C-band systems and more than 4x vs. standard (4.5 THz bandwidth) C-band systems.

This work was partially supported by: Cisco Systems ITROCS research contract; the PhotoNext Center of Politecnico di Torino; the European Union under the Italian National Recovery and Resilience Plan (NRRP) of NextGenerationEU, partnership on "Telecommunications of the Future" (PE00000001 - program "RESTART").

4. References

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