Extending the OCATA Digital Twin for Optical Connections based on Digital Subcarrier Multiplexing

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Abstract: Time-domain digital twin models for single carrier and DSCM signals are developed that propagate features to estimate the impact of filter penalties on the BER. Results show remarkable accuracy, which is used for lightpath provisioning.

1. Introduction

Optical network digital twins (DT) have been lately developed to provide accurate and low computational real-time virtual replicas of Elastic Optical Networks (EON) [1], with many applications, e.g., for optical connection (*lightpath*) provisioning, real-time performance degradation detection, and network misconfigurations localization, among others [2]. Examples of DT for EON include GNPy [3] and OCATA [4]. EON was conceived in the last decade supported by the availability of reconfigurable optical add-drop multiplexers (ROADM) based on wavelength selective switches (WSS), and optical transponders (TP) capable to transmit single carrier (SC) signals. As technology advances, new generations of TPs become available, e.g., a new generation of flexible TP capable to transmit both SC, as well as digital subcarrier multiplexed (DSCM) signals is becoming available [5]. Compared with the SC counterpart, DSCM transmission have better nonlinear tolerance [6] and allows each subcarrier to be independently operated [7]. DSCM systems will also be deployed on ROADM-based EONs, which can impose significant optical filtering penalties as a result of narrowing the transmission passband bandwidth, an effect that becomes severer as ROADMs are cascaded in an optical connection [8]. In this context, optical network DTs need to be upgraded to be able to predict the physical layer impairments affecting not only SC but also DSCM signals. Such technology would complement DTs in all their applications. E.g., during lightpath provisioning phase, DTs can be used to predict the expected Quality of Transmission (QoT) of an optical signal before the lightpath is setup, and thus the optimal format of the signal to be transmitted, in terms of spectral-efficiency and/or resiliency, can be found.

In our previous works in [2], [4], we proposed OCATA as a time domain DT for optical SC signals, which includes machine learning-based models and algorithms for QoT estimation (specifically for the pre-forward error correction (FEC) bit error rate (BER)) and failure management. In this work, we extend OCATA to model DSCM signals. Equipped with such new models, we investigate the performance of SC and DSCM signals on realistic backbone optical networks.

2. Filtering Tolerance of SC and DSCM Signals

Fig. 1 introduces the considered scenario, where OCATA models an end-to-end lightpath between TP-A and TP-Z traversing *n* ROADMs and *n*-1 optical links using standard single mode fibers (SSMF). Route-and-select ROADMs with wavelength selective switches (WSS) and erbium-doped fiber amplifiers (EDFA) as booster and pre-amplifiers are considered. In this paper, we extend OCATA [4] with models for DSCM signals. OCATA models are based on the concatenation of Deep Neural Network (DNN), each modelling a single ROADM or a single optical link (Fig. 1b). For illustrative purposes, the spectrum of the generated 16-subcarrier DSCM signal after TP-A and the spectra after traversing several ROADMs are shown in Fig. 1a-c, as well as for the SC signal. As expected, we observe that the external digital subcarriers (DSC) suffer different filter penalties than the internal ones, which becomes more evident as soon as the number of cascading filters increases. Ultimately, the spectra of the most external DSCs are mostly filtered and those of the neighboring DSCs are also severely affected. However, the spectra of the internal DSCs do not look impacted and can be used for reliable data transmission. Therefore, differently to the SC transmission, where the whole signal degrades by physical layer impairments, in DSCM transmission, such degradation is gradual.

In view of the above, it seems important to provide models for the transmission of the different DSCs, in particular for ROADM propagation. Specifically, we consider differentiated DNN models for the ROADMs: *i*) for the two *external* DSCs (i.e., DSCs 1 and 16); *ii*) the two *intermediate* DSCs 2 and 15; and *iii*) *internal* DSCs 2-14. With such models, we target to: 1) analyze the tolerance of SC and DSCM signals to filter penalties; and 2) to verify the suitability of OCATA for lightpath provisioning so as to decide whether to use DSCM or SC for a given route (ROADMs and optical links) computed over the optical network topology.

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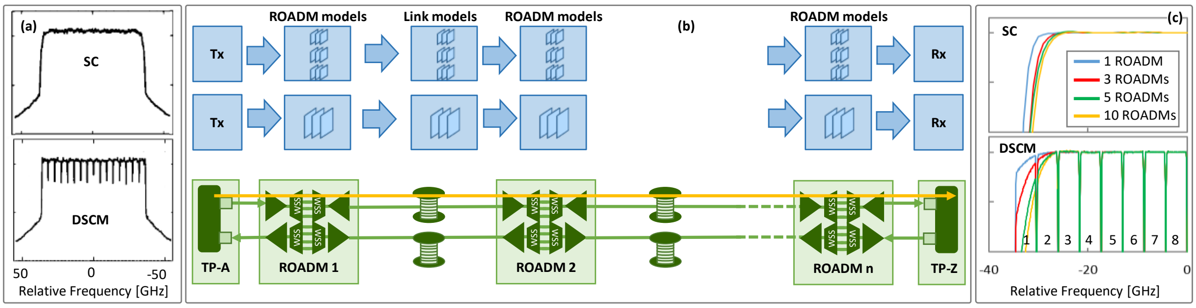

Fig. 1. Overview of the envisioned scenario. Optical data plane (in green) and OCATA DT (in blue) modeling SC and DSCM signals.

3. DT-based Provisioning for SC and DSCM signals

To simplify the analysis, we consider only three sub DSCs under test, i.e., one internal, one intermediate and one external. As for SC transmission [4], Gaussian Mixture Models (GMM) are employed to characterize *m*-QAM constellations with *m* bivariate Gaussian distributions. These latter can be summarized by a set of features $Y=\{Y_i\}$ for each constellation point (CP) *i* in *m*, that are then propagated through concatenated DNNs modeling impairments affecting the signals in an end-to-end lightpath. Due to the different cascade filtering penalties involving the DSCs (see Fig. 1c) specific ROADM models are designed for the three considered DSCs. Finally, different link models are designed for SC and DSCM signals since the latter are expected to be less impacted by both the nonlinear noise and amplified spontaneous emission noise due to their lower baud rate. Moreover, the OCATA DT is equipped with additional models that estimate the pre-FEC BER of the signal based on an additional feature Φ_{out} [2].

Based on the estimation of the pre-FEC BER, Algorithm I lightpath provisioning returns the best format of the signal to be transmitted. The algorithm receives: *i*) a connection request (*rq*) with the required data rate *R*, the selected route as a list of nodes *N*, the baud rate *B*, and the pre-FEC BER threshold, e.g., 10^{-4}; *ii*) parameters and trained models (*ml*) stored in OCATA; and *iii*) some operational parameters (*O*), including the allowed signal types *S* (e.g., SC and DSCM) and modulation formats *MF*. To address a provisioning request, the algorithm searches among the possible combinations of *S* and *MF* as given in the request.

Algorithm I. Lightpath Provisioning

INPUT: *rq, ml, O* **OUTPUT:** *format*

```
1:  Eval ← []
2:    for i in [O.S] and j in [O.MF]:
3:      Y_e ← ml.generateY(rq.D, rq.N, rq.B)
4:      Φ_out,e [i, j] ← ml.processPhiOut(Y_e)
5:      critical ← ml.QoTcl(Φ_out,e)
6:      if critical then
7:        BER_e ← ml.QoTrgr(Φ_out,e)
8:        if BERe < O.th then
9:          Eval[i, j] ← ml.BitRate(O.MF,O.B)
10: return getOptimalFormat(Eval, rq.R)
```

Therefore, for each possible configurations the algorithm generates the expected features Y_e and exploits them to compute the Φ_{out} feature (lines 2-4). That feature together with other lightpath details are given as inputs to a binary classifier that estimates whether the expected pre-FEC BER is above the given threshold *th*. If indeed the QoT is critical, a regressor is executed to estimate the pre-FEC BER (lines 6-7). Finally, if the estimated BER (*BERe*) is found to be lower than threshold *th*, the algorithm assigns an expected data rate to each configuration. The *Eval* matrix detailing the achievable data rate of the signal for each configuration after every node is used by a function that selects the optimal signal format (line 11).

4. Illustrative Results

A MATLAB-based simulator of a digital coherent system is employed to reproduce both SC and DSCM signal transmissions. In both cases, we consider a dual polarization Nyquist-shaped single-λ channel with a roll-off factor of 0.06, operating at 64 GBaud symbol rate and allocated into a 75 GHz spectrum grid. The DSCM signal is composed of 16 DSCs all operating at 4 GBaud spaced with a guard-band of 100 MHz. To simplify the analysis, we consider only 16-QAM as modulation format and pseudo random bit sequences (PRBS) with order equal to 17. The pulse propagation along the fiber is modelled by solving the Manakov equation using the split-step Fourier method with a propagation step-size of 1 km including effects such as fiber loss, arbitrary fiber birefringence, group velocity dispersion, polarization mode dispersion (PMD) and self-phase modulation. Each link consisted of 80-km SSMF spans characterized by fiber loss 0.21 dB/km, dispersion 16.8 ps/nm/km, PMD value 0.04 ps/km$^{1/2}$ and nonlinear coefficient 1.14 W^{-1}km^{-1}. The ROADMs are modeled by randomly concatenating the filter shapes of four different 1×4 WSSs which was obtained experimentally. The –3 dB optical bandwidth of the WSSs is approximately 71 GHz. The EDFAs' noise figure is 5 dB whereas its gain is set to compensate for the span loss and to restore the power to the optimal one at the fiber input (0 dBm for both the SC and DSCM signals). Note that each subcarrier has a launch power of -12.2 dBm and that both signals have a 34 dB OSNR at the transmitter. At the receiver side, digital signal processors capable of performing chromatic dispersion compensation and carrier phase recovery are considered, as well as a MIMO equalizer to compensate for the PMD.

OCATA models were trained and tested over 20 constellation samples each with approximately 20,000 symbols. Fig. 2a shows the variance σ characterizing CP 1 as a function of the number of ROADMs crossed. Both for SC

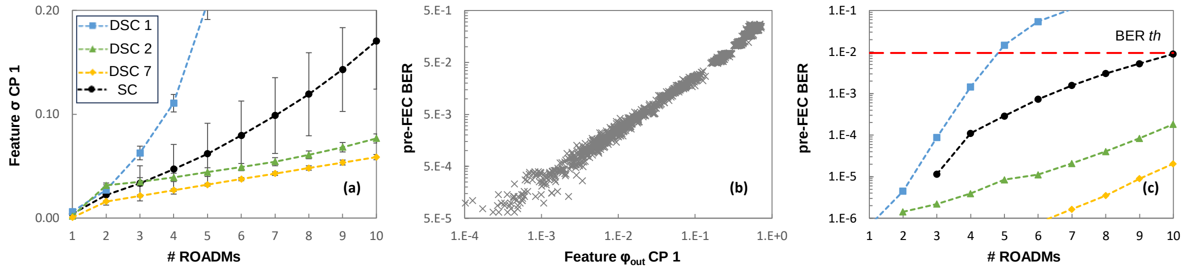

Fig. 2. Observations on the synthetic datasets: σ vs # ROAMDs (a), BER vs Φ_{out} (b), and BER vs #ROADMs (c).

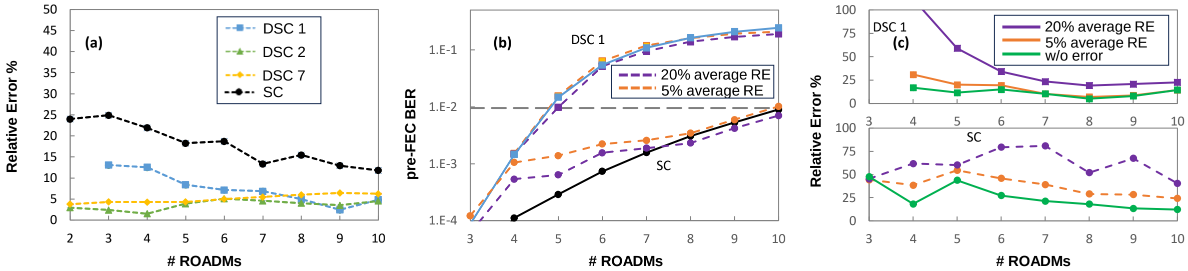

Fig. 3. Accuracy of the DT for physical layer modelling in estimated the expected σ 1 (a) and for QoT estimation (b,c)

and DSCM, we observe that the variance increases as function of this number. Interestingly, we observe different behaviors for σ. In the case of the external DSC σ grows exponentially with the number of ROADMs, anticipating a high impact on its pre-FEC BER; also, the SC signal exhibits high values. Note that σ for the intermediate and internal DSCs grows much more linearly. Fig. 2b shows the linear relationship between the pre-FEC BER and feature Φ_{out} (both in log scale). Note that the pre-FEC BER values hereby shown were obtained considering a minimum number of 100 errors, which is enough for pre-FEC BER values above 10^{-5}. In view of these results, we train a simple linear regression model to be used as QoT estimation as part of Algorithm I. Differently, to classify critical pre-FEC BER values we adopt low complexity binary classifiers. Finally, Fig. 2c shows the pre-FEC BER as function of the number of crossed ROADMs for SC and DSCM signals. We set arbitrarily a 1.5 dB design margin and therefore, for illustrative purposes, we plot a possible operational pre-FEC BER at 10^{-2}. According to the simulations, the external DSC 1 can traverse up to four ROADMs, whereas the internal and intermediate DSCs traverse all considered ROADMs with relatively low pre-FEC BER. As for the SC signal, it supports traversing up to 10 ROADMs before reaching the pre-FEC BER threshold.

Fig. 3a shows the performance of the OCATA models for SC and DSCM as function of the number of ROADMs. The DNNs were configured with the same hyperparameters and evaluated applying 5-fold cross validation over a total of 700 samples. We observe that the DSCM model provides a better overall accuracy than the SC one. Regarding pre-FEC BER estimation, the linear regression model was trained over 1140 samples and tested over the SC signal and for the external DSC. Fig. 3b shows the performance of the model when tested with features with 5% and 20% mean relative errors, respectively; in both cases the linear regression converges. Fig. 3c shows the relative error achieved by the linear regression model when tested with the previous features. Both for SC and DSCM signals, an average relative error of 5% in the modeling do not compromise pre-FEC BER estimation, which is the maximum value that can be tolerated.

Table 1. *Eval* matrix (data rate in Gb/s)

	16-QAM	
#ROADM	SC	DSCM
2	512	512
7	512	448
12	0	448

For illustrative purposes, Table 1 shows the *Eval* matrix computed by Algorithm I for three different lightpaths. In the case of the shortest lightpath with just two ROADMs in its route, both SC and DSCM transmission support the same data rate. However, when the number of nodes in the route increases, filter penalties impact on the external DSC, which reduces the data rate of the DSCM system, so the SC format is preferred. However, for longer routes, DSCM is still able to provide transport capacity.

To conclude, the feasibility of exploiting a time domain digital twin to perform lightpath provisioning for signal carrier and digital subcarrier multiplexed signals has been investigated. Results show good accuracy of the models to estimate the expected optical constellation and the pre-FEC BER.

References

[1] V. Lopez and L. Velasco, *Elastic Optical Networks: Architectures, Technologies, and Control*, Springer, 2016.
[2] L. Velasco *et al*., "Applications of digital twin for autonomous zero-touch optical networking," in Proc. ONDM, 2023.
[3] V. Curri, "GNPy model of the physical layer for open and disaggregated optical networking," JOCN, 2022.
[4] D. Sequeira *et al*., "OCATA: a deep-learning-based digital twin for the optical time domain," JOCN, 2023.
[5] H. Sun *et al.*, "800G DSP ASIC design using probabilistic shaping and digital subcarrier multiplexing," JLT, 2020.
[6] D. Welch *et al*., "Digital Subcarrier multiplexing: enabling software-configurable optical networks", JLT 2023.
[7] L. Velasco *et al*., "Autonomous and Energy Efficient Lightpath Operation based on Digital Subcarrier Multiplexing," JSAC, 2021.
[8] B. Zhang *et al*., "Optical filtering penalty estimation using DNN in EON with cascaded ROADM," Opt. Eng. 2019.