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A Few Milliseconds-Fast SRS-Induced Loss and Tilt Compensation Algorithm for Dynamic C+L-band Networks

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Abstract *We demostrate a ~20 milliseconds fast algorithm implemented in amplifiers for compensation of Stimulated Raman Scattering (SRS) induced loss and tilt in dynamic C+L-band networks. Simulation and lab results matche closely and thus, verify the algorithm. ©2022 The Author(s)*

Introduction

Demand for high speed and high capacity data transmission is stirred-up continuously due to work-from-home initiatives in recent pandamic, upcoming 6G systems, and Industry 4.0 [1]. Therefore, it is expected from network operators to meet these demands by upgrading C-band dense wavelength division multipexing (DWDM) transmission to C+L-bands over optical fiber networks. The key aspect of employing L-band with C-band DWDM system is to provide flexible upgrade without affecting the existing traffic in C-band, when need arises. While conventional C-band suffers through fiber attenuation and elastic nonlinear effects, C+L bands will have additional inealstic stimulated Raman scattering (SRS) induced penalties [2]. SRS causes power transfer within and across the bands from blue to red channels, and hence causing power loss and tilt in the spectrum, along fiber propagation. We name this additional SRS induced loss and tilt, as SRS-loss and SRS-tilt throughout the manuscript. This SRS-loss and SRS-tilt causes re-distribution of power across the bands, redering the instability of receivers and additional optical-signal-to-noise ratio penalty.

As the SRS induced power distribution across the bands are not accounted during the link-budget calculation, it is important to develop inline amplifier gain and tilt profile optmization, to maintain good power profile evolution across the C+L bands, throughout the network. There is myriad of techniques reported, including launch power optmization using LOGON algorithm [3], covariance matrix adaption evolution strategy [4], brute-force exhausive search [5], and non-dominated sorting genetic algorithm [6]. However, time-scale invlove with these techniques is few minutes, niether suitable for fast recovery during failure, nor real-time reconfiguration and control of dynamic C+L network. Another LOGON algorithm for generalized signal-to-noise ratio profile optimization with running time ~5 seconds is discussed in [7]. In this manuscript, we first derive the apporiximate equation for SRS-loss and SRS-tilt, through simulations, under full and partial populations in C+L bands. We further perform the lab-measurements to verify simulations and equations. All three – equations, simulation results, and lab-measurements – matches closely to each other. We use the derived SRS-tilt and SRS-loss equations for pre- and post-compensation at amplifiers. The algorithm implemented at amplifier takes almost ~20 milliseconds, which enable real-time amplifier reconfigurations in C+L links under dynmaic add/drop of channels or fiber-cut, to improve network reliability and system margin.

SRS induced Loss and Tilt

We define the SRS-loss$_{\text{C-/L-band}}$ as effective loss due to SRS in middle channel of C-/L-band (*e.g.*, $\lambda = 1546.92$ nm and 1589.56 nm for C- and L-band, respectively, in 100 GHz-ITU grid) and SRS-tilt$_{\text{C-/L-band}}$ as difference between SRS loss of first and last channels in C- and L-band, respectively, as shown in Fig. 1(a).

SRS-loss and SRS-tilt in dynamic optical network, depends upon various factors, including fiber parameters (attenuaion, Raman-gain coefficient, etc.), power/channel, span length, channel population and distribution across C+L bands, etc. Since, these dependancies can not be explicitly derived through analytical solution, therefore, we perform the simulation of C+L band propagation in presence of SRS effect in fiber and obtained the expression for SRS-loss$_{\text{C-/L-band}}$ and SRS-tilt$_{\text{C/L-band}}$ with reasonable accuracy.

We model the propagation of C+L band channels in optical fiber, including only wavelength dependence loss (WDL) and SRS interactions (we assume other nonlinear effects are negligible in single fiber span), as [8],

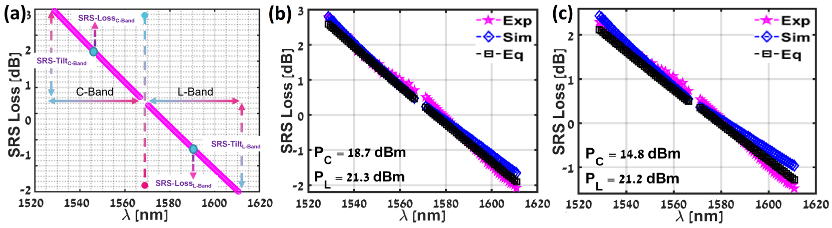

Fig. 1: (a) SRS-Loss$_{\text{C/L-band}}$ and SRS-tilt$_{\text{C/L-band}}$ in C+L DWDM system, SRS-loss$_{\text{C/L-band}}$ spectrum for (b) P_C = 18.7 dBm, P_L = 21.3 dBm, and (c) P_C = 14.8 dBm, P_L = 21.2 dBm.

$$\frac{dP_i}{dz} = -\alpha_i P_i - \sum_{j=i+1}^{N} g_{i,j} P_i P_j + \sum_{k=1,i>1}^{i-1} g_{k,i} P_i P_k \qquad (1)$$

where, P_i and α_i are optical power and fiber attenuation of 'i-th' channel, $g_{i,j}$ is Raman gain coefficient between 'i-th' and 'j-th' channels, and N is total number of channels in C+L band. The 1st, 2nd, and 3rd terms in eq.(1) represent, WDL, loss and gain due to SRS from blue to red channels and vice-versa, respectively.

We simulated the propagation of 50 GHz and 100 GHz-ITU grid-C+L band channels in 100 km−G.652.D and G.655 (Truewave (TW):RS, TW:REACH, and LEAF) fibers, with total optical power−0 dBm to 30 dBm−in each band (when full capacity). We consider equal and unequal power/channel, and uniformly, non-uniformly, and randomly populated and distributed 6 to 192 channels, in C+L band. We perform more than 3000 simulation run for different combination of optical power, channel population and distribution, and fiber types.

By analyzing the simulation results, we noticed that, SRS-tilt$_{\text{C-band}}$ and SRS-tilt$_{\text{L-band}}$ are equal in dB scale and directly proportional to total optical power in mW, irrespective of channel population and distribution, and can be expressed as,

$$\text{SRS-tilt}_{\text{C/L-band}} = \xi \times \kappa \times \frac{0.22}{\alpha} \times (P_C + P_L) \times \frac{1}{100} \qquad (2)$$

where, P_C and P_L are total power (mW) in C- and L-bands, $\xi = 0.9$, κ depend upon fiber-types (= $1, 1.12, 1.45,$ and 1.54 for G.652.D, G.655.A-D (LEAF), G.655.C,D (Truewave RS), and G.656 (Truewave REACH), respectively), and α is fiber attenuation. All the coefficients (ξ, κ, and α) are idenependent of optical power and channel population and distribution. Further, SRS-loss$_{\text{C-band}}$ and SRS-loss$_{\text{L-band}}$ in dB scale can be expressed as,

$$\text{SRS-loss}_{\text{C/L-band}} = \pm\, \chi_{C/L} \times \kappa \times \vartheta_{C/L} \times U_{C/L} \times \frac{0.22}{\alpha} \times (P_C + P_L) \times \frac{\eta_{C/L}}{100} \qquad (3)$$

where, $\eta_{C/L} = \sqrt{\frac{P_{L/C}}{P_C+P_L}}$, P_C and P_L are total power (mW) in C- and L-bands, $\chi_{C/L} = 0.8$ and 0.6 for C- and L-band, respectively. $\vartheta_{C/L}$ and $U_{C/L}$ dpends upon channel population and distribution, respectively and define as, $\vartheta_{C/L} = \min\left[1, 1.25 \times \left(\frac{N_L}{N_C}\right)^{\pm\frac{1}{3}}\right]$, $U_{C/L} = 1 - \delta \times (R_C + R_L - 2) \pm 0.5 \times (R_C - R_L)$, where $\delta = \min\left[1, \left(\frac{N_L}{N_C}\right)^{\pm 1}\right]$, '+' and '−' signs are for C- and L-band, respectively. N_C and N_L are channel populations in C- and L-band, respectively. R_C and R_L repersents the index of uniformity in distribution of channels in C-and L-band, respectively and defined as,

$$R_{C/L} = 1 + \frac{\sum_j \left[f_j - f_{C/L,\text{mid}}\right] \times \text{BW}_j}{4.75 \times \text{BW}_j} \qquad (4)$$

where, f_j is frequency in THz, and BW$_j$ in GHz of 'j'-th channels, $f_{C/L,\text{mid}}$ is frequency (in THz) of middle channel of C/L-band. $R_{C/L} =, >, < 1$ for uniformly distributed, more blue than red, and more red than blue channels, respectively.

Simulation and Experimental Results

We experimentally verified both simulation and eq.(2)-(3), for 96 C+L-ITU channels of 100 GHz spacing and 500 GHz gaurd band between C- and L-bands. All channels are obtained through a MPB Communications comb-source [9], and fed to the 100 km G.652.D fiber. Spectrum at the input and output are measured with optical spectrum analyzer (OSA) of 4 GHz resolution. SRS loss of C+L-band channels are plotted, for experiment (☆), simulation (◇), and equations (□) in Fig. 1(b) and Fig. 1(c) for total band power of, P_C = 18.7 dBm, P_L = 21.3 dBm and P_C = 14.8 dBm, P_L = 21.2 dBm, respectively. SRS loss in experiment, simulation, and equations are matching closely to each other for most of the channels, with maximum offsets between experiment and simulation are 0.25 dB and 0.35 dB and between simulation and equation are 0.18 dB and 0.22 dB, for two different total power combination of C/L-bands in Fig. 1(b) and Fig. 1(c), respectively. Further, SRS-tilt$_{\text{C-band}}$ and SRS-loss$_{\text{C-band}}$ are 2.09 dB, 2.32 dB, 2.13 dB and 1.61 dB,

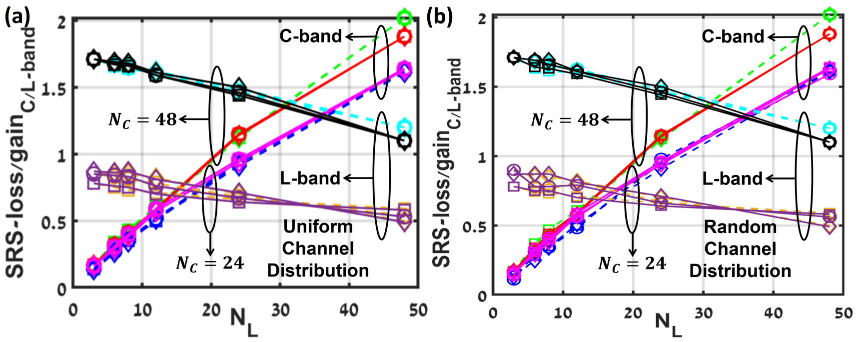

Fig. 2: SRS-Loss$_{C/L\text{-band}}$ vs N_L for (a) uniformly and (b) randomly distributed channel populations in C+L bands.

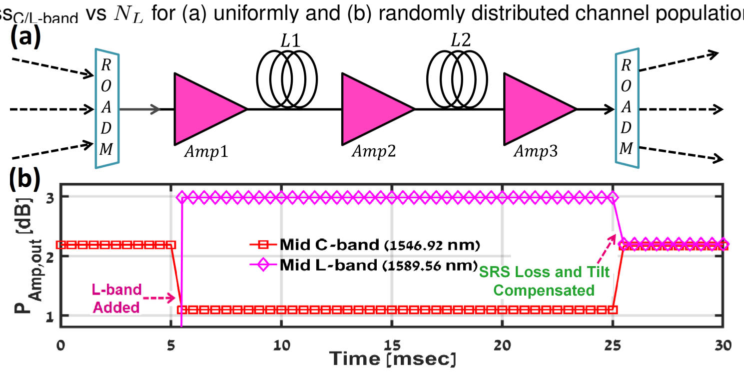

Fig. 3: (a) Pre- and post- compensation of tilt and loss at amplifiers $Amp1$ ($Amp2$) and $Amp2$ ($Amp3$) for SRS effect in fiber span $L1$ ($L2$) and (b) SRS-effect compesnation in 20 milliseconds by amplifiers

1.62 dB, and 1.55 dB in experiment, simulation, and equations, respectively, for $P_C = 18.7$ dBm, $P_L = 21.3$ dBm and $P_C = 14.8$ dBm, $P_L = 21.2$ dBm. Similarly, SRS-tilt$_{L\text{-band}}$ and SRS-loss$_{L\text{-band}}$ are 2.12 dB, 1.93 dB, 2.13 dB and -0.82 dB, -0.68 dB, and -0.85 dB in experiment, simulation, and equations, respectively, for $P_C = 18.7$ dBm, $P_L = 21.3$ dBm and $P_C = 14.8$ dBm, $P_L = 21.2$ dBm. Negative (-) sign suggest actual SRS induced gain in L-band due to power transfer from C-band. Once, we verified the accuracy of simulation results and equations, with experiments, we plotted variation of SRS-loss$_{C/L\text{-band}}$ with number of L-band channels (N_L) for $N_C = 24, 48$ for uniformly and randomly distributed channels in C- and L-bands in Fig. 2(a) and Fig. 2(b), respectively. We compared the three different channel distributions: in entire (○), towards edges (□) and center (◇) of individual C/L-band. We also compared the plot obtained from eq.(3) with simulation. We observe that, SRS-loss$_{C/L\text{-band}}$ increases/decreases with N_L for a fix N_C. Increase in N_L causes more inter-band power transfer (from C- to L-band), while intra-band power transfer in L-band also increases, this resulting in increase in effective SRS-loss in C-band and decrease in effective SRS-gain in L-band. Further, SRS-loss$_{C/L\text{-band}}$ are almost unchanged with uniform and random distribution of channels in entire, towards edge and center of the individual bands. This suggest that SRS-loss$_{C/L\text{-band}}$ depends upon channels populations (N_C and N_L) only and indpendent of how they are distributed across the bands. Simulation results are almost matching with plot obtained through equations (maximum offset is 0.15 dB only for few channels), validates the eq.(3).

Fast SRS Loss and Tilt compensation Algorithm

We propose to pre-compensate the SRS-tilt$_{C/L\text{-band}}$ at amplifer ($Amp1$ and $Amp2$) and post-compesate the SRS-loss$_{C/L\text{-band}}$ at amplifier ($Amp2$ and $Amp3$) for fiber span $L1$ and $L2$, respectively, as shown in Fig. 3(a). We implement our algorithm in the firmware (FW) of the amplifier, with following steps: (I) FW calculates the SRS-tilt$_{C/L\text{-band}}$ and SRS-loss$_{C/L\text{-band}}$ based on the measured input P_C and P_L and known N_C and N_L in the link, in accordance with eq.(2)-(3), (II) value of P_C, P_L, N_C, and N_L are updated frequently to detect any change due to fiber cuts, or channel add/drop, (III) if difference in SRS-tilt$_{C/L\text{-band}}$ or, SRS-loss$_{C/L\text{-band}}$ is more than 0.4 dB, FW adjust the tilt and gain of corresponding amplifiers. Entire process is very fast and takes almost 20 milliseconds as shown by simulation results in Fig. 3(b).

Conclusion

We established SRS-loss and tilt dependency on optical power and dynamic channel population, through simulations and experiements, and used them in algorithm for fast (20 milliseconds) compensation of SRS-effect, at amplifiers.

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