SDN-controlled Photonic System Architectures for Tb/s MAN Connectivity

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***Abstract*—According to the ever-increasing bandwidth pressure and hyperconnectivity, as particularly experienced during recent times, the metro area network (MAN) is a crucial segment to address the related challenges and requirements efficiently in terms of cost, power consumption and footprint. Recently proposed modular programmable photonic system architectures for enabling Tb/s connectivity in dynamic and agile MANs are presented. Special focus is devoted to S-BVT using vertical cavity surface emitting lasers (VCSELs) characterized by high modulation bandwidth and able to operate at long wavelengths and particularly within the C-band. Spectrum and space dimensions are considered to enable multi-Tb/s capacity. This approach combined with photonic integration, modularity and software defined networking (SDN) allows to obtain scalable architectures for future disaggregated optical metro networks. Programmability aspects and recent results achieved in a real network testbed are reported.**

Keywords—S-BVT, VCSEL, SDN, MAN.

I. Introduction

Metro area network (MAN) represents one of the most challenging segments to be addressed due to the rapidly evolving scenario towards a dynamic paradigm. In fact, it is required to give support to the high bandwidth pressure and hyperconnectivity, as experienced and witnessed in recent times, particularly evidenced during COVID-19 pandemic. Accordingly, the critical role of metro networks appears more and more evident to support the constant traffic growth rate and the envisioned beyond 5G scenario and services, also considering the related high societal impact that this may have. The need for high capacity/speed, high quality of service and the stringent requirements in terms of cost and power efficiency pose a set of challenges, which can be satisfied with a suitable synergy of software defined networking (SDN) and photonic technologies [1].

On one hand, the target is providing flexibility, programmability and interoperability in the context of an open and disaggregated paradigm [2], [3]. On the other hand, a reduction of cost, power consumption and footprint should be addressed, adopting cost-effective photonic devices and photonic integration, while efficiently using the available network resources [1]. In this context, the design of programmable photonic system architectures tailored for this segment is key. In particular, photonic transceiver solutions, which are modular and sliceable with adaptive bandwidth/bitrate functionalities, also referred to as sliceable bandwidth variable transceivers (S-BVT), targeting Tb/s speed, are especially relevant.

In this work, recently proposed modular programmable (SDN-controlled) system architectures, allowing an optimal network resources usage, for enabling future connectivity in MAN, will be presented. Special attention will be devoted to S-BVT using vertical cavity surface emitting lasers (VCSELs) at long wavelengths, as promising option for supporting the connectivity evolution in flexible and dynamic large MAN [1], [4]-[6]. The use of multiple dimensions, exploiting both spectrum and space, will be discussed to enable scalability towards multi-Tb/s capacity in a grow-as-needed fashion. Programmability aspects and recent results achieved in a real network testbed, the ADRENALINE testbed [7], will be also reported.

II. Photonic S-BVT-based system architectures

System architectures adopting S-BVTs offer the possibility of enabling software-defined high-speed transmission with advanced functionalities [8]. Particularly, a modular design allows a grow-as-needed approach (according to a pay-as-you-grow model), while facilitating scalability. This is especially relevant for metro networks and to target large dynamic 5G-supportive MANs [5]. In this last case, transit nodes offloading, to all-optically connect access/metro (A/M) nodes to metro/core (M/C) nodes, is an attractive option for operators to save network costs. This requires technological solutions able to support the target high-capacity traffic over large multi-hop paths, which can reach about 150 km, considering an average hop number of 4 for primary paths and 7 for secondary paths [5].

The S-BVT architecture can be based on different transmitter (Tx) and receiver (Rx) options, which have been analyzed for suitably targeting the network segment and specific application [1]-[6]. Two are the main options identified for metro networks: i) S-BVT adopting external modulation with tunable laser source (TLS) at the Tx and direct detection (DD) at the Rx, simply implemented using a PIN with a transimpedance amplifier (TIA); ii) S-BVT adopting direct modulation at the Tx combined with coherent receiver (CO-Rx) [6]. The former approach is characterized by higher cost at the Tx side, compensated by simple DD at the Rx [2]. The latter option allows to have a very cost-effective solution at the Tx with enhanced performance at the expenses of increasing the Rx cost/complexity. Of course, directly modulated (DM) sources at the Tx with DD is the most cost-efficient solution, but at the cost of reducing the achievable reach and target performance [1].

Indeed, the implementation of adaptive multicarrier modulation (MCM) at the digital signal processing (DSP) enables flexibly supporting a variable capacity up to 50 Gb/s per each flow generated at the S-BVT, according to the traffic demand [5]. A comparison of these two proposed approaches can be found in [6].

To further reduce the cost footprint and power consumption of option ii), the use of short cavity InP VCSELs operating at long wavelengths, and particularly within the C-band, is of special interest for metro network applications. Furthermore, dense photonic integration of the modules at the Tx/Rx is the final goal for a very compact and cost/power efficient design. In the present work, we focus on the second S-BVT design option and particularly on the photonic integrated solution proposed in the framework of the H2020 PASSION project [9].

A. VCSEL-based S-BVT and Tb/s connectivity

According to the requirements of large 5G-supportive metro networks, to target up to 50 Gb/s per flow over all-optical paths from low hierarchical level (HL) M/A nodes to high HL M/C nodes, a photonic system adopting VCSEL-based S-BVT has been proposed and implemented [5]. The technological solutions developed with the EU H2020 PASSION project range from photonic integrated VCSEL-based Tx and Co-Rx to cost-effective and novel node architectures enabling spatial/spectral switching, resulting in an innovative photonic system architecture dealing with the needs and challenges of future MANs [10], [11] .

In particular, to target the dynamic Tb/s connectivity, an S-BVT architecture adopting DM-VCSELs and CO-Rx is proposed. It is based on a modular composition of photonic integrated building blocks adopting multiple short-cavity InP VCSEL sources at the Tx [12], [13]. The support of large (about 150 km) multi-hop paths relies on the adoption of integrated CO-Rx adopting TLS as local oscillator [5]. The direct modulation of each VCSEL is performed implementing MCM at the DSP, with either discrete multitone (DMT) or orthogonal frequency division multiplexing (OFDM).

The basic building block is a photonic integrated circuit (PIC) with 40 VCSELs at operating wavelengths spaced of 100 GHz. Considering up to 50 Gb/s per flow obtained thanks to the MCM, up to 2 Tb/s can be achieved [13]. This module can be a standalone S-BVT Tx element used for equipping A/M nodes. Nonetheless, this element can be also seen as the fundamental module of a scalable S-BVT architecture/design which can support up to 8 Tb/s. This is obtained by aggregating the flows generated by 4 modules, fully exploiting the C-band range provided by the module VCSELs, whose operating wavelength are suitably interleaved to obtain 25 GHz of channel/flow spacing [5]. Single sideband filtering, in the optical domain, at the higher HL nodes of the network, allows closely packing the S-BVT flows with 25 GHz granularity. The module composition can be seen in the insets of Fig. 1. By adopting polarization division multiplexing (PDM), this target capacity can be doubled, while the spatial dimension allows to scale even more (by a factor *M*) the achievable rate and supported traffic. Particularly, more than 100 Tb/s can be obtained adopting a bundle of *M*=7 fibers or a multicore (MCF) fiber with *M*=7 cores.

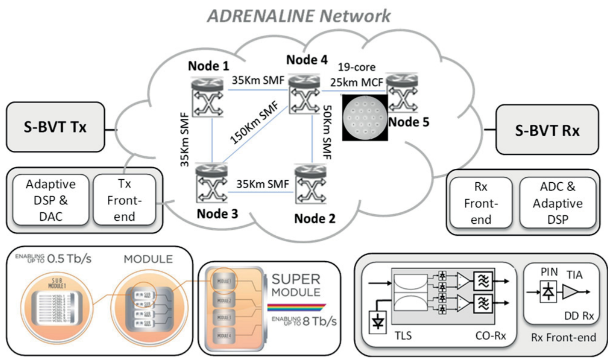

Fig. 1. S-BVT elements and ADRENALINE network. Bottom insets: VCSEL-based S-BVT Tx module and supermodule composition (left); S-BVT Rx front-end options adopting CO or DD (right).

The presented architecture has been assessed within a real testbed network: the ADRENALINE network [7]. It is a photonic mesh network with optical disaggregated nodes adopting wavelength selective switches (WSS) and arrayed waveguide gratings (AWGs) as multiplexer/demultiplexers. As reported in Fig. 1, it consists of 4 nodes (optical cross-connects, OXCs, and reconfigurable add-drop multiplexers, ROADMs) with amplified single mode fiber (SMF) links of

35 km, 50 km and 150 km. It also includes a 19-core MCF with fan-in and fan-out towards node 5.

Adopting VCSEL with bandwidth limited to 10 GHz, a maximum capacity of 36.9 Gb/s in the back-to-back (B2B) case is obtained with DD. This is obtained thanks to the use of MCM modulation, with adaptive bandwidth up to 16 GHz, and applying pre-emphasis at the Tx DSP. In case of using integrated CO-Rx module similar performance in B2B as DD can be achieved. For example, at an OSNR value of 33 dB, 34.6 Gb/s is supported using CO-Rx and 32.8 Gb/s with DD. This performance is higher than the one obtained by adopting a discrete CO-Rx with similar responsivity [14]. Having these B2B results as reference, we have also assessed the performance in case of multi-hop connectivity within the ADRENALINE testbed. After traversing a 2-hop path of 15 km, the performance penalty is negligible, both for DD and CO-Rx. The chromatic dispersion and chirp effects start degrading the performance of the S-BVT architecture based on DD, over longer path [15]. This is most prominent in case of adopting double sideband DMT, while with SSB filtering and CO-Rx, large MAN connectivity over multi-hop paths can be more suitably supported. Over 20 Gb/s capacity per VCSEL flow has been demonstrated along a path of up to 160 km, including 6 hops, with 135 km of amplified SMF links and a MCF of 25 km [14]. This assessment has been performed considering 50 GHz granularity at the network nodes. When considering 25 GHz granularity, the filter narrowing effect impacts on the system performance. This effect could be mitigated with a reduction of the modulated bandwidth for reducing the adjacent spectral channel crosstalk.

Considering higher bandwidth SC-VCSELs, 50 Gb/s capacity per flow can be targeted. This has been numerically demonstrated considering 18 GHz VCSEL and integrated CO-Rx [5]. In particular, the numerical assessment has been performed considering the 160 km 6-hop path. It has been shown that the supported capacity per flow is higher than 40 Gb/s, resulting in a total aggregated capacity of 1.6 Tb/s activating all the 40 VCSEL flows generated at the S-BVT fundamental module. Preliminary experimental tests within the ADRENALINE testbed show that a capacity of 24 Gb/s can be achieved at 23 dB OSNR. At higher OSNR, it is expected that higher capacity can be supported [5], [6], [16].

The spatial dimension is exploited to further enhance the capacity performance of the proposed S-BVT solution towards the support of >100 Tb/s connectivity. If MCF is adopted (instead of using a bundle of fibers for SDM), the impact on the maximum supported capacity due to crosstalk effect and nonlinearities should be considered, especially for large MANs. Preliminary results over the 25 km MCF from ADRENALINE node 4 to node 5, show that the S-BVT VCSEL flow capacity without crosstalk is 26.4 Gb/s. While 23.4 Gb/s is obtained in presence of the crosstalk derived from the activation of the adjacent cores. For assessing large MAN connectivity, longer MCF paths are implemented with an optical fiber loop. Over 20 Gb/s are supported after 50 km, while the capacity obtained for 25 km is halved after 200 km.

III. SDN FOR PHOTONIC SYSTEM PROGRAMMABILITY

Programmability and softwarization of the photonic system elements are key to enable dynamic and agile network control and management, as well as facilitating the integration even in a multi-vendor scenario, by suitably adopting open interfaces. Actually, flexibility and adaptability can be enhanced by the exploitation of disaggregation and open networking paradigms. This leads to potential capital expenditure (CapEx) and operational expenditure (OpEx) savings by promoting a competitive multivendor environment. Specifically, the components of the network can be disaggregated and controlled/reconfigured by using open software. To this extend, open paradigms such as OpenConfig and OpenROADM arises, enabling disaggregated network interoperability, and multi-vendor optical devices/elements configuration [17], [18]. Thanks to the modular S-BVT architecture, transceiver disaggregation can be envisioned at different levels. In particular, the S-BVT can be composed of multiple transceivers/optical components/subsystems from different providers/vendors [2]. Having a baseline disaggregated pool of optical elements enables a high degree of network flexibility and scalability. Hence, the disaggregated (photonic) S-BVT can be suitably configured/programmed [3].

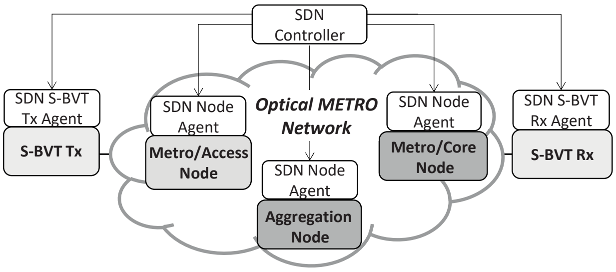

Fig. 2. SDN controller and data plane elements (S-BVT Tx/Rx and network nodes) with corresponding SDN agents.

As shown in Fig. 2, an SDN controller takes over of configuring the underlying data plane elements, including the S-BVT Tx/Rx and network nodes. This is accomplished via the specific SDN agents, over the established path, according to the data plane functionalities and programmable parameters. The first step towards achieving this data plane programmability is thus the identification of the parameters susceptible to be programmed and their correct modeling, according to the designed architecture and the adopted technologies. Yet another next generation (YANG) common data modeling language is used to provide a standard way to describe the network/system elements to be controlled and managed and ease interoperability in a disaggregated optical network scenario [1].

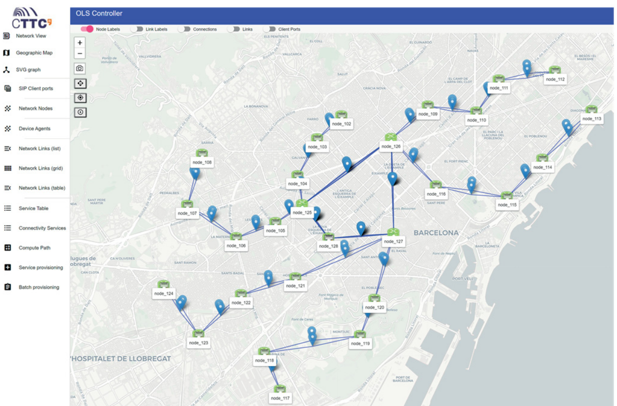

Fig. 3. CTTC SDN controller GUI representing a possible optical MAN with 28 nodes deployed in the Barcelona area.

The path establishment and the appropriate resource allocation is also a functionality handled by the SDN controller. The aim is that the SDN controller computes and selects the spatial (i.e., node and links) and spectral resources (i.e., frequency slot, FS) between the connection endpoints for each incoming request to accommodate the targeted capacity demand. To compute a feasible route, the infrastructure (i.e., network topology and connectivity, resource availability, etc.) as well the system/devices capabilities should be carefully considered. For the latter, this entails considering: i) the optical switching node filtering, ii) the maximum end-to-end path distance, as well as iii) the spectrum continuity and contiguity constraints. In Fig. 3, it is depicted a screenshot example of a candidate MAN network infrastructure rolled out through the Barcelona area comprising of 28 nodes. Such a network view is handled at the SDN controller and visualized thanks to a specific CTTC-deployed GUI tool.

In case of adopting the VCSEL-based S-BVT system architecture, the required input information for the routing and spectrum assignment (RSA) are the availability of the VCSEL source(s) at the S-BVT Tx, the S-BVT CO-Rx, the related supported frequencies, and the available optical spectrum on every traversed network link. An on-line RSA algorithm tailored to the specific characteristics of the proposed photonic system is presented in [19]. The RSA computation outputs per each request the selected VCSEL element(s) of the S-BVT Tx module with the corresponding frequency, the TLS frequency to be selected at the CO-Rx, the nodes and links to be traversed, and the corresponding FS(s). Figure 4 reports an example of workflow adopting the RESTful API, as detailed and assessed in [14]. The established path is the 160 km 6-hop path mentioned in Sec. II.A and demonstrated in [14]. The nominal central frequency of the considered FS is expressed in terms of n (positive or negative integer) defined as 193.100 THz + n*0.00625 THz; while the slot width of the considered FS is in terms of m according to the expression 6.25*m GHz.

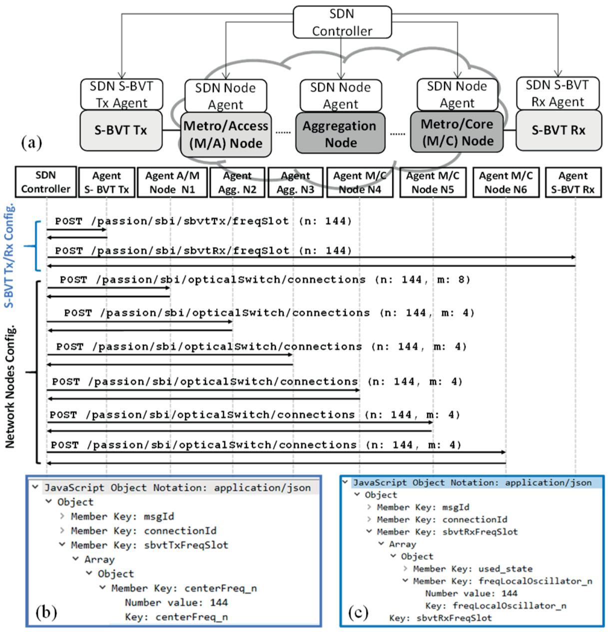

Fig. 4. (a) RESTful API workflow for configuring the photonic system (also including the corresponding schematic). JSON for S-BVT Tx (b) and Rx (c) configuration. In the example, the A/M node filtering is 100 GHz (m=8), while 50 GHz (m=4) granularity is considered at the (transit) aggregation and M/C nodes. The S-BVT Tx VCSEL flow is at 194.000 THz (n=144).

As shown the presented validation illustrates the SDN control – agent interactions relying on a defined RESTful API. That said, this does not preclude that eventually the considered data models for the proposed photonic system could be leveraged (with required extensions) and migrated within the activities carried in both OpenConfig and OpenROADM initiatives.

It is worth mentioning that a recent demonstration of the proposed programmable photonic system, to support future agile disaggregated metro networks, is presented in [20]. It showcases the SDN-controlled activation of a VCSEL-based S-BVT Tx flow and connectivity towards a destination node equipped with an integrated CO-Rx with TLS, traversing multiple white-box nodes of the ADRENALINE network also including 25 km 19-core MCF and a novel integrated spatial switching element [20].

IV. Conclusions

In this work, modular programmable photonic system architectures for enabling Tb/s connectivity in dynamic and agile MANs are presented. S-BVT using VCSELs and adopting PICs are particularly attractive as efficient solution in terms of cost, power consumption and footprint. This approach, based on the photonic technologies developed in the framework of the EU H2020 PASSION project, combined with software defined networking (SDN) allows to obtain scalable architectures efficiently and dynamically handling the network resources including both the spectral and spatial dimensions for future disaggregated optical metro networks. Recent results obtained in a real network testbed, namely the ADRENALINE testbed, have been reported, showing promising performance towards supporting SDN-enabled Tb/s connectivity.

Acknowledgment

This paper is part of a project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement PASSION No 780326. This work has been also partially supported by the Spanish MICINN AURORAS (RTI2018-099178-B-I00) project.

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