Optical Line Physical Parameters Calibration in Presence of EDFA Total Power Monitors

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Abstract: A method is proposed in order to improve QoT-E by calibrating the physical model parameters of an optical link post-installation, using only total power monitors integrated into the EDFAs and an OSA at the receiver.

1. Introduction

In optical fiber networks, the deployment of a generic transparent light-path (LP) between a pair of nodes of a given network is based on two crucial aspects in the management and control of the infrastructure at the physical layer, which are the quality-of-transmission estimation (QoT-E) [1] and design margin definition [2]. However, they turn out to be challenging in multi-span optical lines when the only available monitors are photodiodes embedded within each erbium-doped fiber amplifier (EDFA), measuring the total optical power. This transmission scenario is common in several legacy systems and represents a frequent implementation among network operators, thanks to its simple management – with few monitoring data streams and a simple telemetry control system – and low equipment installation cost. Thus, a solution is direly needed to accurately perform QoT and design margin estimation, making the planning tool within the network controller reliable and open towards the improvement of multiple tasks, such as optical line optimization, tomography and LP computation engine (L-PCE).

In this work, a new methodology is proposed improving upon the approaches presented in [3, 4], which are limited to partial characterization of line elements and require the use of optical channel monitors (OCMs). In addressing the outlined transmission scenario, first, the proposed methodology retrieves the physical characteristics of both EDFAs and optical fibers without any device pre-characterization, only knowing EDFA operational ranges (amplification band limits, total power, gain and tilt). Then, a minimum number of pre-defined measurements are taken, each measuring the system in a different specific configuration of gain and tilt target parameters using only EDFA input/output power monitors and an optical spectrum analyzer (OSA) at the termination of the line.

2. Methodology

The considered transmission scenario is a multi-span EDF-amplified optical link between two adjacent nodes with reconfigurable optical add & drop multiplexers (ROADMs) within a given optical network, where each EDFA has integrated total power monitors at both input and output terminals. Fig. 1-a depicts the diagram of the system set up in the laboratory. The proposed calibration methodology assumes the following: i) all EDFAs are dual-stage with automatic gain control (AGC) and adjustable values of total gain and tilt (vs. wavelength) as target parameters; ii) the procedure is performed after the installation of the cable and/or line equipment, or after cable-cut restoration, but before the beginning of networking operations. The equipment required are i) an amplified spontaneous emission (ASE) source for emulating a fully loaded spectrum at the transmit node; ii) a wavelength-selective switch (WSS) to flatten the ASE source and to create arbitrary spectral holes for gain/optical signal-to-noise ratio (OSNR) measurement; iii) an OSA to measure the spectrum at the receive node. For a specific configuration of the gain and tilt target parameters of the EDFAs, the corresponding optical line measurement consists of collecting the total input/output power levels of the monitors and the spectral power profile provided

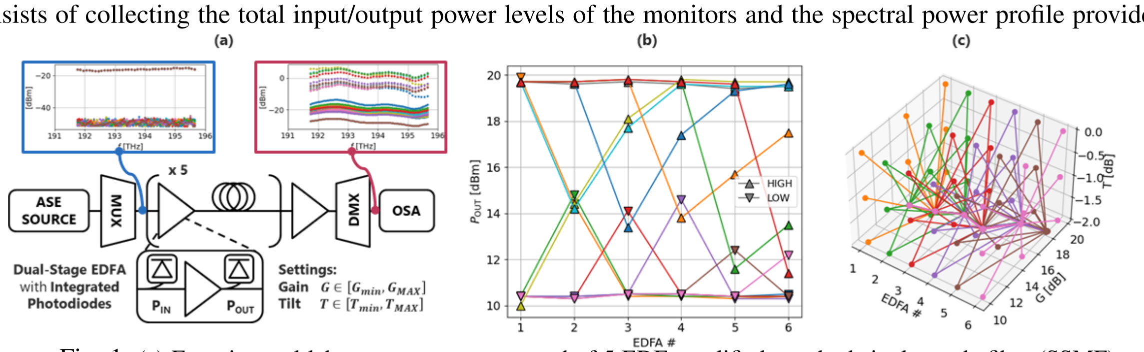

Fig. 1. (a) Experimental laboratory setup composed of 5 EDF-amplified standard single-mode fiber (SSMF) spans, with an ASE noise source filtered by a multiplexer at the transmitter and an OSA at the receiver. (b) Measured EDFA total output power levels of each configuration of the *second* dataset, setting the booster at minimum/maximum gain (low/high power). (c) EDFA configuration 3D representation of the *third* dataset, versus gain, G, and tilt, T, parameters.

by the OSA. Given a digital physical model of EDFAs and optical fibers [1, 5], the conceived calibration method retrieves the physical parameters required to simulate the measured behavior of the system in terms of OSNR. The procedure consists of two consecutive steps: i) measurements acquisition using flat input spectrum and changing the configuration of EDFAs; ii) calibration (optimization) of the physical parameters of the digital model to match the measured metrics (signal or ASE noise power). The objective of the first step is to locally change the properties of each device – gain ripple profile and noise figure for EDFAs, or stimulated Raman scattering (SRS) for optical fibers – modifying the working point of the EDFAs and capturing the accumulation of the effects using the OSA. First, the optical line is set to transparency mode, where the gain of each EDFA is set to the loss of the previous span. If not specified, the slope of all EDFAs is initially set to a single value achieving the flattest spectrum at the receiver for the set gain of the booster (first EDFA of the line). In this way, 3 different data sets are collected, each focused on the calibration of different groups/types of physical parameters. The *first* dataset attempts to characterize the tilting behaviour of each EDFA (f_0, B, K in [5]), and it is collected by initially setting the booster at minimum gain and all EDFAs at 0 dB tilt. For each measurement, starting from the initial configuration, each EDFA is sequentially set to the minimum tilt, maintaining all the others at 0 dB tilt. The *second* dataset focuses on the SRS of optical fibers (effective area, loss coefficient function, Raman gain coefficient, connector losses) and is designed to perform two sequences (low- or high- power in the figure) of line measurements by setting the booster at either minimum or maximum gain. During each line measurement, a single EDFA is set to the opposite gain setting (maximum or minimum) to locally enhance/reduce the SRS effect, and the following EDFAs compensate for the introduced gain/loss gap, restoring the transparency power level. Fig. 1-b represents the output power measured at each span for each dataset configuration (different colored lines), showing where the SRS is enhanced/minimized according to the produced power level. The *third* dataset (Fig. 1-c) involves the calibration of EDFA noise figure parameters (average noise figure vs. gain and tilt target parameters). With the booster set at the center of the gain range, for each measurement, we configure one EDFA's gain and tilt parameter in order to sample the corresponding OSNR condition. The total number of measurements for each dataset is $1+\mathrm{N_{EDFA}}$, $2\times\mathrm{N_{EDFA}}$ and $n_\mathrm{G}\times n_\mathrm{T}\times\mathrm{N_{EDFA}}$, respectively, where $\mathrm{N_{EDFA}}$ is the number of EDFAs along the line, n_G and n_T are the chosen numbers of gain and tilt values defining the granularity of the third dataset. In Fig. 1-c, each 3D contour with same color is a group of configuration associated with parameters changes of one specific EDFA; in the experimental results shown, $n_\mathrm{G}=3$ and $n_\mathrm{T}=3$, for a total of 54 measurements. The second step of the calibration involves the use of the produced datasets aiming to jointly calibrate the physical model parameters of each device throughout a training process. First, the EDFA tilt parameters are analytically derived from the first dataset [5]. Then, given an extracted set of physical parameters, the digital model simulates the scenario in all the configurations measured in the second and third datasets, and the algorithm [6] minimizes the following cost function:

$$\min_{\{x\}} f(x) = \frac{1}{\mathrm{N_{CONF}}}\sum_{i}^{\mathrm{N_{CONF}}}\left[\sigma_{\Delta[\mathrm{P^{dB}}_{\mathrm{SIG};i}(f)]} + |\Delta[\overline{\mathrm{OSNR^{dB}}_i(f)}]|\right], \tag{1}$$

where x is the set of physical parameters to calibrate, $\mathrm{N_{CONF}}$ is the total number of configurations, the index i represents a given configuration of EDFAs' target parameters, f is the optical frequency, $\mathrm{P_{SIG}}$ is the signal power profile. Given an arbitrary frequency-dependent profile $p_i(f)$, $\overline{p_i(f)}$ represents the average value over frequency, $\Delta[p_i(f)]$ is the error operator defined as the difference between the measured and simulated values of the metric

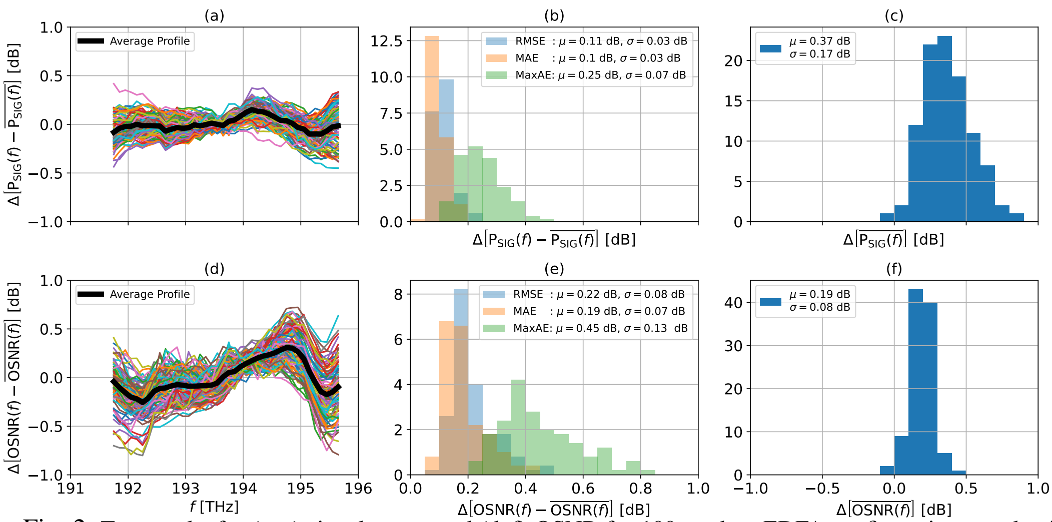

Fig. 2. Test results for (a–c) signal power and (d–f) OSNR for 100 random EDFA configurations, evaluating the error as the difference between the measured metric and simulated one. (a, d) Error of ripple profiles; (b, e) ripple profile error distributions; (c, f) average error distribution.

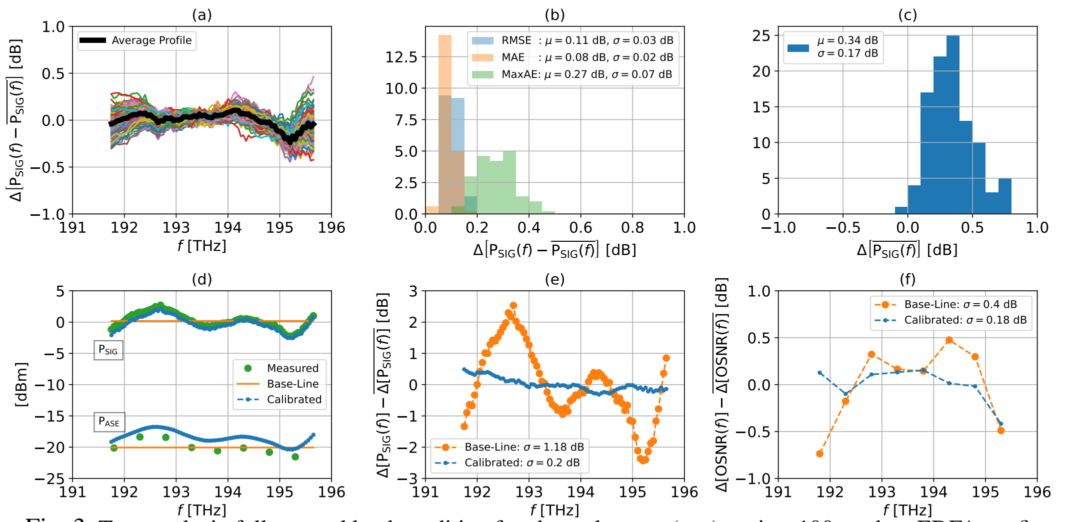

Fig. 3. Test results in full spectral load condition for channel power (a–c) against 100 random EDFA configurations. (a) Error of ripple profiles; (b) ripple profile error distributions; (c) mean error distribution. Test at LOGO configuration against the base-line model (d–f). (d) Signal and ASE power profiles, measured in 8 spectral slots by switching off one channel per time; (e) signal ripple profile error; (f) OSNR ripple profile error.

considered, $\sigma_{p_i(f)}$ is the standard deviation over frequency. In Eq. 1, the terms in the sum weight the signal profile and OSNR average errors over all considered dataset configurations, aiming to find the set of physical parameters that maximizes the match between measured and simulated profiles and average values. This phase involves 8 parameters for each fiber span related to the loss coefficient function, Raman gain coefficient and connector losses, and 4 for each function of the average EDFA noise figure (assumed flat in frequency) with respect to the gain parameter. The total accumulated gain ripple profile is estimated by assuming that all EDFAs have the same intrinsic gain ripple profile (r_0 in [5]).

3. Results

The resulting optical line calibrated physical model (64 parameters) is tested against two other datasets, each of 100 random EDFA gain and tilt configurations. The first dataset is collected using the same half spectral loading used for the calibration (40 alternating channels), while the second one using a full spectral load (80 channels). Figs. 2 (b,e) show that the mean absolute error (MAE) and root mean square error (RMSE) accuracy of the model compared to the first test dataset are approximately 0.1 dB for the signal and 0.2 dB for the OSNR ripple, with a slight bias on the average error distributions (0.37 dB, cf. Fig. 2-c). In full spectral load condition, as depicted in Figs. 3 (a–c), the calibrated model maintains the same degree of accuracy for the channel power error metrics (sum of signal and ASE noise power). In order to evaluate the estimation improvement of the proposed method, the calibrated model is compared to a base-line model at the working point configuration computed via the local optimization global optimization (LOGO) strategy [7]. The base-line model assumes a fixed connector loss and noise figure, a scalar loss coefficient defined at the central channel, and conventional SSMF fiber parameters values. The key result depicting the improvements offered by the proposed methodology is shown in Figs. 3-(d–f). In Fig. 3-d, we highlight the advantages of the calibrated model by showing that it tracks the signal and ASE ripples more closely than the base-line. Figs. 3 (e,f) show the flatness of the signal and OSNR ripple error profiles, respectively. The calibrated model presents a significant reduced dispersion of the error profiles – roughly 0.2 dB standard deviation – with respect to the the base-line, 1.18 dB and 0.4 dB for signal and OSNR standard deviation, respectively. In addition, the calibrated model predicts conservatively an ASE noise profile of roughly 1 dB above the measured one (Fig. 3-d), because of the higher number of channels compared to the calibration spectral load condition.

4. Conclusion

We proposed and experimentally tested a methodology for calibrating model physical parameters of an optical line equipped with only total power monitors, showing a significant improvement in performing QoT-E. To the best of the authors' knowledge, this is the first systematic and explicitly stated demonstration addressing the accurate control of this type of transmission scenario. In future work, we aim to increase the scalability both increasing the number of spans and information coming from the monitoring devices, such as OCMs, transceivers or optical time domain reflectometers (OTDRs), also opening up the possibility of carrying out accurate optical line tomography.

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