Abstract—The combination of Spatial Division Multiplexing (SDM) with flexi-grid WDM enables optical transceivers to provide super-channels exploiting both spectral and spatial dimensions. In this paper we extend the SDM-WDM transceivers to support sliceability for the first time, and make an effective use of spatial and spectral resources. The proposed architecture provides multiple independent spectral-spatial super-channels (i.e., slices) sharing the same transceiver and exploiting different spectrum/core/mode resources. The proposed architecture also enables to monitor the BER of the provisioned slices in order to detect any signal quality degradation due to the provisioning of additional slices.

On the other hand, there is a general trend towards the disaggregation of the optical networks. In this paper we also propose the first open API based on YANG data model and NETCONF protocol for SDN-enabled sliceable SDM-WDM transceivers. The proposed transceiver is experimentally validated in a joint testbed between CTTC and KDDI research.

Index Terms—SDN control; SDM; spatial channels; YANG/NETCONF; slicing

I. INTRODUCTION

Telecom operators are facing a critical issue on the optical transport networks. They need to address the challenge of increasing the capacity by a factor of 10 [1] to accommodate the increasing bandwidth demands forecasted for 5G, Internet of Things (IoT), and Big Data, while keeping a similar cost per user. In the last years, Telecom operators have noted that users are not willing to pay more for additional capacity, experiencing a reduction of margin on revenues in order to cope with the increase of capital expenditures (CapEx) and operational expenditures (OpEx) of their networks [2].

As regards to capacity increase, Spatial Division Multiplexing (SDM) has been proposed as the key technology to overcome the capacity crunch that the conventional optical single-mode fibers (SMFs) are facing to accommodate to support the forecasted 10x growth. Even though the simplest way to make use of the spatial dimension is to deploy bundles of SMFs, the main target is exploiting the spatial dimensions of the optical fiber (i.e., modes and/or cores), having parallel propagation in the same fiber using multicore fibers (MCF), multimode fibers (MMF), or combining cores and modes in few-mode multicore fibers (FM-MCFs). The combination of SDM with flexi-grid DWDM enables to exploit both dimensions and to provide spectral-spatial super-channels (SSSChs) [3] using SDM-WDM transceivers. An SSSCh can be defined as the association of several flexi-grid DWDM channels (spectral) that can be jointly allocated in different modes and/or cores (spatial) in order to create a (logical) channel with the desired capacity. The use of SSSChs enables simplified switching, joint digital signal processing (DSP), and DSP complexity reduction techniques [4].

On the other hand, datacenter operators (e.g., Facebook, Google, Amazon) have consolidated a recognized strategy for achieving efficiency and cost (CapEx and OpEx) reduction by disaggregating the software from the hardware. A good example is the Facebook’s Open Compute Project (OCP) in 2009 [5]. More recently, datacenter operators have started to extend these models to support optical transmission and switching between their datacentres, such as Facebook’s Telecom Infrastructure Project (TIP) started in 2016 [6]. In particular, the open optical & packet transport sub-group is focused on the definition of a DWDM open packet transport architecture. Open DWDM systems include open line system & control, transponder & network management and


Manuscript received June 29, 2018.

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packet-switch and router technologies. The group is working on technical requirements in an effort to produce a disaggregated device specification with a set of fully open APIs which can drive network cost efficiencies. Telecom operators have also started to explore this approach and seek how it might replace the current single-vendor system model. In general, three optical disaggregation models are considered; fully aggregated, partially disaggregated and fully disaggregated. In the first model, a complete optical network system (transponders, ROADM, amplifiers, SDN controller, etc.) is provided by a single-vendor with an open API for control the whole network island in a standard way. In the second model, the transponders are provided by multiple vendors with open APIs whilst the transport system (ROADMs, amplifiers, etc.), known as Open Line System, remains a single-vendor system. In the third model, all optical network elements can be provided by different vendors with standard APIs to the SDN control system. Thus, the adoption of the optical disaggregated model requires to provide open APIs with generic data (information and state) models. It allows any vendor to contribute with new hardware and software to the optical network system.

In this paper we extend the SDM-WDM transceivers to support sliceability for the first time, and enable an effective use of spatial and spectral resources. Much like the Bandwidth Variable Transponders (BVTs) for flexi-grid DWDM networks were extended to support slicing some years ago [7], in this paper we present a sliceable spectral-spatial transceiver (S-SST) that can provide multiple independent SSSChs (i.e., slices). However, the introduction of sliceability in the S-SST may degrade the signal quality due to the interference among the used modes and cores of the provisioned slices sharing the same transceiver. The proposed S-SST architecture enables to monitor the BER of the provisioned slices in order to detect any signal quality degradation. In this paper we also propose the first open API based on YANG data model and NETCONF protocol for the S-SST that enables to discover the transceiver capabilities, provision SDM/WDM slices, and monitor the BER. Previous works in the literature consider YANG/NETCONF for flexi-grid WDM transceivers in disaggregated optical networks [8] but are not extended to also include SDM. Finally, we present a proof-of-concept (PoC) of the proposed SDN-enabled sliceable spectral-spatial transceiver (S-SST) controlled with YANG/NETCONF in a joint testbed between CTTC (Barcelona, Spain) and KDDI Research (Saitama, Japan). This paper extends the work carried out in [9], by providing the following additional contributions:

- A new YANG module for modeling the capability functionalities (e.g. available cores, frequency slots, occupied frequency slots, and the supported modulation, FEC, equalization and monitoring parameters), in addition to the connectivity functionalities.
- Extension of the control plane results in the PoC with traffic captures of the exchange of NETCONF messages.
- Extension of the data plane results in the PoC with the constellation maps for the measured optical channels.
II. SDN-ENABLED SLICEABLE SPECTRAL-SPATIAL TRANSCEIVER ARCHITECTURE

The proposed SDN-enabled S-SST (composed of a transmitter -Tx- and receiver -Rx) architecture (Fig. 1) is based on a modular approach composed of sliceable spectral transceivers (S-STs), mode muxes/demuxes, MCF fan-in/fan-out devices, Tx/Rx DSP, and two SDN agents (for the Tx and Rx). The S-ST provides multiple optical (spectral) channels with bandwidth adaptability (for variable bitrate/distance data flows). The S-STs can be implemented by an array of N BVT modules as presented by the authors in [11]. The BVTs are connected to programmable spectrum selective switches (SSSs) whose bandwidth occupation, central optical carrier frequency and power/attenuation per port can be adaptively tuned by the SDN Tx/Rx agents. An array of F S-STs (where F is the number of supported modes) are mode-multiplexed/demultiplexed.

A programmable Tx and Rx DSP module yielding different transmission schemes is available for each array of S-STs in order to perform joint DSP for all the modes (e.g., featuring Multiple Input Multiple Output – MIMO - equalization) and obtain the BER at Rx. Both the Tx and Rx DSPs are configured by the SDN agents in order to define the optical signal parameters associated to the optical channels. This block is repeated for all the cores supported (M). In our architecture we consider no joint DSP among the cores. It would increase considerable the cost of the transceiver and inter-core crosstalk can be reduced to negligible values provided that the core geometry and spacing are carefully designed. Moreover, a careful allocation of the cores in the path computation process can also help to minimize the impact of the inter-core crosstalk. Finally, the mode muxes/demuxes are connected to the individual cores of a MCF by means of a fan-in/fan-out. This modular approach enables to support MCF, MMF and FM-MCF by adding/removing S-STs, mode muxes/demuxes and fan-in/fan-out devices.

The SDN agent’s purpose is to map high-level operations coming from the SDN controller into low-level, hardware-dependent operations using the proprietary protocols. By means of the SDN agents, the SDN controller can program and configure multiple SSSChs and monitor the BER of the associated optical channels. Each SSSCh is composed of multiple optical channels allocated in different modes and cores, transmitting flows at variable bitrate/distance and different modulation formats/constellations. In particular, the SDN-enabled S-SST can support four different kinds of SSSChs according to the allocation of the flexi-grid DWDM channels, as shown in the example of Fig. 2:

- i) in the same mode and same core (WDM channels

module: sliceable-transceiver-sdm-connectivity
  +rw transceiver-connectivity
  +rw slice* [slice-id]
  +rw sliceid
  +rw optical-channel* [opticalchannel-id]
  +rw opticalchannel-id
  +rw core-id/fiber-id
  +rw mode-id
  +rw frequency-slot
  +rw ncf
  +rw slot-width
  +rw optical-signal* [opticalchannel-id]
  +rw opticalchannelid
  +rw constellation
  +rw bandwidth
  +rw fec
  +rw equalization
  +rw equalizationid
  +rw mimo
  +rw num_taps
  +ro monitor
  +ro ber
  +ro osnr

module: sliceable-transceiver-sdm-capabilities
  +ro transceiver-capability
  +ro available-core* [core-id/fiber-id]
  +ro core-id/fiber-id
  +ro available-mode* [mode-id]
  +ro mode-id
  +ro available-frequency-slot* [slot-id]
  +ro slot-id
  +ro nominal-central-frequency
  +ro grid-type?
  +ro adjustment-granularity
  +ro channel-number
  +ro slot-width-number
  +ro occupied-frequency-slot* [slot-id]
  +ro slot-id
  +ro nominal-central-frequency
  +ro grid-type
  +ro adjustment-granularity
  +ro channel-number
  +ro slot-width-number
  +ro available-BVT [transceiver-id]
  +ro transceiver-id
  +ro supported-constellation [modulation-id]
  +ro constellation-id
  +ro mod-type
  +ro supported-nominal-central-frequency [ncf-id]
  +ro ncf-id
  +ro ncf-channel-number
  +ro supported-frequency-range [range-id]
  +ro range-id
  +ro max-supported-bandwidth
  +ro min-supported-bandwidth
  +ro supported-FEC
  +ro supported-equalization
  +ro supported-monitoring

Fig. 2. Supported spectral-spatial super-channels by the proposed S-SST

Fig. 3. YANG models in-tree for the S-SST connectivity and capability functionalities
ii) in several modes in one core (SDM multi-mode channels – Slice #2);
iii) in several cores in one mode (SDM multi-core channels – Slice #3);
iv) in different modes and several cores (SDM few-mode multi-core channels - slice #4).

SDM channels can be constrained to use the very same wavelength while using different cores either for scaling up the capacity or for implementing signal duplex. Therefore, a simplification of the S-STx and S-SRx can be foreseen, as some wavelength dependent parts can be shared among them depending on the specific design. For example, in the case of implementing external modulation, the laser sources can be shared between several BVTs in order to reduce the cost.

III. OPEN API BASED ON YANG MODEL AND NETCONF PROTOCOL

Disaggregated optical networks require to define a data model for the S-SST and agreeing on the so called SDN controller South-Bound Interface (SBI) - with the corresponding message formats and encodings - towards the SDN agents. We consider NETCONF protocol standardized by the IETF for network control and management. NETCONF relies on YANG as modelling language, used for defining the configurable parameters and state information of the S-SST in XML format. Thus, NETCONF and YANG provide a standard way to offer an open API for the SDN controller’s SBI.

A. YANG model

We have developed a YANG module (sliceable-transceiver-sdm-connectivity.yang) for modeling (i.e., the configuration and state data) the connectivity functionalities of the S-SST in [9]. In this paper, we also propose a new YANG module (sliceable-transceiver-sdm-capabilities.yang) for modeling the capability functionalities. Fig. 3 shows the two YANG modules defined for the S-SST. The YANG models are published online on a public repository [12].

The sliceable-transceiver-sdm-connectivity.yang module encompasses a list of slices (each S-SST can support the configuration of multiple slices). Each slice is composed of a slice ID, a list of optical-channels and a list of optical-signal parameters (associated to the optical-channels). The data that can be configured for the optical-channel list are the optical-channel-id, frequency-slot (n.m), mode-id (optional) and core-id/fiber-id. Core-id is used for multi-core fibers and fiber-id for a bundle of SMFs. As for the frequency slot, it is defined by the nominal central frequency and the slot width. The Nominal central frequency is $193.1 \times 0.00625 \text{ THz}$ (i.e., granularity adjustment), where $193.1 \text{ THz}$ is ITU-T “anchor frequency” for transmission over the C band, and $n$ is a positive or negative integer including 0. The slot width is $m \times 12.5 \text{ GHz}$, where $m$ is an integer greater than or equal to 1.

Regarding the optical-signal list, the configured data is the optical-channel-id (for associating the signal parameters to an optical channel), constellation (e.g., Nyquist-shaped dual-polarization(DP)-16QAM), bandwidth (e.g., 12GHz), forward error correction (FEC) (e.g., Soft-decision (SD)-FEC), and equalization: equalizer (e.g., Least-Mean Square (LMS) 12x12), MIMO (e.g. True/False), and num-taps (e.g., 500). State data of the optical-signal list is the BER in the monitor field.

The sliceable-transceiver-sdm-capabilities.yang module encompasses a list of available cores and a list of available BVTs. Each core or fiber is composed of a core-id/fiber-id and a list of available modes. Each mode encompasses a mode-id, a list of available frequency slots, and another list with the occupied frequency slots. The list of available/occupied frequency slots is composed of state data as the slot-id, the nominal central frequency, and the slot width number (i.e., $m$). As for the nominal central frequency, we specify the grid type, the granularity adjustment, and the channel number (i.e., $n$). As regards the list of available BVTs, the state data defined are a list of the supported modulation format identified by modulation-id and type, a list of supported frequency ranges identified by the maximum and minimum supported bandwidth), a list with the supported nominal

![Diagram of NETCONF message exchange for slice provisioning and monitoring](image-url)

Fig. 4. NETCONF message exchange for slice provisioning and monitoring

- Slice #1;
- ii) in several modes in one core (SDM multi-mode channels – Slice #2);
- iii) in several cores in one mode (SDM multi-core channels – Slice #3);
- iv) in different modes and several cores (SDM few-mode multi-core channels - slice #4).
central frequencies, as well as the supported FEC, equalization and monitoring parameters.

**B. Provisioning and monitoring of slices**

Fig. 4 shows the sequence of NETCONF messages employed for provisioning one slice and monitoring the BER. First, there is an exchange of <hello> messages between the SDN controller and the SDN Tx agent and SDN Rx agent in order to discover the peer’s supported capabilities. For example they can exchange the supported version of NETCONF (e.g. netconf1.0, netconf1.1.), as well as the supported capabilities in the S-SST (e.g. available/occupied frequency slots, available cores, available modes, supported modulation formats, maximum and minimum bandwidth, nominal central frequency range, FEC and equalization, etc.) for both the transmitter and the receiver, as described in the sliceable-transceiver-sdm-capabilities.yang module.

Once the session is open, the SDN controller can request the provisioning, monitoring and removal of one slice or multiple slices through the exchange of <rpc> and <rpc-reply> messages. For example, a user (e.g. the telecom operator) can request to the SDN controller the provisioning of one slice. The user may request some quality of service parameters associated to the slice. When the SDN controller receives the slice provisioning request, it executes a Routing, Spectrum, Core and Mode, and Modulation Assignment (RSCMMA) [10] to define the required SSSCh and the associated optical channels that can be allocated in different cores and modes, as explained in Sec.II. In particular, the RSCMMA process defines the frequency slot, core-id/fiber-id, mode-id, modulation, bandwidth, and equalization parameters for all the optical channels involved in the SSSCh. Then, the SDN controller sends sequentially a rpc<edit-config> message to both the SDN Tx and Rx agents to request the provisioning of one or several SDM/WDM slices, and the agents reply with rpc-reply<ok> (when the hardware configuration is completed) or rpc-reply<error> (if any error has happened). In particular, the SDN controller specifies, in the rpc<edit-config>, the list of optical channel parameters (i.e., frequency slot, mode-id, core-id/fiber-id) and the associated optical signal parameters (modulation, bandwidth and equalization) for each slice as described in the sliceable-transceiver-sdm-connectivity.yang module.

After the provisioning of a slice, the SDN controller can request the BER of all or some of the optical channels of the provisioned slices in order to monitor the impact due to the provisioning of additional (virtual) slices that share the same (physical) transceiver. It is performed by sending a <get> message to the SDN Rx agent. The SDN Rx agents reply with a <rpc-reply> message with the state data requested.

Finally, the user can request to the SDN controller the removal of any provisioned slice at any time. The SDN controller can remove any slice by sending to the SDN Tx and Rx agents a <edit-config> message with the operation attribute to “delete”, and the agents reply with rpc-reply<ok> or rpc-reply<error>. In Sec. IV, we present and experimentally validate a complete workflow for the provisioning, monitoring and removal of slices addressed in the deployed proof-of-concept.

**IV. EXPERIMENTAL VALIDATION**

**A. Experimental setup**

The experimental setup is based on an SDN controller deployed at CTTC in Barcelona (Spain), and an SDN-enabled S-SST (including hardware and SDN agents) deployed at KDDI Research in Saitama (Japan). Both facilities are connected using OpenVPN tunnels on top of internet, as depicted in Fig. 5. The SDN controller implementation is based on the Application-based Network Operations (ABNO) architecture [14] proposed in the Internet Engineering Task Force (IETF). It has been experimentally validated for multi-layer and multi-domain network orchestration in [15] and for IoT-traffic control and congestion in [16]. We have
implemented a YANG NETCONF server for the SDN agents of the nodes, and a NETCONF client integrated as plugin in the SDN controller. The NETCONF client is based on ncclient[17], and the NETCONF server uses Sysrepo [18] integrated with Netopeer2 [19].

The S-SST is based on the SDM transceiver presented by the authors in [13]. It can generate 1824 optical channels through a 6-mode 19-core fiber. In the Tx, a tunable laser with a narrow spectral linewidth (<30 kHz) and high frequency stability is used for a measured channel. The measured channel and other 15 dummy channels are independently modulated using a 2-channel arbitrary waveform generator (AWG) operated at 60 GSample/s for I (In-phase) and Q (Quadrature) components and two IQ modulators, driven by 12-Gbaud Nyquist-shaped electrical multi-level signal (8 levels) for 64QAM. The amplified (by EDFA) signals are combined with 12.5 GHz spacing and polarization-multiplexed (by a polarization multiplexing emulator (PME)) with a delay of 87 ns. After the 16 channels are power-equalized with an SSS, 16-channel WDM Nyquist-shaped DP-64QAM signals are obtained. The WDM signals are split into two branches for the measured core and other cores. After that, the measured signal is divided into 6 paths with the relative delay of 200 ns between subsequent paths for the decorrelation. These signals are 6-mode-multiplexed using a mode multiplexer based on a multi-plane light conversion. Then, the mode-multiplexed signals are launched into the measured core of the fiber through a lens-coupled type fan-in device.

After 11 km transmission, the measured SDM channel is demultiplexed with the fan-out device and mode demux. The 6 signals at the output of the mode demux pass through optical bandpass filters, then, they are detected by the 6 coherent receivers (heterodyne detection with a free-running oscillator). The received electrical signals are digitized at 80 GSample/s using three synchronized real-time oscilloscopes. The stored samples are processed offline. First, the samples are down-converted to base band. After the rectangular-shaping, the samples for all-modes are simultaneously processed by a half-symbol spaced 12x12 MIMO equalizer. The tap size is set to be 200 for all cores, and the tap coefficients are updated based on a LMS algorithm. After that, the BER is measured. On top of the Tx and Rx, we deploy two SDN agents in order to map the high-level operations coming from the SDN controller for setting up the SSS into low-level, hardware-dependent operations of the 16 optical channels, SSS, oscillator, and bandpass filters.

B. Proof-of-concept

The presented experimental S-SST can deploy a total of 1834 optical channels by transmitting 16 optical channels (1 measured + 15 dummy) through the 6 modes and the 19 cores (16x6x19=1824 channels). We split this overall number of optical channels of the S-SST into three slices. The proof-of-concept is based on sequentially provisioning three slices and experimentally measuring the BER of some optical channels of the first slice in order to monitor the impact due to the provisioning of additional slices. All three
slices are based on the fourth type of SSSChs (different modes and several cores) presented in sec.II. Next, we present the four tests involved:

- i) Provisioning of slice1 and BER monitoring: we dynamically provision slice1 by transmitting the measured channel through the 6 modes and 19 cores (114 optical channels in total). Then we experimentally measure the BER of measured channel in all modes in core19.
- ii) Provisioning of slice2 and BER monitoring of slice1: we dynamically provision slice2 by transmitting 8 dummy channels through the 6 modes and 19 cores (912 optical channels in total). Then, we measure the BER of slice1 as in the first step.
- iii) Provisioning of slice3 and BER monitoring of slice1: we dynamically provision slice3 by transmitting 7 dummy channels through the 6 modes and 19 cores (798 optical channels in total). Then, we measure the BER of slice1 as in the first step.
- iv) Removal of all slices: we remove all three provisioned slices.

C. Control plane results

Fig. 6 shows the sequence of NETCONF messages employed for the proof of concept, and Fig. 7 shows the Wireshark screenshot (NETCONF messages sent over SSH and TCP). In the first test, the SDN controller requests the provisioning of slice1 by sending a <edit-config> message to both the SDN Tx and Rx agents. The requested SSSCh is composed of 114 optical channels spanning all 6 modes and 19 cores. For all channels, the nominal central frequency (n) is 39 and the slot width (m) is fixed to 2 (12.5GHz). All of them are configured with DP-64QAM, 12GHz, 12x12 MIMO, 200 taps and LMS. The SDN Rx agent sends the <ok> message after 3-4 minutes, and the SDN Tx agent after 3 minutes (including hardware configuration in both cases). Thus, the overall provisioning time of a slice is between 6-7 minutes. Once provisioned, the SDN controller sends a <get> message to the SDN Rx agent to request the BER of all optical channels in all modes in core 19, and the SDN Rx agent sends a <rpc-reply> message to the SDN controller with the BER data.

In the second test, the SDN controller requests the provisioning of slice2 to the SDN Tx and Rx agents by sending an <edit-config> message. In this message we specify the requested SSSCh composed of 912 optical channels spanning all 6 modes and 19 cores. In this case, eight nominal central frequency (n= 55, 53, 51, 49, 47, 45, 43, 41) with a slot width (m=2) are transmitted through all modes and cores. The optical signal parameters associated to these optical channels are the same as the one used for slice1. After the successful provisioning of slice2, the SDN Tx and Rx agents send a <ok> message to the SDN controller and it starts requesting the BER of the optical channels of slice1, as described in test1.

In the third test, the SDN controller requests the provisioning of slice3, following the same procedure as explained above. Slice3 deploys 798 optical channels also spanning all 6 modes and 19 cores. Seven nominal central frequency (n=37, 35, 33, 31, 29, 27, 25) with a slot width (m=2) are transmitted through all modes and cores, using the same signal parameters as for slice1 and slice2. After the successful exchange of <edit-config> and <ok> messages between the SDN controller and the SDN Tx and Rx agents, the SDN controller requests the BER for slice1 as performed in test1 and test2. It is worth to highlight that the SDN may also request the BER of slice2 and slice 3 based on the requested QoS, but for the sake of simplicity, we have not considered it in the proposed PoC. Finally, in the fourth test, the SDN controller requests the removal of all slices by sending a <edit-config> message with the “delete” operation attribute to the SDN Tx and Rx agents.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Slice1</th>
<th>Slice1 &amp; Slice2</th>
<th>Slice1 &amp; Slice2 and Slice3</th>
</tr>
</thead>
<tbody>
<tr>
<td>LP01</td>
<td>4.37e-3</td>
<td>2.57e-2</td>
<td>2.08e-2</td>
</tr>
<tr>
<td>LP11a</td>
<td>3.52e-3</td>
<td>1.44e-2</td>
<td>1.22e-2</td>
</tr>
<tr>
<td>LP11b</td>
<td>2.54e-3</td>
<td>1.64e-2</td>
<td>1.38e-2</td>
</tr>
<tr>
<td>LP21a</td>
<td>3.98e-3</td>
<td>2.03e-2</td>
<td>1.73e-2</td>
</tr>
<tr>
<td>LP21b</td>
<td>2.01e-3</td>
<td>1.29e-2</td>
<td>1.15e-2</td>
</tr>
<tr>
<td>LP02</td>
<td>2.95e-3</td>
<td>1.47e-2</td>
<td>1.27e-2</td>
</tr>
</tbody>
</table>

Fig. 8. Optical spectrum monitored at the output of the SSS (Tx).
D. Data plane results

Fig. 8 shows the optical spectrum at the output of the SSS (Tx) after provisioning the slice1, slice2 and slice3. Tab.1 shows the BER and Fig. 9 the constellation maps of the measured channel (wavelength = 1550.567 nm) of slice1 for the six modes in core19 after provisioning slice1, after provisioning slice 2, and after provisioning slice 2 and slice 3. The BER limit used is 2.7e-2 (20% overhead SD-FEC [13]) and is processed off-line.

In the case of slice1, since the number of wavelength was one, the channel power was relatively higher than other cases (EDFA: automatic current control mode). Therefore, the transmission performance of slice1 was better than the other cases.

In the case of slice1 and slice2, the performance was slightly worse than when the three slides were provisioned. The reason is that the bandwidth of the measured channel was a little severely limited by the spectrum selective switch (SSS). In the testbed, the SSS was automatically controlled in order to provision optical paths and adjust optical power levels among optical signals. As for the optical power level adjustment, it was difficult to optimally control the edge channel of the slice (such as the case of slice1 and slice2). Therefore, the SSS severely limited the measured channel bandwidth (slice1) in the test.

V. Future activities

We are enhancing the SDN-enabled SDM/WDM transceiver architecture and YANG data model by adding an optical spectrum analyzer (OSA) to measure parameters of the SSSChs. Moreover, we are also extending the SDN controller to make use of the monitored information (BER and OSNR) to reconfigure already provisioned SSSChs and for the provisioning of new SSSChs. In particular, in [20] we present the preliminary results of an SDN monitoring and restoration system to detect soft failures in the provisioned SSSChs and restore the degraded optical channels. This is achieved by dynamically reconfiguring the transmission format, frequency slot, and mode/core to recover the performance.

VI. Conclusion

We have experimentally assessed the first SDN-enabled sliceable spectral-spatial transceiver over a 11-km 6-mode 19-core fiber. It provides independent spectral-spatial super-channels (slices) composed of multiple optical channels allocated in different modes and cores, transmitting flows at variable bitrate/distance and different transmission formats. We have defined an open API for disaggregated optical networks based on YANG data model (configuration and state information) and NETCONF protocol. By means of two SDN agents, the S-SST can be programmed to (re-)configure the SSSChs. We have provisioned multiples slices and measured the real impact on the BER due to the fact of provisioning independent (virtual) slices that share the same (physical) transceiver.

ACKNOWLEDGMENT

Work supported by the Spanish DESTELLO
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