

# Control Plane Solutions for Sliceable Bandwidth Variable Transceivers in Elastic Optical Networks

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**Abstract**—Elastic Optical Networks (EON) are characterized by a flexible grid in which the so called "frequency slots" are allocated dynamically and based on the client signal data rate and modulation format and rely on bandwidth variable transceivers (BVT) and bandwidth variable cross-connects (OXC). A control plane (CP) is used for the efficient and dynamic provisioning of optical connections with recovery. Such emerging optical technologies bring new requirements to the CP related to the efficient flexible spectrum allocation, co-routed connection setup and dynamic and low latency configuration of optical parameters.

Two main CP architectures coexist, with functions like end-point and node addressing, automatic topology discovery, network abstraction, path computation and connection provisioning: the distributed Generalized Multi Protocol Label Switching (GMPLS) – with optional Path Computation Element (PCE) and instantiation/modification – and a control plane based on Software Defined Networking (SDN) with a logically centralized controller and an open protocol such as OpenFlow.

The design of such a CP should involve the abstraction and modeling of the aforementioned new optical devices, and the integration of their capabilities and restrictions. In this paper, we report the specific activities related to integrating (sliceable) bandwidth variable transceivers both into GMPLS and OpenFlow. We define protocol extensions that are experimentally evaluated in scenarios deployed in testbeds.

## I. INTRODUCTION

For the last years, Wavelength Switched Optical Networks (WSONs) have been evolving towards flexi-grid networks. WSON were designed assuming that the optical channels have a fixed spacing and client signals use a fixed amount of optical spectrum (e.g. 50 GHz enabling a 100 Gb/s data rate transmission to use 37.5 GHz with DP-QPSK), but the fixed grid is not adapted for higher data rates and a more efficient management of the optical spectrum is required. In [1] nominal central frequencies (NCFs) are defined with a 6.25 GHz granularity and the required amount of optical spectrum is allocated in "frequency slots" (FS) with variable width. Enablers for flexi-grid networks are the bandwidth-variable transponders (BVT), which generate optical signals supporting multiple modulation formats and bit-rates that can be dynamically modified as well as bandwidth variable optical cross-connects (BV-OXC or Flex-OXC), devices able to switch the signals based on a center frequency and spectrum width.

The ICT IDEALIST project [2], [3] targets architectural design, protocol specification, evaluation and standardization of a control plane, considering both the mature GMPLS/PCE control plane technology as well as the new Software Defined Networking (SDN) approach. The current scope is the control of the media layer [4]: a network media channel transports a single Optical Tributary Signal, or OTS.

## II. SLICEABLE BANDWIDTH VARIABLE TRANSCEIVERS

The reference SBVT (also referred to as Multi-Flow Optical Transponder or MF OTP) architecture is shown in Fig. 1 [5], [6]. It consists of a Configurable/Sliceable Flexible interface module, an optional Flow Distributor module, a Sub-carrier Generation module and a Multi-flow Optical Module. The Configurable/Sliceable Flexible interface module receives client tributaries. The module adapts, through electronic processing, the service information content (e.g., coming from the IP layer) to the photonic layer. This typically involves the adaptation to the Optical Transport Hierarchy (OTH) of the Optical Transport Network (OTN), as detailed in [7], enabling the introduction of forward error correction (FEC) and monitoring information. This way, client traffic can be flexibly adapted, according to a predefined granularity (e.g., 100Gb/s) to a number  $N$  of flows. As an example, 1Tb/s client traffic can be segmented to  $N=5$  flows, to be transported in the network over  $N=5$  Polarization Multiplexed 16-Quadrature Amplitude Modulation (PM-16QAM) sub-carriers. As a further example, 400Gb/s client traffic can be segmented to  $N=4$  flows, to be transported over 100Gb/s Polarization Multiplexed Quadrature Phase-Shift Keying (PM-QPSK) sub-carriers.

A Flow Distributor module can be optionally encompassed. It is an electronic switching matrix which can be used to direct each OTN flow provided by the Configurable/Sliceable Flexible interface module to a specific Flex Sub-carrier module, included within the subsequent Multiflow Optical module, which is in charge of the generation of the  $N$  optical flows. The module relies on a Sub-carrier Generation module for the generation of non-modulated optical sub-carriers.

The Sub-carrier Generation module consists of either in an array of independent laser sources or in a single multi-wavelength source. In the former case, all laser sources are

independent, i.e. their central frequency can be configured to any value within the C band and without additional constraints. In the latter case, the central frequencies within the multi-wavelength source are not independent, i.e., they have to be contiguous with a spectral separation typically limited within few hundreds GHz. Thus, when the sliceable functionality is exploited, additional constraints have to be considered in the routing and spectrum assignment process. However, a multi-wavelength source is less expensive and guarantees more stability than independent laser sources, thus enabling better subcarrier compactness when the sliceable functionality is not exploited (i.e., all sub-carriers are co-routed and contiguous), in turn guaranteeing higher spectral efficiency [6].

The  $N$  independent flows from the OTN layer (in the form of electrical multi-lane aggregates) are then used to modulate the optical sub-carriers within the Multiflow Optical module.

At the transmitter side, data can be encoded, shaped (filtering), and pre-distorted to compensate for possible distortions introduced by the optical layer. Digital-to-analogue converters (DACs) are exploited to adapt the modulation format (e.g., providing multi-level signals for 16QAM). IQ modulators are exploited to modulate each sub-carrier, while polarization rotator (PR) are used to have orthogonal polarizations, needed for polarization multiplexing. All generated sub-carriers are optically multiplexed into a single add/drop port of the Ingress Optical Cross Connect (Flex-OXC or BV-OXC) node.

The multiplexed sub-carriers are then passed to the ingress Flex-OXC optical node. Proper filter configurations are performed according to frequency slot indications. In particular, the BV-WSS filters of the Flex-OXC are configured such that the multiplexed sub-carriers are routed toward the requested outgoing links. Note that, in case the sliceable functionality is exploited, multiple media channels may be generated along different outgoing links and routed across the photonic network up to specific destination node(s).

At the SBVT receiver side, coherent detection is exploited. A polarization beam splitter divides the signal into two arbitrary orthogonal polarizations, which are superimposed with the output of a local oscillator. This laser source is characterized by narrow line-width and higher power compared to the detected signal, thus enhancing the receiver sensitivity.

The polarization components are fed into a 90° hybrid, and afterward mixed with the local oscillator to separate the in-phase and quadrature components, which are then detected by balanced photo-diodes (BPD). This is followed by a radio-frequency amplifier (RFA), and four high-speed analog-to-digital converters (ADCs). Standard DSP blocks such as clock recovery, equalizer and phase recovery follow and terminate the receiver. Finally, decision on the received data and decoding are performed.

The super-channel configuration is achieved by providing the control plane module of the node controller with the number of active sub-carriers and, for each subcarrier, its central frequency modulation format, coding, spectral shaping, FEC and baud-rate.

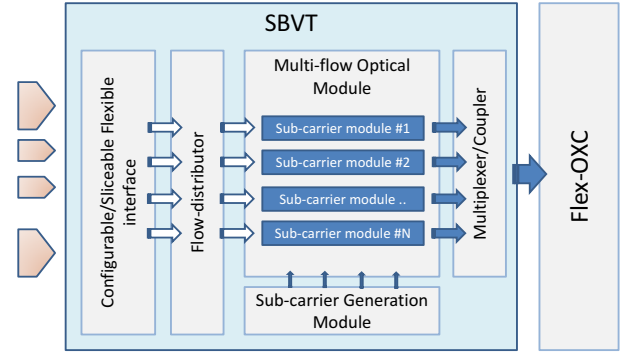


Fig. 1. SBVT architecture

### III. A CONTROL PLANE FOR EON

A CP aims at fulfilling the requirements of fast and automatic end-to-end provisioning and re-routing of flexi-grid connections, covering common functions like addressing, automatic topology discovery, network abstraction, path computation, and connection provisioning. The CP functions can, on a first approach, be distributed or centralized. Either way, they need to be extended to address the new requirements associated to the aforementioned optical technologies: flexible spectrum allocation or efficient co-routed connections. The selection of a centralized or distributed control plane is conditioned by aspects such flexibility and extensibility, availability, already installed deployments, and actual network size and scalability.

#### A. GMPLS Distributed Control Plane

A set of cooperating entities (controllers) execute the CP functions in a distributed manner: each node disseminates the topological elements that are directly under its control and the IGP routing protocol enables the construction of a unified view of the network topology. Path computation is carried out by the ingress node of the connection and signaling is distributed along the nodes involved in the path. The reference architecture is defined by the ITU-T ASON and relies on the GMPLS set of protocols defined by the IETF. A data communication network, based on IP control channels allows the exchange of control messages between GMPLS controllers. Each GMPLS controller manages the state of all the connections (i.e., LSPs) originated, terminated or passing-through a node, and maintains its own network state information (topology and resources), collected in a local Traffic Engineering Database (TED).

#### B. SDN/OpenFlow Control Plane

A single entity (controller) is responsible for the CP functions, commonly using open and standard protocols, such as the OpenFlow protocol (OF/OFPP). The SDN controller performs path computation and service provisioning, configuring the forwarding and switching behavior of the nodes. A centralized control plane provides a method for programmatic control of network resources and simplification of control

plane process. By deploying the control plane intelligence in the controller, resources allocated in hardware nodes for CP functions can be reduced. Such solutions may involve deploying hardware (computational and storage) which is orders of magnitude more powerful than individual controllers.

#### IV. CONTROL PLANE EXTENSIONS FOR SBVT

Regardless of the technology, a control plane for flexi-grid networks must take into account the functionalities, capabilities and restrictions of BVT for an efficient end-to-end service provisioning. In this section, we detail the extensions in terms of protocols and processes. Figure 2 shows the considered architectures, and the flow of messages involved in the provisioning of services.

##### A. GMPLS Extensions

The OSPF-TE protocol has been extended to support the dissemination, via Link and Node Link State Advertisements (LSAs) of TE attributes, gathered into the TED, which is used as input in the path computation (given the specifics of the optical layer, executed at the PCE). The TED captures the status of the TE links and specific attributes of the SBVTs such as the equipped and unused number of sub-carriers per direction (Tx or Rx) along with the aggregated status of the NCFs [8]. The dissemination of the NCF status per TE link is achieved via the Interface Switching Capability Descriptor (ISCD) sub-TLV [9]. The extensions for controlling SBVT-specific resources (i.e., sub-carriers) are twofold: First, OSPF-TE floods the MF OTP attributes using the Port Label Restriction (PLR) sub-TLV, conveying the number of total and available sub-carriers per direction within a MF OTP which can be complemented with the status of the NCFs over the link connecting the MF OTP and its corresponding BV OXC [8]. Second, the signaling protocol conveys information to allow resource reservation and configuration of the optical sub-systems along the path. Once the route is computed, it is passed as an explicit route object (ERO) to the RSVP-TE protocol to set up the LSP. The ERO contents or sub-objects are formed by unnumbered interface IDs, followed by the Label subobject specifying the FS (i.e.,  $n$  and  $m$ ), and at the LSP endpoints, new proposed Transponder subobjects. These Transponder sub-objects allow the endpoints to configure their respective MF OTPs. The Transponder subobject is formed by a variable list of Transponder TLVs. This set of TLVs allows the configuration of a set of sub-carriers forming a super-channel LSP. Each Transponder TLV contains 4 sub-TLVs used to determine: the sub-transponder ID, the sub-carrier FS, the modulation format and the FEC, respectively.

##### B. OpenFlow Extensions

OF version 1.3 supports optical flows provisioning and control. However, flexi-grid is not supported yet and a number of significant parameters and attributes are missing in order to properly configure SBVTs. Initial proposals for extensions specifically suitable for flexi-grid optical networks and SBVT have been presented [10]–[12].

The FLOW\_MOD message, sent by the network OF Controller to the OF node (or Agent), is responsible for configuration of flow entries in each node of the flow. The FLOW\_MOD has to be extended to enforce the proper configuration of the selected SBVT. First, the flexi-grid label (e.g., grid type, channel spacing, central frequency, filter width) is required to configure the Flex-OXC BW-WSS filters of the selected output port of the node. Then, the proper configuration of the selected SBVT requires the indication of the card transmission parameters comprising the following attributes: single/multi carrier optical channel, number of sub-carriers, specification of the sub-carriers including baud rate, central frequency, subcarrier width, modulation format, FEC, code type and rate. Additional proprietary parameters could be included, as the Nyquist flag specified in [13].

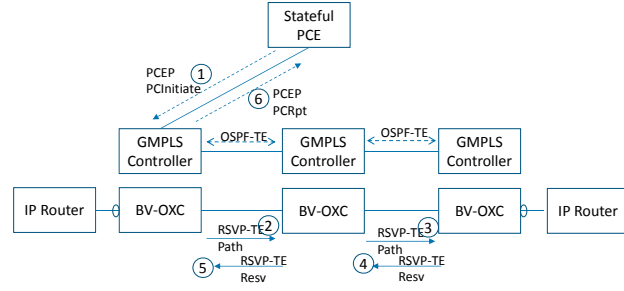
When a single co-routed media channel is computed, a single FLOW\_MOD per node is forwarded. Whereas, when sliceability is considered, the configuration of different media channels originating from the same SBVT is provided with different FLOW\_MOD messages (possibly bundled, if originating from combined computation), each one with different configurations of the Flex-OXC output ports and BV-WSS filters. Therefore, such extensions fully enable the sliceable functionality. Specific extensions enable the implementations of sliceability comprising programmable and asymmetric multi-wavelength (PAMW) signal generation [14]. In particular, the *laser\_type*, *laser\_id* and *tone\_id* attributes identify the laser source type physical laser and the laser instance utilized for that flow. Flex-OXC and SBVT configurations are acknowledged by means of asynchronous or synchronous mechanisms (e.g., using extended PORT\_STATUS messages or novel FLOW\_ACK messages).

The extensions imply that detailed SBVT information (e.g., node architecture, type and number of installed transponders, node/card capabilities) are available at the controller performing advanced path computation including spectrum and transmission parameters assignment. Node/SBVT information can be provided by means of either discovery procedures or enhanced controller-agent OpenFlow session handshake describing the OpenFlow switch architecture and available capabilities [10].

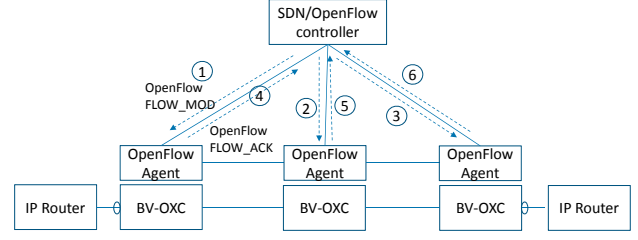
#### V. EXPERIMENTAL PROOF-OF-CONCEPT AND ANALYSIS

In the first experimental testbed, we consider the dynamic establishment of LSP. Each demand  $r$  specifies the source  $s$  and destination  $d$  and the bit rate ( $b$ ). A distance-adaptive RSMA algorithm computes a feasible path specifying the spatial path (ERO), the FS ( $n$  and  $m$ ), the modulation format (DP-QPSK, DP-8QAM or DP-16QAM) and the selected sub-carrier IDs (more than one for super-channel LSPs). If the RSMA computation succeeds, a PCInitiate message is sent from the PCE to the ingress node to trigger the signaling.

We evaluate the performance when the number of sub-carriers at the MF OTPs is varied. Two RSMA algorithms using MF OTP *partial* or *full* information [8] are applied. In the *partial* model, the RSMA is provided only with the



(a) GMPLS/PCE Control Plane architecture and associated message flow showing PCEP and RSVP-TE messages



(b) SDN/OPENFLOW Control Plane architecture and associated OpenFlow message flow

Fig. 2. Considered Control Plane technologies and integration of SBVTs.

available number of sub-carriers per direction (Tx and Rx) at each MF OTP. In the *full* model the *partial* view is extended with the dissemination of the aggregated optical spectrum utilization (NCFs) in the link between the MF OTP and the BV-Flex-OXC. The latter is crucial to facilitate the RSMA selecting a feasible FS which avoids overlapping with the optical spectrum occupied by other flows/sub-carriers as well as dealing with the spectrum continuity constraint (SCC).

The topology is the 14-nodes Spanish network, with links supporting 128 NCFs (6.25GHz spacing). Arrivals follow a Poisson process with mean inter-arrival time of 10s and mean holding time (exponentially modeled) of 100s. Both  $s$  and  $d$  are randomly selected. The requested  $b$  is uniformly distributed as multiples of 100 Gb/s up to 500 Gb/s. The RSMA algorithm iteratively computes a path starting with the most spectral efficient modulation format, i.e., starting from DP-16QAM, DP-8QAM and finally DP-QPSK.

Average setup delay seen by the PCE is around 50ms, including around 10ms for the RMSA algorithm and an average of 40ms for signaling delay, not including hardware latencies. Figure 3 depicts the LSP blocking probability (BP) when the number of sub-carriers per MF OTP is varied (i.e., 5, 10, 15 and 20). The *full* model leads to attain a better BP compared to the *partial*. LSP failures are basically due to path computation failure (RSMA) or signaling error. The former is mainly caused by the lack of available sub-carriers. The latter (signaling errors) occurs when the LSP is being set up. In the *partial* model, the lack of optical spectrum information on the MF OTP interfaces severely complicates the signaling to address both the contention with other flows and the required end-to-end SCC. On the other hand, the *full* model allows mitigating this since the RSMA algorithm computes paths being aware of the NCF status in all the network links including those connecting MF OTPs with the BV OXCs. Thus, the *full* model better addresses the SCC. As the number of sub-carriers is increased the BP attained by *full* model is enhanced since the lack of sub-carriers is less troublesome for the RSMA computation. In the *partial*, the increase of the number of sub-carriers also allows enhancing the BP but up to a certain value (10 sub-carriers). Above this value, observe that the improvement is negligible since the errors are not the

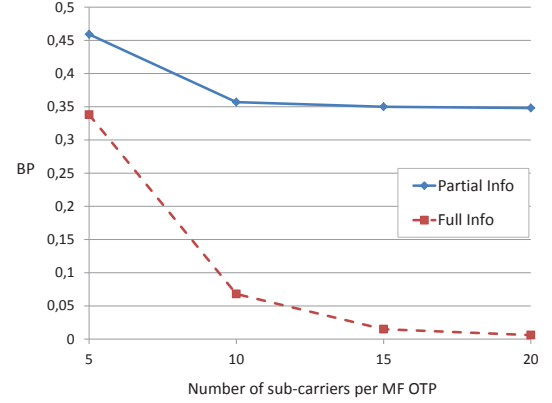


Fig. 3. BP vs number of sub-carriers per MF OTP for *partial* and *full* RSMA

lack of available sub-carriers during computation but the SSC problems when signaling.

The OpenFlow extensions reported in Sec. IV-B have been employed in a real SDN data/control plane experimental testbed at CNIT labs. The EON data plane includes SBVT prototypes with advanced functionalities generating configurable PM-QPSK-modulated superchannels at up to 1 Tb/s exploiting Time Frequency Packing (TFP) technique and coherent detection; commercially available BV-WSSs with configurable filter of 1 GHz granularity; fixed-length optical links (optical amplifiers, fiber spans) and configurable optical recirculating loop to setup different optical reach distances.

Such devices are controlled and dynamically configured by OpenFlow-enabled agents called FlexSwitch, collocated at each network node. OpenFlow sessions are established among each FlexSwitch and the southbound interface of the central OpenFlow controller called FlexController [11], capable of lightpath setup, tear down and dynamic adaptation. In particular, adaptation options include path rerouting, elastic operations (e.g., additional subcarrier activation due to bandwidth increase request), hitless spectrum shifting and code rate change based on the TFP technique [13], [15]. The FlexController stores a TED and a flow database, which are kept updated by information retrieved by FLOW\_ACK messages in the case of controller-driven actions, and by PORT\_STATUS messages in the case of asynchronous events

(e.g., failure, QoT degradations). The TED is enriched with information related to node architecture, functionalities and available modules. The controller implements impairment-aware path computation also accounting for the SBVT capabilities at source and destination (i.e., available/configurable physical parameters). Different path computation and adaptation algorithms are utilized, mainly based on least congested spectrum K-shortest path subject to spectrum continuity constraint and QoT validation, and may include multiple (either in parallel or sequential fashion) actions output [16].

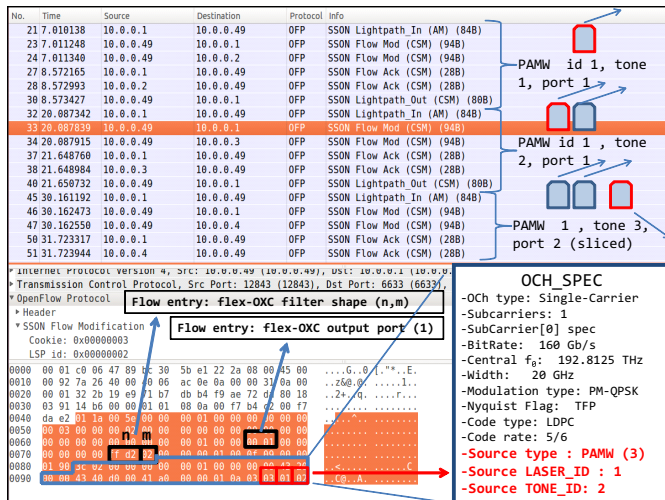


Fig. 4. Capture of extended OpenFlow messages for SBVT lightpath setup.

## VI. CONCLUSIONS

This paper summarizes recent advances in the control of EON, taking into account the capabilities of SBVT. We considered the two CP technologies, GMPLS and OpenFlow. In both cases, we have presented design considerations and the proposed protocol extensions and procedures. To illustrate and validate the approach, two scenarios have been detailed and executed in experimental testbeds. Although exhaustive

performance evaluation is not the scope of this work, the numerical results assess the approaches and provide some insight on parameters such as setup delays and control plane overhead.

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## REFERENCES

- [1] "ITU-T Recommendation G.694.1, Spectral grids for WDM applications: DWDM frequency grid."
- [2] "The IDEALIST ICT project: Industry-Driven Elastic and Adaptive Lambda Infrastructure for Service and Transport Networks." [Online]. Available: <http://www.ict-idealisteu/>
- [3] R. Casellas *et al.*, "IDEALIST Control Plane Architecture for Multi-domain Flexi-Grid Optical Networks," in *European Conference on Networks and Communications (EUCNC)*, Jun. 2014.
- [4] "ITU-T Recommendation G.872, Architecture of optical transport networks."
- [5] N. Sambo *et al.*, "Next generation sliceable bandwidth variable transponder," *IEEE Communications Magazine*, 2015.
- [6] N. Sambo, A. D'Errico, C. Porzi, V. Vercesi, M. Imran, F. Cugini, A. Bogoni, L. Poti, and P. Castoldi, "Sliceable transponder architecture including multiwavelength source," *Optical Communications and Networking, IEEE/OSA Journal of*, vol. 6, no. 7, pp. 590–600, July 2014.
- [7] "Interfaces for the optical transport network (otn)," *ITU-T Recommendation G.709*, Dec. 2009.
- [8] R. Martínez, R. Casellas, R. Vilalta, and R. Muñoz, "Experimental Assessment of GMPLS/PCE-controlled Multi-Flow Optical Transponders in FlexGrid Networks," in *Proc. of Optical Fiber Communication Conference and Exposition (OFC)*, March 2015.
- [9] X. Zhang, H. Zheng, R. Casellas, O. Gonzalez, and D. Ceccarelli, "GMPLS OSPF-TE Extensions in support of Flexible Grid," IETF draft-ietf-ccamp-flexible-grid-ospf-ext-01.txt, December 2014.
- [10] R. Casellas, R. Martínez, R. Muñoz, R. Vilalta, L. Liu, T. Tsuritani, and I. Morita, "Control and management of flexi-grid optical networks with an integrated stateful path computation element and OpenFlow controller [invited]," *Optical Communications and Networking, IEEE/OSA Journal of*, vol. 5, no. 10, pp. A57–A65, Oct 2013.
- [11] F. Paolucci, A. Castro, F. Cugini, L. Velasco, and P. Castoldi, "Multipath restoration and bitrate squeezing in SDN-based elastic optical networks [invited]," *Photonic Network Communications, Springer*, vol. 28, pp. 45–57, 2014.
- [12] L. Liu, H. Choi, R. Casellas, T. Tsuritani, I. Morita, R. Martínez, and R. Muñoz, "Demonstration of a dynamic transparent WSON employing flexible transmitter/receiver controlled by an OpenFlow/stateless PCE integrated control plane," in *Optical Fiber Communication Conference and Exposition (OFC) and The National Fiber Optic Engineers Conference (NFOEC)*, Anaheim, California, USA, March 2013.
- [13] 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," *Lightwave Technology, Journal of*, vol. 32, no. 11, pp. 2079–2086, June 2014.
- [14] 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 *Optical Communication (ECOC), 2014 European Conference on*, Sept 2014, pp. 1–3.
- [15] N. Sambo, F. Paolucci, G. Meloni, F. Fresi, L. Poti, and P. Castoldi, "Control of frequency conversion and defragmentation for super-channels [invited]," *Optical Communications and Networking, IEEE/OSA Journal of*, vol. 7, no. 1, pp. A126–A134, Jan 2015.
- [16] F. Paolucci, A. Castro, F. Fresi, M. Imran, A. Giorgetti, B. B. Bhowmik, G. Berrettini, G. Meloni, F. Cugini, L. Velasco, L. Poti, and P. Castoldi, "Active pce demonstration performing elastic operations and hitless defragmentation in flexible grid optical networks," *Photonic Network Communications*, vol. 29, no. 1, pp. 57–66, 2015. [Online]. Available: <http://dx.doi.org/10.1007/s11077-014-0464-0>