Quantifying and Improving SNR Prediction Accuracy Using Longitudinal Power Monitoring

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***Abstract*— We study the use of longitudinal power monitoring (LPM) to improve SNR prediction for optical links where lumped power losses can be present. We define three scenarios: 1) no knowledge of the presence of power losses, 2) the amplifier gives information on the value of power loss and 3) LPM allows the estimation of both the loss location and the loss value. We determine the prediction gain between scenarios in a case with no uncertainty. We later introduce an uncertainty on the fiber attenuation. We show that LPM can significantly reduce the SNR prediction uncertainty interval down to 0.2 dB while for the amplifier scenario it is 1.7 dB.**

Keywords—optical networks, monitoring, SNR prediction, longitudinal power monitoring.

I. Introduction

Accurately predicting the optical performance or the state of an optical link is crucial for the estimations of margins before network launch but also for the construction of a digital twin, key element for an automated network management [1]. To this end, physical parameters are estimated in commercial products using the digital filters in the receiver side [2], allowing for a low-cost, hardware-agnostic monitoring solution. Most of the time, they represent accumulated value at the end of transmission or end of span, e.g. accumulated chromatic dispersion (CD), polarization-mode dispersion, or polarization dependent losses [3]. However, having distributed information all along the optical line is beneficial for accurate performance prediction. For example, to know the evolution of power, an important parameter for optical performance prediction, amplifiers can monitor their input power and therefore give an information on the total span loss.

To get an information on the evolution of power inside the span at a low cost, a receiver-based technique was proposed in [4] enabling the longitudinal optical power monitoring (LPM). While first papers focused on presenting new and more accurate techniques as in [5], others focused on showcasing various applications and experimental demonstrations [6], [7]. Lately, a few works considered using LPM to improve performance predictions, such as the estimation of the non-linear signal-to-noise ratio (SNR) [8], [9] . In [10], the authors perform a real-time demonstration of LPM and optical line system working together for a fast line system provisioning and a decrease in QoT prediction errors, paving the way for the use of LPM for network management.

In this work, we estimate the accuracy gain from using LPM compared to two other scenarios in different loss configurations. We first do not consider any uncertainty and later introduce an uncertainty on the fiber attenuation.

II. SNR Prediction in Three Scenarios

A. Definition of the three scenarios

The three monitoring scenarios that we choose differ in their level of available information regarding the presence of additional lumped losses in the optical link:

1) no additional loss is known, the only known attenuation is the fiber attenuation value.

2) Amplifiers are able to know the span loss and the additional loss can therefore be inferred. As we do not know the location of the loss, we incorporate it inside the attenuation value:

$$\alpha_{new} = \alpha + \frac{l_{dB}}{L_s},$$

with α the fiber attenuation, α_{new} the updated fiber attenuation, l_{dB} the estimated loss value and L_s the span length.

3) LPM allows us to estimate the loss value, the loss location and the fiber attenuation value.

B. Prediction gains between scenarios

To compare SNR prediction accuracy between scenarios, we first measure the prediction error in dB scale as the difference between the measured SNR (target) and the predicted SNR for the i-th scenario, $i = \{1,2,3\}$:

$$error_{dB,i} = |SNR_{pred,i} - SNR_{meas}|.$$

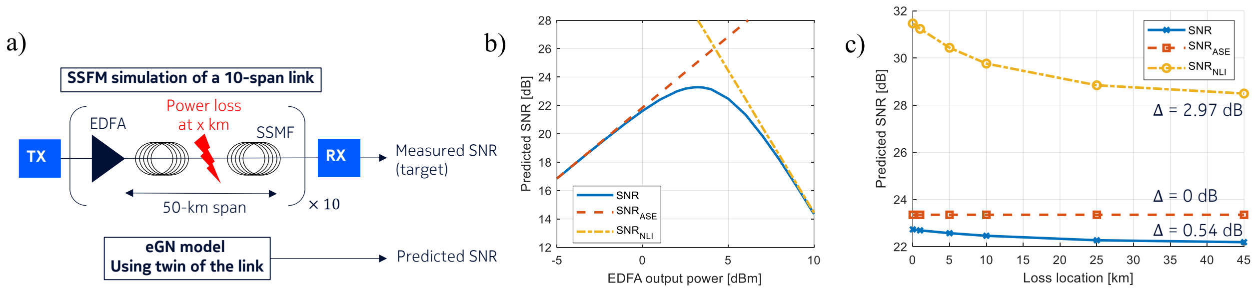

Figure 1: a) Simulation set-up. b) Bell curve. c) SNR, SNR_{ASE} and SNR_{NLI} for various 1.5-dB loss locations and an output power of 3 dBm.

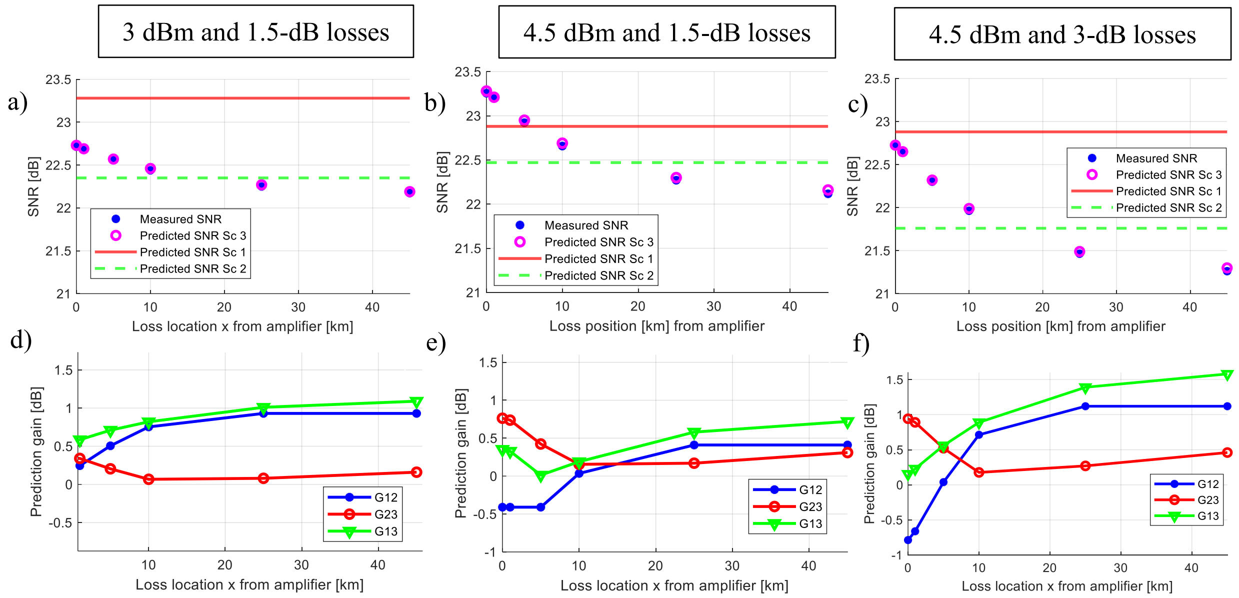

Figure 2: Measured and predicted SNR in all three scenarios as a function of loss locations for a) output power of 3 dBm and 1.5-dB losses, b) 4.5 dBm and 1.5-dB losses and c) 4.5 dBm and 3-dB losses. Prediction gains between scenarios for d) output power of 3 dBm and 1.5-dB losses, e) 4.5 dBm and 1.5-dB losses and f) 4.5 dBm and 3-dB losses. Sc : scenario.

Then, we define the prediction gain $Gij(z_l)$ of scenario j with respect to scenario i when the loss location is z_l as:

$$Gij\ (z_l) = error_{dB,i} - error_{dB,j}.$$

If $Gij\ (z_l) > 0$, scenario 'j' is more accurate than scenario 'i'.

C. Simulation set-up

The simulation set-up is shown in Fig. 1a). In the top half of Fig. 1a), we consider the propagation of a 128-Gbaud QPSK-modulated single channel signal into a 10-span optical link. Each span is 50 km-long and is preceded by an erbium-doped fiber amplifier (EDFA) with a given output power. To simulate amplified spontaneous emission (ASE) noise, fiber attenuation and self-phase modulation (SPM), we use the split-step Fourier method (SSFM). Each span is a standard single mode fiber (SSMF) with an attenuation value of 0.2 dB/km, a dispersion coefficient of 17 ps/nm/km and a non-linear coefficient of 1.3 $W^{-1}\text{km}^{-1}$. We insert a power loss in each span at a location x = {1 m, 1 km, 5 km, 10 km, 25 km, 45 km}. This location is varied to study different configurations but is always the same across the 10 spans. After each propagation, we measure the SNR, which is our target value. The bottom half of Fig. 1a) represents the SNR prediction. For this prediction, we use the enhanced Gaussian noise (eGN) model [11]. We split spans into two to incorporate losses of different values at different locations inside spans. We show in Fig. 1b) the "bell curve" describing the evolution of SNR with power, using SNR predictions without any additional loss highlighting a non-linear threshold (NLT) of 3.25 dBm.

III. Results and Discussion

A. Prelimary observations

For different parameters, we predict three metrics: SNR, SNR_{ASE}, SNR_{NLI}. We plot them as a function of the loss location in Fig. 1c) for an output power of 3 dBm and 1.5-dB losses. For each metric, we measure Δ which corresponds to the difference between maximal and minimum SNR values as the loss location varies within the span. We can see that SNR_{ASE} does not vary between loss configurations as Δ = 0. It is expected as ASE noise only depends on total gain which does not vary with loss locations. However, SNR_{NLI} decreases when the loss location increases. The majority of non-linear effects occur at the beginning of each span. Therefore, when the loss is at the beginning of the span, the power decreases at that location, highly reducing non-linear effects. Thus, the SNR varies between different loss configurations. This shows that not knowing the loss locations when predicting the SNR value can have an impact on its accuracy.

B. Prediction gains estimation

In Fig. 2), we plot the measured and predicted SNRs for the three scenarios for three configurations, for a) an output power of 3 dBm and 1.5-dB losses, b) an output power of 4.5 dBm and 1.5-dB losses and c) an output power of 4.5 dBm and 3-dB losses. In Fig. 2d-f), we plot the prediction gains G_{12}, G_{23} and G_{13} for the configurations a-c), respectively. We note that by construction $G_{13} = G_{12} + G_{23}$.

At 3 dBm, we see that all prediction gains are greater than zero, which indicates that scenario 3 (LPM) is more accurate than scenario 2 (amplifier), which is itself more accurate than scenario 1 (no knowledge). Gains G_{12} and G_{23} are of similar value for losses located less than 5 km away from the amplifier. However, for other loss locations G_{23} is lower than G_{12} by up to 0.8 dB. In this configuration, using EDFA information is already quite relevant for SNR prediction, due to a good estimation of the added ASE noise.

At 4.5 dBm and for 1.5-dB losses, the behavior is different. For losses located less than 10 km away from the EDFA, while G_{23} has a positive value (up to 0.8 dB for losses located 1 m away from EDFA), G_{12} has negative values (down to -0.4 dB). It indicates that scenario 2 (amplifier) is less accurate than scenario 1 (no knowledge) for these locations, while scenario 3 (LPM) is more accurate than scenario 2 for all loss locations. For 3-dB losses, the behavior is similar – scenario 2 less accurate then scenario 1 (no knowledge) for losses located less than 5 km from EDFA. In both cases, for losses located close to the EDFA, scenario 3 (LPM) is more accurate, up to 1 dB, than scenario 2 (amplifiers). For losses located far away from EDFA, scenario 3 is more accurate than scenario 1, up to 1.6 dB. At 4.5 dBm, correctly estimating the non-linear noise matter, therefore using LPM is more relevant than using

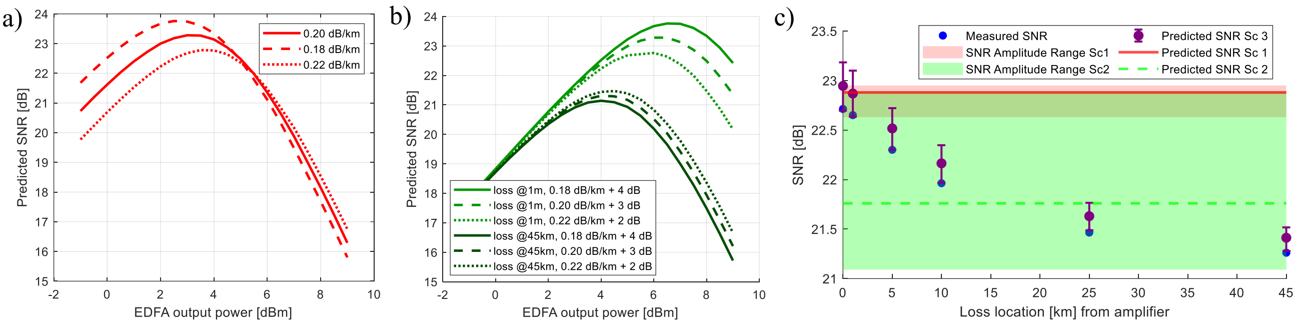

Figure 3: Adding uncertainty on fiber attenuation. a) Bell curves for scenario 1. b) Bell curves for scenario 2 to determine best- and worst-case. c) Predicted SNR ranges for all scenarios. Sc3: when the attenuation value is estimated using PPE.

EDFA information. To conclude, depending on the EDFA output power, it is more critical to estimate either ASE noise or non-linear noise. However, using LPM for SNR prediction is always the most accurate scenario.

IV. Adding Uncertainty

We previously considered an ideal scenario, without any added uncertainty. In this section, we consider that we know the fiber attenuation as follows: $0.2\ \text{dB/km} \pm 0.02\ \text{dB/km}$. We do not consider any other uncertainty. We consider the case of an output power of 4.5 dBm and 3-dB losses.

For scenario 1, we estimate two SNRs, $\text{SNR}(\alpha = 0.18\ \text{dB/km})$ and $\text{SNR}(\alpha = 0.22\ \text{dB/km})$. We consider that they represent the range of values that the SNRs can take when adding the uncertainty. We plot in Fig. 3a) those two SNRs as well as the "ideal" $\text{SNR}(\alpha = 0.20\ \text{dB/km})$ as a function of power. We notice in Fig. 3a) that the range of SNR is maximal and symmetrical in the linear regime. It is minimal around 5 dBm and becomes symmetrical again in the non-linear regime but with an inversed and smaller range.

For scenario 2, we infer the additional loss from the span loss measured by the amplifiers. The span loss depends on the fiber attenuation that we now know with a given uncertainty. Several cases have to be considered: attenuation of 0.18 dB/km and losses of 4 dB, attenuation of 0.22 dB/km and losses of 2 dB, with losses that can be located anywhere. For our SNR range, we choose to consider the best (higher SNR) and worst (lower SNR) case. To have an insight on those values, we plot in Fig. 3b), bell curves for several cases, losses located at 1 m and 45 km away from amplifier, and three cases of attenuation values, all corresponding to a total span loss of 13 dB. From this, we can infer that the best case is when the loss is a 4-dB loss located at 1 m and an attenuation value of 0.18 dB/km. The worst case is when the loss is a 4-dB loss located at 45 km and an attenuation value of 0.18 dB/km.

For scenario 3, we use LPM to estimate the attenuation value, the loss location and the loss value. We consider the estimation of both the loss location and the loss value to be ideal. For the estimation of the attenuation value, we estimate the slope of the LPM profile for each of the 10 spans. We obtain an average value of 0.194 dB/km with a standard deviation of 0.003 dB/km. For the SNR range, we consider the average value plus or minus two times the standard deviation.

We plot in Fig. 3c) the predicted SNRs for the three scenarios versus loss locations and their ranges. We can see that the SNR range for scenario 1 (no knowledge) is asymmetrical, in line with Fig. 3a) for a power of 4.5 dBm. For scenario 2 (amplifiers), we can see that the range spans from 21.1 to 22.9 dB, indicating the relatively high difference between worst- and best-case with this relatively high power. As can be seen in Fig. 3b), this difference would fall to zero for a EDFA output power lower than 1 dBm. Finally, we can see that the SNR prediction for scenario 3 are always overestimated by ~0.2 dB due to the underestimation of the attenuation value by LPM. However, the relatively good estimation i.e., low standard deviation, allows scenario 3 to stay highly relevant compared to the two other scenarios.

V. Conclusion

In this paper, we investigated the use of LPM to improve SNR prediction in optical links with lumped losses. We considered three scenarios and estimated the gain predictions between them. We found that using LPM is useful in all cases, with a more relevant use when the power is slightly higher than the NLT. We considered a more realistic scenario where the fiber attenuation was known with a given uncertainty and LPM is used to estimate it more accurately. In such a configuration, scenario 1 (no knowledge) shows a SNR prediction uncertainty interval of 0.3 dB, but with a high estimation error when the loss is more than 5 km away from the amplifier. Scenario 2 (amplifiers) exhibits a SNR prediction uncertainty interval of 1.7 dB. Scenario 3, incorporating LPM, drastically reduces the SNR prediction uncertainty interval down to 0.2 dB while maintaining close alignment with measured SNR values.

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