Modular SDN-enabled S-BVT Adopting Widely Tunable MEMS VCSEL for Flexible/Elastic Optical Metro Networks

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Abstract: We propose an SDN-enabled S-BVT adopting directly-modulated tunable VCSEL with direct-detection for optical metro networks and spectrum defragmentation. We experimentally assess it over different network paths up to 185km and in presence of adjacent slices.
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1. Introduction

The migration towards a more flexible, efficient and agile paradigm of optical metro networks, characterized by stringent limitation on CAPEX/OPEX and highly dynamic and heterogeneous traffic aggregation/delivery, able to accommodate bandwidth-hungry services as well as low-rate service connections, are posing new challenges, urgently requiring low-cost and power-efficient solutions. In this context, the programmable and modular sliceable bandwidth/bitrate variable transceiver (S-BVT) represents an attractive solution, when suitably tailored for this network segment [1]. Particularly, the adaptability/reconfigurability of multiple parameters by software defined networking (SDN) combined with a modular approach, allows flexible adaptation to the path/traffic condition, with wide range granularity, while saving network resources and costs. The adoption of optoelectronic front-ends based on energy- and cost-efficient photonic technologies, appears as a crucial issue in the S-BVT design/implementation.

Tunable laser sources (TLS) with external modulation enable arbitrary tuning the optical carrier and achieving high performance. However, direct modulation (DM) of the laser source and, particularly, the adoption of VCSEL (vertical cavity surface emitting laser) allow radical reduction of transmitter cost, power consumption and footprint. VCSELs have been usually considered for short-reach, low-datarate applications at 850nm. Recently, their potential has been shown at 1550nm with advanced modulation formats for 100G applications as well as for PONs and metro/access elastic optical networks (EONs) [2-4]. Multicarrier modulation, as discrete multitone (DMT) or orthogonal frequency division multiplexing (OFDM), enables spectral manipulation, implementing bit and power loading (BL/PL) at digital signal processing (DSP). This allows dynamic and flexible adaptation to traffic/channel conditions and spectrum fragmentation mitigation [1], with spectrum granularity even finer than EON (12.5GHz).

In this work, we propose to adopt DM widely tunable MEMS (micro-electro-mechanical system) VCSEL [3] and direct detection (DD) as cost-effective and energy-efficient building block for programmable (SDN-enabled) S-BVTs able to provide improved performance/functionalities, including mitigating spectrum fragmentation, in optical metro networks. We experimentally assess that single-sideband (SSB) OFDM enables to extend the achievable reach. Furthermore, bandwidth/bitrate adaptive DSP combined with widely tunable MEMS VCSEL allows the SDN-enabled module suitably adapting to the dynamic variation of optical metro networks and filling spectral gaps for spectrum defragmentation without requiring a network re-optimization. Thanks to these features, the proposed S-BVT architecture represents a promising candidate for optical metro networks with very fine spectrum granularity.

2. SDN-enabled S-BVT system equipped with widely tunable MEMS VCSEL

The programmable and modular S-BVT (in Fig. 1) consists of an array of N BVTs and an aggregator/distributor of the generated/received multiple flows (slices). The BVT array can be composed of subsets of BVT modules (enabling a scalable pay-as-you-grow model based on pluggable units and photonic integration), whose BVTx front-end are based on either DM VCSEL or external modulator driven by TLS. The BVRx adopts DD for cost-sensitive applications. The BVT DSP allows implementing DMT or OFDM, including margin adaptive (MA) or rate adaptive (RA) BL/PL algorithms. Either double sideband (DSB, or DMT) or SSB transmission (more robust to chromatic dispersion than DMT) can be implemented. If the generated N flows are aggregated by using a spectrum selective switch (SSS), it can act as both aggregator and (SSB) filter bank. The multiple slices are transmitted over the network as a single high-capacity flow or can be split into lower capacity flows routed towards independent paths [1]. The cost-effective and energy-efficient VCSEL-based module also allows suitably filling spectral gaps thanks to its tunability and adaptive narrow bandwidth, resulting in a promising technology option for mitigating the spectrum fragmentation. Furthermore, these features enable an SDN control paradigm: different parameters (related to DSP blocks, BVT front-ends and aggregator/distributor) can be suitably configured on-demand by the SDN controller, by

means of SDN S-BVT agents [1]. This includes DSP mode (channel estimation with uniform loading or transmission with adaptive loading), algorithm (RA/MA), target performance/bitrate, enabled BVT slice, operating wavelength, and SSS parameters such as wavelength, bandwidth and power/attenuation (per port).

For the system assessment, we set-up an array of N=3 BVTs (either considered two subsets), one (BVT$_{VCSEL}$, first subset) based on a widely tunable VCSEL module and the other two (BVT$_{MZM}$, second subset) adopting a TLS and a MZM at the BVTx; the BVRx front-end consists of a pre-amplified DD receiver (PIN with TIA). All BVT modules are equipped with adaptive DSP enabling rate/distance and bandwidth variable transmission. The independent digital signals are converted to analog with a 64GSa/s digital-to-analog converter (DAC); at the BVRx, the photodetected signal is captured by an oscilloscope at 100GSa/s for demodulation and further error counting, considering a target BER of $4.62 \cdot 10^{-3}$ (HD-FEC with 7% overhead over a total of 13.4%). The VCSEL wavelength is widely tunable within a range of up to 60nm. With a fine adjustment of MEMS, bias and temperature control, the VCSEL can be tuned to operate within the C-band with flexgrid granularity (6.25GHz and 12.5GHz frequency slots). The VCSEL transfer functions measured (with a network analyzer) at 1550.12nm and at the edge channels of the ITU grid (1530.33nm and 1561.42nm) are shown in Fig. 1b. When the VCSEL is DM with DMT adopting BL/PL (512 subcarriers on 16GHz), the maximum bitrate, below the target BER threshold, in back-to-back (B2B) is 33.2Gb/s at 1550.12nm, and slightly lower at the edge channels (29.8Gb/s and 31.3Gb/s, respectively), according to the corresponding signal-to-noise ratio (SNR) profile. The channel state information (CSI) is retrieved at the adaptive BVRx DSP with a uniform loaded (4QAM) probing signal. The maximum bandwidth occupation is 10.5GHz (Fig. 1c), corresponding to a spectral occupation of two flexgrid slots of 12.5GHz. In the case of SSB transmission, the spectral occupation is halved and the B2B bitrate below the target BER is 31.7Gb/s at 1550.12nm. This value, slightly lower than DMT, is due to the narrow SSB filtering and the VCSEL wavelength fluctuations.
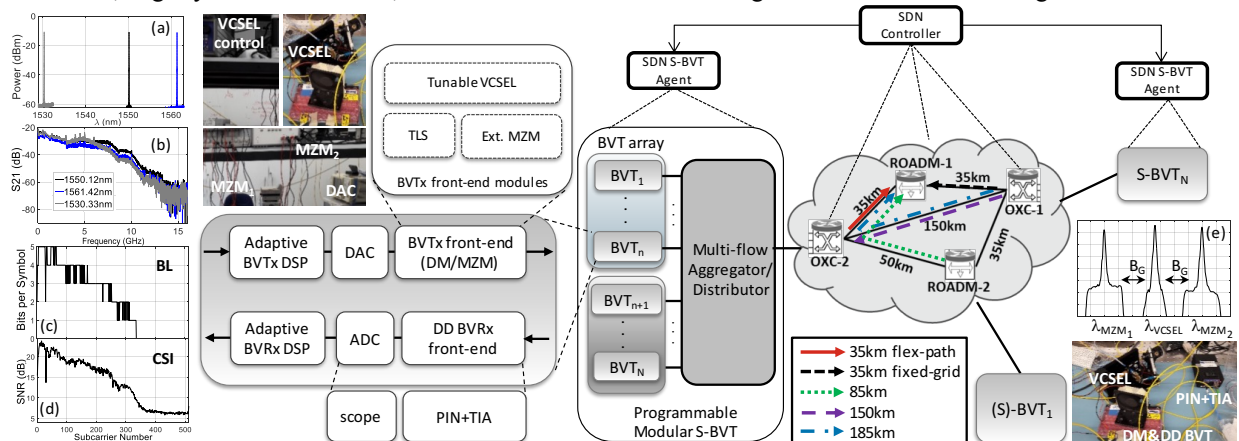

Fig. 1. SDN-enabled S-BVT system schematic; set-up with a VCSEL-based and two MZM-based BVTs (inset pictures); 4-node ADRENALINE network. Insets on the left: (a) OSA measurements of VCSEL spectrum at different wavelengths and (b) corresponding transfer functions (S21), (c) BL and (d) CSI for the VCSEL slice in B2B at 1550.12nm; on the right: (e) received spectra of the BVT slices with B_G=12.5GHz after 35km.

3. SDN-enabled S-BVT assessment for flexible and fixed-grid metro network scenarios

We analyze the performance of the BVT$_{VCSEL}$ in a 4-node network (ADRENALINE testbed) with amplified SSMF (standard single-mode fiber) links of 50km and 35km, and a NZDSF (non-zero-dispersion-shifted fiber) link of 150km (see Fig. 1). At the input/output of the network, the multi-flow is amplified by EDFA working at constant power. We first assess the case of a flexgrid path (flex-path) of 35km. Considering DMT, the bitrate at the target BER (RA algorithm) decreases to 21.1Gb/s with the tunable VCSEL set to operate at 1550.12nm. Similar performance is achieved at 1530.33nm (19.8Gb/s) and 1561.42nm (20.5Gb/s). By configuring the SSS as SSB filter, 28.5Gb/s can be achieved at 1550.12nm. Next, we evaluate the capacity performance of the BVT at 1550.12nm below the BER threshold for DMT and SSB transmission over different ADRENALINE paths of 85km, 150km and 185km (Fig. 1). SSB modulation supports bitrates >20Gb/s up to a 2-hop path of 185km, as shown in Fig. 2a.

In order to assess the BVT$_{VCSEL}$ capability of filling spectral gaps for spectrum defragmentation, we analyze its performance in presence of adjacent slices (Fig.1e) at the varying of the guard-band (B_G). The BVT$_{VCSEL}$ is tuned to operate at 1550.12nm. Each adjacent slice is generated with a BVT$_{MZM}$ equipped with adaptive DSP for a maximum (electrical) bandwidth of 16GHz (corresponding to a flexgrid channel of three 12.5GHz slots in case of DMT). The TLS wavelengths are set to obtain the target B_G, considering the slices spectral occupancy in terms of assigned flexgrid slots. For this analysis, we consider DSB transmission (DMT) over 35km flex-path. Please note that we analyze the same MZM performance at different wavelengths and the aggregator is implemented with a cascade of

couplers emulating SSS insertion loss. When B_G is 6.25GHz, the total bandwidth occupation of the three slices is 112.5GHz. In this case, the BVT_{VCSEL} supports a bitrate of 18.5Gb/s, 9.8% lower than the bitrate obtained when the adjacent slices are disabled (Fig. 2a-c). The bitrate of the BVT_{MZM} at 1549.82nm and 1550.42nm is slightly lower (47.9Gb/s and 46.8Gb/s, respectively) than 48.6Gb/s and 47.2Gb/s, when the BVT_{VCSEL} is disabled. Thus, including the cost-effective BVT_{VCSEL} to the MZM-based BVTs subset, the overall S-BVT capacity increase is 18.2% for the same bandwidth occupation, thanks to the BVT_{VCSEL} capability of filling spectral gaps. For B_G=12.5GHz and a total bandwidth of 125GHz (10 slots), the crosstalk effect is negligible, as the bitrate of all slices at the target BER present rather no penalty. For this case, we analyze the BVT_{VCSEL} capacity at the varying of its output power (adding a VOA in the set-up) with respect to adjacent slices power. The results in Fig. 2d show that the capacity is halved for 6dB relative power. Finally, when B_G is zero and the total bandwidth occupation is 100GHz (Fig. 2e), the BVT_{VCSEL} bitrate decreases to 14.5Gb/s (29.3% penalty also due to the VCSEL wavelength fluctuation within a narrow bandwidth). The adjacent slices are less affected (also for their effective bandwidth occupation, enabling optimized BL/PL performance) given a bitrate of 47.5Gb/s and 48.1Gb/s, at 1549.87nm and 1550.37nm, respectively. This last result shows that the SSS of ADRENALINE flex-path is acting as vestigial sideband (VSB) filter, for the slice at 1550.37nm (slightly shifted towards the edge of the assigned ADRENALINE channel slots). If the number of assigned slots is increased to 10 (125GHz) the obtained bitrate is 46.7Gb/s (in line with the other slice penalty). The minimum bitrate without (w/o) B_G of the BVT_{MZM} at 1550.12nm, with the BVT_{VCSEL} and the other BVT_{MZM} as adjacent slices, is 45.1Gb/s. In any case, an overall S-BVT capacity increase is achieved enabling the BVT_{VCSEL}.

To compare the obtained results over a flexgrid path (with SSS at the network nodes) with a fixed-grid scenario, we analyze the case w/o B_G over a 35km fixed-grid ADRENALINE link (equipped with standard 100GHz arrayed waveguide gratings). As shown in Fig. 2f (OSA measurements), the BVT_{MZM} slices are distorted by the fixed-grid channel profile (VSB filtering). This is evidenced by a bitrate increase of the BVT_{MZM} at 1550.37nm up to 55.3Gb/s.

The SDN controller suitably configures the S-BVT, setting each BVT active slice by means of an SDN agent that maps high level configuration commands, sent via a REST interface, to low level hardware-specific instructions. Fig. 2g shows a configuration enabling the BVT_{VCSEL} at 1550.12nm, in adaptive loading mode with RA algorithm and 9dB gap for successful transmission at the target BER with HD-FEC over the selected path.
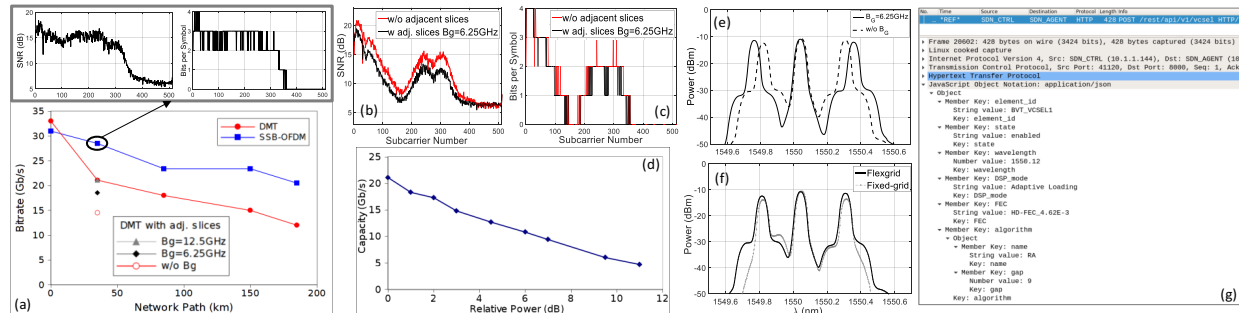

Fig. 2. (a) BVT_{VCSEL} bitrate vs network paths for DMT, SSB and at the varying of B_G; inset (a), (b), (c) CSI and BL (35km flex-path). Capacity performance vs relative power (d). Received S-BVT spectra at the varying of B_G (e) and grid (f). Configuration of BVT_{VCSEL} parameters (g).

4. Conclusions

We propose to adopt DM widely tunable MEMS-VCSEL, as cost-effective and energy-efficient building block, for the implementation of programmable (SDN-enabled) and modular S-BVT suitable for optical metro network applications. We experimentally assessed the proposed module in the ADRENALINE network, achieving up to 33Gb/s bitrate with DMT (B2B) and above 20Gb/s up to 185km 2-hop path with SSB-OFDM. From the analysis in presence of adjacent slices, negligible bitrate penalty has been found for a B_G of 12.5GHz, enabling an S-BVT capacity increase even for lower value of B_G. The S-BVT can be used in both flexible and fixed-grid scenarios (envisioning a soft-migration), even if the latter limits the performance of its advanced features. Thanks to the adaptive DSP and the SDN-enabled dynamic reconfiguration of multiple parameters, the proposed architecture represents also a promising solution to cope with spectrum fragmentation, filling spectral gaps with fine granularity.

5. References

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