

A Fast Amplifier Gain and Tilt Configuration Algorithm for Dynamic C+L-band Networks

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Abstract: We propose a fast amplifier gain/tilt configuration algorithm for C+L-band systems in presence of Stimulated Raman Scattering (SRS). The running time is less than 5 seconds which can be used for real-time dynamic network control. © 2022 The Author(s)

1. Introduction

Future C+L-band networks are envisioned to be flexible, dynamic and software defined with real-time physical layer monitoring, Quality of Transmission (QoT) prediction and physical layer impairment-aware routing, modulation format and wavelength assignments (RMWA). One of the important and unique physical layer impairment in C+L-band system is Stimulated Raman Scattering (SRS), which, among other effects, induce power transfer from high frequency channels to low frequency channels. Such power transfer significantly distorts the signal power distribution across both bands along fiber propagation, rendering complicated inter-dependencies between launched signal power profiles, amplified spontaneous emission (ASE) noise and Kerr nonlinearity-induced interference (NLI).

It is known that the generalized signal-to-noise ratio (GSNR), defined as the ratio of received signal power to the sum of total ASE and NLI, is not a convex function of the signal launched power when SRS is present [1]. Therefore, it is important to develop launched power and inline amplifier gain/tilt optimization methods to maintain good power profile evolution and GSNR across the C+L bands. Typically, one starts with the LOGO algorithm [2] that determines the optimal launched power that best balances between ASE noise and NLI under the assumption of no SRS and full spectral loading. This is followed by fine tuning the amplifier gain/tilt settings to maximize the mean GSNR m while minimize its standard deviation σ across channels to achieve GSNR flatness. There is a myriad of fine-tuning techniques reported in the literature including brute-force exhaustive search [3], covariance matrix adaptation (CMA) evolution strategy [4] as well as non-dominated sorting genetic algorithms (NSGA)-II [5]. However, these algorithms take *minutes* (if not tens of minutes) to run, do not scale well with number of spans and are therefore neither suitable for real-time reconfiguration and control of dynamic networks, nor fast recovery when failures occur. In this paper, we propose to first calculate the pre-tilted transmitted power profile by inverting the SRS effect from the LOGO received power, followed by a gradient ascent algorithm that iteratively fine tunes the amplifier gain/tilt values to maximize $m-\sigma$. Simulation results show that our proposed algorithm produces similar GSNR profiles to other algorithms but has running time in less than *5 seconds*, which renders it a good tool for enabling real-time amplifier reconfigurations in C+L-band links with dynamic channel loadings to improve network margin and reliability.

2. Fast Amplifier Gain and Tilt Configuration Algorithm

For simplicity, we will first assume flat amplifier noise figure (NF). Our proposed algorithm is separated into 3 steps.
Step 1: Neglect SRS effects. Calculate the optimal launched power $P_{LOGO,k}$ for the k^{th} span using the LOGO algorithm that balance between ASE noise and NLI;
Step 2: From the corresponding received power $P_{LOGO,k}-\alpha L_k$ where α is the fiber attenuation coefficient and L_k is the length of the k^{th} span, invert the SRS effects and re-calculate the (tilted) signal power at the beginning of the k^{th} span by solving the SRS power evolution equation [1]

$$\frac{\partial P_n(z)}{\partial z}=-\alpha P_n(z)+\sum_{m=1}^{N}\frac{g_R(\omega_m-\omega_n)}{A_{eff}}P_n(z)P_m(z) \tag{1}$$

backwards where $g_R, A_{eff}, P_n(z), \omega_n$ is the Raman gain coefficient, fiber effective area, signal power and carrier frequency of the n^{th} channel at distance z. Note that by setting the gains $G_{L(C),k}$ and tilts $T_{L(C),k}$ of the k^{th} L(C)-band amplifier to produce such tilted signal power profile at the beginning of each span, the flatness of the power profile at the end of each span is ensured but the GSNR will deviate from the optimal values calculated by step 1.

Step 3: Consider the mean GSNR $m_{L(C)}$ and their standard deviations $\sigma_{L(C)}$ for channels across the L(C)-band. As we want to achieve high and relatively flat GSNR across C- and L-band, we define the cost function $J = m_L - \sigma_L + m_C - \sigma_C$ and propose a gradient ascent algorithm that iteratively fine tune the EDFA gain and tilt values. Initialized at the gain and tilt values after SRS inversion in step 2, the gradient ascent algorithm includes the derivatives $\frac{\partial m_{L(C)}}{\partial G_{L(C),k}}, \frac{\partial m_{L(C)}}{\partial T_{L(C),k}}, \frac{\partial \sigma_{L(C)}}{\partial G_{L(C),k}}, \frac{\partial \sigma_{L(C)}}{\partial T_{L(C),k}}$ which can be computed numerically. The n^{th} iteration updates are then given by

$$G_{L(C),k}^{(n+1)} = G_{L(C),k}^{(n)} + \mu \frac{\partial J}{\partial G_{L(C),k}} \qquad T_{L(C),k}^{(n+1)} = T_{L(C),k}^{(n)} + \mu \frac{\partial J}{\partial T_{L(C),k}}$$

where μ is the step size and the gain and tilt settings will be updated until convergence. Throughout this work, we use (1) to calculate the signal power evolution with SRS and the ISRSGN model [6] to calculate the NLI.

3. Simulation Results

We first study a 96-channel C+L-band system from 186.1 THz to 196.1 THz with 100-GHz channel spacing and 600-GHz guard band between C and L. We assume a Gaussian distributed signal with a baud rate of 64 GBaud and a roll-off factor of 0.1 (a bias can be added to the ISRSGN model [6] for a specific modulation format). The link comprises of 10 homogeneous 80-km spans with a booster and pre-amplifier before fiber launch and at the receiver respectively. We initially assume a frequency-flat noise figure NF_C across C-band that generally increase with decreasing amplifier gain G_C in a nonlinear fashion. We used the measured data from a sample commercial amplifier and derive a cubic polynomial fitting

$$NF_C = -0.0019{G_C}^3 + 0.1346{G_C}^2 - 3.254G_c + 31.13, \qquad G_C \in [10,25]\ dB \tag{2}$$

and assume the L-band noise figure to be $NF_L = NF_C + 0.7$ dB. A wavelength selective switch (WSS) at the end of the 5th span to equalize the accumulated power ripples along the previous 5 spans. The transmitted and received power for step 1(LOGO), step 2(SRS inversion) and step 3(iteration) of the proposed algorithm are shown in Fig. 1. The iteration of gain and tilt are shown in Fig. 1(c) (step sizes are 0.3, 0.2 then 0.1 for the 3rd iteration onwards), indicating that the optimized configurations do not fully compensate SRS effects. This should be expected as the best EDFA settings should strike a balance between mitigating SRS and Kerr effect and hence the pre-tilt should not be fully compensating the SRS-induced tilt.

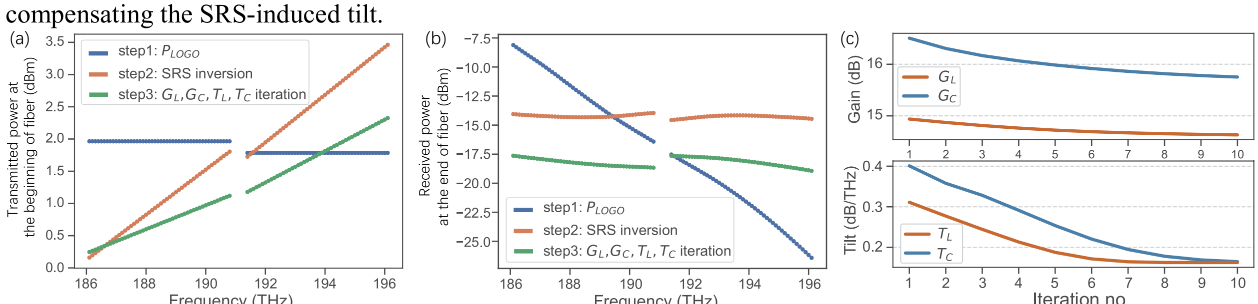

Fig. 1. a) Transmitted power, b) received power and c) evolution of the amplifier gains and tilts G_L, G_C, T_L and T_C in our proposed algorithm.

(a)

	G_L(dB)	G_C(dB)	T_L(dB/THz)	T_C(dB/THz)
Proposed algorithm	14.74	15.74	0.1454	0.1443
CMA-GA	14.74	15.73	0.1504	0.1489
NSGA-II	14.50	15.76	0.1505	0.1288

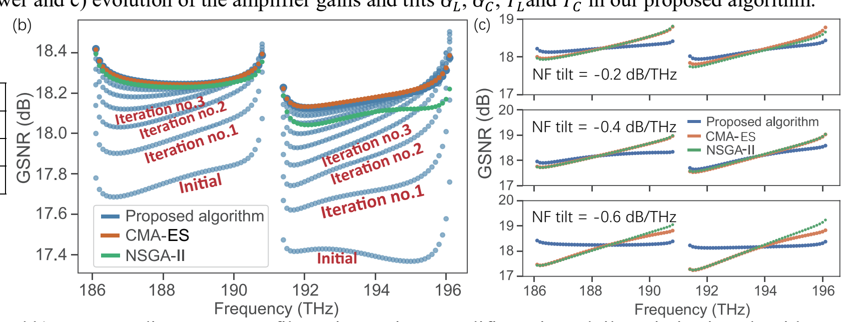

Fig. 2. a) Optimal EDFA gain and tilt settings and b) corresponding GSNR profiles using various amplifier gain and tilt optimization algorithms. c) Optimized GSNR profiles for NF tilt of -0.2, -0.4 and -0.6 dB/THz.

The optimized gain and tilt settings are shown in Fig. 2(a) which are similar to those obtained from CMA and NSGA-II algorithm[4, 5]. Fig. 2(b) shows how the GSNR profiles become larger and flatter with more iterations and the final GSNR profiles are comparable with other algorithms. However, our proposed algorithm only need < 5 seconds to run while CMA and NSGA-II need around 5 mins (all the algorithms are run in Python on a laptop with a 2.6 GHz quad-core Intel Core i7 processor with 16 GB 2666 MHz RAM). Exhaustive search [3] will need even more time. Next, we study NF with -0.2, -0.4, and -0.6 dB/THz tilts for each band and results in Fig. 2(c) show that our algorithm achieves flatter GSNR profiles with the same running-time advantage over CMA and NSGA-II.

Next, we study a representative realistic 10-heterogeneous-span link with length 88.7, 58.4, 74.7, 82.4, 85.3, 87.7, 92.1, 89.7, 89.3, 98.4 km and a NF tilt of -0.4 dB/THz for both C- and L-band. In this case, the amplifier settings needed to be optimized span by span and the corresponding launched power profiles at the beginning of the 2nd, 4th, 6th, 8th and 10th span are depicted in Fig. 3(a). The optimized EDFA gain and tilt settings are shown in Fig. 3(b). Starting from the 1st amplifier, the corresponding GSNR profile after sequentially optimizing each of the 10 amplifier settings (using 5 iterations per amplifier) is shown in Fig. 3(c). Clearly, our algorithm can achieve comparable or better GSNR to CMA and NSGA in realistic heterogeneous-span links and it only require less than 5 seconds running time.

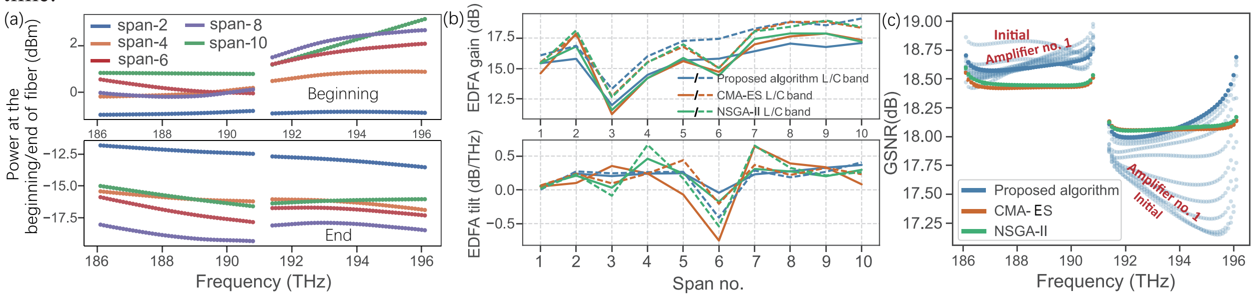

Fig. 3. a) Optimized transmitted and received power profiles, b) corresponding optimal amplifier gain and tilt settings for each span and c) optimized GSNR profiles for a 10-heterogeneous-span link using different amplifier gain and tilt optimization algorithms.

Finally, we consider a dynamic mesh network scenario with three nodes A, B and C in which the aforestated heterogenous span link connects B to C. We assume some channels across the C+L band are from A to C while others are from B to C and a sudden fiber cut (due to unintended damages from road construction, on-site repair, etc.) somewhere between A and B abruptly cuts off a portion of the C- and L-band channels from B to C. In this case, the system will be heavily imbalanced thus highly suboptimal at the moment of disruption as all the amplifier settings are optimized for the original full-load condition. The proposed algorithm will immediately re-optimize the amplifier settings using the revised cost function $J = [N_L(m_L - \sigma_L) + N_C(m_C - \sigma_C)]/(N_L + N_C)$ where N_L and N_C are the number of remaining channels in the L- and C-band after abrupt cut respectively. As an example, Fig. 4(a) shows the GSNR profiles at different points of this dynamic process when 28 high frequency channels in the L-band are suddenly cut. The C-band GSNR is considerably worsened at the moment of disruption, but the proposed algorithm can re-optimize the system under 5 seconds to achieve an even better GSNR after disruption. The gain and tilt values of each span before and after re-optimization are generally different as shown in Fig. 4(b). Fig. 4(c) shows the GSNR profiles when 28 random channels across the C- and L-band are abruptly cut. The L-band GSNR can largely be restored to its original state while the C-band GSNR was worsened but become even better than before cut after re-optimization.

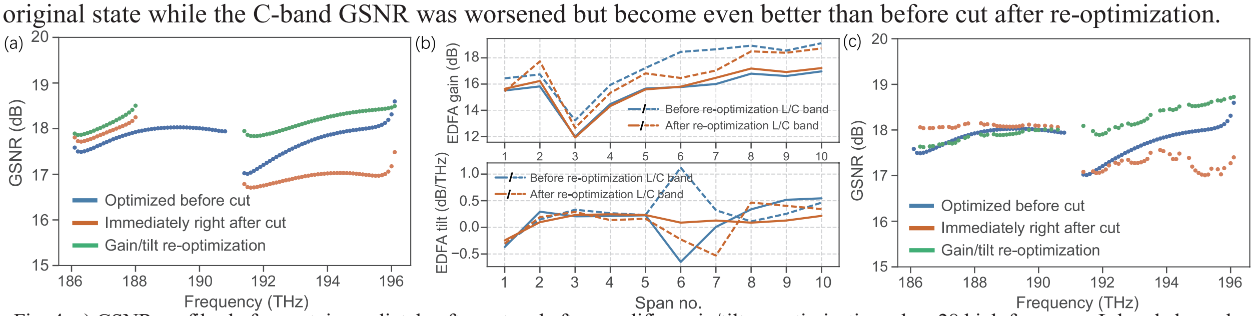

Fig. 4. a) GSNR profiles before cut, immediately after cut and after amplifier gain/tilt re-optimization when 28 high frequency L-band channels are abruptly cut; b) Optimized gain and tilt settings before and after abrupt cut; c) GSNR profiles when 28 random channels are abruptly cut.

4. Conclusions

In this paper, we proposed a fast amplifier gain and tilt configuration algorithm that achieve high and flat GSNR profiles for C+L-band systems. The running time of a few seconds is advantageous for real-time network management and control, which is another step towards dynamic and reliable low-margin optical networks.

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