Real-Time QoT Estimation Through SDN Control Plane Monitoring Evaluated in Mininet-Optical

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***Abstract*— Quality of Transmission (QoT) metrics are used to predict and evaluate optical transmission performance, and have received much attention due to recent interest in real-time software defined networking (SDN) control and the challenges posed by open, disaggregated optical systems. In this letter, we address the QoT-estimation (QoT-E) issue, by focusing on real-time operations, where a dynamic control plane improves path performance estimation accuracy by interrogating optical performance monitoring (OPM) devices in the network. We also recognize the difficulty in testing such control plane procedures over large scale systems, which is a necessary step to validate control plane scalability before it is implemented in real systems. Accordingly, we have developed an optical network simulation system that incorporates physical transmission modeling into the Mininet packet-network emulator to enable the development and evaluation of optical control plane processes that depend on optical transmission performance. In this letter, we use this new tool, Mininet-Optical, to evaluate a SDN QoT-E procedure based on the deployment of emulated OPM nodes at periodic locations in an optical transmission system, which are interrogated by a SDN controller in real-time. Through this new capability, we observe behavior that manifests across a large scale system of 70 in line amplifiers and 15 ROADM nodes and are able show improvements in QoT accuracy up to 3 dB.**

***Index Terms*— Software-defined optical networks, optical network emulation.**

I. Introduction

WHILE the concept of QoT-estimation (QoT-E) has been an important factor in optical systems for a long time, a number of factors have triggered a renewed interest in this topic: the drive towards more dynamic optical networking, the recent focus on disaggregation of the optical layer, and the development of optical SDN control planes, especially with artificial intelligence (AI) for data-driven autonomous networking functions.

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Much progress has been made on the development of accurate analytical signal performance models [1] and, more recently, cognition-based estimators using AI algorithms [2], [3]. The main drawback of such approaches is that they require large amounts of optical link characterization data, which can be complex and expensive to acquire. An alternative to data-expensive ML models is the use of optical monitoring to improve the accuracy of analytical lightpath QoT-E, through detailed, real time data on the characteristics of the optical link. Coherent receivers, for example, can provide generalized optical signal-to-noise ratio (gOSNR) measures based on pre-FEC BER readings, as well as other power anomaly detection measures through digital backpropagation techniques [4], [5]. The development of control methods that combine real-time data collection with QoT-E and provisioning could be considered part of a larger research area [6]. This approach involves the use of real-time control plane operations to gather optical performance monitoring (OPM) information and run algorithms to improve the accuracy of QoT functions, including provisioning and fault management. As of today, a key challenge of such approaches is testing the real-time control plane aspects, as experimental testbeds, especially in academia, are of limited size, typically composed of only few Reconfigurable Optical Add Drop Multiplexers (ROADM) nodes. Indeed, a lack of test platforms and reference systems, similar to the recirculating loops used in transmission system development, has limited this area of research primarily to customized, often not scalable solutions, as reported in the literature [7]–[9]. While many consortia, such as OpenROADM, OpenConfig, OpenDevice, ONF, and TIP, are defining architectures and interfaces for SDN open optical systems, there are few tools for testing optical network control planes in real time over large-scale physical systems or emulated systems incorporating optical transmission physics. Optical controllers such as ONOS/ODTN [8] could benefit from rapid and flexible development on reliable emulated environments, in addition to testing on hardware testbeds, just as Mininet [10] has been used in the development of OpenFlow and SDN control planes; Mininet is a widely used emulator that supports disaggregated packet network emulation and is often used to develop SDN controllers. There are indeed openly available optical network planning and optimization tools such as Net2Plan [11] and OOPT-GNPy [12], which can enable the assessment of network performance for many scenarios. However, they operate as closed simulation environments designed for planning and optimization, leaving assessment and development of optical SDN control system solutions in real time an open issue.

In an attempt to fill this gap, we have developed an extension to the Mininet SDN emulator, *Mininet-Optical* [13], [14], which includes modeling of optical layer transmission as well as emulation of optical devices that can be controlled through

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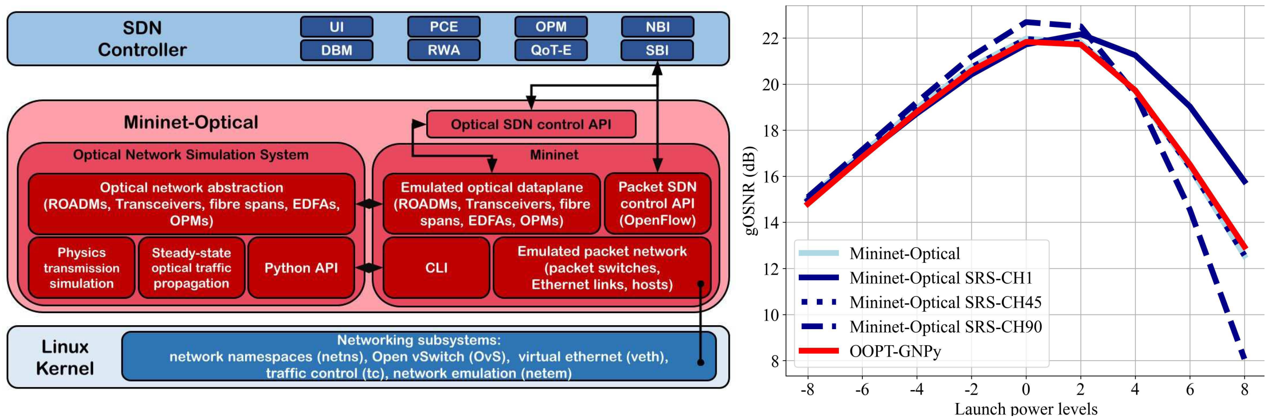

Fig. 1. (*Left*) Mininet-Optical architecture diagram. (*right*) gOSNR performance comparison between the OOPT-GNPy Project [12] and Mininet-Optical (red and light blue curves, respectively) and Mininet-Optical with SRS modeling (dark blue curves) for the first, center, and last channels in a 90 C-band channel transmission.

SDN interfaces. Mininet-Optical enables physical layer models to be used with Mininet to simulate physical components. For example, physical layer effects such as optical fiber NLI noise is modeled with the Gaussian Noise (GN) model [15], and Stimulated Raman Scattering (SRS) modeled through linear approximations [16]. In general, models with different levels of physical detail abstraction can be incorporated depending on the relevant physical system behaviors for the application. In addition to fiber effects, Mininet-Optical can incorporate component models such as Erbium Doped Fibre Amplifier's Wavelength Dependent Gain (EDFA-WDG), in order to account for the unpredictability generated by such active elements.

In this work, we use Mininet-Optical to investigate a real-time control plane QoT-E system that uses monitoring information to optimize its prediction performance. Our contributions are two-fold: i) we present a demonstration of the ability to test control plane operations on large-scale networks with a novel optical network emulation system, Mininet-Optical, built as an extension of the Mininet project, to enhance research and development of optical control planes; ii) we present a QoT-E strategy based on active monitoring of lightpaths in an optical SDN environment that mitigates estimation inaccuracies produced by wavelength dependent power dynamics.

II. The Mininet-Optical Network Emulator

By providing simulation of optical transmission impairments, Mininet-Optical enables the modeling of optical component behaviors, while managing their operation through an SDN control plane. Elements modeled by Mininet-Optical include: transceivers; colorless reconfigurable ROADMs with wavelength selective switches (WSSs) and variable optical attenuators (VOAs) (for channel power leveling); EDFAs for boost-, inline- and pre-amplification; and OPM devices.

Monitoring: The physical layer models in Mininet-Optical enable the use of OPMs for QoT functions in SDN control. This is an important area of SDN control investigation in which an SDN controller must access physical performance information. Through simulation, we can model specific physical effects and evaluate how they impact the SDN control. For this study, we implement the models listed in Table I that capture the salient features of the gOSNR-based QoT evolution with distance in EDFA ROADM-based coherent transmission systems. This allows us to assess their collective effects on the accuracy of QoT-E and the relative benefits of OPM strategies in SDN controllers considering these effects. Using Mininet-Optical, additional physical layer effects, such as polarization dynamics, could similarly be incorporated to evaluate their impact on SDN control. For the OPMs, for example, we model reference coherent receivers to monitor the gOSNR (i.e., measured over a 0.1 nm reference bandwidth). Such OPMs can be positioned at ROADM monitoring ports (typically power taps on the EDFA output), preceded by a tunable filter. The OPMs can be easily modelled in Mininet-Optical and examined at large scale to assess e.g., trade-offs between the number of monitoring points (which would increase cost in a real system) and improvement in gOSNR estimation. In the system, the gOSNR is directly calculated from the received pre-FEC BER as the corresponding optical SNR at the receiver input. Assuming that the ASE and nonlinear noise are the dominant noise sources and both Gaussian (which is often the case); the generalized OSNR can be written in its usual form: $gOSNR = P_s/(N_{ase} + N_{nlo})$, where P_s is the mean optical signal power, N_{ase} is the mean ASE optical noise power and N_{nlo} is the effective mean non-linear optical noise power [15].

Control/Data/Physical Planes: As shown in Fig. 1, the virtual network runs on a single Linux kernel, shown at the bottom. The middle layer shows how Mininet-Optical extends Mininet with optical networking components. These components emulate the control and data plane of optical network elements and connect to simulated models for optical signal transmission. The data plane functionality of Line Terminals (transceivers) and ROADMs is implemented with Open vSwitch. Optical fiber links between ROADM nodes are emulated with virtual Ethernet (veth) links, multiplexed (currently using VLAN bits) to model multi-channel WDM links. The top layer of Fig. 1 (left) shows the control plane interface for external SDN controllers. The internal control API for the optical components is exported to external controllers via a northbound control API, currently REST, extensible in the future to support standard control APIs such as TAPI, OpenROADM, or OpenConfig, for plug-and-play compatibility with hardware networks. SDN controllers can use the external control API to configure and monitor the virtual optical elements, whose behavior is modeled by the physical layer simulation and reflected into the control and data plane emulation.

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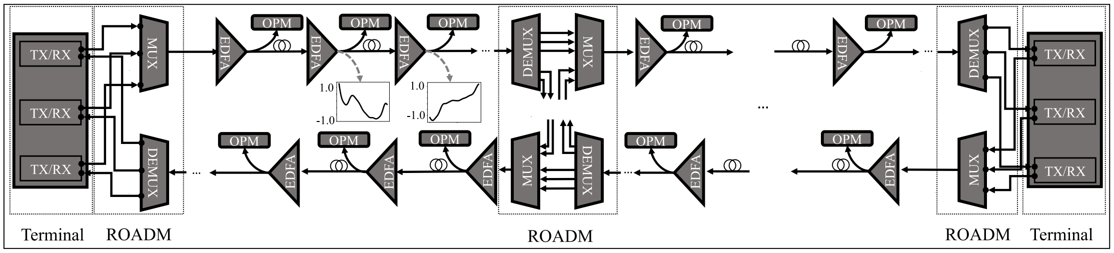

Fig. 2. Linear topology modeled with Mininet-Optical.

TABLE I
PHYSICAL MODELS APPLIED TO THE NETWORK ELEMENTS

Network Component	Physical Model
ROADM	Component Insertion Losses Wavelength-Dependent Attenuation Channel Power Leveling
Optical Fiber	Optical Fiber Linear Attenuation Optical Fiber Dispersion Stimulated Raman Scattering [16] Self-Channel Interference Noise [12] Cross-Channel Interference Noise [12]
EDFA	Linear Gain Wavelength-Dependent Gain Automatic Gain Control Optical Power Dynamics [17] Amplified-Spontaneous Emission Noise

Performance Validation: In the right-hand side of Fig. 1 we show the performance validation of our system against the OOPT-GNPy Project QoT modeling tool [12]. We have modeled a linear topology with 5 ROADM nodes connected by SMF-28 optical fiber links of 240 km, made up of 3×80 km spans. Boost EDFAs at each ROADM output compensate the 17 dB mean ROADM loss, and inline EDFAs compensate the 17.6 dB fiber span loss. The total end-to-end distance is 960 km. We evaluated multiple transmission cases at different power levels with 90 C-band channels and monitored the centered channel at the end of the link. The gOSNR modeling of Mininet-Optical performs closely to the OOPT-GNPy Project, as shown in the light-blue and red curves, respectively, since the SRS effect is cancelled for this particular channel [16]. The dark blue curves show the impact of including SRS on the same 90 channel configuration, monitored at the first channel in the transmission (solid), the centered channel (dotted) and the last channel (dashed). Additional validations against experiments and reports in the literature were also carried out, and will be presented elsewhere.

III. USE CASE AND RESULTS

We evaluate the ability for a control plane to use gOSNR OPM information in real time to improve the performance of a gOSNR QoT-E control module. Our gOSNR QoT-E tool uses the physical layer models from Table I, but without considering wavelength dependent effects, nor channel power adjustments, thus operating as a typical network planning and optimization tool. Our assessments ran over a linear topology, shown in Fig. 2, of 15 ROADM nodes linearly connected by fiber links of 480 km, made up of 6×80 km spans, totaling 6,720 km. However, Mininet-Optical also enables the emulation of mesh network topologies. To model WDG behavior, we used lab measurements of the WDG of 2 EDFAs [17]. The resulting WDG curves were then randomly assigned to each EDFA, as depicted in Fig. 2. We also apply a flat channel equalization at each ROADM, by setting the WSS VOAs appropriately. OPM devices modeling reference receivers are located at the EDFA outputs (including the ROADM EDFAs), and interrogated depending on the monitoring strategy described below. Both the SDN controller and Mininet-Optical were running on the same Ubuntu 18.04 virtual machine on an Intel(R) Core(TM) i7-4770HQ CPU @ 2.20GHz processor and 12 GB RAM.

For the transmission system, 3 different C-band traffic loads were considered, corresponding to 10%, 30% and 90% of the system capacity (i.e., 9, 27 and 81 signals, respectively, for a 90-channel transmission system). To account for wavelength allocation and related system configuration dependencies, two different channel allocation strategies were examined: sequential and random. Before each transmission test, EDFA-WDGs were randomly re-assigned. Thus, each test case can be considered to model a different optical system with the same physical topology. We executed 150 transmission tests for each traffic load and for each channel allocation strategy, generating 900 OPM datasets in total with individual channel gOSNR information. Here gOSNR includes ASE noise and effective nonlinear noise (determined by the GN model) and the impact of SRS. The operations of reading gOSNR values and applying corrections to the prediction algorithm only requires a few ms, thus it can operate in real time. For each test, the SDN controller connects to the REST control interfaces of the line terminals and of the ROADMs to configure the transmission setup (i.e., wavelength, launch power, etc.) and to create the optical paths by installing switching rules, respectively.

In order to assess the maximum deviation of the controller's QoT-E model from the actual QoT in Mininet-Optical (representing the ground truth), we computed the gOSNR absolute error. The highest absolute QoT-E error at the output of each amplifier for all tests is shown in Fig. 3 and Fig. 4, respectively, for the sequential and random channel allocation strategies. The solid curves represent the error of our QoT-E model. As expected, the higher the number of wavelengths used, the worse the QoT-E model performs due to accumulated nonlinearities and power divergence. These results illustrate an important source of error in QoT-E models, which contributes to the use of larger QoT margins in real systems.

Next, we include the use of OPMs, so that the control plane can assess and correct the QoT-E across the link. Our proposed OPM-based QoT-E method replaces the QoT-E estimated values with monitored values at a number of OPM locations, restarting the estimation process from that monitoring point. The gOSNR absolute error of this method is reported in the figures by the colored empty markers. In our analysis, OPM nodes were considered at the end of each inter-node link (every 7-EDFAs). In the figures, at each OPM point (i.e.,

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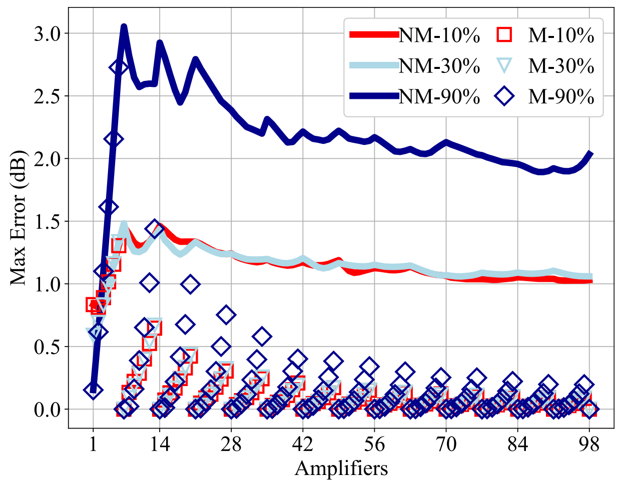

Fig. 3. Maximum absolute error in gOSNR estimation with the baseline QoT-E model without monitoring-based corrections (NM-curves) and with monitoring-based corrections (M-markers). The error is shown after each amplifier, while the monitoring is carried out every 7 amplifiers. These results are for the sequential channel allocation strategy.

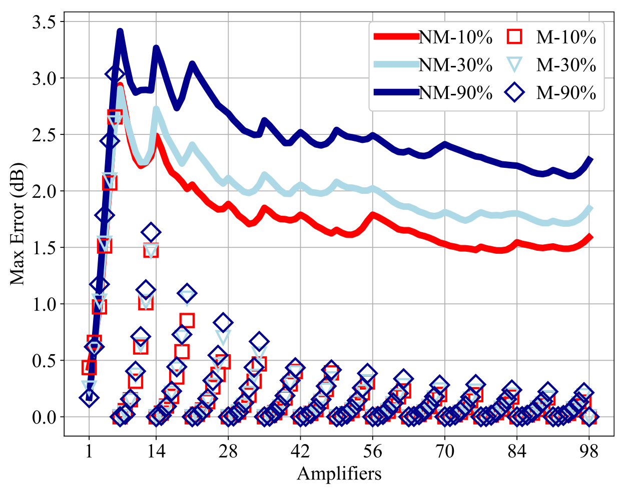

Fig. 4. Results for the same scenario as in Fig. 3, but assuming a random channel allocation strategy.

every multiple of 7 in the x-axis) the QoT-E error goes to 0. From there, the error starts increasing again, until the next OPM node is reached, at which point the error of the QoT-E model is reset again. It is noticeable that by comparing the unmonitored curves with the monitored data points in Fig. 3 and Fig. 4, retrieving monitoring information can reduce the QoT-E error substantially. At the OPM location, the error is reduced between 1.5 and 3 dB at short distances and 1 to 2 dB at the end of the link (i.e., 6,720km). In addition, after the first 7 amplifiers we have an improvement of at least 0.8 dB and 1.2 dB in the worst case (i.e., just before the monitoring), for the lower and higher loads, respectively. Although additional results are not plotted, we repeated the experiment interrogating OPMs every second inter-node link (every 14 amplifiers). We found that despite the substantial reduction in number of OPMs, after the first 14 amplifiers, we have an improvement of at least 0.6 dB and 0.8 dB in the worst case, for the lower and higher loads, respectively.

IV. Conclusion

This letter has introduced a method of adding optical elements and simulated optical physical layer effects to the Mininet network emulation platform, Mininet-Optical, for testing optical control plane functionality over large emulated networks. After briefly introducing how Mininet-Optical operates and how the physical layer emulation compares to other state of the art simulators, we provided a sample experiment to demonstrate its use for studying SDN QoT-E use cases that involve OPM measurements of the physical performance.

With this new capability, considering the wavelength dependent power divergence due to amplifier gain effects and SRS, we observed how the control plane QoT accuracy varies throughout the system. Furthermore, we were able to show the effect of using OPMs at different locations in a network to correct the QoT-E of the control plane. This enables testing the correctness of physical layer control plane operations and evaluation of a wide range of real-time QoT related SDN control methods to achieve greater reliability and functionality.

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