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OpenConfig and OpenROADM Automation of Operational Modes in Disaggregated Optical Networks

ANDREA SGAMBELLURI[1], ALESSIO GIORGETTI[1,2], DAVIDE SCANO[1], FILIPPO CUGINI[3], (Associate Member, IEEE), AND FRANCESCO PAOLUCCI[1]
[1]Scuola Superiore Sant'Anna, 56124 Pisa, Italy
[2]Institute of Electronics, Computer and Telecommunication Engineering (IEIIT), National Research Council (CNR) of Italy, 56124 Pisa, Italy
[3]CNIT, 56124 Pisa, Italy

Corresponding author: Francesco Paolucci (fr.paolucci@santannapisa.it)

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ABSTRACT OpenConfig and OpenROADM are emerging as the most relevant initiatives to support partial disaggregation, in which the optical line system is provided by a single vendor while transponders can be provided, in pairs, by different vendors. This way, vendor lock-in is eliminated at the transponder level, without significantly impacting the transmission performance. Although the above initiatives have defined YANG models reaching a good level of maturity, there are still open issues that prevent the full deployment of vendor-neutral partially disaggregated solutions. Among these, the candidate transmission modes in a transponder, including proprietary solutions, are exposed in the YANG models as opaque attributes called Operational (OP) Modes, thus limiting the awareness and the effectiveness of the SDN controller in the selection of the most appropriate transmission mode. In this work, we focus on the open issues related to the configuration and adaptation of transmission parameters. In particular, we focus on the OpenConfig concept of OP Mode enabling the abstraction of transmission complexity but currently preventing an SDN controller to manage transponders in a fully vendor-neutral way. This work first estimates, through a simulative study, the network performance benefit that is achievable by optimizing the OP mode selection. Then, a telemetry-based automated solution is proposed, designed and implemented to enhance the OP mode concept in case of both provisioning and adaptation scenarios (e.g., upon failure), also considering the impact in the tributary/client network. In particular, the following components have been designed and implemented: (i) software agent for OpenConfig transponders; (ii) software agent for OpenROADM line systems, (iii) an automatic telemetry-assisted monitoring handler; and (iv) SDN control procedures implemented in the ONOS Controller. The proposed components and comprehensive solution have been evaluated in a network testbed encompassing multi-vendor network elements, successfully demonstrating a full vendor-neutral partially disaggregated provisioning and recovery operations.

INDEX TERMS Software defined networking, open disaggregated networks, white box, operational mode, multi-layer optical networks.

I. INTRODUCTION

The introduction of disaggregated Elastic Optical Networks (EON) in the context of Software Defined Networking (SDN) control is pushing transport and cloud operators to deploy and upgrade metro and regional networks based on vendor-agnostic white boxes, breaking vendor-locked solutions and potentially enabling significant CAPEX savings, with the goal to maintain a high level of network configurability and inter-operability [1]. Disaggregation enables full coexistence of optical devices of different vendors in the same network. Inter-operability is assured at the control plane by the Southbound Interface (SBI) between the SDN controller and the control agents of each device, fully compliant with YANG models defined by a number of standardization initiatives (e.g., OpenConfig, OpenROADM). Such compliance, besides standard control procedures (e.g., provisioning, recovery, re-optimization), allows the availability of

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additional operation and maintenance services such as optical monitoring and network telemetry [2].

Besides the possible disaggregation flavours, partial disaggregation is gaining interest among network operators to avoid vendor lock-in of transponders [1], [3]–[5]. Using partial disaggregation, the optical infrastructure (e.g., optical line systems - OLS - including Reconfigurable Optical Add/Drop Multiplexers - ROADM - and amplified links) is provided by a single vendor, however transponder cards may be provided by multiple and different vendors. Since transponders are enforced in pairs, the optical connection is anyway handled by the transponder vendor, thus advanced, and even proprietary transmission solutions, may be implemented and selected (e.g., [6]). Literature works confirm that disaggregated framework enables inter-operability at the expense of potentially reduced overall network performance, due to the locking of proprietary transmission enforcement optimized by single vendor devices [7]. The Control of the whole disaggregated network is in charge of a unique SDN Controller, e.g. provided by the OLS Vendor or a third party company, which has to configure all transponders in a vendor agnostic way. To this purpose, the OpenConfig YANG model has been introduced to provide a standard way to configure, through NETCONF, the common transponder parameters [8], [9].

In OpenConfig, proprietary/advanced solutions are intentionally not included in the disaggregated YANG model and require specific procedures, generally identified as *operational modes* (OP modes) [10]. An OP mode is an abstracted attribute (i.e., a scalar identifier) that defines a full proprietary transmission configuration (i.e., including a set of physical transmission parameters) hiding all the device and vendor-specific complexities. The concept of OP modes enables device vendors to configure transmission parameters using proprietary and optimized approaches and allows the YANG model to remain stable despite of technological evolution (e.g., being capable of rapidly including new proprietary advanced transmission solutions). As a drawback, this approach requires the definition and the implementation of specific workflows to manage the OP modes going beyond the model itself. The definition, implementation and validation of these procedures for an optical connection provisioning exploiting the OpenConfig-based OP-modes has not been discussed yet in the scientific literature. In addition, both the adaptation of OP modes at line side and the related implication and procedures at the client side have not been discussed yet. The latter aspect is particularly relevant if QoS-guaranteed network slicing is applied end-to-end across the whole network [11], in particular, for recovery upon failures.

In this work, with the aim of filling the gap between the open optical network framework and novel vendor-specific and outperforming transmission formats while maintaining the YANG standards stable, we propose to enable OP mode enforcement in disaggregated EON relying on innovative workflows orchestrated by the SDN controller with the support of automatic telemetry-assisted monitoring handler. To this end, the OpenConfig transponder agent is utilized to support OP modes without the need to extend the YANG model. Then, we define and implement the provisioning workflow to assess the transmission performance for different OP modes and transmission parameters, relying on the implemented Telemetry to speed up the performance validation of different transmission solutions. Moreover, we extend OP mode applicability to multi-layer connection adaptation in the case of failure recovery events, extending automation to the client ports of xPonders, and we provide the detailed description of an open-source implementation of an SDN agent that includes a generalized NETCONF agent, suitable for both OpenConfig and OpenROADM models, enhanced with a gRPC-based telemetry service [2]. Finally, we evaluate the proposed solutions in a multi-vendor and multi-layer EON testbed with 100Gbps xPonders cards, extended agents, and telemetry-assisted ONOS controller using hybrid OpenConfig and OpenROADM - based SBI, showing the effectiveness of fully enabling OP modes.

The paper extends preliminary works in [12], in [13] and in [14] with novel contributions, including, besides a detailed related work analysis, an extended workflow providing multi-layer OP mode adaptation in the case of failure recovery, and a novel experimental validation in a comprehensive optical network testbed including extended ONOS, gRPC-based telemetry, OpenConfig-enabled agents, OpenROADM-enabled OLS and OpenFlow-based packet-switched layer. Moreover, this paper reports a novel simulative study targeted to quantify the benefit in terms of blocking probability that is guaranteed by the spectrum save achieved optimizing the Operational Mode choice.

II. TOWARDS OPEN SDN-ENABLED DISAGGREGATION: YANG MODELS AND RELATED WORK

The recent trend of optical disaggregation is offering network operators the possibility to open the network to multi-vendor solutions. Traditionally, optical networks were conceived as a single-vendor solution, providing optical line systems, nodes (e.g., ROADMs) and transceiver cards as black boxes with proprietary and locked technology and API, drastically limiting inter-operability. Recently, the adoption of the SDN paradigm is opening the way to standard API offering common YANG models to describe, abstract, configure and retrieve the status of an optical device. Therefore, nodes may be opened (i.e., white box) offering open API to each node component and allowing to install alternative vendor equipment. For example, partial disaggregation enables xPonders (i.e., transponders or muxponders) of different vendors to be installed inside a ROADM of another vendor, with the only constraint that a lightpath endpoints are of the same vendor.

The need of flexibility and automation has motivated the adoption of the SDN paradigm in the control of optical networks. In this approach, the SDN Controller is an element devoted to the control of the network devices in the network. In the context of EON, the NETCONF protocol has been selected for the communication among controller and network devices in order to enable both the configuration and the monitoring functions. The NETCONF protocol allows the exchange of information among controller and devices, mainly considering the configuration (edit-config) of pieces of configuration and the collection of state parameters. The exchanged data are represented in XML format and typically follow data models, represented according to the YANG syntax (i.e., YANG models). Thus, different device vendors can rely on the NETCONF protocol together with custom/proprietary YANG models in order to enable the SDN paradigm and abstract the network devices. Moreover, by providing custom configuration parameters and monitoring features, advanced and proprietary transmission solutions can be implemented and envisaged.

Considering the optical network disaggregation scenario, where the enrolment of many vendors is at the basis of the network design, a common representation of optical devices is essential in order to enable the communication with the SDN network controller.

In fact, in case different vendors provide the main elements required for the realization of an optical network, i.e., the optical transport infrastructure, (e.g., ROADMs, amplifiers and links) and the optical termination (e.g., transponders/ muxponders), the adoption of common models selected by all the involved vendors is crucial to envisage device compatibility and enhance vendor-neutral control plane.

In the last years, significant research activities have proposed white box disaggregation design, development and control strategies in access, metro and core optical network segments, also due to the work carried out by open source multi-vendor initiatives such as OpenROADM [15] (promoted by big telco and cloud operators), OpenConfig [10] (promoted by Google) and the Telecom Infra Project (TIP) [16] (promoted by Facebook).

Research and industrial initiatives on optical disaggregation have considered two kind of implementations. The former, called *partial disaggregation*, assumes that the optical transport infrastructure is managed by a single vendor, while transponders, provided in pairs, rely on vendor-neutral control. The most important standardization initiative YANG models for partial disaggregation is OpenConfig. The latter, called *full disaggregation*, targets disaggregation of the OLS as well, considering ROADMs as white boxes. In this case the reference standardization initiative for full disaggregation is OpenROADM. Partial disaggregation is considered attractive by many operators and vendors, since it smooths optical data plane complexity without excessively impacting transmission performance (since transponders are provided in pairs). Therefore, OpenConfig has gained consensus for transponder control, however being not really suitable for the control of a fully disaggregated network. On the other side OpenROADM is considered a valid approach to control optical devices as white boxes, at the expense of a substantially increased control complexity. This may lead to the co-existence of the two models in the same network infrastructure.

```
+rw terminal-device
  +--rw config
  +--ro state
  +--rw logical-channels
  |  +--rw channel* [index]
  |     +--rw index
  |     +--rw config
  |     |  +--rw index
  |     |  +--rw description
  |     |  +--rw admin-state
  |     |  +--rw rate-class
  |     |  +--rw trib-protocol
  |     |  +--rw logical-channel-type
  |     +--ro state
  |     |  +--rw index
  |     |  +--rw description
  |     |  +--rw admin-state
  |     |  +--rw rate-class
  |     |  +--rw trib-protocol
  |     |  +--rw logical-channel-type
  |     |  +--ro link-state
  |     +--rw otn
  |     |  +--ro state
  |     |     +--ro pre-fec-ber
  |     |     +--ro post-fec-ber
  |     |     +--ro q-value
  |     |     +--ro esnr
  |     +--rw logical-channel-assignments
  |        +--rw assignment* [index]
  |           +--rw index
  |           +--rw config
  |           +--ro state
+rw components
  +--rw component* [name]
     +--rw config
     |  +--rw frequency
     |  +--rw target-output-power
     |  +--rw operational-mode
     +--ro state
        +--ro output-power
        +--ro input-power
        +--ro laser-bias-current
        +--ro chromatic-dispersion
        +--ro polarization-mode-dispersion
        +--ro second-order-polarization-mode-dispersion
        +--ro polarization-dependent-loss
```

FIGURE 1. **Tree view of OpenConfig YANG model.**

In the following subsection we provide the details of the OpenConfig and the OpenROADM, those considered in this paper for handling operational modes and in the experimental implementation. A detailed gap analysis of the two models in the context of optical transport is provided in [17].

A. OPENCONFIG MODEL

The OpenConfig working group has been established by the main network operators with the target to enable a standard SDN control and management plane for the optical infrastructure by defining a standard set of data models to represent the optical devices in a vendor-neutral way [10]. Specifically, for the optical transponders, a set of YANG models have been designed to enable both the configuration and the monitoring of the main transponders parameters utilizing the well-established NETCONF protocol [8], [9].

Fig. 1 illustrates the tree view of OpenConfig model defined for optical transponders. Each xPonder node includes two main sections: respectively represented with the tag `<terminal-device>` and `<components>`.

The terminal-device section includes all the physical ports, represented as a list of logical channels. Where, each logical-channel includes four main blocks: (i) the `<config>` block exposes the hardware parameters (i.e., index, admin-state, rate-class, trib-protocol, logical-channel-type); (ii) the `<state>` block presents the same values of the config block including also the link-status information; (iii) the <otn>

block includes under state tag, the main parameters to be monitored for an optical signal (i.e., `pre-fec-ber`, `post-fec-ber`, `q-value`, `esnr` highlighting instant, average minimum and maximum values), (iv) the logical-channel-assignments to map the terminal-device element with the logical components (i.e., the optical-channel).

The components section consists of a list of components (physical and logical components) associated with elements listed within the terminal-device section. Each optical-channel component, that refers to an optical line, presents two main sections: `config` and `state`. Under the config section the adopted configuration parameters are included (i.e., frequency, target-output-power and operational-mode), while the state section reports all the monitoring parameters (i.e., output-power, input-power, laser-bias-current, chromatic-dispersion, polarization-mode-dispersion, second-order-polarization-mode-dispersion, polarization-dependent-loss).

B. OPENROADM MODEL

The OpenROADM working-group is composed of both vendors and network operators working on the definition of inter-operability specifications for ROADMs. The defined inter-operability criteria are encoded using YANG data models [15]. Specifically, a set of YANG modules have been designed, in order to represent the complete system, including device, network and service aspects. Regarding the device description, the models cover several device blocks, including transponders, ROADM switch, pluggable optics and amplifiers. The rest of the description focuses on ROADM switches description, highlighting the main functional blocks.

The tree root is the `<org-openroadm-device>` tag, that includes: node identification information (i.e., node-id, node-number, node-type, vendor, model, serial-id), a list of shelves, a list of circuit-packs, a list of interfaces, two lists for internal and external links and finally a list of degrees. Each shelf presents general descriptors (i.e., shelf-name, shelf-type, rack, administrative-state, vendor, model, serial-id, hardware-version, operational-state) and a list of slots. Each circuit-pack, besides general information, includes a list of ports with several descriptors (i.e., port-name, port-direction, label, circuit-id, administrative-state, operational-state, partner-port info used to include bidirectional connection details). In the list of interfaces all the available virtual-interfaces are exposed, including the related general details, the interface type (i.e., OTS, OMS) and the physical/virtual port supporting it. The external link list exposes all the topological information related to external connections with other ROADMs. Physical links list includes all the internal connection among the ports of the different circuit-packs. The list of degrees includes the line directions available in the node, with the related list of ports serving it.

C. RELATED WORKS ON WHITE BOX DISAGGREGATION

In parallel with the open source initiatives aiming at defining the open YANG models, a number of scientific literature works have studied the potentials and the impact of disaggregation in optical networking.

On the data plane side, disaggregated and inter-operable open line systems have been evaluated against proprietary single-vendor solutions. While the single-vendor solution provides optimal performance, disaggregation is demonstrated to be effective in multi-domain deployments, while in single-domain the introduction of additional OEO interfaces may impact its attractivity [7]. Routing and spectrum assignment in white box based on the architecture-on-demand framework have been proposed and evaluated taking into account the number of components used for a connection, the spectrum usage and the path length [18]. The activities carried out by the Telecom Infra Project (TIP), and in particular by the Open Optical and Packet Transport (OOPT) sub-group have resulted in the availability of different open transponder platforms, such as Voyager, Cassini, and Apollo [19].

Large and comprehensive deployments of multi-vendor testbeds have been setup to show inter operability performance of optical disaggregation. The work in [20] proposes an OLS optical link emulator based on the GN-model for network design and validation in a partial disaggregated scenario. The QoT estimator performance is validated in a testbed with optical transceivers provided by eight different vendors. Open optical networks focused on metro data center interconnects have been evaluated by a big operator in [21], exploiting transponders, OLS and ROADM controlled by means of the OpenConfig model. In addition, Open Line Systems and alien wavelengths have been deployed to test resiliency with multi-vendor configurations within European NREN involving interoperability at the ONOS controller level [22]. Finally, open design of vendor-neutral, modular and flexible ROADM line degrees and add/drop stages prototype with TIP OpenDevice YANG model have been detailed and demonstrated in [23] and in [24].

Multilayer disaggregation, enabling the coordination of the optical layer with the IP/MPLS layer to, have been proposed in [25]. The study proposes workflows for virtual link automatic creation, monitoring reconfiguration and optical self-healing, along with extended YANG models to handle monitoring. Full interoperability demonstration have been validated utilizing vendor-diverse packet switching platforms from three different vendors resorting to the same coherent chipset, over an open line system (OLS) [26].

Recently, disaggregation has been exploited also to apply sliceability. The work in [27] implemented a sliceable Bandwidth Variable Transponder (BVT) architecture composed by different BVT cards provided by multiple vendors, targeting narrow filtering and performance across multiple white boxes.

On the control plane, several open-source initiatives recently emerged for the control of disaggregated optical networks (e.g., OpenDaylight [28], ONOS [29]). Among them, the ONOS controller (i.e., Open Network Operating System) has been proposed by the Open Networking

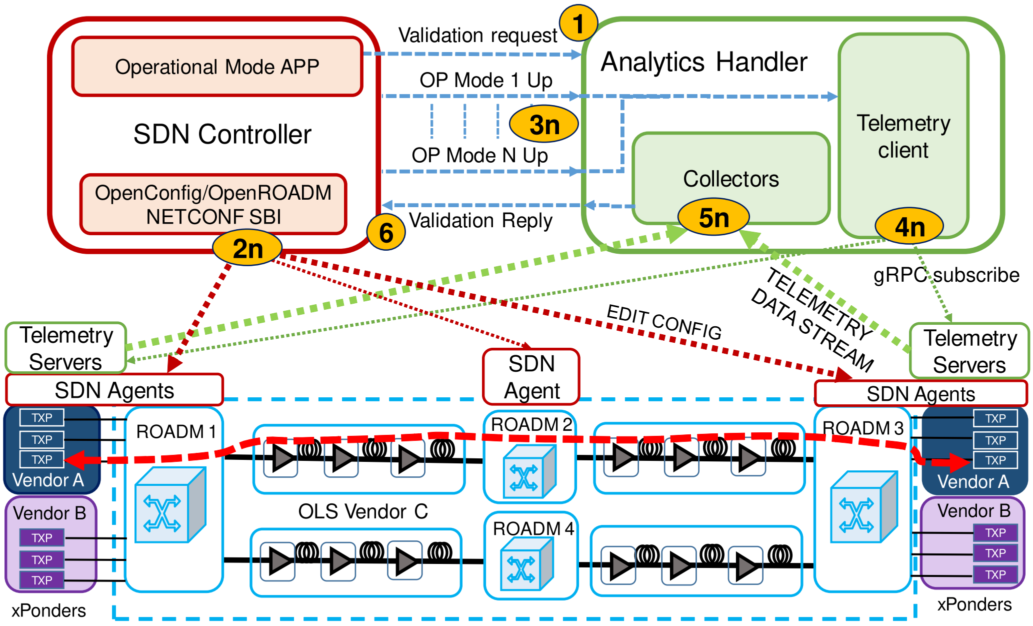

FIGURE 2. Partial disaggregation scenario and Telemetry-assisted operational mode selection for provisioning lightpaths.

Foundation (ONF) with the support of many of the most important telecommunication vendors and operators. Within the ONOS community the Open and Disaggregated Transport Network (ODTN) project has been recently established targeting the extension of ONOS to control and monitor disaggregated optical networks [30]–[32]. Control of partial disaggregated networks using Transport API and OpenConfig have been demonstrated using ONOS, with focus on topology discovery and full lightpath instantiation [33]. In addition, OpenROADM model has been evaluated recently resorting to ONOS in a multi-domain disaggregated scenario [34]. Recently, the ODTN working group has announced a collaboration with the TIP project, to introduce the support of TIP devices into the ONOS controller. A first work where ONOS has been demonstrated to configure and control a Cassini transponder has been published in [35]. Considering the active community working on the ONOS controller we have adopted it for our research work, not only because it provides a wide set of available features simplifying the development of new networking applications, but also to facilitate the exploitation of the new developed features by sharing it with the community.

To the best of our knowledge, there are not works in the literature targeting the issue of exposing opaque OP modes of a transponder in the YANG model of a transponder and its impact in terms of limited awareness of the SDN controller in the proper OP mode selection during path computation and physical parameters selection.

III. TELEMETRY-ASSISTED OPERATIONAL MODES SELECTION IN THE OPTICAL LAYER

The partial disaggregation scenario depicted in Fig. 2 is utilized to describe the operational mode activation and the related issues. The optical network, including ROADMs and the optical links, i.e., the Optical Line System, is provided by a single vendor, i.e., Vendor C in the figure. Conversely, xPonders (i.e., either transponders or muxponders, depending on the granularity available at the switched layers) are multi-vendor, in particular Vendor A and Vendor B provide xPonders attached to ROADM 1 and ROADM3, respectively. The OLS and the xPonders are equipped with SDN agents enabling control communication with the central SDN Controller through the NETCONF-based SouthBound Interface (SBI), each one relying to different YANG models (for example, OLS is based on OpenROADM, xPonders on OpenConfig). In addition, the considered xPonders are enriched with telemetry service, enabling dedicated co-located streaming servers to send continuous monitoring data collected from the digital signal processing hardware stages (e.g., Optical Signal to Noise Ratio - OSNR, Bit Error Rate - BER, input/output optical power). The telemetry services are activated on demand by a novel functional element called Analytics Handler (AH).

Each vendor implements for a given xPonder a set of possible transmission configurations, called OP modes, that are exposed as opaque attributes in the xPonder YANG model and therefore to the SDN controller, not disclosing proprietary parameters explicitly. A number of tunable or tweakable transmission parameters may be considered by xPonder vendors in the identification of a given OP mode (e.g., modulation format, Forward Error Correction (FEC), baud rate, probabilistic constellation shaping parameters, encoding modes, gain). In this paper, for simplicity, we consider the combination set of configurable modulation format and FEC as the list of available operational modes of an xPonder. As an example, Vendor A implements four OP modes obtained by combining two available modulation formats (e.g., Polarization Multiplexed Quadrature Phase Shift

Keying - PM-QPSK,Polarization Multiplexed 16 Quadrature Amplitude Modulation - PM-16QAM) and two FEC (e.g., Hard Decision FEC - HD-FEC and Soft Decision FEC - SD-FEC), while Vendor B exposes 1-9 modes, also including Probabilistic Constellation Shaping). Such modes may be enforced with additional transmission parameters already defined in the OpenConfig YANG model, such as the optical launch power. This means that the SDN Controller might be in the condition of evaluating a relevant list of OP modes, for example during the lightpath provisioning.

However, the SDN Controller, when receives the xPonder model and capabilities, may not be aware of the association between the operational mode and the related modulation format, FEC and other advanced solutions (e.g., constellation shaping), since some of them may be specific/proprietary of the xPonder Vendor as well as per-vendor policy and rules. Such lack of information at the controller currently prevents the optimal computation of OP modes and represents a limit in the utilization of proprietary (and outperforming) transmission solutions in disaggregated networks. Indeed, vendors provide only a list of unspecified operational modes suitable for the OpenConfig YANG model. Thus, preliminary validation may be required to provide the SDN Controller the actual performance and statistics referred to each OP mode along the specific route and frequency slot identified for provisioning. This validation may be performed offline (e.g., certification phase, test sessions during the device commissioning) or online (e.g., during the optical connection provisioning). However, the standard management-based monitoring solutions, employing traditional 15-minutes statistics, are inefficient and time consuming. Thus, a telemetry-assisted workflow coordinated by the SDN controller and the AH is proposed, with specific focus to lightpath provisioning at the optical layer, detailed below, and multi-layer adaptation, detailed in Sec. IV.

A. PROPOSED OPTICAL PROVISIONING WORKFLOW

In this section the selection of the most suitable OP mode for an optical connection xPonder end-points is automated through a coordination between the SDN Controller and the novel AH module and exploiting network telemetry. The coordination relies on the SDN controller NorthBound interface (e.g., REST) and on the telemetry stream subscription mechanism (e.g., gRPC-based). The proposed workflow operates at the optical layer and is executed when an optical connection request is submitted to the SDN controller responsible of the optical layer, just after path computation and route/transponder assignment. In this paper we mainly target preliminary online validation, however the proposed workflow is suitable also for automatic offline validation or certification testing purposes.

The proposed telemetry-enabled OP mode automation workflow is sketched in Fig. 2 and hereafter detailed. When a new optical connection (i.e., end-to-end optical channel) request is submitted to the SDN controller, path computation and spectrum/transponder assignment are executed, so that source and destination xPonder cards of the same vendor are assigned. Thus, the lightpath is first configured and established in both xPonders and the OLS (i.e., see the red dashed optical connection spanning ROADM 1, ROADM 2 and ROADM 3 in the figure) and using a first candidate operational mode on two selected xPonders of vendor A. Then, online validation of different OP modes takes place.

The online validation is orchestrated by the SDN controller in collaboration with the novel AH module. First, a a *Validation Request* is generated by the SDN Controller and sent to the AH (step 1). The request encloses the optical connection end-points (i.e., the agents addresses) and the pre-validated performance constraints (e.g., required OSNR). Then, the SDN Controller submits a set of additional requests for each OP mode available for the considered connection and xPonder pairs, triggering a loop sub-workflow. At each subworkflow step n, the controller configures the the n-th OP mode in the xPonders using the NETCONF-based SBI (edit-config messages) (step $2n$). Once enforced, the controller notifies the AH about the actual configuration of the n-th OP mode, using a *OpMode UP* message (step $3n$).

Each *OP Mode UP* message triggers the activation of a telemetry session to retrieve performance data related to the current OP mode. In particular, a Telemetry Client instance issues a gRPC-based telemetry subscription to the telemetry servers co-located with the cards agents (step $4n$). The subscription includes the following specifications:

1) the required telemetry data sample (e.g., OSNR detected by the Digital Signal Processing module of the coherent receiver)
2) the address of the AH Collectors that will have to receive the monitored data samples
3) the attributes of the telemetry session (e.g., the subscription duration and the data sample interval)

The servers start to generate streaming flow session towards the indicated AH Collectors. Collectors receive and store the requested monitored samples and are in charge of performing statistical analysis (e.g., max/min values, sample distribution), also considering possible transient due to the change of the new OP mode. At the end of all the loop sub workflows, when all the operational modes have been tested and monitored, the AH stores the statistical information of all the candidate OP modes.

At the end of the workflow, as response to the initial Validation Request, the AH sends a *Validation Reply* message to the Controller (step 6). The message encloses the monitored statistics referred to each candidate OP mode, thus allowing the Controller to properly select the most suitable OP mode and configure it as working path. It is worthwhile to note that, in the case of SDN stateful controller, the workflow procedure may be easily extended by including additional connections for telemetry evaluation (e.g., adjacent connections) in order to detect possible impact onto already established and working connections determined by the one under evaluation.

The proposed provisioning workflow is designed without considering stringent time constraints, since it is assumed that it is applied before the lightpath becomes active. The selection of the candidate OP modes to be evaluated in the workflow strictly depends the SDN controller awareness. If the controller is not aware of OP mode features, then all available OP modes will be evaluated. Otherwise, if some awareness is available (e.g., in the form of lookup tables of some transmission performance parameters provided by vendor specifications) then a restricted OP mode candidate list compatible with the connection requirements will be returned. The goal of this system is to allow operators to fully automate disaggregation avoiding long and error-prone lab trials and/or inefficient manual interventions at the controller with continuous upgrade/update sessions. Based on telemetry data acquired during the network lifetime and in different conditions, the system may rely on Artificial Intelligence to reduce the OP mode candidate set during the time and gradually evolve to an optimized OP mode assignment scheme.

IV. MANAGING OPENCONFIG OPERATIONAL MODES IN MULTI-LAYER PACKET OVER OPTICAL NETWORKS

The adaptation of OP modes on the transponder line side and the related implications and procedures on the client side can be considered an open issue that also involves the reconfiguration of the packet-switched layer. The latter aspect is particularly relevant if QoS-guaranteed network slicing is applied end-to-end across the whole network [11]. In particular, the considered use case is focused on traffic recovery after network failures that imply the reconfiguration of both layers if an OP mode adaptation is performed on the optical layer.

This section describes the scenario and the OP mode adaptation issues. Moreover, it proposes a novel comprehensive workflow providing OpenConfig OP mode adaptation at the transponder line side along with the required actions at the client side and on the interconnected packet-based network adopting QoS-guaranteed slicing.

A. REFERENCE SCENARIO

A SDN multi-layer packet-over-optical metro network is considered. The upper layer is based on packet switched elements handled by the controller using OpenFlow protocol. The bottom layer is based on a disaggregated optical infrastructure handled using the NETCONF protocol. Network slicing ensuring traffic isolation and subject to QoS constraints is enabled in such scenario by enforcing end-to-end connectivity including dedicated OpenFlow flow entries on packet-switched devices and lightpath establishment at the optical layer. Network slices are employed with different Service Level Agreements (SLA), based on carried traffic requirements in terms of latency, bandwidth, priority and reliability. In particular, a typical SLA differentiation resides in the amount of bandwidth guaranteed upon failure events. Typically, the edge between the packet layer and the optical layer is subject to additional constraints due to traffic tributary aggregation and granularity, that may preclude or limit a full network slice isolation and independence during a reconfiguration. Thus, adapting OP modes at the line side without considering the SLA implications at the client ports represents a not yet addressed issue.

The scenario depicted in Fig. 3 exemplifies the aforementioned issues. The multi-layer metro network is composed by four switches in the packet-switched layer (i.e., $N1 - N4$) and by three disaggregated ROADMs in the optical layer (i.e., $R1 - R3$). The optical layer includes also two muxponders $T1$ and $T2$, those muxponderes are responsible for multiplexing/demultiplexing P tributary client ports $p_1, \ldots, p_p$ to/from a single optical line port $OL1$. The scenario includes three network slices $S1{-}S3$, deployed onto the same physical topology and with different SLAs. In particular, slice $S1$, spanning $N1$, $N3$ and port p_1 on muxponders $T1$ and $T2$, is assumed to convey high class 100% bandwidth guaranteed traffic, thus requiring full bandwidth recovery mechanisms upon failure. Slice $S2$ is configured on switches $N1$, $N3$, $N4$ and on port $p1$ of $T1$ and $T2$ and carries on low class 50% guaranteed bandwidth, thus allowing temporary throughput reduction during failure events. Similarly, slice $S3$, configured on nodes $N2$ and $N4$ and connected to ports p_2 of $T1$ and $T2$, tolerates 50% throughput reduction.

As defined in the OpenConfig terminal-device model, the muxponders support different OP modes, e.g., OP mode 1 (OP_1) with transmission bitrate $R_1 = 200$ Gbps, Polarization Multiplexed 16 Quadrature Amplitude Modulation (PM-16QAM) modulation format MF_1, and FEC type F_1. Utilizing this mode all the client ports of the muxponder can be exploited (e.g., $P = 8$ at 25 Gbps each), i.e., with reference to Fig. 3 the two ports p_1 and p_2 are utilized. The muxponder also supports an additional mode (OP_2) featuring the same baud rate of OP_1, but with a bitrate $R_2 = 100$ Gbps, modulation format MF_2 PM Quadrature Phase Shift Keying (PM-QPSK) and FEC type F_2. With this configuration only half of the client ports can be exploited (i.e., only p_1 with reference to Fig. 3). Indeed, in commercial muxponders, the tributary flows are typically multiplexed into the OTN line using a rigid framing without performing packet switching.

In a first phase the optical connectivity is established, using OP_1, along a path passing through ROADMs $R1$ and $R3$. A bitrate of 200 Gbps is therefore deployed by fully exploiting the two client ports p_1 and p_2 reported in Fig. 3. If the fiber between $R1$-$R3$ is affected by a failure (e.g., fiber-cut), a backup optical path is computed and established by the SDN controller, e.g., along $R1$, $R2$ and $R3$. However, this longer path introduces additional impairments so that the 200 Gbps bitrate cannot be used. Therefore, the connectivity along the backup path has to use the 100 Gbps exploiting OP_2.

At best of our knowledge, OP modes adaptation has never been experimented before. Moreover, the OP modes adaptation at the muxponder level implies the tear down of port p_2 with consequent total disruption of service $S3$, thus violating its SLA. Therefore, a detailed procedure is needed to account for OP mode adaptation as well as metro network reconfiguration.

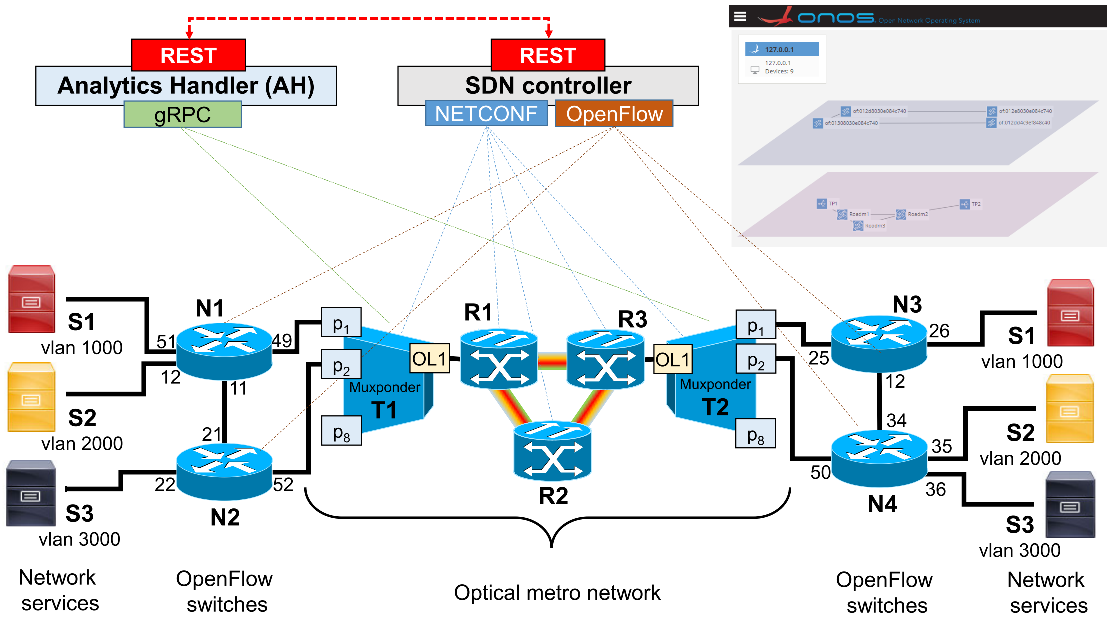

FIGURE 3. Reference multi-layer packet over disaggregated optical network: scenario and experimental setup. A screenshot of the network topology as seen by the ONOS controller is reported on the top-right corner.

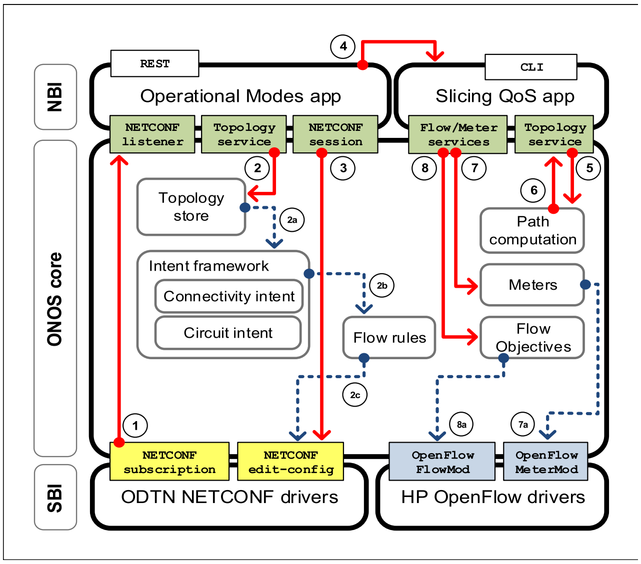

FIGURE 4. Proposed ONOS workflow, highlighting the two implemented applications and the related interactions, represented with red-solid lines. Some extension to the NETCONF and OpenFlow drivers are applied to properly support the hardware included in the experimental testbed.

B. PROPOSED MULTI-LAYER ADAPTATION WORKFLOW

The workflow that we proposed for handling network failures that require the modification of the utilized OP mode has been implemented within the ONOS SDN controller and is illustrated in Fig. 4. Two different applications have been implemented on the ONOS North Bound Interface (NBI), moreover the NETCONF and OpenFlow drivers have been extended on the ONOS South Bound Interface (SBI) to support the specific hardware included in the experimental testbed. Fig. 4 reports with solid lines the interactions that have been specifically developed for this work, while the dashed interactions are part of the ONOS core functionality. The application named *Operational Modes* uses a REST API interface to interact with the Analytics Handler (see Sec. III for details), and monitor the optical devices status exploiting specific NETCONF subscriptions compliant with the OpenROADM description of the ROADMs. As an example, when a ROADM detects a loss-of-light event, NETCONF notification is sent by the ROADM itself to the ONOS controller. The application named *Service QoS* app implements a set of commands within the ONOS CLI to add/manage/remove connectivity services. Specifically, the connectivity services are created by exploiting the intent framework provided by the ONOS core that interacts with Path Computation, Flow Rule and the Meter services. Moreover, the Service QoS app can be dynamically invoked by the Operational Modes app to modify currently established services in case of network events that modify the bandwidth made available by the optical layer.

Three services, i.e., $S1$ $S2$ and $S3$ respectively mapped on VLANs 1000, 2000 and 3000, are initially established and share a single optical connection (i.e., OpticalConnectivity intent) established between the two transponders (using line ports $OL1$). When a failure occurs between ROADMs $R1$ and $R3$, the Operational Modes app receives a NETCONF notification communicating the loss-of-light event (step 1 in Fig. 4). The controller consequently updates its vision of network topology exploiting the Topology service (step 2 in Fig. 4), i.e., the failed link is removed from the topology. Thus the ONOS intent framework is activated to reroute the disrupted OpticalConnectivity intent along the new path $R1$, $R2$, $R3$ (steps 2a, 2b, 2c in Fig. 4).

The Operational Modes app evaluates if the new optical path can be supported using the same OP mode or if it requires the utilization of a different OP mode. In the latter case the app uses a NETCONF edit-config message to update the OP

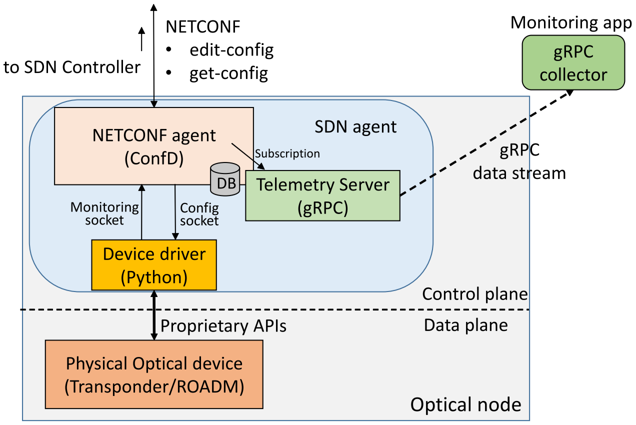

FIGURE 5. SDN agent architecture.

mode of the muxponders and, in our specific case, to turn-off the client ports (i.e., $p2$) that are not usable with the new OP mode (step 3 in Fig. 4). At this point the Slicing QoS app is invoked, in this case the bandwidth available on the optical layer using OP_2 is provided by the Operational Mode app as an input of the Slicing QoS app (step 4 in Fig. 4). Thus, the Slicing QoS app can compute a new path for $S3$ that was using port p_2 (steps 5 and 6 in Fig. 4), and consequently reduce the bitrate of services $S2$ and $S3$ utilizing OpenFlow meters. Specifically, considering the enforced SLAs (steps 7 and 8 in Fig. 4), the bitrate of $S2$ and $S3$ can be reduced by 50% while the bitrate of $S1$ is not modified.

V. SDN AGENT SUPPORTING TELEMETRY-ASSISTED OP MODE SELECTION: DESIGN AND IMPLEMENTATION

In this section we propose and report the implementation design of an SDN agent, supporting both OpenConfig and OpenROADM YANG models and enabling the telemetry-assisted workflows described in Sec. III-A and Sec. IV-B for the operational mode selection and adaptation, respectively. The SDN Agents have been ad-hoc designed in order to manage commercial devices that were not natively SDN-enabled. More specifically, by relying on the proprietary APIs exposed by the optical devices, each SDN Agent enables the configuration, monitoring and telemetry functionalities, in order to expose the main functionalities required in the optical disaggregated approach. The extended SDN Agent code is open source and available for evaluation [36].

Fig. 5 shows the architecture of the SDN Agent. The optical data plane is represented in the bottom part of the figure, while on the top the control plane software architecture is shown. The SDN agent software architecture is composed by three elements: (i) the NETCONF agent, (ii) the device driver and (iii) the telemetry server.

An extended version of the ConfD framework [37] has been adopted for the implementation of the NETCONF agent, creating the NETCONF API to the SDN controller. On the one hand, the `edit-config` RPC is adopted in order to enable the configuration of the main transmission parameters, on the other hand the `get` RPC enables the real-time monitoring of state values stored at the device. In fact, a specific software database (DB) is created by ConfD, according to the adopted YANG modules, and is maintained up-to-date via RPCs. Two sockets (i.e., config socket and monitoring socket) have been implemented allowing the communication with the device driver module for configuration and monitoring purposes.

The telemetry server is the functional block devoted to telemetry activities, handling the subscription requests and activating the data streaming. It has been implemented resorting to the open source implementation of the gRPC with protobuf protocol. The considered Interface Description Language-based model is derived from an open source model proposed by Juniper and fully detailed in our previous work [2], that includes the service interface definitions (i.e., server-streaming RPC) and the structure of the payload messages, mainly identified by a timestamp and a key-value identifier. The telemetry subscriptions, received by the NETCONF agent through the NETCONF API, are parsed and adapted to proper gRPC subscriptions. Each subscription request includes: the gRPC collector (i.e., IP address and port of the collector), the list of parameters to be monitored, the duration and the rate (i.e., sampling time) of the stream. By retrieving the requested data directly from the NETCONF database, the telemetry data stream to the collector is initiated.

Considering xPonders nodes, where several transponders and/or muxponders, possibly of different vendors, are installed, the OpenConfig YANG models have been adopted for the development of the NETCONF agent. The device driver has the role to both send the configuration of the parameters received via config socket to the physical transponder(s) and to send to the NETCONF agent, using the monitoring socket, the data retrieved from the physical device. Proprietary APIs are adopted in the communication with underlying physical devices.

Considering ROADMs, provided by different vendors, the OpenROADM YANG models have been adopted for the development of the NETCONF agent. As discussed previously for the xPonders nodes, the device driver enables both the configuration and the monitoring of the transmission parameters, exploiting config and monitoring sockets. The communication with the underlying physical devices relies on proprietary APIs.

VI. SIMULATION ASSESSMENT

The potential benefit introduced by the optimization of the operational mode is evaluated in a simulated environment in terms of blocking probability reduction. Specifically, the work in [38] quantifies the spectrum benefit that is achievable by selecting the more appropriate operational mode in an metro optical network utilizing a QoT model considering only degradation effects introduced by ROADMs filtering effects. Similar results can be achieved on a core network adopting a more accurate QoT estimation tools [39].

As an example, [38] demonstrates that considering 100 Gbps connection requests one 12.5 GHz frequency slice

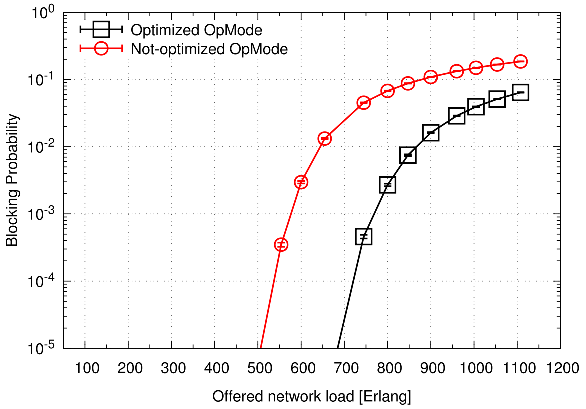

FIGURE 6. Blocking Probability as a function of the offered network load, Pan-European network topology depicted in [41].

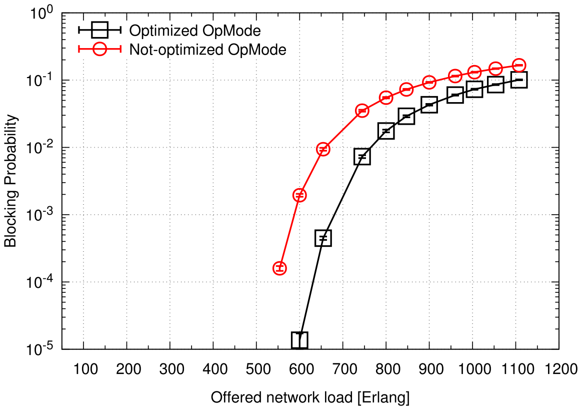

FIGURE 7. Blocking Probability as a function of the offered network load, multi-domain network topology depicted in [42].

can be saved optimizing the operational mode for those paths that traverses up to 8 ROADMs; contextually it demonstrates that considering 400 Gbps connection requests two frequency slices can be saved for paths traversing up to 4 ROADMs and one frequency slice can be saved for paths traversing 5 and 6 ROADMs.

The simulation study has been conducted using a custom built event-driven C++ simulator. The same simulator has been widely used in previous works mainly focusing on performance evaluation of Routing and Spectrum Assignment schemes for optical networks [40]–[43]. The simulator version used in this work is available open-source as a github public repository[1]. Two different network topologies are considered in this simulation study: a Pan-European topology including 27 nodes (depicted in [41]) and 55 bidirectional links and a multi-domain topology including 75 nodes and 146 bidirectional links (depicted in [42]). In both topologies each link includes 256 frequency slices of 12.5 GHz. Traffic is uniformly distributed among node pairs and two bitrate classes, lightpath requests arrive following a Poisson process. The two considered bitrate classes require 100 Gbps and 400 Gbps. Referring to [38], if the optimization of the operational mode is adopted 100 Gpbs requests can occupy a frequency slot of 37.5 GHz or 50.0 GHz (depending on the number of traversed ROADMs), while they are always served with a 50.0 GHz slot if the operational mode optimization is not applied. Similarly, if optimized, 400 Gpbs requests can occupy a frequency slot of 62.5 GHz, 75.0 GHz or 87.5 GHz, whereas if not optimized they are always served with a frequency slot of 87.5 GHz.

The obtained results are illustrated in Fig. 6 and Fig. 7. The two figures report the obtained blocking probability as a function of the offered network load, respectively obtained in the Pan-European and the multi-domain network topologies. The results are obtained by running the simulation tool until the confidence interval of 5% at 95% confidence level or the maximum number of independent trials is reached. All results are then plotted with the confidence interval at 95% confidence level.

First, both figures shows that the spectrum save guaranteed by the operational mode optimization is translated in a significant benefit in terms of blocking probability. Comparing the two figures, it is also clear that the benefit achieved in the Pan-European topology is higher with respect to the benefit obtained in the multi-domain topology. Indeed, considering the QoT estimation tool in [38] spectrum save is obtained only for lightpaths traversing less that 8 ROADMs, while in the multi-domain topology is likely to have longer lightpaths. However, using more accurate QoT tools, e.g.,the GNPy tool [39], similar benefit is achievable also in core networks.

VII. IMPLEMENTATION AND EXPERIMENTAL DEMONSTRATION

The experimental validation of proposed solutions has been carried out on the network testbed including both control plane and data plane illustrated in Fig. 3.

At the control plane level, the testbed includes the ONOS SDN Controller (version 2.2) [29], [31] and the Analytics Handler (AH) module. The ONOS controller has been extended developing specific applications and drivers to properly support the considered use cases (see Sec. VII-A and Sec. VII-B for details), and the Analytics Handler (AH) module, that has been specifically developed for this work. The ONOS controller and the AH module communicates using REST APIs.

At the data plane level, the testbed includes two commercial muxponders (i.e., $T1$ and $T2$), three ROADMs (i.e., $R1$, $R2$ and $R3$), four commercial OpenFlow switches (i.e., $N1$, $N2$, $N3$ and $N4$) and a commercial traffic analyzer (i.e., Spirent SPT N4U) utilized to generate traffic flows with different VLAN tagging.

Differently with respect to the use case described in Section IV, but without affecting the general workflow proposals, the employed commercial muxponders support 10 Gigabit Ethernet tributaries and are capable of performing FEC adaptation only. In particular, each muxponder supports eight 10 Gbps client ports and one line port at 100 Gbps exploiting coherent transmission with PM-QPSK modulation format and supporting two proprietary FEC types: Soft Decision FEC A (SD-FEC-A) and Soft Decision

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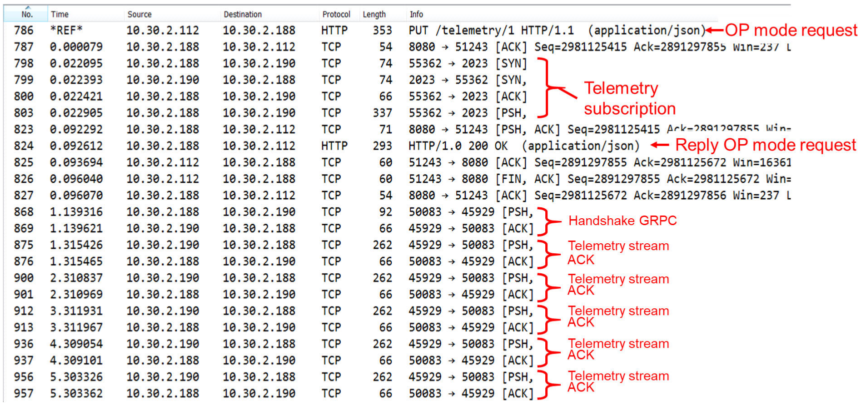
[1] https://github.com/alessiocnit/dalay.



```
No.  Time      Source       Destination  Protocol Length Info
786  *REF*     10.30.2.112  10.30.2.188  HTTP     353    PUT /telemetry/1 HTTP/1.1  (application/json)
787  0.000079  10.30.2.188  10.30.2.112  TCP      54     8080 → 51243 [ACK] Seq=2981125415 Ack=2891297855 Win=237 L
798  0.022095  10.30.2.188  10.30.2.190  TCP      74     55362 → 2023 [SYN]
799  0.022393  10.30.2.190  10.30.2.188  TCP      74     2023 → 55362 [SYN,
800  0.022421  10.30.2.188  10.30.2.190  TCP      66     55362 → 2023 [ACK]
803  0.022905  10.30.2.188  10.30.2.190  TCP      337    55362 → 2023 [PSH,
823  0.092292  10.30.2.188  10.30.2.112  TCP      71     8080 → 51243 [PSH, ACK] Seq=2981125415 Ack=2891297855 Win=
824  0.092612  10.30.2.188  10.30.2.112  HTTP     293    HTTP/1.0 200 OK  (application/json)
825  0.093694  10.30.2.112  10.30.2.188  TCP      60     51243 → 8080 [ACK] Seq=2891297855 Ack=2981125672 Win=16361
826  0.096040  10.30.2.112  10.30.2.188  TCP      60     51243 → 8080 [FIN, ACK] Seq=2891297855 Ack=2981125672 Win=
827  0.096070  10.30.2.188  10.30.2.112  TCP      54     8080 → 51243 [ACK] Seq=2981125672 Ack=2891297856 Win=237 L
868  1.139316  10.30.2.188  10.30.2.190  TCP      92     50083 → 45929 [PSH,
869  1.139621  10.30.2.190  10.30.2.188  TCP      66     45929 → 50083 [ACK]
875  1.315426  10.30.2.190  10.30.2.188  TCP      262    45929 → 50083 [PSH,
876  1.315465  10.30.2.188  10.30.2.190  TCP      66     50083 → 45929 [ACK]
900  2.310837  10.30.2.190  10.30.2.188  TCP      262    45929 → 50083 [PSH,
901  2.310969  10.30.2.188  10.30.2.190  TCP      66     50083 → 45929 [ACK]
912  3.311931  10.30.2.190  10.30.2.188  TCP      262    45929 → 50083 [PSH,
913  3.311967  10.30.2.188  10.30.2.190  TCP      66     50083 → 45929 [ACK]
936  4.309054  10.30.2.190  10.30.2.188  TCP      262    45929 → 50083 [PSH,
937  4.309101  10.30.2.188  10.30.2.190  TCP      66     50083 → 45929 [ACK]
956  5.303326  10.30.2.190  10.30.2.188  TCP      262    45929 → 50083 [PSH,
957  5.303362  10.30.2.188  10.30.2.190  TCP      66     50083 → 45929 [ACK]
```

FIGURE 8. Capture of messages exchanged at the AH.

TABLE 1. Provisioning: Optical connection parameters stored at the SDN Controller.

Defined by ONOS Controller						Provided by AH via REST	
ID	Time [s]	muxponder Id	State	OP mode	Frequency [THz]	Pre-FEC BER (min/avg/max)	OSNR [dB] (min/avg/max)
1	30	11811	Provisioning	1	192.05	3.70E-7/3.86E-7/4.01E-7	25.2/25.51/25.9
1	30	10102	Established	1	192.00	2.20E-6/2.46E-6/3.81E-6	22.43/22.49/22.57
2	30	11811	Provisioning	2	192.05	2.75E-7/2.86E-7/2.89E-7	26.8/27.59/28.7
2	30	10102	Established	1	192.00	2.22E-6/2.38E-6/3.92E-6	22.42/22.47/22.54

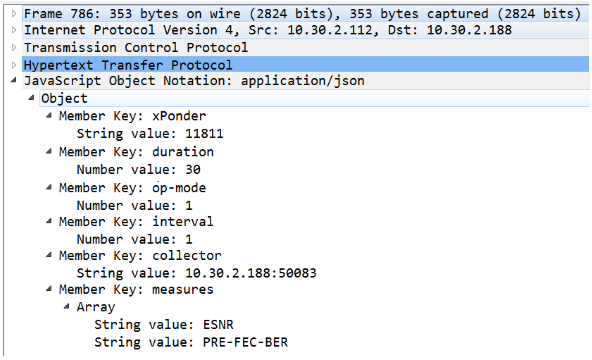
FEC B (SD-FEC-B). They have been equipped with the NETCONF agent described in Sec. V adopting the OpenConfig YANG models [12]. Since modulation format is not configurable, the two supported FEC types (operating with the same PM-QPSK modulation format) are mapped to two distinct OP modes: OP_1 and OP_2. ROADMs have been implemented combining a pair of WSS filters on each degree. In this case, the deployed NETCONF agent is compliant with the OpenROADM YANG models.

The packet-based devices on the data plane are four commercial HP switches (i.e., HP 3800 and HP Aruba 2930) that are controlled by the ONOS controller using the OpenFlow protocol version 1.3.

A. OP MODES: OPTICAL PROVISIONING

For this use case the ONOS controller has been extended, implementing the *Operational Mode* app in order to compute and store the main connection parameters (as shown in Tab. 1) and communicate with the AH module using a REST interface (step 1, 3n and 6 in Fig. 2. The AH module includes the gRPC Client and a database to store the telemetry data received by the device agents.

Considering the optical metro network segment illustrated in Fig. 3, the experiment begins with the establishment of an optical connection between the line port $OL1$ of the two muxponders. To this end, the SDN controller performs the configuration of the two muxponders and of the traversed ROADMs. More specifically, the transponders at 100 Gbps (i.e., respectively T1 and T2) have been configured at the central frequency 192.05 THz, with 0 dBm of output power and default operational-mode (i.e., OP_1). In the traversed ROADMs, the cross-connection among ingress and output ports is configured with a frequency slot of 50GHz, centered at 192.05THz.



```
▷ Frame 786: 353 bytes on wire (2824 bits), 353 bytes captured (2824 bits)
▷ Internet Protocol Version 4, Src: 10.30.2.112, Dst: 10.30.2.188
▷ Transmission Control Protocol
▷ Hypertext Transfer Protocol
◢ JavaScript Object Notation: application/json
  ◢ Object
    ◢ Member Key: xPonder
        String value: 11811
    ◢ Member Key: duration
        Number value: 30
    ◢ Member Key: op-mode
        Number value: 1
    ◢ Member Key: interval
        Number value: 1
    ◢ Member Key: collector
        String value: 10.30.2.188:50083
    ◢ Member Key: measures
      ◢ Array
          String value: ESNR
          String value: PRE-FEC-BER
```

FIGURE 9. OP mode 1 request message (Frame 786 of the capture).

Typically the SDN controller is not aware of the expected performance provided by each *OP* mode and it has no reliable means to assess which OP mode best performs on an identified path. As detailed in Fig. 8, the SDN controller (IP address 10.30.2.112) configures OP_1 (i.e., SD-FEC-A) and, after the initial Validation Request, sends a OP mode message to the AH module (IP address 10.30.2.188) to request the OP_1 telemetry activation of both OSNR and PRE-FEC BER statistics (the request is in frame n. 786, the details of the request are reported in Fig. 9. Subscription takes place and the receiver card server (IP address 10.30.2.190) starts the telemetry stream with sample rate set to 1 second. The stream terminates after 30 seconds and the procedure is repeated to evaluate OP_2 (i.e., SD-FEC-B). In addition, for each session, a further telemetry session was activated to evaluate the performance of an already established and adjacent connection having the same end point on card 10102 (OP mode set to 1 and central frequency already set to 192.00THz). At the end of the whole evaluation, the AH provides all the requested statistics to the Operation Mode

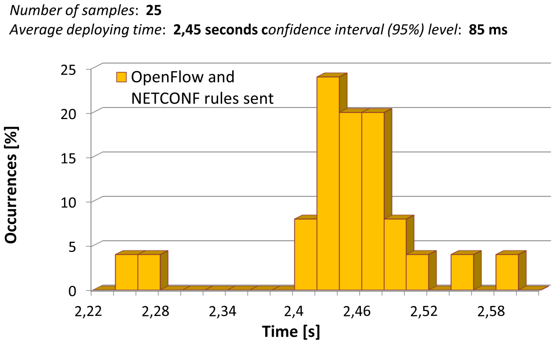


FIGURE 10. Experimental distribution over 25 tests of control plane workflow execution; measured time is the period between step 1 and the last executed event among steps 2c, 3, 7a and 8a, as reported in Fig. 4.

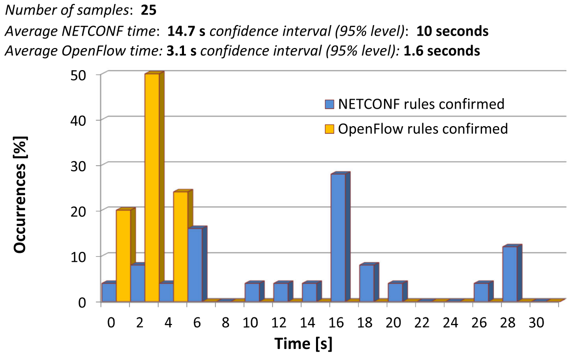


FIGURE 11. Experimental time distribution over 25 tests: confirmation time of OpenFlow and NETCONF configurations.

application at the SDN Controller. The connection under test (i.e., monitored at T2, id 11811) and the existing connection (id 10102) statistics available at the controller are reported in Tab. 1. The table shows that OP_2 outperforms OP_1 in terms of quality of transmission (average PRE-FEC BER 2.86E-7 and average OSNR of 27.59dB), while the existing connection is not negatively impacted for both OP modes. Therefore, the SDN controller selects and configures OP_2 as the most suitable transmission mode for the considered connection. The overall automation procedure requires a very limited additional traffic load in the control plane (i.e., 3.5 kb/s average, 80 kb/s peak) and is performed in around 1 minute for the considered 2 cases. This demonstrates that the implemented automation is faster and more efficient with respect to the traditional 15mins monitoring interval. Moreover, the statistics provided by the AH may be available for additional processing, such as artificial intelligence, in order to further improve the OP mode selection for future connection requests.

B. OP MODES: MULTI-LAYER ADAPTATION

The failure event between ROADMs $R1$ and $R3$ illustrated in Fig. IV has been emulated 25 times on the experimental testbed manipulating the value of the received optical power received by ROADM $R3$. The sequence of events at the controller has been logged to compute the time required to perform the complete workflow depicted in Fig. 4. The performed change of operational mode (i.e., from OP_1 to OP_2) physically modifies only the FEC type adopted by the transponders.

Fig. 10 reports the distribution (obtained over 25 experiments) of the time required at the ONOS controller to execute the entire workflow as illustrated in Fig. 4. Specifically, the measured time refers to the period between step 1 and the last executed event among steps 2c, 3, 7a and 8a. Thus, on average, the new configuration is sent to the devices 2.45 seconds after the reception of the NETCONF message notifying the network failure (i.e., fiber-cut between ROADMs $R1$ and $R3$), and can be considered actually deployed on the device. This result is also quite accurate, indeed the achieved confidence interval (at 95% of confidence level) is about 85 milliseconds.

The ONOS controller periodically refreshes its vision of the devices to obtain a confirmation of previously sent rules. In this regard, Fig. 11 reports the distribution of time on which the ONOS controller obtains the confirmation of the sent OpenFlow and NETCONF rules (i.e., period of time elapsing between the last rule sent to the device and the reception of the refreshed data from the last reconfigured device). Fig. 11 differentiates between the two protocols because the ONOS controller uses different timers for refreshing the configuration of OpenFlow and NETCONF devices, that, considering obtained results, can be respectively estimated in 5 seconds and 30 seconds timers. In this case, the utilization of a periodic timer makes impossible to achieve very accurate results, indeed in Fig. 11 the obtained confidence intervals are about 1.6 and 10 seconds, respectively for OpenFlow and NETCONF rules.

Finally, obtained results show that the control plane workflow is executed in less than 6 seconds. Such interval includes the time required to complete the FEC adaptation on the muxponder, evaluated in around 5 seconds. In general, optical signal adaptation was demonstrated to be fast in experimental prototypes proposed in the literature [44]–[46], while in recent commercial devices a number of hardware and software constraints impose, for a OP mode change, a physical downtime of the order of more than ten seconds up to one minute (e.g., see modulation format adaptation example in [47]). Therefore, the extra time introduced by the ONOS-orchestrated workflow (evaluated in less than 3 seconds, as shown in Fig. 10) represents a fully satisfactory result and implies that multi-layer re-optimization at the switching layer including client/tributaries cards reprogramming is significantly faster with respect to the optical signal adaptation.

VIII. CONCLUSION

This paper first demonstrated, through a simulative study, that the disaggregated optical network performance can be significantly improved by optimizing the selection of the Operational (OP) mode, also if this optimization guarantees the saving of few frequency slots. Then the paper detailed, implemented and experimentally validated workflows and procedures enabling the OpenConfig concept of OP Modes to be effectively adopted in a fully vendor-neutral partially disaggregated scenario. We reported on the implementation of a number of software components including the software agent for OpenConfig transponders and OpenROADM line systems, a telemetry-assisted monitoring handler, and specifically designed procedures at the ONOS controller.

The proposed software components and workflows were experimentally demonstrated in a network testbed encompassing hardware modules from different vendors, successfully enabling the SDN controller to manage transponders in a fully vendor neutral solution through the proposed enhancement of OP modes in case of both provisioning and adaptation, also considering the impact in the tributary/client network. Obtained results shown that all the required control plane operations can be executed in few seconds, largely before the convergence of the optical transmission layer.

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ANDREA SGAMBELLURI received the master's degree in telecommunications engineering from the University of Pisa, Italy, in 2007, and the Ph.D. degree from the Scuola Superiore Sant'Anna, Pisa, in 2015. In 2016, he was a Postdoctoral Researcher with the KTH Royal Institute of Technology, Onlab, Sweden. He is currently an Assistant Professor with the Scuola Superiore Sant'Anna. His research interests include optical networks control plane, including software defined networking (SDN) protocol extensions, network reliability, segment routing application, and multi-domain orchestration. In March 2015, he won the grand prize at 2015 OFC Corning Outstanding Student Paper Competition.

ALESSIO GIORGETTI received the Ph.D. degree from the 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. After some research grants at Consorzio Interuniversitario per le Telecomunicazioni (CNIT), he has been an Assistant Professor with SSSA since 2011. He is currently a Researcher with the Institute of Electronics, Computer and Telecommunication Engineering, National Research Council of Italy (IEIIT-CNR). He is the author of more than 100 publications, including international journals, conference proceedings, and patents. His research interests include optical network architecture and control plane, industrial network design, and software defined networking.

DAVIDE SCANO received the B.S. degree in telecommunication engineering from the University of Pisa, in 2017, the M.S. degree in computer science and networking from the University of Pisa and the Scuola Superiore Sant'Anna, Pisa, in 2019, discussing a research thesis on software defined networking for guarantee QoS in network slicing, and the Ph.D. degree in emerging digital technologies from the Scuola Superiore Sant'Anna, in October 2020. In 2020, he got a Research Scholarship at the Scuola Superiore Sant'Anna. His research interests include software defined networking, next generation software defined networking, optical networks, and disaggregated networks.

FILIPPO CUGINI (Associate Member, IEEE) is currently the Head of Research Area at CNIT, Pisa, Italy. He also serves as a Coordinator of the ECSEL BRAINE Project, and an EU-funded project aiming at boosting Artificial Intelligence at the network Edge. He is the coauthor of 14 patents and more than 250 international publications. His research interests include theoretical and experimental studies in the field of communications and networking.

FRANCESCO PAOLUCCI received the Laurea degree in telecommunications engineering from the University of Pisa, in 2002, and the Ph.D. degree from the Scuola Superiore Sant'Anna, Pisa, in 2009. In 2008, he was granted a Research Merit Scholarship with the Istitut National de le Recherche Scientifique (INRS), Montreal, QC, Canada. He is currently an Assistant Professor with the TeCIP Institute, Scuola Superiore Sant'Anna. He is the coauthor and contributor of 3 IETF Internet Drafts, he coauthored more than 160 publications in international journals, conference proceedings and book chapters, and filed four international patents. He is the coauthor of the 5G-PPP Phase 1 Security Landscape released by the 5G-PP Security Working Group. His research interests include network control plane and service orchestration for edge/cloud computing and network function virtualization (NFV), and optical networks control plane, including software defined networking (SDN) disaggregated networks and white boxes configuration, and telemetry/monitoring and advanced data plane programmability exploiting P4.

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