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Optical Signal Spectrum Prediction Using Machine Learning and In-line Channel Monitors in a Multi-span ROADM System

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Abstract *We measure the performance of separately characterized machine learning-based EDFA models for predicting the optical power spectrum evolution in a 5-span system with six ROADM nodes deployed in the COSMOS testbed, which achieve a mean absolute error of 0.6–0.7 dB after 10 EDFAs under varying channel loading configurations. ©2022 The Author(s)*

Introduction

Adaptive and scalable optical systems employing reconfigurable optical add-drop multiplexer (ROADM) units and flex-grid dense wavelength-division multiplexing (WDM) techniques have been enabling various applications and services that require high capacity and low latency in the underlying optical network. The erbium-doped fiber amplifier (EDFA) is a key hardware component that has been widely deployed in optical transmission systems, and can have a large impact on the end-to-end system performance such as the optical signal-to-noise ratio (OSNR) and quality of transmission (QoT)[1], which depends on the power level of individual wavelength signals. Characterizing the gain spectrum profile of an EDFA is challenging since it is not only a complex function of many parameters such as the gain setting, channel loading configurations, and input power levels, but also a hardware-specific property of individual EDFA components. Since a reconfigurable end-to-end optical link through a mesh ROADM network may include multiple EDFAs of different types (e.g., preamp, booster, and in-line), the multiplicity of system configurations complicates the collection of corresponding end-to-end datasets. Through the use of pre-deployment lab data collection, component-level EDFA gain spectrum modeling for use with QoT estimation methods can provide potentially efficient and scalable power evolution prediction in such multi-span systems.

Recent work has focused on the gain spectrum modeling and optical channel power prediction of EDFAs using both analytical models[2] and machine learning (ML) approaches[3],[4]. It has been shown that ML-based EDFA models using neural networks trained on large measurement datasets can achieve accurate component-level modeling. Multi-span systems with multiple EDFAs have also been considered, with a focus on power evolution and OSNR prediction[5],[6]. In particular, recent work[5] used end-to-end data collection and showed that using separate amplifier models can provide accurate end-to-end results. However, this work did not consider separately characterized EDFAs and used bench-top optical spectrum analyzers (OSAs) to measure the spectrum. Separate data collection using the built-in optical channel monitoring (OCM) capabilities of the ROADM units would allow for flexible in or out of system characterization and re-training without the need of extra bench equipment. However, built-in OCMs are less accurate and need to be studied for use in this application.

In this paper, we study optical signal spectrum prediction of a multi-span system consisting of ROADM nodes constructed using 95 channel, *separately characterized* Lumentum ROADM-20 whitebox units, deployed in the programmable COSMOS testbed[7]. For each EDFA in the multi-span system, we collect a comprehensive set of power spectrum measurements under diverse channel loading configurations using the in-line OCMs that are built into the ROADM-20 whitebox units. Using the separately collected datasets, we develop component-level EDFA gain spectrum models using deep neural networks (DNNs), which predict the output power spectrum based on the channel loading configuration and input power spectrum. Transferring such individual models to a collective multi-span system, extensive experiments with diverse channel configurations show that the trained DNN-based EDFA model can accurately predict the power spectrum after 10 EDFAs with a mean absolute error (MAE) of 0.73 dB and 0.61 dB with two 5-span metro-scale configurations, respectively.

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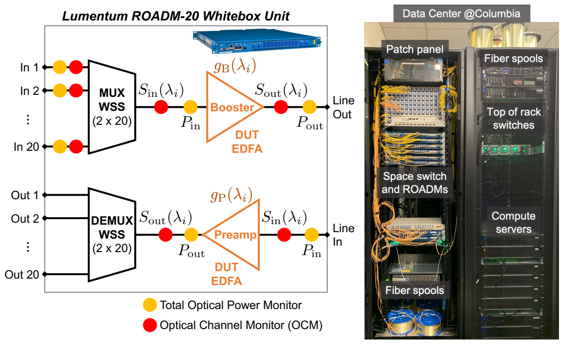

Fig. 1: (Left) Block diagram of the Lumentum ROADM-20 whitebox unit with built-in optical power monitors, which are used for the EDFA gain spectrum measurements. (Right) The programmable optical network in the COSMOS testbed.

Data Collection and DNN-based EDFA Models

We focus on characterizing the gain spectrum of EDFAs that are part of the commercial-grade Lumentum ROADM-20 whitebox units deployed in the COSMOS testbed. Each ROADM unit consists of two optical amplifiers: a receive preamp EDFA at line in and a transmit booster EDFA at line out, and various OCMs, as shown in Fig. 1. For the gain spectrum measurements for each device under test (DUT) EDFA, a comb source with 95$\times$50 GHz channels is used to generate the WDM spectrum in the C-band. In the case with a DUT booster EDFA, the MUX wavelength selective switch (WSS) of the same DUT ROADM is used for channel loading configuration and spectrum flattening. In the case with a DUT preamp EDFA, channel loading configuration and spectrum flattening are performed using the DEMUX WSS of an auxiliary ROADM with one drop port connected to the line in port of the DUT ROADM.

We collect 31,680 signal power spectrum measurements over 250 hours using 10 EDFAs (five preamps and five boosters), each of which is configured with the same setting of a target gain of 18 dB in the constant high-gain mode with no gain tilt. For each EDFA, 3,168 pairs of input and output power spectrum measurements, $S_{\mathrm{in}}(\lambda_i)$ and $S_{\mathrm{out}}(\lambda_i)$, are collected using the built-in OCMs with diverse channel configurations. These include different numbers of loaded channels $n \in \{1, 2, \cdots, 95\}$ with varying power levels in each channel. The total input and output power of each EDFA, P_{in} and P_{out}, are also recorded using the built-in photodiodes (PDs). Note that the built-in Lumentum ROADM-20 OCMs have a channel power measurement resolution of only 0.1 dB.

One component-level DNN model is created for each EDFA for its gain spectrum prediction using the collected measurements with the following architecture. Each DNN consists of six fully connected layers: one input layer, four hidden layers with 256/128/128/128 neurons, and one output layer. The input features include $S_{\mathrm{in}}(\lambda_i)$ and a 95-dimensional binary vector indicating the channel loading configuration, and the output layer predicts $S_{\mathrm{out}}(\lambda_i)$. Each DNN model is trained using the mean square error (MSE) across loaded channels as the loss function and the Adam optimizer, with the ReLU activation function at all layers and a learning rate of 0.01 over 500 epochs.

The collected power spectrum dataset for each EDFA under varying channel configurations and input power levels is divided to training and testing sets with a split ratio of 80%–20%. Evaluation of the DNN model performance shows that 80% and 97% of the test dataset has a mean absolute error (MAE) on the output power spectrum prediction that is within 0.1 dB and 0.2 dB, respectively.

Experimental Setup and Results

We conduct experiments using the open-access COSMOS testbed[7] that is being deployed in West Harlem, New York City. The testbed is designed to facilitate research and experimentation with advanced wireless and optical technologies in real-world scenarios. Fig. 1 shows the main components of COSMOS' programmable x-haul optical network at Columbia University[8], which include a Calient S320 320$\times$320 space switch, a DiCon 16$\times$16 space switch, eight Lumentum ROADM-20 whitebox units, a spooled fiber plant, and dark fiber connections to the colocation site at 32 Avenue of the Americas (32 AoA).

Fig. 2 depicts the experimental setup in the programmable COSMOS testbed, which consists of six ROADM nodes and five fiber spans. Each ROADM node is constructed using two Lumentum ROADM-20 whitebox units with one through port between the east-west WSS pairs. All fiber spools and dark fiber pairs are connected to the space switches, which support programmable connections to each ROADM unit for forming different network topologies. We consider two 5-span configurations with different lengths: 10-25-25-10-10 km and 10-40-50-32-32 km, where each 32 km span corresponds to one dark fiber link. A shaped comb source with different channel loading configurations is added to the first ROADM node and flattened via the MUX WSS before the first EDFA ($S_{\mathrm{in}}^{(1)}$). This signal then dropped at the sixth ROADM node after passing through five fiber spans. For each span configuration, we consider a total number of 101 channel loading con-

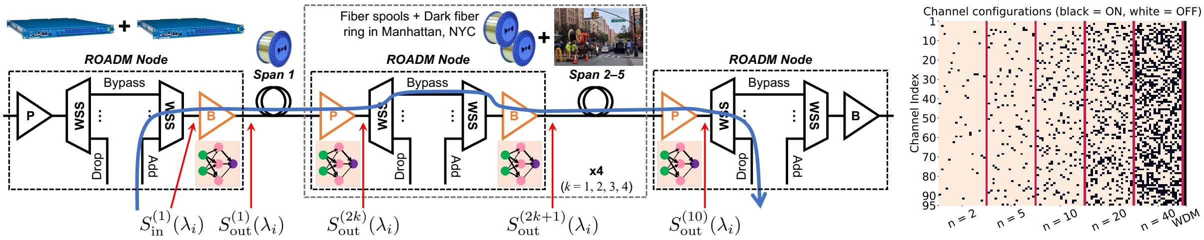

Fig. 2: (Left) The experimental setup consisting of six ROADM nodes and five fiber spans, where $S_{\text{in}}^{(1)}(\lambda_i)$ is a flattened multi-channel signal source with varying channel configurations, and $S_{\text{out}}^{(k)}(\lambda_i)$ is the predicted power spectrum at the output of the k-th EDFA. (Right) Random ($n \in \{2, 5, 10, 20, 40\}$) and WDM ($n = 95$) channel configurations used in the experiments.

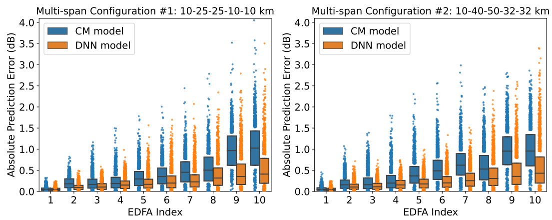

Fig. 3: Absolute error distribution of the power spectrum prediction after each EDFA using the CM and DNN models.

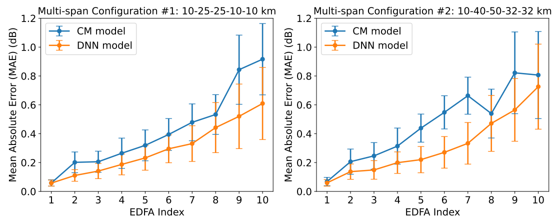

Fig. 4: MAE and standard deviation of the power spectrum prediction after each EDFA using the CM and DNN models.

Tab. 1: Distribution of per-channel absolute prediction error of the output power spectrum after 10 EDFAs and five spans.

Percentile Error [dB]	50-th	99-th	Max
10-25-25-10-10 km, CM model	1.03	2.44	4.05
10-25-25-10-10 km, DNN model	0.41	2.16	3.50
10-40-50-32-32 km, CM model	0.96	2.31	2.86
10-40-50-32-32 km, DNN model	0.43	2.37	3.39

figurations as shown in Fig. 2: (i) random channel configurations with $n \in \{2, 5, 10, 20, 40\}$ and 20 realizations for each value of n, and (ii) WDM channel configuration ($n = 95$).

The power spectrum evolution prediction across 10 EDFAs is performed using the developed component-level DNN model as well as the measured and calibrated passive loss of all fiber spools, dark fiber connections, and the MUX/DEMUX WSS. For performance comparison, we also implemented the analytical center of mass (CM) model for each EDFA using the gain spectrum measurements with single and WDM channel configurations[2]. In particular, for each channel configuration, the output power spectrum of each EDFA is predicted using the CM and DNN models, and the (predicted) output power spectrum of all previous EDFAs in the multi-span system. The per-channel absolute prediction error and MAE are calculated with respect to the ground truth measurements recorded by the built-in OCMs.

Fig. 3 shows the absolute error distribution of the output power spectrum prediction at each EDFA using the CM and DNN models, with the 25-th, 50-th (median), and 75-th percentiles indicated in the boxplot. The results show that for both models, the absolute prediction error accumulates across a larger number of EDFAs, and the DNN model achieves lower median prediction errors than the CM model. The distribution of per-channel absolute prediction error of the final output power spectrum after 10 EDFAs is summarized in Tab. 1. These results are comparable with the ML-based OSNR prediction results, which are based on OSA measurements of 40 end-to-end deployed channels on a 150 GHz grid[5].

Fig. 4 shows the MAE and standard deviation of the predicted output power spectrum after each EDFA. Specifically, with the 10-25-25-10-10 km span configuration, the accumulated MAE (standard deviation) across 10 EDFAs are 0.92 dB (0.25 dB) and 0.61 dB (0.25 dB) for the CM and DNN models, respectively. With the 10-40-50-32-32 km span configuration, the accumulated MAE (standard deviation) across 10 EDFAs are 0.81 dB (0.30 dB) and 0.73 dB (0.30 dB) for the CM and DNN models, respectively.

Conclusions

DNN-based component-level EDFA models are separately measured using built-in ROADM OCMs and evaluated for use in signal power spectrum evolution prediction in a multi-span ROADM system. The DNN models showed improved accuracy over analytical models. In future work, we will investigate methods to mitigate accumulated errors across multiple EDFAs.

Acknowledgements

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