Experimental Evaluation of QoT Uncertainty Reduction Techniques in Network Digital Twins

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***Abstract*—We experimentally demonstrate sequential parameter refinement leveraging lightpath diversity in presence of various levels of uncertainty on parameter knowledge to iteratively improve QoT prediction accuracy by up to 1.8 dB.**

***Keywords—parameter refinement, digital twin, optical networks** (key words)*

I. Introduction

Increasing demand for network traffic in optical communication systems exceed infrastructure scaling capabilities. Combined with limitations on available electrical power and capital expenditure budgets, these conditions necessitate enhanced resource allocation strategies that minimize excess capacity margins. Such strategies enable reallocation of operational headroom to improve system throughput and reliability. Digital twins (DT) have emerged as a transformative paradigm in optical network management. They provide real-time virtual representations of live networks. This enables network operators to simulate, predict, and optimize network operations with unprecedented accuracy. [1,2]. However, the prediction accuracy of DTs depends critically on precise knowledge of system parameters like signal power, transceiver characteristics, amplifier gain and noise figure, fiber attenuation, etc.

The real-time knowledge of system parameters is limited either by missing/inaccurate information, or by measurement uncertainties from monitoring devices. In dynamic environments, systematic biases cascade through network elements, resulting in reduced confidence in simulation-based planning [4]. Multiple existing works explore learning based parameter refinement to estimate the insertion loss [5] and amplifier noise figure [6], both of which are critical for performance estimation, but difficult to measure. However, [5,6] address parameter identification within numerically simulated environments. They lack experimental validation where both temporal dynamics and wavelength dependencies play significant roles. Others present a live learning-based approach enhancing prediction accuracy for new services in [7]. However, their method does not identify individual corrected parameters, instead generalizing corrections to aggregate noise contributions without explicit parameter decomposition.

Indeed, in dense optical networks, individual characterization of each parameter is impractical due to operational constraints. Amplifier NF directly influences QoT prediction accuracy for lightpaths operating in the linear regime. Standard practice assumes uniform, constant NF values across all inline amplifiers. [8] demonstrates that amplifier noise response varies with signal power and spectral tilt, challenging this conventional assumption. However, exhaustive calibration of all amplifiers under all operational conditions remains infeasible. Post-deployment scenarios must rely on in-service measurements to estimate parameters exhibiting the highest uncertainty, enabling practical refinement without requiring comprehensive offline characterization of network components.

In this paper, we propose a physics-based learning algorithm to minimize prediction uncertainty in quality of transmission (QoT) by exclusively refining high-uncertainty parameters that have a high impact on the final QoT prediction, such as amplifier noise figure (NF). It exploits real-time telemetry data and lightpath diversity to rectify the NF assumption errors in inline amplifiers. Then, we experimentally validate it over multiple uncertainty scenarios on an experimental mesh network testbed with commercial transceivers and reconfigurable optical add drop multiplexers (ROADMs), thus demonstrating real-world viability of reducing uncertainty of QoT prediction for unestablished lightpaths.

II. Parameter Correction Algorithm

We sequentially measure bit-error rate (BER) from diverse lightpaths to remove the uncertainty from the affected parameter. For AWGN impacted channels, from [9] we can write the measured BER (BER_m) as a modulation format dependent function of the signal to noise ratio (SNR), such that $BER_m = f(SNR_m)$, where SNR_m is the equivalent measured SNR, which is decomposed as:

$$SNR^{-1} = \alpha(\sum SNR_{ASE}^{-1} + \sum SNR_{NLI}^{-1}) + SNR_{trx}^{-1} \quad (1)$$

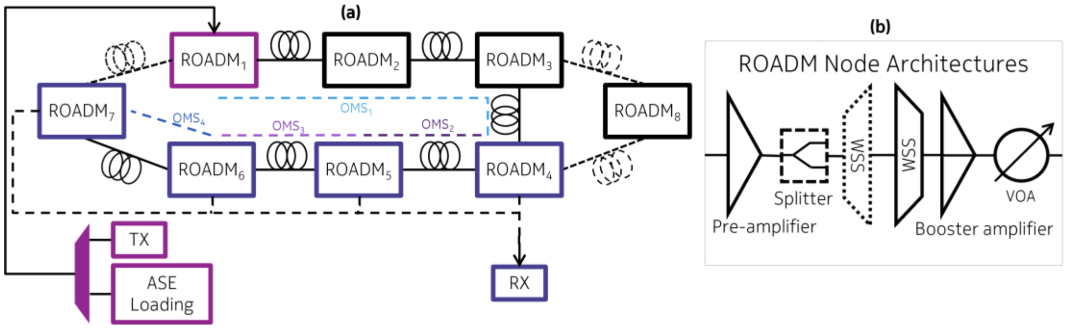
SNR_{ASE} accounts for the amplified spontaneous emission (ASE) from the amplifiers, SNR_{NLI} accounts for the nonlinear Kerr interference from the optical fibers, SNR_{trx} accounts for the transceiver noise, and α is the bandwidth penalty resulting from imperfect receiver.

Transceiver noise is typically calibrated in back-to-back setup pre-deployment and can be further modelled as a power dependent noise source [10] for short distance transmissions. NLI power can be calculated analytically using various models [11]. ASE power is calculated from:

$$P_{ASE} = (G-1)NF \cdot h\nu B_{ref} \quad (2)$$

Where G is the measured amplifier gain, h is the Plank's constant, ν is the channel center frequency, and B_{ref} is the reference bandwidth over which the noise is integrated. Typically we assume that the NF is known from manufacturer datasheets or pre-calibrations.

Fig. 1. (a) Mesh network testbed topology; (b) ROADM nodes architecture: one comprising of a splitter + WSS for broadcasting, and the other comprising of WSS + WSS.



The proposed refinement methodology employs real-time telemetry-based parameter correction. Although it is generally applicable to any singularly significant uncertain parameter, in this work we choose to demonstrate it on a single critical but high-uncertainty parameter, as mentioned above: amplifier noise figure.

Assuming a starting value for the unknown NF, we first estimate signal-to-noise ratio (SNR_e) from eqn. 1, acknowledging substantial uncertainty relative to the unknown ground truth. This practical approximation addresses the inherent limitation of inaccessible true parameter values in operational networks.

The difference between the measured noise and the estimated noise is given by: $\Delta_N = SNR_e^{-1} - SNR_m^{-1}$ in dB. We assume all other parameters (signal power, baud rate, G, SNR_{trx} etc.) are known with lower uncertainty compared to the amplifier NF, and the measurement uncertainty of BER_m is much lower than the uncertainty on the assumption of NF. In the linear domain Δ_N is used as an effective correction factor for the NF of all amplifiers before measurement by: $NF_{\text{eff}} = NF_{\text{old}}/\Delta_{N,\text{linear}}$.

After parameter correction, the refined value is validated by ensuring $|SNR_e - SNR_m|$ is under a user defined threshold. Subsequently, this correction is applied to enhance QoT prediction accuracy for lightpaths sharing the same optical multiplexed section (OMS). Since, each OMS consists of multiple amplifiers, the NFs of the individual amplifiers cannot be decoupled.

The Δ_N calculated by the twin for any given OMS acts as a joint correction factor, such that we estimate the *effective NFs* (NF_{eff}) of all amplifiers within an OMS, instead of the ground truth. Thus, the accuracy of correction performed per NF is inherently limited by the number of devices per OMS.

It enhances parameter knowledge without requiring comprehensive per-device calibration across the network infrastructure. This approach substantially reduces deployment and monitoring complexity. The refinement technique remains applicable in dense network topologies featuring numerous wavelength channels traversing diverse lightpath combinations. Consequently, this enables construction of an NF_{eff} map corresponding to the shortest measurable OMS, facilitating systematic parameter refinement throughout the network.

To generalize, this correction can be performed for all cases where the dominant uncertainty lies on a single parameter. However, for multiple parameters with high uncertainty, this correction must be jointly performed on all, since they cannot be decoupled without additional independent measurements.

III. Experimental Demonstration and Analysis

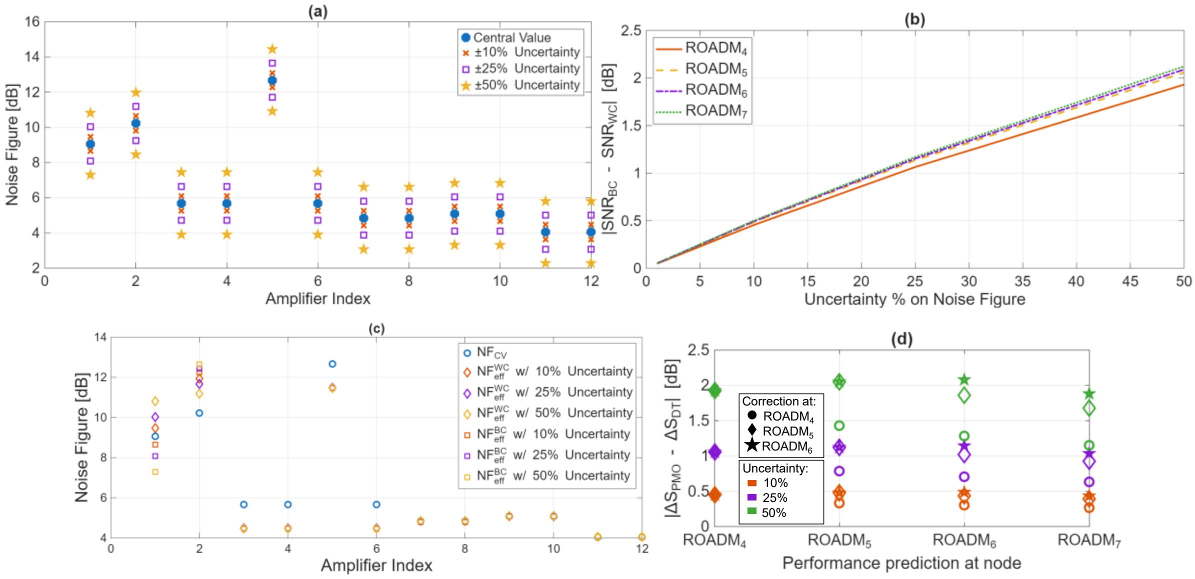
We evaluate this approach on an experimental mesh network testbed equipped with commercial transceivers and ROADMs from multiple vendors. We test our method against three cases of uncertainty on the knowledge of NF within the *present mode of operation* (PMO) which knows the NF with: good accuracy (±10%), moderate accuracy (±25%) and poor accuracy (±50%) around a central value. Here, +X% emulates the worst case (WC) of NF, and -X% emulates the best case (BC), maximizing and minimizing the generated ASE noise, respectively. The DT's goal is to utilize the measurements performed on a shorter lightpath and improve prediction accuracy for a longer lightpath—reducing the prediction uncertainty by minimizing the range of estimated QoT (SNR_e) for BC and WC assumptions. This is achieved directly by reducing the uncertainty on the calibration/assumption of NF.

The experimental network testbed, illustrated in Fig.1(a), comprises eight ROADM nodes arranged in a mesh topology. Each node incorporates a pre-amplifier, booster amplifier, and wavelength selective switches (WSSs) as shown in Fig. 1(b). All ROADMS except $ROADM_3$ has route-and-select architecture, while $ROADM_3$ has broadcast-and-select architecture. A 90 Gbaud DP-QPSK channel under test (CUT) is transmitted at 194 THz, using a commercial coherent transceiver. Its SNR_{trx} was exhaustively calibrated in back-to-back with respect to OSNR and received power, with standard deviation of 0.06 dB. The remaining spectrum, spanning 191.5 THz to 196 THz, is populated with 50 GHz ASE loaded channels at 100 GHz spacing to emulate realistic loading conditions. All 44 channels are launched into the network at $ROADM_1$. A coherent receiver, connected via an optical switch to $ROADM_{4/5/6/7}$ enables us to drop the CUTs at variable transmission distance to measure the BER.

All optical amplifiers operate in constant gain mode with a fixed per-channel launch power of 0 dBm, and the spectrum is flattened using the WSSs in the ROADMs. Although different devices are configured under different modes (high gain or low gain), to achieve the same requirements, allowing us to emulate heterogenous nodes with varying gains and NFs. Operation in linear transmission regime is ensured by maintaining 3 dB margin below the nonlinear threshold to reduce the impact of uncertainty on the nonlinear power introduced by model inaccuracies. We monitor the amplifier gains, WSS attenuations, and total input and output signal powers at each node.

The central values of the channel-specific noise figures (NF_{CV}) for the 12 amplifiers are shown in Fig.2(a). In Fig.2(a), we also show the magnitude of the NF under different degrees of BC/WC uncertainty. In the good accuracy case, NF is known within ±0.42 dB, whereas in the poor accuracy

Fig. 2. (a) Knowledge of NF of the different amplifiers in the network; (b) QoT prediction range by the PMO for different levels of uncertainty when measured at different nodes (c) Effective NF per device post convergence within DT (d) Prediction range improvement of DT compared to the PMO



assumption, NF `diverges by up to ± 1.76 dB. The estimation range $\Delta S = |S_{BC} - S_{WC}|$, represents the uncertainty on the estimation of the lightpath performance. For longer lightpaths, the uncertainties on the NFs of each device add up, and result in a worse ΔS compared to its shorter counterpart.

In Fig.2(b), this is illustrated for reception at different ROADM nodes, where the performance is estimated by the PMO, with different levels of uncertainty on the NF. For all cases, the lowest estimation range ΔS is always for the shortest lightpath, when channel is dropped at $ROADM_4$. The largest range corresponds to the longest lightpath when we receive at $ROADM_7$. Under assumptions of good accuracy, we have a maximum $\Delta S = 0.45$ dB, which is equivalent to an 11% uncertainty on the estimated QoT. For the poor accuracy assumption, at $ROADM_7$ $\Delta S = 2.12$ dB, which is equivalent to a 63% uncertainty on the estimated QoT.

Prediction within the DT:

For the shortest lightpath, the QoT prediction uncertainty remains the same for the DT as it is for the PMO, since no correction can be performed until a measurement is made.

In Fig. 2(c), the effective NFs calculated by the DT per amplifier is shown. For the BC/WC scenarios, the first 2 amplifiers have the strongest divergence from the NF_{CV}, after which the algorithm converges to the same value of NF_{eff} regardless of the uncertainty condition.

Once the effective NFs of the shortest lightpath have been calculated, in Fig. 2(d), compared to the PMO the prediction uncertainty ΔS of the next lightpath reduces by 0.44 dB when the central value of NF is known with good accuracy, and 1.92 dB when it is known with poor accuracy. Successively calculating the effective NFs of the different lightpaths, we show that our method improves ΔS by 10.6%, 26.9% and 54.3% for the three evaluated uncertainty conditions on the longest lightpath when compared to the PMO after correction at $ROADM_6$.

IV. Conclusion

This work experimentally demonstrates an approach to reduce uncertainty on the predicted QoT using lightpath diversity to sequentially refine critical system parameters. Utilizing measurements from multiple lightpaths with varying numbers of network elements, the method decouples interdependent parameters through iterative optimization. The calibration procedure accounts for wavelength-dependent amplifier characteristics, that reduces the overall uncertainty on the parameter by up to 64%. Reducing parameter uncertainty results directly in reduction of uncertainty of the estimated quality of transmission. We show a minimum improvement of 2 dB and 1.81 dB for the shortest and longest transmission lightpath respectively. This technique directly addresses practical challenges in digital twin deployment where complete a priori knowledge of network component parameters is unavailable, enabling more accurate performance prediction in operational networks without enforcing exhaustive pre-deployment calibrations.

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