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Abstract: We experimentally assess the accuracy of NLI estimation using Longitudinal Power Monitoring over a 1483-km heterogeneous link (comprising SMFs and PSCFs) with unequalized channel powers, comparing two different SCI/XCI correction factors.

1. Introduction

Optimizing optical power is a crucial aspect to maximize both throughput and efficiency in optical networks. This becomes particularly challenging in modern ultra-wide-band networks [1], where several wavelength-dependent effects interact simultaneously. In this scenario, the optimization requires advanced models of key components (e.g., fibers, amplifiers) [2, 3], which – in turn – require precise measurements of their parameters. While this is generally feasible for green-field deployments, where all components can be carefully characterized in advance, brown-field scenarios are more difficult to characterize with the same level of accuracy. Consequently, operators must resort to network telemetry data to estimate such parameters, which may not always meet the required accuracy.

Optical Performance Monitoring (OPM) techniques [4] offer valuable solutions by enabling end-to-end measurements of key network parameters directly from the Digital Signal Processing (DSP) of coherent receivers, without the need of external hardware. A key aspect is the estimation of the non-linear SNR ($\mathrm{SNR_{NL}}$), i.e. the SNR accounting exclusively for the contribution of Kerr-induced Non-Linear Interference (NLI) noise. This parameter is essential for transmit power optimization [5], but its estimation at the receiver remains highly challenging [6] and continues to be an active area of research. A recently proposed approach [7, 8] leverages digital Longitudinal Power Monitoring (LPM) [9] to estimate the $\mathrm{SNR_{NL}}$, obtaining surprisingly accurate results. However, with wide-band WDM networks, this approach estimates only a portion of NLI, the Self-Channel Interference (SCI). The work in [8] mitigated this limitation by applying simplified NLI models [5] as correction factors, proving an effective strategy, though still requiring knowledge of certain network parameters. Moreover, the experimental validation was limited to homogeneous networks, i.e., networks composed of identical spans using the same fiber type, with all the WDM channels having the same power, raising questions about the validity of the adopted approximation.

In this work, we experimentally measure the $\mathrm{SNR_{NL}}$ using LPM [7, 8] in a heterogeneous $\sim$ 1483-km WDM optical link, consisting of spans with different length, comprising both G.652 (SMF) and G.654 (PSCF) fibers, with two different launch power profiles. We highlight the differences between the simple approximation proposed in [8], and a complete NLI model [10, 11]. We show that the approximation still achieves good performance, albeit with a slight lower accuracy.

2. Principles

Estimating NLI through LPM on a single WDM channel [8] provides an accurate estimate of the portion of NLI generated by the channel itself, namely the Self-Channel Interference (SCI) [12]. However, this approach neglects another major NLI component: Cross-Channel Interference (XCI), which arises from the nonlinear beating of the other WDM channels with the channel of interest (COI). Multi-Channel Interference (MCI) is typically negligible for high-symbol-rate channels systems operating over links with significant dispersion. Therefore, without loss of generality, the total NLI power can be written as:

$$P_{\mathrm{NLI}} \approx P_{\mathrm{SCI}} + P_{\mathrm{XCI}} = P_{\mathrm{SCI}} \left(1 + \frac{P_{\mathrm{XCI}}}{P_{\mathrm{SCI}}}\right) = P_{\mathrm{SCI}} \cdot \zeta, \tag{1}$$

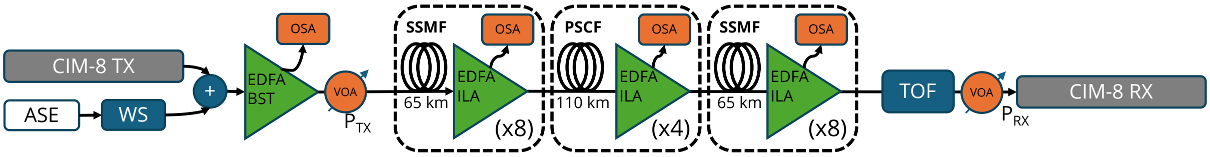

Figure 1: Experimental setup. WS: WaveShaper, BST: Booster Amplifier, ILA: In-Line Amplifier, TOF: Optical Band-Pass Filter, VOA: Variable Optical Attenuator, OSA: Optical Spectrum Analyzer.

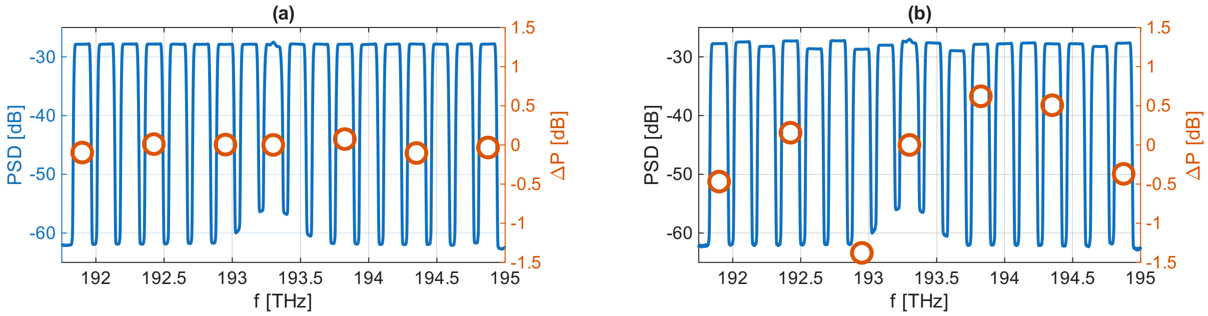

Figure 2: Transmit spectra for the two test cases: (a) equal power across all channels, (b) unequal power distribution (blue lines, left axis). Power difference with respect to the central WDM channel (red circles, right axis).

where ζ acts as a multiplicative correction factor that extends the SCI estimate (e.g., obtained via LPM) to account for the full NLI. In [8], ζ was computed leveraging a simple approximation of the GN-model [5]

$$\log_{10}(\zeta) \approx \frac{1}{4}\log_{10}(N_{\mathrm{ch}}) - 0.0475\left[\log_{10}\left(\frac{B_{\mathrm{L}}}{B_{\mathrm{R}}}\right)\right]^2, \tag{2}$$

where N_{ch} is the number of WDM channels, and B_{L} and B_{R} denote the optical bandwidths to the left and right of the COI, respectively. While this formulation is simple and requires minimal knowledge of the link, it relies on strong assumptions, i.e. an homogeneous link. By contrast, if all link parameters are available, ζ can be computed directly using NLI models that explicitly separate SCI and XCI contributions, such as the one in [10].

3. Experimental Setup and Results

A block diagram of the experimental setup is shown in Fig. 1. At the transmitter, $N_{\mathrm{ch}} = 18$ WDM channels are transmitted, each modulated at ~ 118 GBaud, with a channel spacing $\Delta f = 175$ GHz; this channel spacing was set to enable accurate OSNR measurements. The COI was generated using a commercial transceiver (CISCO CIM-8) and modulated with QPSK, while the other channels were emulated with shaped ASE. A booster (BST) EDFA sets the total transmit power in the line, which consists of 20 spans: 8×65-km spans of G.652 SMF, 4×108-km spans of G.654 PSCF, followed by another 8×65-km spans of SMF. After each span, an EDFA In-Line Amplifier (ILA) is set to fully recover the span loss. At the receiver, an optical band-pass filter (TOF) selects the COI, which is then received by another commercial transceiver (CISCO CIM-8). At the end of each amplifier, OSAs are connected to monitor the spectrum and measure the OSNR. Two different transmit power profiles were tested, as shown in the transmit optical spectra of Fig. 2. In case (a), the power of each WDM channel was equalized to the same level. In case (b), the channel powers were randomized, with a maximum power difference of 3 dB across the channels.

At the receiver, 100 constellation blocks, each $3 \cdot 2^{12}$ symbols long, were captured and used as input to the LPM algorithm [9]. The reference sequence was generated through hard decision of the received constellation; given the low Bit Error Ratio (BER), below 10^{-3}, the impact of erroneous decisions was negligible. An example of estimated power profiles for two different transmit powers, corresponding to the central WDM channel, is shown in Fig. 3, after correcting for the different dispersion and non-linear coefficients of the SMF and PSCF spans [13]. The resulting power profiles were then used to estimate the non-linear SNR [8]. Two approaches were employed to compute the ζ correction factor: the first relied on the approximation of Eq.(2), while the second used the PCFM NLI model [10, 11], assuming full knowledge of the link parameters. The estimation results are displayed in Fig. 4 for the two transmit spectra. The markers represent the estimated nonlinear SNR for different average launch powers (from +2 to +8 dBm), measured across 7 WDM channels, while the solid lines correspond to measured reference values. The latter were obtained by subtracting the OSNR (measured by the OSA) and the

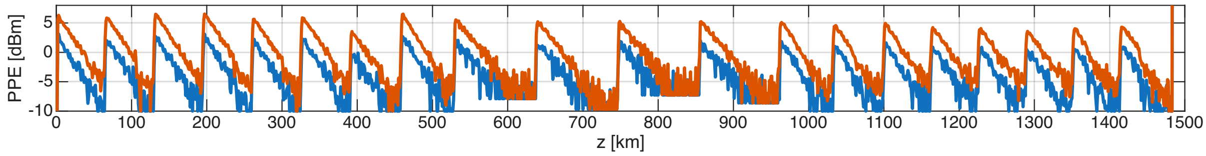

Figure 3: Estimated power profile for two different values of transmit power (4 dBm, blue and 8 dBm, red). The profile was corrected for the different chromatic dispersion and non-linear coefficient of the SMF and PSCF spans.

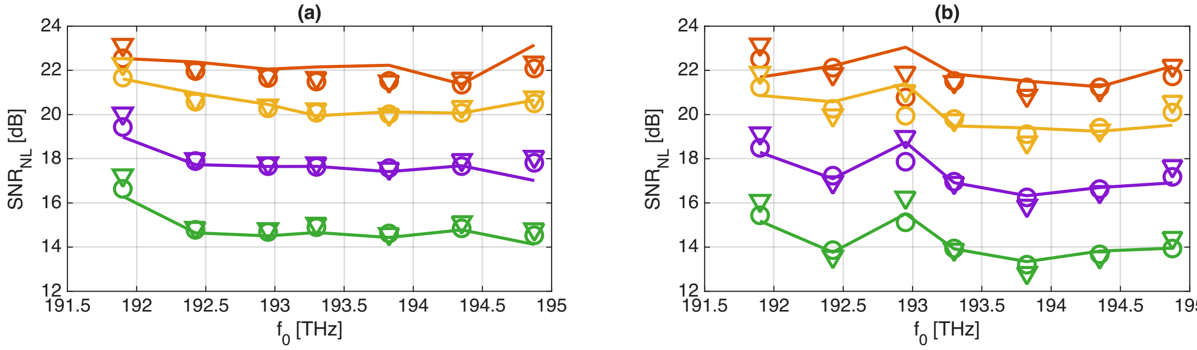

Figure 4: Measured (solid lines) and estimated (markers) non-linear SNR for equal (a) and unequal transmit power (b), at different values of total transmit power. Triangles: ζ computed using (2). Circles: ζ computed with the PCFM NLI model.

back-to-back penalty from the total SNR derived from the transceiver BER. For both correction factor approaches, the estimation accuracy is good across the tested cases, with some degradation at the lowest launch power (+2 dBm per channel), which is far from the optimal power (∼+5.6 dBm). The PCFM-based ζ provided slightly more accurate results, reducing the median estimation error from 0.30 to 0.17 dB in the equal-power case and from 0.40 to 0.26 dB in the unequal-power case. This improvement is more pronounced in the unequal-power scenario, since the simplified approximation's assumptions become less valid under non-uniform power conditions.

4. Conclusion

In this work, we tested the accuracy of the LPM-based non-linear SNR estimation algorithm over a 1483-km heterogeneous link, combining SMF and PSCF fibers, over two scenarios: flat and non-flat transmit power profile. In all the cases, the algorithm provided accurate results, with a median error below 0.5 dB. The use of an NLI model, which required full knowledge of the link's parameters, to compute the SCI/XCI correction factor gave slightly more accurate results, especially with a non-flat transmit power profile. Nevertheless, this works demonstrates the accuracy of LPM-based nonlinear SNR estimation that can be achieved in realistic network conditions.

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