Performance Analysis of QoT Estimator in SDN-Controlled ROADM Networks

Alan A. Díaz-Montiel*, Jiakai Yu†, Weiyang Mo†, Yao Li†, Daniel C. Kilper† and Marco Ruffini*
*CONNECT Centre, Trinity College Dublin, Ireland
†University of Arizona, Arizona, United States
Email: adiazmon@tcd.ie, jiakaiyu@email.arizona.edu, wmo/yaoli/dkilper@optics.arizona.edu and marco.ruffini@tcd.ie

Abstract—**While new SDN control planes promise to provide faster and more dynamic provisioning of optical paths, mis-estimation of optical signal to noise ratio (OSNR) is still an issue that reduces the amount of capacity available in practice to allocate data paths. Typically, additional margins are applied to the estimation of OSNR for given paths, however, in the absence of detailed knowledge on the gain function of EDFAs, these margins are applied equally to all paths, leading to network under-utilisation. In this paper we show this effect over a simulated optical network based on the Telefonica Spanish national topology, emphasising the reduction in capacity due to the incomplete knowledge the network controller has on the exact wavelength and time based variation of EDFA amplifiers gain. We consider this to be of high relevance, as it opens up the road for further experimentation on the use of sparse optical performance monitoring to provide data that can be used to improve the QoT estimation from the control plane of an SDN-based system. The simulation used is based on the Mininet framework. This provides the advantage of testing SDN control planes that can be then utilised on experimental ROADM networks. In order to link SDN controller and the Mininet Emulation environment, we have developed an optical agent capable of simulating the behaviour of ROADMs systems.**

I. INTRODUCTION

Requirements driven by 5G services and the functional convergence of access, metro and cloud networking, are creating new challenges for the access-metro transport network [1], requiring fast dynamic reconfigurability of the optical transport layer above the current state of the art [2].

Dynamic add, drop and routing of wavelength channels can generate optical power dynamics which may result in signal quality degradation. This becomes even more complex in mesh networks, hence, the research community has been recently working on solutions for dynamic optical switching, both in proprietary [3] and open systems [4]. One of the key elements for enabling dynamic switching in ROADM networks is the presence of optical performance monitoring (OPM) functions [5], so that the control plane can operate on a feedback loop that takes into account the state of the active optical channels. OPM techniques are however still in their infancy and require highly specialised tools that are often limited in their capabilities. Recent studies have shown the beneficial impacts of OPM at intermediate nodes, enabling dynamic management decisions to reconfigure and optimise network channels [6]. While Software Defined Networking (SDN) approaches introduce a high level of flexibility for managing network resources, there is a lack of standardised interfaces for optical networking devices (i.e., optical switches), not to mention the absence of open interfaces in the OPM equipment, which leads to high-cost, complex solutions for monitoring in real-time the state of a network. Real-time analysis is crucial for dynamic light-path provisioning and network adaptation, overcoming the suboptimal solution of over-provisioning network resources for system-specific purposes [7]. Furthermore, the additional information provided by the OPM mechanism could not only assist reconfiguration and optimisation of the network performance, but also enable a better use of resources upon service setup (i.e., OSNR estimations, based on distance vs. modulation formats) [5]. However, on-site signal monitoring is still difficult to achieve, mainly because of the high CapEx and OpEx it generates.

To overcome the limitations imposed by OPM techniques, as it is the application of monitoring processes after the installation of network resources (i.e., wavelength allocation), multiple studies have proposed the inclusion of estimation functions for predicting the communication performance of an optical network [13] - [22]. While these approaches have given an insight into the physical impairments, this remains an area that could highly benefit from the use of modern technologies (i.e., machine learning techniques) to optimise the reliability of these functions for resource allocation and/or switching operations. Since it is possible that an estimation is not accurate, margins can be set in order to reduce potential failures. In this study, we analyse the performance achieved by applied fixed margins to a Quality of Transmission (QoT) estimator, which considers OSNR signal degradation, in order to achieve pre-allocation of light-paths, and dynamic switching.

While SDN is playing a major role in the control and management of electronic switching resources, its operation in the optical layer is still left to proprietary and disaggregated implementations. In this study, we also present an SDN control plane with OPM management capabilities based on the OpenFlow v1.5 recommendations, as an extension to the flow-rule capabilities of this protocol. Additionally, we have built an SDN-compatible ROADM network simulator to estimate the loss of performance due to the lack of information about the network. The latter was developed using open-source resources such as the Mininet framework [10], and software-switches [11].

The remainder of the paper is organised as follows. In section II, we provide a review of related work on the usage of QoT estimators that consider various physical impairments of an optical network. Then, in section III, we describe the

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architecture model of our system, as well as the physical impairments considered in the all-optical metro-network. In section IV, we present the experiments and the related results of the consideration of multiple margins to the QoT estimator. In the last section, V, we give our conclusions and present the direction we are taking for future work.

II. RELATED WORK

In [13], the authors studied the impact of OSNR levels of a signal towards near channels for a given set of connections. While they did not consider the addition of optical noise in the in-line optical amplifiers, the interest of a Quality of Transmission (QoT) estimator was first raised, considering some of the physical impairments in an optical network system. The idea of a QoT function was later introduced in [14], which, in combination with a customised routing algorithm, provided simulated performance studies on the feasibility of including these type of functions into the control plane. By considering a non-heterogeneous model of network elements, they evaluated transmission performance for different wavelengths, based mostly on the Chromatic Dispersion (CD) optical impairment. Since high computational resources are inappropriate for Routing and Wavelength Assignment (RWA) functions in the control plane, they determined it was necessary to quantify the estimation error when using the routing tool as a function of the network. Also in [14], the authors proposed the possibility to combine the QoT estimation with monitoring functions, by retrieving information from the optical nodes at fixed periods of time.

In [15] the authors proposed to use QoT estimations as a function of the CD map, to help derive appropriate margins on the dimensioning of an optical network. Under these considerations, they used the estimated results to determine the number of regenerators needed for a given network, as a function of the applied margins. In this study knowing the CD of the system helped reduce the errors of the QoT estimator.

Following a more statistical approach, the authors in [16] considered the introduction of confidence levels for adding margins in both fixed and adaptive manners. They also used the QoT function to determine the number of regenerators needed at a given transmission. However, it was concluded that comparing the required regenerators is not enough to assess the advantages related to a QoT estimation.

In [17], Leplingard et. al. analysed the application of adaptive margins to a QoT estimator, based on the amount of residual CD and non-linear phase experienced by a signal. In this study it was found that the utilisation of adaptive margins decreases the number of mis-estimations. Nonetheless, according to the authors, while the application of margins guarantees safer dimensioning, it is at the expense of including additional equipments.

Today, the evolution of coherent optical transmission has made it possible to easily recover from CD and Polarisation Mode Dispersion (PMD) using digital signal processing at the receiver, so that accurate QoT estimation for these impairments has become redundant [18]. However, in [18], Zami proposed that it is still relevant to consider the OSNR levels and crosstalk attenuation of signals, as input parameters for QoT functions. In addition, it is mentioned that analysing the performance of a transmission channel from a bandwidth perspective is important, especially when considering multiple physical impairments of a system. Zami proposed that the cumulated uncertainties along the light-paths must be also considered, e.g., as the aggregated noise caused by amplification systems.

Software Defined Optical Networks and Elastic Optical Networks are research areas that have been under development in the last decade. Overall, they propose the idea of having programmable optical elements that can dynamically adapt properties such as wavelength bandwidth or modulation formats [20], and the implementation of optical flexi-grid networking devices [19]. In [21] - [22], the authors studied the benefits of applying elastic modulation gains in the Microsoft's optical backbone in the US. They found that a capacity gain of at least 70% is achievable via elastic modulation. Also, they demonstrated how different wavelengths performed differently across the network, looking at multiple segments of it. From the latter, the authors concluded that different wavelengths might benefit from different modulation formats even while sharing paths.

In [23], the authors proposed an analytical framework for a QoT estimator considering spectrum dependent parameters. While assuming OPM monitoring functions capable of reporting the state of the network, the MATLAB simulations presented in this paper demonstrated that they were able to approximate the prediction of the network behaviour with high-accuracy. Although the analysis presented here lacks consideration of physical layer models, it provides an insight on how novel statistical techniques could improve the precision of a QoT function for signal performance in an optical network.

Bouda et. al. [24], proposed a prediction tool that is dynamically configurable considering optical physical impairments as these changed through the network. They included both linear and non-linear effects, such as Q-factor and non-linear fibre coefficients, for predicting accurate QoT. The authors were able to reduced the Q-estimation error to 0.6 dB. However, they believe the accuracy of the parameters in their model could be improved by considering more data variability, e.g., by changing the launch powers or considering measured OSNR levels.

In [25], a data-driven QoT estimator is analysed from a theoretical perspective. The authors commented on the advantages of approaches based on data analysis, in-gather than based on Q-factor estimation, overcoming the dependency of the consideration of physical layer impairments, eliminating the requirement of specific measurement equipment, as well as extensive processing and storage capabilities. While this approach presented high accuracy (between 92% and 95%) the neural network approach taken in this study presented high computational complexity, which is typically unsuitable for the management of all-optical networks.

Summarising, the literature review carried out in this section suggests that there are a number of areas that still need to be properly addressed. We consider there is a need for a QoT estimator that can accurately estimate OSNR signal degradation across nodes with unpredictable fluctuation in loss and gain. The latter could enable elastic configurations. Another missing component in this field is an SDN-based optical monitoring system, that can provide real-time data to help minimise the error of the QoT estimator discussed above.

III. ARCHITECTURE AND MODEL

The network topology we considered in this study is the Telefonica national Spanish telecommunication network model proposed in [31]. It consists of 21 nodes and 34 (inter-city) links, with varied distances. In order to analyse large-scale ROADM networks, we incremented the distances in the given Spanish network shown in Fig. 1 in order to operate on point-to-point connections ranging from 500 km to 4000 km. We have reproduced the topology on the Mininet emulator, developing an abstracted representation of an optical node through the use of OpenFlow software virtual switches (CPqD/ofsoftswitch v1.3 user-space software switch [11]). An example of an optical node architecture is reported in Figure 2: each of the ROADM components (WSS and EDFA) were emulated using separate virtual switches.

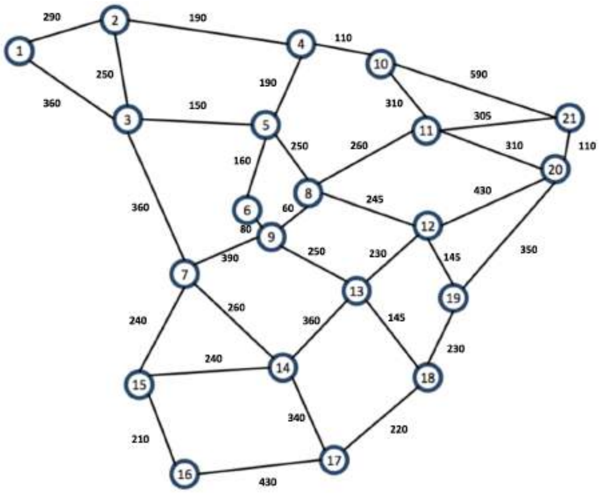

Fig. 1. Telefonica, national Spanish telecommunications network (link distances are reported in km) [31].

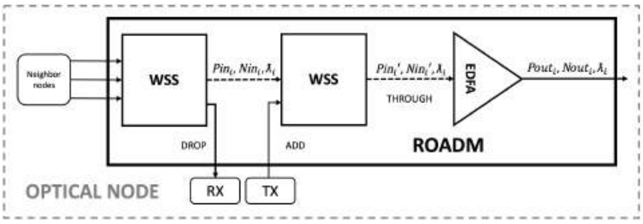

Fig. 2. Logical representation of the ROADM node.

Each output port has a post-amplification Erbium Doped Fibre Amplifier (EDFA), which compensates for the losses of the WSS in the system. In our abstracted optical network, at each link we installed an additional EDFA for each fibre span of 100 km, and an additional one at the end of a link to operate pre-amplification. In our model a colourless implementation was achieved by adopting WSS elements for both add and drop ports. The physical transmission and impairments parameters used in our simulations are given in Table I.

TABLE I
PARAMETERS USED FOR THE PHYSICAL TRANSMISSION AND IMPAIRMENTS

Physical component	Physical impairment
Launch Power	-2 dBm
Fibre Attenuation	0.2 dB/km
WSS Loss	9 dB
EDFA Noise Figure	6
EDFA Gain	20 dB

In order to simulate the optical performance of a signal traversing the nodes, we encapsulate optical transmission parameters (e.g., signal power and noise) in customised Ethernet packets to allow the exchange of this information across the virtual switches. Following an SDN paradigm, we are able to monitor the exchanged packets via the OpenFlow Protocol calls to the devices. Figure 3 depicts the different layers of communication between the entities considered in our model. At the bottom, there is the data plane (DP), which is represented by the virtual network. In between the data and control plane we implemented an optical agent, which is the entity that simulates the optical behaviour of each network element. The optical agent has bidirectional TCP connections to both the Controller and the DP. The SDN controller is in charge of the network control and management operations (e.g., path computation, connection control) that could operate over a real ROADM network with support for OpenFlow Protocol version 1.5. The agent implementation in our model is used to handle the customised Ethernet packets traversing the network, in order to generate data structures for representing the optical performance, as it uses the values stored in the packet header to keep track of the signal power and noise at each port.

The optical agent utilises equations (1) and (2) for computing the signal power and noise values at a given port of a path:

$$P_o(P_i, G_t, \lambda) = P_i * G_t * f(\lambda) \tag{1}$$

$$N_o(N_i, G_t, \lambda) = N_i * (G_t * f(\lambda)) + h(c/\lambda) * (G_t * f(\lambda)) * NF * B \tag{2}$$

$$OSNR = P_o / N_o \tag{3}$$

In equation (1), P_o is the output power out of a given node, P_i the input power, G_t the target gain, and λ the wavelength. We determine the input power as the launched power of the system; target gain is a computed gain per EDFA to maintain the signal power, and $f(\lambda)$ is the ripple function that represents the detailed gain transfer function of the EDFA. In

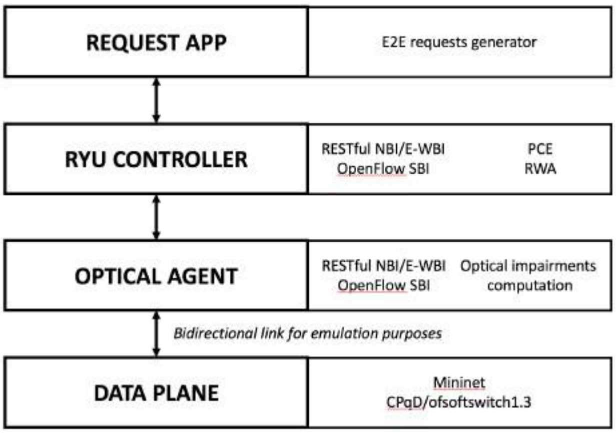

Fig. 3. Layered representation of the complete emulated system.

typical systems, a passive gain flattening filter is manufactured and applied to the amplifiers to compensate for the EDFA gain wavelength dependence. However, this is optimised for a specific operating point and is not tuned to each individual device, which brings in a certain degree of variability. In addition, the gain characteristic of the device will also vary over time. In order to reproduce this effect, since the optical power control stability problem regards the performance of each amplifier [26]-[28], we randomly allocated a different gain function to the different EDFAs of the system. This becomes indeed the main unknown variable in the system that affects the performance of the QoT estimator. In Figure 4, we present the gain functions that are considered for this study. Due to hands-on monitoring procedures and simulations at the CIAN testbed at the University of Arizona, we determined that the signal fluctuation imposed by amplification systems resembles a slowly varying sine function. Then, we shifted these monitored functions to left and right in order to add variability to the signal performance, and maintain the EDFA gain constant.

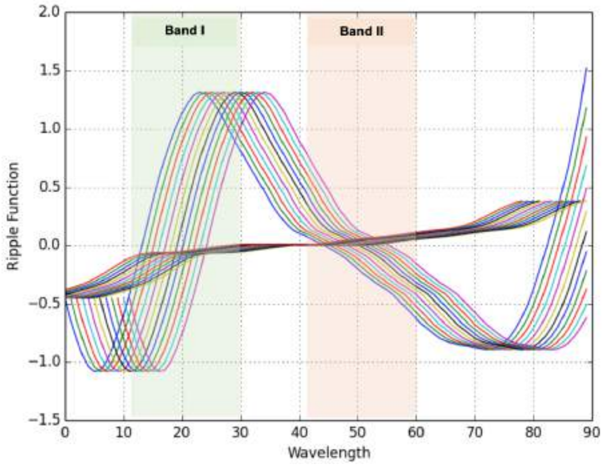

Fig. 4. Wavelength-dependent gain functions utilised for the simulation of detailed EDFA behaviour.

In equation 2, N_o is the output noise, N_i the input noise and G_t the target gain. We determined the input noise to be the generated noise after each phase, being 0 - or none - at the beginning of a single transmission. The system gain is the aggregated gain of the EDFAs that compose a link. We represent this by adding the ripple variation $f(\lambda)$ to the individual target gains *Gt*. Then, *h* is the Planck constant, *c* is the speed-of-light in an optical fibre, *NF* is the noise figure of the amplifiers, and *B* is the bandwidth of a channel in Hertz.

One of the novelties of our study is that we operate the simulations by computing the signal degradation at each node as the packets are traversing the network. Because of the model described in equations 1 & 2, the computation of both output power and noise at each node is dependent of the randomisation of ripple behaviour constraint at each optical amplifier.

In the control plane, we implemented a customised controller based on the Ryu framework proposed by NTT labs [29]. Apart from extending the OpenFlow Protocol descriptions to handle optical parameters, we included networking functions such as path computation, routing and re-routing, as well as OPM capabilities [30]. These are triggered by external applications to enable point-to-point connectivity, or by monitored data retrieved from the nodes. The Northbound Interface of our control plane is developed with RESTful API solutions, allowing for high-level requests from external applications. In addition to the generic networking functions at the control plane, we included an estimation module which performs a prediction of signal degradation given a point-to-point connection. The estimation function implemented in our controller uses the same tools presented in equations (1) & (2). However, assuming it has no detailed knowledge of the exact gain transfer function of each amplifier, it does not assume any such variation (e.g., it assumes a flat unitary ripple function). This calculation is triggered whenever there is a point-to-point request, and determines the feasibility of a light-path to be installed according to the OSNR levels, which are computed using equation (3).

IV. EXPERIMENTS AND RESULTS

The traffic generated for this study consisted of 2,000 end-to-end paths of length between 500 and 4,000 km, across the network topology considered in Figure 1. The experiments were carried out over two different segments of the C-band, shown in Fig. 4, in order to take into account the effect of different gain transfer functions.

Similar to [21], we analysed the feasibility of all the paths in the monitored traffic to be transmitted at different modulation formats, considering the OSNR signal levels of each transmission channel. For the OSNR thresholds, we have assumed those values above BER pre-FEC reported in literature, specifically from [21], which are based on a symbol rate of 32 Gbaud. The modulation formats are QPSK, 8QAM, and 16QAM, with OSNR thresholds, respectively, of: 10 dB, 14 dB, and 17 dB. Carrying out an OSNR analysis of each path, we determined in our model that 36.9% of the traffic could be modulated using 16QAM, 50% at 8QAM, and the remaining 13.1% at QPSK for the first band (1534.8 to 1542 nm). For the second band (1546.8 to 1554 nm), 26.6% of the traffic could be modulated at 16QAM, 70% at 8QAM, and 3.4% at QPSK, when we apply no margins. This constitutes the maximum capacity that the selected paths could carry in the network, if the SDN controller had perfect knowledge on the QoT (in this case the OSNR levels) associated with all paths.

The QoT estimator implemented in our controller predicts the OSNR levels of a given signal traversing a path, as described in Section III. Because the estimation does not consider the optical power fluctuation caused by the amplifiers (only the noise figure is considered), the only option available to improve the likelihood of succeeding in creating a new path is to apply a margin to all the paths. Intuitively, adopting a more conservative margin also reduces the network capacity, as it reduces the number of paths generated.

We have thus analysed the performance achieved when applying different margins to the prediction of the OSNR levels, in order to verify the maximum capacity achievable. The margins are applied to the following formula, which is used to determine whether the results of estimation plus margin is above the required OSNR threshold:

$$OSNR_{est} + M > OSNR_{th} \tag{4}$$

In (4), $OSNR_{est}$ is the estimate OSNR from the controller (which does not know the specific amplifiers gain wavelength dependence), M is the margin applied to the path, and $OSNR_{th}$ the actual required OSNR threshold for setting up the working path. We considered margins from -6 dB (i.e., a conservative approach) to 6dB (i.e., with an aggressive approach). The results are reported in Figure 5. The maximum capacity of the system is the maximum capacity calculated by our simulation using all the possible paths. This would also be the capacity achieved by the SDN controller if it had exact knowledge of the OSNR levels for every path. The curves show that, on one hand, when implementing a conservative margin, i.e., under-estimating the OSNR levels (in the negative region), the QoT estimator progressively rejects the allocation of paths, and the overall capacity decreases accordingly. On the other hand, when the QoT estimator adopts a more aggressive strategy, i.e., over-estimating the OSNR levels (in the positive region), the capacity also decreases progressively, as a higher number of paths does not meet the minimum OSNR threshold for the selected modulation and thus cannot transport data. For the higher values of margin, the QoT estimation will assume that all paths can operate at 16QAM, and the achieved capacity settles at the value of 46% and 32%, respectively for the first and second bands of operation, which are related to the percentage of paths that can support the 16QAM modulation (as already mentioned at the beginning of this section). It is imperative to notice that both under-estimation and over-estimation at the control plane cause discrepancies in the performance of the network because of the misuse of network resources. While constant under-estimation would lead to the non-installation of paths, an over-estimation can lead to the installation of non-feasible paths, hence, installing non-usable resources.

According to our study, the optimal point of the OSNR margin adopted by the controller seem to be around the 0dB value, for both bands examined. However, even at the optimum, since such margins are adopted equally across all paths, the loss of capacity with respect to the maximum capacity is still of the order of 5%-17%.

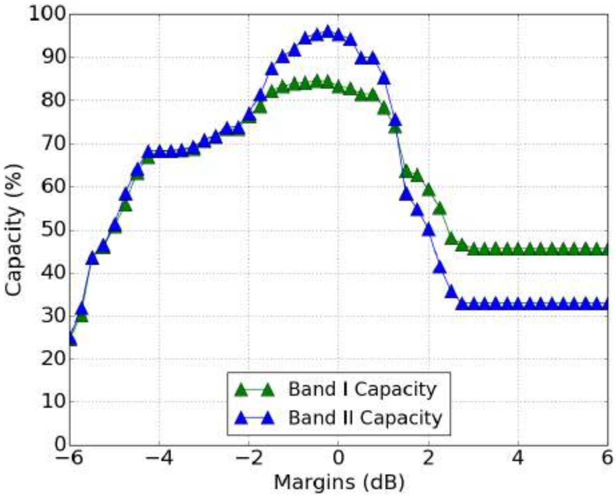

Fig. 5. Network capacity vs. OSNR margins applied by the control plane.

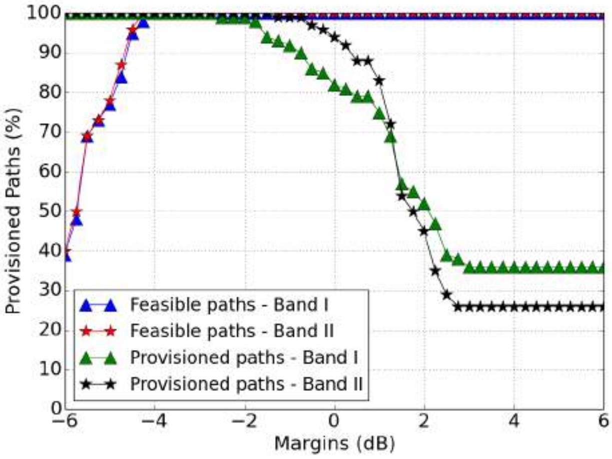

Fig. 6. Comparison of two analysis: Percentage of feasible paths that are provisioned for both bands vs. Margins (dB) (red and blue curves), and provisioned paths above required OSNR threshold for both bands vs. Margins (dB) (green and black curves).

In Figure 6, we show the success rate of two analysis: *(i)* the ratio of number of paths attempted to be installed, with respect to the total number of paths with OSNR levels above BER pre-FEC threshold. A more conservative approach would restrict significantly the attempts of installation, whereas a more aggressive prediction would fall into highly optimistic computations, attempting to install 100% of the paths; *(ii)* we analysed the success rate of the established paths. In other words, how the application of different margins to the QoT estimator affects the accuracy of feasible light-paths. Our results suggest that a conservative approach would increase the accuracy of the prediction of feasible paths, but at the expense of restricting network capacity. Contrasted with Figure 5, it is noted that when over-estimating the feasibility of light-paths, the maximum percentage of feasible paths is 36%, allowing for 46% of the network capacity for the first band. Similarly, this analysis determines that for the second band, only 26% of the paths can be successfully allocated, enabling for 32% of the network capacity.

V. CONCLUSIONS

In this study, we presented a study on the network under-utilisation issue brought by the absence of detailed knowledge on the behaviour of EDFA gain functions across wavelengths and over time. Our simulations, based on the use of a Ryu SDN controller operating over a Mininet emulation of the Spanish national network, showed the difference in network capacity between an optimal situation, where the gain function of the cascaded EDFAs is known in advance, and the real situation, where the controller only uses a flat gain function. By comparing the outcome of the simulator with the prediction of the controller, we could calculate how the use of different margin values for the OSNR affect network capacity. We showed that an aggressive margin strategy, that would tend to over-estimate the available OSNR, reduces the performance, as it favors the adoption of higher modulation rates, leading to situations where the paths created could not operate below the BER threshold. On the other hand, a too conservative strategy that tends to under-estimate the OSNR, would lead to a situation where the controller operates over lower modulation rates, and in some cases declines the creation of wavelength paths (which would instead have worked correctly, according to the Mininet simulation).

As future work, we plan to emulate the use of sparse OPM in the network to gain knowledge on the wavelength and time-varying behaviour of other EDFAs, and feeding the data to machine-learning based techniques to improve the per-path estimation of the OSNR, thus increase the network utilisation.

VI. ACKNOWLEDGMENTS

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