Quality of Transmission Estimation for Planning of Disaggregated Optical Networks

Andrea D'Amico[(1)], Elliot London[(1)], Emanuele Virgillito[(1)], Antonio Napoli[(2)], Vittorio Curri[(1)]
[(1)]DET, Politecnico di Torino, Italy; [(2)]Infinera, Sankt-Martin-Str. 76, 81541 Munich, Germany
Email: andrea.damico@polito.it

***Abstract*—Modern optical networks depend upon advanced software-defined networking (SDN) technologies, which in turn rely on a network abstraction to infer the quality of transmission (QoT). In general, the QoT estimation is based upon the generalized signal-to-noise ratio (GSNR), which takes into account the ASE noise, cross-phase modulation (XPM) and self-phase modulation (SPM) components of the nonlinear interference (NLI). Uniquely, the SPM accumulates coherently, causing the total amount of SNR degradation to depend upon the physical lightpath (LP) history, preventing a fully disaggregated GSNR degradation evaluation. As the current signal symbol rate are increasing, the SPM will provide a progressively more significant contribution to the SNR degradation. We propose a method to evaluate the equivalent SPM component of the NLI that is generated in each fiber span within an optical line system (OLS), independent of the history or configuration of the optical network.**

I. Introduction

Initially, optical networks were designed to have a static implementation – features such as path and channel allocations were established when the network was created and rarely changed. As the rate of traffic has increased, operators have sought a higher degree of flexibility within these networks and have striven towards a more efficient usage of capacity [1]. The first step in pursuit of these ideals has been to introduce wavelength selective switches (WSSs) and bandwidth variable transponders (BVTs) [2]; these devices have enabled optical networks to be flexible, where, according to the path characteristics, rudimentary software-defined networking (SDN) technology could be used to select the most suitable modulation format for a given lightpath (LP). Subsequently, cloud operator requests have required a shift from single-vendor optical systems: first to multi-vendor and then to fully disaggregated networks. In this context, the role of SDN has become far more relevant; a fundamental requirement is to be able to dynamically estimate the quality of transmission (QoT) of each LP in real-time, with a high degree of accuracy. Although these requirements can be carried out in real-time by both numerical simulations and analytical calculations, these approaches do not enable an estimation of the QoT independently from the history of the channel under test, preventing a fully disaggregated optical network model. The present trend for operators and vendors is towards toward high symbol rates, which have been shown to enable single-wavelength transmission up to 600 gigabits per second [3]. In this context self-phase modulation (SPM) becomes particularly important; although the magnitude of this effect is currently limited with respect to the total transmission degradation, it will become more significant as the symbol rate increases, such as in the aforementioned case of high symbol rate transmission.

In this work, we propose a model for the total amount of SPM accumulation, independent of the LP history, by considering an asymptotic approximation of the SPM for a maximal number of identical spans within an optical line system (OLS). This model is sufficiently accurate, conservative and shown to properly scale with the system parameters for a variety of both realistic and extreme simulated fiber configurations and symbol rate scenarios. For validation, this model is compared to accurate split-step Fourier method (SSFM) simulations. This model enables a local equivalent abstraction of the total SPM generated through a LP, hence permitting a fully disaggregated SDN technology to be implemented.

II. Optical Network Abstraction and Disaggregation

Following the present and future needs of network operators, optical networks are required to progress towards full disaggregation. Disaggregated networks have subsystems that are managed independently to one another, relying on common data structures, application program interfaces and multi-vendor components. These characteristics require OLSs from disparate vendors to operate within a single infrastructure to ensure that physical LPs can be transported using multi-vendor transponders. At the most fundamental level this requires a physical layer abstraction for planning purposes, which in turn requires an estimation of the QoT along the LPs. A common parameter used to predict the QoT in state-of-the-art networks that deploy coherent optical technologies is the generalized signal-to-noise ratio (GSNR) [4]. By utilizing the GSNR, an optical network may be abstracted as a graph; the OLSs and re-configurable optical add-drop multiplexers (ROADMs) represent its edges and nodes, respectively [5], while the GSNR degradations due to LP propagation on OLSs is the metric used to evaluate the LP feasibility. Considering a cascade of N optical domains from $i = 1, ..., N$, the total GSNR is given by

$$\mathrm{GSNR}^{-1} = \sum_{i=1}^{N} \mathrm{GSNR}_i^{-1} \,, \tag{1}$$

where GSNR_i is the GSNR of each optical domain, taking into account both the power of the amplified spontaneous

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emission (ASE) and the NLI. For planning and controlling networks the physical layer abstraction must be local: all network elements responsible for disturbance generation must be considered independently to enable a fully disaggregated approach [6], as illustrated in Fig. 1. First, the GSNR can be separated into two contributions: the ASE noise generated by the amplifiers and the NLI generated by the fiber spans. ASE noise is a local effect as it depends on the characteristics of the deployed amplifiers. NLI can be separated into the independent contributions of cross-phase-modulation (XPM) and SPM [7]–[9], as shown in Eq. 1, with each accumulating differently in an OLS. XPM is well approximated as a statistical effect that is both incoherent and local for all realistic use cases [9], [10], whereas SPM generation within a fiber span is a stochastic process that is statistically correlated to the SPM generated in previously crossed fiber spans on the LP route under test [10], [11]. The generation of SPM can thus be described as a non-local, coherent effect – in this scenario it remains the only obstacle to achieving a fully local physical layer abstraction.

III. SPM Accumulation Coefficient

The non-local, coherent behavior of the SPM accumulation over the LP under test is due to the intrinsic nature of the SPM; this quantity is generated by the NLI of the channel upon itself, meaning that the SPM contributions at different spans are statistically correlated and cannot be considered independently. The result is that the SPM generated at a given fiber span has a non-negligible contribution to the total SPM of all subsequent spans, even when a large number of spatially distant spans have been traversed. As a consequence, the magnitude of the SPM measured at the end of an LP is the sum of the SPM generated by all previously crossed fiber spans (the incoherent accumulation, identical for every span), plus a statistically coherent contribution that accounts for the interference between the terms within this sum (the coherent accumulation).

In order to quantify how the coherent accumulation affects the SPM generation as a whole, we perform extensive single-channel numerical simulations using an implementation of the SSFM and evaluate the accumulation of the SPM at different spans. In general, the generation of SPM and the magnitude of its accumulation depends upon various fiber parameters, including the fiber lengths, L_s, and dispersion coefficients, $|\beta_2|$, of each crossed fiber span, along with the signal symbol rate, R_s. To investigate a full set of scenarios, including both realistic and extreme parameter configurations, we consider various examples of a 20-span periodic (each span having identical parameters) OLS, for a broad range of fiber parameter combinations (varying from $L_s = 80$ to 240 km and $|\beta_2| = 2.55$ to 21.3 e-27 ps^2/km, all with a signal launch power of 0.001 W and a 16–QAM (quadrature amplitude modulation) format. For each of these cases the SPM intensity is evaluated after each span, for a variety of symbol rates (between 32 and 84 GBd). One of these configurations is shown in Fig. 2; here, the blue line represents a fully incoherent model that is obtained by using the SPM value generated in the first span multiplied by the number of previously crossed fiber spans. On the other hand, the green dots represent the simulated SPM accumulation obtained using the SSFM. It can be seen that as the number of previously crossed fiber spans increases, so does the discrepancy between these two evaluations of the SNR degradation – this behaviour is present for all of the configurations considered within this work. To overcome this obstacle, let us consider a periodic OLS. In this framework, without any loss of generality, it is possible to express the overall equivalent amount of SPM power increment, $P_{\text{total}}^{(N)}$, that is accumulated after each span, N, generated on a single channel within an LP route as:

$$P_{\text{total}}^{(N)} = P_{\text{SPM}}^{(1)} \left(1 + C_N\right) \ , \tag{2}$$

where $P_{\text{SPM}}^{(1)}$ is the power of the SPM generated in a single span. In the right hand term of Eq. 2, the coefficient C_N takes into account the entirety of the non-local coherent SPM accumulation. Both $P_{\text{SPM}}^{(1)}$ and C_N depend on the fiber parameters of each crossed fiber span, as well as the symbol rate, R_s.

The incremental amount of SNR degradation corresponding to the SPM after each span is presented in Fig. 3; this plot highlights that after a certain number of spans, the SNR

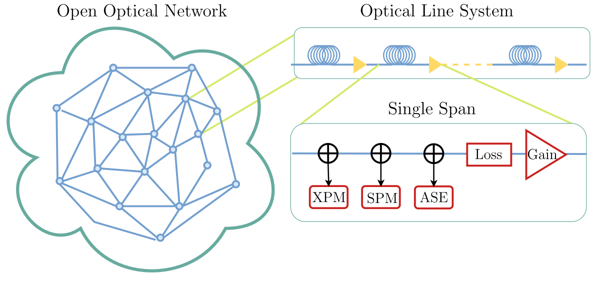

Fig. 1. A disaggregated abstraction of an optical network for QoT purposes, where each component of every OLS is considered independently.

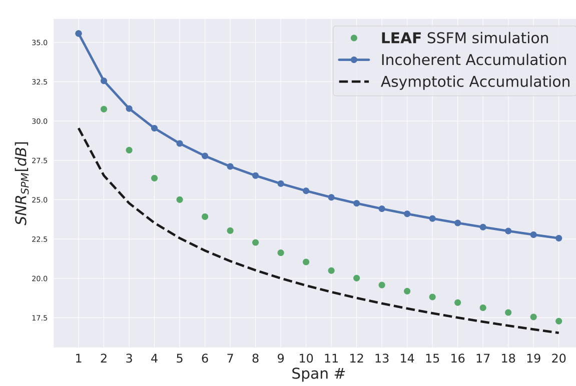

Fig. 2. The SNR degradation as a result of incoherent SPM accumulation, compared with an SSFM simulation that takes into account both coherent and incoherent effects, for a fiber with $L_s = 80$ km, $R_s = 32$ GBd and $|\beta_2| = 6.38$ e-27 ps^2/km. The dashed black line shows the 20-span limit of the coherent accumulation effect.

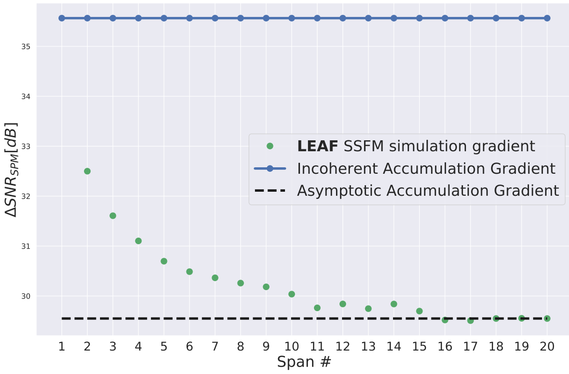

Fig. 3. The SNR degradation increment as a result of incoherent SPM accumulation compared with an SSFM simulation that takes into account both coherent and incoherent effects, for a fiber with $L_s = 80\,\text{km}$, $R_s = 32\,\text{GBd}$ and $|\beta_2| = 6.38\,\text{e-27}\,\text{ps}^2/\text{km}$. The dashed black line shows the 20-span limit of the coherent accumulation effect.

degradation increment tends towards a minimum, meaning that the coefficient C_N reaches a stable maximum value. Crucially, this behaviour allows an upper bound on the SNR degradation caused by the coherent SPM accumulation to be created, in a way which does not depend on the previous crossed spans. For every span within the simulated network we obtain a conservative and sufficiently accurate threshold by applying Eq. 2 to an equivalent periodic OLS composed of many instances of the fiber span in question. Subsequently, for each fiber parameter and signal symbol rate combination we find a coherent coefficient, C_∞, that serves as an asymptotic (large N) value of C_N, presented as the dashed black lines in Fig. 2 and Fig. 3. Most notably, this coefficient represents the maximum value of the coherent SPM that can be generated for a given span configuration. The critical detail in utilizing this approach is that it enables a fully disaggregated network abstraction, as C_∞ does not depend upon the previous spans which have been crossed in the LP. In this work, we evaluate C_∞ for each scenario in the 20-span periodic OLS simulation campaign described in Sec. III, showing the results in Fig. 4, by plotting the simulation values against a parameter that encloses all the physical parameters concerned by the phenomenon, $\theta = \pi|\beta_2|LR_s^2$, with an appropriate dependency. For all unique parameter selections, the coefficient C_N was found to reach a plateau, guaranteeing the reliability of all choices of C_∞. Consequently, by calculating this coefficient it is ensured that the entire SPM effect can be recovered independently of the history of the LP under test.

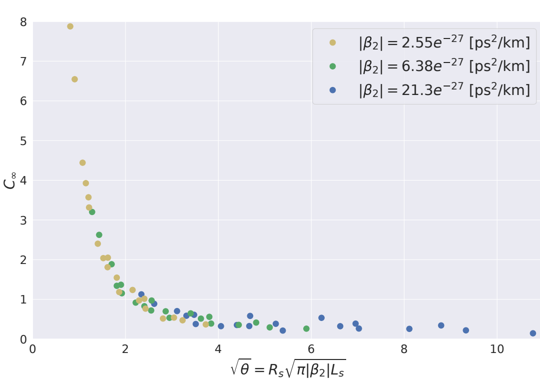

Fig. 4. The coherence coefficient C_N plotted for all configurations in the simulation campaign, with increasing θ values at $N = 20$.

IV. Conclusions

In this study we investigate the main obstacle in preventing a fully disaggregated network abstraction model: the coherent accumulation of the SPM component of the NLI. Unlike the ASE noise and XPM components, the SPM accumulates coherently, preventing a fully disaggregated evaluation of the GSNR degradation. Moreover, the SPM provides progressively more significant contributions to the SNR degradation as signal symbol rates increase. In this work, we first demonstrate that although the coherent accumulation depends upon the history of the LP in question and its configuration settings, the increment by which this component increases reaches a plateau. This enables the calculation of a unique, span-by-span independent coefficient, C_∞, which may be used as a accurate and conservative threshold to compensate for the coherent accumulation of the SPM in a fully disaggregated approach.

Acknowledgments

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