Sliceable transponders: pre-programmed OAM, control, and management

Nicola Sambo, Alessio Giorgetti, Filippo Cugini, and Piero Castoldi

***Abstract*—Sliceable transponders (S-BVTs) are expected to increase flexibility of Elastic Optical Networks (EONs) by providing multiple independent optical flows that can be routed based on operators needs and traffic. The support of several transmission modes (e.g., modulation format, coding, baud rate) also enables to adapt the transmission to the physical layer characteristics. Thus, a proper control of S-BVT configuration is mandatory, as well as the monitoring of optical flows and the management of monitoring information. NETCONF, based on YANG modeling language, is emerging as a Software Defined Networking (SDN) protocol supporting configuration messages as well as messages to exchange monitoring information within the management system.**

This paper presents control and management of sliceable transponders through NETCONF and YANG. Three Operation, Administration, and Mantainance (OAM) procedures are presented to guarantee the maintenance of services in the presence of faults or physical layer degradations: *centralized*, *hierarchical*, and a scheme based on *pre-programmed* OAM. A YANG model enabling the pre-programmed OAM is proposed. Simulations show that hierarchical and pre-programmed OAM provide faster reaction time to degradations.

***Index Terms*—Software Defined Networking (SDN), NETCONF, YANG, OAM.**

I. Introduction

FEXIBILITY requirements of network operators have paved the way to sliceable transponders (S-BVTs) [2]–[5] enabling multiple independent optical flows and the possibility to choose among several transmission parameters such as modulation formats and coding. S-BVTs permit operators to i) optimize network capacity by configuring the transponder to have the most spectrally efficient transmission for the distance required; ii) re-direct optical flows based on traffic dynamics and requirements; iii) monitor end-to-end service quality of transmission (QoT) thanks to the digital signal processing (DSP) of coherent receivers. Moreover, the need of such flexibility together with the reduction of system margins [6]–[8] are bringing to a tight tie between control and management. Indeed, once a lightpath is configured, it is expected that control system may reconfigure S-BVT parameters (e.g., modulation format) based on monitoring information if a degradation of the physical layer occurs. A physical layer degradation is typically referred to as *soft failure* which in turns implies an increase of the bit error rate (BER). Soft failures may require either no action (if BER is still below a threshold for error-free operation) or can be overcome by transmission parameter adaptation (e.g., change of modulation format), thus do not necessary require rerouting as fiber cut. Such degradations can be due to a malfunction/ageing of network devices: for example, an increase of the amplifier noise figure or an increase of fiber attenuation [7]. The management of monitoring information and alarms related to the physical layer requires to be scalable in order to avoid the overloading of controllers and delay transponder reconfiguration.

Software Defined Networking (SDN) paradigm, which separates data from control plane centralizing control operations, is expected to be adopted for the control of Elastic Optical Networks (EONs). OpenFlow has been widely considered in the literature as an SDN protocol to control optical core networks [9]–[11]. Recently, NETCONF is emerging as another SDN protocol for optical networks [12], [13]. NETCONF is attracting interest from service providers and network operators since it presents several advantages: it operates on data encoded in XML, thus commonly used XML tools can be adopted to process NETCONF content; it is based on YANG data modeling [14] instead of bit encoding. YANG is a highly readable language enabling the description of data plane devices in a vendor-neutral way [15], [16]. The interest on YANG is demonstrated by the active work of several consortiums and projects including the presence of operators, service providers, and vendors [17]–[19], which are developing YANG models describing network elements.

This paper presents the control and management of S-BVTs through NETCONF protocol, extending the work presented in [1]. A YANG model for NETCONF is detailed highlighting *configuration* and *state* parameters for the transponder. The former can be configured by external entities (i.e., an SDN controller), the latter can be only read. Moreover, three procedures for Operation, Administration and Maintenance (OAM) are presented: *centralized*, *hierarchical*, and *pre-programmed*. These procedures are compared through simulations in terms of re-configuration delay and recovery blocking probability. With respect to [1], the YANG model for the pre-programmed OAM scheme is presented and simulations are extended considering the survivability of data that cannot be recovered through modulation format adaptation. The hierarchical and pre-programmed OAM provide faster recovery delay from degradations, with respect to a centralized approach.

II. Related work

The work presented in [4] identifies several transponder parameters to be controlled: the number of active optical flows or

Manuscript received December 21, 2017.

N. Sambo (email: nicola.sambo@sssup.it), A. Giorgetti, and P. Castoldi are with Scuola Superiore Sant'Anna, Via Moruzzi 1, Pisa, Italy. F. Cugini is with CNIT, Via Moruzzi 1, Pisa, Italy.

This work was supported by the EC through the Horizon 2020 ORCHESTRA project (grant agreement 645360) and the Horizon 2020 METRO-HAUL project (grant agreement 761727).

This paper is an extended version of the work presented in [1].

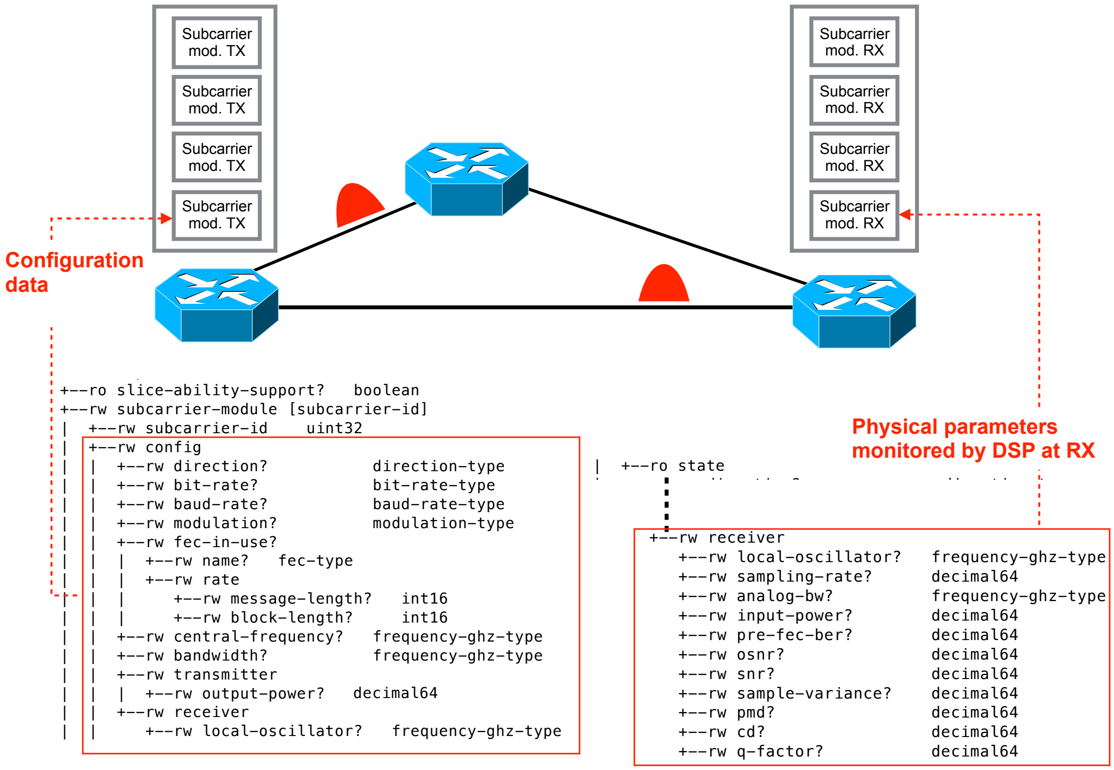

Figure 1. Tree of the YANG model to control and manage S-BVT

sub-carriers, their line rate, modulation format, adopted code or forward error correction (FEC), central frequency, launch power, and the association of Optical Transport Network (OTN) digital streams with a specific optical flow. These key parameters should be controlled and configured for a proper service operation and are included in protocol extensions and messages exchanged between the SDN controller and the device. The survey [20] reviews several studies related to SDN for optical networks, including activities on transponders. Several works assume OpenFlow protocol. As an example, the experiment in [21] demonstrated the control of transmitter and receiver sides through OpenFlow extensions to encompass the aforementioned parameters (e.g., code rate and modulation format). Authors in [22] controlled a S-BVT based on orthogonal frequency division multiplexing (OFDM) technique by adopting a REST-based Application Programming Interface. A first demonstration of SDN-control involving a transponder based on frequency comb, instead of an array of laser (each laser used for an optical flow) has been reported in [23]. In that work, OpenFlow extensions have been proposed to control the radio frequency sources composing the frequency comb generation module, in order to set the spacing among optical carriers. In [10], [24], OpenFlow is adopted to retrieve monitoring information and it is extended to support optical parameters (e.g., BER). Authors in [24] report a study on the relation between the polling rate of monitoring information and the ability to recover degraded signals.

Differently from OpenFlow, NETCONF is not based on bit encoding but it is based on YANG data modeling. A YANG model describes all the parameters to be configured or read (thus, monitored) at a given network element. The NETCONF protocol, pointing to a specific YANG model, operates on such parameters configuring them to specific values or reporting their value to a remote controller. In the case of NETCONF, effort has been done in developing YANG models describing the features of S-BVTs within consortiums and projects (e.g., the OpenConfig project and within the Internet Engineering Task Force —IETF), and in the research community in general [13], [17], [18], [25], [26]. Basically, these works are focused in expressing, with the YANG language, the aforementioned parameters that can be controlled (e.g., modulation format, line rate). Moreover, besides the polling of monitoring information, NETCONF also supports “alarms”. In particular, as detailed in the next section, such feature is highly flexible because NETCONF enables a remote controller to (re-)program the parameters and the thresholds generating alarms [13]. An experimental demonstration integrating transponder and NETCONF has been reported in [27] considering single-flow transponder.

III. Control and Management of Sliceable Transponders with NETCONF

The S-BVT architecture proposed in [4] is assumed. We derive control and management tasks from the IETF Application-Based Network Operations (ABNO) architecture [28]. In particular, an SDN controller is responsible for control tasks, while the OAM Handler for management tasks of OAM. Control tasks for S-BVT include: retrieval of capabilities (e.g., the maximum bit rate supported by the S-BVT) to know the characteristics of the considered S-BVT, configuration of S-BVT, and, if needed, reconfiguration for survivability purposes. Management tasks of S-BVT include: configuration of threshold parameters generating alarms (e.g., if Q-factor is below a given threshold, an alarm is generated), end-to-end monitoring of service, correlation and processing of monitoring information and alarms, and triggering actions to preserve or recover, thus maintain, the affected services.

NETCONF protocol supports the aforementioned tasks. In particular, the retrieval of S-BVT capabilities can be done with the `<get>` message sent by the SDN-controller to the S-BVT agent, which is responsible for carrying out the commands of the SDN controller and notifying the SDN controller about specific events. The S-BVT agent then replies to the SDN controller with a `<rpc-reply>` message specifying transponder characteristics (e.g., maximum supported bit rate). Configuration and reconfiguration is done with a `<edit-config>` message sent by the SDN controller to the S-BVT agent specifying the proper transponder settings. The configuration of threshold parameters generating alarms can be done with the `<create-subscription>` message: the OAM Handler can set in the S-BVT agent the parameters and the related threshold generating alarms. Then, an alarm can be implemented with the `<notification>` message: once a given parameter exceeds the threshold, both specified by the `<create-subscription>` message, the S-BVT agent sends a `<notification>` message to the SDN controller. The `<notification>` message may report the identifier of the monitored lightpath, the value of the parameter exceeding the threshold, and, possibly, a time stamp when the measurement is taken [13]. End-to-end monitoring is done through DSP modules in the S-BVT, whereas correlation of monitoring information and service mantainance is performed by the ABNO OAM Handler [28]. Please, consider that in order to view NETCONF messages (which run by default on the encrypted Secure SHell protocol) traces, it is possible to adopt proper tools (e.g., ConfD) which permit to disable encryption [13].

IV. YANG MODEL FOR CONTROL AND MANAGEMENT

Transponder can be modeled with YANG to be controlled and managed with NETCONF. The active consortiums and projects are developing YANG models also for optical networks, including transponders and S-BVT. The OpenROADM consortium [18] is now considering the flexible grid through a “wavelength” type named “flex-wave”, which defines a central frequency expressed in THz and a width expressed in GHz. The model for the transponder includes administrative information such as the owner and the location, and specifications of physical parameters such as the rate and the modulation format. The OpenConfig consortium [17] developed a model defining a list of operational modes supported by the transponder. An operational mode is given by several parameters such as the symbol rate (or baud rate), the modulation format, and the pulse shaping. Such definitions can be particularly useful because the value of some parameters is locked to the value of others: for example, the adoption of PM-QPSK (polarization multiplexing quadrature phase shift keying) and 28 Gbaud symbol rate automatically gives the value of the line rate, which is 112 Gb/s. IETF also defined YANG model for transponders [26] including several transmission parameters such as the FEC, the modulation format, the bit per symbol, and others. Thus, several YANG models have been developed for optical networks. The convergence towards one of them is not trivial since should be the result of discussions among several operators, service providers, and vendors. The definition of a common model for S-BVT within the most relevant industrial partners in play will be the basemen for “vendor-neutral” networks, but effort in discussions and agreement is still required. In general, OpenROADM presents a wide and comprehensive vision of the current deployed networks but lacks of details in YANG models for advanced optical devices (e.g., S-BVT) and related procedures for the control and management of these devices. IETF includes several models for optical networks: e.g., for interfaces [26], network topology augmentation [29], and tunnels [30]. Regarding OpenConfig, public works on OAM procedures are still at early stage.

Fig. 1 shows the tree diagram of the YANG model for S-BVT we developed. The full code can be retrieved in [31]. The model is organized per sub-carrier reflecting the architecture in [3], [4]. As configuration data (i.e., configurable parameters), some data has to be specified both in transmission and detection (e.g., baudrate, bit rate, modulation format, FEC). Then, different data is present if the “direction” is in transmission or detection: e.g., local oscillator configuration of the receiver or output power at the transmitter. Regarding central frequency and local oscillator, we defined the type “frequency-ghz-type" to discern between the central frequency of a sub-carrier and of a media-channel: the central frequency of a media-channel has to follow ITU-T specifications in steps of 6.25 GHz, thus can be expressed as an integer number, while the central frequency of a sub-carrier of a media-channel composed by several sub-carriers does not necessary follow a grid. Regarding state data (i.e., only readable data such as monitoring parameters), first, configuration data is replicated into state data to enable an operator to verify, as specified by the OpenConfig consortium, the actual configuration of the transponder (not shown in the figure). Then, other state data include monitored parameters as pre-FEC BER, Q-factor, chromatic dispersion (CD), polarization mode dispersion (PMD), signal to noise ratio (SNR), and optical SNR (OSNR) expressed as “decimal64".

V. MANAGEMENT SCHEMES AND RECONFIGURATION

Such section aims at defining OAM procedures for YANG-modelled S-BVT. Indeed, as anticipated, the active aforementioned consortiums and projects still have to detail OAM procedures related to S-BVT including the management of alarms and monitoring information involving such device. To this purpose, we present three different OAM schemes for the processing of alarms and monitoring information, and the maintenance of the service.

- **Centralized**: the workflow of this OAM scheme is presented in Fig. 2. The OAM Handler receives and

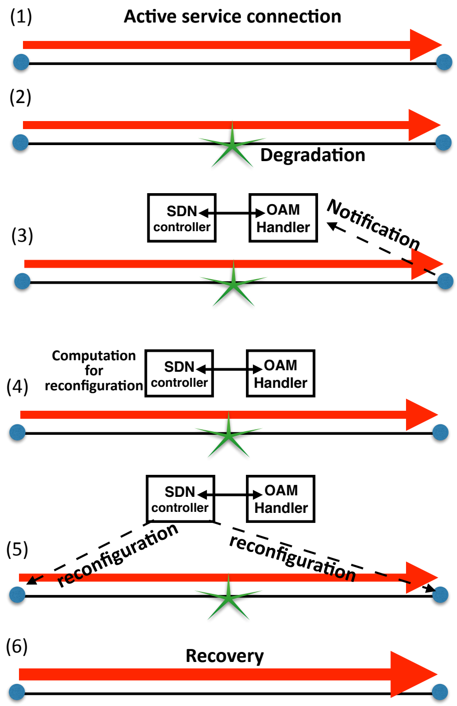

Figure 2. Centralized OAM workflow

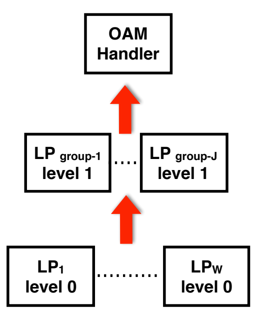

Figure 3. Hierarchical OAM architecture

processes all the alarms (e.g., for failure localization) and, for each lightpath, triggers the SDN-controller to preserve the service if needed. Then, the SDN-controller performs computations (e.g., FEC) for restoration. Computations may involve the reconfiguration of S-BVT at the transmitter and receiver sides, as well as the intermediate nodes (e.g., filters). Upon reconfiguration, lightpath recovered.

- **Hierarchical** : the hierarchical architecture composed by management elements is shown in Fig. 3. Each entity in the hierarchy processes alarms only for a subset of lightpaths (LPs in the figure), thus providing high scalability as demonstrated in [32]. In particular, each entity at level 0 is associated to a specific LP and it is responsible to create an alarm if a monitored parameter falls within a critical threshold (by exploiting the monitor integrated in the S-BVT, please see the Subcarrier mod. RX of Fig. 1). This alarm is then sent to a specific entity at level 1. Fig. 4 shows the workflow. At level 1, each entity is associated to a specific ingress node. In particular, an entity at level 1 receives and processes alarms related to the LPs starting from a given ingress node. Recovery actions (e.g., code adaptation) can be triggered by the monitoring entity at level 1. Otherwise, more complex recovery actions (e.g., rerouting which may require the configuration of intermediate nodes) should involve the SDN controller. In any case, the entity at level 1 propagates an alarm to the OAM Handler (responsible for the whole network) to report the alarm and/or an information about recovered lightpath. More details on the hierarchical architecture and on the recovery actions can be found in [32].

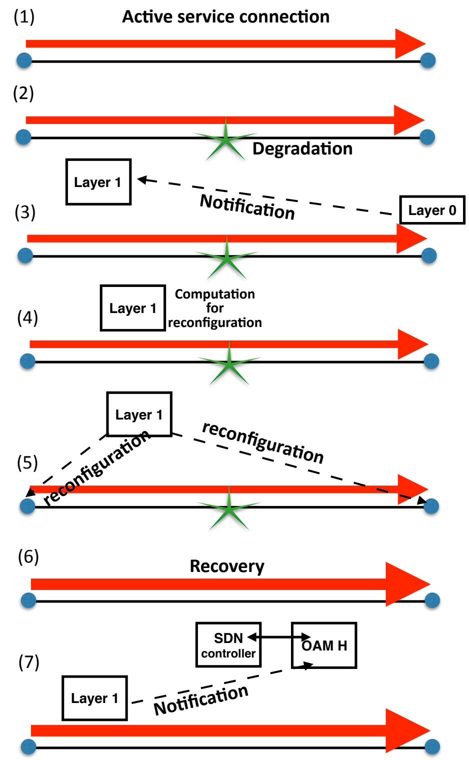

Figure 4. Hierarchical OAM workflow

- **Pre-programmed**: Fig. 5 shows the workflow of the approach. The SDN controller pre-computes the type of restoration (e.g., modulation format adaptation) for a given soft failure. S-BVTs are instructed about the actions to perform in case of degradation, while the lightpath is still active. If a degradation occurs, S-BVT promptly reacts by self-reconfiguring the proper transmission parameters without asking and waiting for computations from the OAM Handler/SDN controller. We assume reconfiguration of S-BVT at transmitter and receiver sides, not of the intermediate nodes. Finally, the OAM Handler is notified about recovery. In the next section, a YANG model enabling pre-programmed OAM is presented.

VI. YANG MODEL FOR PRE-PROGRAMMED OAM

By building on the model for events presented in [16], we propose a model for finite state machine (FSM) enabling pre-programmed OAM. The related tree of the YANG code is

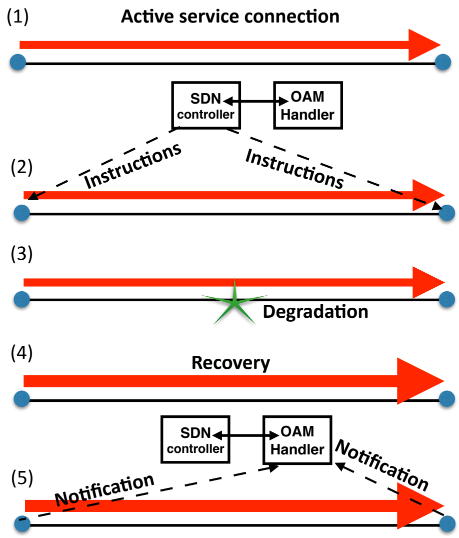

Figure 5. Pre-programmed OAM workflow

```
module: finite-state-machine
   +--rw current-state?   leafref
   +--rw states
      +--rw state [id]
         +--rw id              state-id-type
         +--rw name?           string
         +--rw description?    string
         +--rw transitions
            +--rw transition [name]
               +--rw name                    string
               +--rw description?            string
               +--rw threshold-parameter?    decimal64
               +--rw threshold-operator?     string
               +--rw transition-action
                  +--rw action [id]
                     +--rw id              transition-id-type
                     +--rw type            enumeration
                     +--rw conditional
                     |  +--rw statement    string
                     |  +--rw true
                     |  |  +--rw execute
                     |  |  +--rw next-action?   transition-id-type
                     |  |  +--rw next-state?    leafref
                     |  +--rw false
                     |     +--rw execute
                     |     +--rw next-action?   transition-id-type
                     |     +--rw next-state?    leafref
                     +--rw simple
                        +--rw execute
                        +--rw next-action?   transition-id-type
                        +--rw next-state?    leafref
```

Figure 6. Tree diagram of the YANG model for finite state machine enabling pre-programmed OAM

shown in Fig. 6. The full code can be retrieved in [33]. The attributes of the model are presented below.

<current-state>: it defines the current state of the FSM.

<states>: this element defines the FSM as follows.

<state>: this list defines all the FSM states:

- <id>: this leaf attribute of <state> defines the identifier of the state
- <name>: this leaf attribute of <state> defines the name of the state
- <description>: this leaf is a string describing the state
- <transitions>: this attribute defines a list of transitions to other states in the FSM.
  - <name>: it defines the name of a transition, uniquely identifying the transition
  - <description>: this optional attribute is a string describing the transition
  - <threshold-parameter>: it further describes a transition, as it will be shown next and in Tab. I. It permits to describe transitions triggered by some parameter exceeding a threshold
  - <threshold-operator>: it is used together with <threshold-parameter> and can assume values as "<", ">", "<=", ">="
  - <transition-action>: it defines a list of actions to take during the transition.
    - <action>: this attribute is the list of actions.
    - <id>: this leaf of <action> defines the identifier number of an action.
    - <type>: this leaf of <action> defines the type of an action.
    - <simple>: this leaf defines (differently from <conditional> detailed below) an action that has to be directly executed.
    - <execute>: this attribute actually triggers the effective task (action) to be executed by the hardware (e.g., the change of modulation format). If more actions have to be executed and each is defined as an element of the <action> list, these actions are executed sequentially. Conversely, if more actions have to be executed in parallel, an element of the <action> list should be defined including the several actions to be performed in parallel.
    - <next-action>: this attribute defines the identification number of a next action that has to be taken.
    - <conditional>: this leaf enables a check ("true" or "false") to be verified before executing the action. Based on the check, the proper attributes <execute> and <next-operation> are considered.
    - <statement>: this leaf of <conditional> defines the condition to be verified before executing the action.
    - <true>: this leaf of <conditional> defines a result of the check associated to <statement>. Proper <execute> and <next-operation> attributes are associated with this result of the check.
    - <false>: this leaf of <conditional> defines a result of the check associated to <statement>. Proper <execute> and <next-operation> attributes are associated with this result of the check.
  - <next-state>: this attribute defines the next state of FSM when an action is executed.

Such model finds application in pre-programmed OAM. As an example, an optical flow supporting two FEC types, 7% and 20%, is considered. A two-states FSM is assumed. The states have <name> attribute set to "Steady" and "Fec-Baud-Adapt", respectively. In the "Steady" state, the signal is in normal

Table I
EXAMPLES OF VALUES FOR THE ATTRIBUTES IN THE YANG FOR FSM

Field name	Value
current state	“an existing state id in the FSM”
state	
id	1
name	Steady
description	“whatever string”
transition	
name	BER_CHANGE
description	“whatever string”
threshold-parameter	0.0009
threshold-operator	>
action	
id	3
type	SIMPLE
statement	“whatever string”
execute	“this recalls the change of code redundancy”
next-operation	NULL
next-state	“an existing state id in the FSM”

operational conditions, adopting a 7% FEC, with a pre-FEC BER below an assigned threshold of 9×10^{-4}. A transition from this state is triggered by the transition described with `<name>=BER_CHANGE`, `<threshold-parameter>=`9×10^{-4}, and `threshold-operator = >` expressing a change of the pre-FEC BER above the threshold of 9×10^{-4}. In case the threshold is exceeded, the state machine evolves to “Fec-Baud-Adapt” state by executing an action consisting in a change of the FEC to 20% (executed by the attribute <execute>). Examples of attributes’ values related to such use case are shown in Tab. I.

VII. PERFORMANCE EVALUATION

The proposed OAM schemes are assessed by simulations using a custom built event-driven C++ simulator. The considered Pan-European backbone network topology consists of 27 nodes and 55 bidirectional links [34]. Connection requests follow a Poisson process. The average holding time of each connection is $1/\mu = 2$ hours, while the average inter-arrival time $1/\lambda$ is varied in the range $2.05 - 72$ seconds. The traffic load offered to the network is therefore expressed as λ/μ and is varied in the range $100 - 3500$ Erlang. All requested lightpaths are established using PM-16QAM (polarization multiplexing 16 quadrature amplitude modulation) format occupying 3 frequency slices of 12.5 GHz.

Lightpaths impacted by soft failures (generated on random links) are recovered with modulation format adaptation (from PM-16QAM to PM-QPSK). Such operation, done at fixed baud rate, implies the halving of the bit rate [32]. Indeed, as detailed in [3], a PM-16QAM transports the traffic of eight clients (e.g., 2 $\times$ 100GbE), while a PM-QPSK transports four clients (e.g., 1 $\times$ 100GbE). We assume that each PM-16QAM lightpath is obtained with four clients belonging to a *high-priority* (HP) class and four clients belonging to a *best-effort* (BE) class [32], [35]. This way, high-priority clients are recovered with modulation format adaptation (i.e., the saved rate when passing from PM-16QAM to PM-QPSK), while for the best-effort traffic a new lightpath is established (which likely requires more time than a modulation format adaptation since also involves the configuration of intermediate nodes). Thus, the recovery of best-effort traffic mandatorily involves the SDN controller [34].

The OAM schemes are compared in terms of: i) *control plane recovery delay*, that for HP traffic is defined as the time between the failure and the time in which the change of modulation format is triggered at the source node, whereas for BE traffic it is defined as the time between the failure and the time in which the configuration of the backup path is terminated; ii) *recovery blocking probability* of BE traffic, defined as the ratio between the unrecovered best-effort traffic and the best-effort traffic impacted by the soft failure.

Fig. 7 shows the average recovery delay vs. the offered network load with both the processing time of each alarm and the path computation (including also spectrum assignment) time fixed at 50 ms. These values have been retrieved by experiments in [13], [34]. Centralized scheme experiences the highest recovery delay for both HP and BE traffic. Indeed, in this case a single entity (i.e., the SDN controller) receives and processes all the alarms and path computation requests. Thus, alarms experience a high queuing time before being processed. Hierarchical scheme experiences lower recovery time because each monitoring entity at level 1 processes only a subset of alarms, i.e., only alarms related to lightpaths starting from the same node are actually queued. Moreover, while monitoring alarms are processed at the level 1 entity, path computation requests for BE traffic are processed by the SDN controller, thus the two procedures are decoupled in different network elements and the SDN controller for path computation related to BE is less loaded. Pre-programmed scheme further reduces the recovery delay of HP since S-BVTs can promptly react to soft failures self-reconfiguring the proper transmission parameters without waiting for OAM Handler/SDN controller response. The recovery delay of BE with pre-programmed OAM is comparable, even if slightly lower, with the recovery delay of BE with hierarchical OAM. Indeed, in the two schemes the number of alarms processed by the SDN controller is almost the same since it is related to only BE traffic. With all the schemes, the recovery delay increases with traffic load since more lightpaths are affected by the failure, more alarms are generated, and queuing time consequently increases. Interestingly, the recovery delay of HP traffic with pre-programmed scheme is almost constant with the offered load thus improving the scalability of the network.

Fig. 8 shows the recovery delay vs. the processing time of an alarm with a fixed offered network load of 720 Erlang and a fixed path computation time of 50 ms. The relative behavior of the three compared schemes is confirmed where centralized scheme obtains the highest recovery delay while pre-programmed the lowest. Moreover, the recovery delay of centralized scheme is the only one significantly increasing with the alarm processing time validating the fact that this solution is not scalable. Finally, note that the gap between the hierarchical and pre-programmed schemes for HP traffic slightly increases with the processing time. Thus, making the pre-programmed scheme even more effective for complex alarms with high processing time. Thus, the proposed pre-programmed scheme provides the possibility to reduce the

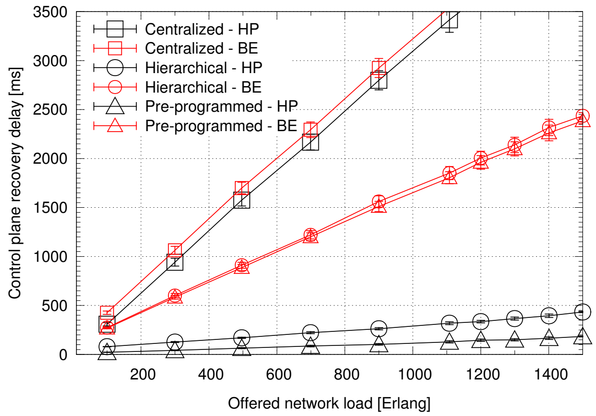

Figure 7. Control plane recovery delay vs. offered network load.

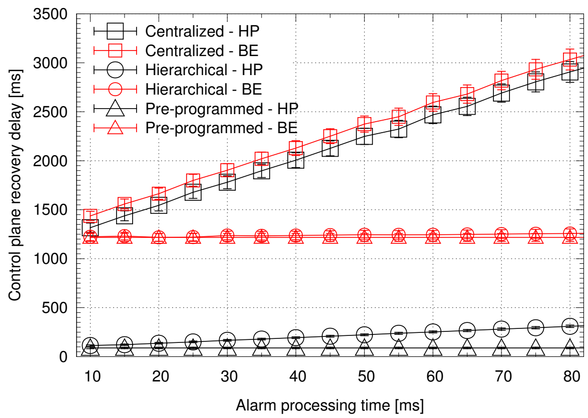

Figure 8. Control plane recovery delay vs. alarm processing time.

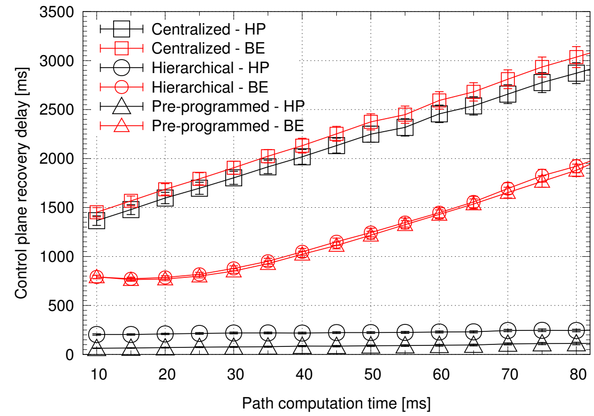

Figure 9. Control plane recovery delay vs. path computation time.

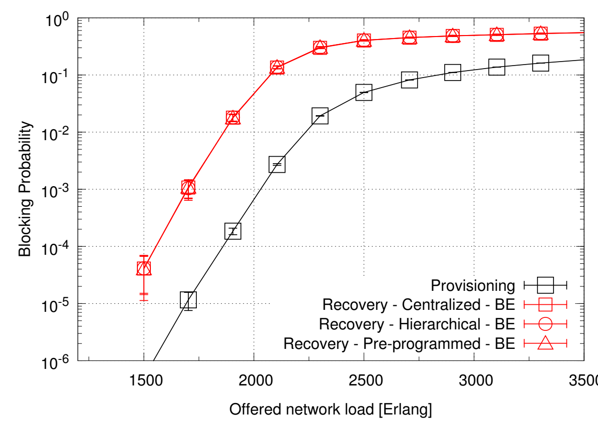

Figure 10. Recovery blocking probability vs. offered network load.

recovery time and to improve the network scalability. However, the flexibility in the selection of possible recovery actions could be reduced. Indeed, for more complex recovery actions (e.g. requiring the configuration of intermediate nodes or a new lightpath setup), the SDN controller should be involved.

Fig. 9 shows the recovery delay vs. the path computation time at the SDN controller with a fixed offered network load of 720 Erlang and a fixed alarm processing time of 50 ms. The relative behavior of the three compared schemes is again confirmed. Moreover, the figure shows that in the hierarchical and pre-programmed schemes, the recovery delay of HP traffic does not depend on the path computation time. Conversely, if the centralized scheme is used, also the recovery delay of HP traffic is degraded by high path computation time.

Finally, Fig. 10 shows the recovery blocking probability of BE traffic vs. the offered network load with both the processing time of each alarm and the path computation time fixed at 50 ms. For completeness, the provisioning blocking probability is also reported. The figure shows that the three proposed OAM schemes achieve the same performance in terms of recovery blocking probability of BE traffic.

VIII. Conclusion

This paper presented control and management of sliceable transponders through NETCONF in a SDN enviroment, where YANG models configuration and state transponder parameters. Currently, several consortiums and projects are working in the development of YANG models (also including transponders). The produced YANG codes are not fully aligned between consortium and consortium, and industry still has to find agreed models. From our side, the considered YANG model for sliceable transponder includes the relevant parameters defined by the aforementioned consortiums. Three OAM schemes are also presented considering scalability issues in the management of alarms. An high workload of a centralized controller to process alarms (e.g., due to soft failure) may result in delaying data plane device reconfiguration upon failure or degradation. Such issue can be overcome with smarter approaches like a hierarchical-based OAM or by pre-programming resilience schemes into data plane devices.

Future studies should also address dependencies within transponder configuration parameters. As an example, depending on the transponder technology, it may happen that if a central frequency is exploited by a sub-carrier module, this central frequency cannot be used by another sub-carrier module of the same transponder. Similarly, specific values of symbol rate and modulation format only enable the configuration of bit rate to a particular value (e.g., 28Gbaud and PM-QPSK result in a bit rate of 112 Gb/s). Such dependencies should be addressed with a proper syntax in the YANG model or with proper implementations of controllers and agents.

References

[1] N. Sambo, A. Giorgetti, M. Dallaglio, F. Cugini, and P. Castoldi, "Control and management of sliceable transponders," in *paper Th.1.A.5, Proc. of ECOC 2017*, sept. 2017.

[2] M. Jinno, H. Takara, Y. Sone, K. Yonenaga, and A. Hirano, "Multiflow optical transponder for efficient multilayer optical networking," *Communications Magazine, IEEE*, vol. 50, no. 5, pp. 56–65, 2012.

[3] N. Sambo, A. D'Errico, C. Porzi, V. Vercesi, M. Imran, F. Cugini, A. Bogoni, L. Potì, and P. Castoldi, "Sliceable transponder architecture including multiwavelength source," *JOCN*, 2014.

[4] N. Sambo, P. Castoldi, A. D'Errico, E. Riccardi, A. Pagano, M. S. Moreolo, J. M. Fabrega, D. Rafique, A. Napoli, S. Frigerio, E. H. Salas, G. Zervas, M. Nolle, J. K. Fischer, A. Lord, and J. P. F. P. Gimenez, "Next generation sliceable bandwidth variable transponders," *IEEE Communications Magazine*, vol. 53, no. 2, pp. 163–171, Feb 2015.

[5] A. Napoli and et al., "Next generation elastic optical networks: The vision of the european research project IDEALIST," *Communications Magazine, IEEE*, vol. 53, no. 2, pp. 152–162, Feb 2015.

[6] Y. Pointurier, "Design of low-margin optical networks," *IEEE/OSA Journal of Optical Communications and Networking*, vol. 9, no. 1, pp. A9–A17, Jan 2017.

[7] P. Soumplis, K. Christodoulopoulos, M. Quagliotti, A. Pagano, and E. Varvarigos, "Actual margins algorithm for multi-period planning," in *2017 Optical Fiber Communications Conference and Exhibition (OFC)*, March 2017, pp. 1–3.

[8] E. Seve, J. Pesic, C. Delezoide, and Y. Pointurier, "Learning process for reducing uncertainties on network parameters and design margins," in *2017 Optical Fiber Communications Conference and Exhibition (OFC)*, March 2017, pp. 1–3.

[9] L. Liu and et al., "Openslice: An OpenFlow-based control plane for spectrum sliced elastic optical path networks," in *Proc. of ECOC*, Sept 2012, pp. 1–3.

[10] F. Paolucci, F. Cugini, N. Hussain, F. Fresi, and L. Potì, "OpenFlow-based flexible optical networks with enhanced monitoring functionalities," in *Proc. of ECOC 2012*, 2012.

[11] M. Channegowda, P. Kostecki, N. Efstathiou, S. Azodolmolky, R. Nejabati, P. Kaczmarek, A. Autenrieth, J. P. Elbers, and D. Simeonidou, "Experimental evaluation of extended OpenFlow deployment for high-performance optical networks," in *2012 38th European Conference and Exhibition on Optical Communications*, Sept 2012, pp. 1–3.

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

[13] M. Dallaglio, N. Sambo, F. Cugini, and P. Castoldi, "Control and management of transponders with NETCONF and YANG," *IEEE/OSA JOCN*, vol. 9, no. 3, pp. B43–B52, March 2017.

[14] M. Bjorklund, "YANG - a data modeling language for the network configuration protocol (NETCONF)," IETF RFC 6020.

[15] A. Shaikh, T. Hofmeister, V. Dangui, and V. Vusirikala, "Vendor-neutral network representations for transport SDN," in *Proc. of OFC*, 2016.

[16] M. Dallaglio, N. Sambo, F. Cugini, and P. Castoldi, "YANG Models for vendor-neutral optical networks, reconfigurable through state machine," *IEEE Communications Magazine*, vol. 55, no. 8, pp. 170–178, 2017.

[17] "http://www.openconfig.net."

[18] "http://www.openroadm.org."

[19] "https://telecominfraproject.com/."

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

[21] N. Sambo, G. Meloni, F. Paolucci, F. Cugini, M. Secondini, F. Fresi, L. Poti, and P. Castoldi, "Programmable transponder, code and differentiated filter configuration in elastic optical networks," *JLT*, 2014.

[22] M. S. Moreolo, J. M. Fabrega, L. Nadal, F. J. Vilchez, A. Mayoral, R. Vilalta, R. Munoz, R. Casellas, R. Martinez, M. Nishihara, T. Tanaka, T. Takahara, J. C. Rasmussen, C. Kottke, M. Schlosser, R. Freund, F. Meng, S. Yan, G. Zervas, D. Simeonidou, Y. Yoshida, and K. I. Kitayama, "SDN-enabled sliceable BVT based on multicarrier technology for multiflow rate/distance and grid adaptation," *Journal of Lightwave Technology*, vol. 34, no. 6, pp. 1516–1522, March 2016.

[23] N. Sambo, G. Meloni, F. Paolucci, M. Imran, F. Fresi, F. Cugini, P. Castoldi, and L. Poti, "First demonstration of SDN-controlled SBVT based on multi-wavelength source with programmable and asymmetric channel spacing," in *Proc. of ECOC*, 2014.

[24] M. Dallaglio, Q. P. Van, F. Boitier, C. Delezoide, D. Verchere, P. Layec, A. Dupas, N. Sambo, S. Bigo, and P. Castoldi, "Demonstration of a SDN-based spectrum monitoring of elastic optical networks," in *Proc. of OFC*, 2017.

[25] J. Vergara and et al., IETF draft-vergara-flexigrid-yang-05, July 2017.

[26] R. Kunze and et al., IETF draft-ietf-ccamp-dwdm-if-mng-ctrl-fwk-06, June 2017.

[27] N. Sambo and et al., "Experimental demonstration of network automation based on qot estimation and monitoring in both single- and multi-domains," in *Proc. of ECOC*, Sept 2017, pp. 1–3.

[28] D. King and A. Farrel, "A PCE-based architecture for application-based network operations," IETF RFC 7491.

[29] X. Liu and et al., IETF draft-ietf-teas-yang-te-topo-13, October 2017.

[30] T. Saad and et al., IETF draft-ietf-teas-yang-te-09, October 2017.

[31] "https://github.com/nicola-sambo/SBVT."

[32] N. Sambo, F. Cugini, A. Sgambelluri, and P. Castoldi, "Monitoring plane architecture and OAM handler," *Journal of Lightwave Technology*, vol. 34, no. 8, Apr. 2016.

[33] "https://github.com/nicola-sambo/FSM."

[34] A. Giorgetti, F. Paolucci, F. Cugini, and P. Castoldi, "Dynamic restoration with GMPLS and SDN control plane in elastic optical networks [invited]," *J. Opt. Commun. Netw.*, vol. 7, no. 2, 2015.

[35] P. Layec, A. Dupas, A. Bisson, and S. Bigo, "QoS-aware protection in flexgrid optical networks," in *2017 Optical Fiber Communications Conference and Exhibition (OFC)*, March 2017, pp. 1–3.