SDN-enabled Sliceable BVT Based on Multicarrier Technology for Multi-Flow Rate/Distance and Grid Adaptation

Michela Svaluto Moreolo, *Senior, IEEE*, Josep M. Fabrega, Laia Nadal, F. Javier Vílchez, Arturo Mayoral, Ricard Vilalta, Raul Muñoz, *Senior, IEEE*, Ramon Casellas, *Senior, IEEE*, Ricardo Martínez, *Senior, IEEE*, Masato Nishihara, Toshiki Tanaka, Tomoo Takahara, Jens C. Rasmussen, Christoph Kottke, Michael Schlosser, Ronald Freund, Fanchao Meng, Shuangyi Yan, Georgios Zervas, Dimitra Simeonidou, Yuki Yoshida, Ken-ichi Kitayama, *Life Fellow, IEEE*

Abstract—**We propose a sliceable bandwidth variable transceiver (S-BVT) architecture suitable for metro/regional elastic networks and highly scalable data center (DC) applications. It adopts multicarrier modulation (MCM), either OFDM or DMT, and a cost-effective optoelectronic front-end. The high-capacity S-BVT is programmable, adaptive and reconfigurable by an SDN controller for efficient resource usage, enabling unique granularity, flexibility and grid adaptation, even in conventional fixed-grid networks. We experimentally demonstrate its multiple advanced functionalities in a four-node photonic mesh network. This includes SDN-enabled rate/distance adaptive multi-flow generation and routing/switching, slice-ability, flexibility and adaptability for the mitigation of spectrum fragmentation as well as for a soft migration towards the flexi-grid paradigm.**

Index Terms—**Sliceable bandwidth variable transceiver (S-BVT), multicarrier modulation, OFDM, DMT, adaptive bit/power loading, software defined networking, flexi-grid networks, WDM networks, inverse multiplexing.**

I. Introduction

In order to address the evermore increasing demand of data-intensive traffic and new services delivery, while flexibly and efficiently managing the available network resources, programmable adaptive transceivers are arising as key enabling elements [1]-[4]. Particularly, the sliceable bandwidth variable transceiver (S-BVT) plays an important role in the operation of next-generation optical networks, by supporting the on-demand configuration of programmable network functions, such as rate, bandwidth, path adaptation, switching and slice-ability [3].

The choice of a suitable transmission technology, facilitating flexibility, adaptability and other advanced functionalities, is crucial for the transceiver design. Cost-effectiveness and scalability are also key design issues particularly for the aggregation/metro network segments and data center (DC) applications [5]-[8].

The combination of digital signal processing (DSP) with multicarrier modulation (MCM), namely orthogonal frequency division multiplexing (OFDM) and, its simplified variant, discrete multitone (DMT), represents an attractive candidate for the implementation of programmable adaptive transceivers. The DSP enables software-defined multi-rate, multi-format, multi-reach and multi-flow optical transmission [3]. Whereas the MCM enables a wide range of granularities (comprising sub- and super-wavelength) with unique flexibility and scalability [9], [10]. In particular, spectral manipulation at the subcarrier level is possible for optimizing the transmission performance and the transceiver capacity, according to the traffic demand, the available bandwidth and the path/channel condition [11].

Thus, in order to face the challenges of the rapid growth of traffic and services to be supported by future optical network, we propose an S-BVT architecture based on MCM technology.

In addition, the S-BVT adopts a cost-effective optoelectronic front-end based on direct detection (DD), making it suitable for inter-DC communication and elastic metro/regional networks.

We demonstrate that the proposed transceiver provides multiple advanced functionalities for optimal network resource usage, including slice-ability, rate/distance and bandwidth adaptability, inverse multiplexing and flexible adaptation to the fixed-grid technology [12].

The S-BVT can be remotely programmed – that is, it can have its functions and operations mode remotely configured –, in view of its integration in a Software Defined Network (SDN) based control plane. This is accomplished by means of an SDN agent, which has been designed and implemented. The agent's

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M. Svaluto Moreolo, J. M. Fabrega, L. Nadal, F. J. Vílchez, A. Mayoral, R. Vilalta, R. Muñoz, R. Casellas, and R. Martínez are with the Centre Tecnològic de Telecomunicacions de Catalunya (CTTC), Castelldefels, Spain (e-mail: michela.svaluto@cttc.es).

M. Nishihara, T. Tanaka, T. Takahara, and J. C. Rasmussen are with Fujitsu LTD., Kawasaki, Japan.

C. Kottke, M. Schlosser, and R. Freund are with Fraunhofer HHI, Berlin, Germany.

F. Meng, S. Yan, G. Zervas, and D. Simeonidou are with the University of Bristol, Bristol, UK.

Y. Yoshida, and K. Kitayama are with Osaka University, Osaka, Japan.

purpose is to map high-level operations coming from an SDN controller into low-level, hardware-dependent operations. This involves defining an information and data model for the S-BVT and agreeing on a so called SDN controller south-bound interface (SBI) – with the corresponding message formats and encodings – towards the agent/S-BVT.

We demonstrate the integration of the S-BVT in a four-node photonic mesh network, namely the CTTC ADRENALINE (All-optical Dynamic REliable Network hAndLINg IP/Ethernet Gigabit traffic with QoS) testbed. The network is, itself, controlled by a generalized multi-protocol label switching (GMPLS) control plane, extended with an active stateful path computation element (AS-PCE) for path computation and provisioning [13]. The AS-PCE acts as a unique interfacing element for the aforementioned SDN controller, ultimately delegating the dynamic lightpath provisioning and establishment of connections (termed Label Switched Paths or LSPs) to the underlying GMPLS control plane.

The optical path and requested/supported rate are software-defined, according to the channel profile, transmission impairments and traffic demand; data flows are selectively filtered and switched to be suitably routed over the network.

Consequently, the SDN controller is responsible for coordinating both the programming of the S-BVTs via their agents and the provisioning of optical channels within the GMPLS/PCE optical network.

In this paper, we extend the content presented in [12] of both data plane and control plane aspects related to the SDN-enabled S-BVT architecture and functionalities demonstration.

Specifically, in Sec. II we thoroughly describe the S-BVT, detailing its building blocks, enabling elements and advanced features. Section III analyzes the S-BVT functionalities, presenting their experimental validation using a multi-partners set-up for different scenarios in the network testbed. They are discussed point by point and the obtained results are summarized and compared in the final subsection. The control plane aspects are expanded in Sec. IV, providing details on the SDN control of the S-BVT and the optical network, related to the experimental assessment. Finally, concluding remarks are provided in Sec. V.

II. S-BVT Architecture and Advanced Features

The S-BVT consists of rate/distance adaptive bandwidth variable transmitter (BVTx) and receiver (BVRx) array, as shown in Fig. 1. The S-BVT building block is based on MCM technology, either OFDM or DMT, enabling individual subcarrier manipulation, channel signal-to-noise ratio (SNR) estimation and equalization. At the multicarrier adaptive DSP modules of the S-BVTx, the OFDM/DMT subcarriers can be individually configured to arbitrarily use any modulation format for the generation of each rate/distance adaptive flow/slice. The bit loading (BL) allows fine bit rate selection and efficient spectrum usage. In order to optimize the system performance, subcarriers with lower SNR ratio are loaded with data mapped with the most robust modulation format and with the strongest code; while a higher number of bits per symbol is

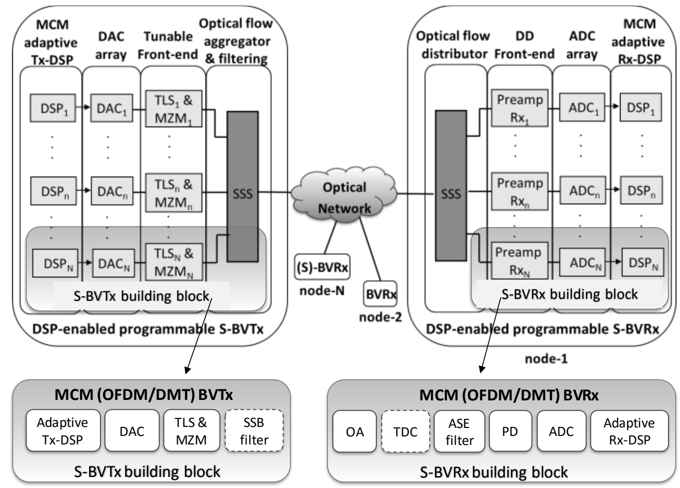

Fig. 1. S-BVT architecture and building blocks.

assigned to the subcarriers with higher SNR (see the insets of Fig. 3). Power loading (PL) is also implemented at the DSP: each subcarrier is multiplied by a gain coefficient to adaptively vary its power according to the SNR profile. This introduces additional flexibility to the system, enhancing the overall performance. Thus, to achieve the target bit rate (and bandwidth occupancy) or expected performance in terms of bit error rate (BER), margin adaptive (MA) or rate adaptive (RA) BL/PL algorithms are executed at the DSP of each S-BVT building block [11], [14], [15]. The adaptive parameters can be suitably selected according to the requested demand, channel profile and network path to be supported.

After the BL/PL DSP modules for adaptive mapping, MCM (OFDM or DMT) is performed. The S-BVTx DSP also includes the insertion of training symbols (TS) for data-aided retrieving of channel state information, which is used for the SNR profile estimation in the BL/PL algorithm [11]. Also a cyclic prefix (CP) is added for reducing the OFDM/DMT inter-symbol interference (ISI) and inter-channel interference (ICI).

The digital signals after the DSP blocks are converted to analog by a digital-to-analog converter (DAC) array.

The S-BVTx optoelectronic front-end consists of an array of N tunable laser sources (TLS) and external Mach-Zehnder modulators (MZM). The array of N TLS can be also implemented as a single laser generating an optical frequency comb of N lines [3]. Both double sideband (DSB) and single sideband (SSB) transmission, can be combined with cost-effective direct detection (DD). The use of SSB, or either vestigial sideband (VSB), increases the robustness against chromatic dispersion (CD) for longer reach transmission [16], [17]. The generated N flows are aggregated by a spectrum selective switch (SSS), which acts as both aggregator and (SSB/VSB) filter bank.

The aggregated flow can be further sliced into data flows with less capacity, concurrently serving multiple destination nodes at variable rate. Furthermore, the traffic demand can be split into multiple flows routed via multiple independent paths to the same end-node, enabling inverse multiplexing [18].

At the S-BVRx, the received flow is distributed by an SSS to the pre-amplified receivers of the DD front-end. The pre-

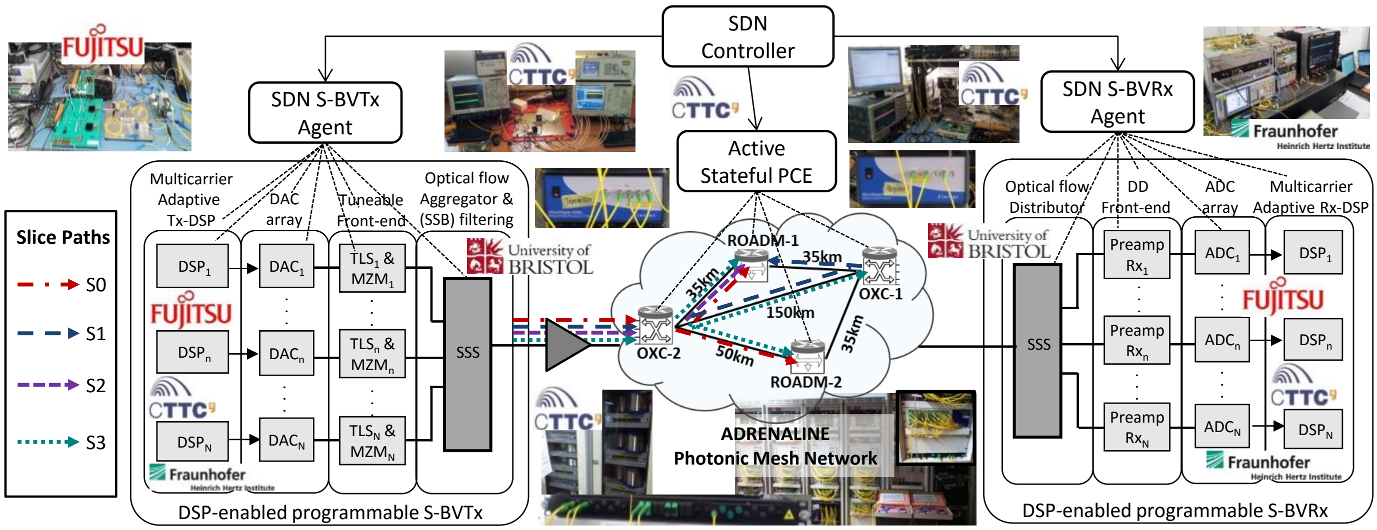

Fig. 2. SDN-enabled S-BVT: schematic and multi-partner experimental set-up. Slice paths established in the analyzed scenarios over the GMPLS-controlled (with PCE) ADRENALINE network are indicated: S0 with dashed-dotted red line, S1 with dashed blue line, S2 with short-dashed purple line, S3 with dotted green line.

amplified filtering stage includes an optical amplifier (OA) and a filter for limiting the amplified spontaneous emission (ASE) noise; it can also include (e.g. in case of using DSB DMT) a tunable dispersion compensator (TDC, indicated in the inset of Fig. 1 with dashed line). After photodetection (PD), analog-to-digital conversion is implemented by an ADC array. Then, the signals are off-line post-processed at the DSP modules, including multicarrier demodulation, data-aided synchronization/equalization and symbols demapping.

Each slice can potentially support up to 100Gb/s net bit rate.

By varying the TLS and the individual subcarrier loading, the optical carrier of each flow can be adapted to the available channel, while suitably allocating and/or squeezing the bandwidth for optimal spectral usage. Similarly, the radio frequency (RF) carrier can be tuned at the DSP, by means of digital upconversion. These features allow a soft migration of fixed grid networks towards a flexible architecture. The fine granularity of MCM also enables a subcarrier-based spectrum defragmentation, without requiring a network re-optimization.

Additionally, since the programmable S-BVT is based on MCM, it intrinsically provides self-performance monitoring in the electrical domain (at the edge-node of the network) [9]. In fact, a set of system parameters required for channel estimation/equalization are acquired thanks to the overhead of information transmitted for a correct detection. It is worth mentioning that, in-band optical SNR (OSNR) monitoring of individual subcarriers can be performed by using a high-resolution optical spectrum analyzer. This enables non-intrusive signal quality monitoring per subcarrier at the nodes of the network. In [19], it has been demonstrated that the measurements in the optical domain are correlated with the electrical SNR and the performance indicator estimated at the edge-node MCM-based receiver. According to the acquired live monitoring information, the control layer can dynamically reconfigure the S-BVT parameters to cope with the signal degradation at specific subcarriers, activating the resiliency mechanism without the need for optical-to-electrical conversion and data demodulation. Indeed, also the OSNR can be estimated from the DSP outcomes. However, it must be taken into account that the response of the optical/electrical components of the receiver is not ideal. Particularly, integrated receivers can be seen as a black box, leading to uncertainty in the evaluation of the OSNR through the electrical SNR. This is often the case when the adopted transceivers are pluggable modules, which is the current preferred option in the metro transport and datacom evolution. In order to avoid the occurrence and prevent the impact of possible systematic errors of the proposed OSNR measuring technique in the software-definition of the optical path and requested/supported rate, a preliminary calibration step can be performed. This allows to find the transfer function between optical and electrical/digital domains, according to the methodology derived in [19].

III. S-BVT FUNCTIONALITIES ASSESSMENT

Different scenarios have been analyzed in the ADRENALINE photonic mesh network, as indicated in Fig. 2, in order to demonstrate the S-BVT functionalities:

- Rate/distance adaptability for optimal spectrum usage
- SDN-enabled multi-flow generation and routing/switching on the network
- Slice-ability, inverse multiplexing and defragmentation
- Unique granularity and grid adaptation thanks to hybrid tune-ability of optical carrier and adaptive subcarrier loading/allocation
- Soft migration of fixed grid to flexi-grid network.

In this section, they are described and their assessment provided, using the multi-partner set-up of Fig. 2. The rate/distance adaptive S-BVT set-up is detailed in Sec. III.A.

The ADRENALINE network consists of four nodes, namely two OXCs (optical cross-connects) and two ROADMs (reconfigurable optical add-drop multiplexers), and five amplified links ranging from 35km to 150km, as indicated in Fig. 2.

The network path set-up is driven by the SDN controller through an AS-PCE and SDN agents located at the S-BVTx and S-BVRx. Particularly, the SDN agents enable channel estimation, programmable arbitrarily selection of TLS wavelength, rate/distance adaptive algorithm according to target capacity/path(s), and suitable forward error correction (FEC) for successful transmission. Further details of the SDN control are provided in Sec. IV.

A. Rate/distance adaptive S-BVT

The S-BVT sub-transceivers array set-up consists of a 100Gb/s-class DMT transceiver [14], [15], and three OFDM transceivers. The former generates a 50GHz bandwidth slice (S0) using a 64GSa/s DAC; the others generate SSB-OFDM slices (S1, S2, S3) using complex FFT and digital RF upconversion. For spectral saving, S1 and S2 use no guard-interval SSB with bandwidth occupancy of 12.5GHz and 20GHz, respectively [20]. S1 BVTx uses, as for the DAC, an arbitrary waveform generator (AWG) at 20GSa/s, while S2 BVTx adopts a higher speed DAC at 64GSa/s. S3 is a SSB-OFDM with 23GHz bandwidth, including 13GHz of guard-interval, generated using an AWG as a DAC at 70GSa/s.

Each BVT (S-BVT sub-transceiver / building block) is able to generate a rate/distance adaptive flow/slice, thanks to the use of MCM and DSP modules implementing loading algorithms. The BL/PL enables MA or RA mode option to select either the target rate or performance. Fig. 3 indicates the rate/distance adaptive transmission per slice and reports two examples of adaptive bit assignment, according to the estimated SNR profile. Specifically, the inset within the figure shows the BL applied to S0 subcarriers for RA transmission over a path of 35 km. Up to 6 bits (64-QAM format) are assigned to the subcarriers with higher SNR. The insets also show the received constellations for 64-QAM, 16-QAM and 4-QAM formats. The other example reports the BL of S1 subcarriers for RA transmission along a path of 150 km. In this case, the maximum number of assigned bits per subcarrier is 4 (16-QAM format). The subcarriers more affected by transmission impairments and component limitations (as evidenced in the SNR profile) are set to lower constellation size or to zero [11], [20].

As additional flexible feature, the TLS of each S-BVT building block can be enabled/disabled and (re)configured to arbitrarily select the central wavelength. The DAC sample rate as well as the optimal bias point of the MZM can be also digitally programmed [21].

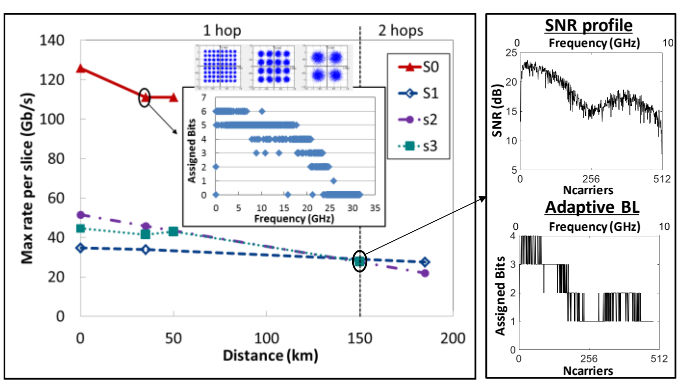

Fig. 3. Rate/distance adaptive performance per slice. In the insets, received constellations and BL assignment according to the channel estimated SNR profile for S0 over 35 km path and S1 after 150 km path, respectively.

A 1:4 SSS based on liquid crystal on silicon technology (LCoS) supports the functionality of aggregation/distribution at the S-BVTx and S-BVRx. Particularly, at the S-BVTx the SSS acts as both variable coupler [22] and optical filter of the multiple flows. This programmable element allows to suitably implement SSB/VSB modulation and to properly transmit the aggregated slices according to the selected parameters of bandwidth occupation/selection, central optical carrier frequency and power/attenuation per port.

At the S-BVRx, after photodetection performed with an array of PIN diodes, S0 is converted to digital by an ADC at 64GSa/s; while S1, S2, S3 are captured by real-time oscilloscopes with sample rate up to 100GSa/s, to be off-line post-processed.

For the demonstration, we consider a target BER of $3\cdot10^{-3}$, assuming hard-decision FEC (HD-FEC) with 7% overhead (OH) [23]. Accordingly, RA BL/PL algorithms are selected at the S-BVT DSP. The OH due to the CP ranges from 1% to 1.9%. The TS used for channel equalization require an OH ranging within 3.3% and 3.9%. This overhead allows self-performance monitoring (e.g. providing channel state information) at the edge-node(s) [9], which is used to obtain the SNR estimation for rate/distance adaptive transmission as shown in Fig. 3 and discussed in Sec. II.

B. SDN-enabled multi-flow generation and routing

Firstly, the S-BVT performance has been assessed in a back-to-back (B2B) configuration. The aggregated flow consisting of four slices, generated at the S-BVTx, is amplified and received at the S-BVRx. At the receiver side, the SSS distributes the flow components to the DD front-end, to be post-processed after ADC. The laser wavelengths for S0, S1, S2, S3 are set to 1553.33nm, 1552.52nm, 1551.72nm and 1550.92nm, corresponding to channel 30, 31, 32 and 33 of the ITU-T 100GHz grid, respectively. The channel SNR estimation is performed after transmitting the probing signals; the rate per slice is maximized for the target BER by properly selecting the loading algorithm at the DSP. The gross rate per slice achieved with adaptive BL/PL is 125.9Gb/s, 34.7Gb/s, 51.6Gb/s and 44.6Gb/s (Fig. 3). Thus, the total S-BVT capacity is 256.8Gb/s.

After the B2B assessment, scenario 1 has been set up: the aggregated flow is transmitted over the 35km path of the network from OXC-2 to ROADM-1 (see Fig. 2 and Fig. 4), where it is recovered by the S-BVRx. After the connection establishment between the origin and destination nodes, delegated to the GMPLS control plane by the AS-PCE, the S-BVT is configured for enabling rate adaptive transmission over the selected path. The DMT signal supports a bit rate of 111Gb/s; S1 and S2 support 34Gb/s and 45.5Gb/s, respectively, while S3 transmits 41.5Gb/s. The total bit rate, achieved selecting the RA mode of the BL/PL algorithm at the DSP array, is 232Gb/s. As shown in Fig. 5, the multi-flow signal is successfully recovered at the S-BVRx, with a BER per flow/slice below $3\cdot10^{-3}$, which is assumed as FEC threshold.

C. Slice-ability and inverse multiplexing

Scenario 2 has been set up for assessing the transceiver sliceable functionality. The aggregated flow is sliced and routed towards different destination nodes. Furthermore, the same end-node is selected for demonstrating inverse multiplexing: the traffic demand (aggregated flow) is split into multiple slices (flows of lower capacity) via independent paths to serve the same destination.

In a first case, an aggregated flow of two slices (S0 and S2) at 111Gb/s and 45.8Gb/s, respectively, is directed to ROADM-1 over the 35km path. Another slice (S1) at 27.1Gb/s goes to the same node through OXC-1 over a 2-hop path of 185km, with a differential delay of 0.75ms [18]. The total data rate adaptively transmitted to ROADM-1 (with inverse multiplexing) is thus 183.9Gb/s. Slice S3 is routed towards another end-node and dropped at ROADM-2 after 50km path. A maximum bit rate of 43Gb/s is successfully recovered at the (S)-BVT located at ROADM-2 destination. The total rate delivery in this scenario is 226.9Gb/s, at increased total distance compared to scenario 1.

In another case (scenario 2b), the multiple flow is sliced and routed over four different paths. The high data rate S0 is directed towards ROADM-2 and successfully transmitted at 111Gb/s over the 50km path. S3 is dropped at OXC-1 after a single hop path of 150km. Due to the transmission impairment, the supported bit rate at the target BER is reduced to 27.8Gb/s. In this scenario, S1 and S2 contribute to a rate delivery of 73.3Gb/s at ROADM-1 with inverse multiplexing. The performance is about the same as previous case: 45.8Gb/s over 35km path and 27.5Gb/s over 2-hop 185 km path, respectively for S1 and S2. The resulting total rate adaptively transmitted below the FEC threshold is 212.1Gb/s.

D. Adaptability

Scenario 3 is set-up to demonstrate the S-BVT ability of adaptation to the grid for spectral saving. Particularly, S2 and S3 are adapted to fit within channel 33. This is achieved by suitably tuning the optical carriers, adaptively loading the subcarriers and selectively configuring the SSS. The parameters to be selected at the S-BVTx are the TLS wavelengths (within channel 33) of S2 and S3 and the RA BL/PL algorithm for maximizing the transmitted rate at the target performance. Similarly, at the S-BVRx the target BER for successful transmission is fixed, by selecting the 7% HD-FEC. After transmitting the probing signal, the channel SNR is estimated and the BL/PL is suitably assigned to the OFDM subcarriers. The SSS is configured to perform SSB filtering and slices/flows aggregation, by programming the proper bandwidth, central wavelength and attenuation at each port. The MZM bias point is also preselected in order to maximize the performance, according to the SSB transmission of S2 and S3. Particularly, for the former slice, it is set in the neighborhood of the quadrature point, while for the latter it is set close by the null point for linear field modulation. The DAC and ADC are set to the maximum sample rate, as detailed in Sec. III.A. After the establishment of the connection between the origin (OXC-2) and destination (ROADM-1) nodes, the two slices are transmitted over the 35km path of the network using a single channel of the ITU-T 100GHz grid (channel 33). S0 is also transmitted over the same path and towards the same end-node on channel 30, for an aggregated bit rate of 183.5Gb/s. S1, which has the narrowest optical bandwidth (12.5GHz), corresponding to 2 slots of the flexible grid, is transmitted over the longest path of 185km (2-hop) for its robustness against CD. This results in a total rate of 210.3Gb/s delivered with inverse multiplexing at ROADM-1.

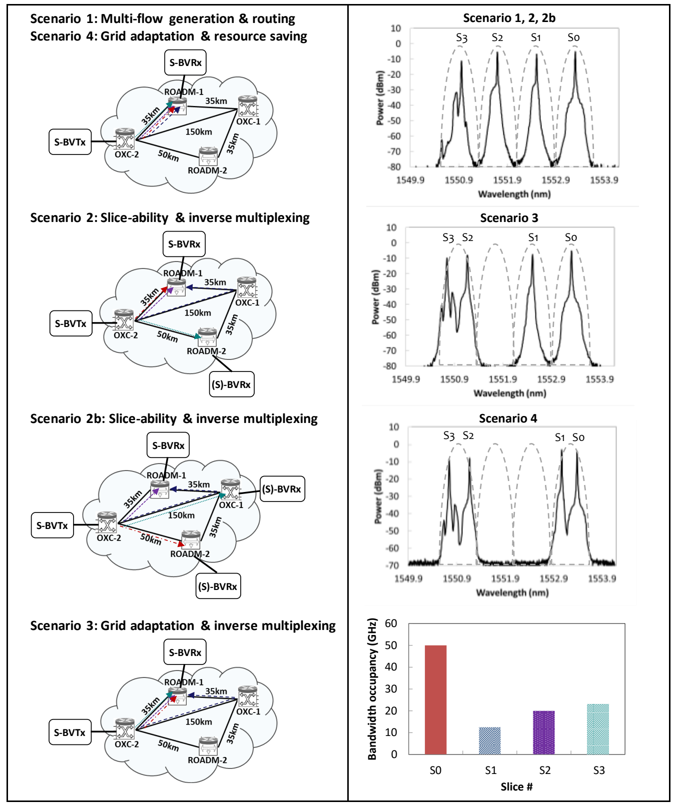

Fig. 4. Scenarios and spectral occupation/saving per scenario/slice.

As a final case, scenario 4 is set up to demonstrate optimal spectral usage and unique S-BVT adaptability. The four slices have been transmitted over the 35km path of the network, occupying only two channels. The same strategy as in the previous scenario (scenario 3) has been adopted for transmitting S2 and S3 on channel 33. The aggregation of S2 and S3 to fit in the same channel supports a total bit rate of 74.2Gb/s. In addition, channel 30 supports 130.9Gb/s, obtained by transmitting S0 and S1 in the same ITU-T 100GHz channel. After the path establishment, the S-BVTx at the origin node (OXC-2) and the S-BVRx at the destination node (ROADM-1) are configured by suitably selecting the appropriate parameters at the DSP and TLS array. Similarly, the parameters of the other S-BVT programmable elements (i.e. SSS, DAC/ADC, MZM and pre-amplified receiver filters) are selected/configured for optimizing the transmission performance. The total rate delivery at ROADM-1 is 205.1Gb/s.

E. Efficient resource usage

Fig. 4 reports the analyzed cases in terms of spectral saving and Fig. 5 summarizes the obtained results.

It is interesting to compare scenarios 1, 3 and 4, where the total S-BVT capacity is transmitted to ROADM-1, over the same path (scenario 1 and 4) or by inverse multiplexing (scenario 3).

In scenario 4, 50% spectral resources can be saved compared to scenario 1, with only 12% rate penalty, when transmitting the four slices over the 35km path. This is achieved thanks to the use of the MCM-based S-BVT. In fact, the tune-ability of the optical carrier (TLS) combined with adaptive subcarrier loading/allocation, enables fine granularity and grid adaptation for a soft migration towards flexible technologies even in fixed-grid networks.

In scenario 3, the penalty in terms of transmitted rate is only 10% for 25% spectral saving, compared to scenario 1, thanks to the transceiver slice-ability. As one or more flow(s) can be directed towards the same end-node through different paths, an optimal spectral/resource usage can be performed without requiring a network re-optimization to avoid spectrum fragmentation. Furthermore, thanks to the rate/distance adaptability of MCM-based S-BVT, the flow(s) more robust against chromatic dispersion can be transmitted over longer path(s).

As evidenced in Fig. 5, for all the analyzed scenarios and per each S-BVT slice the BER performance is below the FEC threshold, which is assumed as target, demonstrating successful

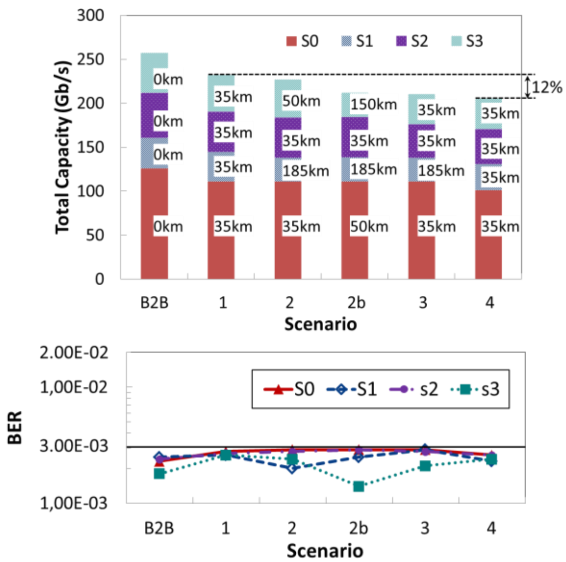

Fig. 5. Summary of experimental results: total capacity and BER performance per slice/scenario.

transmission (with a maximum OSNR of 36.5dB at $3\cdot10^{-3}$ BER). The total capacity is above 200Gb/s, adopting the RA bit/power loading strategy. According to the architecture described in Sec. II, the programmable S-BVT also allows to remotely enable the MA mode of the BL/PL algorithm at each DSP module to set a target rate per slice. In fact, as each S-BVT building block can be individually programmed, the SDN controller can arbitrarily configure each element of the array to operate in MA or RA mode, enabling the slice to support the target rate/performance over the established path, according to the network requirements.

IV. SDN-ENABLED S-BVT

The provisioning of connectivity between the S-BVTs is responsibility of the deployed SDN controller. The control plane procedures and the associated message flow are shown in the Wireshark capture of Fig. 6 and are described next. The capture refers to scenario 4, in particular to slice 2 over the 35km path.

The SDN controller provides a north bound interface (NBI) using representational state transfer (REST) applications programming interface (API) to create optical connections. The operator sends a request using an application that is co-located within the host that is running the SDN controller (IP address 10.1.7.33). The trigger message is thus a REST/HTTP POST message /create_service_call and the HTTP request body includes a JSON (Javascript object notation) encoded message.

Upon reception of such create message, the SDN controller proceeds as follows: i) first, it sets up a bidirectional connection between the two involved optical nodes (source and destination) having the corresponding transceivers and, ii) it configures the S-BVTs appropriately. For the former, the SDN controller ensures connectivity between the S-BVTx and the S-BVRx through the optical photonic network by setting up two associated LSPs (one in each direction), delegating the actual establishment to the AS-PCE and GMPLS control plane. The SDN controller uses the path computation element communications protocol (PCEP) as the provisioning interface and to request this function from the AS-PCE, sending a PC initiate message to the AS-PCE (IP address 10.1.1.111). The AS-PCE, in turn, requests the head end node of the optical network to proceed with the signaling process, which is part of the GMPLS control plane, and conveys the physical path and optical resources to be allocated. When the LSP is successfully established, the head end node notifies the AS-PCE, which in turn replies to the SDN controller with a path computation LSP state report message (PCRpt). Note that, since there are two unidirectional LSPs, this process is done for each direction.

Once the optical channel has been set up, the SDN controller proceeds with the configuration of the S-BVTs, interacting with agents located at nodes 10.1.1.106 and 10.1.1.107. For this, both the SDN controller and the agents located at each S-BVT use a REST- based API: first, the controller triggers the SNR estimation procedure for each slice, using a HTTP POST message (highlighted Wireshark message in Fig. 6). The message includes the parameters to use, including, for example, the algorithm used (rate_adaptive) and the slice identification.

The agents reply with a successful HTTP OK 200 messages.

Finally, the S-BVTx and S-BVRx are configured for a successful transmission, using a similar HTTP/REST method. At this point, the optical channel has been provisioned and the S-BVTs configured. The agents can then notify the SDN controller of the quality of transmission, so the latter can act accordingly.

In the example of Fig. 6, the programmable elements at the S-BVT are the TLS, for enabling slice S2 and setting the wavelength at 1551.16nm (within channel 33, together with S3), and the DSP for BL/PL algorithm selection, channel estimation and performance evaluation. In the reported case, as

RA is selected, the target bit rate is not relevant, while the performance is fixed for a successful transmission. Thus, as shown in Fig. 6, the target BER is set to $3{\cdot}10^{-3}$ using HD-FEC (7% OH). In this experimental assessment, the parameters/values of the other programmable elements (i.e. the SSS bandwidth, wavelength, attenuation and port, the pre-amplified filtering stage, the DAC/ADC sample rate and the MZM bias) are preselected according to the scenario.

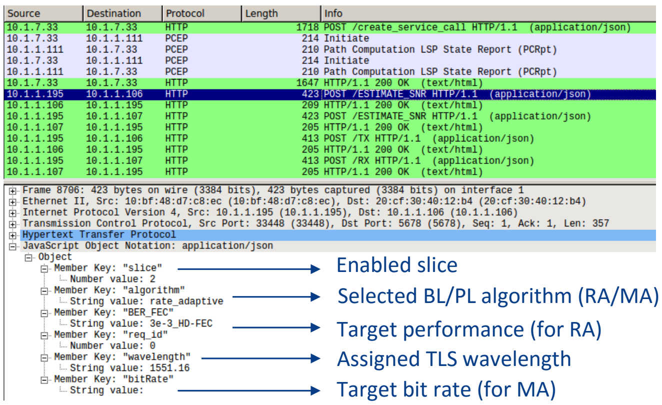

Fig. 6. Wireshark of the workflow run by the SDN controller.

V. CONCLUSION

We propose a high capacity S-BVT architecture based on MCM and DD, which can be remotely programmed. We have demonstrated its integration in a GMPLS/PCE optical network and its multiple advanced functionalities. To this extent a multi-partner set-up has been used, enabling sliceable rate/distance adaptive transmission over multiple paths of the network testbed, for a total capacity above 200Gb/s. The SDN agent, allowing the dynamic control of the S-BVT, has been designed and implemented together with an SDN controller and the corresponding interfaces. This enables the SDN controller to both program the S-BVT and interact with the AS-PCE for the channels provisioning within the optical network based on a GMPLS control plane.

The proposed SDN-enabled S-BVT allows 50% spectral saving at the expense of 12% rate decrease. Also 25% spectral saving is achieved with 10% rate penalty using inverse multiplexing. In addition to efficient resource usage, soft migration to flexible technologies and spectrum fragmentation mitigation are enabled.

Featuring slice-ability, fine granularity, rate/distance adaptability, and cost-effective architecture, the proposed programmable S-BVT is an attractive candidate for future metro/regional elastic networks and highly scalable DC application.

Furthermore, the transceiver can be implemented using photonic integrated circuit technology in order to efficiently scale the system complexity while reducing footprint, cost and power consumption.

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