Optimization of channel powers, Raman pumps and EDFAs in the wideband fiber optic transmission systems

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Abstract: A hybrid Raman/EDFA link design optimization method to maximize fiber capacity is proposed. The optimization method accounts for the interplay of signal power tilts due to channels ISRS, pump ISRS, and EDFA physics.

1. Introduction

Considerable work has been done in high-capacity broadband transmission systems. Signal channel powers optimization including Inter-channel stimulated Raman Scattering Gaussian Noise model (ISRS-GN) of nonlinear propagation [1, 2] was performed assuming generic lumped amplification where noise figure vs wavelength profile is predefined, and any gain profile can be achieved. Optimization of Raman pump powers and pump wavelengths for distributed backward-Raman amplification was also done in [3, 4] without consideration of erbium-doped fiber amplifiers (EDFAs) physical modeling and without individual channels power optimization. An experimental setup with wideband hybrid-amplified system [5] with varying channel power, distributed backward Raman amplification and band-split lumped amplification has also recently been demonstrated. In this paper for the first time to our knowledge we perform wide-band fiber-optic transmission systems modeling, where EDFA configuration, individual channel powers and distributed backward-Raman amplifier pump powers and wavelengths are optimized together targeting total link capacity maximization. We describe the developed modeling and optimization method in detail, which could be applied to any type of the lumped amplifier design, including single doped fiber coil or several sequential coils, with multiple sequential and/or parallel stages [6]. We illustrate how the proposed method allows capturing gain capabilities of the EDFA, together with optimization of Raman pumps wavelengths and power to provide more gain in the channels where EDFA gain is smaller. Channel launch powers results are larger for the channels where Raman gain is smaller and vice versa, sustaining nonlinear-optimum power operation regime of all channels. We find that with the introduction of Raman amplification for 100 km spans over 3000 km distance, average generalized signal to noise ratio (GSNR) can be improved by 7-8 dB relative to EDFA-only amplification and total capacity can be improved by 50%. Moreover, we find that those numbers are similar for all studied signal band configurations including C-band and C+L band, suggesting the impact of ISRS is fully compensated by the optimization and does not need to be considered as an impairment.

2. Link model and optimization procedure

As a basis we used a closed-form ISRS-GN model of nonlinear fiber propagation [1]. The power evolutions of signal channels and Raman pumps along the span distance are calculated by numerical solution of Raman differential equations [4]. The solution of pump powers evolution is applied for finding Raman pumps-induced amplified spontaneous emission (ASE) noise generated within the span [7]. For each computed power evolution, we perform regression-fitting of the ISRS-GN model parameters using one of the two ISRS-GN model variants [1,4], depending on the amount of Raman gain. For EDFA modeling, we employed a variant of a steady-state physical EDFA model [8], with standard configuration and 3.6 dB losses, allowing to accurately capture subtleties of EDFA gain for different input channel occupation scenarios. The physical EDFA model allows the optimized configuration to not only maximize total capacity but also be power-efficient, by providing more of the Raman gain in the channels where EDFA gain is insufficient. The amplifier noise figure (NF) dependence against signal power distribution entering the amplifier for a given channel wavelength allocation is also partly captured by the employed model using a small signal gain approximation, and NF remains small on the order of 4.1 dB. After each span we assumed perfect recovery of the channels' launch powers by use of a variable optical attenuator (VOA) and gain equalizing filter (GFF). In this case, all channel powers out of the hybrid amplifier were required to be equal or larger than the channel launch powers. It would be computationally demanding to optimize Raman pumps and the channel launch powers within a single optimization process because both sets of parameters can have many possible combinations of values and too many system evaluations are required. However, it is possible to split the two optimizations as shown in Fig. 1. Channel powers optimization is done separately from the amplifier configuration optimization and both steps target total fiber capacity maximization. At the channel powers optimization step Raman pump powers and pump wavelengths are fixed, and the EDFA is modeled by specifying a fixed NF vs wavelength profile. At the hybrid amplifier optimization step the channel launch power wavelength profile is fixed and EDFA parameters are refined for each Raman pumps configuration such that residual channel losses are compensated.

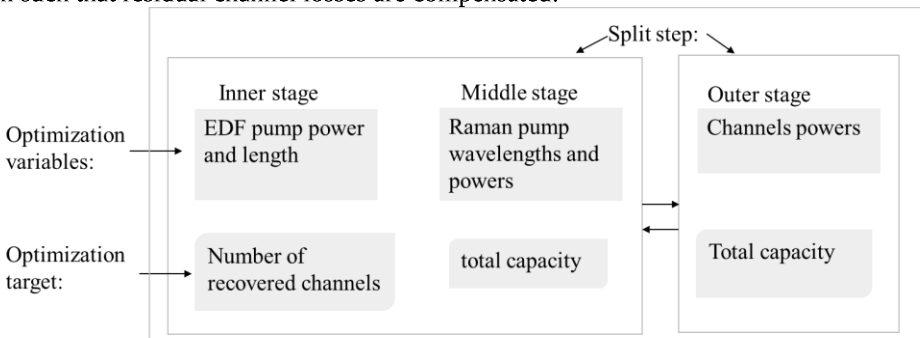
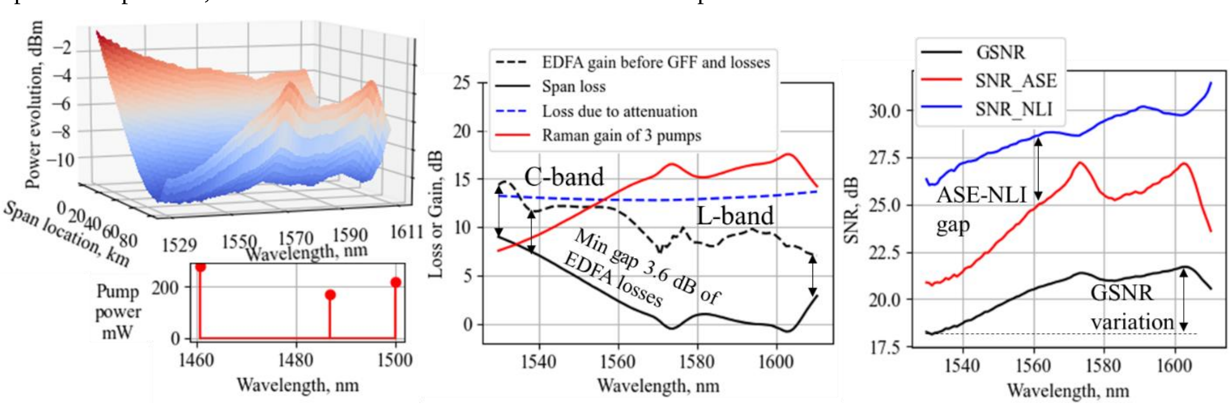


Fig. 1. High-level illustration of the proposed link optimization approach

Optimization methods of each stage can generally be chosen arbitrarily, but in this work, we used the following approaches. For channel launch power optimization, we considered an iterative gradient-descent optimization approach. For Raman pumps optimization, the particle-swarm algorithm is applied. The wavelength limit for pump wavelengths optimization is specified as 100 nm below the edges of signal-occupied bandwidth. For EDFA optimization two stages are considered: the outer stage is 980 nm pump power optimization which targets power efficiency, and the inner stage is the EDF coil length optimization within 1 meter to 150 meters bounds, targeting maximization of the number of recovered channels. Separate EDFAs are employed in parallel for channels below and above 1570 nm for C+L band systems. The transmission system under investigation consists of 100 x 96 GBaud Gaussian-modulated channels with 100 GHz spacing, transmitted over 3000 km link composed of 100 km spans of single-mode fiber, with attenuation of 0.158 dB/km and effective area 80 μm^2. Fig. 2a shows the power evolution and corresponding optimized pump powers where the Raman pump wavelengths and pump power were limited to 3 pumps and 300mW per pump. It can be noticed that total power along propagation distance tends to be such that channels experiencing larger Raman gain will have smaller launch power and vice versa, keeping power at the nonlinear optimum level. Fig. 2b illustrates the span loss and gain profiles for a C+L band system. The black solid line shows the difference between launch power and power entering EDFA, representing the residual loss to be compensated by EDFA. EDFA gain given by the dashed black line is the gain out of EDF before GFF and VOAs. This gain must be at least 3.6 dB larger than the residual span loss, to account for excess losses of the amplifier. It can be observed that the proposed optimization method finds the Raman gain solution which considers the interplay of tilts due to channels ISRS, pumps ISRS and EDFA tilt, ensuring a minimum gap of 3.6 dB between residual span loss and EDFA gain. Final Fig. 2c shows the received SNR curves, for the nonlinear interference noise (SNR_NLI), the amplified spontaneous emission noise generated by the hybrid Raman/EDFA amplifiers (SNR_ASE), and GSNR, estimated by the sum of SNR-NLI and SNR_ASE. It can be noticed the channel power optimization results in the nonlinear operation optimum, where ASE and NLI noises tend to be 3 dB apart.



a). b). c).

Fig. 2. Signal power evolution and optimized Raman pumps (a). Resulting losses and gains (b) and received SNR (c)

3. Evaluation of different system configurations

In this section we present modeling results of the same kind of system considered in the previous section, but extending it to different channel bands, Raman pump power limitations and number of Raman pumps. This allows to evaluate the efficiency of the proposed optimization method in terms of the final GSNR variation in different scenarios and to find out how far the GSNR and capacity could be improved over the EDFA-only amplification by the introduction of the distributed backward-Raman amplification. We considered a single-stage erbium doped fiber for single-band and two parallel EDFAs for split C+L-band amplification. Fig. 3a illustrates the GSNRs statistics of the 7 evaluated scenarios of the channel bands (C-band only, L-band only, and C+L combined) and numbers of Raman pumps (EDFA-only, 3 pumps and 6 pumps) with an imposed 300 mW upper limit for each Raman pump power. It can be observed that the optimization approach generally results in small variation of GSNR within 2-3 dB, suggesting good performance of the proposed method. Achieved GSNRs for links with hybrid amplification are roughly 7-8 dB higher compared to EDFA-only. It can also be noticed that EDFA-only statistics are almost identical for all band configurations with average GSNR on the order of 14 dB, suggesting the impact of ISRS is compensated, and ISRS should not necessarily be considered as an impairment.

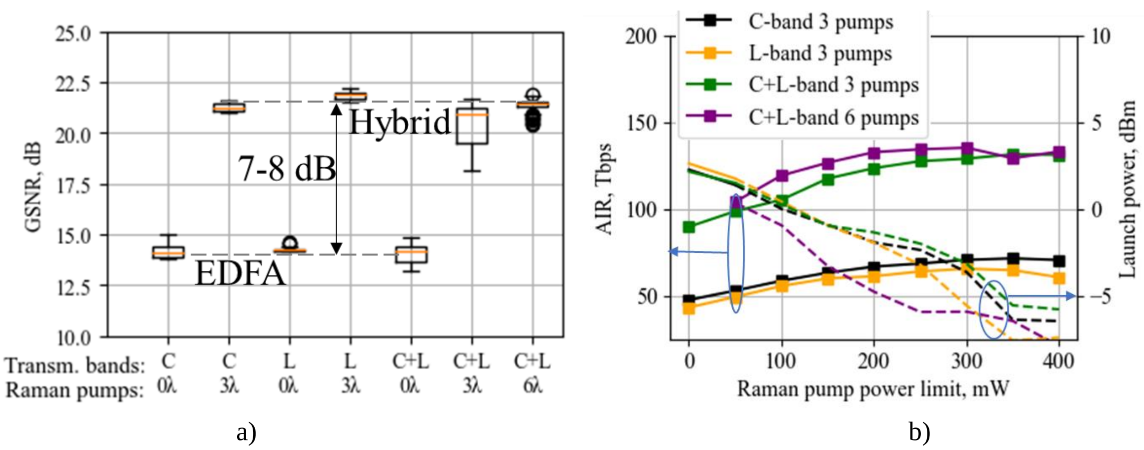


Fig. 3. a). GSNR statistics of the evaluated scenarios, with 300 mW Raman pump power limit of each pump. b). Dependence of achievable information rate (AIR) over the link vs Raman per-pump upper power limit.

Fig. 3b illustrates the achievable information rate as a function of Raman pump power. The AIR generally increases as the Raman pump power limit is increased. However, there is a limit after which AIR saturates as observed with 6-pumps C+L band, corresponding to a minimum overall noise that can be achieved in the studied system, as a tradeoff between EDFA-induced ASE, Raman-induced ASE and Raman-induced NLI. Pump power limits above 250 mW among studied cases generally result in large compensation of excessive Raman gain by GFF.

Conclusions

This work describes a link design optimization method to maximize total link capacity. The proposed method splits the channel powers optimization step from a hybrid amplifier configuration optimization step. The Raman pump powers and wavelengths and subsequently EDFA fibers coil length and pump power are determined iteratively for a fixed channel power distribution and vice versa. The analysis show as the Raman pump power limit is increased, the channel powers decrease to keep power along the span at the nonlinear optimum level. EDFA pump power is displaced by Raman pump powers and tilted optimal channel powers compensate for increasing impact of ISRS. EDFA and Raman gains have additional counteracting tilts. GSNR increases and ASE and NLI noises tend to be 3 dB apart from each other. The results suggest that optimization of channel powers allows avoiding ISRS-induced impairments over the C and L bands.

3. References

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