Programmable disaggregated multi-dimensional S-BVT as an enabler for high capacity optical metro networks

LAIA NADAL,* JOSEP M. FÀBREGA, MICHELA SVALUTO MOREOLO, F. JAVIER VÍLCHES, RAMON CASELLAS, RAUL MUÑOZ, RICARD VILALTA, AND RICARDO MARTÍNEZ

Centre Tecnològic de Telecomunicacions de Catalunya (CTTC/CERCA), Castelldefels, Spain
*Corresponding author: laia.nadal@cttc.es

Received 16 December 2020; revised 23 February 2021; accepted 23 February 2021; published 11 March 2021 (Doc. ID 417766)

To meet the requirements of 5G high capacity optical metro networks, a programmable disaggregated multi-dimensional sliceable bandwidth/bitrate variable transceiver (S-BVT) is proposed. Specifically, transceiver multi-dimensionality is presented exploiting spatial, polarization, and spectral information as a solution to support network capacity and bandwidth scaling 5G requirements. Space division multiplexing is implemented by considering a 19-core multicore fiber enabling capacity scaling with the number of cores, whereas polarization division multiplexing is assessed enabling 50% spectral saving by considering two orthogonal polarization components. Finally, by the implementation of multi-band transmission systems, the optical bandwidth can be increased by a factor of 10, compared to a conventional C-band system. In these last two cases, the existing spectrum and network infrastructure can be reused, bringing new capabilities. In particular, in this work, multi-band transmission is assessed by exploiting the C-band and L-band. Additionally, disaggregation is also addressed at the transceiver level to enhance network flexibility, avoiding vendor lock-in while achieving efficiency and cost reduction. Disaggregation enables assembling open components, devices, and sub-systems into optical infrastructures and networks. On the other hand, the adoption of the software defined networking paradigm enables system/network programmability and reconfigurability, promoting an efficient use of the multi-dimensional network resources. Therefore, in this work, we analyze and experimentally demonstrate different S-BVT advanced functionalities suitable to support the stringent network requirements of 5G. These capabilities include rate/distance adaptability, programmability/configurability, disaggregation, and multi-dimensionality. Different network scenarios have been considered to assess the S-BVT functionalities, enabling Tb/s optical transmission.

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https://doi.org/10.1364/JOCN.417766

1. INTRODUCTION

The emergence of the 5G paradigm and Internet of things (IoT) will leverage high-speed optical networks. 5G enables a wide range of new and innovative industry services and applications based on new technologies, such as distribution of high-definition video, data utilization, and autonomous vehicles. However, satisfying new communications solutions requires meeting diverse and complex technological demands and challenges. Specifically, the growing number of connected devices and the emerging Internet services will drive significant increases in network capacity and bandwidth. Global mobile data traffic will grow seven-fold between 2017 and 2022, and mobile-connected devices per capita will reach 1.5 by 2022, according to Cisco’s report [1]. On the other hand, a yearly bandwidth growth from 20% to 60% is forecast [2]. Hence, the optical network is expected to change towards more flexible and dynamic architectures to deal with this capacity/bandwidth growth. Additionally, from the operator’s point of view, 5G and beyond optical transport networks must support key requirements/challenges dealing with (i) capacity/bandwidth scaling, (ii) flexibility/programmability enhancement, (iii) cost and power consumption reduction, and (iv) latency reduction.

To cope with the (i) network requisite, multicarrier modulation (MCM) such as orthogonal division multiplexing (OFDM) can be implemented, enabling sub- and super-wavelength granularity. High capacity per wavelength can be supported by the implementation of adaptive loading algorithms adapting the transmission parameters (modulation format and power values per subcarrier) according to the channel profile. Additionally, spatial, polarization, and spectral information can be considered, enabling high capacity communication to handle the demand from explosive increases in...
data traffic. In particular, space division multiplexing (SDM) can significantly help increase network capacity by exploiting the space dimension. New spatial degrees of freedom including core and mode multiplexing can be introduced to overcome the physical limits of today’s transport systems. Particularly, multicore fibers (MCFs) are a compact high capacity alternative to standard single-mode fibers (SSMFs) for future capacity expansions in optical networks [3]. Alternatively, multi-mode fibers (MMFs) use different modes to transmit different signals across a single core. Moreover, polarization division multiplexing (PDM) makes it possible to double the spectral efficiency (SE) and introduces an additional dimension that can also be used for routing additional traffic in dense fiber links [4]. Finally, multi-band transmission is a promising strategy to fulfill network stringent requirements in terms of capacity/bandwidth enhancement. This solution aims to transmit over the entire low-loss SMF spectrum, ranging from 1260 nm to 1620 nm, to re-use available optical fibers, postponing new fiber deployments. However, new optical components and network elements should be designed to work beyond the C-band [5,6].

On the other hand, network disaggregation is arising as a promising solution to further enhance the (ii) aspect, related to network flexibility and adaptability [7]. Disaggregation and open networking paradigms promote a competitive vendor environment, having a direct impact on network capital expenditure (CapEx) and operational expenditure (OpEx) [8]. Specifically, network disaggregation promises savings that could make the difference in years of ever decreasing margins on revenues. It makes it possible to separate the hardware (HW) from the software (SW) operating system, promoting an open ecosystem and also achieving efficiency and cost reduction. By the adoption of an open source platform with open application programming interfaces (APIs), multiple components can be combined into complete solutions. In this context, new initiatives such as OpenConfig and OpenROADM are proposed to enable disaggregated network interoperability and multi-vendor optical devices/elements configuration. Furthermore, the software defined networking (SDN) approach enables smooth network programmability by the decoupling of the data and control planes. Therefore, the key is adoption of appropriate SDN agents that configure the network elements (e.g., nodes) and systems/subsystems (e.g., transceivers). Specifically, SDN helps to reduce HW costs, eliminating the need for manual configuration while supporting lower operational costs through efficient network control and virtualization [9]. SDN makes it possible to simplify and automate the operation of optical networks to efficiently allocate and configure the available resources. Finally, decreasing power consumption is also a key challenge that can be met by the adoption of photonic integration and novel photonic technologies aiming to also reduce the transceiver cost and footprint [10].

In this paper, SDN-enabled disaggregated multi-dimensional sliceable bandwidth/bitrate variable transceivers (S-BVTs) are proposed to cope with the high performance capabilities/requisites of 5G. Their modular architecture, which can be upgraded following a pay-as-you grow pricing model, enables adaptive/elastic transmission and ultrahigh capacity in optical metro networks. In particular, the adopted S-BVT can be composed of cost-effective BVTs that can be pluggable and from different providers (multi-vendor). A receiver configuration based on direct detection (DD) is adopted to promote system/network cost effectiveness. Moreover, this configuration can work at different optical bands (multi-band) and can exploit PDM and SDM technologies. By the adoption of an SDN control plane, an efficient use of available multi-dimensional network resources (polarization, spectral, and spatial) can be promoted.

This paper is an extended version of [11], more focused on the exploitation of disaggregation and different multi-dimensional capabilities in addition to SDM. Specifically, here a programmable disaggregated multi-dimensional S-BVT architecture is presented. Accordingly, the different S-BVT functionalities are assessed with experimental validation within the ADRENALINE testbed targeting high data rate transmission.

This paper is organized as follows. Section 2 introduces the envisioned SDN-enabled disaggregated multi-dimensional S-BVT architecture. Section 4, details the multi-dimensional S-BVT capabilities, including (i) modularity/scalability, (ii) programmability, and (iii) open disaggregation and multidimensionality (SDM, PDM, multi-band). The section also includes an experimental assessment of the different S-BVT functionalities. Finally, Section 6 summarizes the paper with its main findings and conclusions.

### 2. SDN-ENABLED DISAGGREGATED MULTI-DIMENSIONAL S-BVT ARCHITECTURE OVERVIEW

The S-BVT consists of an array of bandwidth/bitrate variable transmitters (BVTxs) and receivers (BVRxs) based on DD, as seen in Fig. 1 [12]. According to Fig. 1, at the BVTx side, a digital-to-analog converter (DAC) and a simple optoelectronic front-end, including an external Mach–Zehnder modulator (MZM) and a tunable laser source (TLS), are required. At the BVRx, a simple photo-detector (PIN) followed by a trans-impedance amplifier (TIA) and an analog-to-digital converter (ADC) are envisioned to perform DD. A wavelength selective switch (WSS) can be used at both the sliceable transmitter and receiver to perform multiflow aggregation/disaggregation operations. The WSS at the transmitter can also serve as an optical filter to implement single side band (SSB) modulation. At the digital signal processing (DSP) level, MCM, namely, OFDM, is considered exploiting sub-/super-wavelength granularity. Bit/power loading (BL/PL) algorithms can be implemented to maximize the system capacity/performance and allow efficient spectrum usage [13]. By considering BL/PL, different modulation formats and power values can be applied at each subcarrier according to the channel profile. Additionally, different processes are implemented at the transmitter DSP block including data parallelization and mapping, training symbol (TS) insertion, inverse fast Fourier transform implementation, cyclic prefix (CP) insertion, serialization, and radio frequency (RF) up-conversion. At the BVRx DSP block, RF down-conversion, data parallelization, CP removal, fast Fourier transform implementation, equalization, symbol demapping, and serialization
Programmable disaggregated multi-dimensional S-BVT architecture in high capacity optical metro networks.

processes are performed. Due to the transceiver’s inherent modular architecture, system capacity can be adapted according to network requirements by enabling/disabling different slices [14,15]. In particular, multiple slices/signals can be transmitted in a high capacity single data flow or in different independent flows reaching different destination nodes, enhancing network dynamicity.

The proposed S-BVT can be pluggable and from different vendors/providers to promote network disaggregation [8]. Its flexible architecture makes it feasible to exploit spatial, polarization, and spectral information as a way to provide increased capacity. In particular, different slices can be created and transmitted over multiple fiber modes/cores enabling SDM, due to the S-BVT modularity [11]. Additionally, PDM technology can also be included by considering different polarization components enabled with polarization beam combiners/splitters (PBCs/PBSs) available on demand, as depicted in Fig. 1. Hence, two BVTs can carry the information of two different polarization components and can be aggregated at the transmitter side with a PBC. By enabling PDM, the two slices can be transmitted over the same optical channel, sharing the available spectrum and enhancing SE. Additionally, multi-band technology can be envisioned, at each transceiver, aiming to exploit spectral bands beyond the C-band. Each laser (TLS) module, of each BVT, can be centered at different wavelengths including the entire low-loss optical spectrum of SMF to increase fiber capacity. Hence, the proposed SDN-enabled S-BVT arises as a promising solution for high capacity optical metro network scenarios [16].

3. S-BVT WITHIN 5G METRO OPTICAL NETWORKS

Here, the proposed S-BVT architecture shown in Fig. 1 and explained in Section 2 is presented as a suitable solution to be adopted in 5G metro/regional optical networks. BVTs and alternative transceiver configurations can be adopted instead of S-BVTs [17]. However, the S-BVT architecture is presented as an adaptive and flexible solution that promotes network efficiency and scalability while dealing with 5G metro network requirements. Initial experiments have been performed in [12] to demonstrate different S-BVT functionalities focusing on the flexi-grid paradigm. In this paper, we mainly consider disaggregation and multi-dimensionality exploitation as key enablers to meet the requirements of 5G high capacity optical networks. In [18,19], sliceable spectrum-spatial transceivers are proposed and experimentally assessed by exploiting wavelength division multiplexing (WDM) and multiple fiber modes/cores. SDN agents based on YANG/NETCONF protocols are used to configure the transceiver parameters and network devices, respectively. In this paper, we propose the implementation of OpenConfig SDN agents to configure/program disaggregated S-BVTs. Additionally, here we also investigate and assess PDM, SDM, and multi-band transmission. The proposed programmable disaggregated multi-dimensional S-BVT promotes flexible, efficient, and high capacity transmission suitable to deal with the increasing demand/traffic within 5G metro optical networks.
4. MULTI-DIMENSIONAL S-BVT CAPABILITIES AND FUNCTIONALITIES

In this section, different S-BVT capabilities and advanced functionalities are presented. These include

- modularity, scalability, and rate/distance adaptability;
- programmability and reconfigurability;
- open disaggregation and multi-dimensionality.

A. Transceiver Modularity, Scalability, and Rate/Distance Adaptability

The modular S-BVT architecture presented in Section 2 offers a high degree of scalability, making it possible to adapt the system to network needs/requirements following a pay-as-you grow approach. Different BVTs can be enabled/disabled according to network requirements/targets. Due to the S-BVT’s inherent modularity, system/network flexibility/dynamicity can be fully exploited [12]. In fact, flexibility and scalability are key design issues, particularly for the metro network segment. Hence, sliceable transceivers become suitable solutions to be adopted in optical metro networks to enhance system capacity, flexibility, and elasticity. On the other hand, the implementation of MCM enables a wide range of granularities (comprising sub- and super-wavelengths) with unique flexibility and scalability. Specifically, spectral manipulation at the subcarrier level is possible for optimizing the transmission performance and transceiver capacity, according to traffic demand, available bandwidth, and the path/channel condition. By implementation of loading algorithms, rate/distance adaptability is enabled for optimal spectrum usage [13]. Hence, multiple BVTs can be set at different wavelengths, promoting unique granularity and grid adaptation due to the hybrid tunability of optical carrier and adaptive subcarrier loading/selection [12].

B. Programmability and Reconfigurability

S-BVT programmability and reconfigurability have a key role in the integration of data and control planes to support advanced functionalities, such as sliceability and rate/distance and bandwidth adaptability. Hence, network resources can be efficiently managed, simplifying network operations and enhancing agility. Additionally, greater automation and orchestration of the network can be achieved. Specifically, different system/transceiver parameters such as bandwidth occupancy, forward error correction (FEC), loading algorithm selection, MZM bias, and equalization type can be reconfigured to fully exploit system flexibility, enhancing its performance. Moreover, different transceiver programmable elements such as TLS, WSSs, optical amplifiers (OAs), and DSP can be configured. In particular, the power and the center wavelength of the TLS can be programmed enabling transmission in multiples bands, including the C-band, S-band, and L-band. Moreover, the power of OAs can be programmed, as well as the WSS central wavelength, phase, bandwidth, and attenuation per port.

By the adoption of the SDN paradigm, the proposed disaggregated multi-dimensional transceiver in Fig. 1 can be suitably configured/programmed to adapt to the dynamic variation of network capacity, transmission reach, and path conditions. Additionally, an efficient use of the multi-dimensional metro transport resources can be promoted. Specifically, different cores can be enabled/disabled, further enhancing system/network flexibility also in SDM networks [18]. Specifically, in [18,19], an open application program interface based on a YANG data model and NETCONF protocol is proposed for SDN-enabled sliceable SDM-WDM transceivers. Hence, transceiver capabilities can be enabled by adopting SDN including provision of the SDM/WDM slices. The polarization component to be transmitted can also be selected depending on network needs/requirements. Furthermore, appropriate slice/band selection can be performed according to the network path by suitably configuring the laser sources and switches. Hence, SDN promotes a dynamic network allocation and transceiver reconfiguration, becoming a driver and enabler of OpEx and latency reduction.

C. Openness, Disaggregation, and Multi-Dimensional Capabilities

In this section, disaggregated multi-dimensional transceivers are presented as a solution to enhance system/network capacity. Multiple dimensions, including wavelength, polarization, and space, can be exploited facilitating capacity/bandwidth scalability. Additionally, each BVT can be multi-vendor promoting flexibility and avoiding vendor lock-in. Hence, these particular capabilities are investigated and experimentally evaluated.

1. Towards Open and Disaggregated Transceivers

Proprietary solutions and traditional closed systems are usually costly and provide limited system/network flexibility and dynamicity. Hence, disaggregation becomes a key solution for breaking up monolithic systems and bringing flexibility to the network. It is a crucial building block of 5G and beyond optical metro networks. Network disaggregation enables HW and SW separation, improving optical equipment interoperability. Hence, it allows for rapid deployment of features/functions when needed and in the amount that is needed. In this sense, the S-BVT becomes a major driver towards disaggregation, making it possible to bring openness and innovation to the optical metro segment [8]. Specifically, the S-BVT building blocks can be seen as a set of BVTs from different providers, as shown in Fig. 1, avoiding vendor lock-in. Having a baseline disaggregated pool of transceivers/optical components offers immense flexibility that can potentially maximize resource utilization, having a direct impact on network OpEx and CapEx. A higher level of disaggregation can be considered by envisioning subsystems from different suppliers.

On the other hand, disaggregation depends on the availability of open APIs/data models that can support the configuration of the multi-vendor elements composing the network. In this context, new initiatives such as OpenROADM and OpenConfig are arising to work on the definition and implementation of multi-source agreements for optical white boxes [20,21]. In particular, the OpenConfig model aims to
achieve disaggregated network interoperability, and multi-vendor optical devices/elements configuration. It can be considered in the development of the SDN agents moving towards an open SW/disaggregated ecosystem. By means of these SDN agents, the assignment of transmission/multi-dimensional resources to provision the requested network resources/services can be controlled. Additional challenges arise when considering disaggregated solutions related to system/operational integration. Specifically, not all interfaces, for the efficient management and control of large networks, are sufficiently standardized. Additionally, the integration/compatibility of new disaggregated systems/solutions with legacy network elements and management systems is still a key challenge. Finally, some issues related to management and operational procedures arise when adopting an open system. Specifically, higher complexity to guarantee high-level end-to-end system performance is required when compared to single-vendor systems. Operations such as power control, equalization, and other procedures may be very difficult and may limit the optical reach. Hence, hybrid solutions combining new disaggregated elements and legacy systems can also be envisioned.

In this work, transceiver disaggregation is proposed as a promising solution to efficiently deal with emerging and stringent network requirements. SDN also becomes a key enabler to configure/manage multi-vendor systems/networks. Following the OpenConfig data model, the disaggregated transceiver in Fig. 1 can be suitably configured by a unique SDN agent [8]. According to the model, a particular client is assigned to an optical channel. Specifically, the central frequency, output power, and operational mode of the optical channel can be configured. The operational mode field is vendor specific and provides different channel modes/configurations to be selected, such as modulation, symbol rate, FEC, or available modes in the case of exploiting SDM. FEC mode can be interesting in the case of adopting programmable S-BVTs based on MCM to set the target performance as an input of a loading algorithm, which can be applied as an advanced functionality to maximize the system capacity [8,22]. The OpenConfig data model defines two operations to configure and assigns an optical channel to a client [20]. The first operation, optical channel configuration, is devoted to configuring the programmable elements of the BVTs according to the optical channel frequency and power parameters. The second operation, optical channel assignment, assigns a client port to an optical channel to establish an optical path. Hence, bidirectional communication between two different S-BVTs is fixed.

2. Exploiting the Spatial Dimension: SDM Transmission

SDM technology enables high capacity increase per fiber through spatial multiplexing, supporting the evolution of 5G and beyond optical transport networks. A new spatial degree of freedom is introduced in optical transmission systems to overcome the physical limits of today’s SMF-based systems. Different optical transmission media for SDM can be envisioned including, for example, a bundle of SSMFs, MCFs, and MMFs. Specifically, SDM links can be realized by bundling several SMFs. Additionally, MCFs can be considered, where the signal is transmitted over multiple cores in a single optical fiber. MMF is another SDM link, where different modes are used to transmit different signals across a single core. When implementing SDM technology, different technological challenges and impairments arise and must be overcome, such as scalability in terms of the number of cores/modes and performance metrics. Specifically, mode linear and nonlinear coupling/crosstalk (XT) between spatial channels is a potential disadvantage that can limit the system performance in SDM transmission [23,24].

In this work, MCF transmission is selected as a possible solution to implement SDM. In MCF, linear coupling leads to a periodic transfer of optical power from one core to another and can be mitigated/compensated for by implementing DSP at the receiver side (e.g., multiple-input multiple-output technique, MIMO). According to [24], a simple analytical expression for the statistical mean XT estimation is

$$XT_{\mu} \approx \frac{2k_{pq}^2 R_b}{\beta \Lambda} L,$$

where $k_{pq}$ is the mode linear coupling coefficient between two neighboring cores, $R_b$ is the bending radius, $L$ is the fiber length, $\beta$ is the propagation constant, and $\Lambda$ is the core pitch (or core-to-core distance). With this analytical expression, the XT in MCF can be easily calculated to evaluate/analyze the impact on system performance and have an idea of the limits of core scalability. In [23], it has been demonstrated that linear coupling affects the nonlinear penalty in MCFs. In particular, linear coupling can mitigate the nonlinear impairments to some extent, improving system performance [25]. Another fiber impairment that must be considered is the nonlinear length ($L_{NL}$), which provides the length scale over which nonlinear effects become relevant [11,26].

3. Exploiting Polarization Information

To further improve system/network capacity while improving SE, polarization information can also be exploited [27,28]. Accordingly, different signals can be independently transmitted over orthogonal polarizations of the same optical wavelength. PDM can be introduced as an advanced S-BVT functionality/feature, which can be enabled/disabled according to the network condition/requirements [4]. Specifically, PBSs and PBCs, available on-demand, can be included at the transceivers and at the network nodes, further enhancing system flexibility and promoting an efficient use of the spectrum (Fig. 1). Control of the PBSs/PBCs can become a challenge. However, automatic polarization control systems can be designed to adjust the state of polarization (SOP). On the other hand, with the increase in optical link length, the polarization mode dispersion (PMD) effect appears, which causes misalignment of the SOP between OFDM subcarriers and the optical carrier, resulting in power fading. Specifically, a time delay between the two polarization modes appears as they are transmitted at different propagation constants. Different techniques have been proposed in the literature to mitigate this effect and dynamically equalize the channel, which includes the MIMO technique [28].
4. Exploiting the Spectral Dimension: Multi-Band Transmission

Multi-band transmission is a promising strategy to fulfill capacity network requirements aiming at transmitting over the entire low-loss optical spectrum of SMFs [2,5,29,30]. Significantly increased fiber capacity can be achieved by exploitation of the spectral dimension, while efficiently utilizing the available and deployed optical fiber infrastructure. Additionally, the use of different wavelength bands enables capacity increase while mitigating the number and complexity of additional hardware subsystems [5,31].

By using all available bands from the O-band to the L-band (namely, from 1260 nm to 1625 nm), the optical bandwidth can be increased by a factor of 10, compared to a conventional C-band system. However, some challenges arise when considering multi-band transmission related to the development of key network/system components such as transceivers, OAs, optical filters, and configurable optical switches (ROADMs) [2,31–35]. Hence, multi-band transmission systems still present low maturity but maximize the return on investment of already deployed optical infrastructure. Multi-band technology would be highly competitive against alternative solutions, such as SDM, to maximize capacity in metro network scenarios. However, a combination of both technologies could be envisioned as a solution to deal with stringent network capacity targets.

By adoption of the proposed programmable multi-dimensional S-BVT, per-band slicing can be provided as an advanced transceiver functionality. Multi-band also follows a pay-as-you-grow model that enables operators to install additional bands according to network requirements/targets. Hence, the different multi-dimensional transceivers composing the S-BVT can work at different wavelengths beyond the C-band, covering an extended spectrum. Furthermore, multi-band transmission will need a sophisticated SDN control to efficiently adapt and manage the huge bandwidth.

5. EXPERIMENTAL ASSESSMENT

Different scenarios, summarized in Table 1, are analyzed within the ADRENALINE testbed to assess and demonstrate the S-BVT functionalities/capabilities presented in Section 4 (Fig. 2). The considered scenarios include a B2B configuration (scenario 1) and the transmission over different paths of the ADRENALINE testbed ranging from 25.4 km to 120 km. Scenario 2 considers the 25.4 km 19-core MCF path of the testbed, whereas scenarios 3–5 include 1-hop, 2-hop, and 3-hop ADRENALINE paths based on SSMF, respectively. Table 1 also includes the main results in terms of data rate and bit error rate (BER) of the analyzed scenarios. The ADRENALINE testbed is an SDN/network function virtualization (NFV) packet/optical transport network and edge/core cloud infrastructure for 5G and IoT services. It is composed of five bidirectional amplified links of SSMF ranging from 35 km to 150 km, as indicated in Fig. 2. Additionally, there is a WDM/SDM link based on 25.4 km of 19-core MCF [36]. A recirculating loop has also been considered in the experiments to emulate multiple spans of the path based on MCF. The schematic of the loop is shown in the inset of Fig. 2. Inside the loop, a variable optical attenuator, an amplifier of 19 dB gain, and the 25.4 km 19-core MCF link are included. Eventually, a WSS of 50 GHz bandwidth and centered at 1550.12 nm is taken into account to filter the amplified spontaneous emission (ASE) noise.

Table 1. Assessed Scenarios within the ADRENALINE Testbed

| Scenario | Link (km) | Path | Rate (Gb/s) | Target BER |
|----------|-----------|------|-------------|------------|
| 1        | B2B       | B2B  | 61.1        | 4.62 · 10⁻³ |
| 2        | 25.4      | Node 4 → Node 5 (MCF) | 54          | 4.62 · 10⁻³ |
| 3        | 35        | Node 1 → Node 4 (SSMF) | 54.4        | 4.62 · 10⁻³ |
| 4        | 70        | Node 2 → Node 3 → Node 1 (SSMF) | 46          | 4.62 · 10⁻³ |
| 5        | 120       | Node 2 → Node 4 → Node 1 → Node 3 (SSMF) | 35          | 4.62 · 10⁻³ |

![Fig. 2.](image) Experimental setup for S-BVT functionalities assessment.)
For experimental assessment of the proposed scenarios, a single slice/OFDM signal of 20 GHz bandwidth and 512 subcarriers is enabled at each multi-dimensional S-BVT in Fig. 2. The optical signal occupies two slots of 12.5 GHz of a flexi-grid network. Different modulation formats are implemented, including binary phase shift keying and optimized m-QAM (quadrature amplitude modulation) constellations \((m = 2^l;\ 2 \leq l \leq 8)\), according to the BL/PL algorithm for adaptive mapping. The Levin–Campello rate adaptive (LC-RA) BL/PL algorithm is considered to maximize the system capacity at a fixed/target performance according to the estimated SNR per subcarrier [37]. Each slice is created/acquired using a high-speed DAC working at 64 GSa/s and a 100 GSa/s oscilloscope (OSC) as an ADC. The frequency for down-conversion and up-conversion operations, at the DSP transmitter and receiver blocks, is set to half of the signal bandwidth. The central wavelength of the TLS is varied according to the target scenario, summarized in Table 1. MZMs work at the quadrature point. The WSSs have a bandwidth of 25 GHz and about 6 dB losses. Hence, transmission performance penalties can appear when considering S-BVTs compared to conventional transponders. A target BER of \(4.62 \cdot 10^{-3}\) with standard hard decision FEC (HD-FEC) is fixed [38]. The considered overheads due to TS, CP, and FEC are 4%, 1.9%, and 7%, respectively.

A. Transceiver Rate/Distance Adaptability Assessment

Scenario 1 and scenarios 3–5 are evaluated to assess SBVT rate/distance adaptability. For all the analyzed use cases, the TLS of the enabled BVT is set to 1550.12 nm. First, the S-BVT performance is assessed in a B2B configuration (scenario 1 in Table 1). In particular, S-BVT1, in Fig. 2, is configured enabling a single slice at 61.1 Gb/s. In scenario 3, the data rate decreases after the 35 km SSMF path of the ADRENALINE testbed, achieving 54.4 Gb/s capacity per slice (Fig. 2). In scenario 4, a 2-hop path of 70 km is experimentally assessed. Specifically, 46 Gb/s transmission is enabled at node 1 at the target BER. In the last assessed scenario, a 3-hop path of 120 km of the ADRENALINE testbed is considered ensuring 35 Gb/s at node 3. The aggregated data rate can be increased by upgrading the number of BVTs according to the target network requirements.

B. Programmability/Configurability Assessment

Experimental validation, considering scenario 3, is performed to demonstrate SDN S-BVT capabilities (Fig. 1). Programmability/configurability functionalities are validated by suitably configuring the TLS and DSP of each S-BVT by means of SDN agents. Specifically, in Fig. 3, a Wireshark capture showing the configuration of two disaggregated multi-dimensional S-BVTs set up at 1550.12 nm, including transmitter and receiver sides, is depicted. A total setup time configuration of 270 s is required to configure the programmable elements of both S-BVTs [11]. The DAC and ADC DSP are the most time-consuming operations at the transmitter and receiver sides, respectively. This setup time includes data plane configuration and message propagation. The delays related to transmitter and receiver DSP are about 30–40 s and 80–90 s, respectively.

C. Openness, Disaggregation, and Multi-Dimensional Capabilities Assessment

On one hand, transceiver disaggregation is experimentally validated by assessing scenario 3 in Table 1. The OpenConfig data model is considered for implementation of the SDN agents (Fig. 2). Specifically, for the experimental assessment, the optical channel frequency and power are set to 1550.12 nm and 12.5 dBm, respectively. The open source SW Open Network Operating System (ONOS) is considered for implementation of the SDN controller [39]. ONOS exports as a northbound interface the Open Networking Foundation (ONF) transport API, while it uses several protocols to interact with the underlying network elements (such as OpenConfig, Open ROADM, and OpenFlow). On the other hand, the SDN agent block, depicted in Fig. 2, consists of three parts: (i) an OpenConfig adapter, (ii) an S-BVT agent, and (iii) the different libraries required to control the programmable elements of the S-BVT (i.e., TLS, OA, WSS, DAC DSP, and ADC DSP). The OpenConfig adapter module is responsible for processing/adapting NETCONF messages from the SDN controller to the OpenConfig model. The S-BVT agent maps the high-level actions into several specific low-level actions on the involved programmable elements within an S-BVT by means of developed function libraries [8]. Here, we have evaluated the configuration time of two OpenConfig operations. These operations are related to optical channel configuration and assignment to establish a connection between two S-BVTs. Specifically, a Wireshark capture showing the configuration time of both OpenConfig operations, related to one S-BVT, is depicted in Fig. 4. In the figure, it can be seen that the establishment of an optical channel takes about 79.19 s. On the other hand, SDM capabilities are also experimentally evaluated. In particular, scenario 2 in Table 1 is assessed to validate the SDM capabilities of the proposed multi-dimensional S-BVT (Figs. 1 and 2). In particular, multiple spans \((N)\) of the 25.4 km 19-core MCF path of the ADRENALINE testbed are evaluated, considering a maximum link length of 279.4 km \((N = 11)\). The TLS is set to 1550.12 nm. The signal under analysis is sent to core #1 of an MCF, whereas the adjacent cores (#2–#7) are filled with dummy OFDM signals by using a \(1 \times 8\) splitter, as seen in Fig. 2. The same power (6 dBm) is launched into all the analyzed cores to evaluate system performance including the effect of the XT. Additional experiments are performed considering a WSS inside the recirculating loop to filter the noise introduced by the amplification.
stages (inset of Fig. 2). In particular, this WSS has 50 GHz bandwidth and is centered at 1550.12 nm.

Following the expression of Eq. (1), a mean XT value ($\mu_{XT}$) of $-26.1$ dB is calculated, considering the 19-core 25.4 km ADRENALINE path, evaluated in the experiments. This value perfectly matches the measured XT mean value of the fiber specifications ($-22.5$ dB). Hence, $\mu_{XT}$ can be analytically calculated for different MCF lengths following Eq. (1). Specifically, in [11], the evolution of the mean XT after up to 279.4 km of MCF ($N = 11$) is evaluated. It is shown that the XT degrades system performance in terms of capacity with the increase in fiber length.

Figure 5 depicts the main achieved results in terms of capacity and OSNR versus fiber length. In the figure, it can be seen that a maximum data rate of 57 Gb/s is achieved for ($N = 1$) w/o XT. The data rate slightly decreases to 54.7 Gb/s with a WSS of 50 GHz bandwidth inside the loop. For extended fiber length, similar performance results are achieved considering and w/o including a WSS. For lower WSS bandwidth, the ASE noise can be further filtered at the expense of the filter narrowing effect, which can degrade system performance [22]. Considering XT, 54 Gb/s is achieved at 38.6 dB OSNR. This data rate can be scaled with the number of cores to increase the network overall capacity, enabling 1 Tb/s ($19 \times 54$ Gb/s) transmission. According to [11] and Fig. 6, for a fiber input power of 6 dBm, after 219.3 km, fiber nonlinearities dominate the XT. Hence, at 279.4 km ($N = 11$), a similar performance is achieved with all the analyzed cases, enabling an aggregated capacity of about 0.5 Tb/s ($19 \times 24$ Gb/s).

Additionally, S-BVT PDM capability is validated. Scenario 1 is assessed to experimentally validate the transmission of two polarization components centered at 1550.12 nm. To this end, two OFDM signals/slices can be multiplexed into orthogonal polarization states (PDM), enabling 50% spectral saving and promoting resource dynamicity [4]. Hence, two BVTs from different vendors are enabled, and a PBC/PBS is used at the S-BVT transmitter/receiver to combine/disaggregate the two orthogonal polarization components (Fig. 1). About 100 Gb/s transmission is achieved in a B2B configuration at the target BER [4]. Considering scenario 3, 82 Gb/s aggregated capacity is enabled after 35 km, demonstrating the feasibility of the proposed S-BVT architecture, depicted in Fig. 1. The data rate decreases due to chromatic dispersion and PMD. In particular, this link has a PMD coefficient of about 0.05 ps/√km, according to [4]. Finally, S-BVT multi-band capability is assessed. An S-BVT covering the C- and L-bands is experimentally set up and assessed considering scenario 1 in Table 1 without including any amplification stage, corresponding to a B2B configuration. The laser output power is fixed at 10 dBm, whereas the laser central wavelength is varied in the range of 1550.12 nm to 1610 nm. In particular, Fig. 7 shows the SNR per subcarrier considering the C-band (1550.12 nm) and L-band (1565 nm and 1600 nm). In the figure, it can be seen that a similar performance is achieved working at 1550.12 nm and 1565 nm. However, at 1600 nm,
the subcarriers are more attenuated, and optical amplification will be needed to obtain improved performance. On the other hand, Fig. 8 shows preliminary results of the achieved data rate in a B2B configuration with varying of the laser central wavelength of the S-BVT. It can be seen that the data rate decreases with the increase in optical wavelength. Hence, higher laser output power should be set when moving towards the L-band or even include OAs to maintain system capacity. A similar data rate of about 60 Gb/s is obtained at 1550.12 nm (C-band) and 1565 nm (L band). However, the capacity scaling, when transmitting multiple bands, will be limited to transmission impairments such as stimulated Raman scattering [31,33].

The adoption of the proposed S-BVT architecture in Fig. 1, which includes the exploitation of BL/PL algorithms, enhances system performance, limiting the impact of transmission impairments.

6. CONCLUSION

To handle the demand from the emerging 5G, highly flexible and programmable optical transceivers should be designed. To this end, a programmable disaggregated multi-dimensional sliceable transceiver has been presented and experimentally validated within a metro network, supporting high-speed and spectral-efficient transmission. Different S-BVT capabilities including rate/distance adaptability, configurability, disaggregation, and multi-dimensionality have been assessed to demonstrate high capacity transmission. In particular, its modular and programmable architecture fosters the evolution of current optical networks towards more scalable and flexible solutions to deal with stringent 5G requirements. The S-BVT can be suitably configured and programmed by adopting an SDN control plane that can adapt the transmission according to the network condition/requirements. Open APIs such as OpenConfig can be considered, when exploiting transceiver disaggregation, by configuring the multi-vendor S-BVT with a single agent. The S-BVT is particularly tailored to provide Tb/s transmission in optical metro networks by exploiting spatial, polarization, and spectral information. Specifically, 1 Tb/s can be achieved after 19-core 25.4 km fiber. The data rate decreases to about 0.5 Tb/s after 11 spans of 25.4 km MCF (giving a total length of 279.4 km). By considering multi-band transmission, the optical bandwidth can be increased by a factor of 10, compared to a conventional C-band system, making it possible to reach high capacity targets. Moreover, the transceiver can be implemented by considering photonic integrated technology to further exploit cost effectiveness, while reducing power consumption and footprint.

Funding. H2020 METRO-HAUL (761727); AURORAS (RTI2018-099178-B-I00).

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