

# SDN-enabled S-BVT for SDM Optical Metro/Regional Networks

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**Abstract**—In this paper, we experimentally assess different metro network scenarios including space division multiplexing (SDM) technology to validate the performance of adopting software defined networking (SDN)-enabled sliceable bandwidth/bit rate variable transceivers (S-BVTs). Different network paths of the ADRENALINE testbed, considering standard single mode fiber (SSMF) and multi core fiber (MCF), have been analyzed. A maximum 19-core fiber link of 279.4 km, with 11 spans of 25.4 km, has been evaluated, enabling an aggregated capacity of about 0.5 Tb/s ( $19 \times 24$  Gb/s).

**Index Terms**—Sliceable transceiver, metro networks, multicore fiber, multicarrier modulation

## I. INTRODUCTION

The increasing global mobile data traffic/connections and the appearance of emerging paradigms such as 5G communications and Internet of Things (IoT), make current optical networks to evolve towards more scalable and flexible architectures [1]. Specifically, global mobile data traffic will grow seven-fold between 2017 and 2022 and the number of mobile-connected devices per capita will reach 1.5 by 2022, according to Cisco’s Report [2]. In view of supporting this increase, more stringent network/system requirements in terms of capacity, latency and reliability are required. To this end, software defined networking (SDN)-enabled sliceable bandwidth/bit rate variable transceivers (S-BVT) arise as a suitable solution to provide an adaptive/elastic transmission. The S-BVT consists of rate/distance adaptive bandwidth/bitrate variable transmitter (BVTx) and receiver (BVRx) array. Thanks to its inherent transceiver modularity, system/network flexibility/dynamicity can be fully exploited [3]. Additionally, by the implementation of SDN agents the envisioned S-BVTs can be programmed/reconfigured according to the network requirements. Open application programming interfaces (APIs) and vendor-neutral data models can be considered in the development of the SDN agents moving towards an open software/disaggregated ecosystem [3].

On the other hand, space division multiplexing (SDM) can significantly help increasing the network capacity by exploiting the space dimension. Particularly, multi-core fibers (MCF) are a compact high capacity alternative to standard single mode fibers (SSMF) for future capacity expansions in optical networks [1].

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Here, we propose different metro network scenarios in order to evaluate the SDN and SDM capabilities of the S-BVT, required to meet the expected network requirements in terms of capacity, flexibility and programmability. To that end, we consider the ADRENALINE testbed, which is a fixed/flexi-grid dense wavelength division multiplexing (DWDM) network with white box reconfigurable optical add-drop multiplexer (ROADM) and optical cross-connect (OXC) nodes [4].

## II. NETWORK SCENARIOS AND EXPERIMENTAL SET-UP

Different scenarios have been evaluated, within the ADRENALINE testbed, to validate the performance of the programmable S-BVT, as seen in Fig. 1. Firstly, scenario 1 considers a back-to-back (B2B) configuration between S-BVT1 and S-BVT2. In scenario 2, a bidirectional transmission between S-BVT1 and S-BVT2 is evaluated including a bidirectional 35 km SSMF path and two metro/core edge nodes (MCENs). Whereas in scenario 3, a path from S-BVT1 to BVT4 is established, including 35 km of SSMF, 25.4 km of MCF, two MCENs and an access/metro edge node (AMEN). Finally, in scenario 4, the assessment over multiple fiber spans ( $N$ ) of MCF, which interconnects different AMENs, is evaluated, assessing a maximum link length of 279.4 km ( $N = 11$ ). On the one hand, the AMEN gathers traffic from access networks and hosts a limited set of network services. On the other hand, the MCEN assures metro domain internetworking and provides an extended set of centralised services, allowing the interconnection with the backbone. The S-BVT can be located at the MCEN nodes, whereas simpler transceiver architectures can be envisioned at the AMEN nodes (see S-BVT1, S-BVT2, S-BVT3 and BVT4 in Fig. 1). In Fig. 1, it can also be seen the architecture of an SDN-enabled S-BVT. Specifically, at the BVTx side, a digital-to-analog converter (DAC) and a simple optoelectronic front-end, including an external Mach-Zehnder modulator (MZM) and a tuneable laser source (TLS), is required. Whereas, at the BVRx, a simple photo-detector (PIN) followed by a transimpedance amplifier (TIA) and an analog-to-digital converter (ADC) are envisioned to perform DD. A wavelength selective switch (WSS) can be used at both the sliceable transmitter and receiver to perform multiflow aggregation/disaggregation operations. The WSS at the transmitter can serve also as optical filter to implement single side band modulation (SSB) [3]. At the digital signal processing (DSP) level, multicarrier modulation (MCM) such

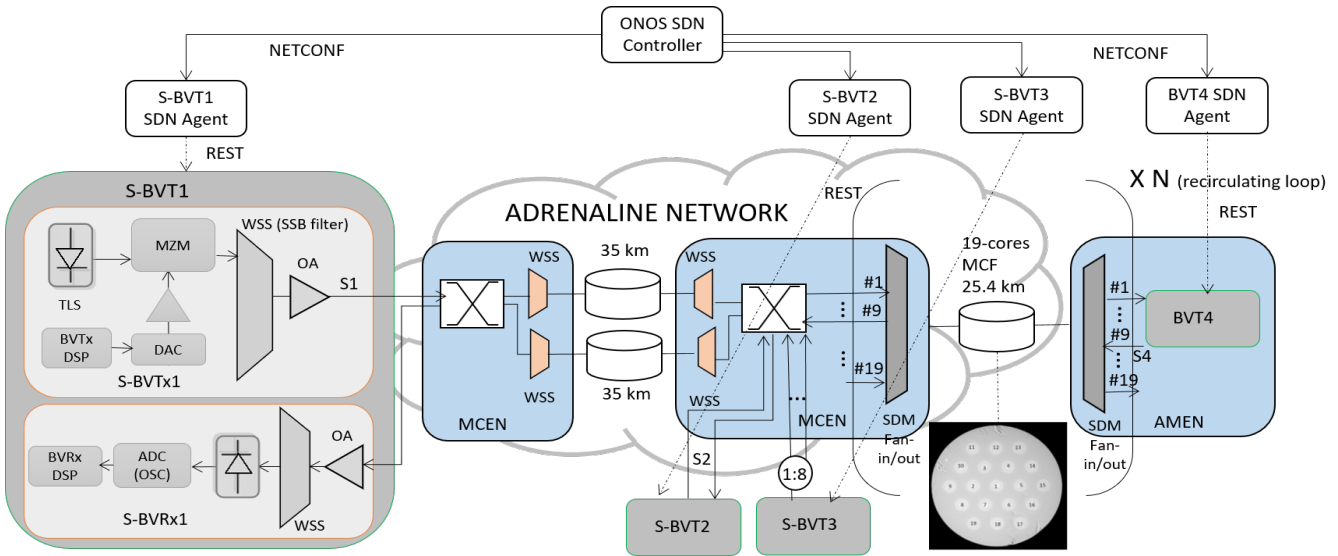


Fig. 1. Network scenarios and experimental setup

as orthogonal frequency division multiplexing (OFDM) is implemented enabling adaptive modulation. Bit/power loading (BL/PL) algorithms are suitably implemented by assigning different bits per symbol and power values to the multiple subcarriers according to the channel profile [3]. In particular, the BVTx DSP block includes data parallelization and mapping, training symbol (TS) insertion, inverse fast Fourier transform implementation, cyclic prefix (CP) insertion, serialization and radio frequency (RF) up-conversion. At the BVRx DSP block, RF down-conversion, data parallelization, CP removal, fast Fourier transform implementation, equalization, symbol demapping and serialization processes are performed.

### III. MCF IMPAIRMENTS

MCF technology enables high capacity increase per-fiber through spatial multiplexing. However, many technological challenges must be overcome, such as scalability in terms on number of cores and performance metrics. Specifically, mode linear and nonlinear coupling/crosstalk (XT) is a potential disadvantage that can limit the system performance in MCF transmission [5], [6]. Linear coupling leads to a periodic transfer of optical power from one core to another and can be mitigated/compensated by implementing DSP at the receiver side (e.g. multiple-input multiple-output technique, MIMO). According to [6], a simple analytical expression for the statistical mean crosstalk estimation is:

$$XT_{\mu} \approx \frac{2k_{pq}^2 R_b}{\beta \Lambda} L, \quad (1)$$

where  $k_{pq}$  is the mode linear coupling coefficient between two neighboring cores,  $R_b$  is the bending radius,  $L$  is the fiber length,  $\beta$  is the propagation constant, and  $\Lambda$  is the core pitch (or core-to-core distance). With this analytical expression, the XT in MCF can be easily calculated in order to evaluate/analyze the impact on the system performance and have an idea of the limits of core scalability.

In [5] it has been demonstrated that linear coupling affects the nonlinear penalty in MCFs. In particular, linear coupling can mitigate the nonlinear impairments to some extent, improving the system performance [7]. Hence, in section IV, we have analyzed the nonlinear length ( $L_{NL}$ ), which provides the length scale over which nonlinear effects become relevant. Specifically, it is calculated as:

$$L_{NL} = 1/(\gamma P_0), \quad (2)$$

where  $\gamma$  is the nonlinear parameter and  $P_0$  is the fiber input power [8].

### IV. EXPERIMENTAL ASSESSMENT

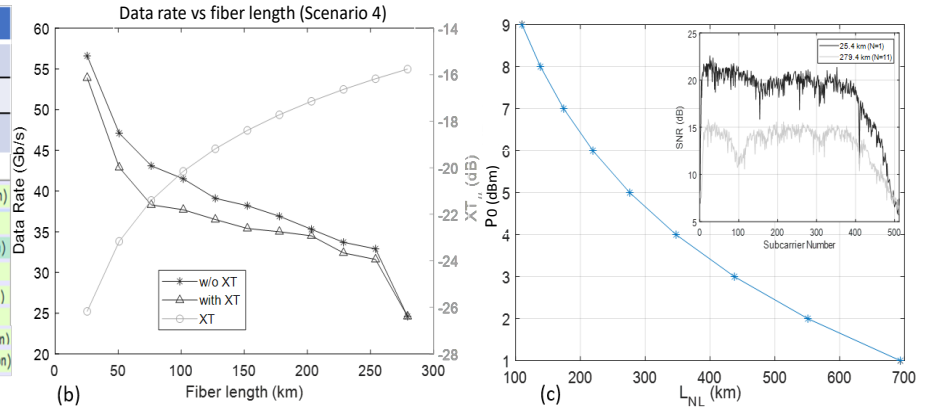
This section presents the experimental results of the performance evaluation of the SDN-enabled S-BVT in the metro scenarios described in section II. A single slice of 20 GHz bandwidth and 512 subcarriers, which works at 1550.12 nm, is enabled at each S-BVT. Each slice is created/acquired using a high-speed DAC working at 64 GSa/s and a 100 GSa/s oscilloscope (OSC), as ADC. MZMs work at the quadrature point and the WSSes have a bandwidth of 25 GHz. A target BER of  $4.62 \cdot 10^{-3}$  with standard hard decision forward error correction (HD-FEC) is fixed. The considered overheads due to TS, CP and FEC are 4%, 1.9% and 7%, respectively. Fig. 2 (a) top summarizes the main results in terms of achieved data rate/reach of scenarios 1-3. Specifically, in scenario 1, S-BVT1 and S-BVT2 are configured enabling slice  $S_1$  and  $S_2$  at 61.1 Gb/s and 60 Gb/s, respectively. The difference, in terms of data rate is due to setup implementation, which includes different transceiver hardware. In scenario 2, the data rate decreases after the 35 km SSMF bidirectional path of the ADRENALINE testbed, achieving 54.4 Gb/s and 43.4 Gb/s capacities. Additional experimental validation has been performed to demonstrate SDN S-BVT capabilities, considering scenario 2. Specifically, in Fig. 1 (a) bottom, a Wireshark

Scenario (1-3)	Rate (Gb/s)	Link (km)
B2B	61.1 (S1); 60 (S2)	-
1-hop SSMF	54.4 (S1); 43.4 (S2)	35
2-hops SSMF+MCF	46 (S1); 36.3 (S4)	60.4

Time	Source	Destination	Info
0.001693	S-BVT1 Agent	PC	POST /api/dac HTTP/1.1 (application/json)
21.075606	PC	S-BVT1 Agent	HTTP/1.0 200 OK (application/json)
42.454270	S-BVT2 Agent	PC	POST /api/dac HTTP/1.1 (application/json)
63.402935	PC	S-BVT2 Agent	HTTP/1.0 200 OK (application/json)
74.654294	S-BVT1 Agent	PC	POST /api/osc HTTP/1.1 (application/json)
172.429065	PC	S-BVT1 Agent	HTTP/1.0 200 OK (application/json)
172.445529	S-BVT2 Agent	PC	POST /api/osc HTTP/1.1 (application/json)
270.877200	PC	S-BVT2 Agent	POST /api/osc HTTP/1.1 (application/json)

(a)



(b)

(c)

Fig. 2. (a) Table summarizing the performance results of assessing scenarios 1-3. Wireshark capture of the configuration of transmitter and receiver of S-BVT1 and S-BVT2. (b) Performance results in terms of data rate of scenario 4. (c) Nonlinear length vs fiber input power. In the inset, SNR profile after 25.4 km ( $N = 1$ ) and 279.4 km ( $N = 11$ ) of MCF.

capture showing the configuration of two S-BVTs, including transmitter and receiver sides, is depicted. In total a setup time configuration of 270 s is required to configure both transceivers [3]. Finally, scenarios 3 and 4 are envisioned to evaluate the SDM capabilities of the proposed S-BVT. Additionally, different cores can be enabled/disabled by the adoption of an SDN control plane further enhancing system/network flexibility. In scenario 3, a 2-hops path of 60.4 km, including SSMF and MCF, is demonstrated, achieving 46 Gb/s and 36.3 Gb/s transmission over core #1 and #9, respectively. In scenario 4, the signal under analysis is sent to core #1 of a MCF, whereas the adjacent cores (#2 – #7) are filled with dummy OFDM signals by using a 1x8 splitter, as seen in Fig. 1. The same power (6 dBm) is launched into all the analyzed cores in order to evaluate the system performance including the effect of the XT. In particular, Fig. 2 (b), shows the crosstalk vs MCF length following the expression of equation (1). According to the equation, a mean XT value ( $XT_{\mu}$ ) of  $-26.1$  dB is calculated considering the 19-core 25.4 km fiber, used in the experiments (see Fig. 1). This value perfectly match the measured XT mean value of the fiber specifications ( $-25.5$  dB). Hence,  $XT_{\mu}$  can be analytically calculated for different MCF lengths following equation (1). Specifically, Fig. 2 (b) shows the evolution of the mean XT after up to 279.4 km of MCF ( $N = 11$ ). In the same figure, the performance in terms of data rate, with and without (w/o) XT, is also envisioned for MCF spans of 25.4 km. A maximum data rate of 57 Gb/s is achieved for ( $N = 1$ ) w/o XT, at 31.6 dB OSNR. Considering XT, the maximum achieved data rate is 54 Gb/s. This data rate can be scaled with the number of cores in order to increase the network overall capacity, enabling 1 Tb/s (19x54 Gb/s) transmission. However, the XT degrades the system performance in terms of capacity at the increase of the fiber length. After 279.4 km, fiber nonlinearities dominate over the XT also according to Fig. 2 (c), where the fiber input power is depicted as a function of the nonlinear length. Hence, at this length, similar performance is achieved with and w/o XT, enabling an aggregated capacity of about

0.5 Tb/s (19x24 Gb/s). Specifically, according to Fig. 2 (c) and equation (2), for a fiber input power of 6 dBm, after 219.3 km the nonlinear effects dominates the transmission.

## V. CONCLUSIONS

SDN-enabled S-BVT becomes a suitable solution to be adopted in SDM optical networks to fully exploit system capacity, flexibility and elasticity. Specifically, in view of the emerging 5G paradigm more stringent requirements in terms of capacity, latency and capital/ operational expenditure arise. Hence, in this paper a solution combining a cost-efficient transceiver with modular, programmable architecture (SDN-enabled S-BVT) and the exploitation of the space dimension (SDM technology) has been validated considering different network scenarios, which include the ADRENALINE testbed. In particular, a maximum aggregated data rate of about 1 Tb/s can be achieved after 19-core 25.4 km fiber, considering XT. The aggregated data rate decreases to about 0.5 Tb/s after 11 spans of 25.4 km MCF.

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