Signal and Raman Pump Launch Power Optimization in a C+L+S+E System Using Fast Power Profile Estimation

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Abstract: We speed up signal and pump spatial power profile calculation with ISRS and backward Raman amplification, demonstrating a 40x computational efficiency increase in the optimization of a 1000km C+L+S+E link by means of a GN/EGN model closed-form.

1. Introduction

Multiband optical transmission systems have arisen as a key technology for increasing the capacity of optical communication networks. The extension from traditional C-band to C+L bands has been commercially implemented, essentially doubling system throughput. Ongoing research is exploring the integration of additional bands, such as the S, E, U, and O bands [1-3]. This introduces significant ISRS, which results in non-uniform power distributions and degraded system performance. To mitigate these effects, backward Raman amplification can be used and has been shown to be quite effective [1].

Accurately modeling the physical layer behavior in these complex, multiband systems is crucial to achieving optimum performance. Two groups, one at UCL and one at PoliTo (in collaboration with CISCO) have independently obtained closed-form solutions (CFMs) that are based on the GN and EGN models. The UCL CFM is detailed in [4], [5], while the CISCO-PoliTo CFM can be found in [6], [7]. These CFMs avoid GN/EGN model integrals, but they still require numerical methods to solve the coupled Raman equations needed to find the spatial power profile of each channel and pump along the fiber. This numerical process often dominates the computational effort, consuming up to 95% of the total time required to evaluate system performance.

Several approaches have been proposed to expedite power profile calculations. For instance, [8] finds a coarse solution by assuming frequency-independent pump depletion, and then takes it as a starting point to find the accurate solution considering actual pump depletion. Though interesting, we did not manage to obtain major speed gains when testing it. [9] focuses exclusively on one propagation direction, projecting the other direction onto it, and uses vectorization techniques to speed up longitudinal power integration. However, this method requires a good initial estimate for the power profile to avoid serious convergence issues in iterative computations.

In this paper, we build upon [9] to both improve its computational efficiency and solve the convergence problem. We then apply this method to a long-haul SMF system, operating over the C+L+S+E bands for a total of 24 THz of optical bandwidth. The system uses three backward Raman pumps. The objective function is set first to maximize throughput, and then to also ensure GSNR flatness. Thanks to the deep optimization made possible by the sped-up algorithm, we show very high throughput (150 Tb/s) with reasonable pump power, together with flat GSNR.

2. Unidirectional Power profile calculation

The spatial power profile of a channel or a Raman pump, along a span can be found using the well-known coupled Raman differential equations. Such equations can be re-written in integral form. For the i-th channel/pump, the power profile $P_i(z)$ is given by:

$$P_i(z) = P_i(0)\cdot\exp\left\{\mp 2\times\alpha_{i,\text{lin}}\times z \pm \sum_{j=1,j\neq i}^{N} C_R(f_i,f_j)\times\int_0^z P_j(\xi)\,d\xi\right\} \tag{1}$$

where N is the total number of channels and pumps, $\alpha_{i,\text{lin}}$ represents intrinsic fiber loss and $C_R(f_i,f_j)$ represents the SRS gain/loss coefficient of the j-th channel/pump onto the i-th channel/pump. The upper signs in the exponential are used when $P_i(z)$ is a forward-propagating channel/pump, the lower signs when it is a counter-propagating pump.

The system of N coupled equations Eq. (1) is very hard to solve when counter-propagating pumps are present because it is a double-boundary value problem which typically needs many forward-backward iterations to achieve a solution. One alternative is [9] which, though iterative as well, only resorts to *forward* solutions, that can be put into a very computationally efficient matrix form, dealing with all the N coupled equations at once. Calling $\mathbf{P}$ a matrix whose rows are the M spatial samples taken at $z = m\cdot\Delta z$ along the span of the i-th channel/pump, that is, $\mathbf{P} = [P_i(m\cdot\Delta z)]_{N\times M}$, we can generate the $(k+1)$-th power-profile iteration from the k-th as follows:

$$\mathbf{P}^{(k+1)\text{-th}} = \mathbf{P}_0^{k\text{-th}} \cdot \exp\left\{\mp 2 \cdot \boldsymbol{\alpha} \cdot \mathbf{z} \pm \Delta z \cdot \mathbf{C}_R \cdot \mathbf{P}^{k\text{-th}} \cdot \mathbf{L}\right\} \cdot \quad , \quad \Delta z = L_{\text{span}}/M \quad , \quad \mathbf{z} = \left(m \cdot \Delta z\right)_{1\times M} \quad , \quad \boldsymbol{\alpha} = \left(\alpha_{i,\text{lin}}\right)_{N\times 1}$$

$$\mathbf{L} = \left[l_{m_1 m_2}\right]_{M\times M} = \begin{cases} 1, & 1 < m_1 < m_2 \\ 1/2, & m_2 > 1 \text{ and } \left(m_1 = 1 \text{ or } m_1 = m_2\right) \\ 0, & \text{others} \end{cases} \quad , \quad \mathbf{C}_R = \left[C_R\left(f_j, f_i\right)\right]_{N\times N} \; , \; \mathbf{P}_0^{k\text{-th}} = \text{diag}\left(P_i(0)\right)_{N\times N} \qquad \textbf{(2)}$$

where $\mathbf{L}$ is a fixed matrix that, when multiplied by $\mathbf{P}$, performs the computation of the integral in the exponent of Eq. (1) according to the trapezoidal method. At the first iteration, Eqs. (2) need to be initialized with a guess of the power profiles for both channels and pumps, $\boldsymbol{P}^{0-\text{th}}$. Then Eqs. (2) generate the next iteration, $\boldsymbol{P}^{1-\text{st}}$ which in turn generates $\boldsymbol{P}^{2-\text{nd}}$, and so on. Ideally, the algorithm has converged when *both* $\mathbf{P}^{(k+1)-\text{th}} = \boldsymbol{P}^{k-\text{th}}$ *and* such solution matches the nominal launch power into the span for both the signals and the Raman pumps.

We found however that the convergence of the original algorithm [9] was narrow and problematic, so that it was essentially unusable. Therefore, we modified it by devising suitable strategies for *adapting* the power profiles fed to Eqs. (2), ensuring that each iteration would generate a solution $\boldsymbol{P}^{(k+1)\text{-th}}$ closer to the final stable one. The computation consists of two phases. In the first phase, to prevent early divergence, we use initial power profiles $\boldsymbol{P}^{0-\text{th}}$ with values substantially lower than the nominal ones launched into the span. This phase iterates Eqs. (2), while gradually scaling up the power profiles by a small step, first of the signals, then of the pumps. When both have been scaled up, the second phase begins, focusing on refining the solution. The procedure looks at the *backward pump* profiles resulting from the k-th iteration, $\boldsymbol{P}^{k-\text{th}}$, from which it extracts the estimated pump powers at the end of the fiber. Then it finds the *difference* between these estimated values and the actual boundary conditions. The method scales the pumps in $\boldsymbol{P}^{k-\text{th}}$ to reduce this gap, then it feeds the modified profile to Eqs. (2) providing a better guess for the next iteration. We point out that at this stage pumps can either undershoot or *overshoot* their boundary conditions and need to be scaled up or down accordingly. Using such dual-phase feedback-guided scaling strategy for both signals and pumps, we have been able to obtain very reliable convergence for the algorithm, which we have tested in very high pump and channel power situations, well beyond practical levels, with excellent results. Despite the algorithm requiring typically 50 to 200 iterations, due to its efficient matrix formulation and inherent features, it has consistently proved about 40x faster than our Matlab reference algorithm (see below). In addition, it has reached convergence in situations where the reference algorithm failed to achieve it. A detailed description and testing of the algorithm can be found in [10].

3. System description and results

We tested the sped-up algorithm on the optimization of a complex 4-band 10-span system. The schematic is shown in Fig.1. The first five spans, all slightly different from one another, were characterized from the experimental set-up used for CFM validation in [11], with fiber loss, dispersion, SPM coefficient and Raman gain spectrum shown in Fig. 2(a) and 2(b). These first five spans were replicated and numerically extended to 100km each, forming a total system length of 1000km. The insertion loss from the MUX/DEMUX and other connectors were assumed to be 4dB. The WDM band boundaries were: L-band 184.50 to 190.35; C-band 190.75 to 196.60; S-band 197.00 to 202.85, E-band 203.25 to 209.07THz. Doped-Fiber-Amplifiers (DFAs) were assumed, with noise-figure of 5dB in C-band, 6dB in L and S-bands, and 7dB in E-band. Each WDM band contained 50 channels, with symbol rate 100 GBaud, 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.2(c). Three backward Raman pumps were also assumed. The system was then optimized. Specifically, the launch power spectrum in each band and the frequency and power of each Raman pump were optimized for *maximum throughput*. Note that the launch power spectrum was described using a cubic polynomial for each band: $P_{\text{dB}}(f) = P_0 + P_1(f - f_c) + P_2(f - f_c)^2 + P_3(f - f_c)^3$, with f_c the center frequency of each band. This spectrum representation requires a total of 16 coefficients (4 per band) and saves significant degrees of freedom compared to a per-channel power optimization. In Fig.3(a) we show the optimized launch power together with the system GSNR. The three pumps settled at: 212.6THz, 24.7dBm; 218.3 THz, 29.7dBm; 219.2 THz, 26.3dBm. The overall throughput was 157.2Tb/s, 4.5x the result of a 6THz C-band alone in [1]. Note that the optimizer needed about 2000 full system evaluations to converge to this result. Fig.3(a) also shows

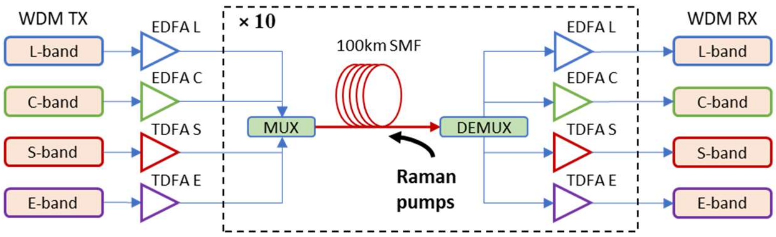

Fig.1: System schematic

OSNR (ASE only), $GSNR_{NLI}$ (NLI only), as well as $OSNR_{DFA}$ which accounts for ASE from DFAs only. The high value of $OSNR_{DFA}$ in S and E bands means that most amplification was sustained there by Raman.

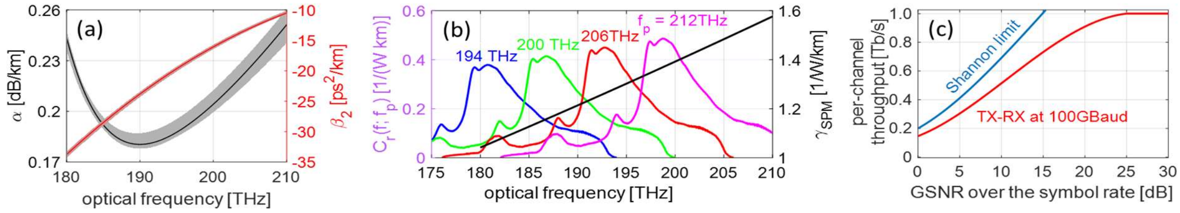

Fig.2: (a) loss and dispersion; (b) Raman gain spectrum and SCI coefficient γ ; (c) transponder net user information rate.

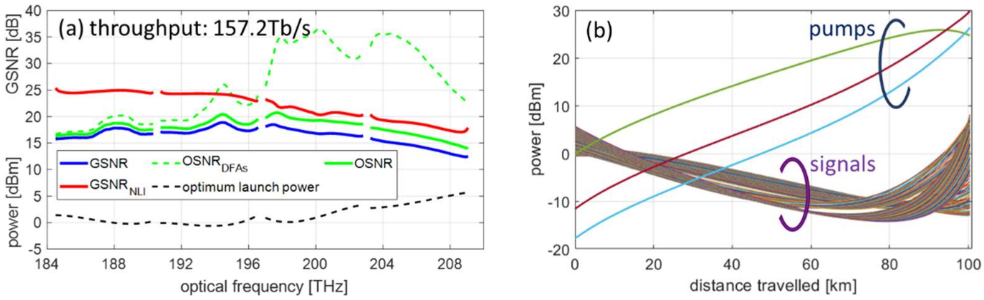

Fig.3: (a) optimum launch power per channel and GSNRs (see text), for throughput maximization; (b) power profile along the first span.

Next, GSNR flatness was incorporated into the objective function to minimize GSNR variations while still maximizing throughput. As a result, the peak-to-peak GSNR variation was reduced from 6.5 dB in Fig. 3(a) to only 1.2 dB in Fig. 4, at the cost of a somewhat reduced throughput (143.5 Tb/s). These challenging optimizations took advantage of the method of Sect.2, which improved computation speed by a factor of about 40 compared with the reference dual-directional Raman solver (bvp4c in MATLAB). As an example, Fig.3(b) shows the power profile of both signals and pumps along the first span, with a resolution of 100m. Across the first (all different) 5 spans, we compared 1,030,000 power values found by the two methods across all channels/pumps, observing a max difference of ±0.05dB, proving the quite good accuracy of the algorithm.

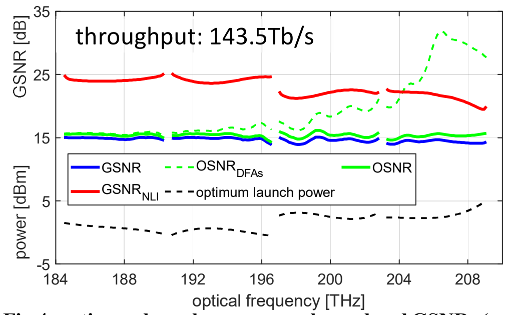

Fig.4: optimum launch power per channel and GSNRs (see text) for throughput maximization while flattening GSNR. The 3 pumps settled at: 214.1THz, 17.7dBm; 219.2 THz, 24.2 dBm; 221.1 THz, 28.9dBm.

4. Conclusion

Fast full system performance estimation is essential for the deep iterative optimization of multiband systems. Its two time-consuming steps are: NLI estimation; channels and Raman pumps spatial power profiles computation. NLI estimation has been solved by ultra-fast closed-form GN/EGN models (CFMs). We have presented here a method that tackles the power profile estimation step by greatly speeding it up, by a factor of about 40, without losing accuracy. We have shown its potential by performing a deep C+L+S+E+Raman system optimization, showing a potential 4.5x throughput increase with respect to super-C systems, while also achieving very good GSNR flatness.

This work was partially supported by: Cisco Systems RISEONE 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").

5. References

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