

Experimental Validation of Deep Learning-based Models for Optical Time Domain Analysis

M. Devigili¹, D. Sequeira^{1,2}, C. Santos³, M. Ruiz¹, B. Shariati³, N. Costa², A. Napoli⁴,
J. K. Fischer³, J. Pedro², and L. Velasco^{1*}

¹Optical Communications Group (GCO), Universitat Politècnica de Catalunya (UPC), Barcelona, Spain (*luis.velasco@upc.edu);
²Infinera Unipessoal Lda., Carnaxide, Portugal; ³Fraunhofer Heinrich Hertz Institute (HHI), Berlin, Germany; ⁴Infinera, Munich, Germany.

Abstract: Optical constellations generated by Deep Learning models trained with datasets generated through simulation are compared to experimentally collected ones. The obtained high accuracy enables its application for optical time domain analysis in complex network scenarios. © 2023 The Author(s)

1. Introduction

Optical networks are complex systems that may use different optical fiber types and devices that can all provide a variety of system parameters. In this regard, optical telemetry data [1] collected from different *observation points*, such as optical coherent receivers, can not only help to minimize the required design margins therefore maximizing the overall network capacity, but also be useful for many other use-cases, from transmission system characterization to real-time autonomous networking, and failure management, just to mention a few. More precisely, the advances in optical coherent receivers and digital signal processing (DSP) have not only paved the way to improve the overall optical network performance, but can also provide a large set of performance parameters and signal measurements that are available for collection [2]. Specifically, the analysis of the in-phase and quadrature (IQ) optical constellation can reveal several physical layer impairments in optical connections (*lightpaths*).

In this regard, the authors in [3] first proposed a deep learning (DL) -based analysis of IQ optical constellations to model linear impairments arising in optical erbium doped fiber amplifiers (EDFA), optical fibers, and wavelength selective switches (WSS) and created a digital twin for the optical time domain named OCATA (an open dataset is available in [4]). Such tool is able to evaluate the linear and non-linear noise that impacts the optical signals propagated through the different optical network components by concatenating DL models that model each of these components. Those models have been previously trained from datasets generated using a MATLAB simulator based on the split step Fourier Method (SSFM), so the concatenated model for the lightpath is available at setup time. As a result, OCATA generates expected optical constellations that mimic the ones that would be received by the coherent optical receiver. In this work, we compare the constellations generated with OCATA with the ones obtained experimentally in [5] to evaluate the accuracy of the models that were trained with datasets from simulation.

2. Experimental setup and OCATA model

Fig. 1a depicts the experimental set up deployed in HHI premises. At the transmitter (Tx) side, 21 DP-16QAM WDM channels with symbol rates of 28 and 32 GBd and channel spacing of 50 GHz were generated using an optical multi-format Tx (OMFT). For simplicity, in this analysis, we focus on the *X* polarization. The modulation losses are compensated by an EDFA (labeled 19 in Fig. 1a). Afterwards, the resulting WDM signal is launched into a reconfigurable optical add/drop multiplexer (ROADM) composed of a WSS, an attenuator and an EDFA. The WDM signal is launched into the optical fiber with optimal launch power of -1 dBm and is then propagated through up to three spans, each composed of two spools of 40 km. For different distances, the setup connects the span EDFAs directly to the coherent receiver using an optical switch (OS). After crossing EDFA 11, the signal is filtered by an optical tunable filter (OTF) with measured bandwidth of 37.34 GHz and is pre-amplified by EDFA 130.

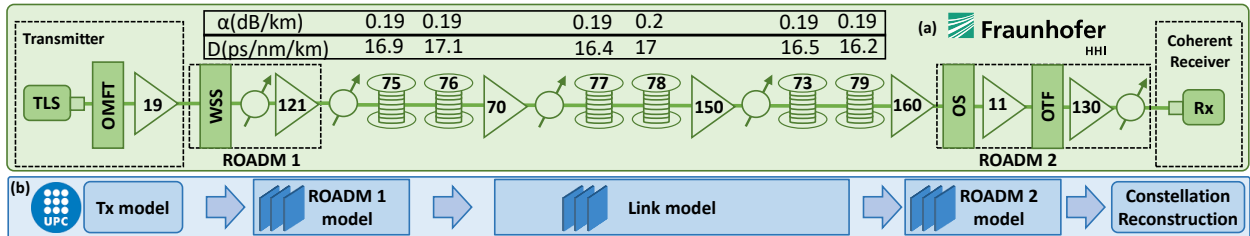


Fig. 1. Experimental setup (a) and concatenated DL models (b).

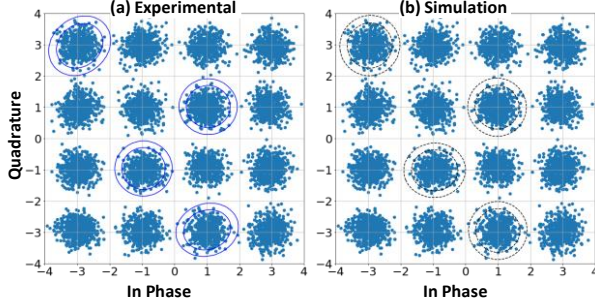


Fig. 2. Experimental (a) and simulated (b) optical IQ constellations.

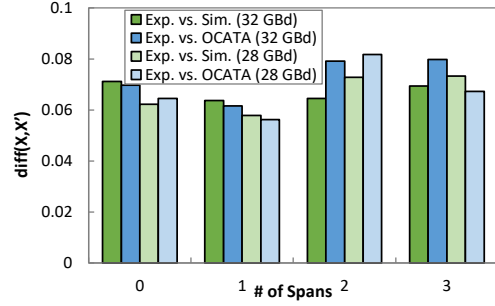


Fig. 3. Comparison of experimental, simulation and OCATA samples.

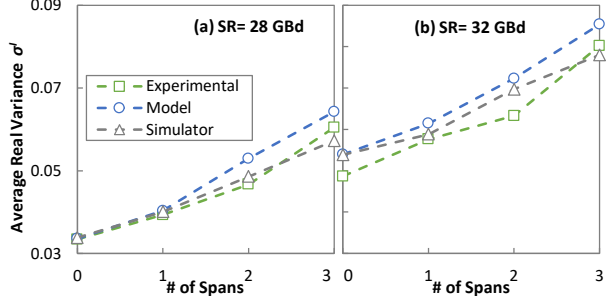


Fig. 4. Average real variance for SR=28 GBd (a) and SR=32 GBd (b).

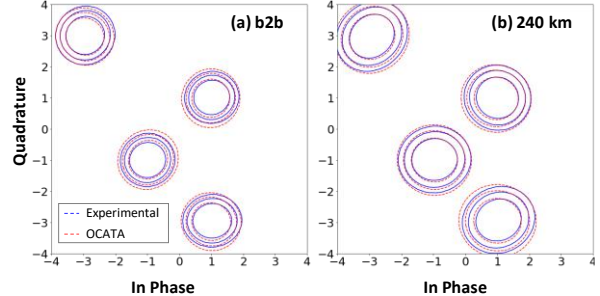


Fig. 5. Experimental and OCATA (b) distributions.

The same setup was simulated in MATLAB. Fiber propagation is emulated through the SSFM considering a step size of 100 meters. Fiber loss and dispersion parameter are set according to the measured parameters shown in the inset in Fig. 1a, and a nonlinear fiber parameter $\gamma=1.14 \text{ W}^{-1}\text{km}^{-1}$ was employed. Gains and noise figures of the EDFAs are the same as the experimental ones. The WSSs are emulated using measured transfer functions from a 1×4 WSS with 50 GHz bandwidth, while the OTF is emulated via an analytical transfer function with the same bandwidth as the experimental one. Fig. 1b shows the concatenation of DL models, where a Tx model generates the expected features input of the add ROADM, which is followed by a link model (except for the back-to-back (b2b) case). Finally, ROADM 2 model emulates signal dropping and distributions of all the constellations points (CP) are reconstructed.

3. Results and discussion

The MATLAB simulator was used to generate datasets with over 8,200 IQ CPs per simulation. The DLs were trained and tested on datasets from 30 and 10 simulations, respectively. Different DL models were generated for the add ROADM, the drop ROADM and for the optical links, which included also nonlinear noise. All models followed the same structure: 20 input neurons, i.e., 5 features \times 4 CPs, 2 hidden layers with 10 neurons, and using: *i*) hyperbolic tangent (*tanh*) activation function; *ii*) root mean squared propagation as optimization algorithm; *iii*) training stage with up to 5,000 epochs; and *iv*) mean square error as loss function. In the experiment, 248,400 IQ CP samples were collected and randomly down sampled to 8,200 IQ CP samples (same simulation). Different transmission distances are considered: *i*) b2b; *ii*) 80 km, *iii*) 160 km and *vi*) 240 km. The comparison between experimental, simulation, and OCATA IQ optical constellations is based on five features extracted from the IQ samples using Gaussian mixture models (GMM): *i*) real and imaginary means (μ^I, μ^Q); *ii*) real and imaginary variances (σ^I, σ^Q) and *iii*) covariance (σ^{IQ}).

Experimental and simulated IQ constellations with SR 32 GBd obtained after transmission along three spans are presented in Fig. 2; the Gaussian distributions of CPs 1, 7, 10 and 15 obtained with the GMM are shown. The Euclidean distance $\text{diff}(X, X')$ comparing features from experimental (X) and simulated or OCATA (X') IQ constellation samples is plotted in Fig. 3 for the considered symbol rates. In all cases, a Euclidean distance below 0.1 is observed. Fig. 4 shows the average σ^I after different number of spans for IQ constellation samples. We observe minor variations only between experimental, simulated, and OCATA IQ constellations, with maximum relative error below 14%. Finally, the Gaussian distributions of the four predicted CPs are compared with the experimental ones in Fig. 5, where the high accuracy of OCATA is clearly observable. In view of these results, the high accuracy of OCATA has been experimentally validated, which also validates this tool as digital twin for optical time domain analysis.

References

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