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QoT Digital Twin for Bridging Physical Layer Knowledge Gaps in Multi-Domain Networks

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Abstract: We propose building a spectrally resolved QoT Digital Twin for optical network domains where models and telemetry are unavailable, by probing transmission on a single spectral slot, using GNPy, and demonstrating accurate experimental results. © 2025 The Author(s)

1. Introduction

The evolution of optical networks is driven by the need for greater flexibility, dynamic resource management, and service customization. In this context, multi-domain architectures are essential to enable integration and cooperation between different network segments, which may be managed by distinct operators. This multi-domain setup also opens the door for advanced service models like Optical Spectrum-as-a-Service (OSaaS), where spectrum resources can be dynamically allocated across domains to meet the varying demands of users and services. A critical factor in ensuring the Quality of Transmission (QoT) in multi-domain environments is accurately assessing and predicting network conditions, such as the Generalized Signal-to-Noise Ratio (GSNR), across different domains.

In this paper, we propose using GNPy [1] as Digital Twin (DT) to address the lack of visibility in one of the network domains. The DT serves as a virtual replica of the optical network, allowing us to emulate network behavior and predict performance metrics. By leveraging real-time data [2] from probing transponders on a fixed spectral frequency and a basic description provided by the hidden network operator, the authors create and analyze a multi-domain DT. This DT will enable QoT-estimation (QoT-e) prior to deploying high-bitrate channels on any point of the spectrum, ensuring reliable performance across the entire optical path. This approach offers a way to infer critical domain characteristics without requiring full access to the network's internal data, making it an effective tool for optimizing multi-domain networks in real-world scenarios.

2. Integrating Digital Twins in Multi-Domain Optical Networks

The integration of DTs across multiple network domains, often controlled by different operators and relying on various technologies, presents unique challenges. One approach is the centralized model, where a single DT manages the entire multi-domain network. In this scenario, the DT aggregates network data from all the domains, providing a unified view of the network's performance. This centralized structure allows for end-to-end optimization, enabling operators to monitor and manage network behavior comprehensively. Despite its advantages, the centralized model raises challenges regarding data sharing between domains. Network operators may be reluctant to provide full access to sensitive data (e.g., topology and inventory), and integrating heterogeneous vendor technologies across different domains can complicate the creation of a cohesive global model. A more flexible option

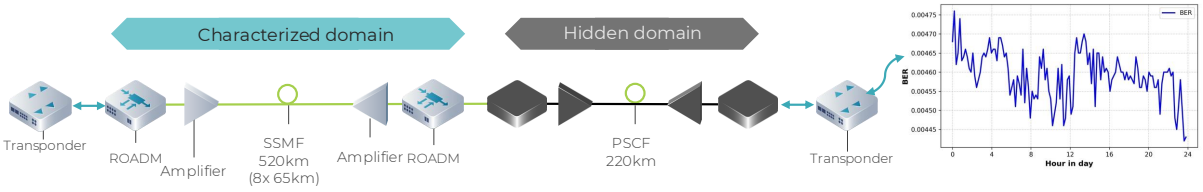


Fig. 1: Experimental laboratory setup. The linear optical network topology made of 2 multi-span EDFA-amplified optical line belonging to two different domains: domain 1 (known) and domain 2 (hidden). The OSaaS-based propagating optical spectrum presents dynamically allocated spectral portions.

is the hierarchical DT model. In this framework, each domain operates its own local DT, while a global DT coordinates interactions between domains [3]. The local DTs handle domain-specific management, while the global DT optimizes network-wide activities, such as resource allocation and inter-domain traffic routing. This approach balances local autonomy with the need for cross-domain coordination, allowing domains to operate independently while still benefiting from a higher level of optimization. Although this model provides flexibility, it introduces the challenge of ensuring smooth communication between local and global DTs, which must handle complex multi-domain interactions. In this paper, we focus on a multi-domain optical network scenario, using hierarchical DT model where there is a significant information gap between two domains (fig. 1). The first domain is fully characterized, with complete access to all network parameters, while the second allows the access only to limited information: number of amplifiers, total length and type of fiber spans. Specifically, the second domain operates under a OSaaS [4] model, where the provider does not share internal models or telemetry but grants access to a defined spectral window. The absence of detailed insights into the characteristics of the second domain introduces uncertainty, making it difficult to model and predict its behavior accurately. To overcome this limitation, we propose leveraging real-time data from the transponders at the boundary of this domain. By analyzing these data, we intend to recover the physical parameters of the unknown domain that are significant for QoT-e, in particular those related to the amplifiers. Specifically, our goal is to estimate the noise figure (NF) of the amplifiers and to understand the working point of the network in terms of gain and tilt for each amplifier along the path. Through this method, the DT can simulate the domain's performance more effectively, using the limited available information augmented by real-world data from the transponders and evaluating whether there is sufficient margin to utilize higher bit rates in the network.

3. Network Parameter Estimation

In this experiment we have control and access to the models of one domain, while the second domain remains completely unknown. We hypothesize that the provider initially allocates a small spectral slot, into which we can insert a probing channel. The probing channel is set up using a QPSK modulation format, which serves as the test signal for our measurements [5]. By using QPSK, we can analyze the performance of the signal as it traverses both domains and use it to extract relevant QoT metrics. Thus, this methodology is leveraging the characterization of the transceiver as defined in [6]. By reading the BER at the receiving transponder, and exploiting device characterization, we can map it to the GSNR. This measurement reflects the quality of the transmission as the signal passes through both domains. Since the second domain is unknown, this setup enables us to estimate the GSNR without needing direct access to the network's internal models. However, the GSNR is not constant across the different frequencies [4], and a single GSNR value is not enough to ensure a QoT-e across all the spectrum. This raises the need for a complete DT in a multi-domain context. The first step is to create the DT in GNPy for the unknown domain based on the available information and making some assumptions. The second domain manager provides the amplifier number and the total fiber length, hence, we assume that the network topology includes a booster amplifier (BST), a pre-amplifier (PRE), and equidistant In-Line Amplifiers (ILAs) along the transmission path. This allows us to calculate the overall loss and distribution of the ILAs more easily. Since the fiber spans of the second domain are made of pure silica core fiber (PSCF), we assume that the attenuation coefficient is the typical value of roughly 0.16 dB/km distributed across a total fiber length of 220 km. Assuming the fiber is divided into equal spans, each ILA and the BST amplifier should provide approximately half of the required gain to compensate for the fiber loss. Thus, each amplifier would need to deliver a gain of around 17.6 dB to ensure that the signal strength is adequately maintained throughout the transmission. However, operators often account for extra losses introduced by various network elements, such as connectors and splices, which can be present at different

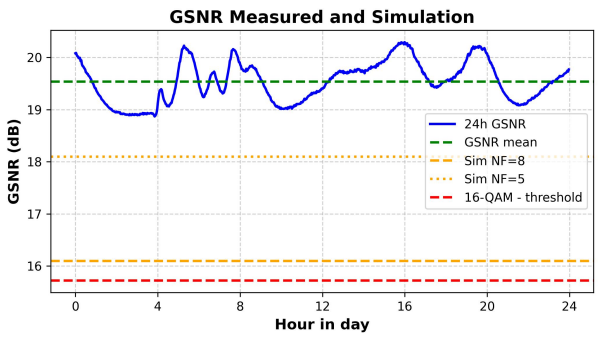


Fig. 2: Observing GSNR evolution in 24 hours compared with NF varying GNPy simulation and 16-QAM modulation format threshold.

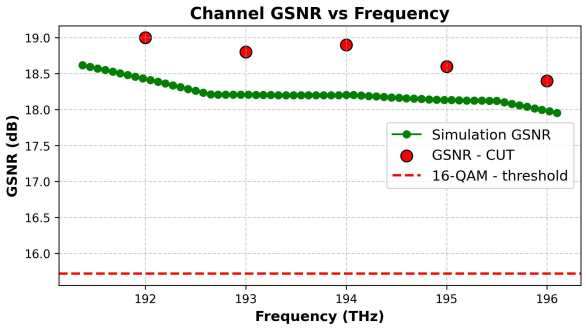


Fig. 3: Comparison between GSNR simulation results (green curve) and deployed Channel Under Test (CUT) telemetry (red dots) vs channel frequency.

	Gain[dB]		Tilt[dB]		Noise Fig.[dB]	
	SIM	MEA	SIM	MEA	SIM	MEA
BST	19.35	19.6	-0.5	-1.7	5.67	4.75
ILA	19.35	19.8	-1	-2.6	4.68	4.72
PRE	19.35	18.5	-1	-0.8	4.68	5.01

	Length[Km]		Total Loss[dB]	
	SIM	MEA	SIM	MEA
Span1	110	108.83	18.85	18.6
Span2	110	108.94	18.85	19.6

Table 1: Comparison between simulated (SIM) data and measured (MEA) telemetry for the hidden domain.

points along the optical path. These additional losses must be considered to adjust the amplifier gains accordingly. Therefore, the optimization strategy likely employed by the network is hypothesized to be a Local Optimization and Global Optimization (LOGO) [7] approach, which is well-validated in the context of core optical networks. Using this strategy and assuming that the network operator has set the network to operate at an optimal working point and that the received spectrum is flat, we can estimate the input power to the fiber. LOGO helps to determine the best working point for signal power across amplifiers in the network, ensuring efficient transmission. This strategy ensures optimal power levels are maintained along the optical path, balancing amplifier gain and tilt to mitigate nonlinear effects such as the Raman effect while maintaining an adequate signal-to-noise ratio for high-quality transmission. However, to fully apply the LOGO method, we also need to know the NF of the amplifiers. In this case, we begin by considering a worst-case scenario, where we assume the NF to be 8 dB for the amplifiers. Given the boundary conditions, the optimal input power for the first amplifier is calculated to be 0.35 dBm. At this stage, we can run the simulation in GNPy, using an amplifier model that aligns with all the assumptions we made so far (NF, gain, tilts, maximum power etc). The comparison between telemetry and simulation is shown in Fig.2. The difference between simulation and data is about 4dB, revealing a significant conservative difference between the simulated values and telemetry. This discrepancy suggests that some parameters, particularly the NF, need to be adjusted. The procedure was iterated until the margin between the measured GSNR and the simulated GSNR converged. In each simulation, the NF was adjusted, both for the LOGO strategy, which affected the launch power, and for the NF used within GNPy. This iterative process allowed for refinement of the NF until accurate alignment with the network's performance was achieved. We found that a NF value of 5 dB produced results that closely matched the network's observed performance. This adjustment also led to a required launch power of 0.07 dBm. The updated simulation (fig. 2), demonstrates a conservative margin of approximately 1 dB, which is consistent with validations found in the literature [8]. Furthermore, fig. 2 compares the threshold for the 16-QAM modulation format. In the initial simulation, there was not enough margin for deployment with this format. While, thanks to the correct DT tuning, the margin in the second simulation is enough to ensure such deployment [9].

We also proved the deployability for a 400 Gbps channel with 16-QAM modulation across different points in the spectrum. Results are shown in fig. 3: the GSNR values obtained vary with frequency, in accordance with the simulation, which maintained a consistent margin across the different frequency points. Table 1 compares the simulation results discussed in previous sections with the values acquired from the real network in the hidden domain. The simulation values do not deviate significantly from the field measurements. However, due the limited information available, it was not possible to fully capture the differences between individual amplifiers and spans. This shows that, while the DT can provide accurate estimations, there are some limitations when it comes to modeling the finer details of the network, especially with unknown components.

4. Conclusion

In this paper, we presented a methodology to develop a DT for multi-domain optical networks, focusing on a scenario where one domain provides limited information. Using a probing channel and basic assumptions about the unknown domain, we were able to estimate key network parameters, such as the NF of the amplifiers and the optimal launch power. By leveraging real-time data and iterating the simulation process, we fine-tuned the DT, aligning the simulated GSNR with the measured values. Our results demonstrate the DT's ability to accurately estimate the QoT, even in cases where full visibility of the network is not available. The conservative margin of approximately 1 dB between simulation and field data is consistent with validations found in the literature, and the method proves effective in supporting the deployment of high-bitrate channels, such as 400 Gbps with 16-QAM modulation.

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