

Extending the OCATA Digital Twin to the Frequency Domain

M. Devigili^{1,*}, M. Ruiz¹, N. Costa², C. Castro³, A. Napoli³, J. Pedro^{2,4}, and L. Velasco¹

¹ *Optical Communications Group (GCO), Universitat Politècnica de Catalunya (UPC), Barcelona, Spain*

² *Infinera Unipessoal Lda., Carnaxide, Portugal*

³ *Infinera, Munich, Germany*

⁴ *Instituto de Telecomunicações, IST, Lisboa, Portugal*

*e-mail: mariano.devigili@upc.edu

ABSTRACT

We extend the OCATA time domain digital twin to the frequency domain. It is shown that deep learning-based models enable to predict the linear and nonlinear impairments affecting the optical constellations, whereas analytical models are suitable to estimate the filter penalties affecting the optical spectrums. Illustrative results show the benefits of the proposed approach for failure detection and identification.

Keywords: digital twin, failure management, optical networks.

1. INTRODUCTION

The term Digital Twin (DT) was first introduced by Michael Grieves in 2003 as a “virtual, digital equivalent to a physical product” [1]. A DT can be defined as “a virtual simulation process that integrates multiple physical quantities, multiple scales, and multiple probabilities using data from physical models, sensor updates, and operational histories” [2]. DTs have been recently proposed to model optical communications where can be defined as virtual replicas of the optical layer.

Examples of applications of an optical layer DT are intelligent fault management and misconfiguration detection, where the real optical signal can be compared to the one generated by the DT to identify discrepancies and estimate their root cause. Note that the same objective can be achieved by applying different methods, like analytical models, simulation, or deep learning (see, e.g., [3]-[5]).

The authors in [6] firstly propose deep learning (DL)-based concatenation models to model linear interference (LI) impairments arising in optical erbium doped fiber amplifiers (EDFA), optical fibers, and wavelength selective switches (WSS), and created a DT for the optical time domain named OCATA [6]. Such DT is able to reproduce the LI and non-linear interference (NLI) noise that impact on optical signals being propagated through the different optical network components that support a lightpath by concatenating DL models of each component. In our previous work [7], we analyzed illustrative use cases to show the application of the proposed dual domain DT and showed its potential to increase the accuracy of the performance estimation for lightpath affected from LI noise. In this work, we extend that analysis by analyzing the same illustrative use cases for a lightpath affected by NLI impairments.

2. OCATA DIGITAL TWIN AND USE CASES

An illustrative network scenario with n ROADMs is represented in Fig. 1b. Each ROADM consists of two wavelength selective switches (WSSs) and an EDFA (except the last one). The ROADMs are connected by optical links which may consist of several fiber spans and inline EDFAs. We assume that the DT has access to the spectral measurements collected from the optical spectrum analyzers (OSAs) in the ROADMs that the lightpath traverses, as well as optical constellations collected from the coherent receiver in transponder (TP) B.

Figure 1b illustrates the proposed extension of the OCATA DT, consisting of the concatenated DNNs for the time domain analysis of the transmitted data signal whereas analytical models are used for the frequency domain. The DNNs model the propagation of constellation points (CPs) in the ROADMs and into optical links, whereas analytical models are used to model the spectral impairments inside the ROADMs. Measurements collected from the network can then be compared to the expected signals generated using the TF-DT.

Let us illustrate the application of the OCATA DT through the analysis of the use cases depicted in Fig. 2. In this case, the configuration a) corresponds to the normal network operation, i.e., without any failure or misconfiguration; b) corresponds to faulty WSSs in an intermediate node where there is Filter Shift (FS) that cuts an edge of the optical spectrum; c) faulty WSSs in an intermediate node affected by Filter Tightening (FT) which cuts both edges of the optical spectrum; d) illustrates the impact of having faulty EDFA at an intermediate node introducing excessive amplified spontaneous emission (ASE) noise to the optical signal. To sum up we consider two failures arising in the frequency domain and one failure generated in the time domain. The objective of this analysis is to understand the benefit of a dual domain DT to detect and identify failures in lightpath affected from LI and NLI impairments.

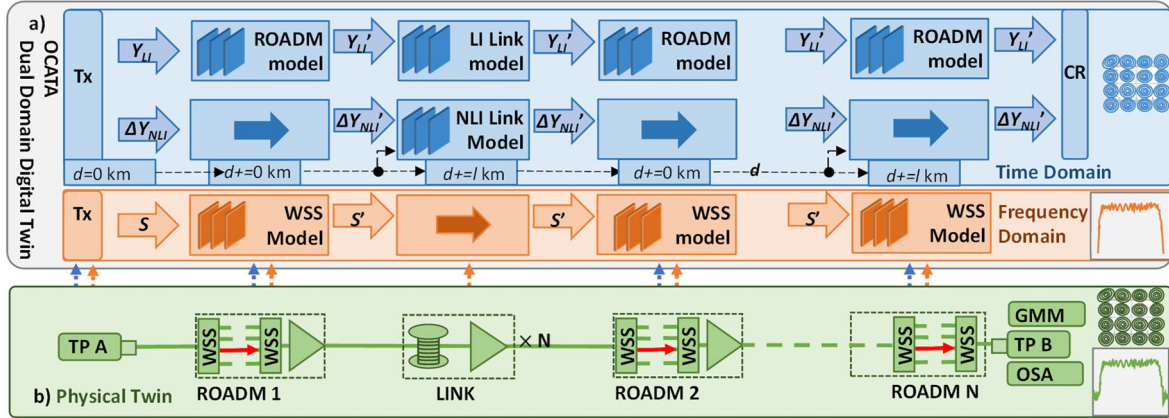


Figure 1. The optical constellation and spectrum generated by an optical lightpath (a) and their virtual replicas based on the OCATA dual time and frequency domain digital twin.

3. MODELS

Figure 1a shows the model of the envisioned TF-DT. In the time domain, the proposed DT predicts LI impairments such as group velocity dispersion (GVD), fiber loss higher order dispersion, filter losses and ASE noise and NLI impairments such as self-phase modulation (SPM) and cross-phase modulation (XPM).

The time domain analyzer consists of three main blocks: *i*) a *constellation generator* with a transmitter model that defines an input optical signal in the time domain and generates its optical constellation. Each constellation point is then sampled and modeled with a Gaussian bivariate distribution. Then, for every optical constellation X , a set of features Y_{LI} that summarizes X is generated. The features Y_{LI} are extracted employing the Gaussian mixture models (GMM)s and consist in the mean and covariance matrix.; *ii*) a *propagation model* that uses Y as features (inputs) of the DNNs modeling the LI impairments. Differently, the DNNs modeling the NLI impairments received as input the NLI residual features ΔY_{NLI} [5]. This model is a data-driven end-to-end machine learning (ML) approach based on the concatenation of DNNs (i.e., the ROADMs' and links' models) which are trained, tested and validated with the synthetic data generated, in this work, using a MATLAB-based coherent system simulator; and *iii*) a *constellation reconstruction* block that converts the propagated features into a received optical constellation.

Differently, in the frequency domain, a theoretically calculated optical spectrum is generated to estimate filtering penalties following the model presented in [4]. The frequency domain analyzer consists of two main elements: *i*) a spectrum generator that generates an ideal square pulse shaped by a raised cosine filter and *ii*) an analytical model that emulates a WSS as proposed in [8]. The impact of the WSS filtering is modelled by concatenating the WSS transfer functions, resulting in a noise-free version of the optical signal.

4. RESULTS

For the targeted test cases, a MATLAB digital coherent system simulator was considered to reproduce the physical layer. The simulated scenario emulates a core optical network with ten ROADMs (see Fig. 1b)

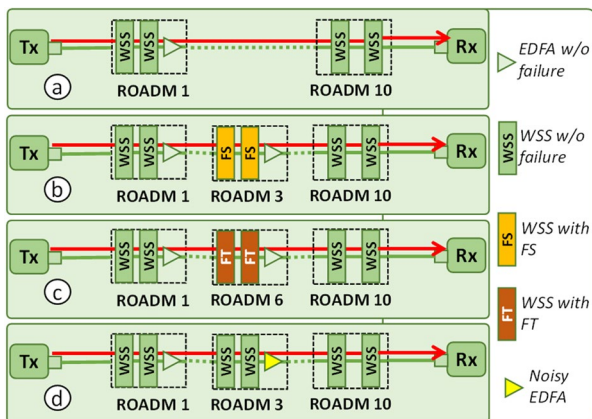


Figure 2. Considered use cases: correct operation (a), WSSs with FS (b) or FT (c) and noisy EDFA (d).

connected by 100km long optical fiber links, each composed of 2 spans of 50km and an EDFA, thus resulting in a total transmission distance of 900 km. We evaluate the performance of the TF-DT considering the transmission of a single 16QAM@64GBd channel, shaped with a root-raised cosine filter with a roll-off factor of 0.06 and with a 0 dBm launch power. The use of a standard single mode fiber with attenuation parameter of 0.21 dB/km and chromatic dispersion parameter of 16.8 ps/nm/km is assumed. The nonlinear parameter is assumed of $1.3 (W \cdot km)^{-1}$ when the NLI impairments are taken into account. The pulse propagation along the SSMF is modelled by solving the nonlinear Schrödinger equation using the split-step Fourier method with propagation step size of 1 km. The EDFAs, used to fully compensate the fiber and ROADM losses, are modelled as having a noise figure of 4.5 dB.

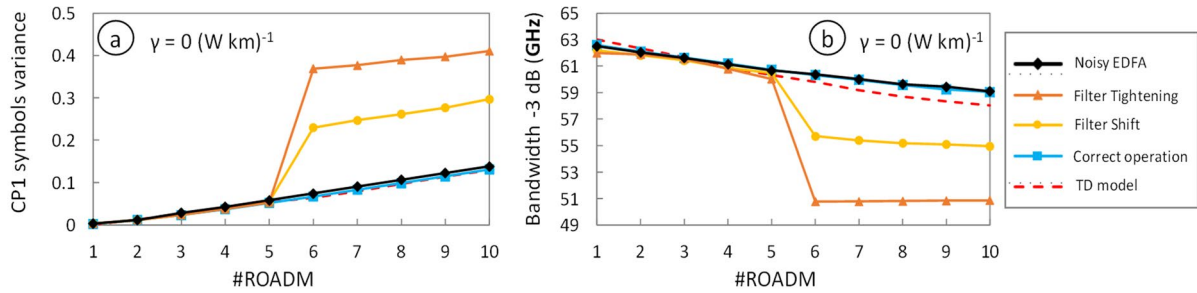


Figure 3. Result analyzing (a) constellation, (b) spectrum considering only the LI impairments [7].

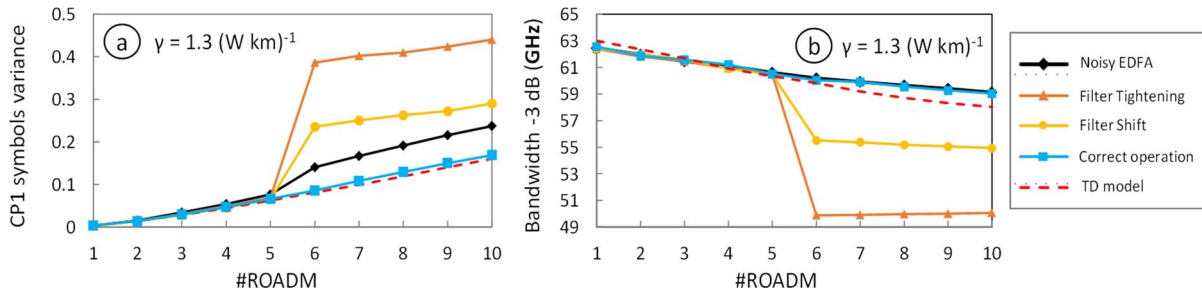


Figure 4. Result analyzing (a) constellation and (b) spectrum when considering both LI and NLI impairments.

The cascade filtering penalties are considered employing measured transfer functions from a 1×4 WSS filter with 75 GHz bandwidth. Finally, DSP blocks capable to perform an ideal dispersion compensation and phase recovery are considered in the Rx. The filter failures are modelled assuming 8 GHz FS and 16 GHz FT whereas the EDFA failure is modelled by adding 10 dB of extra ASE noise to the channel in the amplification process.

Figure 3 and Fig. 4 shows the average results as a function of the number of nodes (and distance) obtained after 20 PBRs simulations for each case. Figure 3 details the results when considering only LI impairments whereas Figure 4 shows the results obtained considering LI and NLI impairments. The four use cases described in Section 2 are evaluated using four different models: the OCATA DT [5] and the expected spectrum of the OCATA digital twin. Figure 3a and Fig. 4a show the symbol variance of CP 1 versus the number of nodes. As expected, the variance increases with the number of nodes (and distance). Figure 3b and Fig. 4b shows the -3dB spectral bandwidth versus the number of nodes. As expected, the bandwidth decreases as the number of cascade WSSs (2 WSS/node) increases.

Comparing the results in Figure 3 and Fig. 4, we observe that symbol variances and the spectral bandwidths of the filter failures have a similar evolution considering NLI impairments or not. In fact, for both the link modelling scenarios the filter failures can be clearly recognized analyzing symbol variance and spectral bandwidth since both metrics go simultaneously to their maximum and minimum values, respectively, after the signal crosses the faulty WSSs. In the case of EDFA failure, as expected it is not possible to detect excessive ASE by analyzing the received signal bandwidth that remained mostly unchanged in Fig. 3b and Fig. 4b. Differently, small changes in the variance of the received constellation points were observed when only LI impairments are considered (see Fig. 3a). On the other hand, the additional noise power produced by the EDFA failure induces SPM-induced NLI noise that clearly affects the optical constellation as shown in Fig. 4b (black curve) where the symbol variance increases after the failure in the intermediate node. Therefore, the results shown in Fig. 3a are overall in accordance with the results obtained in [7] and shown in Fig. 4a, where only LI impairments are considered. However, failures causing an increase of the fiber transmission launching power can be detected analyzing the optical constellations since these failures induce additional NLI impairments.

Therefore, taking into account NLI impairments all the three considered failures, i.e., FS, FT and noisy EDFA, can be detected by analyzing the optical constellations and comparing the received features with expected ones generated with the OCATA time domain digital twin.

Differently the OCATA frequency domain DT can be useful to perform failure identification. In fact, by comparing the expected and received spectra and constellations it is possible to distinguish the considered EDFA failure from the filter failures as the former one does not manifest itself in the frequency domain. Moreover, analyzing the spectrum allows to distinguish between FS and FT. Figure 5 shows the average lower and higher relative frequencies of the observed channel at -6 dB as function of the number of nodes. These features represent the boundaries of the optical spectrum and thus allow to differentiate between FT and FS. In fact, after the signal crosses the WSSs affected by FT there is a significant mismatch between the actual and expected values of these features. Differently, in case of FS only one of two edges of the optical spectrum mismatch from its expected value. In this sense, we can claim that developing a dual time and frequency domain DT has

intrinsic advantages as enables to identify failures generated in the frequency domain analyzing the spectrum and to identify failures generated in the time domain analyzing both the spectrum and the optical constellations.

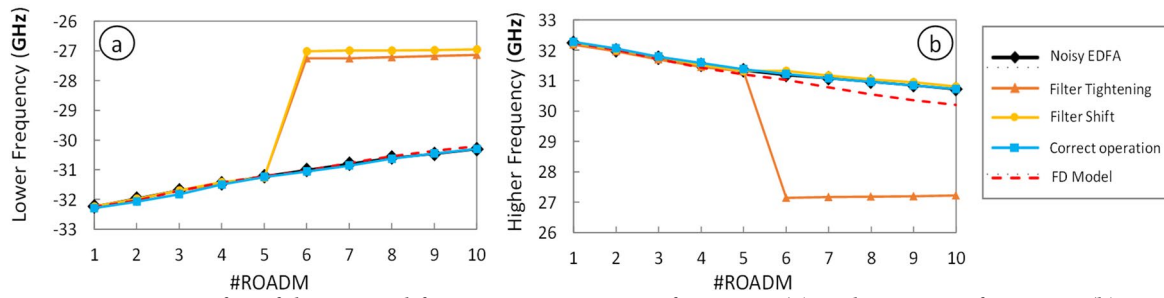


Figure 5. Benefits of the spectral features, i.e., minimum frequency (a) and maximum frequency (b).

5. CONCLUSIONS

The OCATA time domain digital twin is extended to the frequency domain to generate the virtual replica of an optical signal. We show that by analyzing the time domain (constellation) and the optical spectrum OCATA can detect and distinguish among several failures, thus overcoming several limitations of previously proposed approaches.

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