

OCATA Optical Multiband Time Domain Digital Twin: Supporting Lightpath Provisioning with NLI Mitigation in Multiband Optical Networks

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ABSTRACT

Multiband (MB) optical transmission entails large nonlinear impairments (NLI) affecting optical channels differently. Therefore, accurate quality of transmission (QoT) estimation during lightpath provisioning is strictly required to ensure the feasibility of the optical transmission over the computed lightpaths. In this paper, we review the OCATA MB optical time domain digital twin to provide fast and accurate QoT estimation, while reducing the complexity associated with NLI. In addition, we show how NLI noise can be mitigated by optimizing parameters at the receiver side during lightpath provisioning to further optimize network performance.

Keywords: Multiband optical transmission, Optical network digital twin, Nonlinear impairments mitigation.

1. INTRODUCTION

Optical transport networks are essential to address the growing capacity demands driven by beyond 5G (B5G) technologies. To this end, the ITU-T launched a focus group to define a network roadmap for 2030 [1]. Multiband (MB) optical networks are considered a key solution to extend legacy network capacity by exploiting additional spectral bands beyond C and L [2]. However, MB transmission increases nonlinear impairments (NLI), particularly due to inter-channel stimulated Raman scattering (ISRS), which complicates Quality of Transmission (QoT) estimation [3]. Traditional Routing and Spectrum Allocation (RSA) methods, while considering QoT constraints, face scalability challenges in MB scenarios due to ISRS effects and the high number of channels. Machine Learning (ML) techniques, particularly Digital Twins (DTs), offer a promising solution. The OCATA DT, based on deep neural networks (DNNs), has been proposed as a reliable and low-complexity approach for QoT estimation and NLI mitigation, accurately predicting the pre-FEC BER of optical connections [4]. A key challenge remains the generation of large training datasets, as experimental MB data is scarce and simulations are time-consuming. To address this, an efficient method to solve the nonlinear Schrödinger equation has been proposed, significantly reducing computation time for dataset generation [5]. Building on our previous work [6], where OCATA was used for QoT estimation and nonlinear mitigation during provisioning, this paper extends the methodology to support MB transmission. We present OCATA-MB, which integrates scalable QoT estimation and NLI mitigation into the RSA process, supporting route and channel assignment within SDN controllers.

In this paper, we offer a synopsis of the algorithms and the procedures introduced in our previous work in [7].

2. MB Optical Lightpath Provisioning

Lightpath provisioning, involving route and channel selection, is crucial for automated network operation while ensuring required QoT. This section presents the MB scenario, introduces the OCATA-MB digital twin to model accurately model the lightpath considering ISRS effects and enhance QoT in MB optical transmission. Fig. 1 (a) depicts the multiband (MB) optical transmission scenario considered, where transponders at sites A and B can operate across multiple bands (C, L, S). Signals from these transponders are multiplexed and transmitted through optical fibers, with separate optical amplifiers (OAs) per band—such as EDFAs for C and L bands and TDFAs for the S band—alongside waveband (de)multiplexers. This structure enables the expansion of network capacity using MB transmission. However, ISRS affects QoT by unevenly transferring power from higher to lower frequencies, resulting in varying levels of nonlinear impairments across channels. As shown in Fig. 1 (b), channels in the S band generally experience higher pre-FEC BER than those in the C and L bands, limiting their reach. Hence, while C and L bands are more suitable for long-distance connections, overusing them risks depleting available resources and increasing future blocking probabilities.

To address this, a more balanced channel assignment strategy involves selecting channels with acceptable pre-FEC BERs, even if slightly higher, to optimize overall resource utilization. However, this requires evaluating the QoT of all available channels, which can be computationally intensive. Moreover, some connections may still be blocked if no channel meets the QoT threshold. The following sections propose efficient solutions for optimal

The research leading to these results has received funding from the European Commission MSCA-DN NESTOR (G.A.101119983) and the Horizon Europe SEASON (G.A. 101096120); and from the ICREA Institution.

channel assignment and mitigation techniques to enhance the QoT of channels that would otherwise fail to meet the required performance.

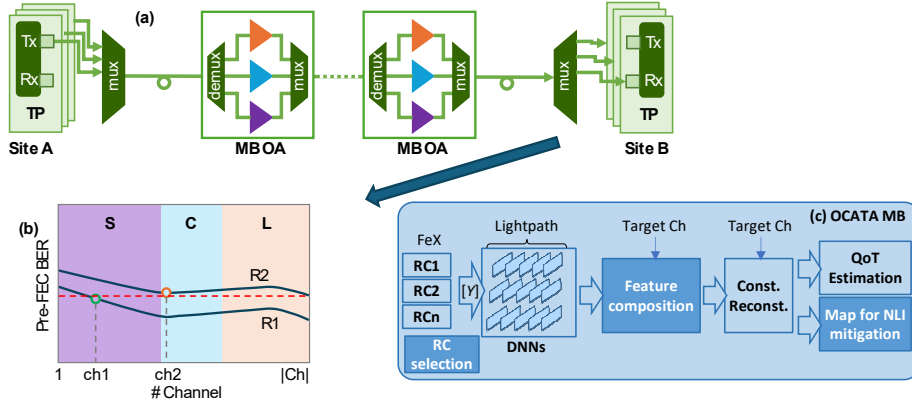


Fig. 1 Overview of the considered MB scenario (a) illustrative performance of MB optical transmission (b) and Main building blocks of the OCATA-MB time-domain digital twin, adopted from [7].

The classical OCATA architecture for C-band, uses DNNs trained on a reference channel (RCh) to model signal propagation by extracting key noise-related features from constellation points (CPs), enabling efficient QoT estimation. However, applying this directly to MB scenarios is challenging due to the ISRS effect, which impacts channels differently and would require an impractically large number of DNN models. To address this, the OCATA-MB architecture (Fig. 1 (c)) introduces a few carefully selected RChs representing different spectral regions, balancing model complexity and accuracy. A Feature Composition block estimates CP features for any channel across C-, L-, and S-band by leveraging the propagated features of these RChs, ensuring scalability. As in the classical approach, a Constellation Reconstruction block reconstructs features for non-propagated CPs, allowing accurate QoT prediction in MB optical networks.

Improving the quality of transmission (QoT) in multiband optical networks requires adapting detection areas of constellation points in the receiver to mitigate NLI. However, finding optimal detection areas for all points is computationally demanding. OCATA-MB tackles this by efficiently computing near-optimal detection maps during lightpath provisioning, enhancing QoT and allowing connections that would otherwise be rejected. The algorithms related to NLI mitigation has been accurately investigated in [4]. With efficient QoT estimation and NLI mitigation, a channel selection algorithm is designed to identify the best channel assignment for a given route. It checks if any channel meets QoT requirements, selects the optimal one if possible, or applies mitigation techniques to improve QoT when no channel initially satisfies the threshold.

3. Proposed Method

OCATA-MB pre-trains DNN models for selected RChs, then during provisioning, it estimates target channel features, optimizes detection areas for NLI mitigation, and selects the best channel assignment ensuring QoT. The RCh selection process analyzes symbol dispersion features (σ^I , σ^Q), which are the variance of symbols for I and Q axes, fits piece-wise linear functions to identify key variation points, clusters these cut-points, selects centroids as candidate RChs, and iteratively adjusts the number of RChs until BER estimation accuracy meets a target threshold without excessive model complexity. The feature composition algorithm identifies the two adjacent RChs of a target channel and linearly interpolates their propagated features to estimate the target channel's features. The NLI mitigation method optimizes CP detection areas by dividing the IQ plane into small squares, computing symbol probabilities for each CP, and assigning each square to the CP with the highest probability. The resulting mapping is sent to the Rx for efficient symbol decoding during lightpath provisioning.

The proposed heuristic addresses the online MB-RSA problem for lightpath provisioning by iterating over candidate routes and available channels to find a feasible solution assisted by OCATA-MB. For each route, it retrieves available channels, selects the optimal one using pre-trained DNN models, and computes detection areas for NLI noise mitigation if required. The channel selection process builds end-to-end DNN models from reference channels, propagates input features, and estimates pre-FEC BER for each candidate channel. Channels are explored based on pre-computed BER curves, using feature composition and reconstruction to refine BER estimation. If a channel meets the threshold, it is selected; otherwise, the search continues. When no channel satisfies the QoT requirement, the best channel is enhanced through NLI mitigation. A grid-based detection area optimization is applied, assigning detection regions to CPs to minimize errors. The pre-FEC BER is re-estimated, and if within limits, the channel and detection areas are selected. If not, no feasible solution is found. The flowchart of the procedures is shown in Fig. 2. Detailed explanations of the procedures can be found in [7].

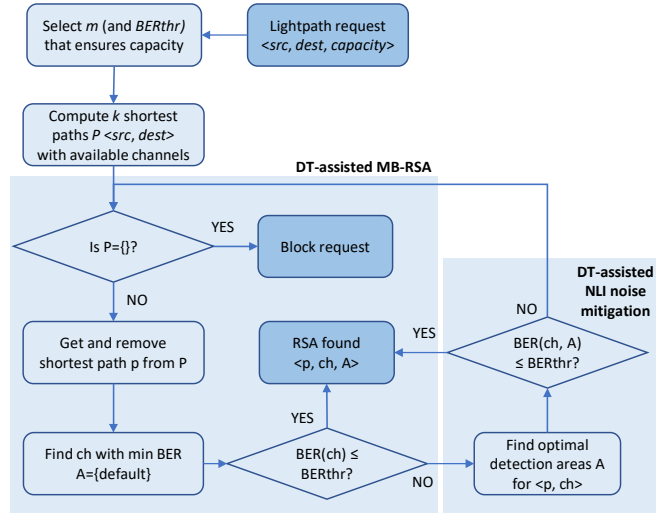


Fig. 2 Proposed DT-assisted MB-RSA procedure; adopted from [7]

4. EVALUATION

This section evaluates OCATA-MB and the MB-RSA algorithm, covering DNN training, RCh selection, nonlinear mitigation, and its integration. A MATLAB-based simulator [5] generated 16QAM@32GBd IQ constellations for a C+L+S WDM system with 337 channels spaced at 50 GHz. Signals propagate through 70-100 km fiber spans with 0 dBm launch power, including ISRS and fiber nonlinearities, modeled via the nonlinear Schrödinger equation using Runge-Kutta. EDFAs/TDFAs are idealized with fixed gain and noise figures. A total of 1,000 samples were generated for DNN training, validation, and testing. DNN models use 20 input features, two hidden layers (12 tanh neurons), and 20 outputs, with specific models trained per RCh and link configuration.

We begin by selecting the RChs used for lightpath provisioning. Fig. 3 illustrates the values of σ features for two outer CPs across all channels. A piecewise linear fit with 6 segments provides a good approximation, resulting in 7 RChs. However, the exact position of cut-points varies for each feature and link configuration. For instance, the 4th cut-point shifts between channel indices 153 and 174, as seen in Fig. 3.

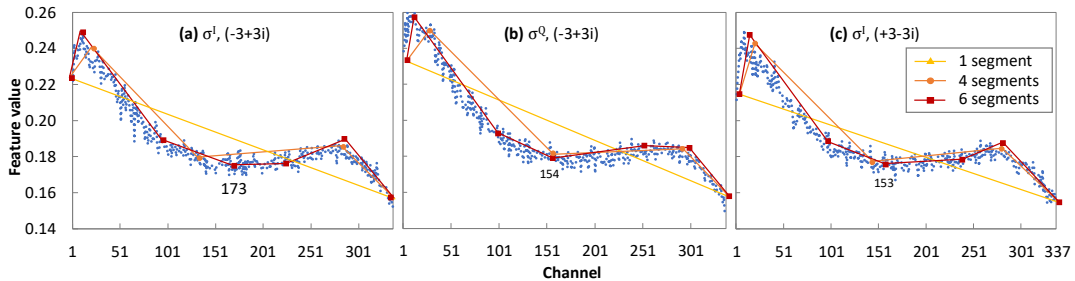


Fig. 3 Value of selected σ features and CPs vs channel index and piecewise linear fitting with 1, 4 and 6 segments.

To assess QoT estimation accuracy, Fig. 4 compares simulated pre-FEC BER with values estimated by Algorithm 6 without NLI mitigation (using square detection areas). Results for RCh 97 and non-propagated channels 180 and 310 are shown over varying distances. The estimations closely match simulations, confirming high accuracy.

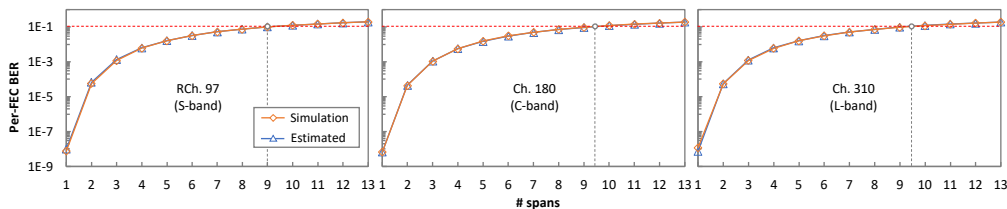


Fig. 4 Evolution of Pre-FEC BER as a function of the number of spans for several channels.

Fig. 5 shows pre-FEC BER estimates with and without NLI mitigation using optimized detection areas for three channels across different spans by dividing the IQ plane into $k = 10,000$ small grids. Results confirm pre-FEC BER improvement for all channels, regardless of distance. The maximum transmission reach varies by channel,

highlighting the need for OCATA-MB to select suitable channels during provisioning. NLI mitigation extends reach by at least one span.

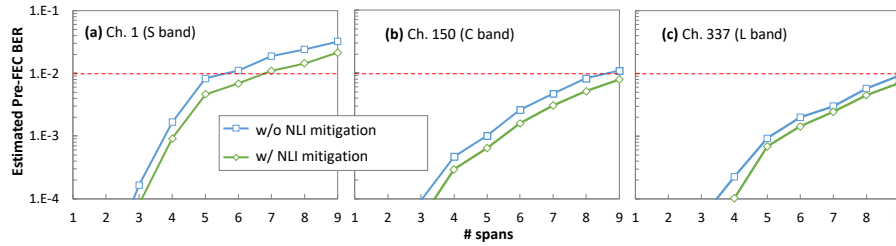


Fig. 5 Real and estimated pre-FEC BER with squared and optimized detection areas vs # spans for ch. 1 (a), 150 (b), and 337 (c).

The OCATA-assisted on-line MB-RSA algorithm was evaluated in a Python-based simulation using a Spanish 10-node core network. A static traffic model was applied, with 1,000 pre-generated connection requests processed sequentially. Routes were selected from up to 3 shortest paths between source and destination nodes, and both with and without NLI mitigation. Fig. 6 (a) shows the number of blocked requests, and Fig. 6 (b) presents the blocking ratio versus the number of requests. The first-fit approach led to the highest blockages, with a 34% blocking ratio after 1,000 requests. Using OCATA-assisted MB-RSA reduced blocked requests by 54%, lowering the ratio to 15.6%. With NLI noise mitigation, blockages dropped by an additional 56%, achieving a final blocking ratio of just 6.8%, resulting in over 80% total reduction.

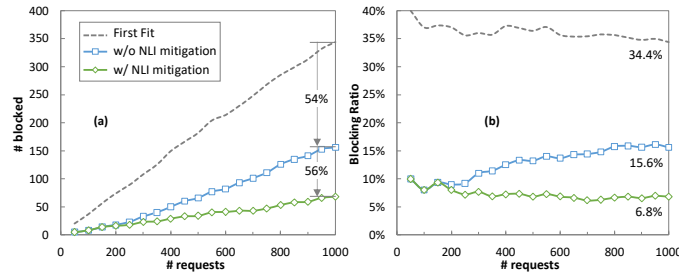


Fig. 6 Number of demands blocked (a) and blocking ratio evolution (b) vs demand number.

5. CONCLUSIONS

A digital twin-assisted lightpath provisioning approach is proposed for multiband optical networks to ensure the required QoT through effective channel and route assignment. OCATA-MB uses DNNs for optical signal propagation, defining reference channels to reduce the number of DNN models and interpolating features for target channels. Nonlinear mitigation optimizes detection areas at the receiver to improve QoT and reduce connection blocking. Simulation results show high accuracy in QoT estimation, particularly pre-FEC BER, and significant improvements in performance. The proposed approach reduced the blocking ratio by over 50% compared to the traditional first-fit algorithm, with an additional 50% improvement when nonlinear mitigation was applied, demonstrating its effectiveness.

REFERENCES

- [1] B. Da and M. Carugi, "Representative use cases and key network requirements for network 2030," Tech. rep., ITU-T FG-NET2030, 2020.
- [2] L. Velasco, F. Cugini, R. Casellas, M. Nakagawa, G. Wellbrock, and X. Chen, "Introduction to the JOCN Special Issue on Advances in Multi-Band Optical Networks," J. Opt. Commun. Netw. 15, AIMON1-AIMON2 2023.
- [3] M. Mehrabi *et al.*, "Multi-band elastic optical networks: inter-channel stimulated raman scattering-aware routing, modulation level and spectrum assignment," J. Light. Technol., vol. 39, pp. 3360-3370, 2021.
- [4] M. Ruiz, D. Sequeira, and L. Velasco, "Deep Learning -based Real-Time Analysis of Lightpath Optical Constellations [Invited]," J. Opt. Commun. Netw., vol. 14, pp. C70-C81, 2022.
- [5] P. Khare, N. Costa, J. Pedro, A. Napoli, F. Arpanaci, J. Comellas, M. Ruiz and L. Velasco, "SSMS: A Split Step MultiBand Simulation Software," in proc. IEEE ICTON, 2023.
- [6] S. Ghasrizadeh, P. Khare, M. Ruiz and L. Velasco, "Using the OCATA Digital Twin to Improve QoT of Optical Connections in Multiband Optical Networks," in proc. IEEE ONDM, 2024.
- [7] Ghasrizadeh, S.; Khare, P.; Costa, N.; Ruiz, M.; Napoli, A.; Pedro, J.; Velasco, L. Digital Twin-Assisted Lightpath Provisioning and Nonlinear Mitigation in C+L+S Multiband Optical Networks. *Sensors* **2024**, *24*, 8054.