Modeling of Fiber Nonlinearity in Wideband Transmission

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Abstract: The ISRS GN model is reviewed which models nonlinear transmission performance including inter-channel stimulated Raman scattering. Utilizing the model, a convex launch power optimization approach is proposed and applied to a transatlantic S+C+L band system.

1. Introduction

The delayed nonlinear fiber response, also known as the Raman response, is crucial for the modeling of wideband transmission systems that operate beyond the C-band. The Fourier transform of the Raman response is the complex valued Raman spectrum. It's imaginary part leads to inter-channel stimulated Raman scattering (ISRS) and has been included in analytical models in integral [1–3] and closed-form [4, 5], including the modulation format dependence [6, 7] and considering non-ideal equalization across the link [8]. Recently, the real part of the Raman spectrum was included in analytical modeling derived from the generalized Manakov equation that models the complete Raman response [9]. However despite these recent advances, large scale optimizations such as launch power optimization can still be computationally expensive as the problem is known to be non-convex [2]. This is especially true when relying on models in integral form that need to be solved numerically.

In this paper, the ISRS GN model in closed-form is reviewed for bandwidths beyond 15 THz where the triangular Raman gain assumption is no longer valid. This assumption can be lifted by power profile matching, enabling efficient modeling of S+C+L band systems and beyond. Additionally, a convex approximation of the non-convex launch power optimization problem is proposed. The approach is applied to a transatlantic transmission system and compared to a particle swarm algorithm.

2. The Gaussian Noise (GN) Model in the Presence of Inter-Channel Stimulated Raman Scattering

The signal-to-noise ratio (SNR) is given by $\text{SNR}^{-1} = \text{SNR}_{\text{ASE}}^{-1} + \text{SNR}_{\text{NLI}}^{-1}$, where $\text{SNR}_{\text{ASE}}^{-1}$ is the SNR due to optical amplifiers and $\text{SNR}_{\text{NLI}}^{-1}$ is the SNR due to nonlinear interference (NLI). Noise contributions from the used transceiver are ignored in this work. The ISRS GN model models the nonlinear interference including the complex valued Raman spectrum which is crucial for wideband transmission. The imaginary Raman spectrum (the Raman *gain* spectrum) leads to ISRS, a process which transfers power from high to lower frequencies during propagation. The real Raman spectrum scales the strength of far-spaced (in frequency) NLI contributions, decreasing with frequency separation [9]. This scaling is not related to dispersion. The ISRS GN model in closed-form [4, 10] was derived from its integral form [1] for very fast, but yet accurate, performance estimations. It is written as $\text{SNR}_{\text{NLI}}^{-1}(f_i)\,P_i^{-2} = R_{\text{SPM}}\eta_{\text{SPM}}(f_i) + \sum_{k=1,k\neq i}^{N_{\text{ch}}} R_{\text{XPM}}(\Delta f)\,\eta_{\text{XPM}}^{(k)}(f_i)$ for channel i, with channel frequency f_i, total WDM channels N_{ch}, launch power P_i, and frequency separation Δf between channel i and interfering channel k. η_{SPM} is the SPM contribution of channel i and η_{XPM} is the XPM contribution of channel k on channel i which are both given in closed-form [4]. The XPM contribution includes modulation format dependent correction terms in closed-form [6]. R_{SPM} and R_{XPM} account for the real Raman spectrum and are obtained from [9]. The ISRS GN model in closed-form models ISRS via a first-order approximation of the actual *normalized* signal power profile $\rho(f,z)$ as $P^{(1)}(z) = \left(1+\tilde{T}_i\right)e^{-\alpha_i z} - \tilde{T}_i e^{-(\alpha_i+\bar{\alpha}_i)z}$ with $\tilde{T}_i = -\frac{P_{\text{tot}}C_{r,i}}{\bar{\alpha}_i} f_i$. This approximation is derived from the triangular Raman gain spectrum. Although named triangular, the approximation uses a linear Raman spectrum which is no longer valid beyond 15 THz. However, this limitation can be lifted by fitting the channel dependent α_i, $\bar{\alpha}_i$ and $C_{r,i}$ of $P^{(1)}(z)$ to the actual power profile $\rho(f,z)$ obtained by the ISRS equations [10]. The wavelength dependent fiber attenuation can be included, too. Subsequently, those parameters are used in the ISRS GN model. SNR estimation of an entire S+C+L band system (solving the ISRS equations, parameter fitting and ISRS GN model evaluation) can be executed in a few hundred milliseconds, suitable for optimization algorithms (the ISRS equation solver was improved since [10]). The approach was validated by split-step simulations in [10].

Fig. 1)a) shows the actual power profile, obtained from the ISRS equations, and its first-order fit. The results assume a launch power of 25.4 dB uniformly distributed and a 60 km span with attenuation profile (min. 0.16

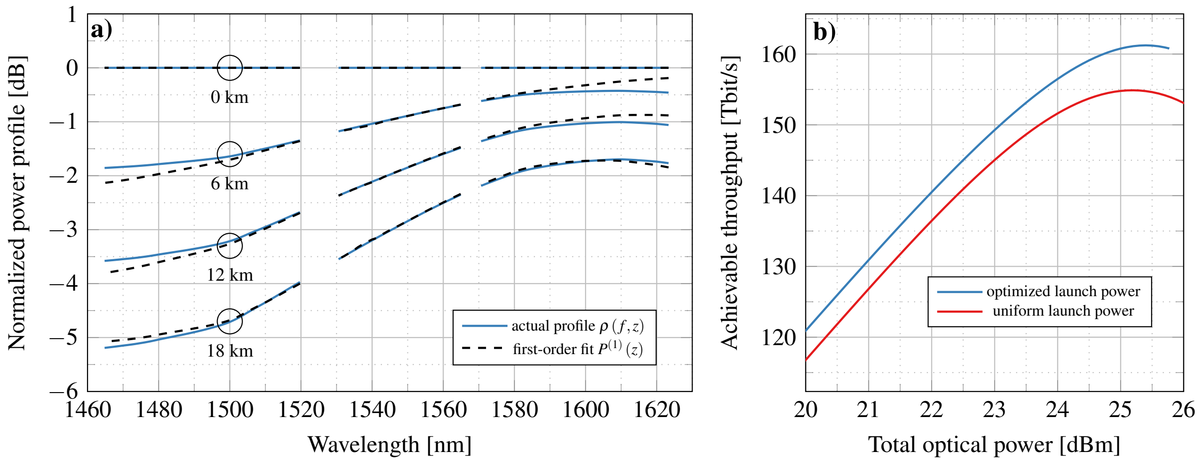

Fig. 1. The actual normalized power profile and its first-order fit for 25.4 dBm launch power are shown in a). The achievable throughput of the system under test using optimized and uniform launch powers is shown in b).

dB/km) and the Raman spectrum of a Corning© SMF-28© ULL fiber taken from [10]. The effective core area was 150 μm^2, similar to the MAREA subsea link [11]. The first-order fit is in good agreement with the actual power profile. The small errors of max. 0.2 dB are negligible in terms of the total NLI and SNR.

3. A Convex Launch Power Optimization Approach in Presence of ISRS

Maximizing the total throughput through launch power optimization without considering ISRS is convex in log-space ($x_i = \log(P_i)$ with inverse operation in SNR computations) but non-convex when including ISRS [2]. Non-convexity means that finding the global optimum is non-trivial and computationally expensive algorithms must be used that may converge to local optima. A convex approximation would enable the use of efficient solvers and guarantee global convergence. The proposed approach is based on iteratively solving a series of convex sub-problems. Launch power optimization is convex in x_i when the ISRS terms are frozen. To freeze the ISRS terms during a sub-optimization step, a convex constraint is introduced that limits the total launch power during a sub-optimization step. The constraint is $\log\left(\sum_{\forall i} e^{x_i}\right) \leq \log\left(P_{\text{tot,m}}\right)$ which is convex in x_i as a sum of exponentials is log-convex. The approach consists of iteratively increasing the total permitted power $P_{\text{tot,m}}$. In each convex sub-optimization step m, the total launch power is limited to $P_{\text{tot,m}} = \Delta_P \cdot P_{\text{tot,m-1}}$, the initial value is the optimum launch power distribution of step $m-1$ and all ISRS terms are frozen and calculated based on $\Delta_P \cdot x_{i,\text{opt.}}$ with $x_{i,\text{opt.}}$ of iteration $m-1$. In this work, a step size of $\Delta_P = 0.1$ dB is used. Due to the power limitation of each iteration, the total launch power *equals* the total permitted power $P_{\text{tot,m}}$ until the optimum total launch power is reached. The algorithm approaches the global optimum because ISRS only depends on the total launch power and its distribution. The approach ensures that ISRS is calculated a priori based on the total power that is actually being allocated within each step. Therefore, it is valid to freeze the ISRS terms within a sub-problem. The approximation of the approach only concerns the relative power distribution. However, the power distribution does not change significantly across iteration steps when the step size Δ_P is small. Even though the approach consists of solving mutliple sub-optimization problems, the global optimum can be reached within minutes due to the efficiency of convex optimization solvers and the ISRS GN model in closed-form.

The proposed launch power optimization approach was applied to a transatlantic S+C+L transmission systems with parameters comparable (not equal) to the MAREA link [11]. A 182×100 GBd signal was considered over a distance of 6600 km (110×60 km). A shaped modulation format with an excess kurtosis of -0.2 dB and spectral gaps of 10 nm and 5 nm between the respective transmission bands were considered. The wavelength dependent attenuation and the Raman spectrum of a Corning® SMF-28® ULL fiber was taken from [10]. A large effective corea area of 150 μm^2 was assumed similar to MAREA resulting in a dispersion parameter $D = 21\frac{\text{ps}}{\text{nm}\cdot\text{km}}$, $S = 0.067\frac{\text{ps}}{\text{nm}^2\cdot\text{km}}$ and $\gamma = 0.55\frac{1}{\text{W}\cdot\text{km}}$. The noise figures were 7 dB, 4 dB, and 6 dB in the S, C and L-band, respectively.

Fig. 2) shows the optimum launch power and the corresponding SNR for a variety of total launch powers to illustrate the proposed algorithm. At a total power of 21.4 dBm, the algorithm allocates an almost uniform launch power. The small variation is due to noise figure differences, the attenuation profile and weak ISRS influencing the linear noise performance. With increased power, the ISRS power transfer becomes stronger resulting in a stronger optimum power tilt. Additionally, the NLI increases leading to performance penalties and the characterstic SNR improvements at the edge of each transmission band. The global optimum launch power was reached at

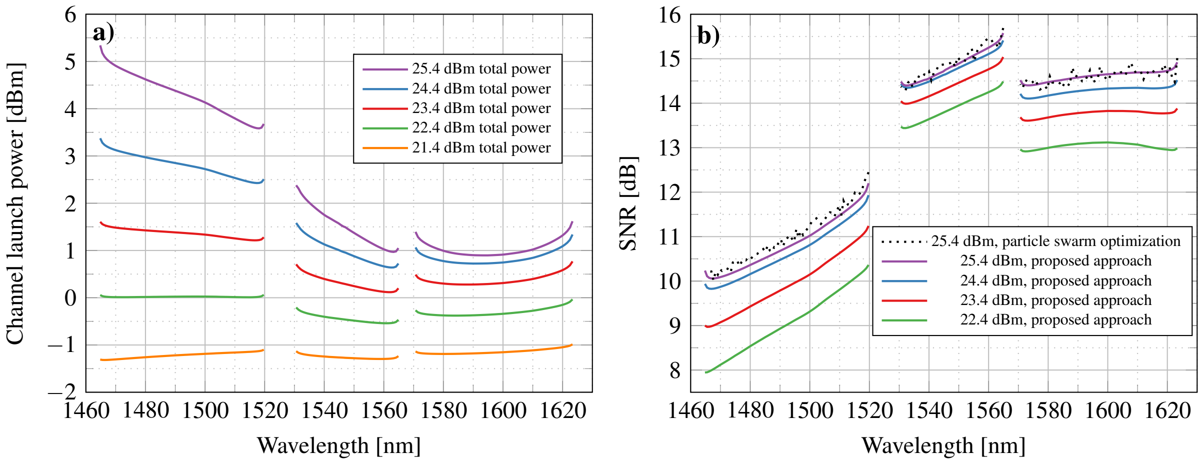

Fig. 2. The optimized power distributions for a given total launch power are shown in a) with their corresponding SNR shown in b). The optimum SNR obtained by particle swarm optimization is shown for comparison.

25.4 dBm total power with an achievable throughput of 161.23 Tbit/s using Shannon's capacity formula. Fig. 1)b) shows the achievable throughput as a function of the total launch power for optimized and uniform launch power distributions. The optimum SNR obtained from a particle swarm optimization algorithm (PSO) is shown in Fig. 2)b). PSO is suitable for non-convex optimization problems but computationally expensive. The PSO algorithm ran for 24 hours using a single core of a standard desktop computer and returned a similar launch power and SNR distribution as the proposed convex approach. This not only validates the proposed algorithm but also illustrates its advantages. The proposed approach only took around 15 minutes to execute on the same machine and returns cleaner, fully converged distributions due to its convex formulation.

4. Conclusion

The ISRS GN model in closed-form was reviewed in the context of wavelength dependent attenuation and optical bandwidths beyond 15 THz, where the triangular Raman gain approximation is no longer valid. Additionally, a new convex launch power optimization approach was proposed for wideband transmission systems yielding fast and robust optimization results when combined with the speed advantages of the closed-form model. Applied to a transatlantic S+C+L band system, comparable to the MAREA link, the approach was found to significantly outperform particle swarm optimization.

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