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Review

Sliceable BVT Evolution Towards Programmable Multi-Tb/s Networking

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Abstract: The sliceable bandwidth variable transceiver (S-BVT) is a key element in addressing the challenges and evolution of optical networks, and supporting the ever-increasing traffic volume, speed, and dynamicity driven by novel and broadband services and applications. Multiple designs and configurations are possible and are evolving towards supporting multi-Tb/s networking, thanks to the adoption of advanced and more mature photonic technologies. In this work, we review and analyze alternative S-BVT design architecture options that target different network segments and applications. We specifically focus on S-BVTs based on multicarrier modulation (MCM), which provide a wide range of granularity and more flexible spectral manipulation. A detailed description of the main elements in an S-BVT and their characteristics is provided in order to give design guidelines. The performance in a real testbed network is also reported, comparing a set of S-BVT configurations that adopt different technologies. Finally, an extensive discussion of the described architecture, functionalities, and results, including programmability aspects, is provided in view of S-BVT evolution towards future optical network requirements and needs.

Keywords: sliceable bandwidth variable transceiver (S-BVT); orthogonal frequency division multiplexing (OFDM); discrete multitone (DMT); direct detection; coherent detection; vertical cavity surface emitting laser (VCSEL)

1. Introduction

Recent years have witnessed rapid growth of the speed and volume of traffic driven by novel and broadband (5G) services. In order to accommodate these changes, optical networks are evolving towards a more dynamic, flexible, programmable, and open paradigm, while novel and suitable technologies are being explored and exploited, improving their readiness towards supporting this new paradigm and providing solutions to related challenges [1–5]. In this context, the bandwidth variable transceiver (BVT), with its advanced functionalities and the ability of being sliceable (S-BVT), has assumed an especially relevant role in the research community over the last few years, following the roadmap of optical networks [5–9]. A BVT is a transceiver able to dynamically vary the optical bandwidth and/or bitrate and adapt to the condition of the established path by selecting specific parameters, such as the modulation format, operating wavelength, target rate/performance, and forward error correction (FEC) coding. The set parameter configuration is delegated to software control as per the traffic demand and targeted reach. A BVT can address a single traffic demand on a single portion of the optical spectrum over a specific network path between the source node and the destination node (also referred to as media-channel). The S-BVT is an evolution of BVT enabling multiple independent flows to be routed into different media-channels towards the same or multiple destination nodes (inverse multiplexing) [6]. Accordingly, the S-BVT supports flexible and programmable multi-flow, multi-rate, multi-format, and multi-reach transmission [7]. It can be seen as a set of virtual transceivers, which are suitably enabled to generate super-channels, simultaneously serving multiple independent traffic demands [6,7]. In addition to this super-wavelength granularity (in the optical domain) associated with multiple optical carriers (i.e. operating wavelength of each BVT), it is also possible to enable spectral manipulation at sub-wavelength granularity (at electrical/digital level) in every single BVT, resulting in a much wider range of granularities. This is achieved by adopting multicarrier modulation (MCM), namely, discrete multitone (DMT) or orthogonal frequency division multiplexing (OFDM). This approach enables to fully exploit the spectral dimension, especially in flexi-grid networks with granularity of 6.25 GHz and 12.5 GHz, or even finer measurements [10]. Furthermore, MCM technologies enable self-performance monitoring, thanks to the overhead of information (e.g. training symbols, TS) allocated for channel estimation and equalization [11].

In addition to spectrum, other dimensions can also be exploited, such as polarization and space, in order to further increase system/network capacity. Polarization division multiplexing (PDM) allows doubling of spectral efficiency (SE), as well as introduces an additional dimension that can be used for routing additional traffic in dense fiber links [12]. Space division multiplexing (SDM) allows scaling of the capacity of a factor, depending on the number of fibers/cores and/or modes used in case of the adoption of fiber bundles or multicore fibers (MCF) and/or multimode (few-mode) fibers [13]. Multi-dimensionality allows to enhance S-BVT performance and improve flexibility as well as supported capacity towards Tb/s networking, not only for long-haul, but also for the metro and access segment [14–16]. In fact, the evolutionary path of optical networks, in view of supporting novel and bandwidth-hungry applications, affects all segments. Especially for metropolitan area networks (MANs) as one of the most challenging segments, it is becoming particularly relevant and most prominent, as forecasted in [17]. Tailored solutions must be envisioned to address the high demand of dynamicity and capacity, while coping with the stringent cost and energy requirements. Accordingly, the role of mature and novel photonic technologies, as well as dense photonic integration able to reduce costs, power consumption, and footprint, is particularly important for the actual and optimal design of transceiver architecture [18,19].

The purpose of this work is to review and analyze alternative S-BVT design architecture options targeting different network segments and applications, also including programmability aspects. We specifically focus on S-BVT architecture based on MCM, which provide a wide range of granularity. In Section 2, we describe the S-BVT architecture, detailing its main elements, and provide design guidelines. The S-BVT performance details and latest results achieved in a real testbed network are reported in Section 3. Furthermore, S-BVT programmability is also discussed in this section, towards the integration of the proposed data plane solutions with a control plane, relying on, for example, a centralized software defined networking (SDN) controller. Finally, Section 4 presents the conclusions, discussing the described architecture, functionalities, and results, with a look towards future optical network requirements and needs, providing our vision of S-BVT evolution and what comes next.

2. S-BVT Architecture: Design and Options

General architecture of the S-BVT is depicted in Figure 1. It is worth noting the modular scheme, based on multiple BVT modules, which ease the grow/pay-as-needed approach, facilitating optical network disaggregation and fostering interoperability [9,19]. When photonic integration is considered, the fundamental/basic module can include multiple BVT front-end modules, which can be activated in a license-based fashion.

In Figure 1, we identify multiple block/elements per BVT at the transmitter (BVTx) and receiver (BVRx), implemented with different technologies and enabling different functionalities:

- Digital signal processing (DSP)
- Digital-to-analogue converter (DAC) and analogue-to-digital converter (ADC)
- Optoelectronic front-end
- Multi-flow (MF) aggregator and distributor

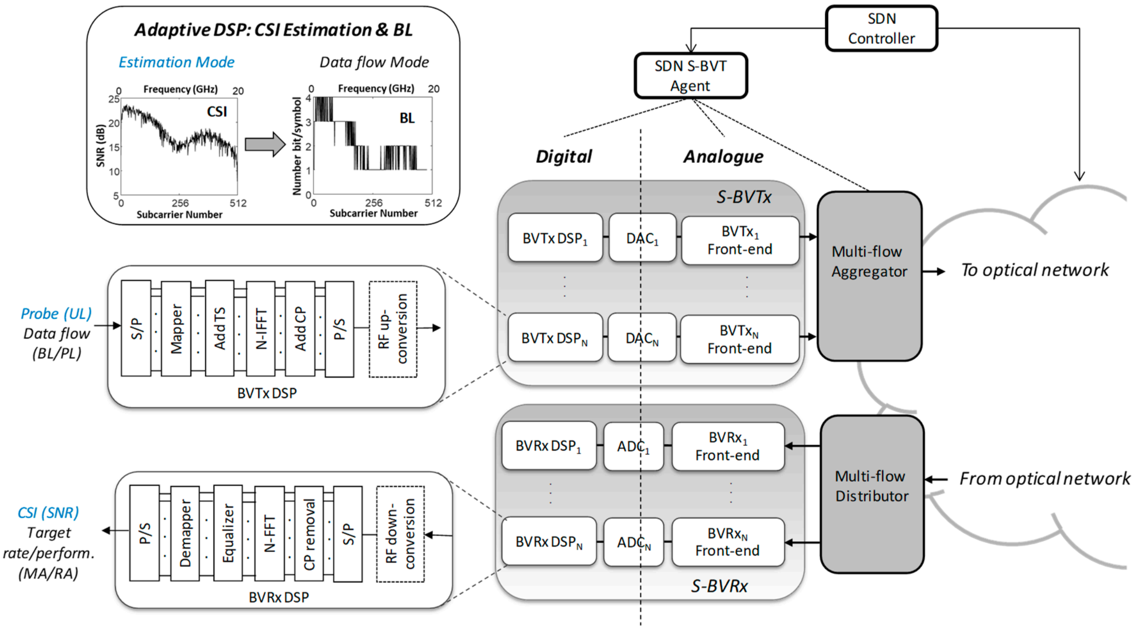


Figure 1. Schematic of a programmable (SDN-enabled) S-BVT. Digital and analogue domains are indicated.

In each BVT module, the DSP supports the MCM, either DMT or OFDM. DMT represents a more cost-effective solution based on real-valued signal flows. It is typically used for intensity modulation in the optical domain, to be easily recovered with DD. However, this scheme is severely affected by chromatic dispersion (CD), resulting in a solution suitable for short distances. OFDM enables the generation of complex-valued signals and can also be combined with linear field (amplitude) and single-sideband (SSB) modulation, to be recovered either with direct detection (DD) or coherent receiver (CO-Rx). The mapper enables uniform loading (UL) of the digital/electrical DMT/OFDM subcarriers. There is a trade-off between spectral efficiency (SE) and transmission reach; since, for short-reach connections, modulation formats with higher SE can be adopted, while in the case of long-haul links, more robust formats (with less SE) should be used. In case of adaptive DSP, a mapper supporting multiple formats is included. This allows adoption of the most suitable modulation format per subcarrier in order to maximize BVT performance, according to the channel state information (CSI), as shown in the inset of Figure 1. Sub-wavelength granularity is defined as the ratio between the slice/flow bandwidth (B) and the number of electrical/digital DMT/OFDM subcarriers (Nsc). For example, considering a B = 20 GHz and 512 = Nsc, the subcarrier spacing and thus the minimum sub-wavelength granularity is 39 MHz.

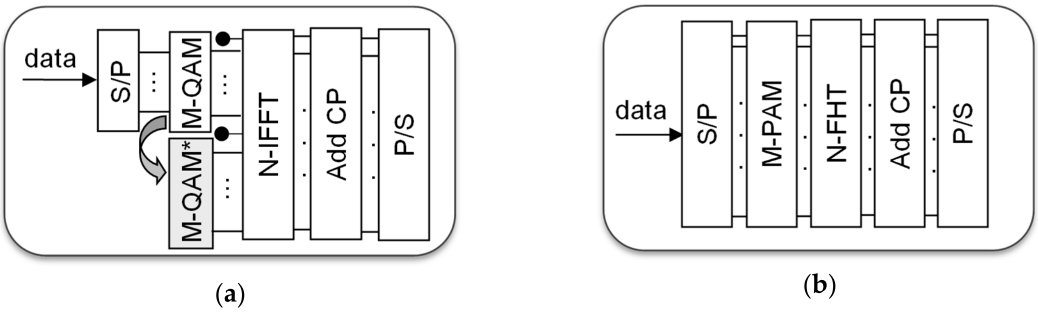
The DAC converts the digital signal into the analogue domain; the sample rate can vary according to the adopted device, trading (similarly to ADC) high performance in terms of speed and bandwidth with cost and complexity [20]. After the DAC, the flow/slice is converted to the optical domain by means of an optoelectronic front-end, which can be based on direct laser modulation (DML) or external modulation. The flows are combined by the MF aggregator and transmitted over the network. At the receiver side, the MF after being distributed is received at the specific BVRx front-end, which can be based either on DD or CO-Rx. The ADC converts the flow to the digital domain to be post-processed at the BVRx DSP.

The S-BVT can be programmable: an SDN controller by means of an S-BVT agent (or more specifically S-BVTx and S-BVRx agents) configures the programmable/variable parameters in both the digital and analogue domains. For different slices/flows to be suitably enabled/disabled, as well as for the frequency slots (i.e. the bandwidth occupancy) and optical carrier (operating wavelength) to be occupied, the target rate or FEC is selected, etc. [7,9,19].

In the following subsections, we provide further details on specific S-BVT elements and functionalities.

2.1. DSP

In order to generate a real-valued signal for intensity modulation, after serial to parallel (S/P) conversion of the input data and suitable mapping, either the real-valued fast Fourier transform (FFT) or the fast Hartley transform (FHT) can be applied, as shown in Figure 2. The latter algorithm enables the use of one-dimensional constellations, specifically M-ary pulse-amplitude modulation (M-PAM) format, and simplified channel estimation, to obtain the same spectral efficiency and performance as FFT processing with M^2-ary quadrature amplitude modulation (M^2-QAM) format [21]. Thanks to the FHT inherent symmetry and self-inverse property, a low-complexity fast processor can be applied, providing an attractive alternative for actual implementation of MCM-based transceivers. Finally, cyclic prefix (CP) is appended before parallel to serial (P/S) conversion.



(**a**) (**b**)

Figure 2. BVTx DSP implementing DMT based on (**a**) FFT; (**b**) FHT.

The individual subcarrier can be adaptively modulated by applying a bit loading (BL) algorithm, using adaptive modulation formats (e.g. binary phase shift keying, BPSK, and L-QAM, with $L = 2^n$ and $2 \le n \le 8$) at the DSP mapper, for achieving multiple rate/reach. For subcarrier with low signal-to-noise ratio (SNR), more robust and less efficient modulation formats (less number of loaded bits) are used, and vice versa in case of high SNR. Similarly, the power value of each subcarrier can be suitably assigned by applying power loading (PL).

Optimal or suboptimal algorithms (e.g. Levin-Campello or Chow-Cioffi- Bingham [22]) can be adopted for the BL/PL assignment to individual subcarriers. The algorithms can be rate adaptive (RA) and margin adaptive (MA). The former maximizes the data rate for a fixed S-BVT performance, while the latter maximizes the S-BVT performance at a given data rate. Loading strategies can be similarly applied to FFT-based or FHT-based S-BVT DSP; in case of FHT, the mirror symmetric subcarrier property of this alternative transform should be considered [23]. In case of adaptive DSP, by selecting the estimation mode, UL (e.g. using 4-QAM format) is applied to retrieve the CSI by means of the SNR profile (see top left inset in Figure 1). With this information, the data flow mode can be activated for optimal BL/PL assignment, according to the target rate/performance over the established connection.

For successful performance, the bit error rate (BER) threshold (e.g. 10^{-3}, 4.62×10^{-3}, or 2×10^{-2}) is set considering the applied FEC coding. To limit the overhead to 7%, hard decision (HD) FEC is adopted; increasing the FEC overhead up to 20%, applying a soft decision (SD) FEC, either a higher bit rate can be transmitted or a longer reach can be covered.

In order to mitigate the high peak to average power ratio (PAPR) of the OFDM signal, a clipping DSP module can be applied. To mitigate the signal distortion due to the clipping noise, an optimal clipping level is selected according to the modulation formats assigned by the mapper. Distortion-less PAPR reduction techniques can also be eventually implemented at the BVTx DSP [24].

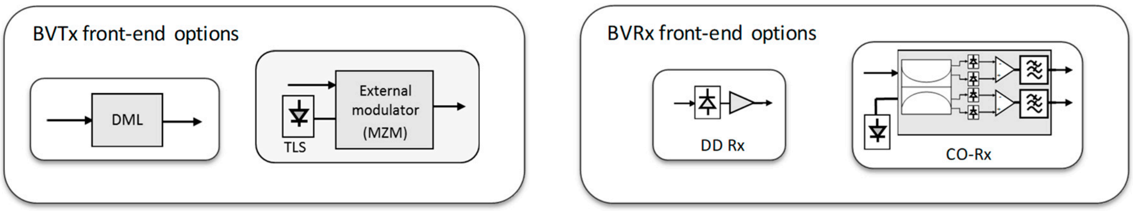
At the DSP, digital up- and down-conversion at an intermediate radio frequency can also be applied according to the selected modulation scheme; this element is particularly relevant in case of multi-band OFDM [8].

In case of CO-Rx, the DSP at the receiver side requires additional modules (e.g. carrier recovery) [8].

2.2. S-BVT Front-End Options

Alternative S-BVT optoelectronic front-end module options can be adopted, according to the specific target network segment and application, as shown in Figure 3.

Specifically, at the S-BVTx, external (intensity or amplitude) modulation or a directly modulated laser (DML) can be used. In case of external modulation, a Mach Zehnder modulator (MZM) driven by a tunable laser source (TLS) is used to flexibly adapt the MZM bias point and the operating wavelength, respectively. For intensity modulation (IM), the MZM is biased at the quadrature point; amplitude modulation (AM) is obtained by biasing the MZM near the null point. The S-BVT can also be designed to have a single multi-wavelength source to drive a set of MZMs, each belonging to a different BVT module. This solution is more compact and cost-effective than using an array of TLS; however, it has limited tune-ability [25].



(**a**) (**b**)

Figure 3. Front-end module options for (**a**) BVTx: DML and external modulator with TLS, (**b**) BVRx: DD and CO-Rx.

Alternatively, intensity modulation can be obtained with DML, which allows to further reduce the S-BVTx module cost. Particularly, the use of vertical cavity surface emitting laser (VCSEL) technology can be considered to dramatically reduce costs, power consumption, and footprint [5]. Different VCSEL options can be envisioned to target specific applications, including widely tunable VCSELs based on a micro-electro-mechanical system (MEMS), or short-cavity (SC) VCSELs at long wavelengths characterized by large bandwidths (>18GHz) [26–28].

At the S-BVRx, either cost-effective DD, with a simple PIN photodetector (PD) followed by a transimpedance amplifier (TIA), or a more complex CO-Rx (see Figure 3b) can be adopted, including a local laser (local oscillator LO) and a suitable optical hybrid.

2.3. MF Aggregator/Distributor

The aggregator/distributor can be a programmable and bandwidth-variable (BV) wavelength selective switch (WSS) implemented in liquid crystal on silicon (LCoS) technology. This S-BVT element can be also realized by using photonic integrated circuit (PIC) technology to be a simple and cost-effective passive element. This option limits the flexibility and programmability of the transceiver architecture, even though with the advent of programmable photonics, it is possible to envision future attractive solutions [29]. A hybrid and electro-optical MCM scheme exploiting both super- and sub-wavelength granularity is proposed and assessed in [30], where the multiple flows are packed into super-channels by optically implementing the discrete wavelet packet transform (DWPT) and its inverse. This allows to increase the S-BVT spectral efficiency and can be either implemented by suitably programming an LCoS-based BV-WSS or using Mach-Zehnder interferometers integrated with silicon-on-insulator (SOI) technology.

2.4. Functionalities

Multiple advanced features and functionalities are enabled by adopting a MCM-based S-BVT, eased by its integration in an SDN control plane. Particularly, MCM and adaptive DSP enable rate/distance adaptability for an optimal spectrum usage. Furthermore, unique granularity and grid adaptation is obtained thanks to the hybrid tune-ability of optical carriers (for example, adopting a TLS) and adaptive subcarrier loading/allocation. Slice-ability, inverse multiplexing, and defragmentation are also supported, together with an SDN-enabled MF generation and routing/switching of the multiple slices on the network. Furthermore, SDN-enabled S-BVT also facilitates a soft migration of fixed grid networks towards a flexi-grid paradigm. In [7], these functionalities are described in detail and their assessment provided for an S-BVT with multiple modules and technologies, supporting a total capacity above 200 Gb/s.

3. Performance and Programmability

Taking into account the different elements and options described in Section 2, the suitable S-BVT design depends on the targeted network segment and application. The fundamental S-BVT elements can be selected according to their cost/complexity and expected performance, identifying different flexibility level and requirements, as summarized in Table 1. In Reference [7] and [19], more exhaustive descriptions and discussions on the S-BVT elements and characteristics reported in Table 1 are provided.

For example, transceivers adopting CO-Rx provide high flexibility and ultimate performance (high capacity for an extended achievable reach), but are more complex and costly than the options based on DD. Similarly, high-speed and large bandwidth DAC/ADC facilitates the improvement of S-BVT capacity and performance. Thus, for cost-sensitive applications, the S-BVT design should take these aspects and the trade-offs related with cost, achievable performance, and flexibility into account.

Table 1. S-BVT elements and characteristics [7,19]; SE = spectral efficiency; L = low; M = medium; H = high.

S-BVT Element	Type	Bandwidth (B)	Cost/ Complexity	Performance	Flexibility
DSP-MCM	DMT	N_{sc} x B_{sc}	L	L/M	H
	OFDM[1]	$B_{DSB}/2$ (2xSE)	M	H	H
DSP-algorithm	Adaptive	H SE	H	H	H
	Uniform	L SE	L	L	L
DAC/ADC	H speed	Large	H	H	M/H
	L speed	Narrow	M	L	L
Tx Front-End	DML	Device B	L	M/L	L[2]
	Ext. Mod	Device B	M/H[3]	H	H[3]
Rx Front-End	DD	PD B	L	M/L	L
	CO-Rx	PD B	H	H	H[4]

[1] SSB-OFDM or with CO-Rx; [2] generally low but depending on the tune-ability of DML (e.g. tunable VCSEL); [3] assuming to adopt TLS; [4] assuming TLO.

According to the different options, alternative S-BVT configurations are possible. Either DMT or OFDM (with or without SSB), implemented with DML (IM) or external modulation (IM or AM) can be combined with DD or CO-Rx. We identify three main configurations: (i) DMT with DD, (ii) SSB-OFDM with DD and (iii) OFDM with CO-Rx. The first option is the simplest with the lowest cost/complexity at the expense of the performance and SE. In fact, the optical B occupation is double compared to the other configurations and it is more affected by CD at increasing reach. The achievable reach can be extended by adopting the second option, since SSB-OFDM is more robust against CD. The ultimate performance can be achieved by adopting CO-Rx (with a tunable LO, TLO, for improved flexibility and adaptability) at the expense of higher cost and complexity at the S-BVRx, with respect to the other options. In addition, hybrid configurations can be envisioned combining different module options to match the specific S-BVT element properties and expected performance with targeted application or use. For example, DMT or SSB-OFDM can also be combined with CO-Rx, for an S-BVT design with simpler and cost-effective S-BVTx able to cope with longer paths and/or more degraded channels.

Table 2 shows different S-BVT configurations and the latest experimental results achieved in a real testbed network, namely the ADRENALINE testbed [31]. This is to provide a performance comparison of the alternative proposed S-BVT schemes on a same experimental platform. It can be observed that an S-BVT based on DMT with DD supports high capacity over short paths. Nevertheless, by adopting a suitable dispersion compensator, the achievable reach can also be extended for high-capacity DMT systems, as demonstrated for a programmable 400 Gb/s DMT transceiver in the same testbed [32].

SSB-OFDM is more robust against CD over multi-hop paths and offers better performance also with the S-BVRx module based on DM-VCSEL (the table reports results for widely tunable MEMS-VCSELs) [33]. Finally, as shown in Reference [30], CO-Rx allows to achieve high robustness against accumulated dispersion.

Table 2. Experimental results in ADRENALINE testbed for different S-BVT configurations.

MCM	S-BVTx Front-End	S-BVRx Front-End	Opt. B[1]	Capacity	Path	Hop #	FEC Limit	Ref
DMT	Ext. Mod.	DD	50 GHz	110 Gb/s	35 km	1	3×10^{-3}	[7]
DMT	DM-VCSEL (MEMS)	DD	25 GHz	21 Gb/s	35 km	1	4.62×10^{-3}	[32]
				12 Gb/s	185 km	2		
SSB-OFDM	MZM&TLS (IM)	DD	25 GHz	50 Gb/s	35 km[2]	1	4.62×10^{-3}	[9]
				35 Gb/s	120 km[3]	3		
SSB-OFDM	DM-VCSEL (MEMS)	DD	12.5 GHz	28 Gb/s	35 km	1	4.62×10^{-3}	[32]
				20 Gb/s	185 km	2		
OFDM	MZM&TLS (AM)	CO-Rx	12.5 GHz	27 Gb/s	25 km	-	4.62×10^{-3}	[30]
				12 Gb/s[4]	185 km	2	1×10^{-3}	[8]

[1] optical bandwidth occupation in terms of flexi-grid slots of 12.5 GHz; [2] with 50-GHz WSS; [3] with 10 cascading nodes including 100-GHz AWGs and 50-GHz WSS; [4] 10 Gb/s net target bitrate (UL) connection.

As described in Figure 4, the ADRENALINE testbed network consists of four nodes: two optical cross-connects (OXCs) and two reconfigurable optical add-drop multiplexers (ROADMs); two of them (OXC-2 and ROADM-1) are equipped with programmable BV-WSS modules, enabling flexi-grid connections. The fixed-grid connections are based on 100-GHz and 50-GHz arrayed waveguide gratings (AWGs). The mesh network has five links ranging from 35 km to 150 km, for a total of 600 km of standard single mode fibers (G.652 and G.655). The network links are amplified by erbium-doped fiber amplifiers (EDFAs).

As shown in Table 2, the effect of traversing multiple nodes and, thus, multiple filtering stages, degrades the performance (filter narrowing effect) and should be taken into account for an optimal design [9,34,35]. This effect is particularly detrimental when the filter bandwidth is narrow (<25 GHz) and, therefore, most prominent in flexi-grid networks.

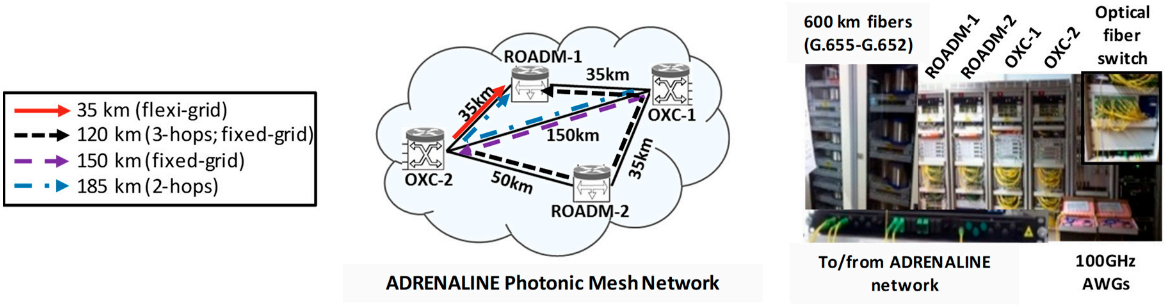


Figure 4. ADRENALINE testbed network with paths considered in Table 2 (left) and picture indicating the testbed network elements (right).

In order to scale with capacity, multiple modules can be integrated in the S-BVT and multiple dimensions can be exploited, including the full available spectrum, polarization, and space.

Particularly, a cost-effective S-BVT adopting DD with PDM capability has been proposed and demonstrated in Reference [12], where the polarization mode dispersion (PMD) effect is also analyzed for the proposed transceiver scheme.

The adoption of MB-OFDM lowers the number of required optoelectronic blocks at the S-BVT to serve multiple endpoints in an optical network. For example, to target a total capacity of 1 Tb/s, considering 10 Gb/s connections and 5 bands per each flow, at most, 20 BVT modules would be required, serving up to 100 endpoints. In Reference [8], it has been demonstrated from a techno-economic point of view that an S-BVT using MB-OFDM based on external modulation (MZM and TLS) and DD is a viable solution (compared to coherent flexi-grid transponders envisioned for core networks) for metro network applications, covering regional paths up to hundreds of kilometers.

Alternatively, in order to further reduce S-BVTx's cost, power consumption, and footprint, the use of multiple modules adopting VCSEL technology (in particular SC-VCSEL with large bandwidth), combined with dense photonic integration, is an attractive solution. It has been recently proposed and is currently being explored to support multi-Tb/s capacity/connections [16,19,28]. A fundamental module with 40 VCSELs integrated on a SOI chip is capable to support up to 2 Tb/s. Following a modular approach, the C-band can be efficiently exploited with a full-featured S–BVT equipped with multiple modules, populating the spectrum with 25 GHz-spaced flows supporting up to 50 Gb/s each, for a total capacity of 8 Tb/s, which can be doubled with PDM. In order to extend the achievable reach, for example to target very large MAN, CO-Rx can be envisioned with a simplified DSP [19,28]. So far, promising results have been obtained in view of validating this S–BVT architecture towards multi-Tb/s networking [16]. In fact, above 100 Tb/s are achieved with 7 fibers in a bundle or 7 cores of a MCF.

3.1. Programmability

Remote configuration of the S-BVT is performed by means of specific agents (see Figure 1), which are software component, enabling to map high-level operation requests from the SDN controller to hardware-dependent operations. The SDN controller configures the S-BVT over an established network connection, according to the received request and based on the elements and features described in Section 2.

Depending on the S-BVT design and specific configuration, multiple parameters can be selected. Examples of S-BVT parameters to be set are the enabled flow (S-BVT module and/or module element), operating wavelength, DSP algorithm (RA/MA), target rate or performance, FEC, etc. [7].

Indeed, the specificities of the adopted configuration and/or technologies (e.g. the use of VCSEL or TLS with external modulation, DD or CO-Rx) as well as the limited tune-ability and/or flexibility of the considered solution, should be taken into account for the S-BVT modeling and programmability handled by the SDN controller [19]. Other next generation (YANG) models are used to adopt a common language to describe the network elements to be controlled and managed, easing migration towards disaggregated optical networks and a multi-vendor scenario [3,9]. Examples of YANG models including proof of concept validations of S-BVT programmability considering different S-BVT configurations, based on alternative technologies, can be found in [19,30,36].

4. Conclusions and Future Perspective

In this work, we reviewed S-BVT architecture based on MCM. We propose the adoption of a modular design that can provide a more flexible and scalable solution in view of the evolutionary path of optical networks towards a more dynamic, disaggregated and ultra-high capacity networking. Different module options are presented, emphasizing on the pros and cons. For a suitable design, the specific network segment or targeted application should be taken into account in order to select the best option for each element and the related trade-offs, considering costs and performance.

The efficient exploitation of multiple dimensions with the softwarization and intelligent control of data plane allows optimal usage of the available resources in the design of high capacity and dynamic as well as highly scalable next generation optical networks.

We propose to adopt adaptive DSP, implementing BL and PL to improve the achievable performance and flexibility, thanks to the wide range tune-ability and spectral manipulation at sub-wavelength level. UL is used to estimate the CSI, which represents valuable information for performance monitoring and adaptation to the traffic demand and channel state. This allows allocating and managing of the network resources, while coping with signal degradation to ensure quality of service.

Different S-BVT configurations have been presented and latest experimental results, obtained in a real testbed network, reported, in order to compare the different approaches, with the aim of providing design guidelines and suitably selecting the S-BVT elements. Dense photonic integration and the use of novel, advanced, and more mature photonic devices/technologies allow us to enable multi-Tb/s networking with reduced costs, power consumption, and footprint. Particularly, promising results have been obtained by adopting modular S-BVT based on DM SC-VCSEL at long wavelengths.

In view of the network evolution, the integration of data and control plane facilitates the implementation of novel advanced functionalities and elements towards the achievement of flexible and highly scalable S-BVT. The S-BVT programmability and modularity foster a migration towards flexi-grid and disaggregated networks. Particularly, this eases a grow-as-needed approach as well as smooth migration from chassis-based (proprietary) network elements to white boxes, enabling interoperability.

With a future perspective, we believe that the next-generation S-BVT will be based on advanced programmable modular photonic transceivers and that this S-BVT evolution will pave the way for the convergence of optical, inter-, and intra-data center networks.

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References

1. Napoli, A.; Bohn, M.; Rafique, D.; Stavdas, A.; Sambo, N.; Potì, L.; Nölle, M.; Fischer, J.K.; Riccardi, E.; Pagano, A.; et al. Next Generation Elastic Optical Networks: The Vision of the European Research Project IDEALIST. *IEEE Commun. Mag.* **2015**, *53*, 152–162.
2. Riccardi, E.; Gunning, P.; de Dios, O.S.G.L.; Quagliotti, M.; Lopez, V.; Lord, A. An Operator view on the Introduction of White Boxes into Optical Networks. *J. Lightwave Technol.* **2018**, *36*, 3062–3072.
3. Campanella, A.; Okui, H.; Mayoral, A.; Kashiwa, D.; de Dios, O.G.; Verchere, D.; Van, Q.P.; Giorgetti, A.; Casellas, R.; Morro, R.; et al. ODTN: Open Disaggregated Transport Network. Discovery and control of a disaggregated optical network through open source software and open APIs. In Proceedings of the Optical Fiber Communication Conference (OFC) 2019, M3Z.4, San Diego, CA, USA, 3–7 March 2019.
4. D'Errico, A.; Contestabile, G. Next generation terabit transponder. In Proceedings of the OFC 2016, W4B.4, Anaheim, CA, USA, 20–22 March 2016.
5. Svaluto Moreolo, M.; Fabrega, J.M.; Nadal, L.; Vilchez, F.J. Exploring the Potential of VCSEL Technology for Agile and High Capacity Optical Metro Networks. In Proceedings of the 22nd Conference on Optical Network Design and Modelling (ONDM 2018), Dublin, Ireland, 14–17 May 2018.
6. Sambo, N.; Castoldi, P.; Riccardi, E.; D'Erico, A.; Pagano, A.; Svaluto Moreolo, M.; Fabrega, J.M.; Rafique, D.; Napoli, A.; Frigeiro, S.; et al. Next generation sliceable bandwidth variable transponder. *IEEE Commun. Mag.* **2015**, *53*, 163–171.
7. Svaluto Moreolo, M.; Fabrega, J.M.; Nadal, L.; Vílchez, F.J.; Mayoral, A.; Vilalta, R.; Muñoz, R.; Casellas, R.; Martínez, R.; Nishihara, M.; et al. SDN-Enabled Sliceable BVT Based on Multicarrier Technology for Multiflow Rate/Distance and Grid Adaptation. *IEEE/OSA J. Lightwave Technol.* **2016**, *34*, 1516–1522.

8. Svaluto Moreolo, J.M.; Fabrega, L.; Martin, K.; Christodoulopoulos, E.; Varvarigos, J.; Fernández-Palacios, P. Flexgrid Technologies Enabling BRAS Centralization in MANs. *IEEE/OSA J. Opt. Commun. Netw.* **2016**, *8*, A64–A75.
9. Nadal, L.; Fabrega, J.M.; Svaluto Moreolo, M.; Casellas, R.; Muñoz, R.; Rodríguez, L.; Vilalta, R.; Vílchez, F.J.; Martínez, R. SDN-enabled Sliceable Transceivers in Disaggregated Optical Networks. *J. Lightwave Technol.* **2019**, doi:10.1109/JLT.2019.2945967.
10. Zhou, X.; Jia, W.; Ma, Y.; Deng, N.; Shen, G.; Lord, A. An Ultradense Wavelength Switched Network. *IEEE/OSA J. Lightwave Technol.* **2017**, *35*, 2063–2069.
11. Fabrega, J.M.; Sevillano, P.; Svaluto Moreolo, M.; Villafranca, A.; Vilchez, F.J.; Subías, J.M. OFDM subcarrier monitoring using high resolution optical spectrum analysis. *Opt. Commun.* **2015**, *342*, 144–151.
12. Nadal, L.; Svaluto Moreolo, M.; Fabrega, J.M.; Vilchez, F.J. Meeting the future metro network challenges and requirements by adopting programmable S-BVT with direct-detection and PDM functionality. *Opt. Fiber Technol.* **2017**, *36*, 344–352.
13. Winzer, P.J.; Neilson, D.T.; Chraplyvy, A.R. Fiber-optic transmission and networking: The previous 20 and the next 20 years. *Opt. Express* **2018**, *26*, 24190–24239.
14. Muñoz, R.; Yoshikane, N.; Casellas, R.; Fàbrega, J.M.; Vilalta, R.; Svaluto Moreolo, M.; Nadal, L.; Martínez, R.; Soma, D.; Wakayama, Y.; et al. SDN-enabled sliceable multi-dimensional (spectral and spatial) transceiver controlled with YANG/NETCONF. In Proceedings of the OFC, San Diego, CA, USA, 11–15 March 2018; p. M2A.5.
15. Fabrega, J.M.; Svaluto Moreolo, M.; Reixats, L.N.; Vílchez, F.J.; Casellas, R.; Vilalta, R.; Martínez, R.; Muñoz, R.; Fernández-Palacios, J.P.; Contreras, L.M. Experimental Validation of a Converged Metro Architecture for Transparent Mobile Front-/Back-Haul Traffic Delivery using SDN-enabled Sliceable Bitrate Variable Transceivers. *IEEE/OSA J. Lightwave Technol.* **2018**, *36*, 1429–1434.
16. Svaluto Moreolo, M.; Martinez, R.; Nadal, L.; Fabrega, J.M.; Tessema, N.; Calabretta, N.; Stabile, R.; Parolari, P.; Gatto, A.; Boffi, P.; et al. Spectrum/Space Switching and Multi-Terabit Transmission in Agile Optical Metro Networks. In Proceedings of the OECC/PSC, Fukuoka, Japan, 7–11 July 2019.
17. CISCO. *Cisco Visual Networking Index: Forecast and Trends, 2017–2022*, White Paper; 2019. Available online: http://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-741490.html (accessed on 3 December 2019)
18. Svaluto Moreolo, M.; Fabrega, J.M.; Nadal, L. S-BVT for next-generation optical metro networks: Benefits, design and key enabling technologies. In Proceedings of the SPIE 10129, San Francisco, CA, USA, 28 January 2017.
19. Svaluto Moreolo, M.; Fabrega, J.M.; Nadal, L.; Martínez, R.; Casellas, R. Synergy of Photonic Technologies and Software-Defined Networking in the Hyperconnectivity Era. *IEEE/OSA J. Lightwave Technol.* **2019**, *37*, 3902–3910.
20. Drenski, T.; Rasmussen, J.C. ADC/DAC and ASIC technology trends. In Proceedings of the *2019 24th OptoElectronics and Communications Conference (OECC) and 2019 International Conference on Photonics in Switching and Computing (PSC)*, Fukuoka, Japan, 7–11 July 2019. doi:10.23919/PS.2019.8818001.
21. Svaluto Moreolo, M.; Muñoz, R.; Junyent, G. Novel Power Efficient Optical OFDM Based on Hartley Transform for Intensity-Modulated Direct-Detection Systems. *IEEE/OSA J. Lightwave Technol.* **2010**, *28*, 798–805.
22. Nadal, L.; Svaluto Moreolo, M.; Fabrega, J.M.; Dochhan, A.; Griesser, H.; Eiselt, M.; Elbers, J.P. DMT modulation with adaptive loading for high bit rate transmission over directly detected optical channels. *IEEE/OSA J. Lightwave Technol.* **2014**, *32*, 3541–3551.
23. Nadal, L.; Svaluto Moreolo, M.; Fàbrega, J.M.; Junyent, G. Adaptive Bit Loading in FHT-based OFDM Transponders for Flexi-Grid Optical Networks. In Proceedings of the ICTON 2013, Cartagena, Spain, 23–27 June 2013.
24. Nadal, L.; Svaluto Moreolo, M.; Fabrega, J.M.; Junyent, G. Low complexity PAPR reduction techniques for clipping and quantization noise mitigation in direct-detection O-OFDM systems. *Opt. Fiber Technol.* **2014**, *20*, 208–216.
25. Imran, M.; Errico, A.D.; Lord, A.; Poti, L. Techno-economic analysis of carrier sources in slice-able bandwidth variable transponders. In Proceedings of the ECOC, Dusseldorf, Germany, 18–22 September 2016.

26. Paul, S.; Gierl, C.; Cesar, J.; Le, Q.T.; Malekizandi, M.; Kögel, B.; Neumeyr, C.; Ortsiefer, M.; Küppers, F. 10-Gb/s Direct Modulation of Widely Tunable 1550-nm MEMS VCSEL. *IEEE J. Sel. Top. Quant. Electr.* **2015**, *21*, 1700908.
27. Muller, M.; Hofmann, W.; Grundl, T.; Horn, M.; Wolf, P.; Nagel, R.D.; Ronneberg, E.; Bohm, G.; Bimberg, D.; Amann, M.-C. 1550 nm highspeed short-cavity VCSELs. IEEE J. Sel. Top. Quantum Electron. 2011, 17, 1158–1166.
28. Svaluto Moreolo, M.; Nadal, L.; Fabrega, J.M.; Vilchez, F.J.; Neumeyr, C.; Gatto, A.; Parolari, P.; Boffi, P. VCSEL-based sliceable bandwidth/bitrate variable transceivers. In Proceedings of the SPIE Photonics West, San Francisco, CA, USA, 2–7 February 2019.
29. Pérez, D.; Gasulla, I.; Capmany, J. Field-programmable photonic arrays. *Opt. Express* **2018**, *26*, 27265–27278.
30. Nadal, L.; Svaluto Moreolo, M.; Fabrega, J.M.; Casellas, R.; Vilchez, F.J.; Martínez, R.; Vilalta, R.; Muñoz, R. Programmable SDN-enabled S-BVT based on hybrid electro-optical MCM. *IEEE/OSA J. Opt. Commun. Netw.* **2018**, *10*, 593–602.
31. Muñoz, R.; Nadal, L.; Casellas, R.; Svaluto Moreolo, M.; Vilalta, R.; Fàbrega, J.M.; Martínez, R.; Mayoral, A.; Vílchez, F.J. The ADRENALINE testbed: An SDN/NFV packet/optical transport network and edge/core cloud platform for end-to-end 5G and IoT services. In Proceedings of the 2017 European Conference on Networks and Communications (EuCNC), Oulu, Finland, 12–15 June 2017. doi:10.1109/EuCNC.2017.7980775.
32. Kai, Y.; Okabe, R.; Nishihara, M.; Tanaka, T.; Takahara, T.; Rasmussen, J.C.; Vilchez, F.J.; Nadal, L.; Fabrega, J.M.; Svaluto Moreolo, M. Experimental Demonstration of a Programmable 400-Gbps DMT Transceiver with Policy-based Control. In Proceedings of the Optoelectronics and Communications Conference/International Conference on Photonics in Switching (OECC/PS), Niigata, Japan, 3–7 July 2016.
33. Svaluto Moreolo, M.; Nadal, L.; Fabrega, J.M.; Vilchez, F.J.; Casellas, R.; Muñoz, R.; Neumeyr, C.; Gatto, A.; Parolari, P.; Boffi, P. Modular SDN-enabled S-BVT Adopting Widely Tunable MEMS VCSEL for Flexible/Elastic Optical Metro Networks. In Proceedings of the OFC, San Diego, CA, USA, 11–15 March 2018; p. M1A.7.
34. Fabrega, J.M.; Svaluto Moreolo, M.; Martin, L.; Piat, A.C.; Riccardi, E.; Roccato, D.; Sambo, N.; Cugini, F.; Potì, L.; Yan, S.; et al. On the Filter Narrowing Issues in Elastic Optical Networks. *J. Opt. Commun. Netw.* **2016**, *8*, A23–A33.
35. Martin, L.; van der Heide, S.; Xue, X.; van Weerdenburg, J.; Calabretta, N.; Okonkwo, C.; Fabrega, J.M.; Svaluto Moreolo, M. Programmable Adaptive BVT for Future Optical Metro Networks adopting SOA-based Switching Nodes. *Photonics* **2018**, *5*, 24.
36. Martínez, R.; Casellas, R.; Svaluto Moreolo, M.; Fabrega, J.M.; Vilalta, R.; Muñoz, R.; Nadal, L.; Fernández-Palacios, J.P. Proof-of-Concept validation of SDN-controlled VCSEL-based S-BVTs in flexi-grid optical metro networks. In Proceedings of the OFC 2019, San Diego, CA, USA, 3–7 March 2019.