Synergy of Photonic Technologies and Software-Defined Networking in the Hyperconnectivity Era

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***Abstract*—Photonic technologies and software-defined networking (SDN) are key to support hyperconnectivity in a globally networked society. We present programmable optical transmission systems and particularly SDN-enabled transceiver architectures for addressing this challenge. Special attention is devoted to promising technologies able to reduce the cost, power consumption and footprint of the optical subsystems and network elements. This is particularly relevant for future agile and high-capacity metro networks, identified to be the most challenging segment. Specifically, the adoption of high-dense photonic integration and long-wavelength vertical cavity surface emitting lasers (VCSELs) is considered for the design of sliceable bandwidth/bitrate variable transceiver (S-BVT) architectures supporting hyperconnectivity. Programmability and technological aspects are discussed, as well as recent results and achievements, focusing on opportunities and limitations provided by the proposed solutions. Starting from the identification of programmable parameters, the photonic transceivers modeling is provided towards their automatic configurability by an SDN controller. An efficient use of the available resources is promoted, while fully exploiting the photonic technology potentialities and exploring advanced functionalities that can be provided.**

***Index Terms*—Sliceable bandwidth/bitrate variable transceiver (S-BVT), software-defined networking (SDN), vertical cavity surface emitting lasers (VCSEL), optical metro networks, photonic integration/technologies.**

I. Introduction

HYPERCONNECTIVITY is a term coined and first used in social science to indicate "the availability of people for communication anywhere and anytime" and refers to a computer-mediated communication (CMC) in networked organizations/communities [1]. CMC itself fosters hyperconnectivity, due to its pervasive use at both local and global level (*glocalization*), creating *local virtuality* despite physical proximity [1]. Hyperconnectivity thus involves person-to-person, but also person-to-machine interaction, using multiple means of communication over the network, to be constantly connected. This also includes machine-to-machine interaction/communication. These concepts, besides any *dystopian* or *utopian* view, affect connectivity in terms of the amount of generated traffic and the need for rapid communication and information access at low cost [1]. From a technological viewpoint, hyperconnectivity is therefore driving a huge capacity increase in a highly dynamic scenario, where future networks should be able to support novel and bandwidth-hungry services, as well as internet-of-everything connectivity [2]. In this scenario, the metropolitan area network (MAN) is foreseen as the most challenging segment, requiring specifically tailored solutions able to offer flexibility, agility and high capacity, while being sustainable to keep low both capital expenditure (CAPEX) and operational expenditure (OPEX). Actually, the metro-delivered traffic is growing faster than the core-delivered traffic, according to [2], and particularly, it is foreseen that the 35% of end-user Internet traffic will be delivered within a metro network by 2021. Thus, effective solutions for timely addressing the technological challenges posed by hyperconnectivity are urgently needed.

In the hyperconnectivity era, a synergy of photonic technologies and software-defined networking (SDN) appears to be crucial to successfully puzzle out this evolutionary scenario. Specifically, these two prominent enablers have the chance to enhance their potential capabilities in the design and implementation of programmable optical transmission systems. The target is, on one side, to lower the cost, power consumption and footprint of the system and/or of each potentially *disaggregated* network element; while, on the other side, to make them *virtualizable* resources available and programmable according to the network needs [3][4].

In this context, the bandwidth/bitrate variable transceiver (BVT) represents a key element [5], which allows integrating, in a synergetic fashion, novel photonic technologies with an

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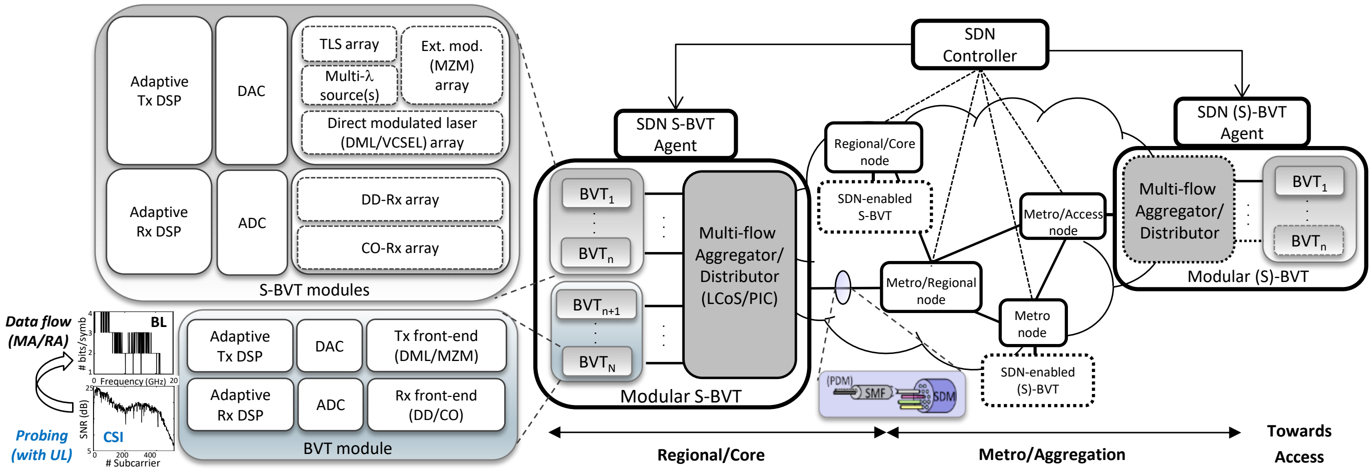


Fig. 1. Envisioned evolutionary network scenario and SDN-enabled adaptive transmission system. Different technology choices for the S-BVT are indicated.

SDN-based control plane [6]. Furthermore, sliceable BVT (S-BVT) architectures able to generate multiple adaptive and variable flows, (re)-configurable via SDN commands, can be designed to have a modular implementation based on photonic integrated circuits (PICs) [6], [7]. Modularity is key to size the S-BVT according to a *grow-as-needed* approach, following a *pay-as-you-grow* model. This also facilitates disaggregation, crucial for enabling multi-vendor interoperability and definitively lowering CAPEX and OPEX [3][4].

Dense photonic integration and suitable novel photonic technologies enable the fundamental block/device/module(s) of the network node element to be characterized by reduced cost, power consumption and footprint, and thus are worthy to be explored and adapted for MAN connection services. For example, vertical cavity surface emitting laser (VCSEL) technology, typically considered for short-reach cost-sensitive applications, is emerging as a promising option to design programmable transceivers for the MAN segment, thanks to the availability of solutions at long-wavelength [8][9][10]. Indeed, when approaching the regional/core segment, it is of prominent relevance achieving ultimate performance in terms of capacity/bandwidth, serving a very high number of sites over an extended reach. Thus, suitable transceiver architectures integrating low-cost and low-power consumption devices should be investigated, considering different options, advantages and limitations of the technological choices, with special attention on the programmability, flexibility and softwarization of the optical transmission system.

With respect to our previous publication [11], this paper is an extended version more focused on how to tackle the evolutionary scenario of MANs in the hyperconnectivity era, dealing with photonic technologies, promising for this network segment and capable to be (re)-configured via an SDN controller. Particularly, the adoption of long-wavelength VCSELs and PIC is considered, as compelling case of synergy of photonic technologies with SDN, particularly relevant for MANs. In this work, further technological and architectural details on the concept of programmable photonic transceivers based on these technologies, as well as latest designs, results and control aspects achievements are provided with respect to [11], particularly focusing on the MAN segment and the related challenges to be addressed. In addition to [11], suitable transceiver architectures are presented, identifying the specific programmable parameters, taken into account technological peculiarities/limitations/advantages, and defining the models to describe them, towards their integration in an SDN-based control plane.

The paper is organized as follows. Section II presents the proposed SDN-enabled adaptive transmission systems, considering the envisioned evolutionary scenario driven by the hyperconnectivity era. Particularly, modular S-BVT architectures based on adaptive DSP are described, indicating possible module options/alternatives suitable for the transmitter (Tx) and receiver (Rx) implementation. The trade-offs related to different photonic technology choices are briefly discussed with a special focus on VCSEL-based photonic transceivers. Section III deals with how to introduce programmability and softwarization in the optical transmission system to enable agile networking and advanced functionalities. Furthermore, the models for VCSEL-based (S)-BVT architectures are provided, considering different technology options. Finally, conclusions are drawn in Sec. IV.

II. SDN-ENABLED ADAPTIVE TRANSMISSION SYSTEMS

Figure 1 shows the envisioned evolutionary network scenario, adopting S-BVTs to facilitate a (soft) migration towards a more flexible paradigm and elastic optical networks (EONs) [5]. There, SDN-enabled centralized S-BVTs of high capacity, located at the metro/regional or regional/core nodes, are able to support ultra-broadband services and high peak rate in a highly dynamic network scenario. These S-BVTs, composed of multiple modules, which can be added in a grow-as-needed approach, give service to distributed (S)-BVTs of lower capacity (and cost), closer to the end-user at the metro/access nodes. The traffic is envisioned to be optically/transparently aggregated/distributed to connect nodes at the edge of the regional/core to nodes at the edge of the metro network. A transparent service delivery at variable data rates could also be envisioned towards the access segment of an SDN-controlled optical network [12]. Depending on the specific node type, hierarchy level, and network requirements, the (S)-BVT can be equipped with a set of modules, which can be integrated on the same photonic platform as pluggable units. Each module can be seen as a single-flow BVT (bottom-left inset of Fig. 1) or as a set of submodules integrating multiple S-BVT transmitters and receivers (up-left inset of Fig. 1). This enables to suitably size the S-BVT with a modular architecture to achieve the target capacity/flexibility, according to the node type, aggregation level or evolution of the network. The multiple flows are aggregated/distributed either by a passive element in PIC or by a bandwidth variable wavelength selective switch (WSS) trading flexibility versus cost. This element can be considered as part of the S-BVT or included in the network node. As shown in Fig. 1, the programmable modular transceiver can be equipped with adaptive digital signal processing (DSP), in order to enhance its flexibility and programmability (including re-configurability and monitoring). This requires digital-to-analog and analog-to-digital conversion (DAC/ADC). At the Tx and Rx, different optoelectronic frontends, photonic technologies and devices can be adopted [6]. External or direct modulation with alternative laser sources at the Tx, and coherent (CO) or direct detection (DD) at the Rx are technology options trading-off ultimate performance against reduced cost/complexity, as it will be detailed in subsection A. In addition to full spectral manipulation with wide range granularity, multiple dimensions can be exploited, such as the polarization and spatial dimensions [6][13]. Polarization division multiplexing (PDM) can be combined with either coherent or direct detection techniques [14]. Space division multiplexing (SDM) can be implemented by using fiber bundles or multi-core fibers (inset of Fig. 1), as envisioned in an evolutionary softwarized scenario [13]. Thus, to target very high capacity per link, both spectral and spatial aggregation approaches are considered.

The SDN controller suitably configures the specific element (device or module), setting each active slice/flow via the corresponding SDN agent that maps high level configuration commands to low level hardware-specific instructions. Accordingly, advanced features are enabled, such as the slice-ability, multi-flow operation and the (re)-configuration of a set of parameters (e.g. bandwidth elasticity), which are specifically related to the adopted architecture and/or technologies [5].

A. Photonic technologies and trade-offs

As previously mentioned and evidenced in the S-BVT of Fig. 1, alternative technologies can be used at both the Tx and Rx sides trading off performance and cost/complexity.

For example, external Mach-Zehnder modulator(s) (MZM) combined with tunable laser source(s) (TLS) is a costlier solution characterized by more flexibility and better performance, with respect to other Tx options based on direct modulated lasers (DMLs). However, taking into account the modulator insertion loss (typically 6-8 dB at quadrature operation) and required chip floor space, DMLs outperform external modulated laser (EML) solutions in terms of cost, footprint, and power consumption, resulting an attractive solution for achieving high-speed performance, particularly if combined with advanced modulation formats [15]. Actually, in [15] a comparison is provided, at the varying of the rate, bandwidth and spectral efficiency, showing that the penalty due to the DML nonlinearity could be negligible in case of adopting specific modulation formats with respect to others. Indeed, the target reach is relevant to determine the suitability of DML as feasible option. CO-Rx enables to achieve enhanced performance over extended reach with respect to simple DD, increasing the system cost/complexity, as it requires an additional local oscillator (LO) at the receiver side, ideally tunable to flexibly adapt over the spectrum.

The independent TLS array for super-channel generation can be suitably replaced by photonic integrated multi-wavelength (multi-λ) locked optical combs, which can be implemented using different technologies [17]. This cost-effective integrated alternative is at the expense of full tune-ability, programmability and flexibility [7],[5]. In [16], it is shown that the adoption of integrated III-V laser arrays and/or combs (with respect to discrete laser sources) can reduce the cost and power consumption down to a factor of 4, thus contributing to further reduce the total cost and power consumption of the transponder. Super-channels and super-wavelength granularity can be enabled, optically processed and managed using devices based on liquid crystal on silicon (LCoS) or planar lightwave circuit (PLC) technology, trading again tune-ability, performance and cost [6], [14]. PIC solutions enabling device programmability have been also proposed, being promising for balancing this trade-off [18]. The adoption of high dense photonic integration allows implementing lower power consumption devices, fostering component sharing and an improvement in the form-factor of pluggable optical interfaces [19]. With the advances in complementary metal oxide semiconductor (CMOS) technology, further power saving in RF components is possible [15], enabling to include advanced DSP to enhance the transceiver performance, adaptability and flexibility. An estimation of the power consumption of different transceiver solutions targeting 400 Gb/s, in terms of electrical and optical interfaces, can be found in [15]. The different options trade off benefits (performance) and costs/complexity; however, the demand for ever increasing bandwidth (towards Tb/s capacities) and dynamic adaptation could be addressed by a suitable combination of PIC and advanced modulation formats, looking forward the advances of the available technologies.

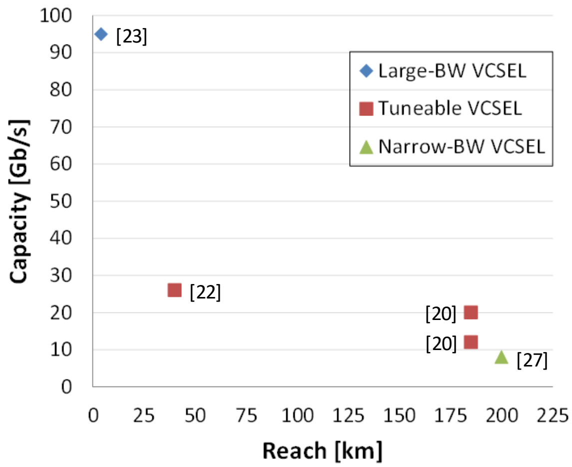


Fig. 2. Capacity vs reach of transceivers reported in the literature adopting different VCSELs, direct multicarrier modulation (DMT/OFDM) and DD.

In the next subsection B, the adoption of VCSEL as appealing candidate technology is discussed for the design of photonic transceivers (combining direct modulation with DD or CO-Rx), particularly focusing on related trade-off and expected performance. Compared to other DML options (e.g. DFB lasers), VCSELs have lower manufacturing cost, due to the easiness of testing them (thanks to the vertical emission), facilitating mass production. Optimized structures in indium phosphide (InP) enable operation at long wavelengths characterized by low threshold current and operating voltage, showing intrinsic lower power consumption (and low losses in silicon waveguides and silica-based optical fibers) compared to edge emitting laser solutions. For very large bandwidth VCSELs (up to 22 GHz), less than 10 mW power consumption has been reported [10]. These features make this choice particularly attractive to be used in both the access and MAN segments of (SDN-controlled) optical networks, with spectrum granularity even finer than EON [20], [21]. In fact, as better detailed in the next sections, taking into account the peculiarities (including benefits and limitations) of the technology choice, special attributes and also advanced functionalities and capabilities can be enabled.

B. *VCSEL-based photonic transceivers*

Even though VCSEL technology is usually considered for short reach and low bitrate applications, mainly at short-wavelength, its potential utilization at long-wavelength has been recently explored for targeting access and metro networks, as well as applications at 100 Gb/s and beyond [20]-[24]. In particular, the evolution of technology towards tunable and large-bandwidth (≥18 GHz) VCSELs [9],[10], which can be directly modulated (DM) with advanced modulation formats, including multicarrier modulation (MCM), opens up new horizon for its adoption, even for the design of programmable transceivers [20],[26]. High-speed operation and higher modulation bandwidth are achieved by a suitable structure design reducing the parasitic effects and the optical cavity length [9], [10]. Fig. 2 shows the performance (reported in the literature) achieved adopting DM VCSEL with MCM and DD. With MCM, we refer to either orthogonal frequency division multiplexing (OFDM) or its simplified version, namely discrete multitone (DMT). Both double sideband (DSB) and single sideband (SSB) modulations are taken into account. It is worth mentioning that it has been envisioned that DMT can be a promising solution to target 1T-class transceivers, taken into account the advances in CMOS technology, towards a reduction of the power consumption required by this modulation format compared to others (such as PAM-4) [25], [15]. Additionally, by reducing the number of subcarriers and DSP complexity further saving is possible [15]. In Fig. 2, three different types of VCSEL are considered: i) widely tunable micro-electro-mechanical system (MEMS) VCSEL, with operating wavelength over a spectrum range of more than 60 nm and a 3-dB bandwidth (BW) of 7 GHz [9], ii) VCSEL with limited tune-ability characterized by large-bandwidth (BW > 15 GHz), and iii) narrow-bandwidth (BW = 4.5 GHz) VCSEL. As it can be observed, DM tunable MEMS VCSEL combined with DD have been successfully demonstrated for supporting up to 26 Gb/s DMT transmission over 40 km in converged wavelength division multiplexing (WDM) passive optical networks (PONs) [22]. It is worth notice that the tunable VCSEL is characterized by low-impedance and wide mode-hop free continuous tuning is realized by electro-thermal actuation of the MEMS [9]. Furthermore, the VCSEL is packaged in a transmit-optical-subassembly (TOSA), which can be easily assembled inside standardized small form factor pluggable (SFP) optical modules [22]. Thus, the same technology results also promising for implementing programmable cost-effective (S)-BVT targeting the MAN segment. In fact, adopting DD, it has been demonstrated that 12 Gb/s (with DMT) and 20 Gb/s (with SSB-OFDM) connections can be supported over 185 km 2-hop path within the optical network of the ADRENALINE testbed [20]. SSB optical filtering can be performed at the S-BVT aggregator stage or at the network nodes, if suitably equipped with bandwidth variable WSS, so that the optical filtering could be performed at any node. In case of adopting narrow-BW VCSEL, a similar path (200 km) can be established at the expenses of the supported capacity (8 Gb/s), considering DMT and DD [27]. For targeting 100 Gb/s and beyond applications, large-BW VCSELs should be adopted. As shown in Fig. 2, 95 Gb/s has been achieved for a short reach (4 km), combining DMT with DD [23].

In order to move the VCSEL-based transceiver performance towards the right-up part of the plot of Fig. 2 (i.e. high capacity and longer reach), the use of large-bandwidth VCSEL combined with CO-Rx appears to be an interesting option, as demonstrated in [24]. In fact, coherent reception allows the recovery of the magnitude and phase of the received signal thanks to the use of a local reference laser (LO). This entails an improved transmission performance and allows the compensation of different impairments, such as the chromatic dispersion, at the receiver side. Indeed, it should be taken into account that the output signal of a typical direct modulated VCSEL features an intensity modulation around a constant bias value [24].

Within the EU-H2020 PASSION project, S-BVT architectures adopting DM large-bandwidth VCSELs and CO-Rx are proposed for achieving multi-terabit capacity networking in MAN [28]. As shown in Fig. 3, the envisioned S-BVT is composed of multiple Tx modules, consisting of submodules equipped with large-bandwidth (≥18 GHz) VCSELs, each operating at a certain nominal central frequency. It is considered that each submodule is equipped with 10 VCSELs and up to 4 submodules are integrated on a silicon-on-insulator (SOI) chip to implement a compact transmitter module. Coupling-losses can be minimized (to less than 0.5 dB) with a suitable PIC design adopting reflecting mirrors to efficiently address optical beams from VCSELs into the waveguides and to deliver optical signals toward a fiber-optic assembly [29]. Assuming that each VCSEL is directly modulated with adaptive MCM formats (adaptive DSP) to generate a flow supporting up to 50 Gb/s, each module can provide a maximum capacity of 2 Tb/s. The use of adaptive DSP enables a modulation format selection per MCM (DMT or OFDM) subcarrier, to achieve the target capacity according to the channel state information (CSI) retrieved at the Rx side (as it will be further detailed in Sec. III A). The S-BVT can be upgraded to achieve higher capacity by adding SOI-chip modules. The channel spacing depends on the number of VCSELs in the (sub)-module(s) covering the C-band. Considering 25 GHz spacing between two consecutive VCSEL operating wavelengths over the C-band, to fully exploit the spectrum resource, a maximum target capacity up to 8 Tb/s can be achieved with M=4 modules, including a total of 160 VCSELs, supporting 50 Gb/s flow each thanks to SSB direct MCM. The architecture further scales to higher capacity with additional modules (M > 4), considering PDM (to double the capacity) and/or SDM (to enhance the capacity by a factor depending on the number of fibers/cores, see inset of Fig. 1). At the receiver (Rx) side, the S-BVT consists of an arbitrary set of integrated CO-Rx (e.g. as in Fig. 3, N modules each integrating n CO-Rx) equipped with tunable LO, operating at the suitable central frequencies to correctly recover the transmitted flows.

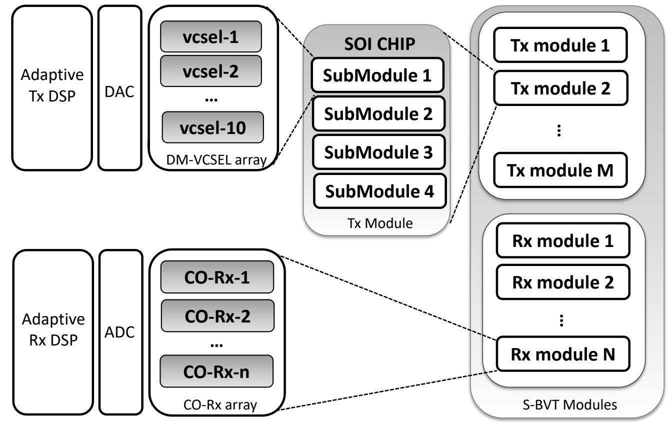


Fig. 3. Modular S-BVT based on large-bandwidth VCSELs and CO-Rx.

Promising results have been obtained, enabling 50 Gb/s per flow over hundreds of km, considering SSB DMT modulation with adaptive loading and CO-Rx [30]. Particularly, each flow has 25 GHz bandwidth occupation (corresponding to 2 frequency slots of 12.5 GHz in EON) and it has been numerically demonstrated, that for an OSNR value of 30 dB, a 50 Gb/s connection can be established over a path of 260 km (4 links with 65 km length), traversing up to 5 WSS (with 25 GHz bandwidth) [30]. This reach can be enhanced of about a factor of 3 (735 km), if we consider that the actual network topology is characterized by shorter fiber spans (35 km). This is mainly due to the additional amplification stages (which in turn imply higher cost) and it is strictly related to the deployed network topology and specific traversed path. In case of DSB DMT and the same bandwidth occupancy (half bandwidth data signal), half of the capacity per flow can be supported over the same path.

III. PROGRAMMABILITY AND SOFTWARIZATION

To fully integrate the programmability and softwarization in the optical system and exploit their inherited advantages, it is crucial considering the peculiarities of the elements and devices to be configured, as well as the limitations/potentialities of the adopted photonic technologies. This also implies carefully identifying the parameters that can be accessible/programmable and involves defining the information model that will be used by the SDN controller. The information model of any generic system identifies in an abstracted way that relevant information to be taken into account by a controller to achieve the actual configuration of the underlying device, network element, etc. This fosters the definition of the control interactions (i.e., interfaces and protocols) between the centralized SDN controller and the elements (i.e., agents), which directly handle the device configuration.

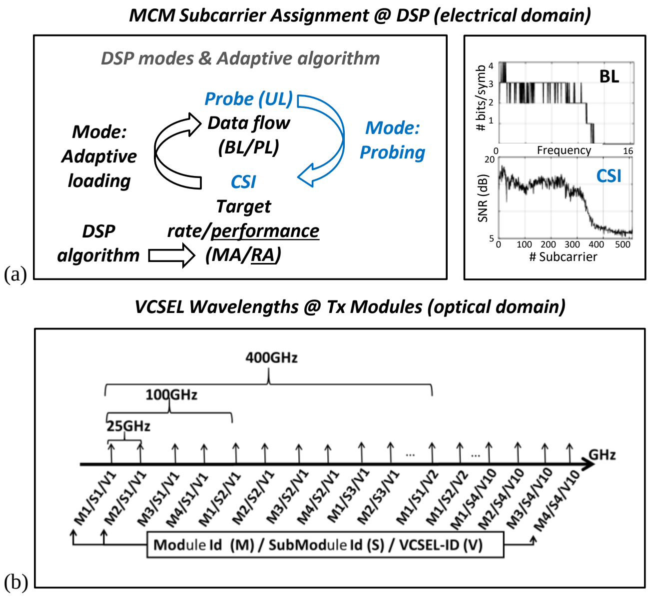


Fig. 4. (a) Subcarrier assignment at the adaptive DSP with example of BL according to corresponding CSI; (b) VCSEL wavelength spacing over the C-band according to Tx (sub)-modules of the S-BVT.

Although a set of subsystem attributes are interesting to be exposed to the SDN controller for enabling functionalities/features and correctly setting-up connections, it is worth notice that low-level and internal aspects (e.g., circuitry and specific attributes) are hidden and should not be exposed to the SDN controller for an agile management.

In the context of attaining targeted SDN programmability of the underlying optical devices and network elements, nowadays different (SDO) groups (e.g., OpenROADM [31] and OpenConfig [32]), are working on having a common and agreed-upon device and network model. The goal is to use open interfaces enabling the programmability of different devices and elements simplifying the development and integration even in multi-vendor scenarios. OpenROADM focuses on defining a vendor-neutral ROADM (reconfigurable optical add-drop multiplexer) as well as transponders and pluggable optics in terms of specification and data models. On the other hand, OpenConfig provides a set of models for the configuration and state model for DWDM (dense wavelength division multiplexing) optical devices. Note that both initiatives are mainly focused on industrial-driven and agreed-upon standards and models, whilst this work has a more research-oriented scope and view. Accordingly, the following interfaces and models are not completely aligned with those promoted by OpenConfig and OpenROADM. However, this does not preclude that eventually the proposed data models could be integrated in the work being done by these initiatives.

A. Functionalities

Different abilities and/or functionalities can be identified for SDN-enabled S-BVTs, such as multi-flow generation, slice-ability and adaptability/elasticity [5]. They are enabled and supported by the SDN controller aiming at attaining an efficient overall resource usage. In particular, advanced functionalities, such as the mitigation of spectrum fragmentation, are enabled by the SDN controller without requiring a re-optimization of the entire network, saving network resources and operating costs. This is achieved thanks to the adoption of softwarized/SDN-programmable (S)-BVTs and their abilities of spectral manipulation at sub-wavelength level and/or filling spectral gaps [5], [20]. The former ability is particularly enabled by the adoption of MCM technology and bit/power loading (BL/PL) algorithms at the DSP [5]. The latter ability is eased by equipping the S-BVT with tunable VCSEL module(s), thanks to its wide-range tune-ability (to set the operating wavelength on the central frequency of the gap to be filled) and adaptive narrow bandwidth (to suitably fill the spectral gap) [20]. In this case, the adoption of this photonic technology offers an opportunity/potentiality to be exploited by the programmable optical system in synergy with the SDN controller, as detailed in [8].

The use of MCM allows obtaining a sub-wavelength granularity of the order of tens of MHz at the digital/electrical level, according to the DMT/OFDM subcarrier number. For example, considering an OFDM signal with 512 (digital/electrical) subcarriers and 20 GHz of bandwidth a subcarrier granularity of less than 40 MHz is obtained. This parameter is flexible and can be adapted at the DSP, according to the target requirement or module design/type. In addition, the adaptability of the DSP is further enhanced by BL/PL algorithm, such as the Levin-Campello or Chow's algorithms [5]. They enable optimal or suboptimal assignment (respectively) per each subcarrier, according to the CSI that is retrieved at the Rx by transmitting a probing (uniform loaded, UL) signal. Specifically, the adaptive mapper enables loading each subcarrier with the appropriate modulation format, including binary phase-shift keying (BPSK) and M-ary quadrature amplitude modulation (M-QAM, with $M=2^l$ and $2 \leq l \leq 8$); in case of UL, 4-QAM is assigned to all subcarriers. Thanks to this approach, the transmission is suitably adapted to the network traffic demand or specific use case requirements over the targeted network path. Specifically, the

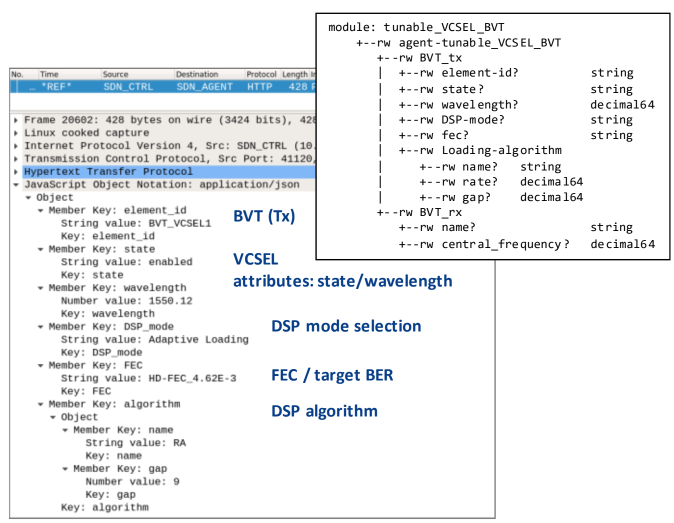


Fig. 5. JSON encoding for programming a BVT module based on DM tunable VCSEL and DD; in the inset, YANG data model considering alternative receiver options.

rate can be maximized at a fixed performance activating the rate adaptive (RA) BL/PL assignment, and the performance can be maximized at a fixed rate with margin adaptive (MA) BL/PL algorithm. This is summarized in the schematic of Fig. 4 (a), where an example of BL is provided for the case of a BVT based on DM tunable VCSEL and DD. The bit assignment and corresponding CSI is shown for the 512 subcarriers of a SSB-OFDM signal with optical spectral occupancy of 12.5 GHz (corresponding to one frequency slot in EON) to be transmitted over a single-hop path of 35 km SSMF [20].

Thus, the SDN-enabled S-BVT is adaptive to multiple rate/reach according to the traffic demand and selected path, for a target performance related to the forward error correction (FEC) choice, offering a wide range of sub- and super-wavelength granularities. Additionally, thanks to its modularity, different capacities are supported according to the network evolution and specific node type or aggregation level.

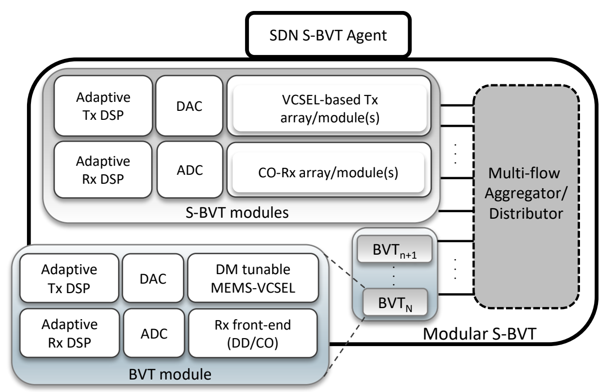
In case of limited tune-ability of the optical source(s) at the Tx, the S-BVT architecture should be carefully designed to overcome/mitigate this limitation and provide the modules with enough flexibility to be used in future agile MANs. For example, following the EU H2020 PASSION project approach described in Sec. II B, the VCSEL wavelengths are assigned to cover the C-band and provide a channel spacing of 100 GHz per each SOI chip module. Adding modules, the spectrum can be fully populated with 25 GHz spaced channel (providing up to 50 Gb/s each), as shown in Fig. 4 (b). Each VCSEL can be enabled/disabled to suitably set-up a metro network connection at the target capacity, by aggregating multiple flows generated at different modules [33]. Thus, spectral/spatial aggregation and slice-ability are enabled, fully and optimally exploiting all the available resources/dimensions according to the SDN controller decisions.

B. *Programmable S-BVT architecture modeling*

In this section, we present the models for SDN-enabled S-BVT architectures, particularly focusing on the use of VCSEL technology in the programmable photonic transceiver design.

Yet another next generation (YANG) common data modeling language is used, since it provides a standard way to describe the network/system elements to be controlled and managed. This fosters and eases interoperability in a multi-vendor scenario towards a disaggregated optical network paradigm [3], [4]. The first step towards a correct modeling of a network element is the identification of the parameters susceptible to be programmed, according to the designed architecture and the adopted technologies.

First of all, we consider an S-BVT with BVT modules based on tunable MEMS VCSEL (as described in Sec. II). Since the VCSEL is tunable over a wide range, in addition to its state (enabled/disabled), a relevant parameter, to be decided and selected by the SDN-controller is the operating wavelength. This selection is related to the frequency slot(s) of the connection to be established or the spectrum gap to be opportunely filled for mitigating the cumbersome spectral fragmentation. In addition to the VCSEL specific attributes selection, including the identifier for enabling/disabling it and the operating wavelength, the SDN-controller should also set the adaptive DSP, for directly modulating the VCSEL, by means of the BVT agent. As described in previous subsection A, the DSP can be set either to *probing* or *adaptive loading* mode. In the former case, a uniform loaded MCM signal is transmitted over the targeted lightpath to retrieve the CSI; in the latter case, a data flow is transmitted with BL/PL assignment realized by the algorithm according to the SNR value per MCM subcarrier. The SDN controller is preferably not exposed to the VCSEL thermo-electrical control as well as to the SNR values and corresponding BL/PL assignment, to avoid overloading it with computational tasks that can be performed locally. The parameters that can be configured by the controller are the algorithm name (RA or MA) and the corresponding value of the target *gap* (value related to the required SNR to achieve a target error probability) or target *rate* to be supported by the established connection. Another important parameter is the FEC to be used, which has an associated bit error ratio (BER) threshold, identifying the quality of transmission over the provisioned lightpath. Figure 5 depicts the resulting YANG model (in tree format) of a BVT based on DM tunable VCSEL, which can adopt either DD or



(a)

```
module: vcsel-SBVT
    +--rw agent-SBVT
    |  +--rw ip-addr-agent    inet:ip-address
    |  +--rw port-agent       inet:port-number
    +--rw sbvt-tx
    |  +--rw direction?      uint8
    |  +--rw tx-module* [mod-id]
    |     +--rw mod-id              uint16
    |     +--rw tx-submodule* [submod-id]
    |        +--rw submod-id    uint16
    |        +--rw vcsel* [vcsel-id]
    |           +--rw vcsel-id                      uint16
    |           +--rw used-state?                   boolean
    |           +--rw bandwidth?                    decimal64
    |           +--rw central-frequency?            decimal64
    |           +--rw selected-central-frequency?   decimal64
    |           +--rw central-freq-tunability?      decimal64
    |           +--rw used-modformat?               modformat-type
    |           +--rw used-fec?                     fec-type
    |           +--rw DSP-mode?                     string
    |           +--rw Loading-algorithm
    |              +--rw name?     string
    |              +--rw rate?     decimal64
    |              +--rw gap?      decimal64
    +--rw sbvt-rx
       +--rw direction?        uint8
       +--rw rx-module* [mod-id]
          +--rw mod-id              uint16
          +--rw optical-receiver* [receiver-id]
             +--rw receiver-id          uint16
             +--rw used-state?          boolean
             +--rw central-frequency?   decimal64
```

(b)

Fig. 6. (a) Modular SDN-enabled S-BVT including modules according to Fig. 3 and based on tunable VCSEL; (b) corresponding YANG model.

CO-Rx. The figure also shows the JavaScript Object Notation (JSON) encoding used for the Tx configuration of a BVT based on the tunable VCSEL and considering the adoption of DD at the Rx [20]. Specifically, the operating wavelength is set to 1550.12 nm, and the DSP is in adaptive loading mode with RA algorithm and 9 dB gap for successful transmission at the target BER ($4.62 \cdot 10^{-3}$ with HD-FEC) over the selected single-hop path of 35 km.

Now we consider the S-BVT architecture of Fig. 6 (a). In addition to the case of Fig. 5, it includes integrated modules based on large-bandwidth VCSELs (as described in Fig. 3) able to provide high capacity. As shown in Fig. 6 (a), BVT modules using tunable VCSELs can be also added as pluggable units to provide improved flexibility and the ability of filling spectral gaps. At the Rx side of the S-BVT, we assume to have a pool of modules adopting CO-Rx and/or DD. Following a modular approach, the architecture can grow as needed suitably adding modules (e.g. the SOI chips of Fig. 3 or additional tunable VCSELs). In light of this, as reflected in Fig. 6 (b), (differently from Fig. 5) the model describing the S-BVT should provide appropriate and unique identifiers to the SDN controller to unambiguously determine a specific VCSEL or pool of VCSELs. This is essential at the time of accommodating a new optical connection, for this specific modular VCSEL-based transceiver implementation. Consequently, every module is identified by a unique id. Within each module, every submodule also receives its own id, and, within a given submodule, each VCSEL has its own id. Thus, the tuple formed by module-id/submodule-id/VCSEL-id (M/S/V with corresponding id number, as shown in Fig. 4 (b)) allows determining a particular VCSEL within the S-BVT. Continuing with the identifier and addressing aspects, the S-BVT should be also identified unambiguously within the context of the entire metro network infrastructure. To do that, the SDN controller refers to a given S-BVT using a node/device identifier. For convenience, it is an unnumbered identifier formed by the IPv4 address of the optical aggregator/switch attached to the S-BVT and the add port identifier (using a 32-bit integer).

Other important attributes to be known by the SDN controller to configure the VCSELs and thus necessary reflected within the S-BVT data model of Fig. 6 (b) are the state (i.e., VCSEL occupied or available), the bandwidth (defining the optical spectrum occupied by the signal generated by each directly modulated VCSEL in GHz), the nominal central frequency or operating wavelength (in GHz), and the selected central frequency (in GHz). These parameters are related to the specific adopted VCSEL technology, enabling either wide or limited fine tuning over a certain frequency range). As previously stated, if the S-BVT is equipped with tunable VCSEL, a more efficient utilization of the overall optical spectrum can be performed, for instance to lower potential spectral fragmentation occurrences, when dynamically serving connections arriving and departing from the network. In this more generalized model, the SDN controller can select the modulation format to be adopted (over a set of modulation format types). As in the case of Fig. 5, also the FEC should be selected as the parameters of the DSP.

The modular receiver is equipped with a set of CO-Rx and DD modules. The YANG data model reflected in Fig. 6 (b) defines the receiver module identifier and its programmable attributes, which are the state (occupied or available) and the central frequency (in case the specific module to configure is equipped with a tunable LO). Please note that it is assumed to have bidirectional connections, otherwise, additional parameters (present at the S-BVTx) should be included in the model for the S-BVRx (such as the modulation format, FEC, DSP mode and algorithm).

In [33] the authors addressed the experimental validation of an SDN-controlled S-BVT over a flexi-grid metro optical network infrastructure. The SDN controller is based on a Path Computation Element Central Controller (PCECC) [34]. Such a SDN controller relies in two southbound interfaces (SBIs) to enable the programmability of the underlying network devices (S-BVTs) and network elements (BV-OXCs). Specifically, the PCE Communication Protocol (PCEP) is used to configure the optical network nodes of the computed path (BV-OXCs), whilst a REST API enables interacting with the S-BVT (Tx and Rx) agents for both retrieving S-BVTs status and their programming (allocating and releasing). Fig. 7 (a) depicts the workflow when a new incoming connection should be set up. First the SDN controller collects the status of all the Tx and Rx devices equipped on every S-BVT via REST GET method. Based on this information, the SDN controller triggers a Routing and Spectrum Assignment Algorithm (RSA) to compute a feasible end-to-end path satisfying the spectrum continuity and contiguity constraints and potentially other technological restrictions such as the maximum distance, etc. If the RSA succeeds, its output is made by: i) the pool of S-BVT (Tx and Rx), i.e., VCSEL-ids, Co-Rxs, and their parametric configuration; ii) the spatial path (i.e., BV-OXCs and links to be traversed) and the frequency slot (i.e., optical spectrum to be allocated). For i), the SDN controller relies on a REST POST method, whilst for ii), the PCEP with extensions to flexi-grid networks is used. The experimental validation of the above workflow was presented in [33] and herein shown in Fig. 7 (b).

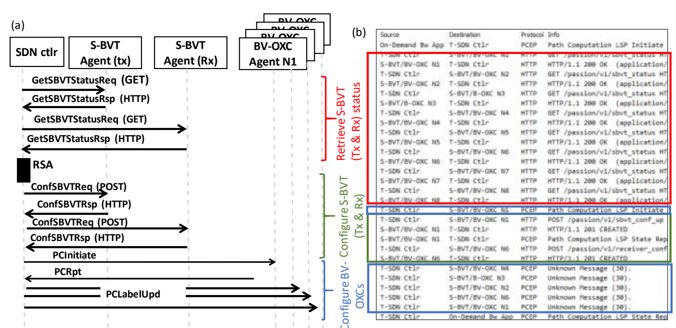


Fig. 7. (a) SDN workflow for programming selected S-BVT (Tx & Rx) Agents and optical network nodes (BV-OXCs); (b) Wireshark screenshot validating the SDN-controlled S-BVTs and optical network

IV. CONCLUSION

In this work we have shown that a synergy of photonic technologies and SDN programmability is of prominent relevance in the hyperconnectivity era. The programmable S-BVT is a key enabling element, where photonic technologies and SDN control meet for supporting hyperconnectivity at low cost, power consumption and footprint. Dense photonic integration and cost-effective photonic devices, like VCSELs, are promising technologies, especially if combined with adaptive DSP and CO-Rx, for the design of S-BVT with Tb/s capacities able to cover the MAN segment. Of course, technology peculiarities and limitations should be taken into account, for a suitable implementation and softwarization. Accordingly, programmable photonic transceiver architectures and the models to be controlled/managed have been provided. Hence, a SDN controller allows fully exploiting the photonic technology potentialities, advanced functionalities, and available resources, including both spectral and spatial dimensions.

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