Advances in SDN control and Telemetry for Beyond 100G disaggregated optical networks [Invited]

RAMON CASELLAS,[1,*] RICARDO MARTÍNEZ,[1] RICARD VILALTA,[1] RAUL MUÑOZ,[1] ALFREDO GONZÁLEZ-MUÑIZ,[2] OSCAR GONZÁLEZ DE DIOS,[3] JUAN PEDRO FERNÁNDEZ-PALACIOS,[3]

[1]*Packet Optical Networks and Services, CTTC/CERCA, Av. Carl Friedrich Gauss n7, 08860 Castelldefels, Spain*
[2]*ZTE, Victor de la Serna 31 6D Madrid, Spain (work done while at Telefónica)*
[3]*Telefónica, Ronda de la Comunicación s/n 28050 Las Tablas (Madrid), Spain*
**Corresponding author: ramon.casellas@cttc.es*

Received 15 December 2021; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

This tutorial considers the evolution of SDN control for optical transport networks in disaggregated scenarios, focusing on its requirements and challenges when applied to "beyond 100G" networks, term that jointly refers to the use of coherent technology, data rates beyond 100G and the evolution of OTN standards to support rates such as 200G, 400G, or 800G. The tutorial covers use-case driven SDN development, new challenges, and requirements, such as the need to account for physical impairments, multiband / SDM control, improved fault/alarm management or optical telemetry and streaming. Finally, the tutorial provides an overview of new trends such as network sharing © 2021 Optica Publishing Group.

http://dx.doi.org/10.1364/JOCN.99.099999

1. INTRODUCTION

This paper, companion article of the ECOC tutorial presentation [1], aims at providing an overview of architectures, emerging use cases, trends, challenges and recent advances related to the applicability of the Software Defined Networking (SDN) paradigm(s) to the control, management and monitoring (operation) of optical networks, focusing on the photonic media layer, to support ever increasing data rates (within the so called *Beyond 100G* networks) with especial emphasis in specific scenarios involving (partial) disaggregation, along with related recent developments, work items, open questions, where selected and simplified data models are used for illustrative purposes, while remaining industry relevant. It is complementary to previous tutorials dealing with the basic concepts of control plane [2] and the detailed view of relevant SDN protocols [3].

The structure of this paper is as follows. In this Section, we provide an overview of basic common terms and frameworks. We start with the concept of model driven development, which applies to aspects related to configuration, control, and monitoring, and we present the two most common optical disaggregation models. We briefly discuss what "beyond 100G" means and what the direct implications in controllers are, notably in terms of configuration of terminals. Finally, we present the current "use case" driven specification that is taking place in Standards Development Organizations (SDOs) and related initiatives. In Section 2, we detail the reference architecture in this work, focusing on the partially disaggregated scenario with OpenConfig models for terminal devices and Transport API (TAPI) for the controllers' North Bound Interface (NBI). Section 3 presents the evolving use cases and requirements that include aspects such as a better and uniform coverage of physical layer impairments (PLI) in support of e.g., externalized path computation, multiband (MB) optical networking or Space Domain Multiplexing (SDM). Section 4 is dedicated to optical monitoring and streaming telemetry, both from a device perspective as well as from a network domain (controller) perspective. Section 5 provides a short overview around the concepts of infrastructure sharing, network virtualization and current research collectively known as (transport) network slicing. Finally, Section 6 concludes the paper.

A. Model Driven Control and Telemetry

The wide adoption of a "*Model Driven*" approach has been a fundamental step in the development of SDN for transport networks. The term refers to the design of (distributed) systems based on the systematic use of *data models*, and in particular for the control, management, monitoring and operation of Optical Networks and devices. Data models are representations of a system, made of the composition of concepts which are used to know, understand, or simulate a *subject*. They are abstract formalization of objects and entities, including their relevant parameters, roles (e.g., device, component, port), relationships: (e.g., Contains, Composed-Of), and cardinalities (e.g., 1:1 or 1:N), including constraints such as referential integrity.

The benefits of model driven development are well-known: enhance the understanding of a system; provide non-ambiguous specification; convey system details and the structure of data and underlying semantics and act as reference and specification with self-documentation. In practice, data models are released in portable text files described with a Data Modelling Language (DML) and define how, for example, a user or controller can interact with and configure a device, and what events or telemetry data points it generates. It can also describe a network in terms of graph elements such as links or nodes or a provisioned service along with the resources it uses. Models can be consumed by humans and/or machines and are used for modeling a wide range of entities such as services, control &

management constructs (topologies, connections), devices, etc. Data models can be versioned, automatically processed, validated, and used with appropriate toolchains, thus avoiding error-prone and repetitive tasks so business logic and applications can be developed around them.

A DML, such as *Yet Another Next Generation* (YANG) [4] is thus used to define data models, describe a device, system or service capabilities, attributes (including configuration and operational data), operations and asynchronous notifications. DMLs are expected to support increasing modeling requirements, i.e., the ability to define complex models and to support mechanisms for extensibility and augmentation.

A key aspect in the industry adoption of a DML is its *ease of use*, including its integration into common and existing workflows, frameworks, and languages, enabling non-ambiguous specification used by multi-source agreements, SDOs, often along with companion documents, reference implementations, best practice guidelines to help module authors [5].

From the point of view of features, it is useful that a DML is strongly typed, able to define composable, reusable and constrained data types (and units), supporting regular expressions and common data types like lists or maps. It should be able to capture entity relationships, between different actors, including sub-typing, containment, composition, and aggregation (with cardinality annotations) and referencing. Complex modules should be created by composition or inheritance, augmenting existing models and enabling reuse and a hierarchy of model refinements.

A transport protocol, such as NETCONF [6], RESTCONF [7] or gRPC [8] allows entities to access and modify data, providing primitives to view and manipulate such data, and suitable encodings as defined by the data-model. Such protocols are required to be flexible, efficient, and secure, and a common design is that, ideally, data models should be protocol independent. As a common operation, the transport protocol must support Create/Read/Update/Delete (CRUD) operations and to retrieve operational, statistics, telemetry data. Macroscopically, transport protocols are characterized by key parameters such as overhead (due, in particular, to the verbosity of the encoding), latency, simplicity, or robustness [3]. The differences between protocols also result in their respective preferred applications and uses cases: an HTTP based, JSON encoded protocol is more suitable for a controller NBI while a binary optimized bidirectional protocol is more efficient for large scale telemetry. Modern protocols support bi-directional flow, full-duplex capabilities, and security & credential management (TLS/SSL), advanced flow control. Advanced features include supporting multiple clients with per client /session fine locking and transactional semantics with rollback capabilities or sequential consistency, including synchronization primitives. As with DMLs, protocols also benefit from toolchain availability, tools for automatic generation of stubs/skeletons of client/servers, etc. and extended programming language support, including common targets such as high performance (C/C++), general purpose systems programming (Java), emerging system languages (Go) or as web-based frontend languages (Typescript / JavaScript), enabling developers to focus on the business logic, high-level entity manipulation, abstract from low-level details and the growth of an application ecosystem using Open-Source Software (OSS), such as libraries or command line tools.

Finally, functional architectures exploiting data model development for device remote configuration, control and monitoring with efficient telemetry have relied on common paradigms such as client/server or publisher/subscriber. However, the application to large scale, high bandwidth and low latency scenarios justify research on complex architectures with hierarchical and/or cluster arrangements.

B. Optical Disaggregation

Optical disaggregation refers to the deployment models with a flexible and modular network element architecture, potentially mix and matching devices from different vendors, while ensuring interoperability through standard interfaces.

In a *partially disaggregated scenario,* Optical Terminals (OTs) and Optical Line Systems (OLS) are supplied by different vendors. It is a model of particular interest since, typically, OT show a faster pace of innovation (e.g., with coherent technology), shorter lifetimes that the OLS and represent most of the cost of the WDM network. New Optical Data Centre Interconnects (DCI) solutions could be deployed over existing OLS, while keeping carrier class functionalities in terms of restoration, performance, fault management, discovery. In a *Full (component – level) disaggregation* the transport system is also disaggregated, and the optical network elements (e.g., ROADMs) can be provided by different vendors.

It is worth noting that disaggregation applies to both single and multi-domain networks. The case where multiple OLS are interconnected (see Fig.1) is of special interest. It is required to address the establishment of Optical Channel (OCh) or, generically, media channel (MC) services/connections across multiple domains, while ensuring a satisfactory quality of Transmission (QoT).

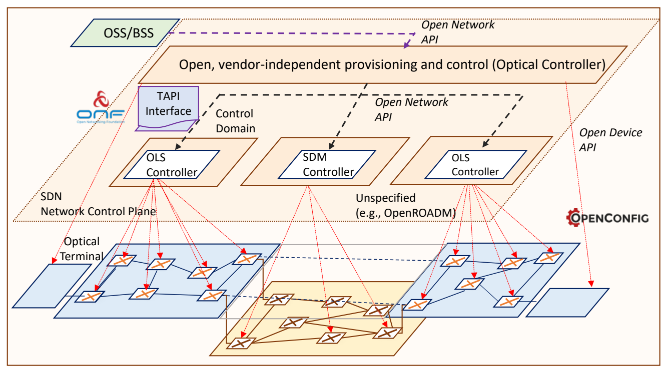

Fig. 1. Partial Optical Disaggregation architecture with multiple domains, including a SDM switching layer.

1. Open Optical-Terminals

Open Optical Terminals (OT) cover transponders, switchponders, muxponders, or similar devices with the ability to switch and multiplex multiple client signals into optical signals. For such terminals, OpenConfig data model(s) are significantly implemented and adopted across industry actors, including Open Source SDN Controller implementations (e.g., Open Disaggregated Transport Network ODTN project [9]). Several interoperability events have shown a high level of compliance to OpenConfig models, showing a uniform understanding of the hardware components hierarchy. The configuration of multiplexing stages and cross-connection logic discovery is widely implemented and the fundamental operation of optical channel configuration (the specification from an SDN controller of the frequency, transmit power, and operational mode) is well supported across many implementations. Ongoing work covers, notably, increased support in terms of performance indicators.

Implementations support flexible assignment of tributaries to line ports, with different multiplexing stages (logical channel cross-connections) accounting for hardware capabilities and constraints as well as flexible selection of operational modes and of optical layers. Further work is needed to clarify current model usage, best practices, guidelines, reference implementation agreements and to improve the models to support Beyond 100G and multiple optical tributary signal (OTSi) as explained later.

2. Open Optical Line Systems

The optical line system (OLS) encompasses the analog devices such as ROADMs, or in line amplifiers (ILAs). The role of the OLS controller is to provide a certain level of abstraction, thus enabling a parent controller to request optical channels (or generally speaking, variable sized media channels) between OLS client ports (which often correspond to ROADM add/drop ports). The OLS controller is responsible for ensuring sufficient performance of the channels.

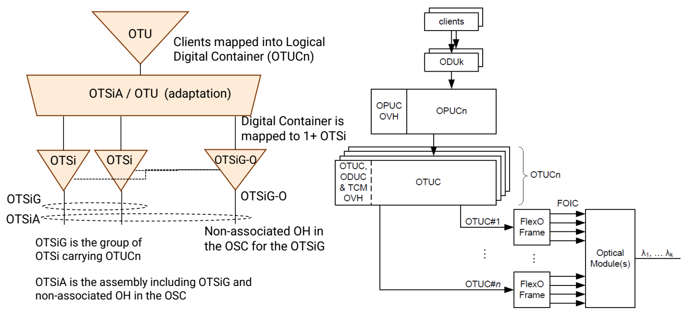

Fig. 2. Mapping a 200G-800G client signal to an OTSiG (ITU-T OTN Functional model [10]).

C. Beyond 100G

The term "beyond 100G" means related things in different contexts: i) the definition and subsequent adoption of ITU-T "Optical Transport Network (OTN) 3.0", including the definition of Optical Tributary Unit OTU-Cn interface, ii) the alignment of the photonic media with client rates e.g., IEEE 200GE, 400GE and iii) the systematic use of "advanced optical technologies" such as coherent transmission (e.g., PM-16QAM), the adoption of silicon photonics, advanced FEC algorithms and pre-compensation, high speed analog/digital conversion (ADC) and complex digital signal processing (DSP) along with increasing capacity requirements that are addressed combining multiple degrees of freedom and switching including new layering and constraints.

1. OTN 3.0 - Question 11 of Study Group 15 (Q11/15)

The term "OTN 3.0" has been used to refer to the extensions of the existing Optical Transport Network (OTN) architecture for rates beyond 100 Gbit/s and to support new signals such as 400GE efficiently [10]. The first phase with G.709-2016, [11] introduced of Optical Transport Unit--Cn (OTUCn), Flexible OTN (FlexO) and supporting flexibility in FEC selection.

Let us detail the mapping and adaptation of a client signal such as 400GE into one or more optical signals with the help of Fig.2.

In a simplified way, no client signals are *directly* mapped into Optical Payload Unit-Cn (OPUCn). Client signals are first mapped into an Optical Payload Unit (OPU) within an Optical Data Unit-k (ODUk or ODUflex). Such ODUk is multiplexed into an OPUCn by asynchronously mapping it into an intermediate structure called an Optical Channel Data Tributary Unit (ODTUCn). The overhead of the ODTUCn is the information required for timing justification between the client ODUk rate and the ODTUCn rate. The OPUCn then becomes the payload of the Optical Data Unit-Cn (ODUCn). The ODUCn is only carried point to point between adjacent ODU switching nodes, it is only a Multiplex Section layer entity and cannot be switched. The ODUCn signal is encapsulated into a OTUCn signal that defines the section layer, so one OTUCn signal contains one ODUCn. The components of the interface signal can go through the same fiber and optical switches (i.e., the same Optical Multiplex Section trails) such that the OTUCn signal can be managed as a single entity.

The OTUCn interface/signal is defined as an n × 100Gbit/s modular structure, to support data rates beyond OTU4, allowing for 200G, 400G, 600G or higher rates. An OTUCn is composed of n x OTUC. The specification of OTUCn in [11] excludes interface specific functions such as FEC, scrambling and bit alignment. The definition of the OTUCn is decoupled from the OTN interface, so the FEC can be selected based on application requirements and delegated to the FlexO signals (detailed later). The OTUCn signal consists of n interleaved 3824 columns by 4 row frames, which do not include a FEC area and is operated at n times a basic rate that is represented by OTUC. In other words, the FEC for the OTUCn signal is interface specific, the OTUCn and ODUCn frame formats are identical, except for the population of the OTUC-specific overhead fields. Different interfaces (such as short reach or long reach) can define different FECs. ITU G.709 defines an RS(255,239,8) code (i.e., a Reed-Solomon using 8-bit symbols) as the base FEC integrated into OTUk frames, with 6 dB of coding gain. For the OTUCn interface, the FEC is independent from the OTUCn frame and optimized for the interface type. G.709.1 defines the Flexible OTN (FlexO) short reach interface based on RS(5440,5140,10) FEC, also with 6dB of coding gain, but with less overhead. The mapping between

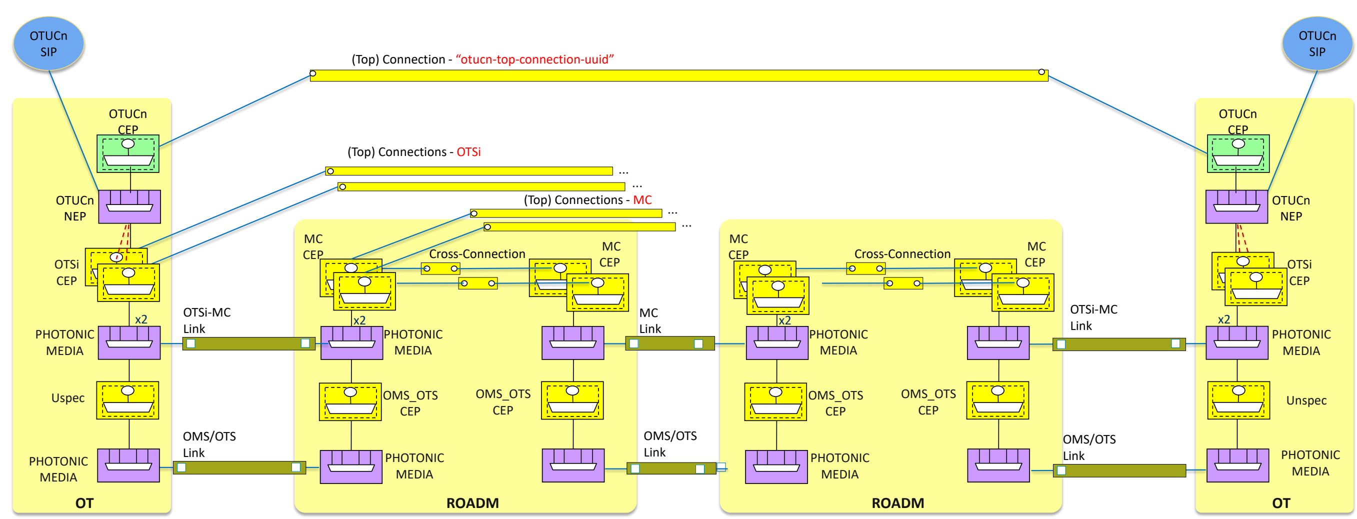

Fig. 3. TAPI representation of a network topology, connectivity services and connections.

the OTUCn and the optical layer is quite flexible. The OTUCn is the logical digital container into which clients are mapped, and that container is mapped into one of more Optical Tributary Signals (OTSi). The OTSi group (OTSiG) is the group of optical tributary signals carrying the OTUCn, and the OTSi Assembly (OTSiA) is the OTSiG plus the non-associated overhead .

ITU Recommendation G.709.1 defines the Flexible OTN (FlexO) short reach interface based on RS(5440,5140,10) FEC (i.e., an RS code using 10-bit symbols) and transmits each OTUC element as a separate 100Gbit/s optical signal using 100GbE/OTU4 optical modules. ITU Recommendation G.709.3 defines the Flexible OTN long-reach interface, by providing an interoperable interface for OTUCn transport signals, FlexO, long-reach interfaces that support bonding (i.e., grouping) of multiple of these interfaces such that an OTUCn (n ≥ 1) can be transferred via one or more optical tributary signals (OTSi) over one or more physical interfaces. In order to mitigate the impairments of accumulated noise it uses forward error correction (FEC) types with a higher coding gain than the FEC type deployed in FlexO short reach interfaces. Next, let us consider how the OTUCn signal is adapted in the optical media layer. The OTUCn signal consists of n OTUC instances. The OTUCn signal is mapped into the payload of n FlexO signals, each FlexO signal containing the bits of one OTUC signal. The transport n FlexO signals using m interfaces of data rate x relies on the FlexO-x-<fec>-m interface group with x ≥ 1, m ≥ 1 and <fec> representing a FEC with a net coding gain higher than the RS(544,514) FEC. The n FlexO signals are mapped into m FlexO-x-<fec> signals with m = ceil(n/x). For example, to map n=4 OTUC signals using 200G PHY transponders (x=2) the group is of m=2. In other words, m represents the number of PHY interfaces at rate x using k physical lanes needed to transport an OTUCn signal. Note that x also represents the number of FlexO signals that are contained in a FlexO-x-<fec> signal (frame/multi-frame aligned interleaved), plus FEC parity and FlexO-x-<fec> overhead.

FOICx.k stands for FlexO Interface of order Cx with k lanes, where x refers to the data rate (1 for 100G, 2 for 200G PHY etc.) and k the number of lanes per PHY interface (e.g., k=4). Each FlexO-x-<fec> signal is split into k FlexO-x-<fec> lane signals (FOICx.k-<fec>). The k lane signals are modulated onto one OTSi, which is transported via one media element. There are total mk FOICx.k-SC lane signals and m OTSi.

For example, FOIC1.4 or FOIC1.2 represent a 100G PHY interface (and can carry 1 FlexO OTUC instance of an OTUCn) with 4 or 2 lanes, respectively. FOIC4.8 represents a 400G PHY using 8 lanes. FlexO-1-SC-m is an interface group using 100G interfaces with m = n and Staircase FEC. As an example of client signal transport, an IEEE 400GE 802.3bs signal can be mapped to an ODUflex structure, in turn mapped into an ODUC4. The ODUC4 / OTUC4 is transported as 4 FlexO OTUC instances over 4 FOIC 1.4 physical interfaces, using 4 lanes, such as 100G QSFP28 transponders.

In simple terms, fully standardized interfaces may be inversely multiplexed over 100G, 200G or 400G optical tributary signals. For example, a 200 Gbit/s transmission can aggregate the two OTUC components into a 200Gbit/s stream for transmission over a single carrier or multiplex the two OTUC components independently on a separate polarization mode of an advanced modulation format.

D. Use Case driven SDN development

Recently, the development of SDN architectures and data models is being driven by a set of operator-defined scenarios and uses cases. For example, the Open Networking Foundation (ONF) TAPI Reference Implementation Agreement (RIA) TR-547 v.1.1 [12] includes a set of use cases related to different aspects of network operation, and details how the different data models can be used in this regard. In the scope of the Telecom Infra Project (TIP) Open Optical & Packet Transport (OOPT) project group, the Mandatory Use case requirements for SDN for Transport (MUST) project has been created. The main objective of MUST is to accelerate and drive the adoption of SDN standards for IP/MPLS, Optical and Microwave transport technologies, through: SDN common architecture; Agreed standard APIs; Commonly defined use cases. In particular, MUST has published the TIP OOPT MUST Optical whitepaper [13], including the target architecture for Disaggregated Open Optical Network as well as functions associated with the use cases and the degree of "Disaggregation" of the monolithic transport optical system.

2. REFERENCE ARCHITECTURE

A. Device and Network Models

Common device models are the OpenConfig [14] terminal device and platform (for Open Optical Terminals) or OpenROADM [15] for ROADM devices. In this work, we will consider the TAPI data model(s) for the controller NBI, both the parent controller as well as the OLS controller, as described next [16]. This does not preclude the usage of alternative models such as the OpenROADM network model [15] or Internet Engineering Task Force (IETF)topology, Traffic Engineering (TE) and Impairment models [17]. As detailed in subsequent sections of the paper, the reasons to focus on TAPI are many-fold, including space limitations and the fact that the TAPI models are considered mature, have been used in interoperability tests driven by OIF and here exist reference implementation agreements. Lately, the Telecom Infra Project MUST (Mandatory Use Cases for SDN Transport) group has published the "MUST Optical SDN Controller NBI Technical Requirements" based on TR-547 as NBI, while covering disaggregated deployment scenarios which remain the scope of the tutorial

B. TAPI SDN North Bound Interface

The fundamental goal of the SDN NBI is to provide a basic set of functions related to topology management, service provisioning and path computation. With model driven design, this means a set of data models and an associated protocol constitute the NBI. In this paper, we consider the ONF TAPI as the set of data models. TAPI models have been used in multiple interop events to demonstrate their applicability to the orchestration of multiple domains and provides a uniform and coherent set of YANG models covering the aforementioned functions.

Recent versions of TAPI (2 and later) have largely increased support for the photonic media layer, allowing a new degree of flexibility in the provisioning of digital (ODU/OTU) and optical (OTSi/media channels) connectivity services. TAPI already includes mechanisms to constrain the provisioning, notably in terms of route inclusion and exclusions, which has been a key functionality to apply path restrictions as provided by an external planning tool. The set of TAPI models are complex, covering many aspects of the control and management of transport networks. In this regard, the availability of companion documents such as RIA and similar documents help consolidate model usage. Given the ubiquity of the HTTP protocol, ease of use from the point of view of clients and implementation of HTTP servers, RESTCONF has been extensively used as NBI.

TAPI is based on a context relationship between a server and client. A Context is an abstraction that allows for logical isolation and grouping of network resource abstractions for specific purposes/applications and/or information exchange with its users/clients over an interface. It is understood that the APIs are executed within a shared Context between the API provider and its client application. A shared Context models everything that exists in an API provider to support a given API client. The context includes the following (simplified) information: i) The set of Service-Interface-

Points (SIPs) exposed to the TAPI client applications representing the available customer-facing access points for requesting network connectivity services. The PHOTONIC_MEDIA Layer: Models the OCH, OTSi, OTSiA, OTSiG, OMS, OTS and Media channels as per [18]; ii) a topology-context which includes one or more top-level Topology objects which are dynamic representations of the network; iii) a connectivity-context which includes the list of Connectivity-Service and Connection objects created within the TAPI Context and iv) a notification-context which includes the list of notification subscriptions and, optionally, the list of notifications emitted through each notification subscription stream.

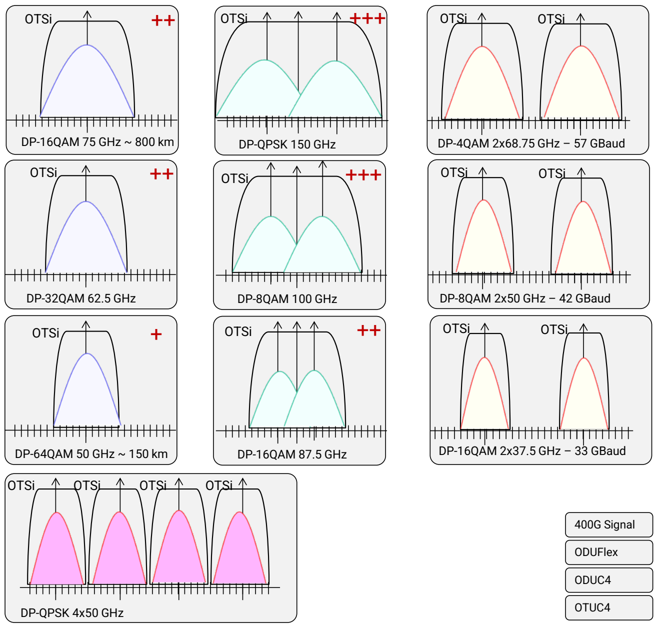

Fig. 4. Mapping a 400G client signal to an OTSiG (examples)

The TAPI Topology is an abstract representation of the topological-aspects of a particular set of Network Resources. It is described in terms of the underlying topological network of Nodes and Links that enable the forwarding capabilities of that set of Network Resources. The TAPI Node is an abstract representation of the forwarding-capabilities of a particular set of Network Resources. It is described in terms of the aggregation of set of ports (Node-Edge-Point, or NEP) belonging to those Network Resources and the potential to enable forwarding of information between those edge ports. The TAPI Link is an abstract representation of the effective adjacency between two or more associated Nodes in a Topology. It is terminated by Node-Edge-Points of the associated Nodes.

The Node-Edge-Point (NEP) represents the inward network-facing aspects of the edge-port functions that access the forwarding capabilities provided by the Node. Hence it provides an encapsulation of addressing, mapping, termination, adaptation, and OAM functions of one or more transport layers. The Node-Edge-Points have a specific role and directionality with respect to a specific Link. The Connection-End-Point represents the ingress/egress port aspects that access the forwarding function provided by the Connection. The Connection-End-Points have a client-server relationship with the Node-Edge-Points. The Connection-End-Points have a specific role and directionality with respect to a specific Connection.

There is significant support for the provisioning of data services using single channel transport (OCh, assuming fixed grid spacing). That said, with the major adoption of flex-grid spacing and the industry moving to 400G and 800G, the controller must be able to configure optical devices exploiting the provided flexibility. This means that the optical SDN controller must support the establishment of OTSi/OTSiG and the OLS controller must support the provisioning of MC/MCG to accommodate such flexibility. The dynamic configuration of services must consider the increased programmability of optical devices and, notably, optical terminals. This includes the fact that, as shown in Fig.4 a 400G service can be supported over a combination of N (1…4) OTSi (OTSiG) with single carrier or multi-carrier modulations, modulation formats and FECs, a clear tradeoff between spectral efficiency, QoT performance and reach (e.g., a single OTSi single carrier modulation DP-64QAM at 50GHz for a reach of ~150 Km, or four OTSi with DP-QPSK at 50 GHz each). The spectral efficiency is based on reach, number of carriers and whether they are adjacent.

Let us illustrate the basic concepts of the TAPI model and the provisioning of a B100G service with the help[1] of Fig. 3. Using a RESTCONF/TAPI SDN NBI, a client may request (RESTCONF GET operation) the network topology from the TAPI (topology) context. The topology will contain 4 nodes (2 ROADMs and 2 OT) and 6 links (3 representing OMS/OTS links and 3 representing MC links). Each node has a corresponding set of NEPs. With the TAPI context, two OTUCn SIPs enable the provisioning of OTUCn services. The client may request a connectivity service provisioning (RESTCONF POST operation) specifying 2 connectivity service endpoints (CSEPs) which refer to the SIPs and provide additional parameters, such as the FEC to use, the number of ODUC instances and, optionally, a list of OTSi CSEPs that provide the frequency slot requested for each individual OTSi, along with its application identifier, modulation format and transmit power.

Upon successful (e.g., 200G service with N=2) the server will instantiate 5 "top-level" connection objects (one for the OTUCn service, two for each OTSi and two for the MC), each of them referring to the instantiated CEP objects (which, in turn, reflect current configuration). For further details, please see [12].

Extension to model an Open Optical-Terminal

Main attributes

```
+--ro operational-mode-capabilities
      +--ro description?                                string
      +--ro modulation-format?                          modulation-format
      +--ro modulation-format-proprietary
      |  +--ro description?    string
      +--ro bit-rate?                                   bit-rate
      +--ro baud-rate?                                  decimal64
      +--ro min-osnr?                                   decimal64
      +--ro grid-type?                                  grid-type
      +--ro adjustment-granularity?                     adjustment-granularity
      +--ro otsi-media-channel?                         decimal64
      +--ro effective-media-channel?                    decimal64
      +--ro central-frequency-min?                      uint64
      +--ro central-frequency-max?                      uint64
      +--ro fec
      |  +--ro fec-coding?                   fec-coding
      |  +--ro fec-coding-proprietary
      |  |  +--ro description?    string
      |  +--ro gain?                         decimal64
      +--ro min-output-power?                           decimal64
      +--ro max-output-power?                           decimal64
      +--ro input-power-sensitivity?                    decimal64
      +--ro min-q-value?                                decimal64
      +--ro chromatic-dispersion-tolerance?             decimal64
      +--ro differential-group-delay-tolerance?         decimal64
      +--ro filter
      |  +--ro shape?       string
      |  +--ro order?       uint32
      |  +--ro roll-off?    decimal64
      +--ro sop?                                        String
```

Fig. 5. Example Yang-tree model to characterize an operational mode (simplified). Similar constructs exist at IETF and OpenROADM

1 For simplicity we are assuming a single SDN controller and a flat network

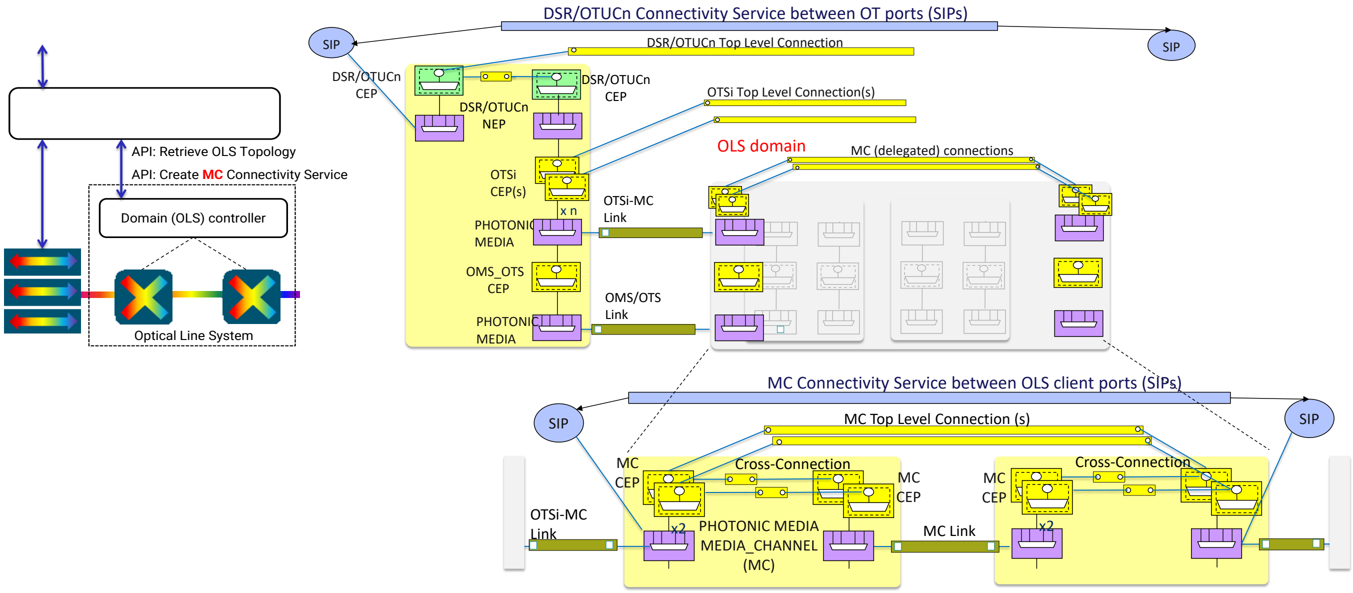

Fig. 6. View from the Optical and OLS controllers and TAPI representation.

C. Operational Modes

A direct consequence is that such flexibility is provided by the OT, yet it must be known to the optical controller, and it is a quasi-static information that remains invariant for long timescales. OpenConfig [14] addressed this by using operational modes, the details of which are not explicit. The list of supported modes can be dynamically discovered by an SDN controller.

Ongoing work is trying to detail relevant properties of the different modes so they can be used during Routing and Spectrum Assignment (RSA) processes and resource assignments (see Fig. 5). Since this information is not expected to change, it is still an open question how to render this detailed model information available to SDN controllers and path computation entities without adding additional complexity to the underlying devices.

D. TAPI-enabled OLS SDN Controller

Section 2.B has provided the fundamental concepts and provisioning workflow in the case of a single SDN controller and a flat network (which could correspond to a fully disaggregated scenario, down to the ROADM level). In the scope of partial disaggregation, several controller arrangements are possible. For example, it is possible to have a dedicated SDN controller only for the Open Terminals and another SDN controller for the OLS, thus requiring an additional controller layer for network orchestration. The scope of this paper is to consider the Optical controller for both the OT and OLS in such a way that the Optical Controller acts as a client of (and delegates the provisioning of MC to) the OLS controller. As a consequence, the provisioning of a OTUCn service involves the coordination of two controllers: the OLS controller (see, for example [19]) and the optical SDN controller. In this setting, it is assumed that the optical controller orchestrates the whole provisioning, ensuring consistent configurations and delegating the provisioning of media channels as detailed next.

The OLS SDN controller is thus responsible for providing one or more media channel (MC) services (*media channel group* or MCG) between OLS client ports (see Fig. 6). The level of detail regarding the OLS topology is typically configured by policy. Reference implementations [12] suggest one TAPI node per ROADM and ILA. As with the optical SDN controller, the MCG may span one or more multiple add/drop ports. The OLS controller must map the corresponding MC configurations to the corresponding SBI interface (e.g., instantiating the OpenROADM connections between the involved add/drop and degree ports) when applicable. Since the MCG provisioning is driven by the Optical controller, the OLS controller should support a *constrained provisioning,* that is, the Optical SDN controller should be able to provide constraints to the frequency slots of the media channels (based on e.g., tunability constraints of the OT), Quality of Transmission (QoT) constraints or routing constraints that may affect the selection of links and paths. Fig. 6 (bottom) shows the TAPI representation of the OLS context, showing the SIPs involved in an MCG request and the instantiation of the supporting MC connections.

Note that, in principle, the OLS controller remains unaware of the client(s) (OTSi) transported over the respective media channel(s). That said, it should support the ability to monitor a given OTSi by monitoring the optical spectrum that transports it (OTSiMC).

E. TAPI-enabled Optical SDN Controller

The optical SDN controller may support a combination of connectivity services, either: *i)* abstracting the optical domain and offering Digital Signal Rate (DSR) or Layer 2 (e.g., Ethernet) services that correspond to the OT client ports or *ii)* enabling the configuration of the optical parameters of the OT line ports, directly requesting the OTU applicable parameters and corresponding OTSi(G) ones[2]. The provisioning of an OTU/OTSiG service may involve one or multiple physical line ports (e.g., each one supporting a single OTSi).

Assuming the former case, for illustration purposes, the client requests an OTU service between source and destination line ports and provides the number of OTSi component(s), and for each component, the application identifier, modulation format, transmit power and allocated central frequency and optical spectrum bandwidth.

[2] Note that at the time being, direct provisioning of OTSiG is not in scope of TAPI. It is modelled as server constraint(s) upon provisioning of an OTU service.

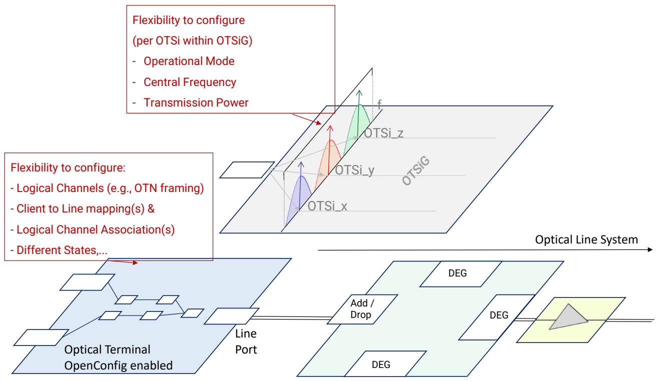

Fig. 7. Open Terminal programmability, from the optical SDN Controller

Either way, the Optical SDN controller must: i) request the corresponding MC services to the OLS controller NBI, ii) map the corresponding OTI/OTSiG configurations to the corresponding SBI interface, thus potentially affecting one or more OpenConfig port components and instantiating the logical associations between OT client ports and line ports (Fig. 7).

Fig. 6 (up) shown a graphical representation of the Optical SDN controller TAPI context showing the DSR/OTUCn connectivity service and how it relies on an MCG connectivity service provided by the OLS controller. The level of aggregation of the OLS domain from the point of view of the Optical SDN controller is defined by controller's policy. It may export, for example, the full topology of the OLS or aggregate it as a single node with the corresponding "abstract" MCG cross-connections (that correspond to OLS end-to-end media channels).

In summary, the flexibility provided by the SDN controller during OTUCn service provisioning must match the flexibility exposed by the terminal device. At the time of writing, OpenConfig support for an OTSiG within a single or multiple line port components is still a work in progress.

3. EVOLVING REQUIREMENTS AND USE CASES

A. Effective Power management in Disaggregated Scenarios

Power management is a key aspect of service provisioning and increasingly important in disaggregated scenarios since not all devices under the direct control of a single controller. A solution being currently defined involves, for example, qualifying OLS service interface points with the *supportable* maximum and minimum *output* power that such ports can deliver to terminals as well as *tolerable* maximum and minimum *input* power at such service points. Combined with the information that is available for a given operational mode at an OT (such as the proposed min and max output power), it is possible to get an estimation of the power budget and compute paths that are, a priori, potentially feasible from an optical power perspective.

Similarly, once a service has been provisioned, the information objects reflecting active configuration (e.g., TAPI CEP objects) should reflect *intended* maximum and minimum *output* power (to be delivered to the local OT) as well as the *expected* maximum and minimum *input* OT launch power, specifying constraints related to power tolerance at the input.

B. Multiband optical Networks

Optical transmission exploiting multiple optical bands is the sole solution in the context of wavelength switched optical networks that increases network capacity without compromising network node connectivity and without exhausting the operator's deployed fiber reserve, although potentially needing upgrades on the transceivers, optical amplifiers, and ROADMs.

Multiband (MB) or *wide band* refers to the usage of optical spectrum "beyond" the currently deployed C band -- and its quasi-uniform behavior for all channels within the band e.g., in terms of reach – (see Fig. 8) extending the spectrum used by wavelength division multiplexing to the entire set of available low-loss bands (L, C, S, E and O) in standard single-mode fibers (SSMFs), accounting for band effects and constraints, including hardware limitations.

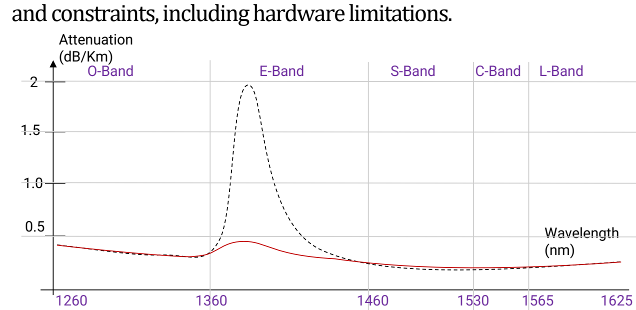

Fig. 8. Attenuation per optical band (E band attenuation has been mitigated with the usage of G.652.D fibers)

The extension of the SDN control plane to support multiple bands is currently being discussed. While it is acknowledged that specific scenarios such as migrating from C to C+L may not require significant extensions to an SDN controller or management system, from a modelling perspective, a key question is how an arbitrary number of bands (and their corresponding frequency ranges) are efficiently represented in the SDN Controller, minimizing overhead, and avoiding excessive numbered of managed entities and, at the same time, allowing different hardware configurations and per-band physical impairment characterization. This includes clarifying the use of entities such as Optical Multiplex Sections and/or the existence of monitoring points on a per band basis or agreeing on whether a single OTS entity is enough to reflect fiber connectivity and/or whether each optical band should have its own OMS entity. Intermediate solutions involve characterizing existing OMS entities with a list of potentially supportable *frequency ranges* for each band, but this may fail to account for band specific limitations. Path computation algorithms that are implemented within the respective controllers or external path computation elements shall be extended to account for multiband aspects, including limitations in reach, amplification, or physical impairments, which are elaborated on in Section 3.D.

C. SDM Networks

Space division multiplexing (SDM) transmission jointly exploits the spectral and the spatial dimension of the fiber (i.e., frequencies, cores, and modes), relying on SDM super-channels and exploiting multicore fibers (MCF), multimode fibers (MMF), combining cores and modes in few-mode multicore fibers (FM-MCFs), or by deploying bundle of SSMFs. Initial efforts focused on link capacity improvement with little consideration of the implementation of switching systems and showed strong coupling between different spatial modes. Regarding SDM switching, strong coupling renders mode switching prohibitive, but core (and fiber) switching is feasible. Weakly-coupled MCFs have shown C+L transmission of 19-core fibers for long haul communications [20]. Recently, SDM *switching* provides spatial paths beyond point-to-point transmission [27, 28]. Fully flexible ROADMs would require WSS with a high port count, and core switching nodes are already being developed.

From the point of view of SDN, current data models do not cover SDM transmission or switching. Experimental data models and proof-of-concept have extended TAPI photonic media layer including a new *photonic media layer qualifier* related to the SDM domain, allowing the dynamic provisioning of SDM connectivity services with a combination of core and core/mode switching at the intermediate nodes. Service interface points (service abstracted ports) as well as Node Edge Points (such as ports) are extended to convey the availability of cores and/or modes [21].

Like in MB networks, required extensions not only involve modeling switching operations and core/mode cross-connects, but also affect path computation and RSA processes, accounting for optical channel crosstalk, core coupling (low) and mode coupling. SDM may require MIMO DSP be applied to undo channel crosstalk and equalize all modes (Full MIMO in coupled MMF) or mode groups (Partial MIMO in weakly-coupled MMF), where all modes or group of modes must be jointly routed from the source to the destination nodes along the same path to perform joint MIMO DSP equalization.

In all, MB and SDM networks effectively introduce additional constraints and/or switching layer(s), thus rendering RSA and provisioning processes more complex. Further work is required to account for MB and SDM from an standards perspective.

D. Physical Impairment Aware Resource Assignment

At 100G, 200G, 400G and beyond, accounting for physical impairments is critical. However, the lack of common, standard, and open data models (physical layer effects and models are hard to reach consensus on) has limited innovation and has prevented disaggregated or modular architectures at the control plane level. Current systems need to interoperate with heterogeneous monitoring information sources and proprietary and costly simulation tools are difficult to interoperate with or to integrate in provisioning operator workflows.

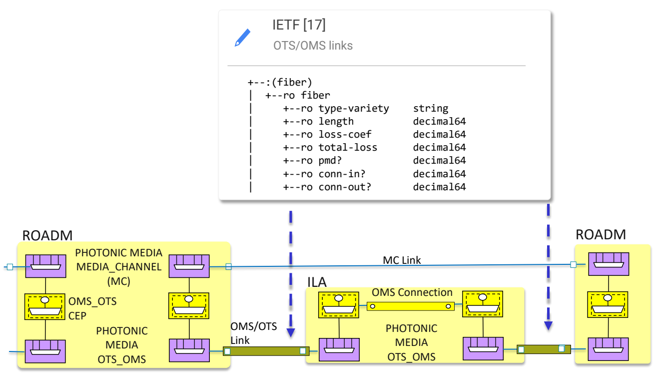

Fig. 9. Example PLI attributes being defined for OMS/OTS links (Fibers)

However, the complexity of RSA and, ultimately, the benefits of the usage of Machine Learning (ML) assisted solutions are driving the use of externalized path computation entities and/or ML systems, including Net2Plan [22] or GNPy [23]. Both software tools have been used as a path computation and/or QoT validation tools, either in dynamically or statically defined scenarios. Although Net2Plan has been experimentally extended to use TAPI topological information [24], GNPy still relies on an (evolving) specific data model for its inputs, loosely based on IETF drafts. Consequently, a question recently arose related on how to extract and provide GNPy inputs from a running SDN system [25]. The Telecom Infra Project (TIP) Open Optical and Packet Transport Project Group has announced the successful demonstration of open optical networks control and management by the Converged Architectures for Network Disaggregation & Integration (CANDI) [26]. After successful initial proof-of-concepts, different initiatives are currently a work in progress in this regard. Note that this applies from the point of view of a network-wide model, and controller NBI, and is complementary to the existence of amplifier device models such as the ones in OpenConfig or OpenROADM.

1. IETF CCAMP Working group

The IETF Common Control and Measurement Plane (CCAMP) WG develops a large number of data models, following an approach in which generic constructs are defined in a data model and technology specific extensions are added as augmentations. In this regard, an IETF CCAMP draft optical-impairment-topology-yang contains a collection of YANG definitions for impairment-aware optical networks and, in particular, augments the *ietf-te-topology* elements to: i) define transponder nodes with their list of transceivers and the supported modes; ii) extend traffic engineering (TE) link parameters to include OMS attributes such as generalized Signal to Noise Ratio (SNR), equalization mode or per carrier power or spectral density and to describe a list of composing OMS-elements, that correspond to either amplifiers (and their operational parameters such as actual gain, variable optical attenuator (VOA) parameters or tilt target) or fibers, with attributes such as fiber type, length, loss coefficient, total loss, PMD or insertion losses.

2. OpenROADM Network Model

OpenROADM network model (v.10, 2021-09-24) relies on IETF network and network-topology models and augments network-topology link objects for ROADM-to-ROADM links, so for unamplified links (spans) attributes like span loss in dB, fiber types or total PMD. For amplified links, augmentations include a list of amplified-links, which each section is either an in-line amplifier (ILA) or a span (as in the not amplified case). Each ILA in the OMS section is characterized in terms of amplifier type, type-variety, gain range, span loss aging margin, gain (overall amplifier signal gain, excluding ASE, including VOA attenuation, and retrieved from operational PM value), tilt and VOA attenuation (including the reference to their planned value)

3. ONF TAPI Working Group

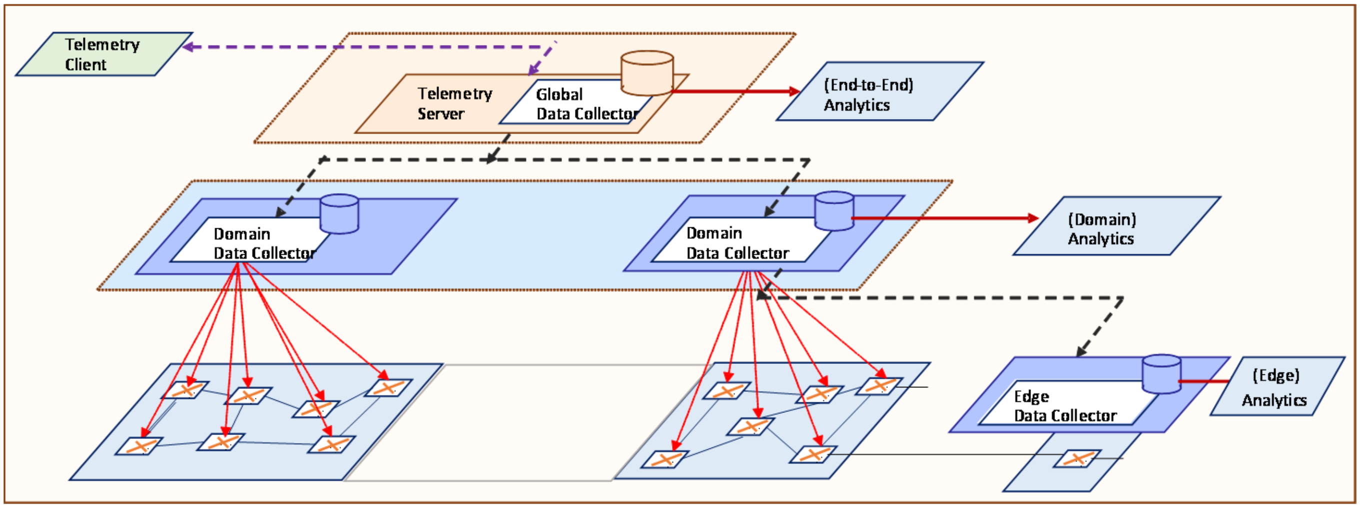

Fig. 10. Addressing telemetry scalability issues with hierarchical telemetry and optical streaming architectures

The ONF TAPI WG is working on extensions to the topology and connectivity data models addressing PLI extensions and, more specifically, in support of using GNPy as externalized path computation tool, performing a gap-analysis with current TAPI 2.3 models. First, extensions should cover capability, resource, and topology discovery: a TAPI client (such as the OSS/BSS) shall be able to retrieve the required information from a TAPI context and entities and to project (map) such information as GNPy inputs. This may involve extending the existing topology, connectivity, and physical-equipment inventory. Second, it should be possible to perform connectivity service provisioning with GNPy inputs, covering the photonic media layer and the OMS and OTS layer qualifies. Finally, it should be possible to perform a dynamic connectivity service modification or adjustment, based on GNPy output changes and continuous operation. Some targeted use cases are: i) to perform QoT estimation for a (potential) lightpath or OTSi service (validate the OSNR/BER knowing the physical path, previously computed by the orchestrator) or ii) to compute a path for a potential OTSi service and target QoT, including a full PLI-aware RSA process , which may require the ability to support dynamic configuration of amplifiers.

Ongoing work involves modeling amplifiers, capturing different amplifier types, and to be able to reflect their configuration into entities that capture operational state (e.g., TAPI CEPs). GNPy already provides a well-defined set of amplifier types (e.g., variable gain, dual stage) along with relevant data model according to its type. For example, a variable gain amplifier is characterized by its operational frequency range, minimum gain, flat gain, maximum output power or Noise Figure at max and min gains, as well as its current gain and tilt. Static (invariant) data may be exported as part of amplifier profiles, yet dynamic data should eb reflected as part of the actual device configuration.

Dynamic amplifier configuration is being discussed as part of the OMS layer provisioning and, at the time of writing, the dynamic creation of OMS connectivity services is left for further study.

Several SDOs are thus working on extending their data models in support of physical layer parameters. The IETF, OpenROADM and ONF TAPI working groups are clearly characterizing entities such as transceivers operational modes, fiber types and key parameters or amplifier types and their operational values. While the data models are not completely equivalent (due, in part, to the need to align to their pre-existing frameworks, constructs and information models), model mapping remains relatively straightforward.

4. OPTICAL MONITORING & STREAMING TELEMETRY

A. Drivers and Motivations

Monitoring the operational state of the network is crucial for network health and efficient traffic management. This implies a holistic network/service monitoring and a robust support for alarms, general notifications and Performance Monitoring across multiple uses cases, domains, and technologies. Current issues include the need to deal with heterogeneity in terms of protocols, data models, and data sources (MIB modules, YANG models, IPFIX flow information, system logs), requiring a huge integration effort and data model mapping. It is often argued that the evolution towards autonomous networks relying on massive telemetry (understood as the data collection from multiple sources towards a centralized repository) data needs to rely on the usage of "model driven telemetry" [29] and common protocols and frameworks.

Additionally, optical monitoring [30] in the scope of disaggregated networks is challenging: i) although the OLS may deal with express channels to scale, it may be needed to monitor individual OTSi within a given media channel; ii) the OLS controller may not export telemetry data and it may not be possible to obtain such data from the analog devices; iii) the information must be correlated with terminals specially in terms of PLI and power management. Work in optical telemetry [31] has clearly shown the need for distributed collectors and hierarchical systems and the need to move from a "polling" based approach to a model where different sources are configured to generate events asynchronously, although the polling-based mode may still be the only available approach, and it becomes a trade-off between sampling frequency, processing requirements and resource usage.

Macroscopically, current research on optical telemetry needs to address multiple aspects: scalable telemetry architectures, featured data models and efficient transport protocols and applications. This needs to be detailed from a two-fold perspective: from the point of view of the actual devices (*device-based telemetry*), and from the point of view of the controller (*controller-based telemetry*).

B. Controller based Telemetry

Telemetry and asynchronous notifications in general, is a key part of a SDN controller NBI, and complements current functions based on a request/response model. Any SDN notification subscription service offered by an SDN controller NBI must allow several client applications to subscribe to asynchronous notifications about the changes occurred in the network, specifying for example, object types and identifiers involved in the notification (i.e., Connectivity-Service, Connection…), the networking layer, or the notification type (Creation, Change, Deletion, Alarm, Threshold Crossing). For example, the TAPI RIA [12] defines a set of extensible models in support of controller-based notification.

1. Fault Management and monitoring

A specific subset of optical monitoring concerns the support of Fault and Performance management. Fault Management comprise a set of functions that detect, isolate, and correct unusual (faulty) operational behaviors of a telecommunication network and its environment. In the scope of a disaggregated network scenario, further standardization is needed to favor the adoption of a common fault management (alarm notification) framework. For example, the TAPI RIA [12] uses the "*TAPI Standard Alarm and TCA List*" when identifying notifications related to alarms and threshold crossing alerts. The document specifies terminology and identifiers related to alarms and threshold crossing alerts (TCA,) with a description of established semantics and their relationships with specific technologies derived from applicable standards as well as additional alarms not currently known to be standardized. The objective is that implementations should align the representation of network behavior to entries in the list. For example, TAPI addresses Alarm Event Notifications function (ITU-T G.7710 Section 7.2.11) and based on ITU-T recommendation X.733. Current application covers the ODU/OTU as well as the photonic media layers.

2. RESTCONF based notifications

Typically, the SDN Controller NBI data model incudes which YANG notifications can be generated and their information objects. RESTCONF servers that support notifications declare such support in their capability listing, where such notifications preserve aspects of NETCONF event notifications [32] either utilizing the Server-Sent Events [33] and with XML or JSON encodings. WebSockets (WS) as specified in [34] have also been used for the same purposes to support RESTCONF notifications. SDN controllers expose supported notification streams by populating the "restconf-state/streams" container in the "ietf-restconf-monitoring" module [7]. Clients can subscribe to notifications subscription mechanism as defined in Section 6.3 of [7]. Additionally, the server may support the "filter" query parameter, to indicate the target subset of the possible events being generated.

C. Streaming Telemetry and gNMI

Regardless of device-based or controller-based, current methods based on NETCONF or RESTCONF are showing important limitations [3], in terms of, for example, efficiency or latency, especially when the volume of monitored data increases. In view of this, there is an evolution from *optical monitoring* towards *streaming telemetry.* In [29] authors report on the design, implementation and experimental demonstration of a telemetry service exploiting the gRPC protocol to enable on-demand streaming of real-time monitoring parameters, dynamically retrieved from a configurable set of network devices, through standard YANG-defined models.

A (data) stream can be defined as a "typically long-lived and unidirectional data flow, generated by one or more source(s) based on a set of subscription specific parameters". Data streams are well-known in software engineering, streamline functional programming and pipelining. One of the benefits of adopting unified data modeling is allowing subscriptions to be defined directly over the underlying data models. In other words, telemetry behavior is configured at the device, including model-driven telemetry parametrization.

Streaming Telemetry protocols and architectures such as gRPC/gNMI are increasingly being used to export telemetry data from devices [3]. The main concepts behind the use of gRPC/gNMI are the *destination-groups*, such as destination addresses, port, transport, and encoding format, the *sensor-groups*, which contain the sensor paths representing the path in the hierarchy of a telemetry YANG data model and allow specifying the subset of the data should be streamed from the device and the actual *subscriptions*, which binds the destination-group with the sensor-group and sets the streaming method(s). Additionally, *cadence-driven* telemetry continually streams data (operational statistics and state transitions) at a configured cadence, supporting higher frequencies to identify data patterns and *event-driven* telemetry optimizes data that is collected at the receiver and streams data only when a state transition occurs. In short, *conditional telemetry,* based on configured settings and conditions enables flexible filtering and configuration of telemetry data *at the source.* As another possible approach, the use of publisher/subscriber architectures and/or Kafka platforms [35] enable multiple producers and consumers thus scaling streaming platforms.

1.Hierarchical Architectures for Scalability

With increasing network sizes, telemetry sources and sampling frequencies of data (i.e., volume), having a single collector entity does not scale. Although the usage of dedicated streaming platforms such as Kafka [35] mitigate this scaling issue, other approaches rely on the deployment of hierarchical collectors (Fig.10). Such architectures enable the deployment of *local* control loops as well opportunities in terms of local data processing and filtering.

2. Cluster deployments for Robustness

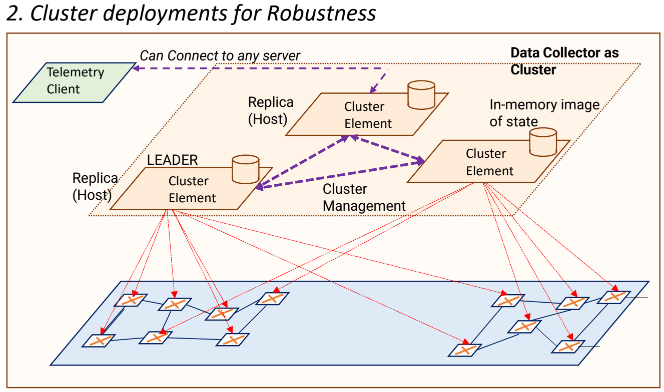

Fig. 11. Addressing Telemetry Robustness by deploying Collectors as clusters.

At any given level at the hierarchical telemetry architecture, a single entity is potentially a performance bottleneck or a single point of failure, potentially isolating a (significant) part of the network. In view of this, a current approach is to deploy a *cluster* logically acting as a single collector. As such, multiple servers are part of a cluster, and a telemetry client (or a higher-level entity) may connect to any server in the cluster (see Fig. CLS). A cluster management protocol enables basic cluster functions (coordination and synchronization with high throughout and low-latency; leader selection, etc.) and ensures key functions like *sequential consistency*, where updates will be applied in the order that they were sent; *atomicity.* updates either succeed or fail, there are no partial results; *single image*, a client will see the same view of the service regardless of the server or reliability and *timeliness,* clients view of the system is guaranteed to be up-to-date within a certain time bound.

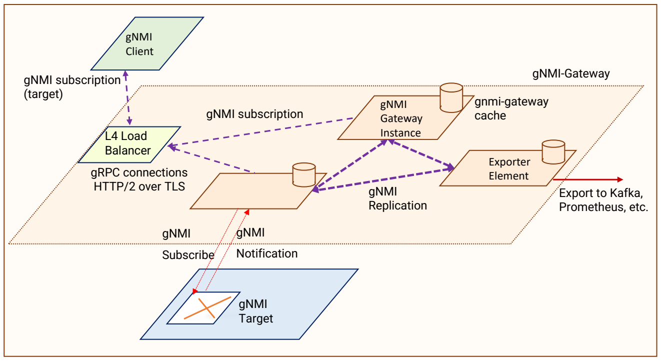

Fig. 12 The usage of gNMI-Gateway to scale device telemetry

A concrete example of implementation of such architecture is the gNMI-Gateway (GGW) project [36]. GGW is a distributed and highly available service for connecting to multiple gNMI targets, that covers common use-cases such as to provide multiple streams to gNMI clients while maintaining a single connection to gNMI targets, provide highly available streams to gNMI clients, distribute gNMI target connections among multiple servers, export gNMI streams to other data formats and protocols (see Fig. 12). A gNMI client can connect, e.g., to a L4 load balancer, that distributes clients between gNMI gateway instances. The gNMI instance synchronize notifications between themselves (only one instance has a gNMI subscription with the gNMI target).

C. Controller-based Streaming telemetry

The usage of RESTCONF and/or RESTCONF notifications as part of a controller NBI has important limitations, especially in terms of state synchronization between client(s) and the SDN controller. Recently, [37] proposes a streaming based reporting and notification mechanism of ongoing change of state of the controlled system as part of a Management-Control solution. The stream provides engineered flow such that peak load is averaged using some mechanism such as backpressure and/or selective pruning of detail. The streaming approach focuses on conveying TAPI entities, i.e., yang sub-trees, provide an opportunity for event time reporting that is structured to allow for reporting of time uncertainty and allowing a client to achieve and maintain eventual consistency with the state of the controlled system simply by connecting to the stream(s) and achieve full system realignment and efficient recovery from temporary streaming channel communication failures. The primary application is one where a provider (SDN controller) is offering an ongoing flow of state updates to a client, where the client maintains an ongoing live view of the state of the instances of elements in the controlled system.

Such approaches are complementary to well-established RESTCONF NBI and may rely on the usage of publisher/subscriber architectures, including the usage of a Kafka Streaming Platform to publish, store and subscribe to events, relying on keys, values, and timestamps, while allowing the recording of the history of what has happened in the world as an ordered sequence or chain of events. For example, [38] shows the usage of a Kafka broker allowing an OLS controller to export network events (see Fig. 13).

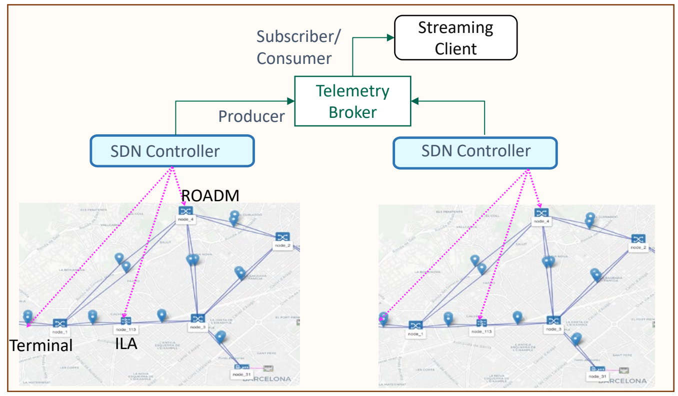

Fig. 13. Controller-based streaming telemetry [38]

5. INFRASTRUCTURE SLICING AND VIRTUALIZATION

Network slicing enables the deployment of logical networks (*slices*) over the same physical infrastructure and, macroscopically, generalizes the notion of network virtualization [2]. Each slice is tailored to the requirements of a particular vertical, service, or application. Each network slice can be controlled by a different operator, such a mobile virtual network operator (MVNO).

The role of optical networks is increasing in this scope. A significant number of works have addressed research related to how to setup optical connections in support of the logical links that interconnected such functions (for example, see [39]). Recent work covers the concept of "spectrum services" and "transport network slicing".

A. "Spectrum Services"

A relatively straightforward application of a partially disaggregated model involves having a common OLS provider that is used by multiple operators that share the infrastructure. As seen in Fig. 14, each operators' optical controller is responsible for the control of the optical transceivers as well as requesting media channels from the OLS controller. It is thus the responsibility of the OLS controller to perform resource allocation and partitioning to each operator. Current research is addressing mechanisms to dynamically request associations of resources to given clients (i.e., tenants) and sharing models, generically known as slicing, described next.

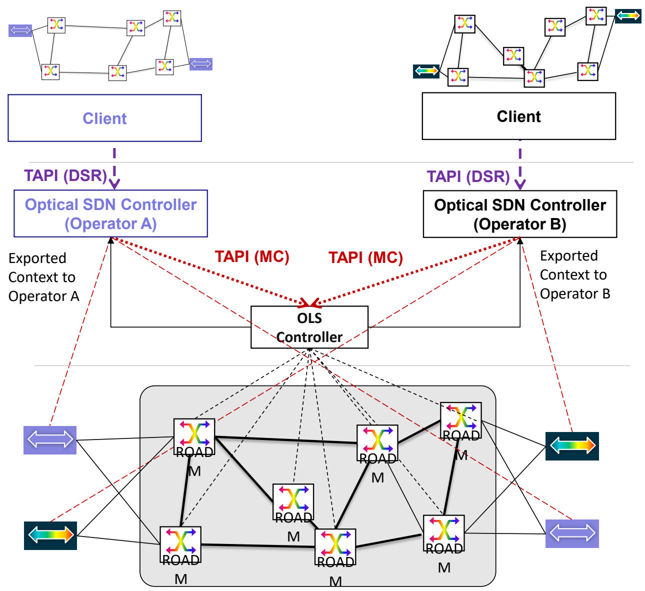

Fig. 14. "Spectrum services" as an optical network sharing application.

B. Towards Optical Network Slicing

Regarding the relationship with 3GPP network slicing, the ITU-T Q11/15, addressed the initial requirements [40] for 5G mobile transport networks and the architecture of Metro Transport Network (MTN). MTN requires strongly isolated network slicing (hard slicing) based on either OTN or Ethernet layers, as well as transport network requirements for support of 5G mobile fronthaul, mid-haul, and backhaul networks in both standalone and non-standalone configurations and to support the requirements for network slicing in 5G mobile transport networks.

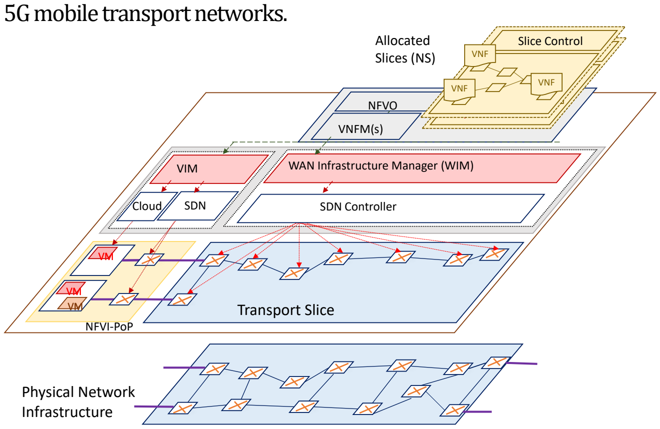

Fig. 15. Virtual Optical Networks (Transport Slices) in support of Network Slicing

Macroscopically, 3GPP network slices will be supported using the logical subsets of transport resources offered by SDN *virtual networks* concept related to the partitioning and sharing of subsets of logical resources. to enable differentiated network slicing. Thus an active open work item is the coordinated management and control of the 5G core network, transport network, and radio access network (RAN).

The IETF is currently working [41] on the concept of IETF network slice, focusing on IETF technologies that provide connectivity and assurances of meeting a specific set of objectives with respect to network resources use, defined between several endpoints (known as customer edge (CE) devices over a shared underlay network. The realization can be achieved in a form of either physical or logical connectivity using VPNs, virtual networks (VNs), or a variety of tunneling technologies such as Segment Routing, MPLS, etc.

In this context, the optical infrastructure (and, in particular) the Optical Line System becomes the underlay network that is shared and the different architectural solutions (e.g., ACTN [42]) can be used for the dynamic provisioning and lifetime management of IETF Network Slices. As shown in Fig. 15, network slices (as a set of interconnected functions in support of a service or application) and the concept of IETF Network Slice (formerly known as Transport Slice) are complementary.

6. CONCLUSIONS

In this tutorial, we have provided an overview of selected ongoing developments in the field of SDN control of optical networks, with emphasis in the aggregation, metro, and core segments with specific care when considering partial disaggregated systems, a disaggregation model that remains quite relevant industry-wise.

Fundamental aspects such as device configuration and network control are reasonably well covered, yet other aspects such as efficient telemetry are being addressed relatively recently.

Model driven development -- with data modeling languages and adapted protocols -- is well adopted in the industry, so the current focus is the standardization of information and data models addressing gaps, missing features, or covering recent developments from the data plane. The level of maturity of the models is diverse: some data models such as OpenConfig or OpenROADM device models or TAPI topology and connectivity models are stable and well-known, other models such as OAM, path computation or physical impairments still require significant work.

It is worth modeling that, in the scope of SDOs and related fora, refinements in the data models used in controllers NBIs are being driven by new use cases (such as externalizing the path computation function to a planner tool while retrieving dynamic and operational data from running controller elements) defined by operators.

A common question relates to actual implementations of the discussed architectures and data models. Due to space limitations, let us mention that OIF revealed the results of its 2020 Transport SDN [43] Application Programming Interface (API) Interoperability Demonstration in white paper. The white paper includes details on the test topology, testing methodology, technical specifications, use cases and findings. The Interoperability Demonstration achieved its objective of evaluating interoperability for a partially disaggregated operator network using standard interfaces. Participants supported (21) integrations between vendor solutions in (29) TAPI use cases and (31) OpenConfig operations over a 10-week testing period.

We have insisted in two key aspects being addressed: first, the definition of physical layer models and impairment characteristics, and second, the integration of large-scale optical telemetry (at different levels: device and controller with network abstractions), including Fault and Performance Monitoring. It is well-known that the development of efficient and scalable telemetry is a key enabler for machine learning enabled network operation and for autonomic networking in general.

Funding Information. This project has received funding from the European Union's Horizon 2020 research and innovation programme, B5G-OPEN Project, grant agreement No. 101016663 and Spanish Grant AURORAS RTI2018-099178-B-I00 funded by MCIN/AEI/ 10.13039/501100011033 and by ERDF A way of making Europe.

Acknowledgment. The work has been partially done in the context of the ONF TAPI working group, related to the standardization of TAPI extensions for the photonic media layer and Reference Implementation Agreement (RIA) 1.1. We would like to thank Andrea Mazzini, Nigel Davis, Arturo Mayoral and Ronald Zabaleta for their contributions.

References

1. R. Casellas et al, " Advances in SDN control for Beyond 100G disaggregated optical networks", tutorial within ECOC 2021, Sept 2021. 10.1109/ECOC52684.2021.9605881
2. R. Casellas et al., "Control, Management, and Orchestration of Optical Networks: Evolution, Trends, and Challenges," J. Lightwave Technol. 36, 1390-1402 (2018)
3. R. Vilalta et al., "Experimental evaluation of control and monitoring protocols for optical SDN networks and equipment" JOCN, Vol. 13, No. 8, pp. D1-D12, August 2021
4. M. Bjorklund, ed., "The YANG 1.1 Data Modeling Language", RFC 7950, DOI 10.17487/RFC7950, August 2016, <https://www.rfc-editor.org/info/rfc7950>.
5. M. Bjorklund, ed., "Network Management Datastore Architecture (NMDA)", RFC 8342, DOI 10.17487/RFC8342, March 2018, <https://www.rfc-editor.org/info/rfc8342>.
6. Enns, R., Ed., Bjorklund, M., Ed., Schoenwaelder, J., Ed., and A. Bierman, Ed., "Network Configuration Protocol (NETCONF)", RFC 6241, DOI 10.17487/RFC6241, June 2011, <https://www.rfc-editor.org/info/rfc6241>.
7. Bierman, A., Bjorklund, M., and K. Watsen, "RESTCONF Protocol", RFC 8040, DOI 10.17487/RFC8040, January 2017, <https://www.rfc-editor.org/info/rfc8040>.
8. gRPC "gRPC: a high performance, open-source universal RPC framework," https://grpc.io/
9. A Giorgetti, A Sgambelluri, R Casellas, R Morro, A Campanella, "Control of open and disaggregated transport networks using the Open Network Operating System (ONOS)," Journal of Optical Communications and Networking 12 (2), A171-A181, 2020
10. Steve Trowbridge, " Hot topics in Optical Transport Networks", In proceedings of OFC2018, [online https://www.itu.int/en/ITU-T/studygroups/2017-2020/15/Documents/OFC2018-1-SG15-Hot-topics-OTN.pdf]
11. ITU-T G.709: Interfaces for the optical transport network, G.709/Y.1331 (06/20), https://www.itu.int/rec/T-REC-G.709
12. R. Casellas, editor, Open Networking Foundation (ONF) TR-547 "TAPI v2.1.3 Reference Implementation Agreement", (RIA) v1.1, December 2021
13. TIP OOPT MUST Optical Whitepaper "Target Architecture: Disaggregated Open Optical Networks", v.10. 16-jul-2021
14. OpenConfig project http://openconfig.net
15. OpenROADM device and network models, https://github.com/OpenROADM/OpenROADM_MSA_Public
16. ONF Transport API project https://wiki.opennetworking.org/display/OTCC/TAPI
17. IETF Network model draft-ietf-ccamp-optical-impairment-topology-yang https://github.com/ietf-ccamp-wg/draft-ietf-ccamp-optical-impairment-topology-yang/blob/master/ietf-optical-impairment-topology.tree
18. ITU-T G.872: Architecture of optical transport networks, ITU-T G.872 2017, https://standards.globalspec.com/std/10165255/ITU-T G.872
19. R. Casellas et al, "An OLS Controller for Hybrid Fixed / Flexi Grid Disaggregated Networks with Open Interfaces", in Optical Fiber Communication Conference, OFC2020, San Diego, USA (2020)
20. D. Soma, Y. Wakayama, S. Beppu, S. Sumita, T. Tsuritani, T. Hayashi, T. Nagashima, M. Suzuki, H. Takahashi, K. Igarashi et al., "10.16 peta-bit/s dense sdm/wdm transmission over low-dmd 6-mode 19- core fibre across c+ l band," in 2017 European Conference on Optical Communication (ECOC), (IEEE, 2017), pp. 1–3.
21. C. Manso, R. Muñoz, N. Yoshikane, R. Casellas, R. Vilalta, R. Martínez, T. Tsuritani, I. Morita, TAPI-enabled SDN control for partially disaggregated multi-domain (OLS) and multi-layer (WDM over SDM) optical networks [Invited] , IEEE/OSA Journal of Optical Communications and Networking (JOCN), Vol. 13, No. 1, pp. A21 - A33, January 2021
22. Net2plan – The open-source network planner http://net2plan.com
23. GNPy Optical Route planning library https://gnpy.readthedocs.io/en/master/
24. Miquel Garrich , Francisco-Javier Moreno-Muro , Maria-Victoria Bueno Delgado , Pablo Pavon Mariño "Open-Source Network Optimization Software in the Open SDN/NFV Transport Ecosystem", Journal of Lightwave Technology, vol.37 n1, 2019
25. J. Kundrát, A. Campanella, E. Le Rouzic, A. Ferrari, O. Havliš, M. Hažlinsky, G. Grammel, G. Galimberti, and V. Curri, "Physical-layer awareness: Gnpy and onos for end-to-end circuits in disaggregated networks," in Optical Fiber Communication Conference, (Optical Society of America, 2020), pp. M3Z–17
26. E. Le Rouzic, A. Lindgren, S. Melin, D. Provencher, R. Subramanian, R. Joyce, F. Moore, D. Reeves, A. Rambaldi, P. Kaczmarek, K. Weeks, S. Neidlinger, G. Agrawal, S. Krishnamoha, B. Raszczyk, T. Uhlar, R. Casellas, O. González de Dios, V. Lopez, "Operationalizing partially disaggregated optical networks: An open standards-driven multi-vendor demonstration",OFC2021 Conference, Virtual, June 2021.
27. D. M. Marom, P. D. Colbourne, A. D'errico, N. K. Fontaine, Y. Ikuma, R. Proietti, L. Zong, J. M. Rivas-Moscoso, and I. Tomkos, "Survey of photonic switching architectures and technologies in support of spatially and spectrally flexible optical networking," IEEE/OSA J. Opt. Commun. Netw., vol. 9, no. 1, pp. 1–26, 2017
28. J. M. D. Mendinueta, S. Shinada, Y. Hirota, H. Furukawa and N. Wada, "High-Capacity Super-Channel-Enabled Multi-Core Fiber Optical Switching System for Converged Inter/Intra Data Center and Edge Optical Networks," in IEEE Journal of Selected Topics in Quantum Electronics, vol. 26, no. 4, pp. 1-13, July-Aug. 2020, Art no. 4501113, doi: 10.1109/JSTQE.2020.2969558.
29. F. Paolucci, A. Sgambelluri, F. Cugini and P. Castoldi, "Network Telemetry Streaming Services in SDN-based Disaggregated Optical Networks", Journal of Lightwave Technology (Volume: 36, Issue: 15, Aug.1, 1 2018)
30. Z. Dong, F. N. Khan, Q. Sui, K. Zhong, C. Lu, and A. P. T. Lau, "Optical performance monitoring: A review of current and future technologies," Journal of Lightwave Technology, vol. 34, no. 2, pp. 525–543, Jan 2016.
31. Luis Velasco, Patricia Layec, Francesco Paolucci, and Noboru Yoshikane, "Introduction to the JOCN Special Issue on Advanced Monitoring and Telemetry in Optical Networks", Vol. 13, Issue 10, pp. AMTON1-AMTON2 (2021)
32. S. Chisholm, H. Trevino, "NETCONF Event Notification", RFC5277, July 2008, <https://www.rfc-editor.org/info/rfc5277>.
33. Hickson, I., "Server-Sent Events", World Wide Web Consortium Recommendation REC-eventsource-20150203, February 2015Considerations <http://www.w3.org/TR/2015/REC-eventsource-20150203>.
34. Fette, I. and A. Melnikov, "The WebSocket Protocol", RFC 6455, DOI 10.17487/RFC6455, December 2011, <https://www.rfc-editor.org/info/rfc6455>.
35. Andrea Sgambelluri et al, "Reliable and Scalable Kafka-based Framework for Optical Network Telemetry", Journal of Opt. Comm. and Netw. May 2021 DOI: 10.1364/JOCN.424639
36. gNMI Gateway https://github.com/openconfig/gnmi-gateway and https://netflixtechblog.com/simple-streaming-telemetry-27447416e68f
37. N. Davis, editor, ONF TR-548 "TAPI v2.1.3 Reference Implementation Agreement. TAPI Streaming", v1.1, December 2021
38. R.Vilalta et al. "Optical Network Telemetry with Streaming Mechanisms using Transport API and Kafka" , ECOC 2021

39. Abubakar Siddique Muqaddas et al, "NFV orchestration over disaggregated metro optical networks with end-to-end multi-layer slicing enabling crowdsourced live video streaming", Journal of Opt. Comm. and Netw Vol. 13, Issue 8, pp. D68-D79 (2021)
40. ITU-T G.8300, "Characteristics of transport networks to support IMT-2020/5G", 05/20
41. IETF Internet Draft, "Framework for IETF Network Slices" https://datatracker.ietf.org/doc/html/draft-ietf-teas-ietf-network-slices-05 (2021), work in progress.
42. D. Ceccarelli,Y. Lee, "Framework for Abstraction and Control of TE Networks (ACTN)",IETF RFC8453. August 2018.
43. TAPI Interoperability event (including white paper) https://www.oiforum.com/technical-work/2020-oif-transport-sdn-api-interoperability-demo/

Ramon Casellas (SM'12) graduated in Telecommunications Engineering in 1999 both from UPC, Barcelona and ENST Paris, where he completed a PhD degree in 2002. After working as an Associate Professor (2002-2005) he joined CTTC in 2006, where he currently holds a Senior Researcher position. He has participated in several R&D projects funded by EC, Spanish National Research programmes, and industrial contracts and published over 250 conference and journal papers in the field of Optical Networking. He has served as ONDM Program Chair (ONDM2018), General chair (ONDM2020), and OFC2021 Program Chair. His research interest areas include GMPLS/PCE architecture, Software Defined Networking (SDN), Network Function Virtualization (NFV), Traffic Engineering and Distributed control schemes, with applications to Optical and Disaggregated Transport Networks.

Ricardo Martínez (SM'14) is a graduate and PhD in Telecommunications Engineering of the Universitat Politècnica de Catalunya (UPC) in 2002 and 2007, respectively. Since 2013, he is Senior Researcher of the Communication Networks Division (CND) at CTTC. He has been involved in several European, national and industrial research projects. His research interest areas include service and resource orchestration, NFV and SDN solutions, cloud and network resource placement and allocation algorithms over heterogeneous infrastructures and technologies (metro, core, edge, packet, optical, etc.).

Ricard Vilalta (SM'17) graduated in 2007 and received his Ph.D. degree in telecommunications in 2013, both from the UPC. He is a senior researcher at CTTC, in the Optical Networks and Systems Department. He is an active contributor in several standardization bodies such as ONF, ETSI and IETF. He has been involved in several international, EU, national and industrial research projects. Currently, he is Project Coordinator of 5GPPP TeraFlow project.

Alfredo Gonzalez graduated in Telecommunications Engineering in 2004 from the University Alfonso X El Sabio in Spain. He oversaw Telefonica global SBI/NBI specification for optical networks controllers from 2019 to 2021 as expert in optical transmission (DWDM). In Sept 2003 he joined Alcatel where he started his career in the designing and deploying DWDM networks. In 2008 he joined Telefonica I+D where he was involved in many transformation and automation projects for the development of control plane architecture. Since 2012, Alfredo has been working in the main departments of Telefonica, as TIWS or Global CTO in charge of defining the strategic network planning and trying to impulse the automation of the optical network. Currently Alfredo is the solution manager of ZTE. In charge of implement and design the SDN interfaces to improve the behavior of the optical layer.

Raul Muñoz (SM'12) is graduated in Telecommunications Engineering and received a Ph.D. degree, both from the Universitat Politècnica de Catalunya (UPC), Barcelona, Spain. He is Research Director, Head of the Optical Networks and Systems Department, and Manager of the Communication Networks division at CTTC. He has participated and/or promoted above 50 R&D projects funded by EC, Spanish National Research programmes, and industrial contracts. He has been Project Coordinator of 5 Spanish research projects, the coordinated EU-Japan FP7 STRAUSS project, and the H2020-MSCA-ITN ONFIRE project. He has served as general chair of ONDM 2020 & WWRF39, and TPC chair of ECOC 2015 & ONDM2019. His research interests include control and service management architectures (SDN, NFV, MEC) for future optical networking and communications.

Óscar González de Dios received his M.S. degree in telecommunications engineering and Ph.D. degree (Hons.) from the University of Valladolid, Spain. He has 20 years of experience in Telefonica, where he has been involved in a number of European research and development projects (coordinator of B5GOpen, Teraflow, IDEALIST, Metro-Haul, STRONGEST, ONE). He has coauthored over 100 research papers and 17 IETF RFCs. He is currently the head of SDN Deployments for Transport Networks, called iFUSION in Telefonica Global CTIO. His main research interests include photonic networks, flexi-grid, interdomain routing, PCE, automatic network configuration, end-to-end MPLS, performance of transport protocols, and SDN. He is currently active in several IETF Working Groups such as OPSAWG and TEAS, active contributor to Openconfig and is the Co-Chair of CANDI WG in OOPT Telecom Infra Project.

Juan Pedro Fernández-Palacios Giménez received the MS in Telecommunications Engineering from Polytechnic University of Valencia in 2000. In Sept. of 2000 he joined Telefonica I+D where his research activities where focused on the design of new data and control plane architectures for IP over optical networks. He is author of 6 patents filled in Europe and US and more than 100 publications in conferences and journals. He was coordinator of two European research projects on optical transport networks (MAINS and IDEALIST) between 2011 and 2014. In 2013 he joined the Telefonica Global CTO office as Head of Transport. In 2016, he also took this position in Telefonica-O2 Germany. Since June 2017 he is leading the Integrated Transport Centre, a global organization in Telefonica in charge of defining the strategic network planning and technology for IP, DWDM, MW and satellite networks.