Disaggregated SCI Estimation for QoT-E in Mixed Fibers Network Segments

E. Virgillito[1,*], A. Castoldi[2], A. D'Amico[1], S. Straullu[3], R. Bratovich[2], F. M. Rodriguez[2], A. Bovio[2], R. Pastorelli[2] and V. Curri[1]

[1]Politecnico di Torino, Torino, Italy ([*]emanuele.virgillito@polito.it), [2]SM-Optics, Vimercate, Italy, [3]LINKS Foundation, Torino, Italy

Abstract: We propose a spatially disaggregated model for self-channel noise coherent buildup in mixed fibers lines including dispersion compensated spans. We show that properly modeling coherence is crucial for accurate GSNR estimation.

1. Introduction

Dual-Polarization coherent transmission dominates the backbone network market segment with optical line systems (OLS)s made up of dispersion uncompensated fibers spans. The access and metro segment instead still largely employs legacy intensity modulated-direct detected (IMDD) trasnceivers at 10 Gbps, thus using inline dispersion compensating units (DCU). The recent technological advancements on the coherent transceivers have made available open optics pluggables able to deliver 400 Gbps with a small footprint for short reach and long haul accordingly to the OpenZR+ standard. Furthermore, optical networking is evolving towards openness and disaggregation [1,2], with the aim of providing network features as slicing, virtualization and dynamic reconfiguration accordingly to the traffic request. However, while optical system vendors push towards the upgrade to cutting edge technologies, network operators aim at maximize the return of investment (ROI) of the installed hardware and deployed fiber. In this context, being able to route coherent lightpaths (LP) through dispersion-managed (DM) segments may enable cost savings and added network flexibility. Indeed, while the upgrade of DM segments to fully coherent technology by removing DCUs is certainly foreseen, in some cases it may be still too costly or it may disrupt existing legacy traffic. Exposing networking function as path computation requires a (semi-)analytical modeling tool to assess the degradation due to non-linear propagation induced by Kerr effect implemented in a quality-of-transmission estimator (QoT-E) software module. It is well known that the non-linear propagation of coherent LPs in UT system is well modeled with the non-linear interference (NLI) [3] noise made up of the self- (SCI) and cross- (XCI) channel interference produced by a channel under test (CuT) on itself and by the other co-propagating channel, respectively. The gaussian noise (GN) model [3] implemented in available open source QoT-E tools as GNPy [2] provides adequate NLI estimation. The physical mechanism allows for a spatially and spectrally disaggregated approach: as outlined in Fig.1, each span introduces its amount of NLI noise which can be modelled as additive white gaussian noise (AWGN) source, possibly independent on the propagation history, and each channel (CuT included) its contribution per span on the CuT [5] Such disaggregated features are crucial in open and reconfigurable networking as not all the channel details (e.g. modulation format) or their propagation history may be known (e.g. alien wavelengths). Also, especially in the metro segments, OLS are typically far from being uniform links, exposing instead mixed fiber types [4] and devices, so that is the scenario where disaggregated architecture may come in handy [1]. When considering DM OLS, an equivalent approach may hold, however the limited residual dispersion per span $D_{RES,i}$ set by DCUs severely enhances SCI intensity due to its spatial coherent accumulation. Furthermore, a proper SCI estimation is important also in UT scenario as the market trends to enlarge the symbol rate, making SCI predominant w.r.t. XCI. In this work we prosecute the development of the disaggregated model for coherent SCI accumulation in mixed fiber OLSs including DM and UT spans of [6,7]

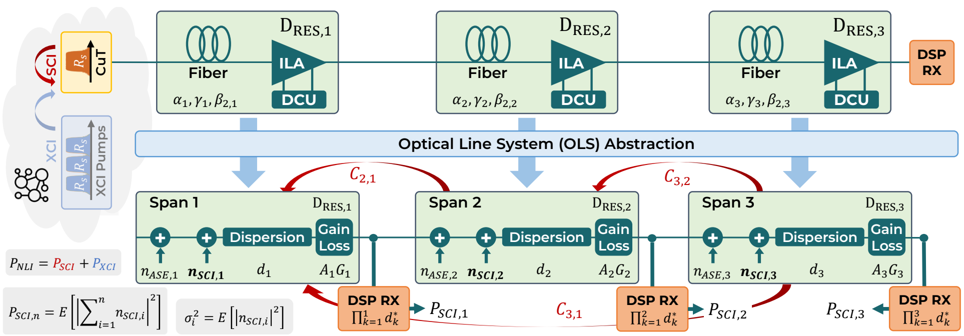

Fig. 1. 3x span example of mixed fibers UT/DM optical system (up) and its system abstraction (down). In simulation we receive at the end of all the spans to obtain the P_{SCI} accumulation.

to the undistorted CuT case. We show that the SCI coherence correction scales well in mixed fibers scenario and restores a conservative overall estimation of the generalized signal to noise ration (GSNR) w.r.t. to the case where the plain incoherent GN (IGN) model is used.

2. SSFM Simulation and SCI Coherence Modeling

As shown in Fig.1, we first focus on the propagation of a single coherent channel on the OLS to review the SCI modeling [7]. Each span introduces its own *pure* SCI contribution which is modeled as an additive noise field $n_{SCI,i}$, equivalently put at the fiber start, whose intensity is σ_i^2 and its well modeled by IGN model [3]. Each noise field propagates thjroughout the OLS and gets the effects of dispersion d_i (which includes the DCU compensation), gain G_i and loss A_i of the subsequent fiber spans. We assume here and throughout the paper that the OLS in operated in transparency, so that $A_i G_i = 1$. Since each SCI term is generated by the same channel data sequence, the contributions of two span i, j are correlated and sum up coherently at the receiver after electronic dispersion compensation. The correlation between the i-th and j-th terms is accounted by the $C_{i,j}$ coefficient, which decreases with the amount of dispersion accumulated between span j and span i, $i > j$. Note that under strong coherency, the SCI is not anymore spatially disaggregated as it thus depends on the LP propagation history. However, during path computation we know the path physical parameters so it is possible to reconstruct the coherence. Hence, the amount of total SCI noise introduced by the i-th span $\Delta P_{SCI,i}$ is:

$$\Delta P_{SCI,i} = \sigma_i^2 + 2\sum_{j=1}^{i-1} C_{i,j}\sigma_i\sigma_j \tag{1}$$

Hence, we estimate the total SCI using the *pure* terms σ_i^2 and the correlation coefficients $C_{i,j}$. We tested Eq.1 with a large split-step fourier method (SSFM) simulation campaign, considering uniform OLSs (all spans have the same physical parameters) and mixed fibers OLSs. In Fig.2 we report the $\Delta P_{SCI,i}$ evolution of a 400ZR channel ($R_s = 64$ GBaud, DP-16QAM) on a uniform OLS made of 16x 80km long SSMF fibers spans with inline residual dispersion of $D_{RES} = 40$ ps/nm at end of each span, a typical value for a DM OLS. We receivet the CuT using a coherent DSP receiver at the end of each span (using LMS adaptive equalizer and optmized carrier phase estimation algorithm) to measure the accumulated $P_{SCI,i}$ and calculate $\Delta P_{SCI,i} = P_{SCI,i} - P_{SCI,i-1}$. All the simulations here and throughout the paper have been done with ASE noise generation turned off to isolate only the NLI (SCI) noise. We have simulated the *reference* total SCI (square marker) without CuT predistortion of the CuT (blue curve), as when the LP gets deployed, and with 102400 ps/nm of predistortion (red curve), as a channel which has accumulated dispersion in a previous segment. The pure SCI σ_i^2 is obtained by turning off Kerr effect ($\gamma = 0$) in all the spans except the i-th (green curves). The $C_{i,j}$ coefficients instead are derived from Eq.1 from simulation with $\gamma = 0$ in all the spans except i-th and j-th (always with predistortion). We have thus collected $C_{i,j}$ from several link configurations involving different dispersion and loss coefficients and D_{RES}, arranged in uniform and mixed configurations. We found that the $C_{i,j}$ scales almost universally with the ratio between $\theta_{span}^2(i,j) = (R_s^2 \pi \sum_{k=j}^{i-1}(\beta_{2,k}L_s + \beta_{DCU,k}))^2$ and $\theta_{eff}(j) = R_s^2 \beta_{2,i} L_{eff,i}$. The former is set by the amount of dispersion accumulated from span j to $i-1$, the latter by the j-th dispersion coefficient and effective length, as shown in Fig.3. From this dataset we obtain an interpolated curve (black) used to pick the $C_{i,j}$ once the parameter $\theta_{span}^2(i,j)/\theta_{eff}(j)$ is known, for whatever OLS configuration. Fig.2 confirms that the IGN well models the *pure* SCI worst-case, i.e. when predistortion is applied (triangles). When the channel is undistorted instead (pentagons), a slow *gaussianization* [9] is observed due to the small D_{RES}. With such inline compensation, the overall SCI is around 10 dB larger that the pure terms due to the strong coherence. We have thus tested the model and reconstructed the coherence using Eq.1 (dashed curves), using the black curve of Fig.3 to obtain the $C_{i,j}$. The predistorted curve is built using IGN for the pure σ_i^2. The undistorted model curve uses the SSFM undistorted pure σ_i^2, though they could be obtained analytically [9]. In

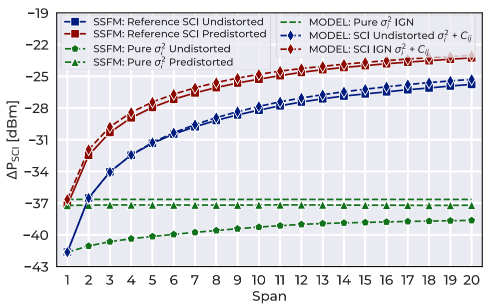

Fig. 2. $\Delta P_{SCI,i}$ added by each span on a 20 x 80km SSMF spans OLS.

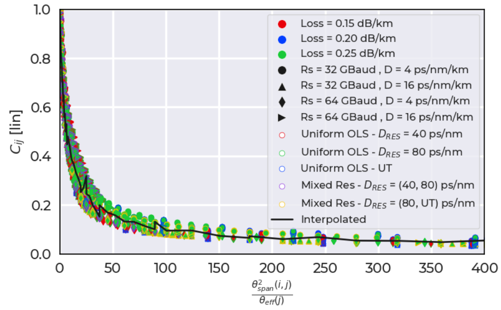

Fig. 3. The C_{ij} vs $\theta_{span}^2(i,j)/\theta_{eff}(j)$ for all the scenarios

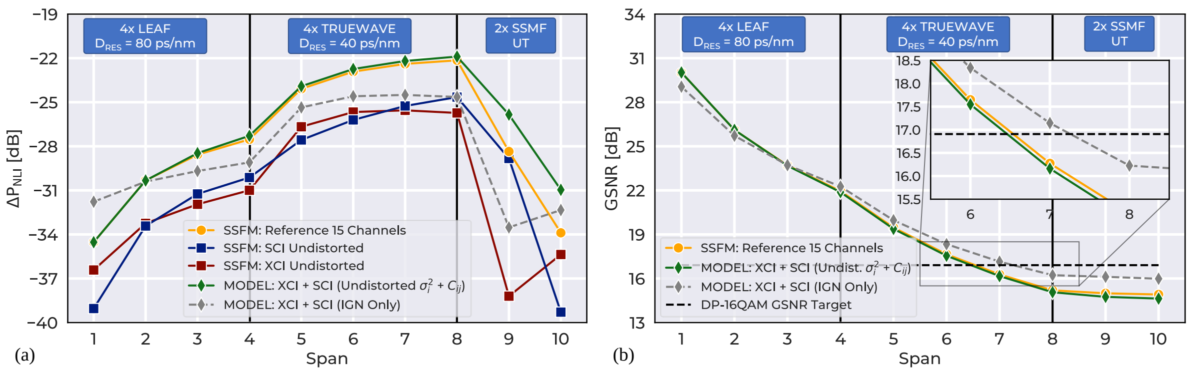

Fig. 4. ΔP_{NLI} per span (a) and accumnulated GSNR (b) in the considered mixed fiber type and mixed D_{RES} OLS.

both of the cases, the model follows conservatively the reference SSFM curves with a great accuracy. Since the $C_{i,j}$ are obtained by predistorted simulations in both cases, we can also consider the coherence effect as substantially independent upon gaussianization from a practical point view. Indeed, gaussianization is a phenomenon involving the pure term, intrinsic to the i-th span, while coherence involves the interaction of different spans contributions.

3. GSNR Estimation for QoT-E

We have seen that not considering the SCI coherent accumulation in DM OLSs may lead to underestimate its intensity by several dB. We now study how much sthis impacts the overall GSNR (Eq.2) evaluation.

$$GSNR^{-1} = OSNR^{-1} + SNR_{SCI}^{-1} + SNR_{XCI}^{-1} \tag{2}$$

The GSNR considers the ASE noise contribution due to inline amplifiers (ILA)s (OSNR) and the NLI terms due to SCI and XCI: We have now tested a mixed fiber OLSs of 10x fiber spans configures as in blue boxes in Fig.4. All fiber types have different loss, dispersion and non-linear coefficients. We propagate 15x 400G channels (64 GBaud, DP-16QAM, 75 Ghz WDM grid), undistorted at $P_{ch} = 1$ dBm, being the CuT the center channel. This is a realistic scenario since when deploying coherent channels on DM OLSs, part of the spectrum is allocated to 10G channels and another portion must be kept as a guard-band between 10G and 400G channels to make the 10G-to-100G XCI negligible [8]. We have first run a *reference* simulation to obtain the total ΔP_{NLI} (SCI + XCI) evolution. Then, we extract the ΔP_{XCI} contribution subtracting from the reference ΔP_{NLI} curve the $\Delta P_{SCI,i}$ component obtained with a single channel simulation on the same OLS. The resulting P_{NLI} components introduced per span are reported in Fig.4(a). Fig.also reports the overall NLI estimation using the plain IGN (grey) and the coherent model of Eq.1 for SCI an the simulated XCI. We may notice that the IGN version not conservative and underestimates NLI by more than 3 dB. The coherent model instead follows well the evolution in the mixed fiber OLS and always gives a conservative estimation. As a last step, we add the OSNR to the estimated NLI (Eq.2) to evaluate the accumulated GSNR at end of each span of the OLSs. The OSNR assuming an EDFA noise figure of 4.5 dB. The accumulated GSNR is plotted in Fig.4(b) for the reference SSFM simulation and the two modeling approaches. To demonstrate the implications of the SCI underestimation in path computation, we also indicate the GSNR threshold for DP-16QAM (16.7 dB) of a commercial transceiver. The reference curve shows that the actual system reach is up to the 6-th span. However, the IGN approach overestimates the GSNR by about 0.7 dB, which would have led to a wrong estimation of the reach up to 7 spans. The coherency model here presented instead correctly predicts the available GSNR with a negligible gap to the reference simulation.

4. Conclusions

We have presented a semi-analytical model able to properly predict the coherent SCI accumulation in both UT and DM OLS. We have shown that neglecting such effect in DM OLSs may lead to an overestimation of the GSNR and system reach in the path feasibility process.

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