Complexity Versus Accuracy Tradeoffs in Nonlinear Fiber Propagation Models

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Abstract: Some of the most widespread analytical models for nonlinear propagation in fiber optic coherent systems are reviewed, highlighting the tradeoffs between accuracy and complexity in different transmission scenarios, including wide-band optical systems and short-reach links.

1. Introduction

The nonlinear interference (NLI) noise generated by the nonlinear interaction between different WDM channels is a major limiting factor to the capacity of long-haul coherent optical systems. As transmission power is increased, the nonlinear Kerr effect degrades the system performance, preventing operation at the transmission rates that would be achieved in a linear system [1]. This performance limitation motivated the development of several nonlinear compensation techniques, as well as of analytical models for signal propagation in an optical fiber. These models, which have become widespread in recent years, are useful tools for system designers in predicting the behaviour of optical networks without the need of resorting to time-consuming numerical Split-Step Fourier (SSF) simulations. In the following, the most used analytical models of nonlinear propagation in uncompensated coherent optical transmission systems are briefly reviewed, highlighting some of the main trade-offs between accuracy and complexity in different transmission scenarios, including wide-band optical systems and short reach links.

2. The GN models and their assumptions

Most of the models that predict the performance degradation in optical fiber communications due to Kerr nonlinearity solve the nonlinear Schrödinger equation (NLSE) analytically using a first-order perturbation approach [2]. Among them, those based on the 'GN-model' approach [1] have become quite popular, thanks to a good balance between accuracy, complexity and ease of use. Their simplicity, with respect to other models, derives from the assumption that, in highly dispersive channels such as uncompensated long-haul coherent systems, each WDM signal can be treated as Gaussian noise.

A detailed investigation of GN-model errors and limitations was proposed and extensively discussed in [1]. Overall, the GN-model accuracy for uncompensated systems appears to be rather satisfactory and typically adequate for dealing with many practical scenarios. The simplest close-form expressions of the power spectral density (PSD) of the NLI can be obtained assuming an incoherent combination of the NLI components generated in each span during propagation, i.e., under the assumption that that NLI adds up in power at the end of the link. Assuming the propagation of equal channels with approximately rectangular spectra over equal fiber spans with lumped amplification, the PSD of the NLI at the center frequency can be evaluated as [1]:

$$G_{\mathrm{NLI}}\left(f_c\right) = N_{span}\,\frac{16}{27}\,\frac{\gamma^2 L_{\mathrm{eff}}^2 P_{\mathrm{ch}}^3}{\pi\left|\beta_2\right|\alpha R_s^3}\,\mathrm{asinh}\left(\frac{\pi^2}{2\alpha}\left|\beta_2\right| R_s^2\left[N_{\mathrm{ch}}^2\right]^{\frac{R_s}{\Delta f}}\right)$$

where N_s is the number of spans, γ is the fiber nonlinearity coefficient, N_{ch} is the number of WDM channels, R_s is the symbol rate, Δf is the channel frequency spacing, α is the fiber loss coefficient and β_2 is fiber dispersion. L_{eff} is the effective length, defined as: $L_{eff} = [1-\exp(-2\alpha L_s)]/(2\alpha)$, with L_s the span length. The accuracy of this incoherent GN model (IGN-model) in predicting system performance appears to be quite good for practical system configurations. Several applications of the GN-model heavily exploit its closed-form approximate solutions, among which link throughput analysis and optimization [3], derivation of approximate 'design rules' which provide a simple variational dependence of performance on system parameters [4], identification of the potential and limitations of non-linearity DSP-supported mitigation [5] and, derivation of an overall optimization and control strategy for new-generation optically routed network [6]. The breadth of these applications clearly demonstrates the extent of the impact of the availability of a simple and effective model of non-linear propagation.

However, it has been shown that the signal-Gaussianity approximation used in the GN-model derivation can be inaccurate, especially in the initial part of a multi-span link [7]. In fact, the dispersed signal is only first-order

Gaussian, whereas multiple samples of the signal do not have a jointly Gaussian distribution [8]. The fact that the GN model neglects this aspect leads to several limitations, among which the inability to resolve the format-dependent NLI generation. Removing the Gaussian assumption thus requires taking into account not only the 2nd moment of the launched signal, but also higher order moments. In this way, the models of nonlinear propagation become more complex in terms of computational effort, but the accuracy is increased. In particular, a detailed modelling of all the NLI components is obtained, including short-correlated quasi-circular noise and long-correlated nonlinear phase noise (NLPN) and polarization noise [7,8]. The enhanced-GN model (or EGN model [7]) is a complete and accurate model in the frequency domain, but computationally very complex and thus not adequate for real-time applications, where closed-form formulas are typically employed [6,9] at the expenses of a reduction of the estimation accuracy.

3. Application scenarios

3.1 High-symbol rate transmission with shaped constellations

Lately, strong industry innovative trends have developed towards a quick-paced uptake of Gaussian-shaped constellations and a swift increase in symbol rates, with rates up to 128 Gbaud and beyond foreseen in the short-medium term. The EGN model appears to be extremely reliable, across all the explored parameter space, as shown in [10, 11]. It handles all formats, QAM and Gaussian constellations, spacing values and symbol rates from 8 to 512 Gbaud, within a very small error bracket vs. simulations. Interestingly for real-time applications, simpler models of the GN type appear to increase substantially their accuracy as the symbol rate goes up. The effect is more evident at longer reaches, where accumulated dispersion is larger, and the signal is more spread-out. Moreover, for Gaussian-shaped constellations, the EGN model remarkably coincides with the much computationally simpler GN model [11].

3.2 Wide-band optical systems

Models based on the conventional nonlinear Schrödinger equation, which assumes an instantaneous nonlinear response, cannot be applied to transmission bandwidths beyond the C-band, where the delayed part of the nonlinear response (due to the Raman effect) becomes significant and cannot be neglected [12]. The conventional GN-model has been thus recently extended to account for inter-channel stimulated Raman scattering (ISRS) by either introducing effective attenuation coefficients [13,14] or by deriving a GN model subject to a generic signal power profile [14–17]. The 'ISRS GN models' enable an accurate modeling of nonlinear propagation in wideband optical systems that occupy the entire C+L band or beyond. In order to reduce the computational complexity of these models and make them real-time, Closed-Form Model (CFM) approximations have been proposed [18–21] capable of assessing whole links in fractions of a second. The CFMs were originally derived from a closed-form incoherent GN model approximation proposed in [1], which was then extended to take into account the frequency-dependence of both loss and dispersion, and the impact of ISRS [21–23]. Furthermore, the link function of the ISRS GN model can be combined with the formalism derived in [7], to account for arbitrary (non-Gaussian) modulation formats [24–26]. The CFMs were also augmented with various correction terms to improve their accuracy and bring them to EGN-model level [21,24,27], also using machine-learning techniques [21,23,28]. Recently, two examples of application of ISRS GN-model closed-form formulas to the maximization of the information throughput [29] and to the quality of transmission (QoT) estimation [30] have been reported.

3.3 Short-reach optical systems

Most closed-form equations derived for the GN-model do not account for short span lengths and extremely low-losses, due to the approximations made to derive them, which are based on the assumption that $e^{-2\alpha L_s} \ll 1$. The closed-form formulas proposed in [31,32] remove this assumption and are thus able to account for extremely low span losses, as well. In [33], a closed-form expression capable of accurately estimating the NLI in the presence of ISRS for any fiber span length and for fibers with extremely low-losses (~ 0.02 dB/km) is derived. The proposed closed-form expression accounts for all modulation formats, wavelength-dependent attenuation and dispersion. When compared to the ISRS GN model in its integral form, the estimation error of the non-linear SNR is always lower than 1 dB, even for very short span lengths and extremely low values of fiber loss.

5. Conclusions

The field of the investigation of NLI modeling has been extremely active over the last decade. The obtained results and developed practical tools have been extensively used by the community, both in transmission and in optical networking sectors. Several close-form analytical and semi-analytical formulas are currently available for different application scenarios, often offering a favorable accuracy versus relative simplicity trade-off.

6. References

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