Enhancing Optical Link Performance with Per-Span Nonlinear SNR Estimation Enabled by Longitudinal Power Monitoring

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***Abstract*—We experimentally demonstrate the extraction of per-span nonlinear interference (NLI) contributions using Linear Least Squares Longitudinal Power Monitoring (LLS-LPM). This receiver-side DSP technique enables accurate estimation of the nonlinear signal-to-noise ratio (SNRNL) for each span in an optical link. By combining these estimates with optical signal-to-noise ratio (OSNR) measurements, we propose a simple and effective method to determine the optimal launch power on a per-span, per-channel basis. This approach improves power optimization in wavelength-division multiplexed (WDM) systems, particularly in scenarios with span heterogeneity or channel power imbalance. Experimental validation over a 5×85 km G.652 SMF link confirms the effectiveness of the method and highlights its advantages over cumulative metrics traditionally used at the receiver.**

***Index Terms*—Optical communications, Optical performance monitoring, Optical networks, Network optimization**

I. Introduction

The continuous growth of data traffic demands that optical networks operate at maximum efficiency. A key strategy for optimizing the performance of wavelength-division multiplexed (WDM) systems is the fine-tuning of the launch power for each channel. This optimization is crucial for balancing the trade-off between maximizing the optical signal-to-noise ratio (OSNR) and minimizing the detrimental effects of fiber Kerr-induced non-linear interference (NLI). The signal-to-noise ratio of NLI ($\mathrm{SNR_{NL}}$) is a fundamental metric in this context, as its accurate estimation enables effective power optimization strategies [1] in a wide range of modern optical communication scenarios [2].

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Among the various techniques available for monitoring optical link parameters, Linear Least-Squares Longitudinal Power Monitoring (LLS-LPM) [3] has emerged as a powerful receiver-side Digital Signal Processing (DSP) algorithm. It can estimate the power evolution of a channel of interest (COI) along the link with minimal knowledge of the system's parameters, making it highly valuable for network monitoring and optimization [4], [5]. LLS-LPM has also been successfully applied to the estimation of the $\mathrm{SNR_{NL}}$ [6], [7]. A known limitation is that the algorithm primarily estimates the NLI contribution from self-channel interference (SCI) [8], while cross-channel interference (XCI) must be assessed separately. However, this limitation is small in modern systems characterized by high symbol rates [9] and the common practice of using ASE noise to load the amplifiers.

A significant challenge in network optimization is that most $\mathrm{SNR_{NL}}$ estimation techniques only provide a cumulative value at the end of the link. This is insufficient for disaggregated networks or links with heterogeneous spans, where the optimal launch power may vary from one span to another. The LOGO strategy [1] addresses this by enabling independent power optimization for each span, which is achieved by maintaining a 3-dB difference between the span-specific $\mathrm{SNR_{NL}}$ and the OSNR. While per-span OSNR can be readily measured with Optical Spectrum Analyzers (OSAs), obtaining a span-specific $\mathrm{SNR_{NL}}$ has traditionally been difficult, often relying on complex NLI models that require extensive knowledge of the link's characteristics.

In this work, we overcome this limitation by using LLS-LPM to experimentally measure the per-span $\mathrm{SNR_{NL}}$. While a similar goal was pursued in [10] using a correlation-based method, we propose, for the first time to our knowledge, to combine our per-span $\mathrm{SNR_{NL}}$ estimates with OSNR measurements. This combination yields a simple yet effective metric for determining the optimal launch power on a per-channel and per-span basis, providing network operators with actionable insights for link optimization.

II. Span-wise non-linear SNR estimation

The foundation of our approach is the Linear Least-Squares Longitudinal Power Monitoring (LLS-LPM) technique [3], which provides an estimate of the power evolution of the channel of interest (COI) along the optical link. This is achieved by solving the following linear system:

$$\hat{\gamma}' = \left[\Re\left(\mathbf{G}^\dagger\mathbf{G}\right)\right]^{-1}\Re\left(\mathbf{G}^\dagger\mathbf{A_1}\right). \tag{1}$$

In this equation, $\mathbf{A_1}$ is the first-order perturbation term of the received signal, which captures the impact of NLI generated along the link and is computed at the receiver's DSP. The matrix $\mathbf{G}$ is the perturbation matrix, whose columns describe how a perturbation at a specific location along the fiber propagates to the end of the link. The vector $\hat{\gamma}'$ represents the estimated longitudinal power profile of the COI, discretized over the link length.

Once the power profile $\hat{\gamma}'$ is known, we can estimate the NLI contribution up to an arbitrary distance D within the link. Following the principles of the first-order regular perturbation model [11], the NLI field at distance D can be reconstructed as:

$$\hat{\boldsymbol{A}}_1[D] = \begin{bmatrix}\boldsymbol{p}_0 & \dots & \boldsymbol{p}_{D-1}\end{bmatrix}\begin{bmatrix}\hat{\gamma'}_0\\ \vdots \\ \hat{\gamma'}_{D-1}\end{bmatrix}. \tag{2}$$

Here, the elements $\hat{\gamma'}_i$ are the components of the power profile vector $\hat{\gamma}'$ estimated by LLS-LPM. The vectors $\boldsymbol{p}_i$ are defined as:

$$\boldsymbol{p}_i = -j\Delta z \cdot \mathrm{D}_{z_i,D}\left[\mathrm{N}_p\left[\mathrm{D}_{0,z_i}\left[\boldsymbol{A}_{\mathrm{ref}}[0]\right]\right]\right]. \tag{3}$$

Each vector $\boldsymbol{p}_i$ models the generation of NLI over a small fiber segment of length Δz at position z_i and its subsequent propagation to distance D. This model involves three operators: $\mathrm{D}_{z_i,z_j}[\cdot]$, a linear operator that applies chromatic dispersion (CD) from position z_i to z_j; $\boldsymbol{A}_{\mathrm{ref}}[0]$, which is the transmitted reference signal; and $\mathrm{N}_p[\cdot] = \left(\|\cdot\|^2 - \frac{3}{2}P_A\right)(\cdot)$, a nonlinear operator representing the Kerr effect, where P_A is the average power of the reference signal. Essentially, the vectors $\boldsymbol{p}_i$ are the first D columns of the perturbation matrix $\mathbf{G}$ from (1), but without the final propagation step from D to the end of the link.

With the reconstructed NLI field $\hat{\boldsymbol{A}}_1[D]$, we can compute the cumulative $\mathrm{SNR_{NL}}$ at distance D. Following the method in [8], this is done by taking the ratio of the Power Spectral Densities (PSDs) of the reference signal and the NLI field at the center of the spectrum (zero frequency):

$$\mathrm{SNR}^{\mathrm{c}}_{\mathrm{NL}}[D] \approx \frac{G_{A_{\mathrm{ref}}[D]}(0)}{G_{\hat{A}_1[D]}(0)}. \tag{4}$$

By calculating $\mathrm{SNR}^{\mathrm{c}}_{\mathrm{NL}}[D]$ at the end of each span, we can then isolate the NLI contribution generated within each individual span, as will be detailed in the next section.

III. Power optimization

We consider a link consisting of N_{s} fiber spans, each followed by an EDFA. Under the assumptions of incoherent accumulation of NLI and ASE [1], with no interaction between them, the total Generalized Signal-to-Noise Ratio (GSNR) at the end of the link can be computed (in linear scale) as follows:

$$\frac{1}{\mathrm{GSNR}} = \sum_{i=1}^{N_{\mathrm{s}}}\left(\frac{1}{\mathrm{OSNR}_i} + \frac{1}{\mathrm{SNR}_{\mathrm{NL},i}}\right). \tag{5}$$

In this equation, the terms OSNR_i and $\mathrm{SNR}_{\mathrm{NL},i}$ represent the OSNR and the $\mathrm{SNR_{NL}}$ contributions from the i-th span only, respectively. They can be easily computed from the cumulative SNRs as

$$\frac{1}{\mathrm{SNR}_{\mathrm{NL},i}} = \frac{1}{\mathrm{SNR}^{\mathrm{c}}_{\mathrm{NL},i}} - \frac{1}{\mathrm{SNR}^{\mathrm{c}}_{\mathrm{NL},i-1}} \tag{6}$$

The same operation can be done with the OSNR. For the first span, we set $\mathrm{SNR}^{\mathrm{c}}_{\mathrm{NL},0} = \infty$ and OSNR_0 equal to the transmit OSNR (induced by the transmitter and the booster amplifier).

Then, an overall figure-of-merit parameter [2] can be defined, which gives the approximate difference between the current launch power and the optimal one.

$$\Delta P \text{ [dB]} = \frac{1}{3}\left(\mathrm{SNR_{NL}} \text{ [dB]} - \mathrm{OSNR} \text{ [dB]}\right) - 1 \tag{7}$$

This is a function of the overall nonlinear SNR and OSNR, as computed at the receiver.

In real networks, though, this optimal launch power may vary across spans due to differences in fiber and amplifier characteristics. Following the LOGO strategy [1], the optimal power in each span is attained when the ratio between the NLI power generated within the span and the ASE power introduced by the subsequent amplifier is approximately $1/2$. This allows for the computation of a span-specific figure of merit

$$\Delta P_i \text{ [dB]} = \frac{1}{3}\left(\mathrm{SNR}_{\mathrm{NL},i} \text{ [dB]} - \mathrm{OSNR}_i \text{ [dB]}\right) - 1 \tag{8}$$

IV. Experimental setup and results

To test this approach, we conducted an experiment using the setup shown in Fig. 1. At the transmitter, a commercial transceiver (Acacia CIM 8) generates a PM-QPSK signal at ~ 118 GBaud, shaped with a root raised cosine with a 10% roll-off. Using a WSS the signal is then combined with 17 other WDM channels in the C-band, emulated using shaped ASE [12], with a channel spacing of 175 GHz. After a booster amplifier, the WDM comb is sent to a line made by 5×85-km spans of G.652 SMF, followed by EDFAs in constant gain

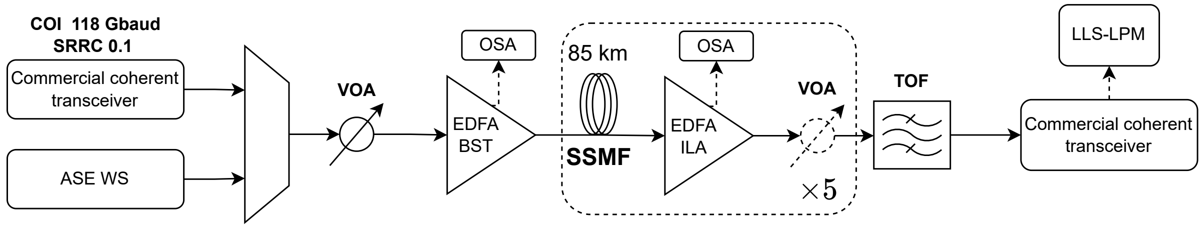

Fig. 1. Experimental setup of a17 $\times$ 118-GBaud WDM comb over al 5 $\times$ 85-km SMF link. The In-Line Amplifiers (ILAs) are in constant gain mode. At the beginning of the third span, a Variable Optical Attenuator (VOA) is placed to reduce the launch power on the third and subsequent spans.

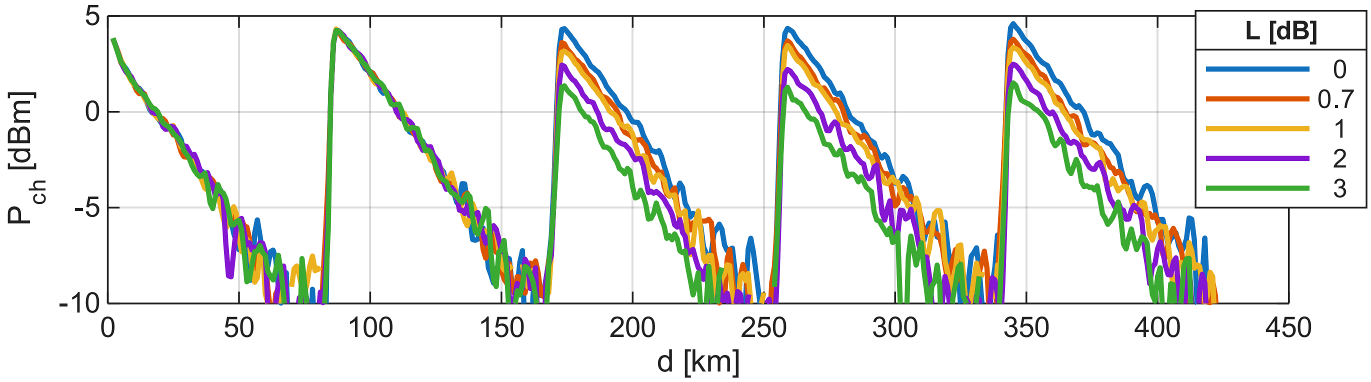

Fig. 2. Power profiles estimated with Linear Least Squares Longitudinal Power Monitoring (LLS-LPM) with a 1-km spatial resolution, as a function of the attenuation of the VOA at the beginning of the third span.

mode, where the gain and the tilt were set to recover the span loss and to equalize the relative power of the WDM channels, respectively. The total transmit power in the line was set to 16.55 dBm, corresponding to a per-channel transmit power of $+4$ dBm. At the beginning of the third span, a Variable Optical Attenuator (VOA) is placed to control the span transmit power, with an attenuation L that was varied between 0 and 3 dB. This allowed to reduce the transmit power in the third and subsequent spans, without modifying the EDFA parameters, which would otherwise introduce variations in both the gain tilt and the noise figure. OSAs are placed after each amplifier to measure the per-span cumulative OSNR. At the end of the line, an optical band-pass filter selects the central channel, which is then received by a commercial transceiver. From the transceiver's real-time DSP, we extract several blocks of the received constellation, each of $12\,288$ samples. This information, along with the cumulated chromatic dispersion, is then given to a LLS-LPM algorithm to generate 100 power profiles, which are then averaged.

For this experiment, we leveraged the card's real-time DSP, which was set to transmit random data. On one hand, averaging multiple profiles obtained from different data sequences allowed us to generate clean profiles [13]. On the other hand, this approach required the use of hard decision at the receiver to reconstruct the reference signal, which is known to introduce a power offset dependent on the symbol error rate [14], [15]. To eliminate potential inaccuracies caused by symbol errors, we opted to transmit a QPSK signal, which – at the distances considered – was received with a negligible bit error rate. The resulting averaged power profiles, shown in Fig. 2, have a spatial resolution of $\Delta z = 1$ km. As the profiles were derived from different data sequences [13], they appear clean, although a power offset is observed in the first span. This offset is expected given the chosen modulation format [16]. However, in practical scenarios, higher-order constellations are typically employed, which would significantly enhance the accuracy of LLS-LPM in the first span.

After running LLS-LPM, the per-span nonlinear SNR is calculated using (4). This value is then used to compute the overall ΔP using (7); The results are shown in Fig. 3. It can be seen that the SNR (blue circles) is optimized when the VOA at the third span is set at $L = 1$ dB, and this is consistent with the overall ΔP (red squares), which gives $\Delta P = 0$ exactly at that point. However, while it gives the correct value of optimal power, it comes with the (implicit) assumption that all spans are homogeneous, and that the booster amplifier is noiseless. In fact, it can be clearly seen from Fig. 3 that the values of ΔP are not consistent with the value attenuation L at the third span. Therefore, while this value is easy to compute, it is rather useless for the purpose of optimizing the per-span transmit power.

Fig. 4 instead shows the per-span ΔP_i results, computed using (8). The analysis begins from the second span, due to the known inaccuracies of LLS-LPM in the first span. Compared to the previous results, these findings are significantly more informative for the operator. Notably, we observe that in the

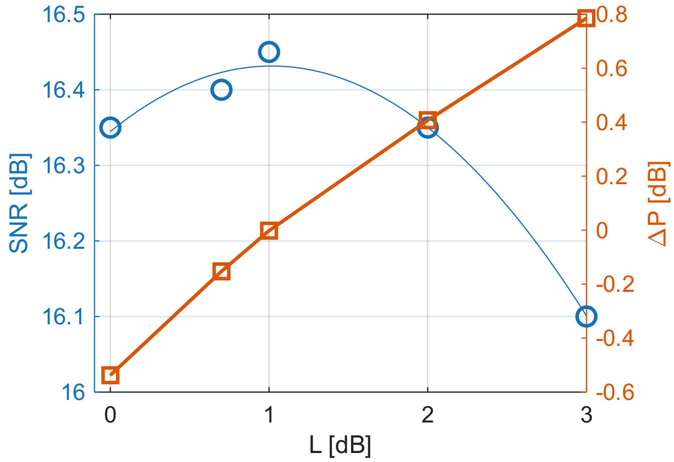

Fig. 3. Signal-to-Noise Ratio (left axis, blue circles), and overall figure-of-merit ΔP (right axis, red squares), both computed at the end of the link, as a function of the VOA's attenuation L placed at the beginning of the third span.

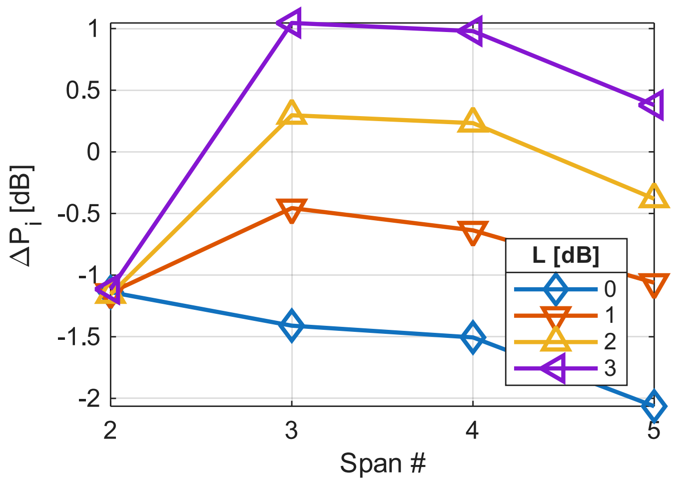

Fig. 4. Per-span figure-of-merit ΔP_i as a function of VOA's attenuation L, which sets the transmit power of the third and subsequent spans.

second span the power should be reduced by approximately 1 dB. Furthermore, the different transmit power values in the third (and subsequent) spans yield different ΔP_i values. The optimal setting corresponds to an attenuation between 1 and 2 dB, which is different from the previously computed cumulative ΔP.

V. Conclusions

In this work, we applied LLS-LPM to a 5×85 km link using a 118-GBaud commercial linecard, leveraging its real-time DSP and using hard decision on the received constellation to reconstruct the reference signal. A variable attenuator was inserted at the beginning of the third span to reduce the transmit power in that and subsequent spans. The resulting power profiles clearly captured both the presence and magnitude of the attenuation. We then proposed to use these profiles to estimate the total and per-span nonlinear SNR. Combined with OSNR measurements, this enabled the computation of a simple metric for per-span, per-channel transmit power optimization. This metric provided more detailed insights than the cumulative metric measured at the receiver. Future work should expand this also to systems with hybrid EDFA/Raman amplification [6], [17].

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