Transparent Service Delivery in Elastic Metro/Access Networks with Cost-Effective Programmable Transceivers

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ABSTRACT

In this paper, we present and experimentally validate a transparent signal delivery scheme using programmable sliceable bandwidth/bit rate variable transceivers (S-BVTs), for converged optical access/metro networks. A programmable transceiver based on discrete multitone (DMT) directly modulated vertical cavity surface-emitting laser (VCSEL) and direct detection (DD) is proposed to efficiently increase the cost-effectiveness and scalability of the network. Variable data rates are enabled for a maximum optical spectrum occupancy of 9 GHz, while coping with a minimum power budget of 20 dB in the access segment. This allows to fully exploit system flexibility while enabling photonic integration.

Keywords: Optical access, elastic optical networking, multicarrier modulation.

1. INTRODUCTION

5G services are conceived around the joint use of different heterogeneous resources (including transport, fixed and mobile), while combining networking and cloud functions. In this sense, the access segment is the one more subject to an imminent change, since a paradigm where the central office (CO) is re-architected as datacenter (CORD) is gaining popularity [1]. This paradigm relies on three different pillars: i) software defined networking (SDN), ii) network functions virtualization (NFV) and iii) elastic cloud services, whose combination brings a unique, cost-effective and agile approach for network deployment and management [1].

Interestingly, these cloud functionalities can be hosted in distributed datacenters, located at different metro nodes, and close to the edge of the operator network, coexisting with the ones in charge of mobile front-/back-haul traffic [2]. This would produce a shift on traffic demands of the access segment. Accordingly, connectivity between different distributed data centers and the end users would be required. The former are typically located at the metro nodes and the later at the far end of a passive optical network (PON) tree. Even different signal delivery schemes can be envisioned for providing this connectivity, the overlay of these novel access signals over existing fixed optical metro/aggregation and access infrastructures constitutes a cost-effective approach.

The combination of SDN and elastic optical networking, enabled at data plane level by the adoption of the flexible channel grid and programmable sliceable bandwidth/bit rate variable transceivers (S-BVTs), opens the door to a truly dynamic and adaptive management of optical networks [3], [4]. Specifically, (S)-BVTs deliver data flows, with variable spectral occupancy and rate, according to the network and path conditions. This is especially interesting for achieving the pursued integration between optical metro and access. In fact, approaching this paradigm, specific channels can be set up according to the requirements of the services to deliver. Furthermore, SDN also enables to transparently configure a virtual access network over the optical metro/access infrastructure, seeing it as a private network slice. For example, certain CO services/functions would be located at a selected node of the metro network segment, while the different customer premises equipment (CPE) related to those services/functions could be scattered along one or multiple access trees. They are interconnected by a meshed metro/aggregation network including different access exchange nodes (ENs). In this scheme a highly centric traffic pattern is expected, posing different requirements in terms of cost and data rate compared to typical transmission technologies for the transport/core networking.

In this paper, we propose to transparently deliver access services in a converged metro/access environment, combining SDN and elastic networking for taking advantage of the already deployed fiber infrastructure. In order to cope with that in a cost-effective way, we validate a signal delivery scheme, focusing on the upstream signals. To that extend, we use bandwidth/bit rate variable transceivers (BVTs) based on discrete multitone (DMT), directly modulated vertical cavity surface-emitting lasers (VCSELs) and direct detection (DD).

2. NETWORK SCHEME AND SIGNAL DELIVERY

The network and signal delivery scheme is depicted in Fig.1. There, programmable S-BVTs are present at the metro/aggregation nodes [4]. At the other end of the network, each CPE has a programmable BVT. The

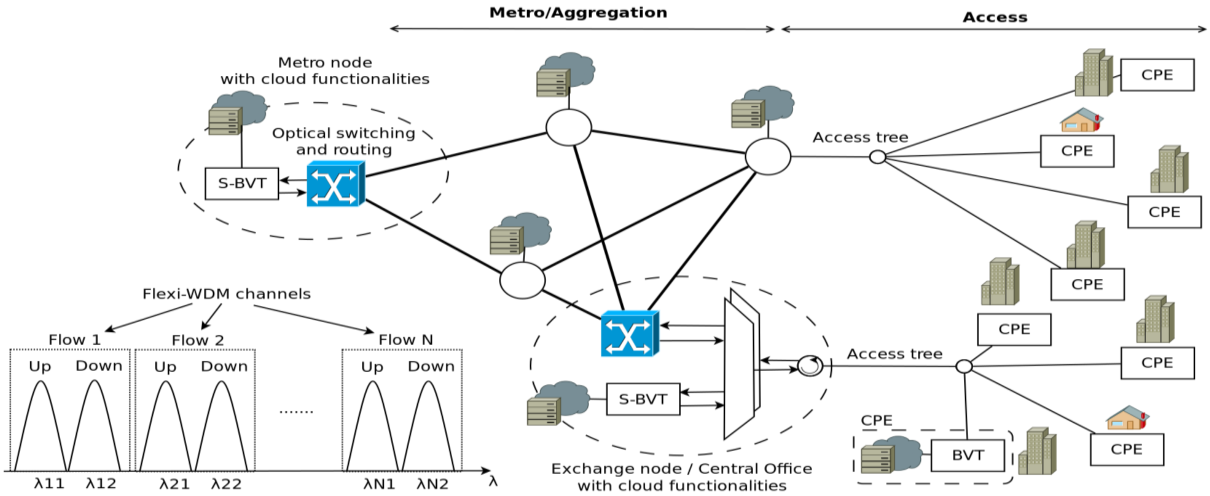

Figure 1. Network and signal delivery scheme

(S-)BVT can be remotely configured by the SDN control and orchestration planes, for an optimal management of the network resources [3], [4]. The parameters to be configured at each (S-)BVT include wavelength, spectral occupancy and modulation format/power per flow.

In order to ensure full compatibility with the deployed optical metro and access networks, a specific wavelength plan is envisioned. In fact, we propose a wavelength overlay of point-to-point (PtP) wavelength division multiplexed (WDM) channels within the C-band, in order to provide the aforementioned services while reusing existing infrastructure. This is shown in the inset of Fig. 1, where each data flow occupies a dedicated flexi-WDM channel, including frequency duplexing for guaranteeing a simultaneous up/downstream communication also in the access PON tree. This approach is fully compatible with existing access standards, since legacy access standards (e.g. GEPON, GPON) use 1490 nm for downstream; while late standards (e.g. 10G-EPON and XGPON) recommend the range of 1575-1580 nm also for downstream. Regarding the upstream, all the cited standards envision the use of O-band. Additionally, NG-PON2 standard envisions the establishment of PtP WDM channels for the access services delivery in the C+L bands.

At the ENs of the metro network, the access downstream signals coming from the metro nodes are filtered out and transparently routed/dropped to their destination access tree. For the upstream, a similar operation is performed at the same ENs: aggregation/filtering is performed after the passive tree in order to facilitate a transparent switching and routing towards the appropriate metro node. It should be noted that there is no strict constraint to the metro part of the network, since commercial flexi-grid spectrum selective switches and optical amplifiers typically operate at C-band.

Regarding all the options for implementing the (S-)BVTs, those based on DD orthogonal frequency division multiplexing (DD-OFDM), are the most attractive for cost-effectively coping with the flexibility requirements of elastic optical networks [4]. In fact, OFDM also provides advanced spectrum manipulation capabilities, including arbitrary sub-carrier suppression and bit/power loading (BL/PL) [5]. Thanks to these features, DD-OFDM transceivers can be ad hoc configured for achieving a certain reach and/or coping with a targeted data rate adopting low complex optoelectronic subsystems [4][5].

A transceiver front-end architecture similar to the one reported in [6] can be envisioned for downstream, featuring an external modulation and DD. Alternatively, other options can be also suitable, like employing a low-cost coherent reception, significantly improving the network performance [7]. Nevertheless, the upstream is always more cost-sensitive, as its transmitter is placed at the different CPEs. Thus, a simple and cost-effective transmitter front-end should be envisioned. Interestingly, the combination of directly modulated VCSELs and DMT can be a suitable option for a strong cost reduction. In fact, VCSELs constitute a low-cost alternative thanks to its manufacturing/testing simplicity; while DMT is especially suitable for appropriately tailoring the waveforms to be generated with direct modulation of lasers.

3. EXPERIMENTAL SETUP AND RESULTS

Fig. 2 shows the experimental setup implemented to validate the proposed upstream signal delivery scheme. A programmable and cost-effective BVT based on DMT is adopted at the CPE side. Specifically, a 5 GHz DMT electrical signal is created by randomly generating, parallelizing and mapping a data stream into different constellations, including BPSK and M-QAM formats (being M a power of 2, ranging from 2 to 256). Uniform loading, as well as BL/PL algorithms are implemented to efficiently adapt the transmission parameters (power and modulation format) of each subcarrier according to the channel profile [5]. After constellation mapping, 4 training symbols (TS) are included every 196 DMT frames to correctly equalize the signal at the receiver. The digital signal processing (DSP) block also includes the insertion of a cyclic prefix (CP) of 1.9%, a 512-points inverse fast Fourier transform (IFFT) implementation and a clipping process. The clipping level is fixed according to the maximum assigned modulation format level, while the resulting OFDM subcarriers are spaced 19.5 MHz. A pre-emphasis digital filter, whose impulse response is modeled as a 2nd order Gaussian filter, is applied to compensate the performance degradation due to the frequency response of the arbitrary waveform generator (AWG), working at 10 GS/s.

For optical modulation, a VCSEL of 4.5 GHz bandwidth and centered at $\lambda_{VCSEL}=\lambda_{11}$=1539.61 nm is used [8]. The resulting optical signal passes through an isolator and is transmitted over the access tree, towards the EN of

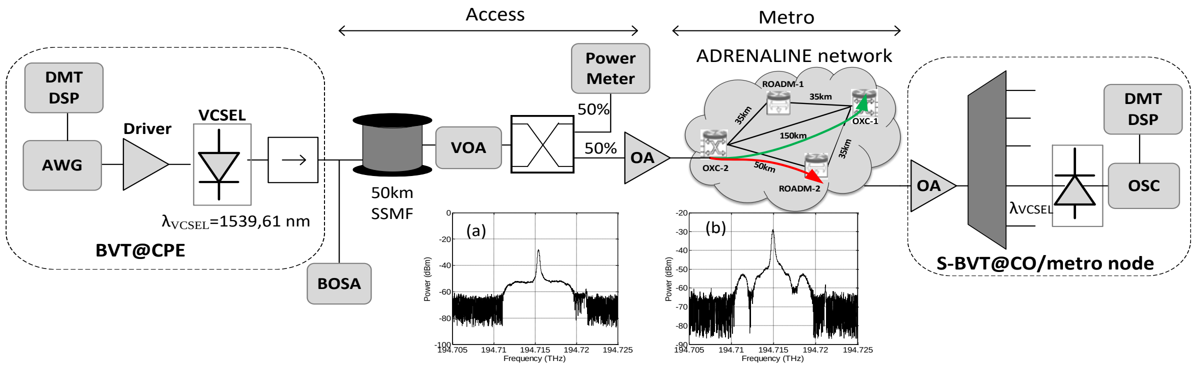

Figure 2. Experimental setup. In the insets: transmitted spectra, implementing BL/PL,(analyzed with a Brillouin OSA (BOSA) in (a) the B2B.and (b) after 50 km access link and 50 km metro link.

the metro network. The optical power at the transmitter output is -1.8 dBm. The feeder section of the access tree is composed of a 50 km fiber spool of standard single mode fiber (SSMF). At this point, the signal power is monitored to perform sensitivity measurements for system performance evaluation. Next, the resulting amplified access signal feeds the ADRENALINE testbed, which is a 4-node photonic mesh network interconnected with amplified links of lengths ranging from 35 km to 150 km (as shown in Fig. 2). At the EN/metro node, a programmable S-BVT, is used to recover the transmitted data. In the experiments, one S-BVT building block is enabled to process a single optical flow, of λ_{VCSEL}, which is pre-amplified with an optical amplifier (OA) and suitably selected/filtered with an arrayed waveguide grating of 100 GHz spacing. The received signal is photodetected with a PIN photodiode and analog to digital converted by means of an oscilloscope (OSC), working at 100 GS/s. At the receiver DSP block, parallelization, CP removal, FFT processing, equalization, TS removal, demapping and serialization processes are performed.

Fig. 3 shows the experimental results. In particular, different scenarios are considered to test the converged access/metro segments. A back-to-back (B2B) configuration and different access/metro paths are evaluated, achieving variable data rates at different sensitivities by implementing the Levin Campello rate adaptive BL/PL algorithm [5]. In all cases, a target bit error ratio (BER) of $4.62\cdot10^{-3}$ is fixed corresponding to a hard decision forward error correction (HD-FEC) of 7 % overhead [9]. Specifically, DMT subcarriers are loaded with different number of bits per symbol and suitable power according to the channel profile, ensuring the target BER. The signal to noise ratio (SNR) per subcarrier is depicted in Fig. 3 (a) and (c) considering a B2B configuration and two links of 50 km, corresponding to a path containing the access and metro segments (red path of Fig. 2). The corresponding bit assignment per subcarrier is depicted in Fig. 3 (b) and (d), respectively. Interestingly, Figs. 3 (c) and (d) show a notch around 2.5 GHz (inside the DMT signal bandwidth), corresponding to the VCSEL chirp value, limiting the SNR of the central subcarriers. In order to ensure the target BER, the central subcarriers are set to 0 while the ones with higher SNR are loaded with high-level modulation formats. The optical spectra corresponding to Figs. 3 (a-d) after applying BL/PL, are depicted in the insets (a) and (b) of Fig. 2, which are measured with a high resolution optical spectrum analyzer (BOSA). There it is shown the frequency gap due to subcarriers set to 0, limiting the total signal bandwidth occupancy to 9 GHz.

In Fig. 3 (e) the achieved data rate at different received optical power, measured at the edge access/metro node, is shown ensuring the target BER, as it can be seen in Fig. 3 (f). The BER is calculated by error counting. As expected, the maximum achievable data rate decreases when increasing the power budget of the access tree. A maximum data rate of 15.6 Gb/s is achieved at -22.4 dBm in B2B, which corresponds to a 20.6 dB power budget for the transmitted power. On the other hand, the data rate decreases to 5.7 Gb/s at -34.5 dBm of received power. Next, the impact of transmission over the fiber link in the access tree is taken into account by introducing a 50 km SSMF spool. In this case, a maximum data rate of 11.8 Gb/s can be ensured, featuring >20 dB power budget (-22.6 dBm received power). As next step, in order to demonstrate the transparent delivery of access services over converged metro/access infrastructure, we experimentally assess transmission over two different paths, of 50 km and 150 km, of the ADRENALINE testbed in addition to the 50 km fiber spool. Fig. 3 (e) shows that, at -22 dBm, 8.9 Gb/s can be transmitted after 50 km of access tree and 50 km of the ADRENALINE testbed

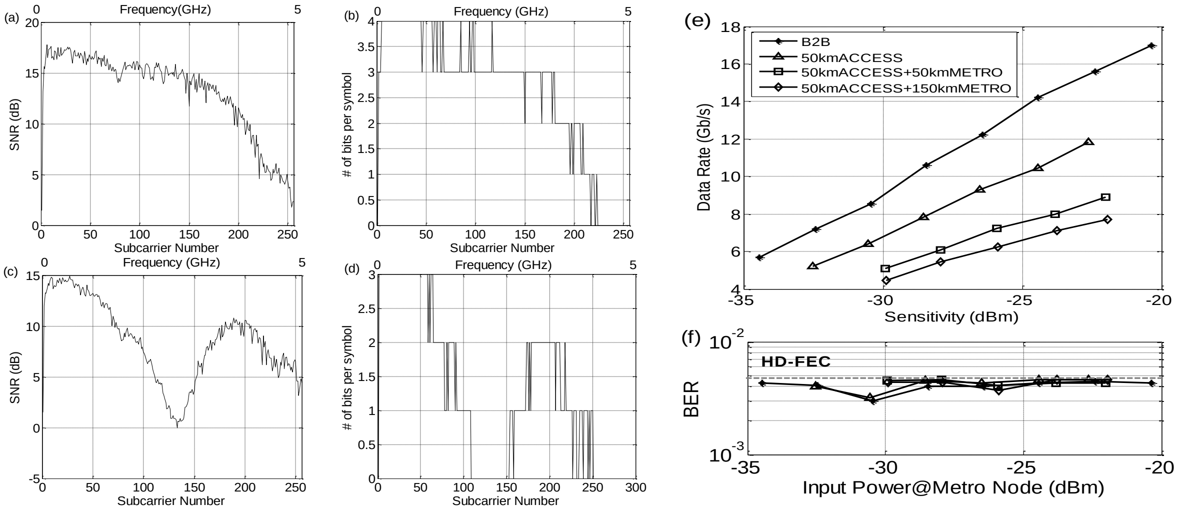

Figure 3. (a) SNR and (b) BL assignment in a B2B configuration. (c) SNR and (d) BL assignment after 50 km access link and 50 km metro link. (e) Achieved data rate versus measured input power at the metro node.

(red path). Thus, the achieved data rate is halved compared to the B2B configuration, due to chromatic dispersion and laser chirp. Finally, a maximum data rate of 7.7 Gb/s is achieved at -22 dBm when transmitting over 200 km, including both access and metro segments (green path of Fig. 2). In this case, the data rate only decreases of 1.2 Gb/s with respect to the 50+50 km case, as the 150 km path of ADRENALINE network is a non-zero dispersion shifted fiber.

4. CONCLUSIONS

Successful transmission at variable data rates has been experimentally assessed in an SDN converged metro/access elastic optical network by using cost-effective DMT transceivers adopting VCSELs and DD, for a BER of $4.62\cdot10^{-3}$ at 20 dB power budget. A maximum transmission distance of 200 km has been successfully demonstrated, considering 50 km PON tree and a 150 km path of the ADRENALINE testbed. This supposes a drastic reduction in terms of cost and energy efficiency, since the manufacturing cost of the VCSELs is substantially lower than other common options (e.g. DFB lasers), and all of the transceiver devices can be integrated in the same photonic platform, for example in a Si wafer. Thus, photonic integration can be envisioned for enhancing the network efficiency in terms of cost, power consumption and footprint.

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