Experimental Validation of a Converged Metro Architecture for Transparent Mobile Front-/Back-Haul Traffic Delivery using SDN-enabled Sliceable Bitrate Variable Transceivers

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***Abstract*— We experimentally demonstrate transparent and dynamic delivery of mobile front-/back-haul in converged optical metro architecture, employing SDN-enabled S-BVTs based on adaptive multicarrier modulation. The proposed architecture is specifically tailored for a transparent services delivery across the access and metro network segments. Therefore, several challenges are discussed, such as functional split requirements and bidirectional transmission (duplex) over these different segments. In order to prove the validity of this concept, network experiments have been carried out in a hybrid metro/access testbed. Results show successful connectivity at distances up to 175 km, including the access segment, and capacities beyond 20Gb/s per flow.**

***Index Terms*— Multicarrier modulation, discrete multi-tone, orthogonal frequency division multiplexing, flexi-grid networks, optical packet switching, software-defined networking, sliceable bandwidth variable transceiver.**

I. Introduction

5G services are conceived around the joint use of different heterogeneous resources (including transport, fixed and mobile), while combining networking and cloud functions. Precisely, for mobile networking, it is proposed to host 5G core functionalities in distributed data centers located at different local metro nodes and close to cell sites [1][2][3][4].

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One of the key services to deliver in such networking environment is the mobile front-/back-haul. There, 5G metro nodes can contain virtual pools of baseband units (BBUs), featuring different functional splits, that are connected to a majority of remote radio units (RRUs) located in the cell sites. This service also entails a strict delay budget that would be difficult to achieve in a centralized approach. In fact, the delay budget is highly contributed by the distance of the physical locations. Therefore, the sites processing the radio signal should move towards the cell side in order to provide a more affordable delay budget. Thus, mobile front-/back-haul traffic is significantly decreased when compared to a centralized approach, and more cost-effective equipment can be employed, reducing the associated CapEx and OpEx. In fact, in a centralized approach, all this traffic is delivered to a central site where user data are processed. Therefore, this central site may become the bottleneck when traffic volume grows (e.g. as expected in mobile front-/back-haul). So, maintaining a centralized approach may not be technically feasible or even come at a high cost. For example, very high capacity channels could be needed, featuring high spectral efficiency, and the equipment related would be of high cost.

Different radio access network (RAN) architectures can be envisioned for providing this distributed connectivity. Interestingly, the overlay of mobile back-/front-haul over existing fixed optical metro/aggregation and access infrastructures constitutes a cost-effective approach. However, approaching such a converged architecture is challenging, as it should meet the needs of the network subscribers while supporting the new traffic.

The advent of elastic optical networking, enabled by the adoption of the flexible channel grid and programmable transceivers, opens the door to an enhanced management of optical networks [5][6]. This is especially interesting for achieving the pursued integration between optical metro/access and RAN. In fact, by approaching this paradigm, specific channels can be set up according to the specific requirements of the services to deliver. Therefore, elastic

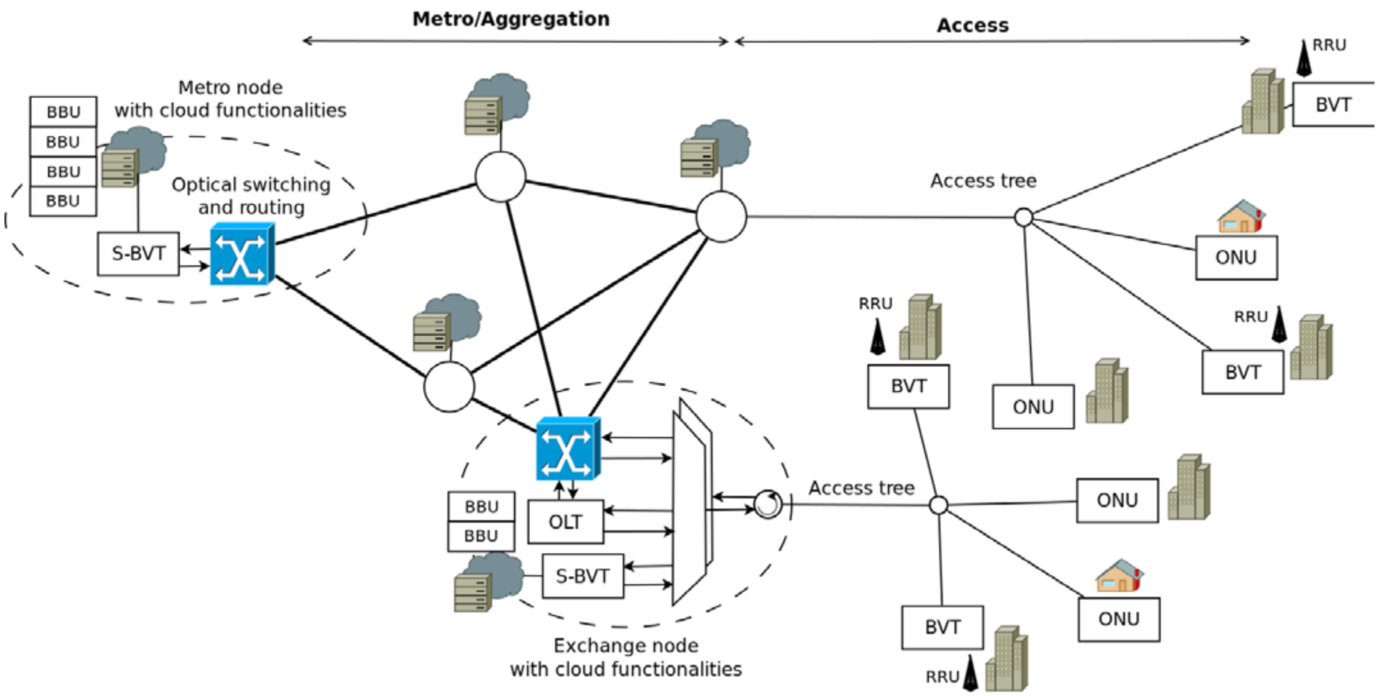


Fig. 1. Converged metro/access concept for the proposed mobile front-/back-hauling.

networking also enables to transparently set a RAN over the optical metro/access by means of a dedicated channel. For example, a pool of BBUs would be located at a selected node of the metro network segment, while the RRUs could be scattered along one or multiple access trees, both interconnected by a mesh of exchange nodes (ENs). In this scheme a more distributed traffic pattern is expected, posing different requirements in terms of latency, cost, and data rate compared to typical transmission technologies for the transport/core networking.

In this paper, we propose to transparently and dynamically deliver mobile front-/back-haul in a converged metro/access environment, following the elastic networking paradigm in order to take advantage of the already deployed fiber infrastructure. In order to cope with that, we propose to use sliceable bandwidth variable transceivers (S-BVTs) based on orthogonal frequency division multiplexing (OFDM). For keeping a low cost solution, direct detection (DD) is employed. Therefore, an experimental proof-of-concept in a photonic meshed network (the ADRENALINE testbed) is provided, underlining the potential of these transmission technologies for the envisioned scenario.

The paper is structured as follows. In section II the proposed network and signal delivery schemes are detailed and discussed. Afterwards, section III provides the actual testbed implementation details. Section IV deals with the experiment results. Finally, conclusions are drawn in section V.

II. Network Scheme And Signal Delivery

The network and signal delivery scheme is depicted in Fig. 1. There, programmable S-BVTs are present at the 5G metro nodes in order to concurrently serve different cell sites. At the other end of the network, each cell site has a programmable BVT. The (S-)BVTs can be remotely configured by the control plane, for an optimal management of the network resources [6][7]. In addition to the bitrate variability that can cope with a dynamic traffic variation (e.g. daily traffic variation), the (S-)BVTs also feature other benefits also there are other benefits such as the capability to attain a specific capacity demand for a given connection [5][8]. Additionally, the S-BVTs can be shared to concurrently serve more than one connection. Therefore, multiple paths can be assigned to a given S-BVTs, in order to keep it highly utilized and reduce the total number and cost of transmission solutions [8]. The parameters to be configured at each (S-)BVT include wavelength, spectral occupancy and modulation format/power per flow. So, the proposed (S-)BVTs deliver data flows with variable spectral occupancy and rate, according to the network and path conditions.

Among all the options for implementing the (S-)BVTs, those based on DD-OFDM are the most attractive for cost-effectively coping with the flexibility requirements of elastic optical networks [6]. In fact, OFDM provides advanced spectrum manipulation capabilities, including arbitrary sub-carrier suppression and bit/power loading. 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 [6][7].

In order to ensure full compatibility with the deployed optical metro and access networks, a specific wavelength plan is envisioned. In fact, legacy access standards (e.g. GEPON, GPON) use 1490 nm for downstream; while late standards (10G-EPON and XGPON) recommend the range of 1575-1580 nm also for downstream [9][10][11]. Regarding the upstream, all the cited standards envision the use of O-band.

Thus, the entire C-band is available for performing a wavelength overlay of channels in order to provide different additional services over the same access infrastructure [12]. Interestingly, NGPON2 also offers the option to establish virtual point-to-point (PtP) links, assigning different wavelength division multiplexing (WDM) channels to different services [13]. For PtP WDM, an expanded spectrum option is available in order to flexibly reuse unoccupied spectrum. These channels could be allocated in the range of 1530–1565 nm, values also belonging to the C-band.

At the exchange nodes of the metro network, the mobile front-/back-haul signals are filtered out and transparently routed/dropped to their destination access tree. This fact does not pose any strict constraint, since commercial standard flexi-grid spectrum selective switches (SSS) and optical amplifiers typically operate at C-band. Also, each exchange node includes the corresponding optical line terminals (OLTs) and aggregation switches/units for delivering fixed access services to the network users across the corresponding access trees.

We propose to employ the same wavelength for upstream and downstream for maximizing the utilization of the network resources and spectral efficiency in the access segment. Since the access part of the network is a single fiber tree, this approach comes at the expense of the transmission performance degradation. So, the main challenge of this signal delivery scheme is regarding the establishment of bidirectional transmission over this converged infrastructure. Precisely, the metro part of the network usually relies on a dual fiber duplex, while the access segment typically implements a dual-wavelength duplex. Nevertheless, in order to optimize the usage of the network resources, the same wavelength should be used for upstream and downstream. Therefore, an interesting point is how to deal with that in the access segment, where typical deployments feature a single fiber tree. In principle, a single fiber bidirectional transmission employing the same wavelength would be desirable in order to facilitate the network management while covering the maximum number of potential locations for RRUs. In that case, bidirectional transmission over more than 10 km of standard single mode fiber (SSMF) will be highly affected by the Rayleigh backscattering effect [14], which is something that should be taken into account when dimensioning a specific front-/back-haul deployment. This effect could be mitigated by employing different wavelengths for upstream and downstream, at the expense of increasing the complexity of the metro network segment, where a dual fiber duplex is commonly employed. As an alternative, we should note that the feeder cables of the access segment cover the majority of the distance (from the exchange node to the splitter distribution hub) and typically have a loose-tube design containing several fibers, some of them being unused [9]. Thus, in case the RRUs can be directly attached to the splitter distribution hub, a dual-fiber duplex across the entire transmission link (including metro and access segments) can be ensured with no need for deploying new cables, but limiting the places where the RRUs can be deployed. However, a high cost should be taken into account in case new cables should be deployed for approaching this dual-fiber duplex.

Regarding the dimension of traffic to support, it should be noted that the most bandwidth hungry service is the mobile front-haul based on the common public radio interface (CPRI), which on the other hand does not allow any dynamic management of the capacity in the transport network, since this kind of traffic requires high constant bit rate independently of the cell loads. In order to relax these requirements, several radio functions can be decentralized and adopted by the RRUs, trading latency and data rate against flexibility. This is envisioned in the recent recommendations from the 3GPP [15], where different functional splits have been reported. Thus, different requirements in terms of data rate and latency have been set according to each functional split. For example, split options 1-2 can tolerate up to 10 ms of one way latency, while option 8 tolerates only up to 250 µs [15]. This entails a high limitation of the transmission distance depending on the functional split adopted, since the transmission delay is mainly contributed by propagation. In fact, for transmitting up to 100 km, a propagation delay of about 500 µs should be expected in SSMF. This requires a functional split at PHY2 or MAC-PHY level [15][16], relaxing the bitrate requirement [15][17]. Regarding capacity the requirements are of up to 4 Gb/s for split options 1-2 and beyond 150 Gb/s for option 8 [15]. Consequently, all this should be taken into account when dimensioning the use of specific network resources in order to provide such services. Indeed, the most bandwidth hungry connections (i.e. those requiring split options 7-8) should be served by the immediate nodes (e.g. the exchange nodes) in order to meet the stringent latency requirements, while the ones with a more relaxed latency budget (e.g. those connecting metro nodes with large distance between them) could also relax the capacity requirement (i.e. as for split options 1-2). Furthermore, it is desirable to have mechanisms for the dynamic management of bandwidth and/or capacity in the transport network, being the (S-)BVT one of the suitable technologies for that. In fact, the (S-)BVTs can be adapted to the actual load at radio cell level as it is aggregated.

A centralized software defined networking (SDN) controller is proposed for efficiently managing the devices and provisioning the services. In fact, all the proposed network systems can be programmed by means of the corresponding SDN agents, allowing an automated path establishment between the metro nodes and the cell sites, across the two network segments.

III. Experimental Setup

Figure 2 depicts the experimental setup for N=2 flows. The digital signal processing (DSP) and electrical up/downconversion at the transmitter/receiver are common to the S-BVT and BVT, either for downstream or upstream. This DSP is performed off-line, following the steps detailed in Fig. 2 according to [6]. There, randomly generated data are parallelized and mapped into the corresponding constellation (ranging from BPSK up to 256 QAM). Adaptive bit/power

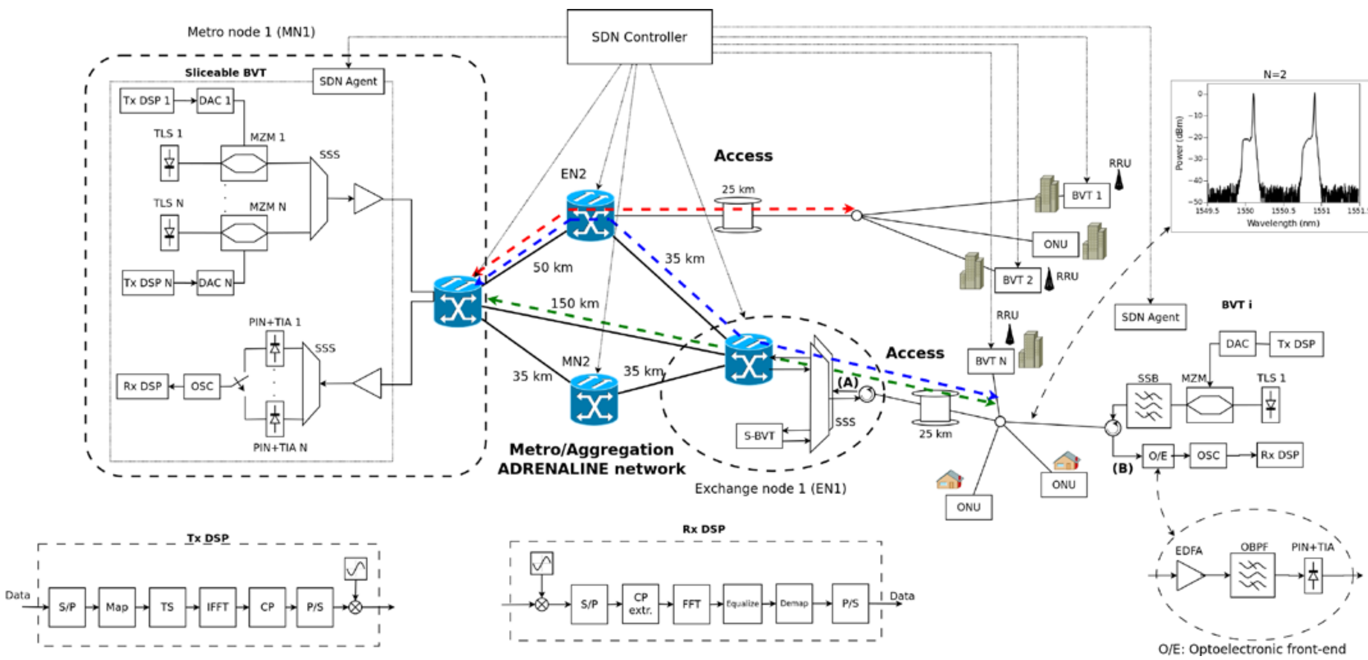
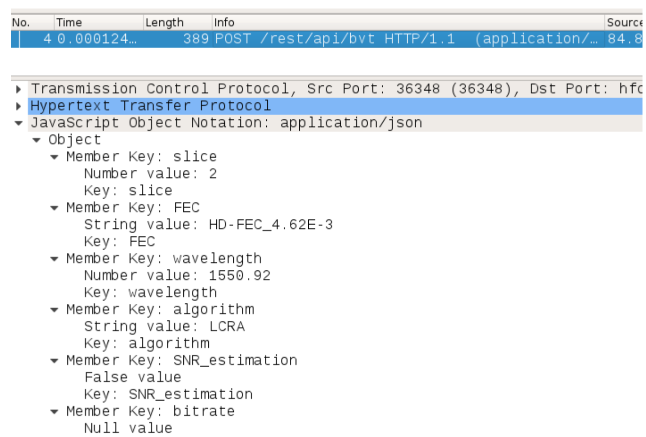


Fig. 2. Experimental scheme for testing the proposed mobile front-/back-hauling.

loading is implemented using the rate adaptive version of the Levin-Campello algorithm [6] in order to test the maximum capacity per flow that the system can offer. Then, 4 training symbol (TS) are included every 100 OFDM frames. The resulting symbols feed an inverse fast Fourier transform (IFFT) of 512 subcarriers. Afterwards, a 2% cyclic prefix (CP) is added and the obtained OFDM symbols are then serialized. The digital OFDM signal, fixed to be running at 20Gbaud, is clipped and upconverted to an intermediate frequency of 10GHz by mixing with a digital oscillator. The resulting signal is converted to the analog domain by a digital to analog converter (DAC) at 64GSa/s. This signal drives the corresponding Mach-Zehnder modulator (MZM) biased at the quadrature point and excited by a tunable laser source (TLS). For the BVT, the resulting signal after modulation passes through a tunable optical filter of 25 GHz, slightly detuned for obtaining an optical single sideband (SSB) signal. For the S-BVT, the flows after each MZM are aggregated using an SSS, configured to have 25 GHz bandwidth per channel and detuned for SSB generation. Two flows are generated at 1550.12 nm (flow 1) and 1550.92 nm (flow 2), as shown in Fig. 2 inset.

The optical signal generated at the S-BVT is injected into the ADRENALINE testbed, whose simplified scheme is depicted in Fig. 2. It is a 4-node photonic mesh network with amplified links of different lengths, ranging from 35 km to 150 km [18]. A 25 km fiber spool is attached to selected ENs in order to emulate the feeder section of the access trees. The power delivered to each tree is set to +5 dBm for the downstream signal. In the upstream, the signal at the BVT output (-4.2 dBm) is injected to the 25 km fiber spool and suitably routed in the ADRENALINE testbed.

At the receiver, the incoming signal is filtered out and photodetected. At the BVT an optoelectronic front-end (O/E)


No. Time Length Info Source
4 0.000124… 389 POST /rest/api/bvt HTTP/1.1 (application/… 84.8
Transmission Control Protocol, Src Port: 36348 (36348), Dst Port: hfc
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JavaScript Object Notation: application/json
Object
Member Key: slice
Number value: 2
Key: slice
Member Key: FEC
String value: HD-FEC_4.62E-3
Key: FEC
Member Key: wavelength
Number value: 1550.92
Key: wavelength
Member Key: algorithm
String value: LCRA
Key: algorithm
Member Key: SNR_estimation
False value
Key: SNR_estimation
Member Key: bitrate
Null value

Fig. 3. Sample JSON object for the configuration of the S-BVTs at maximum capacity.

that would include a high bandwidth avalanche photodiode is emulated by the combination of gain-stabilized EDFA, optical band pass filter (OBPF) and PIN diode. This combination is calibrated to obtain a -28 dBm sensitivity at 10^{-3} bit error ratio (BER) for non-return to zero (NRZ) on-off keying (OOK) transmission at 10.7 Gb/s. At the S-BVT reception side, an EDFA is acting as preamplifier, prior to an array of PIN diodes and TIAs used for photodetection. Either at the BVT and S-BVT, the photodetected current is digitized by a real-time oscilloscope (OSC) running at 100 GSa/s. Afterwards, the baseband OFDM signal is recovered after downconversion and off-line demodulated, according to [6].

The SDN controller configures the (S-)BVTs by setting slices active, forward error correction (FEC), central wavelength of slice and bit/power loading algorithm. Also, two operation modes are available at each (S-)BVT: signal-to-noise ratio (SNR) estimation and data transmission. When operating in SNR estimation, all the OFDM subcarriers are

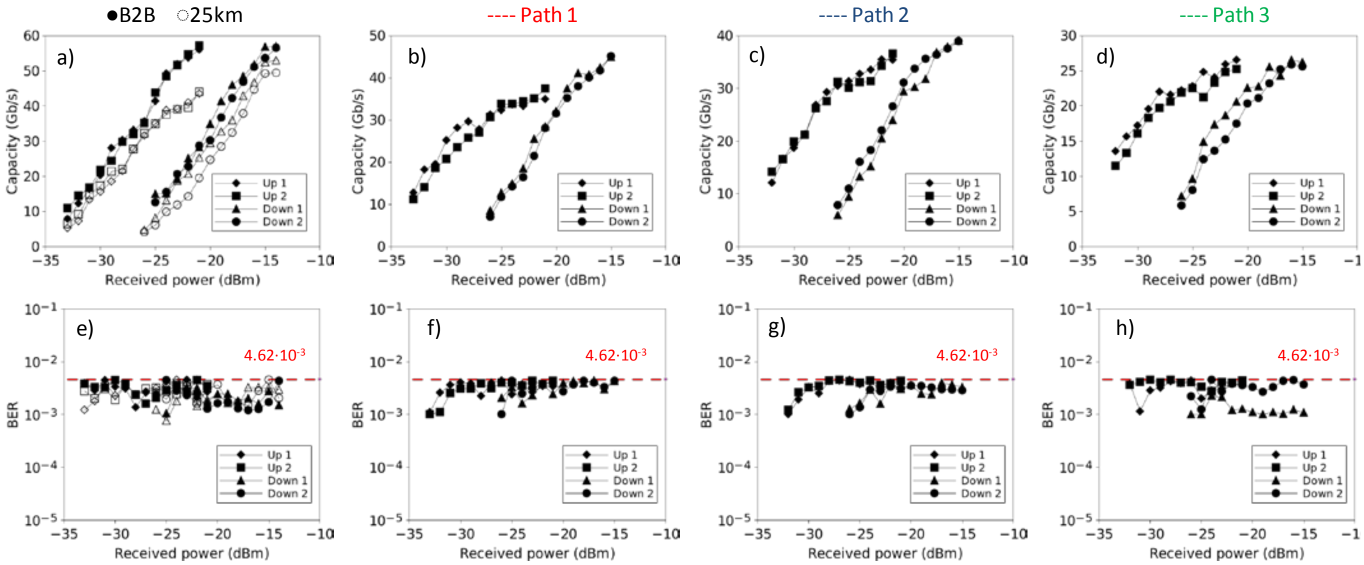

Fig.4. Experimental results in terms of maximum capacity (a, b, c, d) and BER (e, f, g, h) versus received power for the cases of: (a,e) B2B (filled markers), after 25 km (open markers); (b,f) path 1; (c, g) path 2; (d, h) path 3.

TABLE I
NETWORK PATHS EXAMINED IN THE EXPERIMENTS

ID	Route	No. of hops	Length*
Access	Access tree	-	25 km
Path 1	MN1-EN2	1	75 km
Path 2	MN1-EN2-EN1	2	110 km
Path 3	MN1-EN1	1	175 km

* Includes 25 km of the access segment.

automatically set to operate using 4QAM modulation at the transmitter while, at the receiver, the noise and power of each received symbol are estimated and further averaged per subcarrier. This information is collected by the corresponding agent and passed to the SDN controller. In turn, the SDN controller uses this information in order to accommodate the suitable modulation format at each OFDM subcarrier according the targeted performance. Then, the (S-)BVTs are set to operate in transmission mode, ensuring that the optimum modulation format is used. A sample configuration is shown in Fig. 3. Since offline processing is employed, the reconfiguration of the transceivers is limited by the processing time of the computer employed.

IV. RESULTS AND DISCUSSION

In order to analyze the performance of the proposed approach, the experiments are focused to determine the maximum achievable capacity in a precise number of cases. First a back-to-back (B2B) configuration is tested. Next, we test the maximum achievable capacity after bidirectional transmission over 25 km for considering the access segment. Finally, the different flows are transmitted over the ADRENALINE testbed and the access tree, covering different paths in order to prove the sliceable functionality while featuring full bidirectionality. The different paths tested are summarized in Table I.

The network is envisioned to cover a power budget of 20 dB in the access tree. In addition, we set a 3 dB power margin.

TABLE II
MAXIMUM CAPACITY FOR 20 DB POWER BUDGET

Case	Downstream 1550.12 nm	Downstream 1550.12 nm	Upstream 1550.12 nm	Upstream 1550.92 nm
B2B	46.0 Gb/s	42.2 Gb/s	32.6 Gb/s	31.5 Gb/s
Access	36.0 Gb/s	32.4 Gb/s	26.5 Gb/s	26.6 Gb/s
Path 1	41.1 Gb/s	38.0 Gb/s	28.1 Gb/s	26.8 Gb/s
Path 2	31.8 Gb/s	35.6 Gb/s	28.8 Gb/s	27.3 Gb/s
Path 3	25.5 Gb/s	23.2 Gb/s	21.7 Gb/s	20.4 Gb/s

Since the transmitted power is +5 dBm for downstream and -4.2 dBm for upstream, the received power threshold is set to -18 dBm for downstream and -27.2 dBm for upstream. The received power is measured after optical attenuation at points (A) and (B) of Fig. 2 for upstream and downstream, respectively. Please note that point (A) is placed at the entry point of the access tree, since it corresponds to one of the ends of the PON.

Figure 4 shows the results for the analyzed cases, assuming a $4.62 \cdot 10^{-3}$ BER threshold for a 7 % FEC overhead [19]. In all these cases, we ensure a BER below this value (Fig. 4e-h). Furthermore, the capacity values at the proposed power thresholds are detailed in Table II. The BER measurements where performed by error counting on a total of 491520 symbols, each featuring a different modulation format according to the bit loading algorithm. Therefore, in the worst case we might assume that all the symbols feature BPSK, achieving a BER resolution of $2.04 \cdot 10^{-6}$.

In the back to back configuration (Fig. 4a, filled markers) we obtain a maximum gross capacity well beyond 55 Gb/s per flow, either for upstream or downstream. At the received power threshold, the maximum capacity is more than 42 Gb/s for downstream while for upstream is slightly higher than 31 Gb/s.

Figure 4a (open markers) shows the results when featuring bidirectional transmission over a 25 km fiber spool, emulating the feeder section of the access tree. There we can observe that the results are aligned with the back to back case, but with power penalties of around 2 dB for downstream at the received power threshold. For upstream the capacity is limited to about 26.5 Gb/s for both flows. This is due to the optical signal to Rayleigh backscattering ratio (OSRR) caused by bidirectional transmission over a single fiber [14]. The OSRR measured is of 34.3 dB for downstream and 18.5 dB for upstream. This case is reported in tables II and III under the *access* label.

For proving the sliceable functionality while featuring full bidirectionality, the different flows are transmitted over the ADRENALINE testbed and the access tree, covering different paths of MN1-EN2 (path 1, red), MN1-EN2-EN1 (path 2, blue) and MN1-EN1 (path 3, green). Results are shown in Fig. 4b-d and Fig. 4f-h. There we can see how the accumulation of optical noise, and dispersion impacts on the system performance (besides the limited OSRR due to the optical tree). In the worst case (path 3, Fig. 4d), we observe a capacity penalty of less than 45 % with respect to the back-to-back for all the cases, achieving 20 Gb/s per flow and beyond at the received power threshold.

Table III summarizes the functional split options compatible with the results obtained. In fact, it comes after carefully balancing transmission delay and capacity obtained in the experiments. Regarding the transmission delay, we assume that it is mainly due to propagation over fiber and, thus, transmission distance is the main constraint. For the capacity, we take into account the values obtained in table II and compare them with the requirements reported in [15]. When targeting only the access part of the network (up to 25 km), the propagation delay is relatively small and the achievable functional split is limited to option 7a, due to the capacity reported in table II. Nevertheless, when increasing the transmission distance, the accumulated path delay also increases, limiting the attainable functional split. In fact, when envisioning path 3 (175 km, including access segment) the accumulated delay is limiting the functional split to option 3.

TABLE III
LATENCY AND FUNCTIONAL SPLIT CONSIDERATIONS

Case	Delay[1]	Maximum functional split[2]
Access	122.6 µs	7a
Path 1	367.8 µs	5
Path 2	539.4 µs	5
Path 3	858.1 µs	3

[1] Estimated from the specifications of the fibers employed.
[2] According to [15].

V. CONCLUSION

A transparent delivery of mobile front-/back-haul in a converged metro networking scenario has been experimentally demonstrated with SDN-enabled DD-OFDM (S-)BVTs. Results show successful connections from BBUs to the RRUs when serving different paths up to 175 km along a converged metro/access scenario, attaining the requirements of different functional split options. Therefore, a trade-off is found, enforcing a balance between capacity and transmission distance. At small distances the (S-)BVT flexibility allows to adapt the bit rate to the RRU requirements for a functional split option 7a, while large distances are limited by the propagation delay and the minimum attainable functional split option is 3. Thus, the proposed architecture offers a promising solution for serving the multiple endpoints when featuring a flexible functional split.

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REFERENCES

[1] J. M. Fabrega, M. Svaluto Moreolo, L. Nadal, F. J. Vílchez, R. Casellas, R. Vilalta, R. Martínez, R. Muñoz, J. P. Fernández-Palacios, L. M. Contreras "Experimental Validation of a Converged Metro Architecture for Transparent Mobile Front-/Back-Haul Traffic Delivery using SDN-enabled Sliceable Bitrate Variable Transceivers" in Proc. ECOC 2017, Sep. 2017, paper M.2.A.5

[2] NGMN, "Next Generation Mobile Networks 5G White Paper", February 2015, published.

[3] P. Rost, C. J Bernardos, A. De Domenico, M. Di Girolamo, M. Lalam, A. Maeder, D. Sabella, D. Wübben, "Cloud technologies for flexible 5G radio access networks," in *IEEE Communications Magazine*, vol. 52, no. 5, pp. 68-76, May 2014.

[4] 5GForum white paper "5G Vision, Requirements,and Enabling Technologies," March 2016

[5] N. Sambo, P. Castoldi, E. Riccardi, A. D'Erico, A. Pagano, M. Svaluto Moreolo, J. M. Fabrega, D. Rafique, A. Napoli, S. Frigeiro, E. Hugues-Salas, G. Zervas, M. Nölle, J. K. Fischer, A. Lord, J. P. Fernández-Palacios "Next Generation Sliceable Bandwidth Variable Transponders," in *IEEE Communications Magazine*, vol. 53, no. 2, pp. 163–171, Mar 2015.

[6] M. Svaluto Moreolo, J. M. Fabrega, L. Nadal, F. J. Vilchez, A. Mayoral, R. Vilalta, R. Muñoz, R. Casellas, R. Martínez, M. Nishihara, T. Tanaka, T. Takahara, J. C. Rasmussen, C. Kottke, M. Schlosser, R. Freund, F. Meng, S. Yan, G. Zervas, D. Simeonidou, Y. Yoshida, K. Kitayama "SDN-enabled Sliceable BVT Based on Multicarrier Technology for Multi-Flow Rate/Distance and Grid Adaptation," *Journal of Lightwave Technology*, vol. 34, no. 8, Apr. 2016

[7] J. M. Fabrega, M. Svaluto Moreolo, A. Mayoral, R. Vilalta, R. Casellas, R. Martínez, R. Muñoz, Y. Yoshida, K. I. Kitayama, Y. Kai, M. Nishihara, R. Okabe, T. Tanaka, T. Takahara, J. C. Rasmussen, N. Yoshikane, X. Cao, T. Tsuritani, I. Morita, K. Habel, R. Freund, V. Lopez, A. Aguado, S. Yan, D. Simeonidou, T. Szyrkowiec, A. Autenrieth, M. Shiraiwa, Y. Awaji, N. Wada "Demonstration of Adaptive SDN Orchestration: A Real-Time Congestion-Aware Services Provisioning Over OFDM-Based 400G OPS and Flexi-WDM OCS," *Journal of Lightwave Technology*, vol. 35, no. 3, pp. 506-512, Feb. 2017

[8] V. Lopez, L. Velasco (eds.), *Elastic Optical Networks*, Springer, 2016

[9] A. Girard, *FTTx PON Technology and Testing*, EXFO Electrical Engineering, 2005.

[10] ITU-T recommendation G.987 (2012)

[11] Physical Layer Specifications and Management Parameters for 10 Gb/s Passive Optical Networks, IEEE 802.3av Standard, 2009

[12] J. M. Fabrega, M. Svaluto Moreolo, M. Chochol, G. Junyent "Decomposed Radio Access Network Over Deployed Passive Optical Networks Using Coherent Optical OFDM Transceivers," *Journal of optical Communications and Networking*. vol. 5, no. 4, pp. 359-369, Apr. 2013

[13] J. S. Wey, D. Nesset, M. Valvo, K. Grobe, H. Roberts, Y. Luo, and J. Smith "Physical layer aspects of NG-PON2 standards—Part 1: Optical link design [Invited]," *Journal of optical Communications and Networking*, vol. 8, no. 1, pp. 33-42, Jan. 2016.

[14] M. O. van Deventer, *Fundamentals of Bidirectional Transmission over a Single Optical Fibre*, Springer Science & Business Media, 2012

[15] 3GPP TR 38.801 V14.0.0 "Technical Specification Group Radio Access Network; Study on new radio access technology: Radio access architecture and interfaces" (2017)

[16] U. Dötsch, M. Doll, H. P. Mayer, F. Schaich, J. Segel and P. Sehier, "Quantitative analysis of split base station processing and determination of advantageous architectures for LTE," in *Bell Labs Technical Journal*, vol. 18, no. 1, pp. 105-128, June 2013.

[17] T. Pfeiffer "Next generation mobile fronthaul and midhaul architecture," *Journal of Optical Communications and Networking*, vol. 7, no. 11, Nov. 2015

[18] R. Muñoz, L. Nadal, R. Casellas, M. Svaluto Moreolo, R. Vilalta, J. M. Fabrega, R. Martínez, A. Mayoral, F. J. Vilchez, "The ADRENALINE Testbed: An SDN/NFV Packet/Optical Transport Network and Edge/Core Cloud Platform for End-to-End 5G and IoT Services," in Proc. EuCNC 2017, Jun. 2017

[19] ITU-T recommendation G.975.1 (2004)