Multi-band Optical Network Assisted by GNPy: an Experimental Demonstration

M. Devigili
Universitat Politècnica de Catalunya
Barcelona, Spain
mariano.devigili@upc.edu

P. Nadimi Goki, N. Sambo, P. Castoldi
Scuola Superiore Sant'Anna
Pisa, Italy
name.surname@santannapisa.it

L. Potì
CNIT
Pisa, Italy
luca.poti@cnit.it

A. D'Amico, V. Curri
Politecnico di Torino
Torino, Italy
name.surname@polito.it

***Abstract*—Multi-band transmission is attracting the interest of research community because of its prospects to increase network infrastructures life. Indeed, current deployed systems mainly exploit the C band, thus deployed fibers can still offer a wide range of available spectrum. In this paper, quality of transmission (QoT) estimation is considered as fundamental control step for light path setup in order to check the proper feasibility of transmission along a computed light path. We demonstrate multi-band networking with channels on C and S bands in a testbed including a re- circulating loop. As a QoT estimator, the open-source GNPY module is extended in order to consider the typical impairments of a long-haul multi-band transmission and validated in this multi-band scenario for assisting connection setup with quality of transmission estimation. The measurements on the testbed demonstrated the correct operations of the multi-band data plane testbed, particularly with reference to the GNPy estimations and thus validate the QoT estimator for C+S band transmission.**

***Index Terms*—multi-band, GNPy, QoT, S-band, GN model, GGN model.**

I. Introduction

The global IP traffic is increasing due to the growing number of Internet users, IoT applications, mobile connectivity and devices [1]. In this scenario, deployed fibers (single mode fibers – SMFs) are reaching their saturation [2]. Thus, in response to this emerging need the research community is investigating the migration toward multi-band (MB) optical networks [3] as they promise to provide a big jump in terms of transmission capacity. Indeed, currently SMFs are used in the C band and, only in some recent network upgrades, in C+L. The exploitation of other bands (e.g., E, S [4], [5]) may be an effective solution for upgrading network capacity while avoiding the installation of new fibers. MB networking is supported by the large availability of G.652.D SMFs presenting negligible absorption peak [6].

MB systems have been investigated through ad-hoc experimental investigations that focused mainly on the transmission aspects. In [7], a transmission along L+C+S was demonstrated for 40-Gb/s channels. Similarly, in [8], a 40-Gb/s transmission over the S band was demonstrated along installed fibers without affecting existing traffic in the C-band. More recently, a 5-band transmission (from O- to L-band) was demonstrated [9] where the effects of stimulated Raman scattering (SRS) are investigated considering S and L bands.

Regarding physical layer modelling, in [10], the Gaussian noise (GN) model is extended to account for impairments relevant in wide-band transmissions, as SRS, defining the generalized Gaussian noise (GGN) model. Recently, the open-source GNPy tool [11] has been released implementing both GN and GGN models for quality of transmission (QoT) estimation.

This paper presents an experiment of data plane for a MB optical network. The GNPy QoT estimation tool (implementing the GGN model) assists the connection setup to verify lightpath's QoT. The measurements on the testbed including a re-circulating loop will demonstrate the correct operations of the MB data plane testbed, particularly with reference to the estimations provided by GNPy. The GNPy QoT estimation tool has been validated several times for C band transmissions (e.g., [12]–[14]) and recently as well for the C+L band [15]. In this paper, the first validation of GNPy for a C+S band transmission is presented to the best of our knowledge.

The remaining of the paper is organized as follows. Section 2 motivates and introduce the reference network architecture. In Section 3, we describe the experimental setup. The main results are presented and discussed in Section 4 where the estimations are compared with the measurements. Finally, Section 5 draws the main conclusions.

II. MB optical network assisted by GNPy

The implementation of a MB network requires a performance estimation method to verify the quality of transmission based on the assigned path and channel parameters (e.g., launch power, baud rate). The general reference network architecture considered in the paper consists of a MB optical network controlled by a centralized SDN controller including the GNPy estimation tool. Upon connection request, the SDN controller performs routing and spectrum assignment and evaluates QoT of the computed light path. In case of acceptable QoT (e.g., bit error rate – BER – below a threshold), the SDN controller configures the proper data plane devices associated to the computed light path (e.g., writes the value of configuration parameters in local controllers of the devices). Based on such a reference architecture scenario, this paper is mainly focused on GNPy based QoT estimation and on its experimental demonstration.

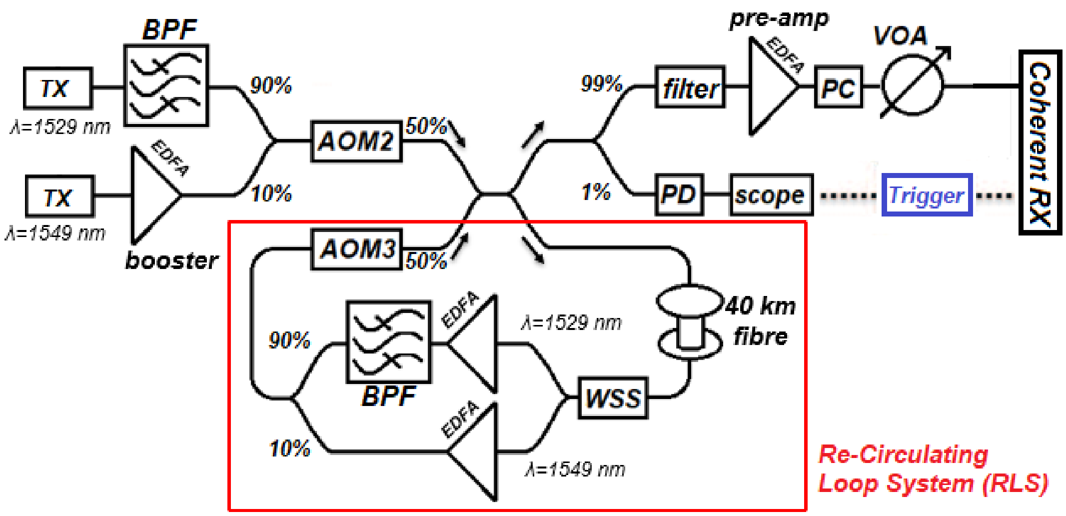

Fig. 1. A blockdiagram showing the experimental testbed used to emulate a long-haul core optical network. It can be subdivided in three modules: transmitter, transmission link (i.e., contained in the re-circulating loop system) and receiver.

The GNPy tool was modified in order to consider other relevant effects in long-haul MB transmissions: *i)* the SRS induced power transfers from-low wavelength channels to high-wavelength ones. Such nonlinear effects were accounted employing the GGN model; *ii)* the attenuation wavelength-dependency [6], where the fiber loss increases significantly outside of the conventional band. To take this into account, channel-dependent fiber losses were set in the QoT estimator; and *iii)* the band dependent amplification (e.g., EDFA in the C band, while TDFA in the S band [16]). This was modelled by assigning band dependent noise figure (NF) and gain parameters to characterize the amplifiers in GNPy.

The objective of this experimental study is to verify whether the GNPy tool can be employed as a QoT estimator in the considered MB network architecture.

III. Experimental Setup

Fig. 1 shows the block diagram of the experimental data plane. The transmission sources were operating at approximately 1529 nm and 1549 nm, respectively, and were set at the maximum supported power (14 dBm) in order to have a proper launch power at the fiber input (e.g., around -2 dBm), despite the undergone system losses before reaching the re-circulating loop system (RLS).

The two channels are modulated using separate nested Mach-Zehnder modulators (MZM)s. Both these external IQ modulators received the same information signal – a N=11 pseudo random bit sequence (PRBS) with 28-Gbaud symbol rate. The DAC was used to periodically output pulse shaped electrical signals which drove the MZM based IQ-modulators. Dual polarization quadrature phase shift keying (DP-QPSK) signal was achieved. DP was obtained by splitting the signal into two orthogonal polarizations that were de-correlated by delaying them with respect to each other and finally combined by a polarization beam combiner (PBC) as shown in Fig. 2.

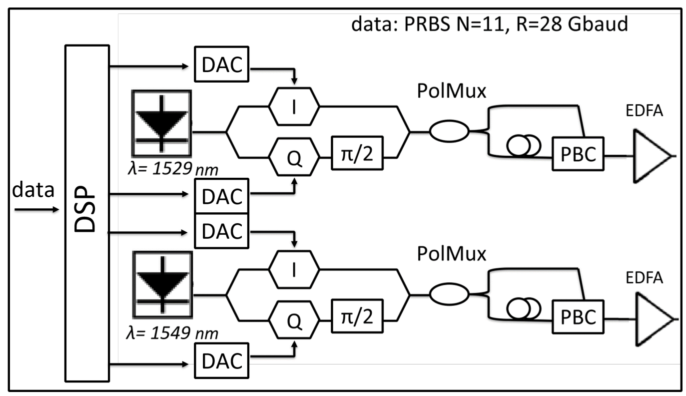

Fig. 2. Transmitter scheme. The QPSK modulation was implemented through an interferometer composed by balanced MZMs on each of the arms and by a 90-degree phase shifter on one of the arms. Differently, dual polarization was obtained with a polarization multiplexer (PolMux) and introducing delay among the orthogonal components before combining them.

The S band signal had a $\sim$ 9 dBm total power at the output of the transmitter. This power was reduced to $\sim$ 7 dBm after the filtering of the ASE noise through a band pass filter (BPF). The C band resulted to have a power of $\sim$ 2 dBm. A booster Erbium-doped-fiber amplifier (EDFA) was exploited to set approximately the same launch power over the two distinct channels. The two modulated signals were multiplexed on the same fiber by a 2x1 coupler with a split ratio of 90:10 selected to preserve the power for the more critical S-band channel. Thus, the coupler input carrying the 90% of the power was assigned to the S band channel, while the 10% input to the C band channel in order to give a higher power to the S band channel.

A long-haul transmission line was emulated through a RLS loaded with a $\sim$ 10 dBm wavelength division multiplexing (WDM) signal through the acusto-optic modulator (AOM2),

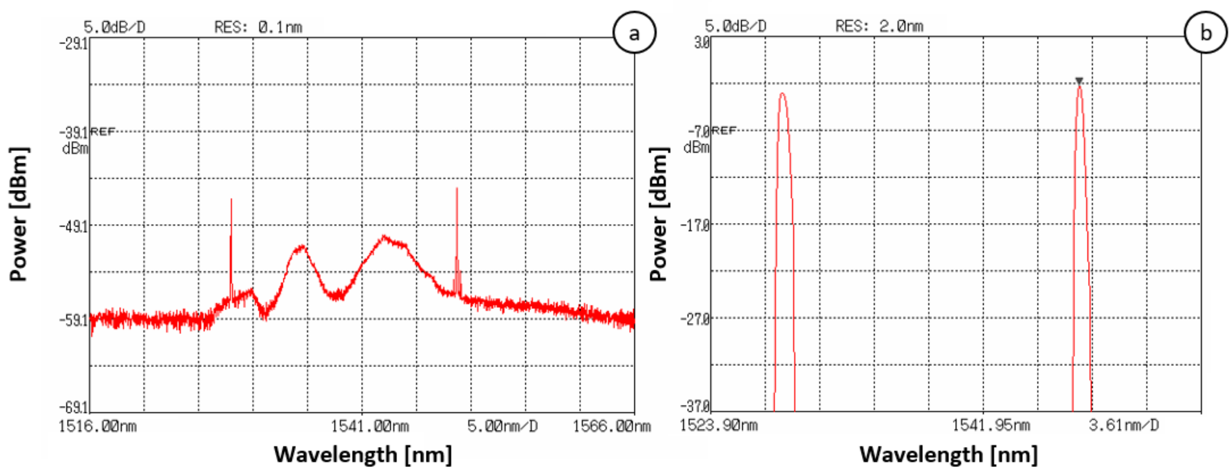

Fig. 3. Captures realized with an *Ando* Optical Spectrum Analyzer (OSA) at the input of the RLS. (a) Optical spectrum of the WDM signal. (b) Power evaluation of the S-band (on the left) and of the C-band channels (on the right) before being launched inside the fiber.

whose insertion loss was 4 dB, and a 2x2 coupler with a splitting ratio of 50:50. Fig. 3 (a) shows the optical spectrum at the RLS input. Among the two channels, the spectral shape of ASE noise can be seen clearly. This relatively high noise was generated by the amplifiers integrated in the transmitter and by the noisy C band booster amplifier. At each circulation, the WDM signal was propagated along a 40 km SMF. The S band and C band channels entered in the fiber with a launch power of -3.0 dBm and -2.3 dBm as shown in Fig. 3 (b) and as expected they experienced different fiber losses of 8.5 dB and 7.9 dB, respectively. The re-circulating loop includes also a wavelength selective switch (WSS) operating in the range of 191.250–196.275 THz which allowed to switch the C and S-band signals over two different output ports in order to enable a dedicated amplification per band. At the end of the loop, AOM3 was used to enable re-circulation through 2x2 input port, or to empty the system after each run. At the loop output, a 1x2 splitter (99:1) sends most of the power to the coherent receiver for data recovery and performance estimation. A small amount of power is finally provided to an oscilloscope after opto-electronic conversion for loop synchronization (i.e., selecting the proper propagation distance) and receiver triggering.

At the receiver side, a pre-amplifier was employed in order to compensate the losses introduced by the RLS and by the filter. Moreover, before the receiver, a polarization controller (PC) and a variable optical attenuator (VOA) were included to align the I-Q signal polarizations and to control received power, respectively. In the coherent homodyne detector, the optical signal was demodulated employing the polarization- and phase-diversity technique. After a polarization beam splitter (PBS), the received QPSK signals were mixed with the LO through a 90° optical hybrid, whose outputs were sent to four couples of balanced photo-diodes (see Fig. 4). The four photo-detected signals were sampled and digitised through a real-time oscilloscope. The sampled signals were saved

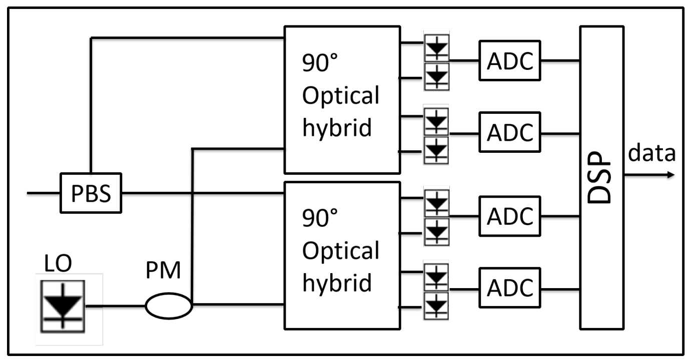

Fig. 4. Coherent Receiver scheme. The In-phase and Quadrature-phase electrical signals of both channels were detected employing the polarization- and phase- diversity technique; PM: polarization maintainer, ADC: Analog to Digital converter

for offline digital signal processing (DSP). Finally, symbol decisions were made and the BER was computed. The BER was evaluated on a number of cycles higher than 100 after which possible to detect minimum BER values in the order of 10^6.

IV. Measurements and Estimations

Fig. 5 (a) shows the measured BER in logarithmic scale of the transmitted channels as a function of the distance reached by the S band and C band channels. For the C band, the FEC threshold (i.e., the maximum bit error rate that allows to recover data) was set to $1.5{\times}10^{-2}$ as in [17] whereas for the S band the considered FEC threshold was 3×10^{-4}.

The experimental testbed aims at emulating a lightpath of a long-haul optical network where the transmission line is composed by 40 km links and the in-line amplification is performed by two distinct EDFAs, each one dedicated to a specific band. The system power losses introduced jointly by the AOM3 and by the $2\times$ 2 coupler ($\approx$ 7 dB) may be interpreted as insertion losses of a reconfigurable optical

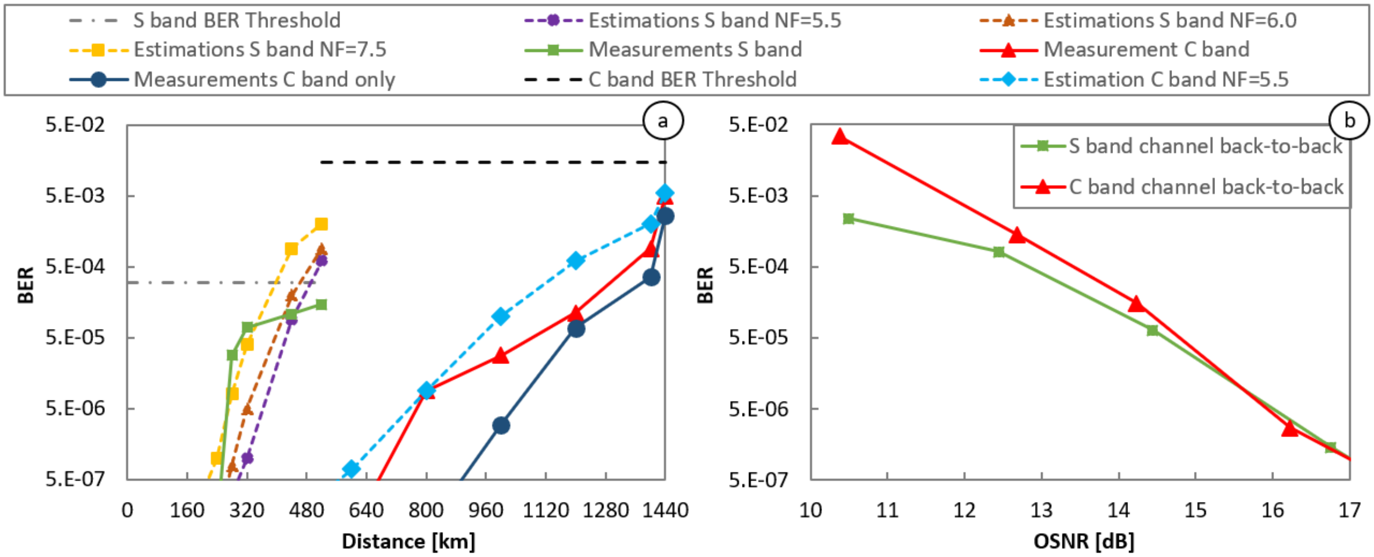

Fig. 5. (a) BER Measurements (continuous lines) and Estimations (dotted lines) in function of the propagation distance for the DP-QPSK S and C band channels with the corresponding pre-FEC BER Thresholds (dashed lines). (b) Back-to-back characterization of the transceivers for the S band and the C band signals modulated with dual polarization QPSK modulation format and 28 Gbaud symbol rate.

add/drop multiplexer (ROADM) in a core optical network with $\approx$ 16 dB spans.

As expected, the C band channel presented better performance (i.e. a lower BER) when launched alone into the fiber than when multiplexed together with the S band channel, given non-linear impairments induced by the S-band channel (e.g., cross-phase modulation - XPM). However, the XPM and the SRS induced by the S-band channel did not excessively affect the performance of the C band channel, which still reached 1440 km (i.e., 36 spans). Regarding the S band channel, it had a shorter maximum reach of 520 km (i.e., 13 spans) due to its lower launch power, the higher experienced attenuation, and the lower available amplification gain. In addition, the S band channel suffered of cascaded filtering effects induced by the BPF.

Fig. 5 (a) also compares the BER measurements with the BER estimations. The GNPy tool was adapted to the experimental lightpath with some channel-dependent system parameters (e.g., fiber loss, WSS loss, EDFA gain and NF) derived from power measurements computed along the first re-circulating loop. The QoT estimations in terms of general signal-to-noise ratio (GSNR) were then translated into BER estimations through the TRX/RX characterization in back-to-back shown in Fig. 5 (b) similarly as in [12].

Regarding the C-band channel, the GNPy estimator provided a conservative QoT estimation, i.e., similar or higher BER compared to the one of the measurements. Thus, if this model was applied in a control plane architecture – where a network controller holds a GNPy module to verify path feasibility – then the Software Define Networking (SDN) controller would set up a lightpath with acceptable QoT. In other words, the GNPy module, when asked to estimate the BER for a link having a DP QPSK modulation format, a 28 Gbaud symbol rate would always give a BER value higher than the actual one. For the S band channel, the EDFA's NF was unknown and therefore estimations assuming different NF values were performed as ahown in Fig. 5 (a). For short distances, the S band QoT estimation was optimistic. This was due to the unknown NF. However, the estimated BER was lower than the measured one only for values below the pre-FEC BER threshold (e.g., for distances between 200 and 400 km). Conversely, for more critical distances (e.g., larger than 400 km), the GNPy tool was conservative providing an estimated BER higher than the measured one. Thus, in conclusion, the extended GNPy tool provides conservative estimations both in S and C bands.

V. Conclusions

This paper presented an experimental demonstration of a MB optical network assisted by the GNPy QoT estimation tool. In the experimental MB data plane, one S band and one C band DP-QPSK signals propagated for 1440 km and 520 km, respectively. Moreover, comparing the BER measured over the data plane with the BER estimated with the developed GNPy extension, it is possible to see that at high BERs – approaching the pre-FEC BER threshold – the GNPy tool is effective in providing reliable or slightly overestimated BER values, thus validating its suitability for conservative QoT estimation in such C+S band transmission.

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REFERENCES

[1] Cisco annual internet report (2018–2023) white paper. [Online]. Available: https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html

[2] R.-J. Essiambre and R. W. Tkach, "Capacity trends and limits of optical communication networks," *Proc. of the IEEE*, vol. 100, no. 5, pp. 1035–1055, 2012.

[3] N. Sambo, A. Ferrari, A. Napoli, N. Costa, J. Pedro, B. Sommerkorn-Krombholz *et al.*, "Provisioning in multi-band optical networks," *Journal of Lightwave Technology*, vol. 38, no. 9, pp. 2598–2605, 2020.

[4] N. Sambo, A. Ferrari, A. Napoli, J. Pedro, L. S. Kiani, P. Castoldi, and V. Curri, "Multiband seamless network upgrade by exploiting the E-band," in *Proc. of ECOC*, 2021.

[5] N. Sambo, B. Correia, A. Napoli, J. Pedro, P. Castoldi, and V. Curri, "Transport network upgrade exploiting multi-band systems: S- versus E-band," in *Proc. of OFC*, 2022.

[6] A. Ferrari, A. Napoli, J. K. Fischer, N. Costa, A. D'Amico, J. Pedro *et al.*, "Assessment on the achievable throughput of multi-band ITU-T G.652.D fiber transmission systems," *Journal of Lightwave Technology*, vol. 38, no. 16, pp. 4279–4291, 2020.

[7] F. Boubal and et al., "4.16 Tbit/s (104 /spl times/ 40 Gbit/s) unrepeatered transmission over 135 km in S+C+L bands with 104 nm total bandwidth," in *Proc. of ECOC*, 2001.

[8] H. Thiele, L. Molle, R. Freund, H.-J. Tessmann, D. Breuer, W. Jacobi, and M. Arbore, "40-gb/s s-band WDM transmission over installed fiber links using erbium-based fiber amplifiers," in *Proc. of OFC*, vol. 2, 2005.

[9] S. Okamoto, K. Minoguchi, F. Hamaoka, K. Horikoshi, A. Matsushita, M. Nakamura, E. Yamazaki, and Y. Kisaka, "A study on the effect of ultra-wide band WDM on optical transmission systems," *Journal of Lightwave Technology*, vol. 38, no. 5, pp. 1061–1070, 2020.

[10] M. Cantono, D. Pilori, A. Ferrari, C. Catanese, J. Thouras, J.-L. Augé, and V. Curri, "On the interplay of nonlinear interference generation with stimulated Raman scattering for QoT estimation," *Journal of lightwave technology*, vol. 36, no. 15, pp. 3131–3141, 2018.

[11] Telecom-infra-projec oopt pse group: gnpy documentation. [Online]. Available: https://gnpy.readthedocs.io/_/downloads/en/v2.3/pdf/

[12] A. Nespola, S. Straullu, A. Carena, G. Bosco, R. Cigliutti, V. Curri *et al.*, "GN-Model validation over seven fiber types in uncompensated PM-16QAM Nyquist-WDM Links," *IEEE Photonics Technology Letters*, vol. 26, no. 2, pp. 206–209, 2014.

[13] A. Ferrari, M. Filer, K. Balasubramanian, Y. Yin, E. Le Rouzic, J. Kundrat, G. Grammel, G. Galimberti, and V. Curri, "Experimental validation of an open source quality of transmission estimator for open optical networks," in *Proc. of OFC*, 2020.

[14] A. D'Amico, E. London, B. Le Guyader, F. Frank, E. Le Rouzic, E. Pincemin, N. Brochier, and V. Curri, "GNPy experimental validation on flex-grid, flex-rate WDM optical transport scenarios," in *Proc. of OFC*, 2021.

[15] A. Ferrari, K. Balasubramanian, M. Filer, Y. Yin, E. Le Rouzic, J. Kundrat, G. Grammel, G. Galimberti, and V. Curri, "Assessment on the in-field lightpath QoT computation including connector loss uncertainties," *Journal of Optical Communications and Networking*, vol. 13, no. 2, pp. A156–A164, 2021.

[16] L. Rapp and M. Eiselt, "Optical amplifiers for multi–band optical transmission systems," *Journal of Lightwave Technology*, vol. 40, no. 6, pp. 1579–1589, 2022.

[17] Forward Error Correction (FEC) and Bit Error Rate(BER) . [Online]. Available: https://www.juniper.net/documentation/us/en/software/junos/interfaces-ethernet/topics/topic-map/fec-ber-otn-interfaces.html