Towards Advanced High Capacity and Highly Scalable Software Defined Optical Transmission

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ABSTRACT
Software defined optical transmission (SDOT) and sliceable programmable transceivers, exploiting multiple dimensions and photonic technologies, enable to support future networks with advanced and novel functionalities, meeting the capacity and reach targets, according to the segment requirements. Programmability and modularity are crucial for scalability and functional disaggregation, facilitating a migration towards flexible and disaggregated networking paradigms, where the infrastructure can be suitably sized, growing as needed.

This work focus on SDOT enabling technologies, design guidelines and related trade-offs in terms of complexity and cost. Furthermore, SDOT programmability and modularity are discussed.

Keywords: Software defined optical transmission (SDOT), sliceable/multi-flow bandwidth/bitrate variable transceiver (S-BVT), multicarrier modulation (MCM), flexi-grid, disaggregated optical networks.

1. INTRODUCTION

In order to support future 5G networks and accommodate multiple services from different sectors with stringent requirements, the optical infrastructure, including different and convergent network segments, is required to suitably combine multiple technologies with advanced and novel functionalities and be able of managing high capacity and dynamic traffic.

The softwarization and intelligent control of data plane allow an optimal usage of the available resources, including the efficient exploitation of multiple dimensions and granularities, which is a key challenge, and at the same time a key enabler, for the design and implementation of programmable high capacity and highly scalable software defined optical transmission (SDOT). In this context, the sliceable/multi-flow bandwidth/bitrate variable transceiver (S-BVT) arises as a key element, since it implements a range of advanced functionalities, that include the support of multiple flows or spectrum slices, different bitrates and dynamic adaptation of modulation format and symbol rate to different network conditions and requirements [1]. In addition, the S-BVT can be programmable and capable to generate multiple slices that can be grouped in superchannels of different sizes, with increased optical spectral efficiency thanks to tight spectral packing [2].

Programmable – by software defined networking (SDN-enabled) - transceivers allow advanced and specific functionalities at the digital signal processing (DSP) for different optoelectronic frontends, adaptive to the dynamic variation of network capacity, transmission reach and path conditions. Indeed, further efforts should be devoted to the identification and modelling of programmable elements as well as feasible/suitable technology solutions, taking into account the limitations and complexity of the SDOT system. Particularly, innovative, flexible high-speed DSP-based subsystems, capable of parametric and structural adaptation, should be designed and implemented to make efficient use of network resources. Furthermore, the adoption of flexible and photonic technologies can be envisioned for the implementation of photonic transceivers able to meet ultimate performance, targeting specific network segment and cost/energy efficiency requirements.

SDOT and S-BVT are also key elements enabling functional disaggregation, according to the concept of disaggregated network, which recently has been gaining popularity, since it allows telecom operators and service providers to appropriately migrate and size their infrastructure, growing as needed [3]. In view of an evolution towards this paradigm, different data plane aspects have to be redesigned to provide the scalability pursued by the service providers. To this extent, suitable transmission technologies should be considered; modularity, programmability and flexibility are crucial to cope with a fully functional disaggregation and with the increasing requirements in terms of capacity and reach for the targeted networking segments.

In [4], the S-BVT benefits, design and key enabling technologies have been identified and described particularly for next-generation optical metro networks. The present work further elaborates on programmable SDOT, exploiting multiple dimensions and photonic technologies, generalizing the guidelines provided in [4] and particularly focusing on the enabling technologies with the related trade-off in terms of complexity and cost. In addition, special attention is devoted to programmability and modularity aspects in view of a migration towards a disaggregated network paradigm and enhanced scalability.

2. ENABLING TRANSMISSION TECHNOLOGIES

The suitable transceiver technology to be adopted depends on the targeted network segment and application. Indeed, the benefits of different approaches and solutions can be exploited and combined to design novel hybrid transmission architectures. For example, coherent detection transceivers provide flexibility and high capacity for long-haul application [2], but are costly and energy-inefficient for the metro segment. To target this last segment, which poses several challenges in terms of traffic dynamicity, cost and energy consumption, a reduction of the transceiver cost is mandatory. To reduce transceiver cost, alternative approaches combine intensity or amplitude modulation at the transmitter, while adopting direct detection (DD) at the receiver. DD transceivers provide energy-efficient low-cost solutions, but in order to target extended reach at high capacity DSP should be adopted. Actually, DSP and advanced modulation formats provide flexible, adaptive and high capacity solutions. Interestingly, a hybrid approach, keeping coherent detection at the receiver while simplifying the transmitter scheme, has been also proposed [4].

Figure 1 provides a schematic including different elements and technology options that can be adopted and combined to design a modular S-BVT architecture. The BVT module array is arbitrarily and suitably composed according to the network needs, design requirements and available resources, specifically related to the network segment/node or the envisioned converged network (access/metro, metro/regional, metro/core).

Tunable laser sources (TLS) with external modulation can be used for arbitrary tuning the optical carrier and achieving improved performance. However, direct modulation of the laser source can be considered to further reduce the transmitter cost. Particularly the adoption of VCSELs can be envisioned to provide energy-efficient, low-cost solutions with small footprint. Actually, VCSELs are usually considered for short-reach and low-data-rate applications at 850nm. Highest bitrates have been achieved adopting 4-level pulse-amplitude modulation (4-PAM), carrierless-amplitude-phase (CAP) modulation and discrete multitone (DMT) modulation [5]. Coherent detection has been proposed to flexibly extend the achievable reach, showing the potential of VCSELs for 100G and beyond metro network applications at 1550 nm, also adopting polarization division multiplexing [6].

This promising approach can be envisioned to implement programmable S-BVT enabling advanced features such as slice-ability, multi-flow operation (thanks to the multi-flow aggregator/distributor element) and the reconfiguration of a set of parameters. Successful transmission at variable data rates, up to 16 Gb/s with 9 GHz maximum spectral occupation, has been experimentally assessed in an SDN converged metro/access elastic optical network by using cost-effective DMT transceivers implemented with VCSELs and DD [7]. A maximum transmission distance of 200 km has been successfully demonstrated considering hard-decision forward error correction (HD-FEC). Indeed, adopting larger bandwidth VCSELs, and high-performance digital-to-analog and analog-to-digital converters (DAC/ADC), high capacities can be achieved and by combining this approach with coherent detection, the achievable reach can be extended to target the metro/regional segment.

DMT, as simple implementation of the orthogonal frequency division multiplexing (OFDM), enables spectral manipulation with very fine granularity (sub-wavelength level), and is considered a promising candidate to support future 1T-class transceivers [8]. Specifically, system flexibility is achieved at the sub-wavelength level by the implementation of bit and power loading (BL/PL) algorithms at the adaptive DSP module element, which allows different modulation formats and power values per subcarrier according to the channel profile [1].

Actually, the adoption of multicarrier modulation (MCM) represents a suitable option for increasing flexibility, thanks to both the sub-wavelength and the super-wavelength granularity. To exploit the super-wavelength granularity and meet the increased capacity and higher data rate demands of future optical networks in a cost-effective manner, MCM superchannels can be generated in combination with direct-detection (DD) reception. More complex optical implementations based on coherent detection can be also considered to deal with highly demanding data rate/reach targets. The superchannel generation can be implemented in either the optical or the electrical domain; in order to take benefit of both domains, a hybrid approach can be envisioned [9].

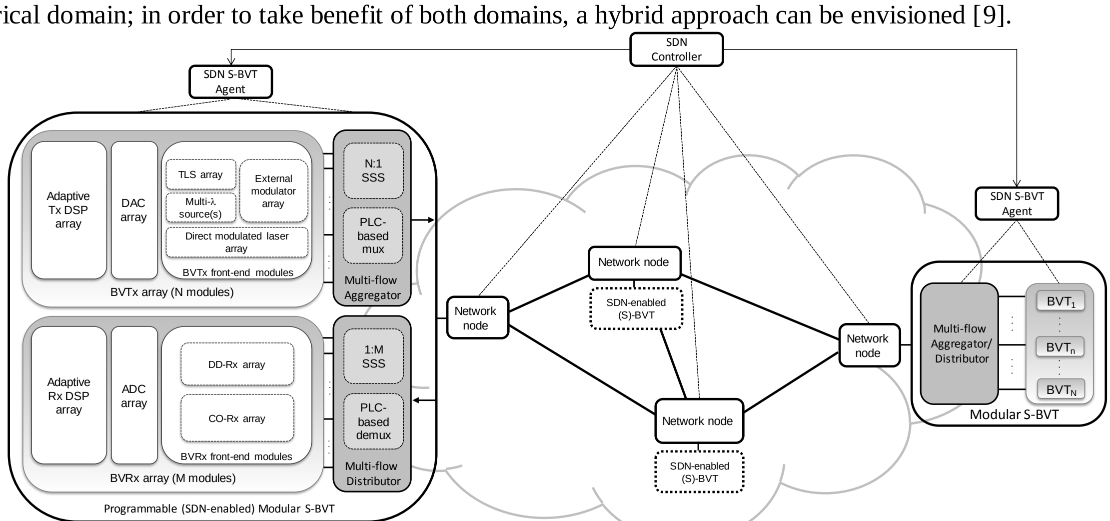

Figure 1. Example of a generic network. Each node can be fixed-grid or flexi-grid and equipped or not with programmable (SDN-enabled) (S)-BVT depending on the degree of migration towards a full flexible paradigm. A schematic for modular S-BVT composition with different technology options of its elements is also illustrated.

In [9], we propose a hybrid and electro-optical MCM scheme exploiting super/sub-wavelength granularity for flexible/efficient multiple-flow transmission within elastic optical networks. Specifically, multiple OFDM electrical signals/flows are multiplexed into superchannels by optically implementing the discrete wavelet packet transform and its inverse. This approach is proposed to increase the spectral efficiency, as the multiple flows can be packed with no guard-band and unlike the fast Fourier transform, the wavelet finite bases functions present both time and frequency localization, enabling simpler implementation [9].
Additionally, the system/network flexibility is fully exploited by including programmable spectrum selective switch (SSS) at the network nodes to enable efficient superchannel transmission according to the network condition.

2.1 Multiple dimensions and photonic technologies

The efficient exploitation of multiple dimensions, including the spatial one, together with the adoption of suitable photonic technologies and novel photonic devices enable to achieve very high capacity transmission while targeting cost, power consumption and footprint requirements. The spectral manipulation enabled by the SDN-enabled S-BVT, particularly adopting MCM, allows to obtain a wide range of granularities from the sub-wavelength level (DSP-enabled) to the super-wavelength level (enabled by the multi-flow aggregator/distributor), as illustrated in Fig. 2. Flexible superchannels with this vast granularity range are considered for optimal spectral resource usage [2].

The most versatile source for the multi-flows generation is an array of TLS that can arbitrarily select the most suitable carrier wavelength per each BVT of the sliceable transceiver. The adoption of a multi-wavelength source or an array of direct modulated lasers can be advantageously introduced to replace the array of TLS, at a cost of limiting the tune-ability range of the S-BVT optical carriers. In particular, the adoption of VCSELs allows a radical improvement in terms of cost reduction and energy efficiency. In fact, the manufacturing cost is substantially decreased with respect to other common options (e.g. DFB lasers), and the transceiver devices can be integrated in the same photonic platform. For the optical superchannel generation, N orthogonal carriers, can be created using a single laser source and a comb generator. Cost and power efficient schemes, such as multi-wavelength locked lasers and planar lightwave circuits (PLC), can be adopted for generating the optical subcarriers [2]. The resulting subcarriers independently drive external optical modulators, which can be integrated on the same substrate with photonic integrated circuit (PIC) technology for a compact footprint and to lower the cost and energy consumption. Similarly, dense photonic integration can be also adopted to implement the receiver (either DD or coherent) array, for example based on Indium-Phosphide (In-P) technology.

Regarding the multi-flow aggregator/distributor, in [9], where a hybrid electro-optical MCM scheme based on wavelet packets has been proposed and experimentally assessed, it has been proven that this element can be optically implemented either adopting PLC devices or suitably programming a liquid-crystal-on-silicon (LCoS) SSS (see Fig. 1). This scheme enables to pack multiple flows at 40Gb/s [9]. The PLC-based aggregator, using Mach-Zehender interferometers (MZIs), can be integrated employing silicon-on-insulator (SOI) technology further enhancing power efficiency. Alternatively, the LCoS-based bandwidth variable SSS can be suitably programmed by selecting the appropriate attenuation/phase of each port to fix the transfer function corresponding to the resulting concatenated wavelet filtering stage.

Another dimension advantageously exploited to save spectral resource and enhance the transmission capacity is the polarization dimension, combined with either coherent receivers or DD. Particularly, a programmable S-BVT based on DD and polarization division multiplexing (PDM) capability to enhance spectral efficiency and flexibly distribute independent data flows has been demonstrated in [10]. For an actual low cost implementation, the polarization controller (PC) and beam splitter/combiner elements, along with the photodetection stage of each S-BVT module, can be integrated in a SOI substrate. Furthermore, the PCs can be designed to be programmable, automatically controlled and available on-demand at the node(s).

Finally, to address very high capacity link target both spectrum and space dimensions should be considered. Either fiber bundle or more advanced solutions, like multi-core and/or few-mode fibers, can be envisioned.

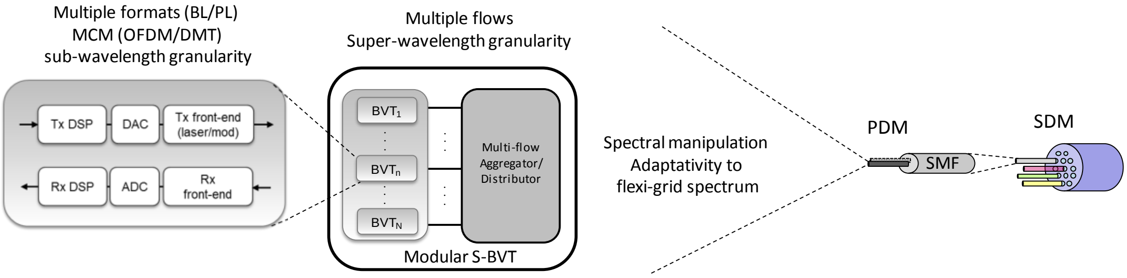

Figure 2. Multiple dimensions to be exploited in SDOT: spectrum (sub- and super-wavelength level), polarization, and space (which can include few modes, multiple cores or fibers in a bundle).

3. ON PROGRAMMABILITY AND MODULARITY

To facilitate a migration towards flexi-grid and/or disaggregated network paradigms, according to the operator roadmaps and service provider needs, the programmability and modularity of the SDOT system are crucial. The modular architecture shown in Fig. 1 supports and eases this migration, enhancing scalability and allowing to appropriately size the infrastructure, following a grow-as-needed approach. Additionally, programmable modular SDOT and S-BVT facilitate a smooth migration from chassis-based (proprietary) network elements to network white boxes, to address interoperability aspects. Furthermore, SDOT based on SDN-enabled S-BVT inherently provides flexibility, enabling optimal network configuration and management. For example, the network capacity can be optimized adaptively configuring the SDOT system to the suitable rate/format(s) for the required performance (e.g. in terms of reach and/or quality of service) and for the targeted network segments [1, 2, 4].

As detailed in Sec. 2, the S-BVT design targets optimum technology solution for increasing the transceiver capacity at extended optical reach, while maintaining low transceiver cost, complexity and footprint. In view of modularity and design trade-offs, the different elements available at the network node enable to compose suitable subsystems, depending on cost and functional requirements. On the programmability of SDOT, it is particularly relevant the choice of the functionalities that can be moved to software and virtualized [4].

To enable programmability and remote configuration, the SDOT subsystems are bound to agents (see Fig. 1), each being a software component that enables operation requests according to the associated data plane element. The agent maps high-level operations coming from the SDN controller into hardware-dependent operations. A given agent may act on behalf of one or multiple (a composition of) elements/modules. For example, the array of BVT modules included in the S-BVT may share a single agent instance [1]. The softwarization of data plane and the integration of data and control plane facilitate the implementation of novel advanced functionalities towards the achievement of flexible and highly scalable SDOT [1-4]. In this context, performance monitoring represents a key enabler for SDOT to suitably adapt the transmission, allocate and manage the network resources and cope with signal degradation, ensuring quality of service [4].

4. CONCLUSIONS

SDOT with programmable (SDN-enabled) modular sliceable transceiver architectures, based on novel energy- and cost-efficient photonic technologies, suitably exploiting multiple dimensions (ranging from the spectral subwavelength level to the space dimension), enable to meet the requirements of future networks, while providing high capacity and scalability. Depending on the segment and/or the specific applications, suitable enabling technologies can be adopted. Adaptive DSP combined with alternative and hybrid technology solutions, including direct modulation/detection or coherent schemes, for sliceable/multi-flow or superchannel transmission are envisioned. Dense PIC integration allows further meeting ultimate performance in terms of cost, power consumption and footprint. Scalability and functional disaggregation, for efficient SDN programming and resource saving, as well as advanced functionalities can be achieved with programmability and modularity.

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