Link Tomography for Amplifier Gain Profile Estimation and Failure Detection in C+L-band Open Line Systems

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Abstract: We experimentally demonstrate a distance-wise, wavelength-dependent link tomography extraction scheme using receiver DSP. This approach permits the estimation of gain spectrum and tilt in C+L-band EDFAs with a maximum mean absolute error of 0.6 dB. © 2022 The Author(s)

1. Introduction

The deployment of optical Multiband (MB) [1] systems allows a cost-effective exploitation of the full transmission window (approximately 40 THz of bandwidth) of single-mode fibers (SMF) and is considered as a near-term solution to cope with the rapid traffic growth. However, the success of the MB approach heavily depends on optical performance monitoring (OPM) solutions that can reliably measure wavelength-dependent and spatially-distributed physical characteristics of the optical networks in a cost-effective way. In that respect, the development of additional OPM capabilities for the end terminals (i.e., transceivers) can bring significant cost reduction compared to the deployment of numerous in-line monitoring devices. Recently, several monitoring features have been demonstrated by solely exploiting receiver digital signal processing (DSP) modules [2-6] due in part to their capability in unveiling multi-span link properties (e.g., longitudinal power profile [2][3], frequency response of passband filters [4], span-wise chromatic dispersion mapping [5], Raman gain [6]), thus minimizing the requirements of distributed node-level monitors.

In [2], the authors proposed an *in-situ* power profile estimator (PPE) that reconstructs the channel power evolution along the link with impressive sub-km [3] resolutions by uniquely processing the received signal. In this contribution, we propose and experimentally demonstrate a receiver-DSP based link-tomography that extends the *in-situ* PPE introduced in [2] by revealing not only a distance-wise, but also wavelength-dependent power profile in a C+L-band system over 280 km of SMF. We showcase the benefits of our proposed solution for two different use-cases: 1) to accurately estimate the gain spectrum of each individual Erbium-doped fiber amplifier (EDFA) deployed along the fiber link, and 2) to identify soft-failures caused by amplifier gain tilt [7]. Our demonstrated solution brings additional benefits to partially disaggregated networks in which third-party terminals operate over multi-vendor networks where infrastructure information cannot be always shared [8].

2. Principle

The link tomography scheme proposed in this work is inspired by the *in-situ* PPE proposed by T. Tanimura et al. [2]. Figure 1(a) depicts the schematic of our proposal. The considered setup can be understood as a partially disaggregated system, comprised of an open line system (OLS) and third-party terminals [9]. After the optical signal is received by a coherent receiver and digitized by a real-time oscilloscope (RTO), the link-accumulated chromatic dispersion c_{tot} is blindly estimated and fully compensated by the chromatic dispersion compensator (CDC) block. Then, the resulting signal is fed to a data-aided equalizer (DAEQ) for polarization demultiplexing and subsequently split into tributaries, namely, Tributary 1 and 2. After the reloading of c_{tot} to the Tributary 1, the resulting signal is used in a simplified back-propagation algorithm that consists of three steps: 1st) a partial CDC of $n \times c_{tot}/N_{seg}$ (n: integer

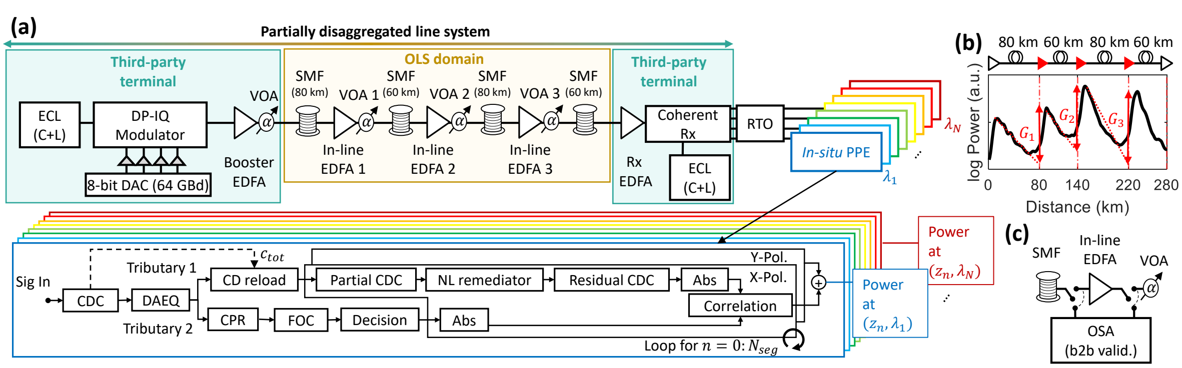

Figure 1: (a) Experimental testbed and DSP scheme used in the link tomography. (b) Output of the *in-situ* PPE, where G_1, G_2 and G_3 indicate the estimated gain of the 1st, 2nd and 3rd in-line EDFA (at fixed wavelength), respectively. (c) Scheme used for the b2b validation.

number, i.e., $n = 0, 1, 2, \ldots, N_{seg}$, and N_{seg}: total number of link segments); 2nd) a nonlinear (NL) remediator, which compensates for any point-wise nonlinear phase noise due to Kerr effect and is implemented via the formula $u_{out,\mathrm{X/Y}}[k] = u_{in,\mathrm{X/Y}}[k]\exp\left(-j\varepsilon\left(|u_{in,\mathrm{X}}[k]|^2 + |u_{in,\mathrm{Y}}[k]|^2\right)\right)$ (u_{in}/u_{out}: digital representation of the input/output complex-valued electric field, k: sample index, X/Y: horizontal/vertical polarization, ε: a fixed hyperparameter); and 3rd) a residual CDC of $c_{tot} - n \times c_{tot}/N_{seg}$. For the signal Tributary 2, we utilize a standard receiver DSP chain to recover the signal to an as-close-as-possible version of the reference waveform, i.e., before the link propagation. This is performed by using carrier phase recovery (CPR), frequency offset correction (FOC) and a decision based on the nearest complex symbol. Finally, we calculate the correlation between the processed Tributary 1 and 2 to obtain a numerical indicator of the signal power at a distance z_n (w.r.t the receiver side). The construction of the full longitudinal power profile is obtained when this operation is looped for $n = 0, \ldots, N_{seg}$. In order to extend this scheme to the frequency domain, the above-described principle must be carried out for all the N allocated WDM channels in the link, symbolically represented in Figure 1(a) by $\lambda_1, \ldots, \lambda_N$. Then, the results from each individual *in-situ* PPE are overlaid to construct the proposed link tomography.

To validate the relevance of this approach, we utilize the proposed link tomography for two different use-cases. The goal of the first use-case is to solely rely on the transceiver monitoring capability to estimate the gain spectra of the 1st, 2nd and 3rd in-line EDFAs, highlighted in red in Figure 1(b). That is possible because the p-th in-line EDFA gain (G_p), for a fixed wavelength, can be estimated from the *in-situ* PPE, as shown in Figure 1(b). It is important to highlight that in this work we added a variable optical attenuator (VOA) at the output of the EDFA to avoid a high input power into the fiber. Therefore, the link tomography always delivers the resulting gain of the two devices, i.e., EDFA + VOA. To obtain the exact gain of the amplifier, we add a positive correction term $A_{p,\mathrm{VOA}}$ to G_p to account for the attenuation of the p-the VOA, which is constant for each EDFA and known *a priori*. We emphasize that this term is only needed to accommodate the fact that in our testbed the EDFA and VOA virtually behave as a single device. In the second use-case, we demonstrate the benefits of the link tomography to detect EDFA soft-failures, such as gain tilt.

3. Experimental setup and discussion

The experimental testbed used in this work is shown in Figure 1(a). The transmitter is composed by a 4-ch 84 GSa/s digital-to-analog converter (DAC), and a commercially available C-band optical multi-format transmitter comprising a quad-set of driver amplifiers and a DP IQ-modulator. Two tunable external cavity laser (ECL) sources were utilized to cover the tested wavelengths in the C-band (1527.5 – 1565 nm), and L-band (1570 – 1600 nm). Then, a 64-GBd DP 16-QAM signal generated with a 2^{15} random bit sequence and shaped with a root-raised cosine pulse filter with roll-off factor 0.1 was transmitted over a 280-km SMF link consisting of two 80-km spans (1st and 3rd span) and two 60-km spans (2nd and 4th span). All three in-line EDFAs deployed in the link were operated in the wavelength intervals of 1540-1565 nm (C-band) and 1570-1605 nm (L-band). After the signal is received, it is digitized by a 200 GS/s RTO and followed by the receiver-DSP chain detailed in section 2. The emulation of the multiple WDM carriers was performed by varying tuning the ECL in steps of 2.5 nm, since, in essence, this was a single-channel experiment.

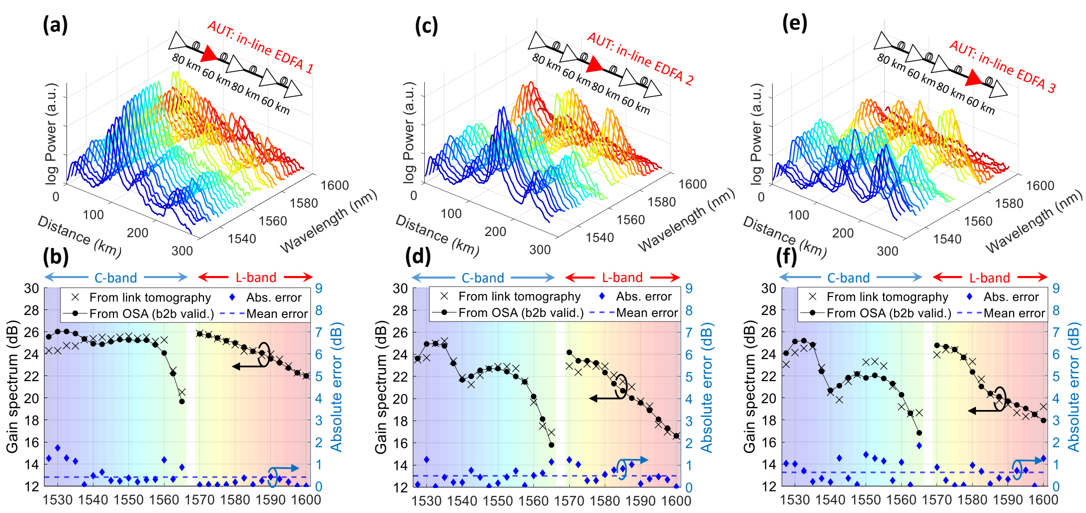

Figure 2: Link tomography used to estimate the spectral gain profile in the commissioning mode when the AUT is the in-line EDFA (a) 1, (c) 2 and (e) 3. Estimated gain spectrum for the in-line EDFA (b) 1, (d) 2 and (f) 3. Results obtained for $\varepsilon = 0.004$, $N_{seg} = 280$, $N = 29$.

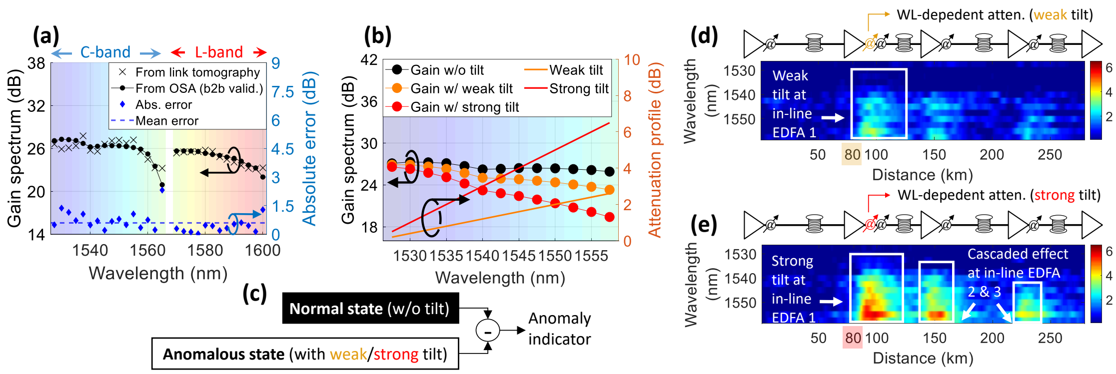

Figure 3: (a) Estimated gain spectrum of the AUT 1 in the operation mode. (b) Gain spectra of the AUT 1 without and with emulated gain tilts. (c) Anomaly detection scheme to visualize gain tilt. Anomaly indicator for (d) weak and the (e) strong tilt profiles.

In this work, we introduce two gain characterization methodologies: (1) *commissioning* and (2) *operation* modes. We define the *commissioning* mode as a procedure where the *p*-th amplifier under test (AUT) spectral gain is measured after setting a constant input power (- 8 dBm in this work). We achieve this by calibrating the (*p*-1)-th VOA whenever a new wavelength is set. In the *operation* mode, we measure the effective gain imposed by the AUT on each WDM channel *without intervening in the link*. Both methodologies were benchmarked against the back-to-back (b2b) validation of the AUT, acquired from the optical spectrum analyzer (OSA) and illustrated in Figure 1(c). Figure 2(a,c,e) show the link tomography obtained from the *commissioning* mode for the 1st, 2nd and 3rd in-line EDFAs. As indicated in Figure 2(b,d,f), the gain spectra obtained from the link tomography (cross-like markers) show very good agreement relative to the OSA b2b validation (circle-like markers), with mean absolute errors (dashed line) of 0.4, 0.5 and 0.6 dB for the 1st, 2nd and 3rd in-line EDFA, respectively. Note that, the link tomography can be obtained following the *operation* mode as well. In Figure 3(a), we provide the obtained gain spectrum of the 1st in-line EDFA (with mean absolute error of 0.6 dB) in the *operation* mode (without intervention in the link).

To inspect the capability of our proposal in diagnosing gain tilts caused by the 1st AUT, we use the *operation* mode to obtain the link tomography. The emulation of the gain tilt is then performed by inserting a wavelength-dependent attenuator at the output of the AUT 1 programmed with two attenuation profiles (from 1527.5 to 1557.5 nm), i.e., weak/strong tilt (straight lines in Figure 3(b)). The b2b characterization of the AUT 1 (gain without tilt) and of the set AUT 1 + wavelength-dependent attenuator (gain with weak/strong tilt) are plotted in Figure 3(b). To visualize the anomalies, we simply subtract anomalous link tomography from the normal state link tomography, i.e., without tilt (Figure 3(c)). As shown in Figure 3(d) and Figure 3(e), the anomaly indicator captures with fidelity the two tested tilt profiles, which are denoted by the gradual coloring of the heat map (stronger in Figure 3(e)) along the wavelength axis starting at approximately 80 km. In Figure 3(e), it is also possible to visualize a strong cascaded effect at the in-line EDFA 2 and 3 due to the fact that the tilt at the in-line EDFA 1 becomes so severe that the subsequent amplifiers can no longer maintain a constant output power. Therefore, this proves that the proposed scheme can be efficiently used to detect failures in EDFAs without additional testing equipment and access to infrastructure information.

4. Conclusion

In this work we have proposed and experimentally demonstrated a receiver-DSP scheme that extracts distance-wise, wavelength-dependent channel power evolution from the received signal. This scheme can be applied to estimate the gain spectra of C+L-band EDFAs with maximum mean error of 0.6 dB and has proven to be efficient in visualizing soft-failures like amplifier gain tilts. This approach can be used as a fault detection tool in optical multiband systems.

5. Acknowledgment

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6. References

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