

# GNPy: an open source planning tool for open optical networks

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**Abstract**—We present GNPy: an open source software abstracting the physical layer of an optical network. GNPy has been developed by the physical simulation environment (PSE) team in the telecom infra project (TIP) consortium. We experimentally demonstrate the accuracy of the tool in predicting the quality of transmission (QoT) in a network, and then we demonstrate how GNPy can be used to address physical layer upgrades and how this can lead to large benefits in the network.

**Index Terms**—Open source, Open Optical Networks, WDM data transport

## I. INTRODUCTION

Operators want to improve the network efficiency given the increasing traffic demand and resource-constrained limits. Furthermore, optical infrastructures can be optimized [1] to exploit the available capacity of the network [2]. An accurate quality of transmission (QoT) estimator (QoT-E) is fundamental to achieve such a goal. Thus, open optical networks challenge the status-quo by defining multi-source agreements and YANG models - such as OpenConfig and OpenROADM [3]–[5] - and by giving to the operators the possibility of performing vendor-neutral planning and analysis, relying on the estimation of network performance. This way, operators and vendors are able to assess the network performance off-line and on-line, in a reliable and comparable way. Such capability is functional for optimizing and automating the infrastructures' usage in a software-define network (SDN) context such as OpenDaylight (ODL) [6] and open network operating system (ONOS) [7]. Such a reference is provided by the Physical Simulation Environment (PSE) working group [8], [9] within the Telecom Infra Project (TIP) as open source software called "GNPy" [10]. As shown in Fig. 1, GNPy needs a description of the status of the network, then it computes the physical impairments of each path: GNPy has a QoT-E engine. The QoT-E evaluates the QoT parameter: the generalized signal-to-noise ratio (GSNR) [11], which evaluates both the amplified spontaneous emission (ASE) noise and the non-linear interference (NLI) [12], [13]. Such information can be used by the SDN controller for network operations as the verification of the path feasibility and bitrate maximization of a lightpath. In order to demonstrate the reliability of GNPy, it has been extensively validated via experiment in [9], [12]–[14].

In this work we review the last, and most extensive validation of GNPy to show its accuracy and then, we demonstrate how GNPy can be used to design the physical layer of the network and to plan amplifier upgrades.

This paper is structured as follows: in Sec. II the general structure of the software is depicted and then a focus on the QoT-E engine is given. Then, the Sec. III introduces the test-bed in Microsoft lab used for validating GNPy and the results of such validation. Later, Sec. IV shows the use of GNPy to assess a physical layer upgrade and how it is used as basis for techno-economic analysis. Finally, in Sec. V we draw the final conclusions.

## II. GNPy STRUCTURE

The general structure is depicted in Fig. 2. GNPy provides many features built around a core engine that assess the propagation effects to estimate the quality-of-transmission (QoT). The core engine simulates the propagation between two points in a network. The network is built using network elements, such as the fiber, the erbium-doped fiber amplifier (EDFA), the ROADM node and the transponders. During a simulation, the core returns the generalized signal-to-noise ratio (GSNR) [11] of each channel along the path as the GSNR has been proven as metric for the QoT for modern dispersion uncompensated multilevel-modulated coherent WDM optical communications [12]. To have meaningful results, GNPy requires a set of parameters describing each network element of the network. In stable releases of the code, these parameters can be provided to GNPy in JSON format or via XLS files internally converted into a JSON structure. Amplifiers can be abstracted according to three different data models [15] depending on the actual knowledge on the amplifier:

- 1) A *black-box model*, for which some key attributes are not available.
- 2) An *operator model* that describes proprietary equipment used when the knowledge is limited to a small amount of NF-gain values.
- 3) A *white-box model* that defines precise NF versus gain for open devices providing such information.

This capability of having different models is a key for enabling a multi-vendor application. Based on this it is possible to model both a green field or brown field configuration.

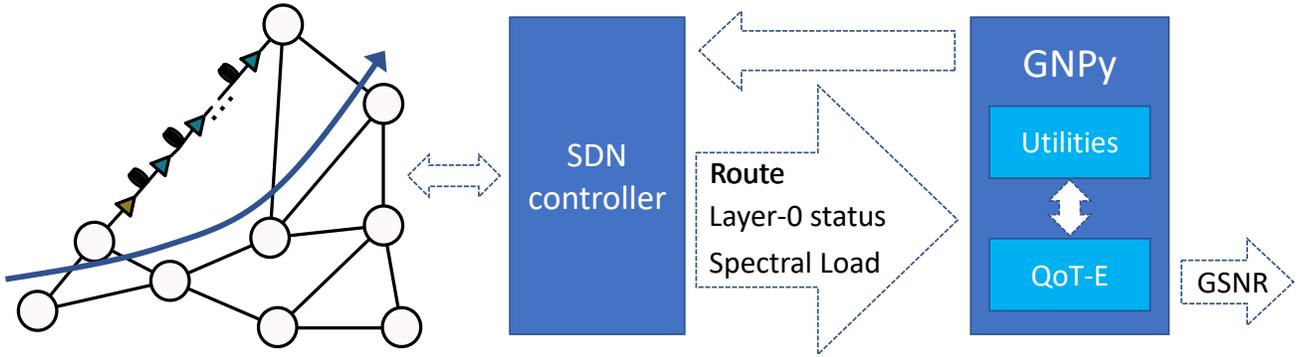


Fig. 1: Block diagram for using GNPpy in a SDN environment.

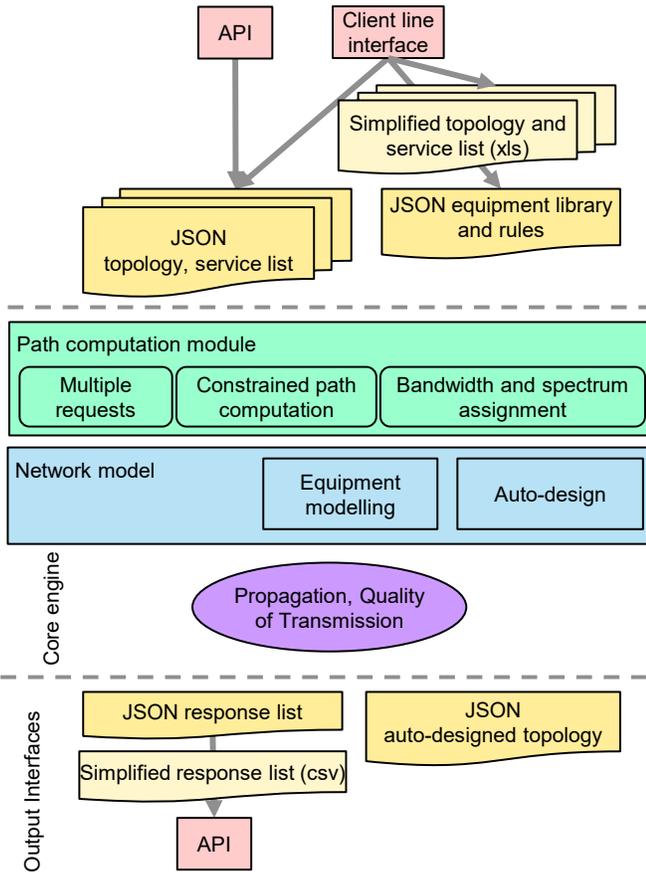


Fig. 2: GNPpy structure.

In some scenarios such a precise description is not feasible. Thus, GNPpy has an *auto-design feature* able to configure the amplifier according to some heuristics and design rules. This feature has been presented in [15].

When auto-design is used, the input topology is incomplete. The spans have not all amplifiers, and the amplifier model and operating point is not known. In this case, auto-design selects suitable amplifiers from an equipment library and it splits fiber spans that are too long.

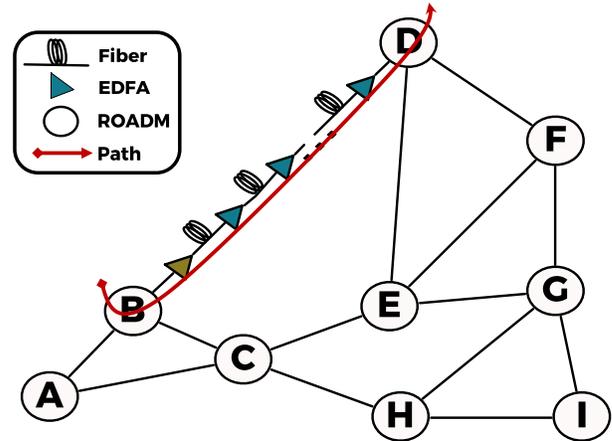


Fig. 3: GNPpy path propagation

The user experience is eased by a set of features for what-if scenarios and planning as it allows the assessment of many requests on the same network, and on the same configuration. GNPpy supports also usual planning constraints as disjunction of the paths, spectrum assignment, selection of mandatory nodes and the selection of the transponder mode, etc. This feature can be interfaced via JSON file whose structure is based on [16]. The path computation module implements the shortest path algorithm and it enables the development of an API to integrate the optical line system controllers. Such API was featured in an open disaggregated transport network (ODTN) demonstration [17]. The path feasibility is estimated by GNPpy in a release of the TransportPCE controller project [18].

#### A. The quality of transmission estimator of GNPpy

GNPpy needs a network description provided via JSON file. Such network is abstracted as optical impairment-aware topology [16], [19] made of network elements and it returns the GSNR of each channel along a path as shown in Fig. 3. Network elements are fibers, amplifiers, ROADM nodes and transceivers. Given such description of the network, GNPpy computes the GSNR between a source node and a destination

node through a path by using the *spectral information*. Aim of spectral information (SI) is to propagate the information about the WDM comb. Such information is the signal power, the symbol rate, the signal roll-off, the channel frequency, the total ASE noise power and the NLI power. The SI propagates along the path on the network through each element. The network elements update the spectral information attenuating or amplifying the signals and the ASE and NLI noise contributions and by adding new noise disturbances. In particular, a ROADM node adds some ASE noise in the add/drop channels and it equalizes the spectrum. The amplifier amplifies the power values and introduces new ASE noise. The ASE noise is evaluated as:

$$P_{ASE}(f) = hfNF(f)G(f)B_{ref}, \quad (1)$$

where  $h$  is the Planck constant,  $G(f)$  is the gain and  $B_{ref}$  is the reference bandwidth equal to the channel symbol rate. The fiber attenuates and introduces some NLI because of the Kerr effect taking into account also the stimulated Raman scattering [20]–[23].

The stimulated Raman scattering (SRS) is assessed by a numerical Raman solver that evaluates the solution of the set differential equations describing the RS effect [24]. Then, the NLI contribution of each fiber span is treated as an equivalent additive white Gaussian noise disturbance that takes into account the SRS according to the generalized Gaussian noise (GGN) model [20]–[23], and this contribution is evaluated as:

$$P_{NLI}(f) = G_{NLI}(f)B_{ref}, \quad (2)$$

where, the  $G_{NLI}(f)$  is the NLI power spectral density which depends on the fiber parameters and on the WDM spectral occupancy. Finally, the transceiver at the end of the path computes the GSNR of each channel that includes both the optical signal-to-noise ratio (OSNR) and the non-linear signal-to-noise ratio ( $SNR_{NLI}$ ). Those quantities are defined as:

$$OSNR_i = \frac{P_{S,i}}{P_{ASE}(f_i)}, \quad (3)$$

$$SNR_{NLI,i} = \frac{P_{S,i}}{P_{NLI}(f_i)}, \quad (4)$$

$$GSNR_i = \frac{P_{S,i}}{P_{ASE}(f_i) + P_{NLI}(f_i)} = (OSNR_i^{-1} + SNR_{NLI,i}^{-1})^{-1}, \quad (5)$$

where  $P_{S,i}$  is the signal power of the  $i$ -th channel and  $f_i$  is its central frequency.

### III. EXPERIMENTAL VALIDATION

Fig. 4a and Fig. 4b show the test-bed used: it emulates a commercial network and have six ROADM nodes and five amplified segments. In the network, the longest bidirectional path is 2000 km long. Each ROADM degree has a booster amplifier and a pre-amplifier, while each optical segment is  $\sim$ 400 km long. Each optical segment has five fiber spans and four inline amplifiers (ILA): three Erbium Doped Fiber Amplifiers (EDFA) and a hybrid EDFA/Raman amplifier (HFA). The length of the spans is between 65 km and 120 km, and the

fibers are G.652 standard single mode fiber (SSMF) and G.655 larger effective area fibers (LEAF). The line system (LS) has been configured by a proprietary LS controller. Commercial multi-vendor transponders generate 26 channels under test (CUT) grouped into five media-channels (MC). Three MCs are comprised of six channels, and the remaining three MCs are made of four channels. As shown in Fig. 5, the CUTs are distributed in a 4.65 THz bandwidth as follows: the two four-channel MCs are at the edges of the spectrum, one MC is in the middle and the other two MCs are in the midpoints between the central MC and the external ones. The remaining portion of the spectrum is filled with filtered ASE noise as shown in [25]. The result is a full C-band spectral load between 191.35 THz and 196 THz. The transponders support the following modulation formats: polarization multiplexed (PM)-QPSK, PM-8QAM and PM-16QAM. The signals are root-raised cosines having roll-off equal to 0.2 and symbol rate equal to 34.16 GBaud.

The GSNR is estimated from the QoT-E of GNP<sub>y</sub>, by probing the state of the network by querying it via Microsoft SDN line system monitoring tool, based on REST. Thus, the network data such as the power levels evaluated by photodiodes along the network, the configuration parameters, and the channel plan are collected. Most of the missing parameters can be retrieved from the data-sheets of the network equipment. Furthermore, a missing crucial parameter is the loss of the fiber connectors; for this, we assume a value of 0.75 dB as in [12], [13]. This information populates the topology JSON file used by the QoT-E. The actual OSNR has been measured by using the built-in functionality of the optical spectrum analyzer (OSA). Then, the actual GSNR has been measured by characterizing the back-to-back (B2B) performance of each transponder as BER vs. OSNR, then measuring the BER and, finally, inverting the B2B curve. Finally, errors are computed as the difference between the estimated GSNR and the measured one. We tested several propagation distances and modulation formats: PM-QPSK at 2000 km and 4000 km, PM-8QAM at 400 km, 800 km, 1200 km, 1600 km and 2000 km and PM-16QAM at 400 km, 800 km and 1200 km, in both directions. The 4000 km path was obtained by looping back the signals over the 2000 km path.

We first observe the 2000 km using PM-8QAM modulation as shown in Fig. 6, which reports the measured OSNR (green diamonds), the measured GSNR (orange triangles), the estimated OSNR (red line) and the estimated GSNR (blue line). The OSNR has an error always within 0.4 dB except from two outliers at 192.4 THz and at 193.75 THz. The discrepancy between the measured GSNR and the estimated one is within 1 dB. In this case, GNP<sub>y</sub> shows good results by predicting the frequency variation of the two metrics. Finally, Fig. 7 shows the distribution of the errors. It can be noted that 90% of the errors are within 1 dB, and many are positive, meaning that they are not conservative and the largest value is 1.4 dB.

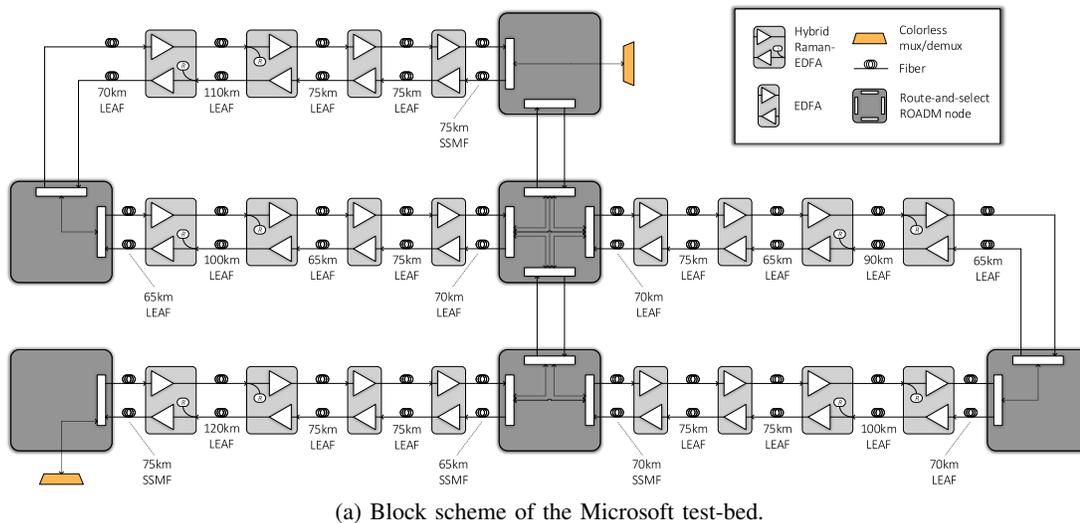


Fig. 4: The block scheme (a) and a photo (b) of the Microsoft test-bed.

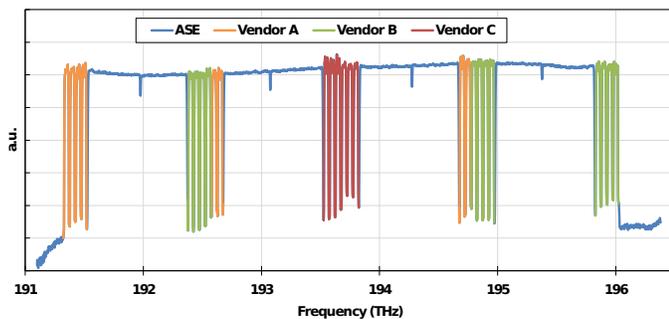


Fig. 5: Transmitted spectrum. Channels of different vendors are reported with different colors.

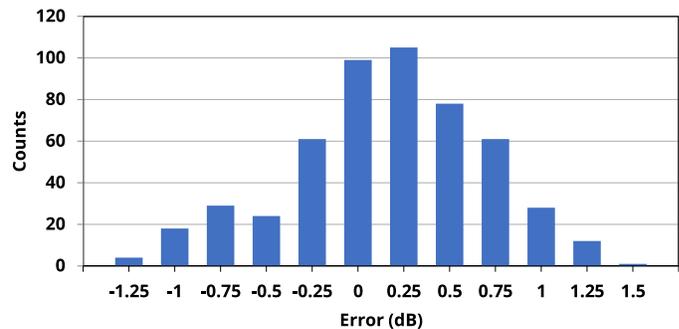


Fig. 7: Error histogram.

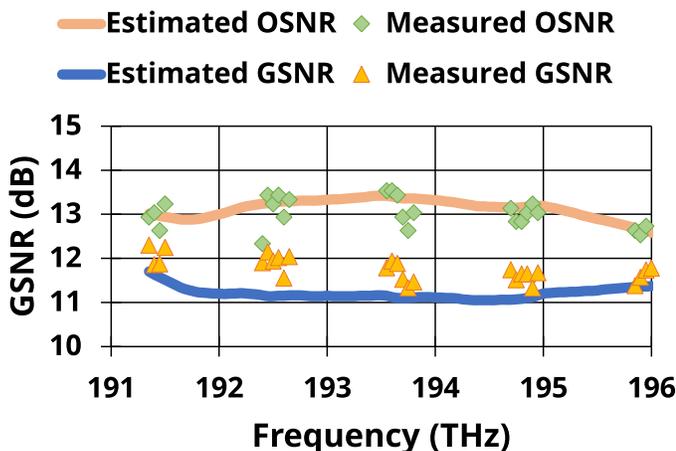


Fig. 6: Comparison of measured and estimated OSNR and GSNR from PM-8QAM @ 2000 km

#### IV. METHODOLOGY AND RESULTS

In this section we use GNPY to analyze the impact of a physical layer upgrade on the GSNR and throughput distribution in the network. We analyze the German network [26] depicted by

Fig. 8 having 17 nodes and 26 links. We assume that all the fiber spans are standard single mode fibers (SSMF) having an attenuation coefficient ( $\alpha$ ) of  $0.2 \text{ dB/km}$ , a dispersion coefficient ( $\beta$ ) of  $21.27 \text{ ps}^2/\text{km}$  and a non-linear coefficient ( $\gamma$ ) of  $1.27 \text{ 1/W/km}$ . The amplifiers are erbium-doped fiber amplifiers (EDFA) having 5 dB noise figure. We assume a 50 GHz fix-grid made of 96 spectral slots in the C-band. The channels have 32 GBaud of raw symbol rate and 25 GBaud of net symbol rate. We assume elastic transceivers able to use polarization multiplexed (PM)-QPSK, PM-8QAM, PM-16QAM, PM-32QAM and PM-64QAM. Thus, the transceivers have a GSNR vs throughput characteristic as shown in Fig. 9, and thus a throughput of 100, 150, 200, 250 and 300 Gbps can be used if the path GSNR is larger or equal than 12, 16.5, 20, 24.5 and 27 dB respectively. The transmitted power and the amplifier gain are computed by the auto-design engine by assuming full spectral load. Then, the path computation module is used to compute the routing space according to a k-shortest path algorithm [27] having  $k=15$ . Consequently, we use the GNPY core engine to evaluate the GSNR and the maximum achievable throughput of each path in the routing space. Then, we assume to assist all the EDFAs in the network

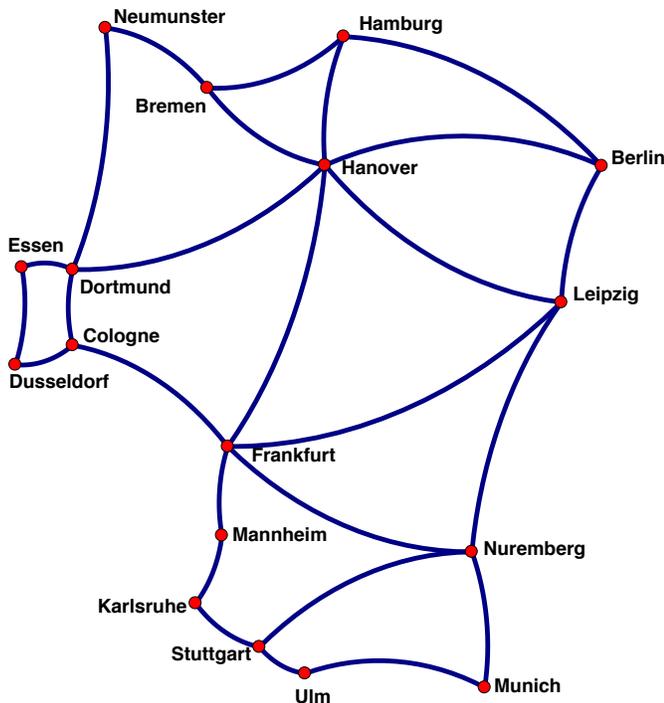


Fig. 8: German network topology.

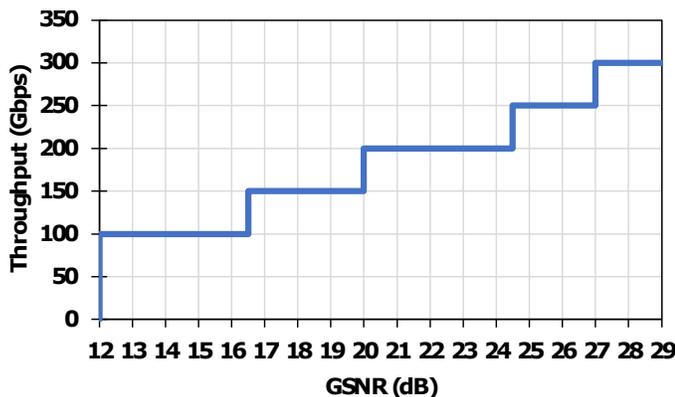


Fig. 9: Throughput vs GSNR of a transceiver.

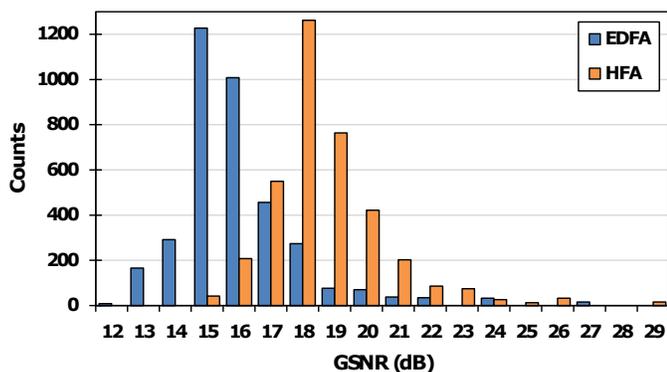


Fig. 10: GSNR histogram.

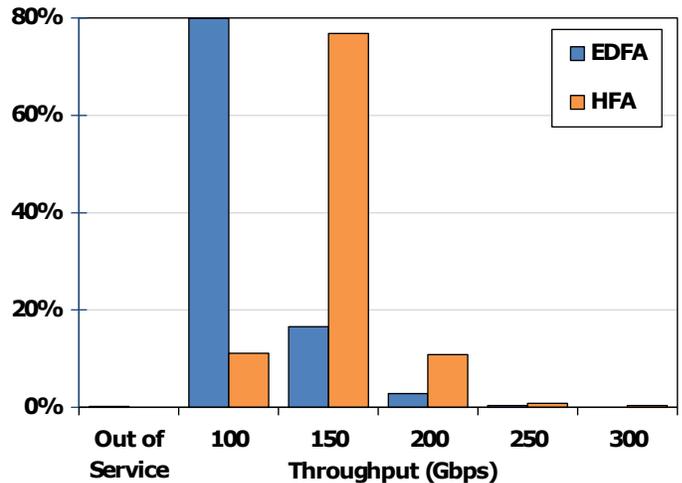


Fig. 11: Throughput distribution.

with some Raman amplification to have HFAs. The net effect of this physical upgrade is an overall equivalent noise figure of 0 dB as shown in [28], [29]. Given, such upgrade we recompute the GSNR and the throughput, and we compare them with the previous ones. Fig. 10 depicts the GSNR histogram of the paths in case only EDFAs are used (blue bars) and in case all the amplifiers are promoted to HFA (orange bars). The Raman amplification benefit moves the average GSNR from 15.5 dB to 18.1 dB, giving an average gain of 2.6 dB. Furthermore, 90% of the paths are between 13 dB and 18 dB in case EDFAs are used and the upgrade moves this range between 16 dB and 21 dB. Fig. 11 reports the throughput distribution for the full-EDFA network (blue bars) and the full-HFA network (orange bars). A 0.2% of the paths are out of service in case only EDFAs are used as their GSNR is smaller than the threshold of 100 Gbps, while these paths are all enabled in case HFAs are used. By using a pure EDFA solution, 80% of the paths reach only 100 Gbps, while the use of HFA 77% of the paths achieve 150 Gbps and, in general HFAs promote 70% of the paths to a higher throughput. It can also be noted that, using EDFAs or HFAs, the throughput of 250 Gbps and 300 Gbps are used by only 0.4% and 1.2% of the paths respectively.

## V. CONCLUSION

We introduce the structure of GNP<sub>y</sub> also focusing on the QoT-E engine. Then we show the tes-bed led in Microsoft labs. The data are retrieved from SDN controller and data-sheet demonstrating the usability of GNP<sub>y</sub> in an automated environment. The QoT-E of GNP<sub>y</sub> demonstrates excellent accuracy in estimating both the OSNR and the GSNR as the error is within 1.25 dB for 99% of the cases. Finally, we show how GNP<sub>y</sub> can be used to assess the network performances of the German topology and how it can be used to identify the benefit of promoting EDFAs to HFAs. To do that, GNP<sub>y</sub> computes the routing space of the network and then, it evaluates the GSNR and the throughput of each path according to the network before and after the upgrade. GNP<sub>y</sub>

shows good potentialities of such upgrade as more than 70% of the paths are promoted to a higher order modulation format. Such a tool can be the basis for more targeted analysis as in [30] and then, it can be used as core engine of a techno-economic analysis.

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