SDN-enabled S-BVT for Disaggregated Networks: Design, Implementation and Cost Analysis

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***Abstract*—Software-defined networking (SDN) and disaggregation are key technologies to fulfill the requirements of 5G and beyond optical metro networks. Indeed, open networking solutions will reduce vendor lock-in, achieving increased flexibility and programmability of the network. SDN-enabled sliceable bandwidth/bitrate variable transceivers (S-BVTs) are proposed to be adopted in metro networks in order to provide sustainable capacity growth and hyper-scalability, while enabling disaggregation and network flexibility/reconfigurability. We propose a transceiver modular approach following a pay-as-you grow model, which allows the S-BVT to be adapted to the traffic demand and network requirements. In fact, the S-BVT solution can be seen as a set of bandwidth/bitrate variable transceivers (BVTs) that can be pluggable and multi-vendor. Hence, SDN agents have been developed based on an OpenConfig vendor-neutral data model in order to efficiently reconfigure the S-BVTs fostering network agility and adaptability. Specifically, an optimized agent implementation is experimentally validated in order to increase the network efficiency and reduce the setup configuration time of an optical channel. Two slices/BVTs of 50 Gb/s each are successfully enabled and programmed to establish a high capacity flow of 100 Gb/s. The cost/power consumption of the proposed solution, based on direct detection (DD), is analyzed showing significant savings compared to 100 Gb/s coherent (CO) technology.**

***Index Terms*—Sliceable bandwith/bitrate variable transceiver (S-BVT), software defined networking (SDN), disaggregated optical networks.**

I. Introduction

CURRENT metro networks are evolving towards more flexible and scalable solutions in order to efficiently support the increasing traffic demand and emergence of heterogeneous 5G services [1]. Additionally, stringent network requirements, such as i) high flexibility, ii) high capacity, iii) hyper-scalability, iv) low capital expenditure (CapEx) and operational expenditure (OpEx), v) low latency and vi) low power consumption, must be met. Meeting these challenges is possible relying on disaggregation and open networking paradigms, which also promote a competitive vendor environment [2], [3]. Different disaggregation models can be envisioned in the optical domain according to [4], that include full aggregation, partial disaggregation, full disaggregation based on white boxes and full disaggregation based on bare metals. The first approach refers to a mono-vendor scenario with pure black boxes and proprietary transport system and control. The second approach envisions a partial disaggregated scenario with a proprietary optical network infrastructure based on wavelength division multiplexing (WDM) and multi-vendor transceivers. A fully disaggregated scenario based on white boxes includes not only multi-vendor transceivers, but also other multi-vendor optical network elements such as nodes, line amplifiers, etc. Finally, the ultimate level of disaggregation addresses an ecosystem of optical subsystems (amplifiers, filters, attenuators etc.) on separate blades for rack mounting.

Network disaggregation is also achieved by separating hardware (HW) from software (SW) to improve optical equipment interoperability. Different software-based features and functions for management and control, were traditionally integrated on optical equipment. Thanks to the adoption of open APIs and vendor-neutral data models they can be implemented separately from hardware, moving towards an open software ecosystem [5], [6]. This facilitates system upgrades and further enhances network flexibility. However, disaggregation depends on the availability of open APIs and service and data models that can support the configuration of these elements. In this context, new initiatives such as OpenROADM and OpenConfig are arising in order to work on the definition and implementation of multi-source agreements for optical white/brite boxes [5], [6]. In particular, the OpenConfig model aims to achieve disaggregated network interoperability, and multi-vendor optical devices/elements configuration. Disaggregation is a crucial building block of the 5G and beyond optical metro networks. In addition to this, capacity and flexibility can be further increased by the adoption of multicarrier modulation (MCM) technology, such as orthogonal frequency division multiplexing (OFDM), meeting flexibility/capacity network requirements. High capacity per wavelength can be supported by the implementation of adaptive loading algorithms, which allows different modulation formats and power values per each subcarrier, according to the channel profile. The digital signal processing (DSP) enables software-defined multi-rate, multi-format, multi-reach and multi-flow optical transmission [7], whereas the MCM enables a wide range of granularities (comprising sub- and super-wavelength) with unique flexibility and scalability. On the other hand, in order to expand the

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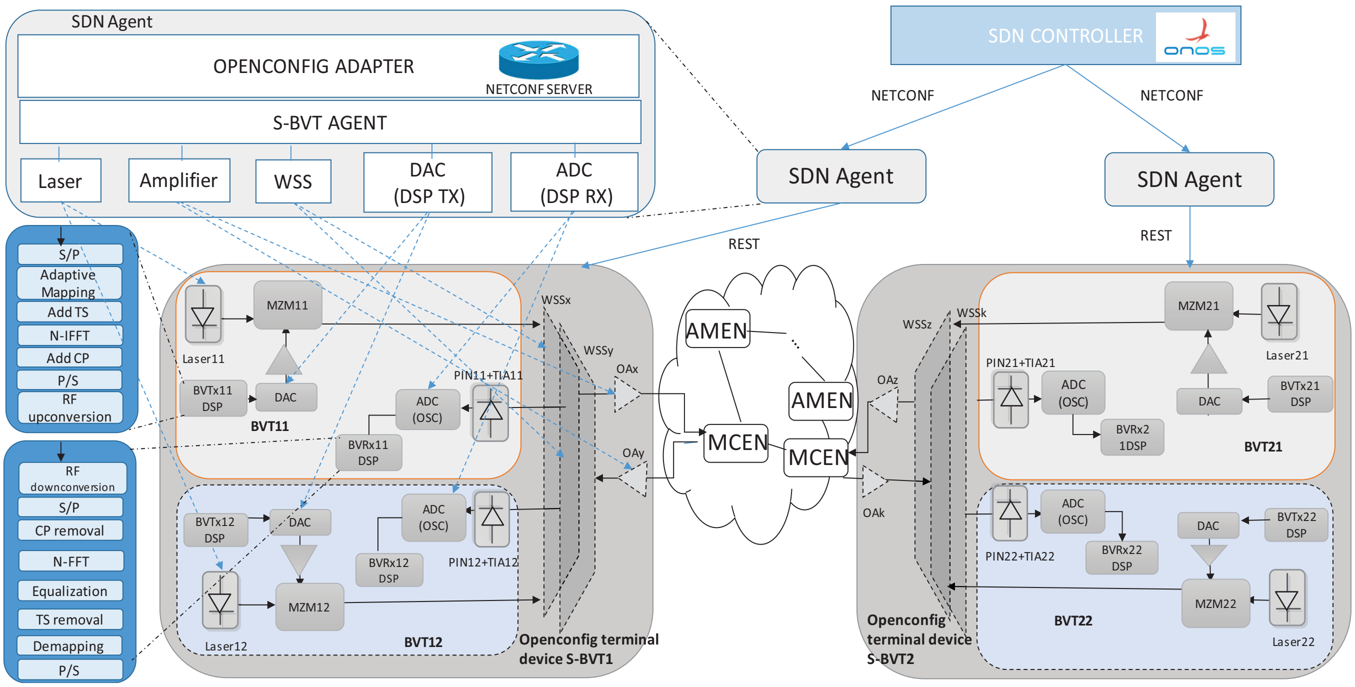

Fig. 1. Disaggregated optical network scenario including SDN-enabled S-BVTs at the metro/core edge nodes (MCEN).

network capacity beyond the limits implied in Shannon and Moore's law, other dimensions can be exploited (such as space) [8].

The implementation of novel, spectrally efficient and adaptive transmission solutions, based on the adoption of modular programmable sliceable bandwidth/bitrate variable transceivers (S-BVTs) enhances not only capacity and flexibility, but also hyper-scalability. 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 sliceability and modularity of the transceivers are key to adapt the system to the network needs/requirements following a pay-as-you grow approach. Hence, the capacity can be increased by enabling more slices also fostering network agility. Requisite (iv) and (v), dealing with CapEx, OpEx and latency, can be met by the implementation of software defined networking (SDN) agents that can dynamically reconfigure/program the S-BVTs according to the network condition. Additionally, a key supporting ingredient to lower network CapEx is the availability of pluggable transceivers. S-BVT can include different pluggable transceivers providing a pay-as-you-go pricing model, attractive to metro deployments that will introduce another element of flexibility to the network. Thanks to photonic integration and photonic technologies the cost, power consumption and footprint of the transceivers can be reduced, addressing (vi) requisite [9]–[11].

Hence, we propose the adoption of SDN-enabled S-BVTs based on MCM and direct detection (DD) in disaggregated optical metro networks. Specifically, we implement SDN agents for each S-BVT, which can be composed of different (pluggable) bandwidth/bit rate variable transceivers (BVTs) of different providers/vendors. This paper is an extended version of [12], more focused on identifying the benefits of adopting a disaggregated sliceable transceiver, in terms of functionalities, cost and power consumption. Additionally, an efficient approach, which reduces the configuration set-up time of an optical channel, is considered here for developing the SDN agents. On the other hand, a cost and power consumption analysis is provided, also including the economic impact of transceiver disaggregation. This paper is organized as follows. Section II introduces the envisioned disaggregated scenario, focusing on the role of the proposed programmable S-BVTs. It also explains the transceiver architecture based on MCM and DD. Finally, the section ends with the implementation of OpenConfig SDN agents, which are developed to reconfigure and program the transceiver according to the network condition. Section III, includes the performance assessment of the SDN-enabled S-BVTs with different configurations. Then, section IV includes a cost analysis of the transceivers, in comparison with coherent detection technology. The economic impact of the S-BVT disaggregation is also analyzed. Finally, section V summarises this article with its main findings and conclusions.

II. Disaggregated Sliceable Bandwidth/Birate Variable Transceivers

A. Role of optical sliceable transceivers in disaggregated networks

The current trend towards disaggregated networking has also reached optical transmission systems, which also contribute to establish an open multi-vendor ecosystem. In Fig. 1, a disaggregated scenario is shown including the proposed SDN-enabled S-BVTs in order to fully exploit network flexibility and adaptability. In particular, an optical metro network considering different nodes, such as metro/core edge nodes

(MCEN) and access/metro edge nodes (AMEN), is envisioned. On the one hand, the AMEN gathers traffic from access networks and hosts a limited set of network services. On the other hand, the MCEN, assures metro domain internetworking and provides an extended set of centralised services, allowing the interconnection with the backbone. Hence, the proposed SDN-enabled S-BVT can be located at the MCEN nodes, promoting a high capacity dynamic and flexible optical metro network. Simpler transceiver architectures can be considered in the AMEN [8]. The S-BVT provides disaggregation of the different optical components (BVTs) and also of HW from SW; while meeting the previously identified network requirements. Specifically, transceiver programmability and automation is enabled by the implementation of SDN vendor-neutral OpenConfig agents defined in section II-C. By means of these SDN agents the assignment of the transmission resources to provision the requested services can be controlled. Thanks to the adoption of open common data models, the SW can be separated from HW. Each S-BVT building block (BVT) can be programmed and reconfigured with the same agent according to the network path independently of its provider/vendor.

In Fig. 1, there is an example of two S-BVTs, with 2 slices/BVTs enabled (S-BVT1 with BVT11 and BVT12 and S-BVT2 with BVT21 and BVT22), located at two different MCEN. In particular, two slices at 50 Gb/s, giving a total capacity of 100 Gb/s, are enabled at each S-BVT. However, transceiver sliceability/modularity allows to rightsize its architecture and grow as needed, while fostering a disaggregated, multivendor environment, where each BVT or even different sub-systems may belong to different providers (see Fig. 2). Having this 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. An evolutionary architecture can also be envisioned including different BVTs, enabled on demand and based on different technologies. Specifically, more complex transmitter modules modulating phase and quadrature components (IQ) can be included. While, at the receiver side BVRx modules based on a coherent configuration can be adopted in order to deal with long reach/core network applications [13].

B. S-BVT modular architecture

The S-BVT consists of an array of white box bandwidth/bitrate variable transmitters (BVTxs) and receivers (BVRxs) based on DD that may belong to different vendors/providers (see Figure 1 and 2). Each BVT is based on OFDM technology. Accordingly, bit/power loading (BL/PL) algorithms can be implemented to maximize the system capacity/performance and allowing an efficient spectrum usage [14]. Different modulation formats and power values per subcarrier can be considered according to the channel profile. Each BVT has a digital signal processing (DSP) block devoted to generate and demodulate OFDM signals. In particular, different processes are implemented at the transmitter DSP block including data parallelization, symbol mapping, training symbols insertion, inverse fast Fourier transform (FFT) implementation, cyclic prefix insertion, serialization and radio frequency (RF) upconversion, to create real OFDM signals. At the receiver DSP block, RF downconversion, parallelization, CP removal, FFT implementation, equalization, TS removal, demapping and serialization processes are considered. The digital signals after the DSP transmitter blocks are converted to analog by using digital-to-analog converters (DACs).

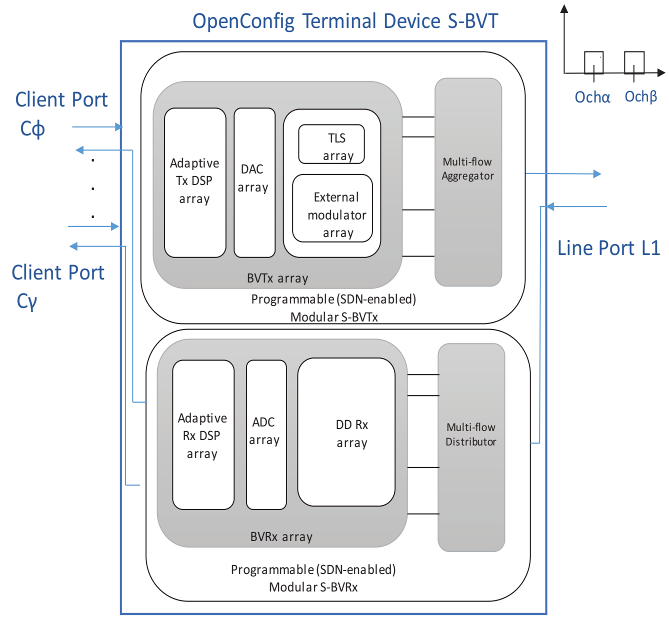

Fig. 2. OpenConfig terminal device architecture

The S-BVTx optoelectronic front-end consists of an array of external Mach-Zehnder modulators (MZMs) driven by tuneable laser sources (TLSes) (see Fig. 2). The generated slices/signals are aggregated into a high capacity flow with a wavelength selective switch (WSS) that acts as both single side band (SSB) filter and optical aggregator. By implementing SSB modulation, resilience against fibre chromatic dispersion is increased, enhancing the system performance. At the S-BVRx, the received flow is distributed by WSS to the different DD front-ends, which includes PIN photodiodes and analog-to-digital converters (ADCs).

C. Programmability and SDN capabilities

The adoption of the SDN paradigm promotes a dynamic network allocation and transceiver reconfiguration becoming a driver and enabler of OpEx reduction. Additionally, in order to foster a vertical disaggregation of the transceivers by separating the data plane from the control plane, open data models such as OpenConfig or Open-ROADM initiatives are arising. These initiatives allow to move toward a more dynamic, programmable method for configuring and managing multi-vendor systems/networks [5], [6], [15]–[17]. Thanks to the implementation of vendor-neutral data models, low-cost white box hardware platforms can be controlled, reducing vendor lock-in which can also results into a CapEx reduction.

Within this context, the network scenario of Fig. 1 is proposed based on the adoption of SDN-enabled multi-vendor

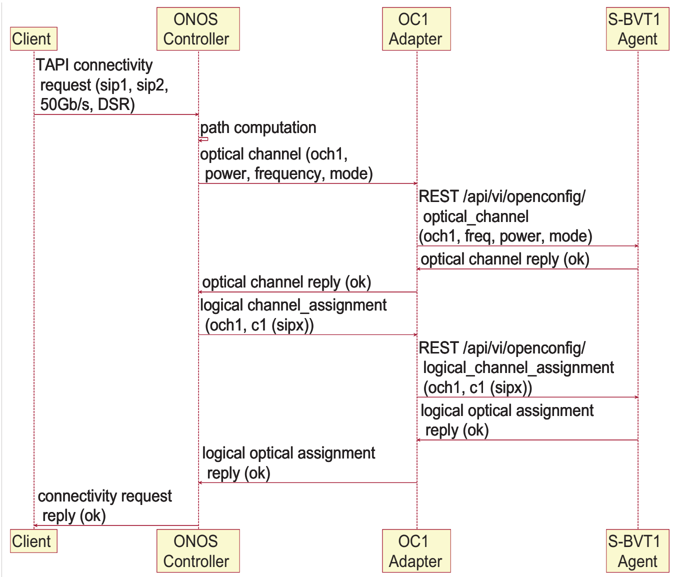

Fig. 3. Uml sequence diagram showing the operations related to setup an optical channel.

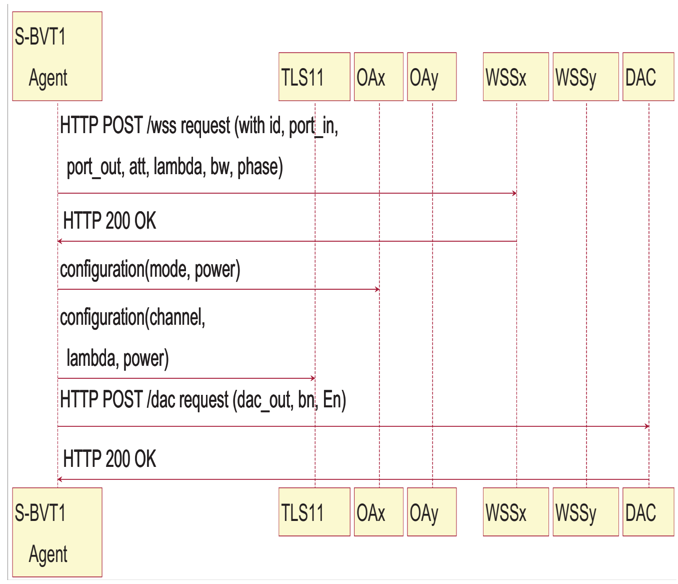

Fig. 4. Uml sequence diagram showing the operations related to setup/configure BVTx11.

S-BVTs, which can be programmed according to the network needs achieving an efficient use of metro transport resources. The OpenConfig vendor-neutral data model is selected for the development of the transceiver SDN agents, while open source software ONOS (open network operating system) is proposed for the implementation of the SDN controller [5], [16]. ONOS exports as a northbound interface the ONF Transport API, while it uses several protocols to interact with the underlying network elements (such as OpenFlow, OpenConfig, Open-ROADM). It also introduces innovative state management techniques necessary to build a robust distributed SDN controller. On the other hand, each S-BVT has an SDN agent based on the OpenConfig model. Hence, an S-BVT (e.g. S-BVT1) can be seen as a part of an OpenConfig terminal device, which can be located at any point/node of the network (see Fig. 1 and Fig. 2). The S-BVT can be programmed and configured to establish a bidirectional connection with another terminal device (e.g. S-BVT2) located at a different network node. According to Fig. 1, a set of interfaces, which control each individual sub-system element (such as lasers, optical amplifiers and WSSes), are available at the agent side. The SDN agent also includes the Openconfig adapter (OC adapter) and the S-BVT agent (see Fig. 1). The OpenConfig adapter module is responsible for processing and adapting the NETCONF messages from the SDN controller to OpenConfig model. On the other hand, the S-BVT agent is responsible for mapping the high-level actions into several specific low-level actions on the involved optical elements within an S-BVT (i.e. TLS, optical amplifier (OA), WSS, DAC DSP and ADC DSP) by means of the developed function libraries. In order to fully exploit the transceiver adaptability/flexibility, a set of programmable elements and reconfigurable parameters have been identified. Specifically, the capacity per slice, MZM bias, forward error correction (FEC), loading algorithm selection and equalization type are a set of parameters that can be reconfigured. Similarly, the DAC/ADC (DSP), the TLS(central wavelength, power), the WSS (bandwidth, central wavelength, phase and attenuation per port) and optical amplifiers (OAs-power and operational mode) are network elements that can be programmed by a suitable SDN control plane by means of SDN agents. In particular, the OpenConfig model allows to select the central frequency, output power and operational mode of an optical channel (Och). According to the specified frequency/power values, the different programmable elements composing the S-BVT can be suitably programmed. Regarding the operational mode field, it is vendor-specific and can be associated to a particular channel mode/configuration, such as modulation, symbol rate, FEC, SNR. Hence, by means of this operational mode field, loading capabilities can be exploited further enhancing the transceiver capacity/performance. Thus, the S-BVT can be suitably programmed to maximize system performance while providing rate/distance/capacity adaptability for optimal spectrum usage [14].

III. SDN-ENABLED S-BVT ASSESSMENT

In this section, the experimental assessment of two S-BVTs, properly configured according to the network requirements, has been performed. Specifically, two S-BVTs (S-BVT1 and S-BVT2) with a single slice per transceiver (S_{11} and S_{21}) are enabled. Each slice has 20 GHz bandwidth, 512 subcarriers and works at 1550.12 nm, corresponding to channel 34 of the ITU-T 100 GHz grid. A target BER of $4.62 \cdot 10^{-3}$ with standard hard decision (HD)-FEC is considered [18]. Each building block of an S-BVT is composed of different subsystems from different providers, giving different performance. Specifically, 40Gb/s and 60Gb/s capacity is achieved by S_{11} and S_{21} with uniform loading, respectively in a back-to-back (B2B) configuration. Hence, the same modulation format per subcarrier is considered. Alternatively, as an advanced transceiver capability BL/PL algorithms can be implemented, increasing system capacity, at the target BER, to 70.4 Gb/s and 67.23 Gb/s per slice [14]. Thus, a target capacity of 50 Gb/s per slice can be guaranteed. In fact, 100 Gb/s transmission (2 X 50 Gb/s) can be maintained after 35 km metro network 1-hop path, as demonstrated in [19]. This capacity is also ensured after 50 km of standard single mode fiber (SSMF). The data rate decreases to 40 Gb/s and 30 Gb/s per slice after 100 km and 200 km of SSMF, respectively.

On the other hand, SDN agents are implemented and experimentally validated for properly configuring the S-BVTs according to the network condition/requirements. Figure 3 and Fig. 4 show two UML sequence diagrams related to the setup of a bidirectional connection between BVT11 (S-BVT1) and BVT21 (S-BVT2), and the properly configuration of one of the transceivers, within the disaggregated scenario depicted in Fig. 1. As depicted in Fig. 3, firstly a client sends a TAPI connectivity request to the SDN controller in order to establish a bidirectional 50 Gb/s connection between two S-BVTs (e.g. S-BVT1 and S-BVT2). Then, the SDN controller sends NETCONF messages to the SDN agents. Within the SDN agent, two different operations are implemented according to the Openconfig model, as observed in Fig. 3 and Fig. 5: (i) optical channel configuration and (ii) optical channel assignment. The first operation is devoted to program the elements of the BVTxs, according to the optical channel frequency and power parameters. In particular, BVTx11 elements (TLS11, OAx, WSSx and DAC DSP) are configured followed by BVTx21 (TLS21, OAz, WSSz and DAC DSP). For simplicity, only the operations to configure BVTx11 are reported in Fig. 4. The second operation assigns a client port to an optical channel, as depicted in Fig. 2. Specifically, C1 and C3, which carry information of the different configured BVTs/slices (S11 and S21), are assigned to the same optical channel (och1) to establish a bidirectional communication. In Fig. 3 it can be seen an example of this operation regarding C1 (S11).

Unlike other previous works of the authors, [19] and [12], where a simpler implementation consisting of a shared/integrated DAC/ADC DSP library is considered, here a separate module, is implemented (see Fig. 1). The main purpose of this implementation change is to reduce the setup time in the establishment of an optical channel and to increase the system/network efficiency. Considering this approach, a BVTx and a BVRx of the same (S)-BVT can be independently configured. In particular, each S-BVT is integrated with the corresponding control interfaces, data models and control/management elements, such as the SDN controller/agent. Hence, here we can redefine and simplify the operations required to establish an optical channel. Specifically, in this new approach, channel configuration operation can be simplified by only configuring the transmitter (BVTx) with the frequency and power of the optical channel. The SNR and BER calculations performed at the receiver side, ADC library, are not necessary for configuring the optical channel. In order to achieve this information, the NETCONF generic operation GET can be performed, as seen in Fig. 5. In [19], channel assignment and configuration operations related to S-BVT1 takes 271 s, as both Tx and Rx transceiver sides must be enabled due to limitations in the agent implementation.

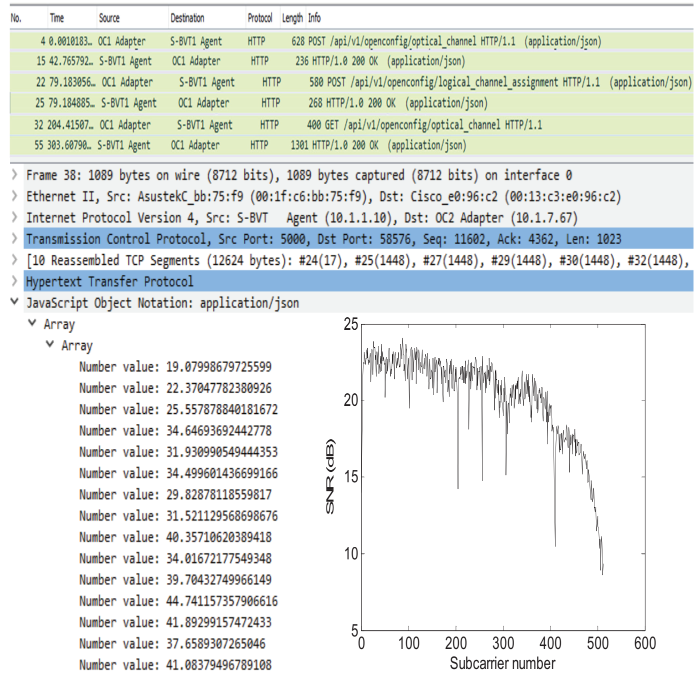

Fig. 5. Wireshark capture showing the retrieved SNR values per subcarrier. In the inset SNR profile.

Conversely, in this work, as the proposed approach considers separated DAC/ADC libraries, the optical channel operation is simplified achieving a reduced setup time in the optical channel establishment of 79 s, as seen in the wireshark capture of Fig. 5. The channel information in terms of signal-to-noise ratio (SNR) per subcarrier, in B2B configuration, is depicted in Fig. 5, where also appears a wireshark capture with this information.

IV. Cost and Power Consumption Analysis

A. Programmable S-BVT

The modular transceiver architecture of Fig. 1 shows a number of important cost-saving opportunities thanks to the adoption of cost-effective optoelectronic subsystems and simplified DSP solutions at the S-BVT. For example, the use of DD at the receiver side reduces the S-BVT cost of of about $25\% - 35\%$ with respect to coherent solutions [7]. In fact, DD components only include simple photodetectors and ADC, along with a WSS shared among all the BVTs. Furthermore, the power consumption and footprint of the S-BVT can be further reduced thanks to the photonic integration of key subsystems [8]. Here, we investigate the cost/resource/power consumption savings, of the proposed programmable S-BVT based on DD, which enables 100 Gb/s (2 X 50 Gb/s) with respect to coherent (CO) solution at 100 Gb/s (4 X 25 Gb/s) [7], [20]. Specifically, the CO-transceiver includes an IQ transmitter (Tx) based on a nested MZM and a CO-receiver (Rx) based on balanced photodetectors both with dual polarization. Table I shows the number of required components to implement both configurations.

In this light, the unitary cost of the proposed S-BVT based

Component	S-BVT DD (2 X 50 Gb/s)	CO 100 Gb/s
MZM	2	1 (nested)
Driver	2	4
DAC	2 ports	4 ports
ADC	2 ports	4 ports
TLS	2	1
LO	-	1
WSS_{Tx}	2 ports	1 port
WSS_{Rx}	2 ports	1 port
Photodetector (PD)	2	4
Hybrid	-	1

TABLE I
NUMBER OF ELEMENTS FOR TWO DIFFERENT CONFIGURATIONS BASED ON S-BVT WITH DD AND STANDARD 100 GB/S CO TECHNOLOGY

on DD, consisting of individual parts, comprises:

$$BVTx : C_{TLS}+C_{MZM}+C_{driver}+\frac{C_{DAC}}{M}+\frac{C_{WSS_{Tx}}}{N}. \quad (1)$$

$$BVRx : C_{PD}+\frac{C_{ADC}}{M}+\frac{C_{WSS_{Rx}}}{N}. \quad (2)$$

where M and N are the number of ports of the DAC/ADC and WSS, respectively. We have considered that the WSSes at Tx/Rx sides are the same. Hence, the total cost for the 100 Gb/s S-BVT (2 X 50 Gb/s) is:

$$C_{SBVT} = 2*C_{TLS}+2*C_{MZM}+2*C_{driver}+ \\ +2*\frac{C_{DAC}}{M}+2*\frac{C_{ADC}}{M}+4*\frac{C_{WSS}}{N}+2*C_{PD}. \quad (3)$$

On the other hand, the 100 Gb/s CO-transceiver, comprises:

$$Tx(IQ) : C_{TLS}+C_{nested_{MZM}}+4*C_{driver}+4*\frac{C_{DAC}}{M}+\frac{C_{WSS}}{N}. \quad (4)$$

$$Rx(CO) : C_{LO}+4*C_{PD}+C_{Hybrid}+4*\frac{C_{ADC}}{M}+\frac{C_{WSS}}{N}. \quad (5)$$

We have assumed that the cost of a nested MZM is approximately equal to the cost of 2 simple MZMs, as the nested MZM modulates the phase and the quadrature components of the input signal. Moreover, the cost of the local oscillator (LO) is the same as the laser cost ($C_{LO} = C_{TLS}$), since TLS can be used as LO. CO implementation requires balanced photodetectors (PD), at the receiver side, whereas simple PIN are included in the proposed S-BVT based on DD. Balanced photodetectors and PINs with similar features present almost the same cost (C_{PD}). Then the CO 100 Gb/s transceiver cost compared with the S-BVT cost is:

$$C_{CO} = C_{SBVT}-2*\frac{C_{WSS}}{N}+2*C_{driver}+ \\ +2*\frac{C_{DAC}+C_{ADC}}{M}+C_{Hybrid}+2*C_{PD}. \quad (6)$$

From equation (6) it can be stated that:

$$2*\frac{C_{WSS}}{N} \ll 2*C_{driver}+2*\frac{C_{DAC}+C_{ADC}}{M}+C_{Hybrid}+ \\ +2*C_{PD}. \quad (7)$$

Hence, from equation (6) and (7) the benefits of adopting the proposed SDN-enabled S-BVT based on DD and MCM in disaggregated optical networks are also evidenced in terms of cost.

Concerning growth, the S-BVT cost grows linearly since a new 50 Gb/s slice requires the same number of components, only the WSS and ADC/DAC is shared among the S-BVTs. In particular, the proposed 100 Gb/s S-BVT (50 Gb/s X 2) can evolve towards 800 Gb/s S-BVT (100 Gb/s X 8). Despite the cost seems to grow linearly with the increasing of the number of transceivers/slices of the S-BVT, thanks to photonic integration a higher cost reduction can be achieved [8], [11]. Hence, according to [20], the relative cost of a pluggable 800 Gb/s discrete multitone (DMT) transceiver, with respect to the 100 Gb/s transceiver is about a factor of 2.2. In [20], it is also highlighted the cost benefits of adopting a MCM modulation (in particular the use of DMT in comparison to PAM4).

Regarding the power consumption, both the transceiver hardware and DSP parts of the two configurations should be considered. Specifically, the power consumption of the hardware of the S-BVT configuration based on DD is lower than the one of the CO 100 Gb/s transceiver, according to equation (7). Regarding the DSP, it should be taken into account that in the CO implementation, additional processing such as the carrier recovery should be considered. However, the DSP block of the S-BVT also includes the processing related to the loading algorithm implementation (see Fig. 1). By considering pluggable transceivers and equivalent form factors, an estimated power consumption can be obtained according to [20]. On this regard, CFP2 form factor transceiver is a suitable option for the envisioned programmable S-BVT. Specifically, 800 Gb/s transceiver is close to CFP2-class power consumption, which is about 12 W, where about 79% of this power consumption is due to DSP. As evolutionary path, smaller form factors such as QSFP28 can be considered further reducing the cost and power consumption of the proposed solution [21].

B. Economic impact of transceiver disaggregation

By exploiting disaggregation at the transceiver level, network agility and flexibility is promoted while allowing important cost savings thanks to avoiding vendor lock-in [4], [22].

Following [23], the hardware cost of a packet switch represents between 50% and 60% of the total cost of the packet switch itself; the remaining 40%−50% typically belongs to the Operating System license and SW. Concerning transceivers, we may estimate that the amount of software and licence only represents 25%, thus telcos could potentially acquire transceivers at 75% of the original cost and further rely on open-source SW projects and only pay the cost of extra SW features for the SDN agents. Such customized SDN SW may be developed in-house or externally, opening new business opportunities to third parties. Indeed, existing open source initiatives in the SDN context for WDM transport are gaining momentum and expected to reach maturity in the short to medium term. In fact, according to the OpenHub portal [24], ONOS has had more than 14K commits from about 450 software contributors and accounts for about 1 Million lines of code at the time of writing.

Thus, the disaggregation of optical transceivers in metro scenarios, where a large majority of the CapEx belongs to the digital-to-WDM equipment (transponders, muxponders and switchponders) can provide important cost savings [4].

In particular, in our partial disaggregated scenario of Fig.1, the programmable S-BVTs are composed of different BVTs that may have been manufactured by different vendors.

Hence, as different suppliers are put into competition, the price of the transceivers should decrease in comparison with a fully aggregated scenario, where a single vendor provides all the hardware. On the other hand, when considering a fully disaggregated solution based on either white boxes or bare metals blades, system flexibility further increases. However, additional costs have to be considered, which includes the cost of system integration or the buying from third parties of software for network control. In particular, according to a recent techno economic analysis presented in [4], the cost of integration should not exceed 15% of the total CapEx. Regarding the economic impact of disaggregation, CapEx reduction can be achieved if a hardware and software cost reduction of about $20\% - 25\%$ can be ensured [4]. By the adoption of the SDN paradigm, also an OpEx reduction is envisioned, independently of the level of disaggregation that is supported.

V. Conclusion

SDN-enabled S-BVT has been demonstrated to be a suitable solution for disaggregated optical networks, meeting at the same time significant challenges of 5G and beyond networks. In fact, the S-BVT can be composed of different BVTs of different providers promoting a fully disaggregated ecosystem. Hence, S-BVT SDN agents have been developed following the OpenConfig vendor-agnostic data model. Specifically, a proof-of-concept of the integration of the disaggregated transceiver with optimized SDN agents has been demonstrated, showing significant preliminary configuration setup time reduction in the establishment of an optical channel. It has been identified that the proposed sliceable transceiver based on DD and MCM leads to reduced complexity in terms of cost/power consumption compared to alternative coherent transceivers. In addition to the intrinsic cost and power consumption savings, thanks to the adoption of a DD receiver scheme, in comparison with its CO counterpart, it is worth remarking that the proposed solution also features modularity and easy integration with open-source control software. This allows further CapEx reductions for disaggregated network scenarios. Thus, altogether our approach can lead to cost reductions on hardware and software, but more importantly it allows faster operations, improving agility and flexibility thanks to its demonstrated integration with SDN open control. The level of integration and performance of the disaggregated optical transceivers can be a future challenge that should be investigated. Additionally, by the adoption of pluggable transceivers, further cost, power and footprint savings can be achieved, innovatively exploiting the great potentials that photonic technologies have to offer. Hence, the S-BVT modular architecture plays an essential role in disaggregated optical scenarios.

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