Power Allocation Optimization in the Presence of Stimulated Raman Scattering

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Abstract *We leverage the simplicity of closed-form expressions of the nonlinear interference variance in the presence of stimulated Raman scattering (SRS) for fast pre-emphasis optimization in wideband wavelength division multiplexing (WDM) terrestrial systems with sparse dynamic gain equalizers.*

Introduction

Multi-band C+L optical communication systems are a viable solution to increase the system capacity[1]. For such wide bandwidths, the amplification of lower frequencies at the expense of higher frequencies induced by inter-channel stimulated Raman scattering (SRS) becomes a non-negligible impairment. Power allocation strategies to counteract the unbalances introduced by the SRS gain are pivotal in the design of the link[2–5]. Unfortunately, the complexity of split-step Fourier method (SSFM) simulations for ultra-wideband transmissions is often unmanageable[6]. Therefore, analytical models to estimate the system performance stand out as the best candidate for link design optimization. In this work, we approach the problem using the DGE-SRS-GN model closed-form expression proposed in[7,8] for the estimation of the nonlinear interference (NLI) variance. Such a model is a generalization of the closed-form SRS-aware Gaussian noise (GN) model in[9] extended to scenarios with a few dynamic gain equalizers (DGEs) regularly placed along the link to remove the inter-DGE accumulated SRS gain. The DGE-SRS-GN model can also account for a non-flat wavelength division multiplexing (WDM) signal power pre-emphasis to counteract the residual SRS effects[8].

In this work, we exploit such a model with in-line DGEs to optimize the pre-emphasis in order to maximize either (i) the minimum signal to noise ratio (SNR) in the WDM comb or (ii) the total capacity.

Signal power pre-emphasis

Let us define the SRS gain on the WDM channel centered at frequency f_i from the input of link up to the end of the mth span, as[10]:

$$H(f_i, m) = \frac{P_{\mathrm{t}} e^{-mP_{\mathrm{t}} L_{\mathrm{eff}} C_{\mathrm{r}} f_i}}{\sum_{\ell=1}^{N_{\mathrm{ch}}} P_\ell e^{-mP_{\mathrm{t}} C_{\mathrm{r}} L_{\mathrm{eff}} f_\ell}} \qquad (1)$$

where P_{t} is the total WDM power, L_{eff} is the fiber effective length, C_{r} is the coefficient of the triangular approximation of the Raman gain[10], N_{ch} is the number of WDM channels, and P_ℓ is the channel power launched into the link. After applying a pre-emphasis in the form of an opposite-sign SRS gain, the launched channel power can be expressed as

$$P_i = H(f_i, -\bar{k})P \qquad (2)$$

hence a gain $H(f_i, -\bar{k})$ applied to a uniform power allocation, i.e., $P_\ell \equiv P$ in Eq. (1), where the factor $\bar{k}$ sets the amount of counter SRS-tilt imposed at the transmitter side. Such a factor can be seen as the number of spans after which the channel power P is restored thanks to the selected pre-emphasis. Note that P_i coincides with the uniform power allocation when $\bar{k} = 0$.

SNR with sparse DGEs

We aim at estimating the SNR of a link having sparse DGE positioning for the SRS gain equalization on the signal power. Fig. 1 shows an example of the link under test, with a total of N spans subdivided into N_{D} sections of N_{s} spans each, with end-section DGEs. All line amplifiers have flat gain equal to the span loss and identical noise figure. In this work, contrary to[8], we model

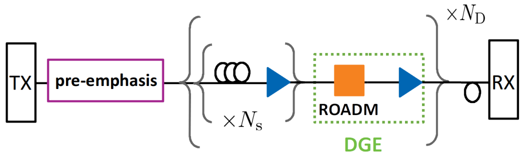

Fig. 1: Sketch of a generic link structure with N_{D} sections of N_s spans each. The DGE node is the cascade of a lossy ROADM and an amplifier.

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the DGE as a lossy filter followed by a noisy flat amplifier restoring the TX total power P_t. Such a model emulates the equalization usually performed in a reconfigurable optical add-drop multiplexer (ROADM) node by means of wavelength selective switches (WSSs).

The SNR of a generic WDM channel centered at frequency f_i can be expressed as[11]

$$\mathrm{SNR}(f_i) = \frac{P}{\sigma^2_{\mathrm{NLI}}(f_i) + \sigma^2_{\mathrm{ASE}}(f_i)}. \qquad (3)$$

where the two variances σ^2 account for NLI and amplified spontaneous emission (ASE), both impaired by SRS. Assuming identical spans and N_D link sections, the variance of the ASE noise introduced by the line amplifiers generalizes to

$$\sigma^2_{\mathrm{ASE}}(f_i) = hf_iFBN_\mathrm{D}\left(G\sum_{n=1}^{N_\mathrm{s}} H^{-1}(f_i,n) + G_\mathrm{D}\right) \qquad (4)$$

where: h is the Planck's constant, B is receiver noise equivalent bandwidth, F is the amplifier noise figure, G is the gain of each end-span amplifier, and G_D is the gain of the amplifier within the DGE node that recovers its losses. The term $H^{-1}(f_i,n)$ accounts for the SRS gain experienced by the ASE noise introduced by the nth amplifier up to the DGE output. An equivalent block diagram representation of a link section is sketched in Fig. 2. Note that the signal power is transparent over a link section.

In this framework, the NLI variance σ^2_{NLI} can be estimated by means of the DGE-SRS-EGN model[7,8]. In this work, we focus on Gaussian-distributed symbols hence we exploit the DGE-SRS-GN model closed-form expressions[8] which include the signal power pre-emphasis in Eq. (2).

As a sanity check of the SNR estimation based on the DGE-SRS-GN model, Fig. 3 shows a comparison with SSFM simulations for a 4×100 km link of single- mode fiber (SMF) with frequency-flat attenuation $\alpha = 0.2$ dB/km, dispersion $D = 17$ ps/(nm·km), dispersion slope

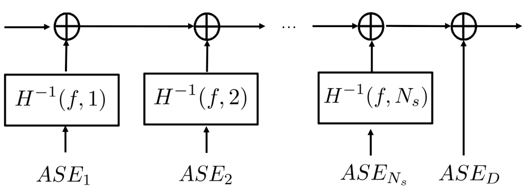

Fig. 2: Equivalent block diagram representation of a link section. ASE_n, $n = 1,\dots N_s$, is the variance of the ASE noise introduced by the nth amplifier before propagation. ASE_D is the noise variance introduced in the DGE node.

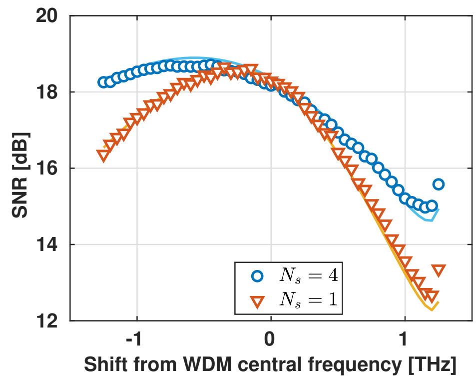

Fig. 3: SNR vs. frequency with a DGE at each span-end ($N_\mathrm{s} = 1$) and without inline DGEs ($N_\mathrm{s} = 4$). Markers: SSFM simulations. Lines: DGE-SRS-GN model.

$S = 0.057$ ps/(nm^2·km), and nonlinear coefficient $\gamma = 1.26$ 1/(W·km). We focused on a simple scenario of 51 WDM channels with Gaussian-distributed symbols, symbol rate $R = 49$ Gbaud and channel spacing $\Delta f = 50$ GHz. The pre-emphasis was applied with a factor $\bar{k} = 4$ at a total WDM power of 20 dBm. To stress the model, we artificially inflated the Raman gain slope to $C_\mathrm{r} = 5 \times 0.028$ (THz·km·W)$^{-1}$ to emphasize the SRS over the 2.5 THz bandwidth of the signal, a value for which reliable SSFM double checks were feasible. The amplifiers' noise figure was $F = 5$ dB. Each DGE node introduced both SRS-dependent losses due to the passive equalization additional 11 dB of losses due to the WSSs cascade in the ROADM node. Fig. 3 shows the RX SNR obtained with the placement of a DGE at each span-end ($N_\mathrm{s} = 1$) and without inline DGEs ($N_\mathrm{s} = 4$). For both cases, the theoretical estimation is in good agreement with the simulations.

Optimization problem

We next optimize the power allocation in terms of total WDM power P_t and pre-emphasis factor $\bar{k}$ for link topologies with different numbers of DGEs. We considered two different optimization strategies. The first strategy aims at maximizing the performance of the worst channel in the WDM comb, thus avoiding penalizing some users due to SRS-induced unbalances, namely

$$(P_\mathrm{t}, \bar{k})_{\mathrm{opt}} = \underset{P_\mathrm{t},\bar{k}}{\mathrm{argmax}}\, (\min \mathrm{SNR}(f_i)) \qquad (5)$$

where the min is taken among the WDM channels. We call it the *max-min* strategy. The second strategy aims at maximizing the link achievable information rate (AIR) when treating NLI as a Gaussian noise (no NLI suppression is considered):

$$(P_\mathrm{t},\bar{k})_\mathrm{opt} = \underset{P_\mathrm{t},\bar{k}}{\mathrm{argmax}} \left(2B \sum_{i=1}^{N_\mathrm{ch}} \log_2(1+\mathrm{SNR}(f_i)) \right). \tag{6}$$

We call this the *max-AIR* strategy. For these optimizations, the link under test was composed of 12×100 km of SMF with the same parameters used for Fig. 3, except for $C_\mathrm{r} = 0.028$ (THz·km·W)$^{-1}$. The transmitted signal was composed of 201 WDM channels carrying Gaussian-distributed symbols, with R and Δf as in Fig. 3, for a total bandwidth of 10 THz. We considered four link topologies with DGEs placed every $N_\mathrm{s} = 1, 2, 3$ or 4 spans. For each link topology, we varied the power P_t from 20 to 24 dBm, by steps of 0.5 dB, and $\bar{k}$ from 0 to 4, by steps of 0.1, and tested all the combinations of $(P_\mathrm{t}, \bar{k})$.

Results

The optimized pair of total power and pre-emphasis factor $(P_\mathrm{t}, \bar{k})_\mathrm{opt}$ values for the two strategies are reported in Fig. 4 for the different link topologies. The figure shows that each DGE placement along the link calls for a different power allocation. In particular, note that the max-AIR strategy accepts $0.5-1$ dB more power.

The SNR at the optimal power allocation is reported in Fig. 5, versus the frequency shift with respect to the central WDM frequency. Such an SNR is almost frequency-flat for the max-min strategy (solid lines), hence yielding similar performance for all channels. On the other hand, the SNR curves maximizing the total capacity exhibit up 2 dB of tilt across the bandwidth for $N_\mathrm{s} = 1$.

The estimated total AIR and minimum SNR in the WDM comb are represented in Fig. 6 for max-AIR (top) and for max-min (bottom). The figure shows that, in both cases, the best link topology

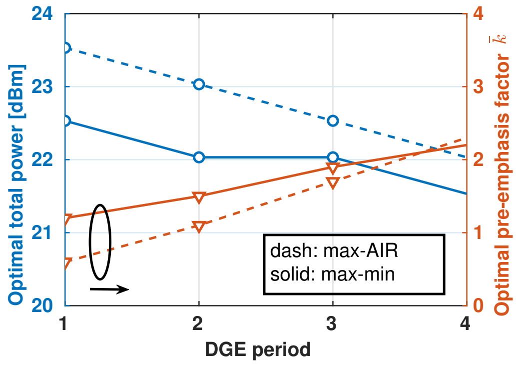

Fig. 4: Optimal total power (left axis) and optimal pre-emphasis factor (right axis) vs. the DGE period N_s, i.e., number of spans between two equalizers, for the two strategies.

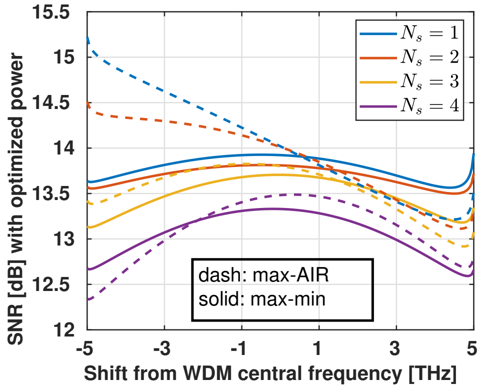

Fig. 5: SNR with optimized powers for the two strategies vs. frequency, for a DGE period of $N_\mathrm{s} = 1, 2, 3, 4$ spans. $N = 12$ spans. Dashed: max-AIR strategy. Solid: max-min strategy.

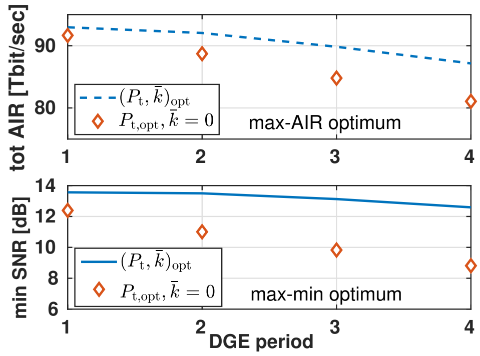

Fig. 6: Optimal values of total AIR (top) and minimum SNR in the WDM comb (bottom) vs. the DGE period N_s. Lines: with pre-emphasis. Makers: without pre-emphasis ($\bar{k} = 0$).

is the one having a DGE at each span-end. Nevertheless, for the max-min strategy, we note that less than 1 dB of penalty is introduced by the cost-saving topology $N_\mathrm{s} = 4$. For the max-AIR case, such a DGE placement implies a 10% capacity reduction, although with a smaller SNR tilt as shown in Fig. 5. Figure 6 also reports the optimization results obtained without pre-emphasis $(\bar{k} = 0)$. We note that the benefit of the $\bar{k}$-optimized pre-emphasis increases for the increasing distance between neighboring DGEs.

Conclusions

We leveraged the simplicity of the DGE-SRS-GN closed-form expressions for a fast signal power pre-emphasis optimization, in the form of an opposite SRS-tilt, to maximize either (i) the SNR of the worst performing channel or (ii) the total capacity. We showed that the link design maximizing the total capacity yields non-equal channel performance. Such an unbalance can be mitigated by reducing the number of inline DGEs at the expense of a 10% capacity reduction.

Acknowledgments

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