POLITECNICO DI TORINO
Repository ISTITUZIONALE

Experimental Demonstration of Partially Disaggregated Optical Network Control Using the Physical Layer Digital Twin

Original
Experimental Demonstration of Partially Disaggregated Optical Network Control Using the Physical Layer Digital Twin / Borraccini, Giacomo; Straullu, Stefano; Giorgetti, Alessio; Ambrosone, Renato; Virgillito, Emanuele; D'Amico, Andrea; D'Ingillo, Rocco; Aquilino, Francesco; Nespola, Antonino; Sambo, Nicola; Cugini, Filippo; Curri, Vittorio. - In: IEEE TRANSACTIONS ON NETWORK AND SERVICE MANAGEMENT. - ISSN 1932-4537. - STAMPA. - 20:3(2023), pp. 2343-2355. [10.1109/tnsm.2023.3288823]

Availability:
This version is available at: 11583/2984167 since: 2023-11-28T15:44:02Z

Publisher:
IEEE

Published
DOI:10.1109/tnsm.2023.3288823

Terms of use:

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

07 May 2026

Experimental Demonstration of Partially Disaggregated Optical Network Control Using the Physical Layer Digital Twin

Giacomo Borraccini, *Member, IEEE*, Stefano Straullu, *Member, IEEE*, Alessio Giorgetti, Renato Ambrosone, *Graduate Student Member, IEEE*, Emanuele Virgillito, *Member, IEEE*, Andrea D'Amico, *Member, IEEE*, Rocco D'Ingillo, *Graduate Student Member, IEEE*, Francesco Aquilino, *Member, IEEE*, Antonino Nespola, Nicola Sambo, Filippo Cugini, *Member, IEEE*, and Vittorio Curri, *Senior Member, IEEE*

***Abstract*—Optical communications and networking are fast becoming the solution to support ever-increasing data traffic across all segments of the network, expanding from core/metro networks to 5G/6G front-hauling. Therefore, optical networks need to evolve towards an efficient exploitation of the infrastructure by overcoming the closed and aggregated paradigm, to enable apparatus sharing together with the slicing and separation of the optical data plane from the optical control. In addition to the advantages in terms of efficiency and cost reduction, this evolution will increase network reliability, also allowing for a fine trade-off between robustness and maximum capacity exploitation. In this work, an optical network architecture is presented based on the physical layer digital twin of the optical transport used within a multi-layer hierarchical control operated by an intent-based network operating system. An experimental proof of concept is performed on a three-node network including up to 1000 km optical transmission, open re-configurable optical add & drop multiplexers (ROADMs) and whitebox transponders hosting pluggable multirate transceivers. The proposed solution is based on GNPy as the optical physical layer digital twin and ONOS as intent-based network operating system. The reliability of the optical control decoupled by the data plane functioning is experimentally demonstrated exploiting GNPy as open lightpath computation engine and software optical amplifier models derived from the component characterization. Besides the lightpath deployment exploiting the modulation format evaluation given a generic traffic request, the architecture reliability is tested mimicking the use case of an automatic failure recovery from a fiber cut.**

***Index Terms*—Open optical networks, software-defined networking, multi-vendor, disaggregation.**

Manuscript received 18 November 2022; revised 16 March 2023 and 24 May 2023; accepted 17 June 2023. Date of publication 23 June 2023; date of current version 9 October 2023. The presented results have been obtained with the support of the NextGenerationEU partnership on "Telecommunications of the Future" (PE00000001 - program "RESTART") and of the EU Horizon Europe research and innovation program, ALLEGRO Project, GA No. 101092766. The associate editor coordinating the review of this article and approving it for publication was M. Tornatore. *(Corresponding author: Giacomo Borraccini.)*

Giacomo Borraccini, Emanuele Virgillito, Andrea D'Amico, Rocco D'Ingillo, and Vittorio Curri are with the Department of Electronics and Telecommunications, Politecnico di Torino, 10129 Turin, Italy (e-mail: giacomo.borraccini@polito.it; emanuele.virgillito@polito.it; andrea.damico@polito.it; rocco.dingillo@polito.it; vittorio.curri@polito.it).

Stefano Straullu, Francesco Aquilino, and Antonino Nespola are with the Advanced Computing, Photonics & Electromagnetics, LINKS Foundation, 10138 Turin, Italy (e-mail: stefano.straullu@linksfoundation.com; francesco.aquilino@linksfoundation.com; antonino.nespola@linksfoundation.com).

Alessio Giorgetti is with the Istituto di Elettronica e di Ingegneria dell'Informazione e delle Telecomunicazioni (IEIIT), Consiglio Nazionale delle Ricerche (CNR), 56122 Pisa, Italy (e-mail: alessio.giorgetti@ieiit.cnr.it).

Renato Ambrosone is with the Department of Electronics and Telecommunications, Politecnico di Torino, 10129 Turin, Italy, and also with The Italian Research and Education Network, GARR Consortium, 00185 Rome, Italy (e-mail: renato.ambrosone@polito.it).

Nicola Sambo is with the Telecommunications, Computer Engineering, and Photonics Institute, Scuola Superiore Sant'Anna, 56127 Pisa, Italy (e-mail: n.sambo@sssup.it).

Filippo Cugini is with the Photonic Networks & Technologies National Lab, Consorzio Nazionale Interuniversitario per le Telecomunicazioni, 56124 Pisa, Italy (e-mail: filippo.cugini@cnit.it).

Digital Object Identifier 10.1109/TNSM.2023.3288823

I. Introduction

SERVICE providers and network operators are showing interest in disaggregated optical networks, vendor-neutral control and management, and multi-vendor interoperability as a way to overcome vendor lock-in and save capital outlay [1], [2] given that data traffic is constantly increasing in various network segments ranging from core/metro networks to 5G/6G front-hauling [3]. A specific example is the separation of control, data, and management planes, which has become more important in recent years. Disaggregation and automation may help operators to overcome vendor-lock-in at the control plane level when used in conjunction with the specification of control and management of transponders, transceivers (TRXs), and re-configurable optical add & drop multiplexers (ROADMs). Thus, the goal is to achieve a more dynamic level of infrastructure management, which allows the system to be easily configured and updated, both from a software and hardware point of view, integrating the structure with additional devices and features. For these reasons, in recent years there has been a significant push towards the use of open and disaggregated solutions in a context of software-defined networking (SDN), in which the entire network is supervised by a single central controller capable of interfacing with different network elements (NEs) that are part of the physical layer [4]. This evolution will allow for apparatus sharing and slicing, besides offering cost-effective and efficient solutions,

© 2023 The Authors. This work is licensed under a Creative Commons Attribution 4.0 License.
For more information, see https://creativecommons.org/licenses/by/4.0/

and facilitating the implementation of resilient optical network infrastructure with the highest capacity utilization.

A considerable amount of effort is going into creating standardized data models that vendors and operators can all utilize. The Yet Another Next Generation (YANG) [5], [6] data modeling has emerged as the preferred language for interacting with the control and management system. The Network Configuration (NETCONF) protocol, which was established by the Internet Engineering Task Force (IETF), supports YANG [7]. Open and disaggregated networking is being defined by a number of consortia and initiatives, including OpenConfig [8], OpenROADM [9], and Telecom Infra Project (TIP) [10], which include major operators, service providers, and manufacturers. For the definition of transponders, the OpenConfig consortium has proposed the YANG data format (e.g., [11]) and various solutions on the market currently support the OpenConfig YANG data model [12].

The quality of transmission estimation (QoT-E) is another feature that has to be addressed in case the impairment due to the optical fiber transmission is significant, particularly for lightpath (LP) provisioning and maintenance. An LP is a transmission channel in the optical domain, defined by the physical path between a source and a destination node, which does not include any optical-electronic-optical conversion, and the frequency slot used, thus implying the wavelength continuity. As far as coherent transmission technology is concerned, the ability to recover the constellation phase noise by means of carrier phase estimation (CPE) algorithms and the linear mapping between optical field and electric received signals allows to model the optical transmission as an additive white and Gaussian noise (AWGN) channels, enabling optical transmission through transparent LPs using coherent technology. In this condition, the generalized signal to noise ratio (GSNR) [13] can be employed as a unique figure of merit for QoT. The GSNR is determined by dividing the power of the channel being tested by the total of the accumulated amplified spontaneous emission (ASE) noise caused by optical amplifiers and the non-linear interference (NLI) impairment caused by signal propagation in fiber. In a context dominated by the contributions deriving from fiber optic propagation, such as core and backbone networks, the use of a digital twin of the physical layer is necessary for the purposes of automated management of the infrastructure, which allows the QoT-E by exploiting suitable physical models.

In order to enforce fundamental transmission parameters on transponders and ROADMs for LP provisioning or restoration, SDN controllers have so far used QoT estimators, even if further improvements are required to adequately handle the optical control and data planes technology's complexity [14], [15], [16]. Considering the market trend towards the deployment of optical multi-band transmission [17], expanding SDN controllers to include such optical amplifiers is a required feature to cope with scalability and performance challenges. From this point of view, even the possibility of making the optical lines interfaceable with the SDN controller in a multi-vendor context in order to obtain information from the physical layer does not appear to be a viable way yet, leading to the adoption of partially disaggregated solutions in which each proprietary optical line is managed by a specific controller. Moreover, the inclusion of open packet-optical nodes housing pluggable TRXs has an additional impact on complexity and resilience since it needs the SDN controller to operate on the setup of new parameters, such as at the packet level.

In the light of the outlined scenario and the challenges to be undertaken, the main idea of this work is to clarify and demonstrate the role of the digital twin of the physical layer within the general control structure, being crucial for achieving the maximization of the optical network capacity and determining its robustness and resilience. The main contributions of this work can be summarized as follows:

- an open and partially disaggregated optical network architecture is presented and systematically described in terms of software modules and functionality;
- the decoupled operation of the optical control plane and data plane is shown on the base of the key role of the physical layer digital twin, which in the first case works as QoT estimator while in the second one estimates the highest modulation format available for a given physical path;
- the operation of the data plane has been formalized by defining the LP properties in base of the modulation format estimation made by the digital twin of the physical layer;
- the operation of the optical control and data planes of the presented architecture has been fully validated on a multi-vendor triangular-topology network.

The article consists of five sections. In Section II, the main works related to the implementation of open and disaggregated optical network solutions are reviewed. In Section III, an architecture for the control of an open and disaggregated optical network is presented in terms of involved actors and their interactions, providing further details regarding the functioning of the optical control plane exploiting a cognitive approach, and of the data plane. In Section IV, the experimental apparatus set up to validate the proposed network architecture is reported, focusing on the instrumentation, the various implementation choices and the adopted precautions. In Section V, the experimental results obtained during the various steps of the validation are reported and commented on. In particular, it is observed: the cognitive process of the control plane as regards the characterization of the physical layer and the optimization of the working point of the amplifiers, the transmission performance of the two paths present in the topology, the functioning of the deployment and recovery procedure of LPs with relative time lapse measurements. Finally, in Section VI the conclusions are outlined.

II. Related Works

Operating an overview on the use of protocols and data structures aimed at promoting the development of open SDN [18], [19], there are several works in the literature that show how to configure NEs or subsystems using NETCONF/YANG, transport performance parameters and reconfigure these elements according to them. With the aid of specially created data models, it has been demonstrated that NETCONF and YANG can configure and monitor transponders [6], [20], [21]. The authors of [22] created two

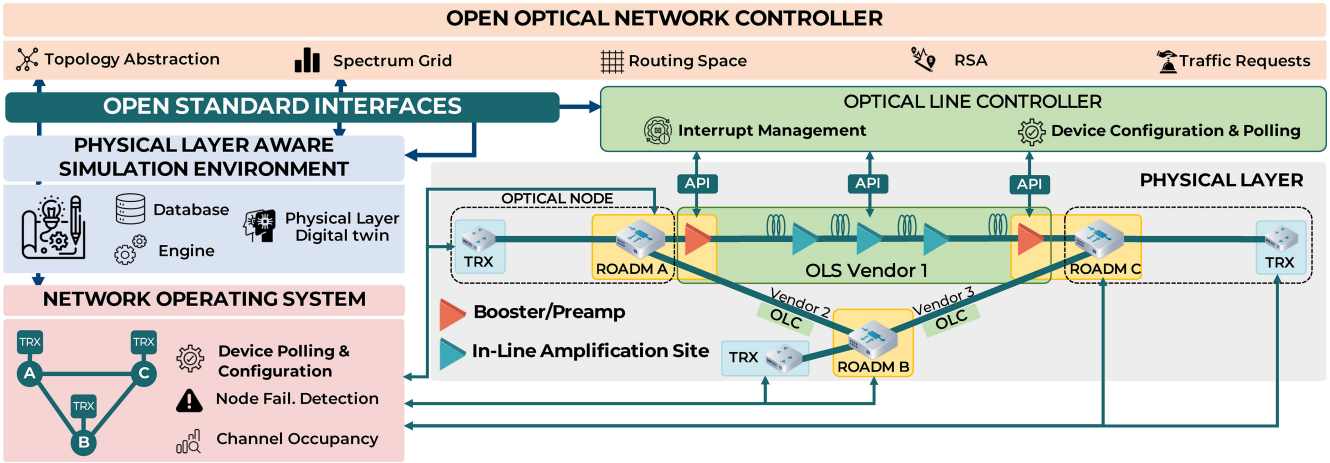


Fig. 1. Abstract scheme of the open and disaggregated optical network architecture, designed to independently implement the optical control and data planes through the interaction of the various outlined actors.

different types of agents: an OpenConfig-based transponder agent and an OpenROADM-based line system agent. YANG is used in [23] to enable device configuration, monitoring of operational data and physical parameters, local control loops for basic parameter reconfiguration/tuning, and notifications incorporating alarms. In [24], the authors demonstrate disaggregation allowing automated optical path protection through an SDN controller. In [25], a sliceable transponder supporting spectrum and space dimensions is supplied with the implementation of an OpenConfig-based agent (i.e., the local controller of a device). Telemetry applications based on the gRPC protocol [26] have also been modeled using YANG. Exploiting NETCONF and other industry-standard protocols, ONOS controller performs discovery and control of the network topology [27].

From the side of the development of a reliable physical layer digital twin, the AWGN abstraction of LPs has been implemented in the TIP's Gaussian noise simulation in Python (GNPy), an open-source and vendor-neutral QoT estimator [10], [28]. The implementation and effectiveness of GNPy have been experimentally tested in different test-beds under various conditions, showing the capability of this tool to be a valid candidate as physical layer digital twin [29], [30].

In the context of open and disaggregated optical networks, a first demonstration of the combined use of ONOS and GNPy is reported in [31]. Then, the authors experimentally verified the functioning of a partially disaggregated optical network with a linear topology (up to 1400 km of distance) [32]. Furthermore, the functioning of the physical layer digital twin and the optical network controller within the overall infrastructure orchestration has also been highlighted in [33], partially demonstrating the data plane operation.

This work is meant to be the continuation and extension of the previous ones, providing an organic formalization of the role assumed by the digital twin of the physical layer within the architecture of the open network and an all-encompassing vision of the overall control system orchestration. Differently from other works in which disaggregated and open optical network solutions are presented, this one is aimed at defining and demonstrating the functioning of a possible network architecture with the same properties, including the case of metro and core networks, in which it becomes essential to be able to maximize the infrastructure capacity by optimizing the operating point of the system by implementing a specific control strategy and base the transmission operations by correctly defining the properties of the connections (e.g., modulation format). From an implementation point of view, a multi-vendor triangular-topology network is operated starting from a proposed partially disaggregated architecture controlling both open packet-optical nodes, i.e., packet switches hosting pluggable coherent TRXs, and a completely effective optical data plane. The ONOS open SDN controller exploits NETCONF protocol [34], [35] with OpenConfig vendor-neutral YANG data models for the control of pluggables and ROADMs from multiple vendors. The GNPy tool is leveraged for the configuration of the optical amplifiers and the modulation format estimation, guaranteeing full visibility and control of the analog parameters (e.g., gain profile) while freeing the SDN controller from the burden of controlling all network Erbium-doped fiber amplifiers (EDFAs) [36]. In this way, the SDN controller can maintain visibility of network parameters, while the GNPy tool can practically evolve as a physical layer digital twin solution for the entire optical infrastructure.

III. Network Architecture

The proposed optical network architecture is designed to work in an open and disaggregated context, aiming to achieve interoperability among multi-vendor equipment and decouple the optical data and control planes. Specifically, the target approach is a partially disaggregated management [37] in which each node-to-node optical link is typically provided by a single vendor. Thus, the NEs of a line are meant to be handled by a single controller, collapsing the management to a single element from a network point of view. The representation in Fig. 1 schematizes an abstract network structure.

Starting from the physical layer (PHY), the optical hardware infrastructure is composed of TRXs, ROADM white-boxes, optical fiber spools and optical amplifiers. A couple of booster (BST) and pre-amplifier (PRE) is assumed to be

integrated in a single ROADM for each switching direction. In this network architecture, a single optical line system (OLS) is defined as a ROADM-to-ROADM optical line, thus including the BST and the PRE of the ROADMs at both line terminals. Each amplification site along an OLS can host amplifiers of different technologies, e.g., erbium-doped fiber amplifiers (EDFAs) or Raman amplifiers, and telemetry devices, such as an optical time domain reflectometer (OTDR), photodiodes and optical channel monitors (OCMs). An optical node consists of a ROADM and the set of TRXs placed in a specific location within the geographical footprint of the optical network.

The optical equipment is managed by the cooperation of four different software modules: (i) the network operating system (NOS); (ii) an optical line controller (OLC) for each OLS composing the optical network; (iii) the physical layer aware simulation environment (PLASE); and (iv) the open optical network controller (OONC). The communication among the modules, TRXs and ROADMs is performed exploiting open standard interfaces and protocols (REST, NETCONF, etc.).

The NOS is aware of the status of the optical nodes and their connections, building an abstraction of the network topology and directly controls each TRX and ROADM within the network. Furthermore, the NOS must properly manage different types of failure detected at the PHY, both from nodes and lines. Each OLC is responsible for the management of the corresponding OLS, which is generally provided by a specific vendor. The OLC communicates through defined application programming interfaces (APIs) with all the amplification sites of the OLS and the BST and the PRE, collecting telemetry information by means of device polling, configuring the amplifiers' working point and notifying status information derived from interrupt management. The PLASE represents the building block of the network architecture within which all the intelligence regarding the PHY is collected. In particular, the PLASE stores data related to the PHY, such as datasets or amplifier/ROADM/TRX/fiber characterizations. The digital twin of the physical layer (PHY-DT) represents the central element of the PLASE, including the model of the physical layer and allowing to simulate the behavior of the system. On top of this, several computational algorithms (e.g., analytical and/or numerical procedures, artificial intelligence techniques) are run to fulfill different tasks related to the implementation of optical control, which relies on the PHY information knowledge and the interrogation of the PHY-DT. The PLASE directly communicates both with the OLCs and the OONC. With respect to the OLCs, the PLASE collects telemetry data from the NEs, performing fundamental operations such as the working point optimization of a specific OLS and the LP computation engine (L-PCE) [38].

The OONC implements the system north-bound interface exposed towards the network users. This module orchestrates the deployment process, for instance, it transparently realizes the LP allocation and recovery in the optical network, interacting with the other software modules (i.e., the NOS and the PLASE). Specifically, the OONC constructs the description of the spectrum grid by supplying a single configuration for the active channel frequencies via a static external configuration recording the center frequencies for all optical WDM signals. As a result of the topology abstraction offered by the NOS, the routing space is then created and contains details on all conceivable pathways inside the network as well as the availability of the channel wavelength along each path. By making use of such structures, the OONC carries out the routing spectrum assignment (RSA), helped by the PLASE transmission performance indicators, in response to incoming traffic requests from outside pairs of source-destination nodes. In the following, the behavior of the proposed network architecture is illustrated, focusing individually on configuring the OLS and setting up the LPs, including configuring the ROADMs and TRXs.

A. Cognitive OLS Control

The optical control plane is in charge to manage the optical equipment in order to maximize the exploitation of the installed resources in terms of transmission performance. This task requires the possibility to choose the most advantageous strategy for the amplifiers' working point setting, while minimizing the allocated margins [39]. The latter condition is directly related to the degree of knowledge of the PHY's devices, both lumped (optical switches, connectors, EDFAs) and components inducing distributed effects such as fibers or Raman amplifiers. In particular, the effect of lumped losses and fibers can be appreciated only in field by means of the indirect estimation of their properties. In this perspective, the network provisioning can be performed downstream of a *probing* procedure using the available monitors and telemetry in order to completely characterize the PHY, in order to reduce the margin allocation. The *cognitive* property is the main feature of a class of optical networks bearing the same name [40], [41]. In the network context described above, the optical control plane is represented by the collection of all the OLCs supervised by the PLASE. In the following, the procedural steps that lead to the network provisioning are described focusing on the case of a single OLS (Fig. 2). The procedure can be repeated over all the OLS, with no loss of generality, given the partial disaggregation context. However, the process that leads the OLS to be ready to perform network operations is entirely dependent on the choices dictated by the OLS vendor, especially in the type of data that the OLC exposes.

After the installation and before starting any network operation, an OLS undergoes a tuning procedure targeting the definition of the working point of each amplifier along the line. This procedure is meant as an automated probing of the OLS, aiming to achieve a more accurate knowledge of the PHY, capturing the behavior of the system directly from the field and consequently adjusting the model adopted by the PHY-DT within the PLASE. Such procedure is composed of three steps:

- Configuration of the equipment using predefined settings;
- Telemetry measurements of the quantities of interest;
- Device polling in order to collect the information.

A dedicated representational state transfer (REST) API is used to transfer data from the OLC to the PLASE and vice versa.

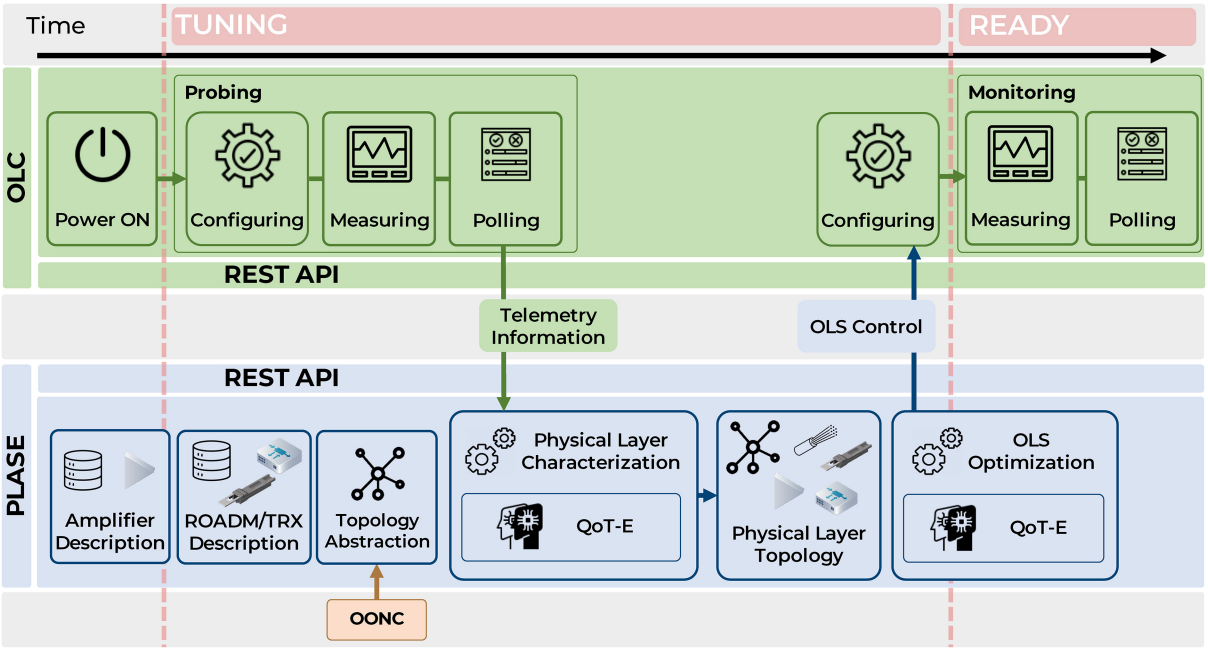


Fig. 2. Qualitative time line of the proposed cognitive optical control plane operation that leads an OLS to be ready for use.

The PLASE estimates the lumped losses and the properties of the fibers matching the collected measurements with the configuration of the equipment during the probing procedure, completing the characterization of the PHY.

At the end of the probing procedure led by an OLC, the related PHY descriptions of amplifiers, TRXs and ROADMs are stored in a static database shared with the PLASE. On top of such a detailed PHY model, the OONC provides the topology abstraction, describing the available physical connections between TRXs and ROADMs, thus allowing the PLASE to identify the available OLS within the network. Hence, the PLASE is able to build the complete network PHY topology retrieving for each OLS the corresponding virtualization combining the virtual topology, the data measured by the telemetry during the probing procedure and the PHY descriptions.

The PLASE defines the settings of each amplifier within the specific OLS on the basis of the physical layer topology in order to optimally match the transmission strategy. The devised architecture assumes full spectral load operation at the basis of the optical control. This is equivalent to defining the working point with respect to the worst case scenario in terms of transmission performance. This assumption allows to decouple the operation of the data and control planes at an operational level, ensuring that the evaluation of the maximum modulation format cardinality for a specific path and wavelength is conservative even after the deployment of further LPs. Furthermore, the working point of the amplifiers is kept frozen at the state defined at the optimization phase, without modifying the total power propagating through each optical line system. In this way, possible out-of-services due to optical reconfiguration and also the generation of transients propagating throughout the network are minimized.

Once the configuration is received, the OLS is ready to operate as soon as the OLC sets the amplifiers at the design working point. During operations, the OLC periodically monitors the OLS status through polling of the telemetry devices.

B. Connection Setup, ROADM & TRX Control

The optical control plane is also in charge of managing the setup of optical connections, or LPs, between couples of source-destination (SRC-DST) nodes based on the traffic requests coming from the application/IP layer. The LP's resource allocation is made specifying the characteristics of the optical tributary signals in terms of occupied wavelength and modulation format, and then arranging the corresponding assigned path along the optical network [30]. Furthermore, robust management of the previously allocated LPs has to be guaranteed, both fulfilling new requests and intercepting or possibly predicting failures, in order to promptly take countermeasures against a possible LP out-of-service. In the described context, the operations of the optical data plane are entrusted to the OONC supported by the PHY-DT which performs the QoT estimation. In this work, the focus is first on the deployment of a set of LPs between a couple of nodes to satisfy a given generic traffic request. Second, the management of the traffic recovery is addressed, providing for the automatic re-establishment of the lost connections in case of hard failures.

The proposed qualitative time line of the operations is depicted in Fig. 3. During the network initialization, the NOS establishes a communication with all the network optical nodes in order to identify which are the available physical connections between the nodes and retrieve the status of the current spectral occupancy in terms of already deployed LPs. The OONC receives this information from the NOS and consequently draws a network topology abstraction and the initialization of the routing space on the basis of the acquired spectrum grid. The collection of such physical TRX/ROADM

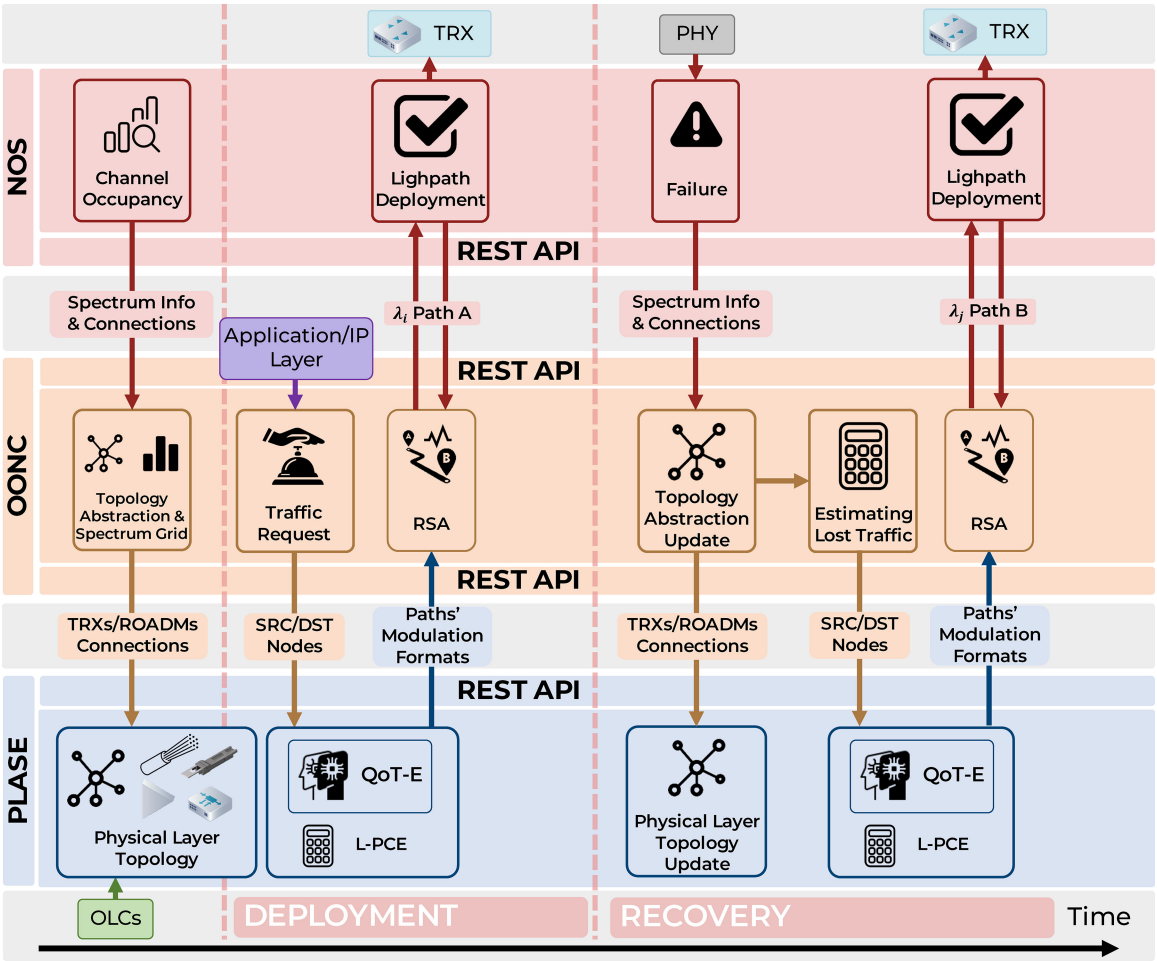


Fig. 3. Qualitative timeline of the operations of establishing a connection following an LP request and recovering after a failure detection.

connections is sent to the PLASE which are integrated with its OLS knowledge to create the complete picture of the PHY topology.

Once all the OLSs are ready to use, the optical network system is operational and the handling of incoming traffic requests is performed online. In particular, a generic traffic request, accompanied by information regarding the pair of SRC/DST nodes and the requested bit rate, commissions the deployment of one or more connections to the OONC. Then, the nodes' pair is forwarded to the PLASE which calculates the available maximum modulation format through the PHY-DT for all the channels (wavelengths) and for all the physical paths having the request nodes as end points, by executing the L-PCE on the basis of the PHY topology and the TRX characterizations. The OONC receives the evaluated modulation formats of all the available paths and performs the RSA defining the characteristics and the needed number of the LPs to deploy in order to satisfy the traffic request. In particular, as preliminary step, the current routing space is used to check the path feasibility for all the retrieved modulation formats, selecting only the available channels that ensure wavelength continuity on a certain path. The complete definition of each LP during the application of the RSA can require constraints and specifications which depend on the adopted algorithm. Finally, the LP is practically put into operation by properly configuring the TRXs operational mode and the ROADMs directly through the NOS with the proper interfaces. At the end of the operation, the NOS reports the outcome (success/failure) to the OONC in order to correctly manage the traffic request.

Moving ahead into the time line shown in Fig. 3, the process to counteract hard-failures is described in the following. During the life-cycle of an optical network, indeed, several types of failures may occur (e.g., due to fiber cuts), causing LP out-of-service. Focusing on hard failures due to fiber cut events, the detection of such events can be performed both at the OLS level – with an interrupt received by the NOS through the OLC – or at the node's level – observing the TRX or ROADM telemetry stream directly at the NOS level. In the proposed architecture, as first step, the NOS intercepts the failure coming from the PHY at the optical node side and the OONC proceeds modifying the network topology abstraction. This means that the failing link is removed from the available physical connection list of the topology abstraction defined during the provisioning phase. Then, this update is posted to the PLASE in order to keep track of the PHY topology changes. At this point, the OONC tries to re-establish the traffic lost due to the hard-failed link. This is done by repeating the previously described deployment procedure for all the lost LPs, using the same SRC/DST node pairs and original requested rates.

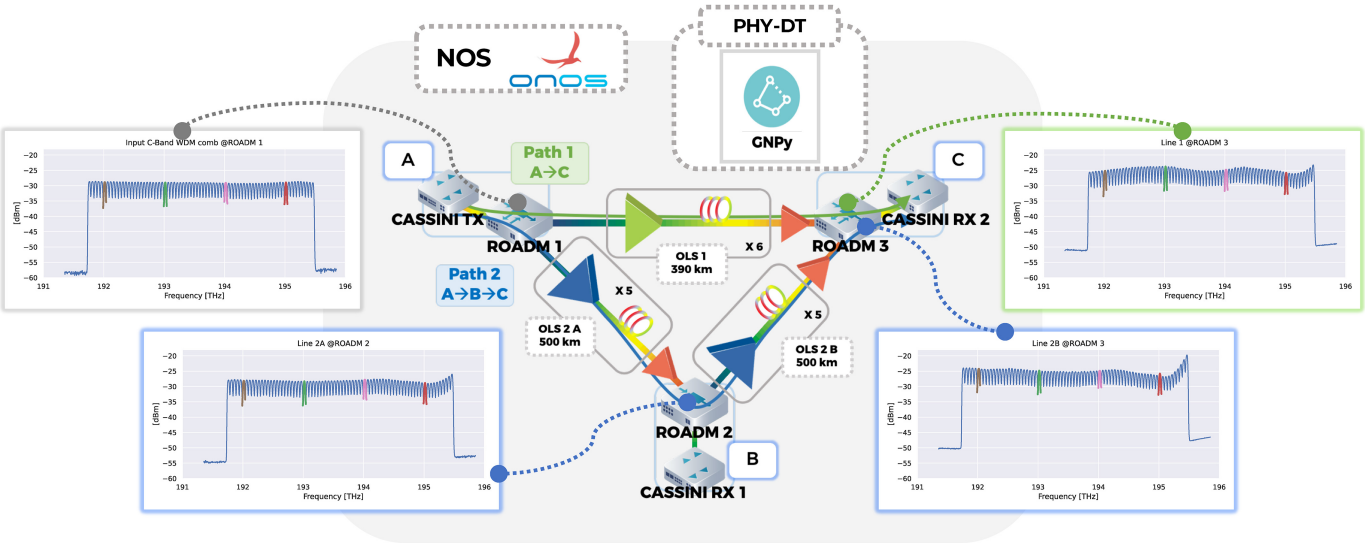


Fig. 4. Experimental setup of the optical network set in laboratory, including the spectra of the C-band WDM comb propagated through the various optical nodes. ONOS holds the role of NOS and GNPy represents the PHY-DT.

It is remarkable that this approach is carried out on a *best effort* basis: it may allocate the re-established LPs on different wavelengths accordingly to the availability on the new physical paths. In addition, it may even split up the original requested rates in multiple optical channels delivering lower rates accordingly to the maximum modulation format available in the new physical paths.

IV. Experimental Setup

An experimental setup has been built in LINKS Foundation's photonics laboratory, aiming to demonstrate the feasibility of such modular, open and disaggregated optical network architecture by means of a proof of concept. The experimental setup emulating an optical network is depicted in Fig. 4 and it is composed of 3 optical nodes (labeled as A, B and C), each equipped with commercial TRXs and ROADMs and connected by 3 different multi-span amplified OLSs, obtaining different optical paths for the channels under test (CUTs). The TRXs are CFP2-ACO/DCO coherent pluggables from Lumentum, programmed to generate 4 independent signals (DP-QPSK or DP-16QAM modulated) and to continuously monitor the related bit error rate (BER), providing an updated average value every 15 seconds. The transmitters and receivers of the mentioned TRXs are plugged into Cassini AS7716-24SC [42] boxes, open network packet-optical boxes built by Edgecore that can host line card slots to incorporate ACO/DCO optical ports based on coherent digital signal processing and optical TRXs from leading optical technology partners. Each Cassini is operated by OcNOS, a proprietary operating system supplied by IP Infusion, providing configuration and monitoring facilities by means of NETCONF interfaces.

A C-band wavelength division multiplexing (WDM) comb centered at 193.5 THz and composed of 75 channels, 50 GHz spaced, modulated at 32 GBd each, is generated at the *Node A* side: 4 CUTs, centered at 192, 193, 194 and 195 THz, respectively, are generated by the TRXs (*Cassini TX*), while a commercial wave shaper filter (1000S from Finisar) is programmed to shape the output of an ASE noise source, generating 71 channels that, coupled with the 4 CUTs, assemble the 75 channels OLS spectral load with no loss of generality because of the large time constant characterizing the physical effects within EDFAs.

ROADM 1 can be configured to add the 75 channels and to route them towards *Node C*, either through *Path 1* or *Path 2*. The former straight, *OLS 1*, connects *Node A* to *Node C* through 6 spans, each based on commercial EDFA operating in constant gain mode and followed by a standard single mode fiber (SSMF) of 65 km nominal length. *OLS 2A* and *OLS 2B*, composing *Path 2*, consist of 5 amplified SSMF spans of about 100 km each. In the middle of *Path 2*, *ROADM 2* can drop the CUTs, so that their BER can be evaluated (*Cassini RX 1*), or forward them towards *Node C*. *ROADM 3* finally drops the 4 CUTs and *Cassini RX 2* evaluates the related BERs, either if they are propagated through *Path 1* or *Path 2*.

The software implementation includes ONOS, version 2.7.0, as NOS with some additional custom features developed for this proof of concept. For the first time, ONOS is capable to provide the frequency slot occupation per link with a granularity of 12.5 GHz using new custom REST endpoints. Moreover, specific drivers have been developed enabling the control of the TRXs through the Cassini's OcNOS operating system, including the configuration of the desired modulation format. In particular, ONOS has been extended to provide visibility of the optical spectrum resource availability to the OONC module. Moreover specific software drivers have been developed for ONOS to correctly configure the YANG model exposed by OcNOS to represent the corresponding Cassini box.

For this proof of concept, a QoT-driven approach is adopted, aiming to favour a vendor-agnostic network management. As a QoT estimator, GNPy represents the PHY-DT of the control system intelligence, providing the optical propagation model within the PLASE. ONOS and the PLASE are hosted in two

different servers in order to emulate the cloud environment. ONOS's server is equipped with Intel Pentium CPU G860 @3.00 GHz and 16 GB of RAM. The PLASE runs in a server powered by Intel Core i7-4980HQ CPU @2.80 GHz and 16 GB of RAM. The OONC is implemented as a Python framework orchestrating the other software modules, exposing multiple REST endpoints developed based on the Flask library. Each OLC exploits a Secure Shell (SSH) protocol, that allows to open a control flow enabling to set and poll the EDFA's working parameters (e.g., gain, tilt) and performance monitors (e.g., OCM output, total optical input and output power).

V. Results

In the following, all the experimental results related to the validation of the network optical transmission and the LP-recovery use-case are reported and commented, illustrating the relevant observations and details in terms of practical implementation. Both the PHY characterization and OLS control optimization methodologies adopted in this work are taken from [36].

The experimental setup presents two different models of erbium-doped fiber In-Line Amplifier (ILA) according to the nominal length of the specific fiber span (65 or 100 km) and a BST and a PRE integrated in the Lumentum ROADMs. Preliminarily, both the ILA types have been characterized at full spectral load (C-band) in constant gain mode varying the gain and tilt parameters with different values of total input power. Each collected dataset is used to create a machine-learning model, one for each amplifier type, training 2 different artificial neural networks, abstracting the behavior of the gain profile and the introduced ASE noise profile, respectively [43]. This choice allows to accurately model the resolved frequency behavior of the EDFAs as all the target parameters, gain and tilt, and input power vary, which could not be done using interpolation techniques on the device characterization data. The ROADM's BST and PRE have been similarly characterized at full spectral load in constant output power mode for different output power values varying the total power of the input C-band spectrum. The software abstraction of these components is obtained for both the applied gain and introduced ASE noise linearly interpolating in logarithmic units the measured quantities. Both the TRX types (ACO/DCO) have been characterized in the back-to-back (B2B) to obtain the BER vs. SNR curves and consequently retrieving the related SNR threshold assuming 10^{-2} as pre-FEC (forward error correction) BER threshold for each available modulation format. In order to measure the GSNR, as graphically explained in Fig. 5, the used method is to translate the measured BER from the Cassini by means of the B2B characterization obtaining the corresponding SNR [44]. Concerning the ROADMs, after verifying the centering of the channels in the grid and the position of the filters, the penalties due to the filtering and the polarization dependent loss (PDL) have been neglected, considering the scenario of 32 GBd symbol rate channels on a 50 GHz fixed-grid and the overall cascade of NEs, EDFAs and ROADMs [45].

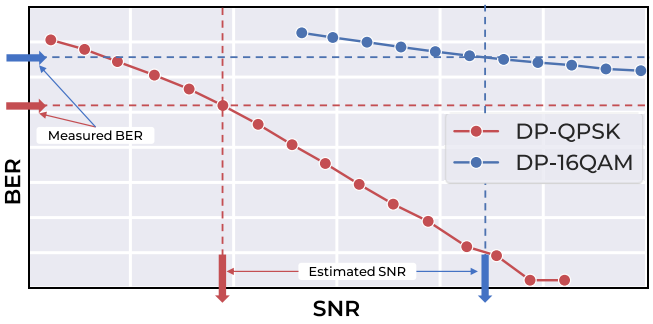


Fig. 5. SNR estimation procedure using TRX B2B curves given the measured BER.

TABLE I
Physical Layer Characterization Results: Complete Set of Retrieved Parameters

OLS	SPAN	L_S [km]	C_R [1/W/km]	D [ps/nm/km]	$l(0)$ [dB]	$l(L_S)$ [dB]
1	1	65.5	0.34	16.6	5.5	0.1
	2	65.3	0.34	16.8	1.4	0.3
	3	65.5	0.44	16.7	1.6	0.1
	4	65.6	0.34	16.7	0.2	1.4
	5	65.2	0.42	16.7	0.5	0.4
	6	65.8	0.34	16.5	0.1	1.3
2 A	1	106.2	0.34	17.5	3.6	0.2
	2	107.5	0.44	17.9	1.2	0.7
	3	106.2	0.44	17.7	1.5	0.1
	4	108.8	0.42	17.7	0.6	0.1
	5	108.3	0.42	17.8	0.2	0.1
2 B	1	106.2	0.42	17.9	1.1	0.2
	2	106.8	0.34	17.7	0.1	0.1
	3	106.4	0.34	17.7	0.2	0.7
	4	107.3	0.42	17.8	0.2	0.1
	5	108.3	0.42	17.8	0.5	2.3

A. Physical Layer Characterization

The measurement process bringing to the definition of the PHY topology starts with an OTDR analysis, performed for each fiber span measuring the fiber span length, L_S, and the positions of eventual lumped losses, $l(z)$, present along the specific span. After that, the BST and each in-line EDFA are set in ASE mode providing at the corresponding output a full C-band ASE spectrum with arbitrary shape. The latter is measured by OCMs at both terminals of each fiber span. The two ASE power levels are defined accordingly to the characteristics of the installed apparatus, such as EDFAs' maximum total output power and fiber span total losses, and to the telemetry sensitivity.

The PLASE characterizes each fiber span through an optimization strategy that aims to reproduce the experimental measurements using the PHY optical propagation model. The PHY parameters to estimate for a single fiber span are the Raman efficiency scale factor, C_R, the loss coefficient function, $\alpha(f)$, the input, $l(0)$, and the output connector losses, $l(L_S)$, and the eventual lumped losses detected by the OTDR, $l(0 < z < L_S)$.

The results of the PHY characterization are shown in Table I and Fig. 6. Given a specific OLS within the optical network, each fiber span is characterized in terms of the PHY parameters described above. In addition, the dispersion coefficient, D, has been measured for each span before the complete installation of the equipment. As per the data-sheet,

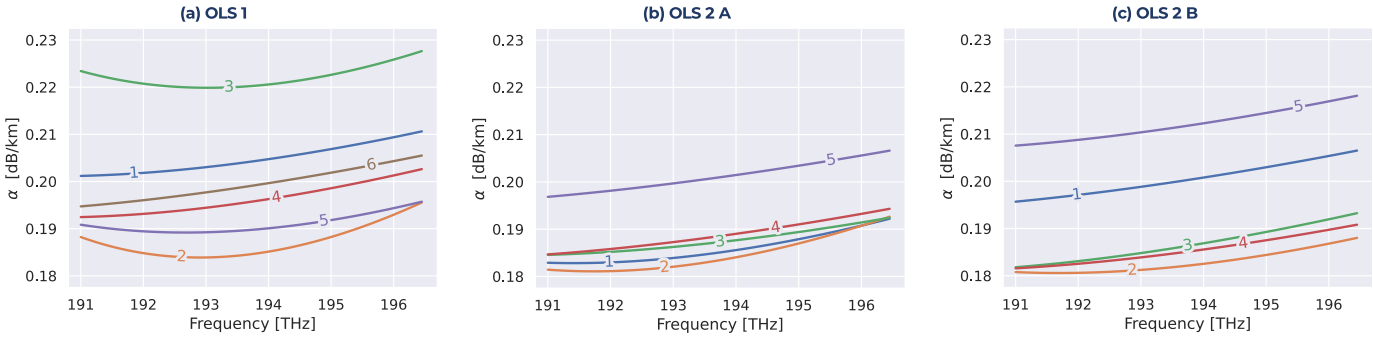


Fig. 6. Physical layer characterization results: retrieved loss coefficient functions for each optical fiber span within the network set in laboratory.

TABLE II
EDFA OPTIMAL WORKING POINT

OLS	AMPLIFIER	G [dB]	T [dB]	P_{OUT} [dBm]
1	BST	–	–	21.8
	ILA 1	15.0	-0.1	–
	ILA 2	15.0	-1.4	–
	ILA 3	15.0	0.0	–
	ILA 4	15.0	0.6	–
	ILA 5	15.7	-1.0	–
	PRE	–	–	20.0
2A	BST	–	–	21.8
	ILA 1	23.3	-5.0	–
	ILA 2	22.1	-5.0	–
	ILA 3	21.6	-1.9	–
	ILA 4	22.9	-1.0	–
	PRE	–	–	23.0
2B	BST	–	–	19.2
	ILA 1	22.0	-5.0	–
	ILA 2	22.2	-4.8	–
	ILA 3	23.3	-1.9	–
	ILA 4	23.0	-1.4	–
	PRE	–	–	20.0

the equivalent representations retrieved by the characterization process correspond to the properties of the SSMF type.

B. OLS Control & Transmission Performance

On the basis of the PHY topology, the PLASE optimizes the amplifier working point feeding the PHY model with the retrieved parameters. The result of the optimization process is reported in Table II. The chosen optimization algorithm is a stochastic evolutionary optimization strategy, aiming to homogeneously maximize and flat the GSNR profile along the whole band considering the propagation model of the fibers and amplifiers. All the amplifiers integrated within the ROADMs (BSTs and PREs) are set to work in constant output power mode. Instead, the in-line amplifiers are set in constant gain mode. The adjustment of the amplifier's working point takes place for each single OLS by modifying the device setting parameters, such as total output power, gain or tilt, consulting the PHY-DT for each extracted configuration and evaluating the resulting GNSR profile at the PRE output of the considered OLS according to the following objective function expressed in logarithmic units:

$$\max_{\{\mathrm{G},\mathrm{T}\}} \left\{ \overline{\mathrm{GSNR}^{\mathrm{dB}}} - \sigma_{\mathrm{GSNR}^{\mathrm{dB}}} - |m_{P^{\mathrm{dBm}}_{\mathrm{SIG}}}| \right\}, \tag{1}$$

where $\overline{\mathrm{GSNR}}$ and σ_{GSNR} are the average and standard deviation of the GSNR profile, respectively, and $m_{P^{\mathrm{dBm}}_{\mathrm{SIG}}}$ is the linear regression angular coefficient of the signal power profile expressed in dB/THz.

The evaluation of the network transmission performance obtained following the described cognitive approach is operated by setting the amplifier working point and estimating the GSNR of each CUT for both the LPs on the base of the measured BER. Each GSNR estimation is compared to the GSNR value predicted by GNPy, determining the related resulting margin. The latter is calculated without considering any other contribution, as if the system worked at zero margin. The summary of the experimental measurement campaign is presented in Table III. The measure of the BER using the DP-16QAM modulation format has been possible only for the case of the short path, *Path 1*. Observing the results, the fact that DCO TRXs provide larger margins than ACO ones is remarkable, presenting a higher intrinsic device robustness. This difference in margin between the two TRX types is mainly due to the different digital signal processing implementation of the receiver and their capability to mitigate the optical transmission penalties (e.g., chromatic dispersion, polarization-mode dispersion) [30]. The latter cannot be taken into account during the TRX B2B characterization of the TRX as no optical propagation is involved in the process. The presence of these penalties is evident in both the TRX types observing a reduction of the margins in case of the longer path with respect to the shorter one. Comparing the results inherent to *Path 1* for the different modulation formats, it is noted that the estimated GSNRs for the ACOs are comparable, as can be expected given that the degradation introduced by the network does not change. Instead, there is a non negligible variation for the DCO TRXs changing the modulation format. Since the QoT is very high for these TRXs, this can be explained by the working point location within the B2B curve, which is affected by a greater uncertainty during the characterization phase. The GNPy GSNR prediction is conservative in all the cases, obtaining a satisfactory result by working with zero margin. Given these considerations, the degree of flatness of the measured QoT also corresponds to the prediction on the basis of the optimization criterion.

C. Lightpath Deployment & Recovery

In order to test the network behavior, a use-case experiment is conducted following the three main steps described

TABLE III
NETWORK TRANSMISSION PERFORMANCE VALIDATION RESULTS

		Path 1 (A –>C)				Path 2 (A –>B –>C)			
		CUT 1 DCO (192 THz)	CUT 2 ACO (193 THz)	CUT 3 DCO (194 THz)	CUT 4 ACO (195 THz)	CUT 1 DCO (192 THz)	CUT 2 ACO (193 THz)	CUT 3 DCO (194 THz)	CUT 4 ACO (195 THz)
GNPy Prediction [dB]		24.0	23.7	23.7	23.6	18.4	17.8	18.1	17.6
DP-QPSK (100G)	BER	1.6e-8	9.5e-8	1.2e-08	8.6e-08	4.2e-05	1.9e-04	3.5e-05	1.4e-04
	GSNR [dB]	27.1	24.6	27.5	24.7	19.1	17.7	19.2	18.0
	Margin [dB]	3.1	0.9	3.7	1.1	0.6	0.0	1.1	0.4
DP-16QAM (200G)	BER	3.9e-03	9.9e-3	4.2e-03	1.1e-02	–	–	–	–
	GSNR [dB]	26.3	25.0	26.0	24.7	–	–	–	–
	Margin [dB]	2.3	1.3	2.2	1.0	–	–	–	–

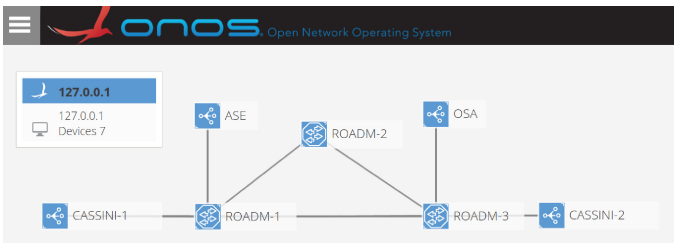
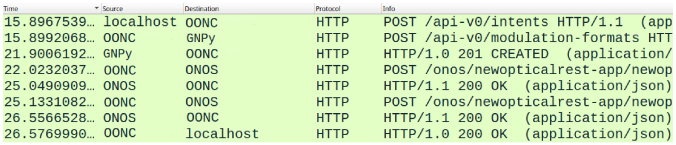


Fig. 7. ONOS topology (optical nodes and links) of the experimental setup.

in Fig. 3. During the boot phase, ONOS instantiates a control plane connection with all the physical devices (i.e., 2 Cassini boxes and 3 Lumentum ROADMs). Fig. 7 is a screenshot of the ONOS GUI showing all connected devices and the considered optical links. Two emulated devices are included (i.e., ASE/OSA), acting as logical termination points of the 71 ASE-shaped channels. Given the topology and spectral occupancy information provided by ONOS, thanks to the custom developed ONOS endpoints, the OONC is able to summarize the network status in terms of physical paths and free channels, initializing the routing space.

For the considered use-case, a traffic request of 400G between nodes A and C is generated and sent to the OONC. The PLASE replies with the modulation formats computed for each channel frequency for all the paths having the same SRC and DST nodes. The OONC performs the RSA algorithm to select the available channels with the highest cardinality of the available modulation format. The chosen LPs are sent to ONOS through the developed REST interfaces, which operatively deploy the LP on the devices. Based on the transmission performance simulation shown in Table III, the traffic request is satisfied with two DP-16QAM on the shorter path, *Path 1*. All the exchanged REST requests regarding the deployment of the LPs satisfying the given traffic request are described in Fig. 8.

As last step, a hard failure is emulated on *OLS 1* with the two active connections. Once ONOS notifies to the OONC the change of the PHY, the topology abstraction is updated and the lost traffic is estimated. Thus, the LP deployment procedure is triggered on the updated topology, trying to recover the lost traffic between nodes A and C. As the DP-16QAM is not



Time	Source	Destination	Protocol	Info
15.8967539…	localhost	OONC	HTTP	POST /api-v0/intents HTTP/1.1 (app
15.8992068…	OONC	GNPy	HTTP	POST /api-v0/modulation-formats HTT
21.9006192…	GNPy	OONC	HTTP	HTTP/1.0 201 CREATED (application/
22.0232037…	OONC	ONOS	HTTP	POST /onos/newopticalrest-app/newop
25.0490909…	ONOS	OONC	HTTP	HTTP/1.1 200 OK (application/json)
25.1331082…	OONC	ONOS	HTTP	POST /onos/newopticalrest-app/newop
26.5566528…	ONOS	OONC	HTTP	HTTP/1.1 200 OK (application/json)
26.5769990…	OONC	localhost	HTTP	HTTP/1.0 200 OK (application/json)

Fig. 8. REST requests exchanged between the software modules to satisfy a generic traffic request coming from the application/IP layer (by Wireshark).

Time	Source	Destination	Protocol	Info
11.091335753	localhost	OONC	HTTP	POST /api-v0/errors HTTP/1.1 (appl
11.127307751	OONC	GNPy	HTTP	POST /api-v0/modulation-formats HTT
17.236051299	GNPy	OONC	HTTP	HTTP/1.0 201 CREATED (application/
17.362465178	OONC	ONOS	HTTP	POST /onos/newopticalrest-app/newop
18.487326339	ONOS	OONC	HTTP	HTTP/1.1 200 OK (application/json)
18.573653680	OONC	ONOS	HTTP	POST /onos/newopticalrest-app/newop
21.201772318	ONOS	OONC	HTTP	HTTP/1.1 200 OK (application/json)
21.207483642	OONC	GNPy	HTTP	POST /api-v0/modulation-formats HTT
27.168019805	GNPy	OONC	HTTP	HTTP/1.0 201 CREATED (application/
27.285936842	OONC	ONOS	HTTP	POST /onos/newopticalrest-app/newop
28.606968544	ONOS	OONC	HTTP	HTTP/1.1 200 OK (application/json)
28.692266427	OONC	ONOS	HTTP	POST /onos/newopticalrest-app/newop
31.219421985	ONOS	OONC	HTTP	HTTP/1.1 200 OK (application/json)
31.224022594	OONC	localhost	HTTP	HTTP/1.0 200 OK (application/json)

Fig. 9. REST requests exchanged between the software modules to recover the lost traffic after a hard-failure (by Wireshark).

feasible along the longer line to recover the whole 400G lost traffic, 4x DP-QPSK intents are chosen. In a design phase, to protect the entire required traffic in the event of a failure, 2 additional TRXs to those available in the experimental setup have to be considered and kept idle under normal conditions (4x DP-QPSK TRXs total on the longest path). In fact, idle TRXs may be needed considering the dynamic nature of the traffic, e.g., scheduling is typically done considering peak traffic while network failures may also occur at a time when the network is underutilised. Alternatively, it is also possible to hypothesize that the bit rate may be reduced and part of the traffic lost depending on the traffic class [46]. In the proposed experiment, the case where 2 idle TRXs are dynamically activated in case of failure is considered, to show that the proposed solution (i.e., the control workflow involving the various components of the control plane) is able to dynamically understand what network resources are available when the failure occurs and leverage them to recover the highest possible fraction of disrupted traffic. All messages exchanged during the LP recovery process are shown in Fig. 9.

The time lapse measurements regarding the control interactions performing the LP recovery are summarized in Table IV. These measurements refer to a single 200G LP recovery (2x

TABLE IV
LIGHTPATH RECOVERY TIME LAPSE MEASUREMENTS

Interaction	Time [sec]
Topology Update	0.017
Lost Traffic Estimation	0.012
L-PCE	6.580
Lightpath Establishment	4.870
Total Recovery	**11.708**

DP-QPSK deployed LPs), which is comparable with the initial case of 400G LP deployment (2x DP-16QAM deployed LPs). The two most significant time-consuming processes are the L-PCE and LP establishment, spending roughly 4.5 and 6.5 seconds, respectively. The first one is a CPU-bound process where the dominant contribution is given by the computation of the various artificial neural networks simulating the optical amplifier behavior. Because of this, a reduction of roughly one order of magnitude in execution time is expected using a dedicated hardware and further software optimization. The LP establishment process is consistent with other experiments available in literature, where most of the time is required by the specific device to set the connection [35]. Also this value can be decreased by means of hardware updates and next-generation TRXs. The time-lapse measurement considered for LP establishment involves the configuration process between ONOS and each device via NECONF protocol until the reception of the acknowledgment, not including the time interval needed for the actual hardware configuration. For this operation, the typical TRX configuration time is on the order of tens of seconds.

VI. CONCLUSION

An architecture for the control of an open and disaggregated optical network has been presented in terms of the players involved and their interactions, highlighting the independent operation of the optical control and data planes by means of the key role assumed by the PHY-DT. As a proof of concept, a multi-vendor triangular-topology optical network experimental setup has been built to verify the suggested network architecture. The main adopted management strategies are the use of the optical network at full spectral load and a QoT-driven cognitive vendor-agnostic process of the control plane with regards to the characterization of the PHY and the optimization of the amplifiers' working point. The implementation of the software framework involves ONOS as network operating system and GNPy as PHY-DT. The tested features of the proof of concept were the transmission performance of the two LPs in the topology as well as the operation of the deployment and recovery procedure through relative time lapse measurements, obtaining deployment time intervals compatible with recent analogous works.

As future works, the feasibility of implementing this control framework in generic open and multi-vendor contexts will be investigated. The central themes are related to the availability of data coming from the various network elements, the definition of interfaces that exploit standard protocols and shared data structures as regards the use of the PHY-DT. Given that the considered infrastructures are extensive and the optical transmission part is not negligible to define the a feasible LP modulation format, the positioning of the PLASE in a software-defined direction or aiming for a solution closer to the edge will also be evaluated.

ACKNOWLEDGMENT

The authors wish to thank Lumentum, Telecom Infra Project, Cisco, IP Infusion, Open Network Foundation for providing hardware and software.

REFERENCES

[1] "An open approach for switching, routing, and transport." Nov. 2016. [Online]. Available: https://code.facebook.com/posts/1977308282496021/an-open-approach-for-switching-routing-and-transport/

[2] E. Riccardi, P. Gunning, O. G. de Dios, M. Quagliotti, V. López, and A. Lord, "An operator view on the introduction of white boxes into optical networks," *J. Lightw. Technol.*, vol. 36, no. 15, pp. 3062–3072, Aug. 1, 2018.

[3] T. Barnett, S. Jain, U. Andra, and T. Khurana, "Cisco visual networking index (VNI) complete forecast update, 2017–2022," in *Proc. Americas/EMEAR Cisco Knowl. Netw. (CKN)*, 2018, pp. 1–30.

[4] A. S. Thyagaturu, A. Mercian, M. P. McGarry, M. Reisslein, and W. Kellerer, "Software defined optical networks (SDONs): A comprehensive survey," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2738–2786, 4th Quart., 2016.

[5] M. Bjorklund, "YANG—A data modeling language for the network configuration protocol (NETCONF)," IETF, RFC 6020, 2010.

[6] M. Dallaglio, N. Sambo, F. Cugini, and P. Castoldi, "Control and management of transponders with NETCONF and YANG," *IEEE/OSA J. Opt. Commun. Netw.*, vol. 9, no. 3, pp. B43–B52, Mar. 2017.

[7] R. Enns, M. Bjorklund, J. Schoenwaelder, and A. Bierman, "Network configuration protocol (NETCONF)," IETF, RFC 6241, Jun. 2011.

[8] "Openconfig." Accessed: 2023. [Online]. Available: http://www.openconfig.net

[9] "Open ROADM MSA." Accessed: 2023. [Online]. Available: http://www.openroadm.org

[10] "Infraproject." Accessed: 2023. [Online]. Available: https://telecominfraproject.com/

[11] "Fujitsu network communications." Accessed: 2023. [Online]. Available: https://www.fujitsu.com/us/products/network/products/1finity-t600/

[12] A. Dochhan et al., "Metro-haul project vertical service demo: Video surveillance real-time low-latency object tracking," in *Proc. Opt. Fiber Commun. Conf. Exhibit. (OFC)*, 2020, pp. 1–3.

[13] M. Filer, M. Cantono, A. Ferrari, G. Grammel, G. Galimberti, and V. Curri, "Multi-vendor experimental validation of an open source QoT estimator for optical networks," *J. Lightw. Technol.*, vol. 36, no. 15, pp. 3073–3082, Aug. 1, 2018.

[14] S. Azodolmolky et al., "Experimental demonstration of an impairment aware network planning and operation tool for transparent/translucent optical networks," *J. Lightw. Technol.*, vol. 29, no. 4, pp. 439–448, Feb. 2011.

[15] R. Borkowski et al., "Cognitive optical network testbed: EU project CHRON," *J. Opt. Commun. Netw.*, vol. 7, no. 2, pp. A344–A355, Feb. 2015.

[16] N. Ellsworth, T. Zhang, S. Troia, G. Maier, and A. Fumagalli, "Enhancing cross layer monitoring on open optical transport networks," in *Proc. Opt. Fiber Commun. Conf.*, 2023, p. 14.

[17] T. Hoshida et al., "Ultrawideband systems and networks: Beyond C+L-band," *Proc. IEEE*, vol. 110, no. 11, pp. 1725–1741, Nov. 2022.

[18] P. Berde et al., "ONOS: Towards an open, distributed SDN OS," in *Proc. 3rd Workshop Hot Topics Softw. Defined Netw.*, 2014, pp. 1–6.

[19] J. Medved, R. Varga, A. Tkacik, and K. Gray, "OpenDayLight: Towards a model-driven SDN controller architecture," in *Proc. IEEE Int. Symp. World Wireless Mobile Multimedia Netw.*, 2014, pp. 1–6.

[20] N. Sambo et al., "Experimental demonstration of a fully disaggregated and automated white box comprised of different types of transponders and monitors," *J. Lightw. Technol.*, vol. 37, no. 3, pp. 824–830, Feb. 1, 2019.

[21] N. Sambo et al., "Field trial: Demonstrating automatic reconfiguration of optical networks based on finite state machine," *J. Lightw. Technol.*, vol. 37, no. 16, pp. 4090–4097, Aug. 15, 2019.

[22] A. Sgambelluri, A. Giorgetti, D. Scano, F. Cugini, and F. Paolucci, "OpenConfig and OpenROADM automation of operational modes in disaggregated optical networks," *IEEE Access*, vol. 8, pp. 190094–190107, 2020.

[23] L. Velasco et al., "Building autonomic optical Whitebox-based networks," *J. Lightw. Technol.*, vol. 36, no. 15, pp. 3097–3104, Aug. 1, 2018.

[24] J. Kundrat, J. Vojtech, P. Skoda, R. Vohnout, J. Radil, and O. Havlis, "YANG/NETCONF ROADM: Evolving open DWDM toward SDN applications," *J. Lightw. Technol.*, vol. 36, no. 15, pp. 3105–3114, Aug. 1, 2018.

[25] L. Nadal et al., "Programmable disaggregated multi-dimensional S-BVT as an enabler for high capacity optical metro networks," *J. Opt. Commun. Netw.*, vol. 13, no. 6, pp. C31–C40, Jun. 2021.

[26] F. Paolucci, A. Sgambelluri, F. Cugini, and P. Castoldi, "Network telemetry streaming services in SDN-based disaggregated optical networks," *J. Lightw. Technol.*, vol. 36, no. 15, pp. 3142–3149, Aug. 1, 2018.

[27] A. Campanella et al., "ODTN: Open disaggregated transport network. Discovery and control of a disaggregated optical network through open source software and open APIs," in *Proc. Opt. Fiber Commun. Conf. Exhibit. (OFC)*, 2019, pp. 1–3.

[28] "Telecom Infra Project." Accessed: 2023. [Online]. Available: https://github.com/Telecominfraproject/oopt-gnpy

[29] E. Virgillito, R.-P. Braun, D. Breuer, A. Gladisch, V. Curri, and G. Grammel, "Testing TIP open source solutions in deployed optical networks," in *Proc. Opt. Fiber Commun. Conf. Exhibit. (OFC)*, 2021, pp. 1–3.

[30] V. Curri, "GNPy model of the physical layer for open and disaggregated optical networking," *J. Opt. Commun. Netw.*, vol. 14, no. 6, pp. C92–C104, 2022.

[31] J. Kundrát et al., "Physical-layer awareness: GNPy and ONOS for end-to-end circuits in disaggregated networks," in *Proc. IEEE Opt. Fiber Commun. Conf. Exhibit. (OFC)*, 2020, pp. 1–3.

[32] G. Borraccini et al., "QoT-driven optical control and data plane in multi-vendor disaggregated networks," in *Proc. Opt. Fiber Commun. Conf.*, 2022, p. 5.

[33] G. Borraccini et al., "Disaggregated optical network orchestration based on the physical layer digital twin," in *Proc. Opt. Fiber Commun. Conf.*, 2023, pp. 1–3.

[34] "Open networking." Accessed: 2023. [Online]. Available: https://opennetworking.org/onos/

[35] A. Giorgetti, A. Sgambelluri, R. Casellas, R. Morro, A. Campanella, and P. Castoldi, "Control of open and disaggregated transport networks using the open network operating system (ONOS)," *J. Opt. Commun. Netw.*, vol. 12, no. 2, pp. A171–A181, 2020.

[36] G. Borraccini et al., "Cognitive and autonomous QoT-driven optical line controller," *J. Opt. Commun. Netw.*, vol. 13, no. 10, pp. E23–E31, 2021.

[37] Q. Pham-Van et al., "Demonstration of alarm correlation in partially disaggregated optical networks," in *Proc. Opt. Fiber Commun. Conf.*, 2020, p. 6.

[38] A. D'Amico et al., "Enhancing lightpath QoT computation with machine learning in partially disaggregated optical networks," *IEEE Open J. Commun. Soc.*, vol. 2, pp. 564–574, 2021.

[39] Y. Pointurier, "Design of low-margin optical networks," *J. Opt. Commun. Netw.*, vol. 9, no. 1, pp. A9–A17, 2017.

[40] G. S. Zervas and D. Simeonidou, "Cognitive optical networks: Need, requirements and architecture," in *Proc. IEEE 12th Int. Conf. Transp. Opt. Netw.*, 2010, pp. 1–4.

[41] W. Wei, C. Wang, and J. Yu, "Cognitive optical networks: Key drivers, enabling techniques, and adaptive bandwidth services," *IEEE Commun. Mag.*, vol. 50, no. 1, pp. 106–113, Jan. 2012.

[42] "Open optical & packet transport project." Accessed: 2023. [Online]. Available: https://telecominfraproject.com/oopt/

[43] G. Borraccini, A. D'Amico, S. Straullu, F. Usmani, A. Ahmad, and V. Curri, "Iterative supervised learning approach using transceiver bit-error-rate measurements for optical line system optimization," *J. Opt. Commun. Netw.*, vol. 15, no. 2, pp. 111–118, 2023.

[44] G. Borraccini et al., "Using QoT-E for open line controlling and modulation format deployment: An experimental proof of concept," in *Proc. IEEE Eur. Conf. Opt. Commun. (ECOC)*, 2020, pp. 1–4.

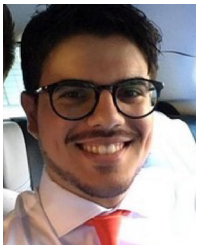
[45] A. D'Amico et al., "Experimental probing and modeling of the PDL impact on the optical signal-to-noise ratio," in *Proc. Opt. Fiber Commun. Conf.*, 2023, p. 6.

[46] N. Sambo, F. Cugini, A. Sgambelluri, and P. Castoldi, "Monitoring plane architecture and OAM handler," *J. Lightw. Technol.*, vol. 34, no. 8, pp. 1939–1945, Apr. 15, 2016. [Online]. Available: https://opg.optica.org/jlt/abstract.cfm?URI=jlt-34-8-1939

Giacomo Borraccini (Member, IEEE) received the master's degree (cum laude) in electronic engineering from the Politecnico di Torino in 2019 with a thesis on Raman gain optimization in multiband optical transmission, where he is currently pursuing the Ph.D. degree with the PLANET Team, OptCom Research Group. His activity is focused on the development of methodologies and algorithms that make it possible to automate and make an open optical network cognitive at the physical layer, aiming at maximizing capacity by optimizing transmission quality. The covered topics include the definition of automatic procedures for physical-layer characterization, management and optimization of the optical transmission using analytical models, artificial intelligence, and optimization algorithms. Since June 2020, he has actively contributed to the development of the GNPy scientific library within the Telecom Infra Project (PSE Working Group).

Stefano Straullu (Member, IEEE) received the graduate degree in telecommunications engineering from the Politecnico di Torino, Turin, Italy, in 2005, with a thesis on the realization and testing of optoelectronic subsystems for packet-switched optical networks, completed in the PhotonLab of Istituto Superiore Mario Boella, Turin; and the Ph.D. degree in electronics and communications engineering from the Politecnico di Torino, with a thesis on next-generation passive optical networks. In 2006, he joined the Integration Testing Team, Motorola Electronics S.p.A., Turin. Since May 2009, he has been a Researcher with the Optical Communication Unit, Istituto Superiore Mario Boella (currently, LINKS Foundation), Turin. His main research interests are focused on the performance analysis and design of optical transmission systems and the application of digital signal processing techniques in optical links. He has published more than 100 journal and conference papers.

Alessio Giorgetti received the Ph.D. degree from Scuola Superiore Sant'Anna (SSSA), Pisa, Italy, in 2006. In 2007, he was a Visiting Scholar with the Centre for Advanced Photonics and Electronics, University of Cambridge, U.K. He was an Assistant Professor with SSSA from 2007 to 2020. He is currently a Researcher with IEIIT-CNR, Italy. His research interests include optical network architectures and control plane, industrial networks design, software-defined networking, and quantum communications. He is an Active Software Contributor to Open Network Foundation Projects. He is the author of more than 100 publications, including international journal articles, conference proceedings, and patents.



Renato Ambrosone (Graduate Student Member, IEEE) was born in Aversa (CE), Italy, in 1998. He received the bachelor's degree in computer science engineering from the Università degli Studi della Campania in 2019, and the master's degree in computer networks and cloud computing with a thesis named "Autonomous and Softwarized Management of Disaggregated Open Optical Networks." He is currently pursuing the Ph.D. degree with the Optical Communications Research Group, Politecnico di Torino. During his thesis work he did an internship at GARR, with which he currently collaborates with the development of open optical networks. His research topics concern the control of disaggregated and partially disaggregated optical networks focusing on the integration of a quality of transmission estimator.

Emanuele Virgillito (Member, IEEE) was born on 29 June 1989 in Catania, Italy. He received the B.Sc. degree in telecommunication engineering from the University of Catania in 2013, the M.Sc. degree in telecommunication engineering from the Politecnico di Torino in 2016 with a thesis on multicore optical fiber systems abroad at the Instituto Superior Tecnico, Lisbon, and the Ph.D. degree from the Politecnico di Torino in 2021 with a thesis on the observation and modeling of physical-layer phenomena in open optical networks. He is currently an Assistant Professor with the Politecnico di Torino. His research activity is mainly focused on the study of the physical-layer impairment for the orchestration and management of modern open and disaggregated optical networks. He is also involved in environmental sensing using telecommunications optical fiber systems.

Andrea D'Amico (Member, IEEE) received the M.Sc. degree (cum laude) in theoretical physics from Pisa University in 2016. He is currently pursuing the Ph.D. degree in electric, electronic and communication engineering with the Politecnico di Torino. His current research activity includes the implementation of analytical models of fiber-optic nonlinear propagation and the application of artificial intelligence techniques to open optical network for planning and controlling. In 2017, he worked with NTT DATA, Milan, as a Software Engineer, where his activity included the implementation of big data solutions for an international telecom company. In 2018, he won the Postgraduate Research Scholarship "Nonlinear Interfering Theory Extension of Wide Band Optical Networks" at the Electric, Electronic and Communications Department, Politecnico di Torino. Since early 2019, he is an Active Member of the Telecom Infra Project, working in the Physical Simulation Environment Group and contributing to the design and implementation of GNPy.

Rocco D'Ingillo (Graduate Student Member, IEEE) was born in Bitonto, Italy. He received the master's degree (with Hons.) in electronic engineering from the Politecnico di Torino in October 2021 with a thesis about modeling of ultra wideband (UWB) coherent transceivers and ROADMs for open networking applications. He is currently pursuing the Ph.D. degree in electrical, electronics and communications engineering with the Team PLANET, Optical Communication Group, Politecnico di Torino. The research activity is about modeling and characterization of UWB coherent transceivers and photonic integrated circuits focusing on indium phosphide application for novel Mach–Zehnder electro-optical modulators development and application in optical networks. Other research activities are related to ROADMs characterization and machine-learning-aided control for multivendor optical networks optimization and management. He collaborates with Lumentum Company, Milan and with LINKS Foundation laboratories, Turin.

Francesco Aquilino (Member, IEEE) was born in 1994. He received the master's degree in communication and computer network engineering from the Politecnico di Torino, Italy, in 2019, with a thesis on User Classification in Satellite Network for Traffic Congestion Avoidance completed in the Turin Network Operation Center, Skylogic Spa (a subsidiary company of the Eutelsat Group). The collaboration with Skylogic continued even after achievement of the master's degree as a Broadband Service Operation Engineer. He also worked in TIM with the role of Pre-Sales Engineer in the Enterprise Division, TOP companies, to support the evolution of the fiber infrastructure of an important oil company. Since March 2022, he has been working as a Researcher with LINKS Foundation. He is currently collaborating in several research activities with the Politecnico di Torino and companies (Cisco Photonics and SM-Optics).

Antonino Nespola received the M.S. and Ph.D. degrees in electrical engineering from the Politecnico di Torino, Turin, Italy, in 1995 and 2000, respectively. From 1997 to 1998, he was a Visiting Researcher with the Photonics Laboratory, University of California at Los Angeles. He then coordinated the Optical System Unit in Corning OTI from 1999 to 2003, focusing on high-speed modulators. In 2003, he joined Pirelli Labs working on SiPh optical modulators in synergy with the scientists of the Microphotonic Center, Massachusetts Institute of Technology. Since 2004, he has been the Coordinator of the Optical Communication Unit, Fondazione LINKS and is an Adjunct Professor with the Politecnico di Torino. His main research interests are the performance analysis and design of coherent optical systems and data-center links based on VCSELs. He is the author or coauthor of more than 140 papers in leading journals and conferences and holds five U.S./European patents.

Nicola Sambo received the Ph.D. degree from Scuola Superiore Sant'Anna (SSSA), Pisa, Italy, in 2009. He is currently an Assistant Professor with SSSA. His activity is focused on optical networks, ranging from signal transmission to control plane, protocol analysis, and network design. He collaborates with several industrial and academic partners. He took part in several international projects, such as the EU Horizon 2020 ORCHESTRA where he was a Work Package (WP) Leader. He is currently a WP Leader involved in the EU ITN MENTOR Project and in the Italian PRIN FIRST Project. He is the author of about 200 publications, including international journals, conference proceedings, and patents.

Filippo Cugini (Member, IEEE) is the Head of Research Sector with CNIT, Pisa, Italy. His main research interests include theoretical and experimental studies in the field of communications and networking. In particular, the focus is on flexible optical networks, disaggregated solutions, software-defined networking, edge computing, and network programmability, including P4. He currently serves as a Project Coordinator of the EU-funded projects BRAINE (Big Data Processing and Artificial Intelligence at the Network Edge), SmartEdge (Semantic Low-Code Programming Tools for Edge Intelligence), and SEASON (Self-Managed Sustainable High-Capacity Optical Networks). He is the coauthor of 14 patents and more than 300 international publications.

Vittorio Curri (Senior Member, IEEE) is a Full Professor of Optical Communications and Networks with the Politecnico di Torino. He has also worked as a Visiting Researcher with Stanford University and UCSB from 1997 to 1998. His research activities include the analysis of the physical layer impact on networking for the planning and control of open and disaggregated optical networks, using AI techniques. He is an integral part of the team responsible for developing transmission models of lightpaths as Gaussian noise channels. He serves as a Scientific Chair of the GNPy open-source project within the TIP Consortium. With over 400 scientific publications, he has been a Guest Editor for special issues in *Journal of Optical Communications and Networking* and *Journal of Lightwave Technology*. He has been a TPC member, or invited as a keynote speaker and tutor, at major IEEE and OPTICA conferences. Furthermore, he has been actively involved in numerous projects funded by various companies and by the European Union, as a Principal Investigator.

Open Access funding provided by 'Politecnico di Torino' within the CRUI CARE Agreement