# Cost-Effective Data Plane Solutions Based on OFDM Technology for Flexi-Grid Metro Networks Using Sliceable Bandwidth Variable Transponders

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***Abstract*—In an evolutionary metro network scenario, it is proposed to adopt flexi-grid technologies and centralize the IP functionality, locating the Broadband Remote Access Servers (BRASes) in fewer sites of a regional photonic mesh network, in order to reduce CapEx. Therefore, cost-effective data plane solutions, able to support multiple low bit rate connections, using 12.5 GHz channels, are required for this network segment.**

**In this paper, we present a cost-effective bandwidth variable transponder (BVT) based on OFDM technology suitable for flexi-grid metropolitan area network (MAN), using low-complexity digital signal processing (DSP) and direct detection (DD). The design guidelines are provided for this data plane solution, which has been numerically analyzed and experimentally validated in a photonic mesh network. Furthermore, a sliceable BVT architecture is proposed for enhancing the capacity of the BRAS node in order to serve several Multi-Tenant Units (MTUs).**

***Index Terms*—Optical Metro Networks, Flexi-grid, Optical OFDM, Bandwidth Variable Transponders.**

## I. Introduction

The advent of elastic optical networks (EON) and flexi-grid technologies, as well as the advance of transmission techniques in terms of capacity and flexibility has led to undertake new goals and challenges, blurring the boundaries of the protocol stack. On the one hand, the network architecture and the related control and management are reconsidered to be designed and extended, taking into account the new advanced features of transceivers and nodes. On the other hand, new data plane solutions and technologies are investigated and developed, for supporting the evolutionary approach and scenarios of future networks and services. Common drivers are the ever increasing request of capacity and services and the need of reducing costs.

Flexi-grid granularity, using 12.5 GHz (or even 6.25 GHz) spectrum slots, has been proposed to improve efficient utilization of the optical spectrum, also in presence of super-channels for high-rate connections [1]. In this context, the reduction of channel width enables the creation of low bit rate connections, which may be used in metropolitan area networks (MAN). Thus, an evolutionary approach for this network segment has been also envisioned and novel scenario proposals have been considered [2]. Furthermore, the benefits of elastic transponder in optical metro networks have been investigated, showing significant performance improvement in ring architecture using coherent technology [3].

Typically, metro architectures are composed by two main levels of aggregation and the IP functionality (i.e. traffic classification, routing, authentication, etc.) is implemented in the Broadband Remote Access Server (BRAS). BRASes are usually located at the second level of aggregation and distributed in many sites along the area covered by the MAN, causing a high Capital Expenditure (CapEx) impact.

Recently, main network operators are expanding their photonic mesh to the regional networks, so it has been proposed to co-locate BRASes in fewer locations reducing investment. In an evolutionary scenario, the BRAS capability could be centralized, co-locating the servers in a transit router in order to further reduce the cost associated to the IP equipment [2]. Thus, for the proposed metro scenario, transmission techniques for core networks are not required, whereas a more cost-effective solution must be investigated.

In this paper, after describing the envisioned scenario, we address mesh flexi-grid metro networks, proposing a cost-effective bandwidth variable transponder (BVT) design. It is based on orthogonal frequency division multiplexing (OFDM) using a low-complexity digital signal processing (DSP) and combined with direct detection (DD) [4]. Programmable BVT based on OFDM technology enables advanced modulation parameters and flexible functionalities, which can be managed by the control plane. In particular, given the unique subwavelength granularity offered by the OFDM, adaptive modulation, bit and power loading schemes and subcarriers selection/suppression are suitably selected for rate and distance adaptive transmission [5]. The network efficiency and flexibility can be further enhanced adopting programmable BVT, whose capacity can be sliced in multiple flows serving different destination nodes [6].

The proposed BVT and its advanced functionalities have been analyzed by numerical simulations and experimentally assessed within the ADRENALINE photonic mesh network [7]. Here, we report the obtained results, giving the BVT design guidelines. Furthermore, a sliceable BVT (S-BVT) architecture for flexi-grid metro networks is presented and a proof of concept is provided.

## II. Evolution Of Metro Network Architecture

Current metro architectures are composed of a first level of aggregation, indicated as Multi-Tenant Unit (MTU), and a second level of aggregation named Access level, as indicated in Fig. 1. The former is in charge of collecting traffic from the Optical Line Terminals (OLTs); the latter aggregates the traffic from the MTUs mainly through direct fiber connections. MTU switches are connected to a certain number of BRAS servers distributed in the regional area.

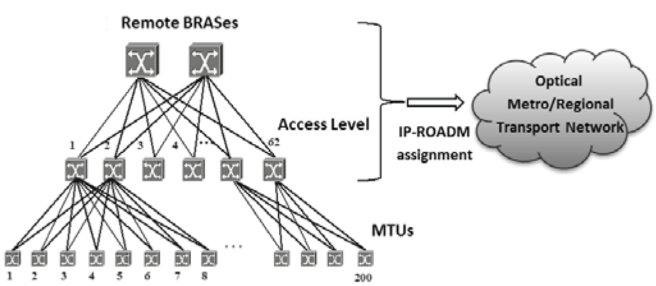


Fig. 1. Current metro architecture.

Recently, the network architecture is evolving towards a centralized BRAS scenario, moving the IP functionality to the transit level. In this proposal aiming at reducing costs, the BRASes are located at two (for redundancy purposes) transit sites.

Different architectural options can be considered for this evolutionary scenario [2]. Fixed-grid regional photonic mesh network can provide connections between the MTUs and the BRAS, replacing the second level of aggregation with an adaptation layer. Alternatively to the WDM network, a flexi-grid solution can be proposed in order to improve the efficient utilization of the optical spectrum, introducing a granularity of 12.5 GHz spectrum slots (according to the ITU-T Recommendation G.964.1 [8]), which better fit with the low bit rate connections required by the first level of aggregation. In fact, we can assume that the traffic demand per each MTU (aggregating traffic from the OLTs) is 10 Gb/s.

Particularly, flexi-grid photonic mesh can benefit from the use of bandwidth variable transponder and sliceable BVT at the BRAS servers (see Fig. 2), as it will be discussed in the following sections. In fact, an S-BVT is able to generate/receive an aggregated flow of several channels, with e.g. 10 Gb/s capacity each (MTU channels), and has the capability of slicing it into multiple flows of variable capacity to be transmitted towards different destination nodes.

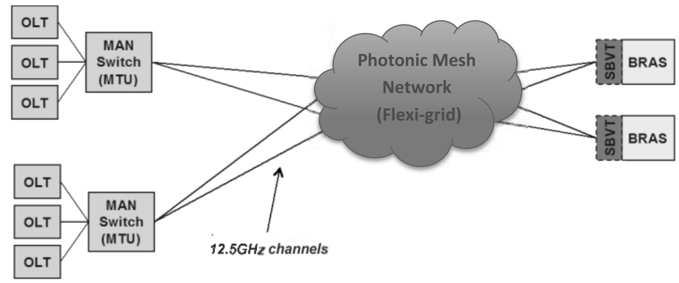


Fig. 2. Evolutionary flexi-grid metro network scenario with S-BVT at the BRASes.

## III. Cost-Effective BVT Based On OFDM Technology

According to the evolutionary metro network scenario, we propose the cost-effective elastic OFDM BVT described in Fig. 3, for rate and distance adaptive transmission in flexi-grid MAN. The bandwidth and bit rate can be varied at the DSP level by software, selecting the suitable modulation format and number (*N*) of OFDM subcarriers. The optical carrier of the flexi-grid channel is selected at the tunable laser source (TLS). Thanks to the subwavelength granularity of OFDM, the rate can be adjusted to the request with fine granularity by using bit loading (BL). Adaptive strategies can be adopted, according to the channel condition, so that data mapped with the most robust modulation format are supported by the subcarriers with lower signal to noise ratio (SNR), in order to improve the robustness against the transmission impairments. To further improve the achievable reach at a certain rate, power loading (PL) schemes can be also implemented.

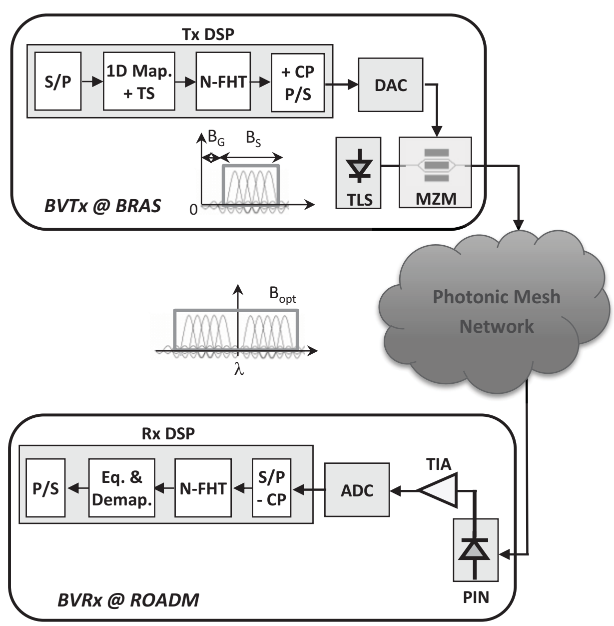


Fig. 3. Schematic of cost-effective bandwidth variable transmitter (BVTx) and receiver (BVRx) for flexi-grid metro networks.

A low-complexity DSP based on the fast Hartley transform (FHT) is used. Only real algebra and one-dimensional (1D) modulation format (M-PAM) are required to obtain the same spectral efficiency and performance as FFT-based DD OFDM systems using $M^2$-QAM, as experimentally demonstrated in [9]. Additionally, half-length training symbol (TS) sequences are inserted for simplified channel estimation and low-complexity equalization [9]. In order to limit the high OFDM PAPR, symmetrically clipping is applied to the digital signal. In our design, an optimal clipping level for the considered modulation formats has been selected, according to previous theoretical study and extensive simulations [10]. The clipping and quantization noise can be further reduced by applying distortionless PAPR reduction techniques, which have low-complexity thanks to the FHT properties [10].

For a cost-effective transponder design, the simple DD receiver is combined with double side band (DSB) modulation. This transponder architecture only requires a single digital-to-analog converter (DAC) at the transmitter and one analog-to-digital converter (ADC) at the receiver side, without the need for an optical single-side band filter. Additionally, the mixing at an intermediate radio frequency (RF), for a software-defined tuning of the electrical signal band over the spectrum, is performed in the digital domain without requiring any electronic hardware. Nevertheless, DSB OFDM transmission limits the achievable reach, due to the power fading induced by the chromatic dispersion (CD). Thus, for transmitting along optical paths in a flexi-grid MAN, the spectral occupancy of the optical OFDM signal must be reduced in order to mitigate the self-cancellation between the carriers at the two sidebands of the optical carrier [11].

Furthermore, as a scenario constraint, we assume that the optical spectrum occupancy of the channels is limited to 12.5 GHz. The spectral efficiency can be enhanced by minimizing the guard band and using higher size constellations. We have experimentally demonstrated that, using an external Mach-Zehnder Modulator (MZM) biased at the quadrature point, the guard band between the OFDM signal and the optical carrier can be reduced up to 89%, at the expenses of the receiver sensitivity [9]. Thus, in order to minimize the guard band and consider a low-cost laser with linewidth of the order of MHz, we assume a guard band ($B_G$) equal to 500 MHz as optimal for an electrical OFDM signal bandwidth ($B_S$) of about 5 GHz (see the inset of Fig. 3).

### *A. Numerical Analysis*

We have numerically analyzed the performance of the BVT of Fig. 3, designed according to the proposed guidelines. At the DSP, an FHT with $N$=256 subcarriers modulates the mapped M-PAM sequence. Optimized training symbols are added for an overhead of 0.78%; 10% cyclic prefix is appended to the OFDM frame for compensating the intersymbol interference. The digital signal is symmetrically clipped with an optimum clipping level of 9.5 dB and converted to analog considering a uniform quantizer with 8 bit resolution [10]. The MZM biased at the quadrature point is driven by an optical source modeled as a standard continuous wave (CW) laser centered at a wavelength of λ=1550 nm. The optical network is replaced by a SSMF link (G.652). The propagation over the fiber link is modeled using the split-step Fourier method. We assume a dispersion coefficient of 17 ps/(nm·km), a nonlinear coefficient of 1.3 $W^{-1}·km^{-1}$ and a loss factor of 0.2 dB/km. The receiver is modeled as a PIN photodiode with 0.7 A/W responsivity, overall thermal noise value of $12.87·10^{-12}$ A/√Hz, and dark current of 1 pA. The detected signal is analog-to-digital converted and processed at the receiver DSP to be demodulated, equalized and demapped.

A maximum electrical signal bandwidth $B_S$ of 5.5 GHz with a minimum guard band $B_G$=500 MHz have been considered. Variable BL schemes using BPSK, 4PAM and 8PAM formats are analyzed in order to obtain a net data rate of 10 Gb/s for channels with maximum optical bandwidth of 12.5 GHz. The distribution of the modulation formats onto the subcarriers is selected according to the channel profile. To this extend, the SNR of the different OFDM subcarriers is estimated after transmission in a fiber link of 120 km, for which the dispersion impairments significantly affect the transmission [12]. It has been found that the subcarriers at the edge of the OFDM signal spectrum are more affected by the channel impairments. Hence, the most robust format, BPSK, is assigned to those subcarriers. Similarly, the subcarriers presenting the highest SNR are filled with 8PAM format. The rest of subcarriers are mapped with 4PAM format, according to FHT mirror symmetry and a suitable SNR threshold, depending also to the target bit rate.

TABLE I
BL SCHEMES AND ACHIEVABLE REACH

| BPSK(%) | 4PAM(%) | 8PAM(%) | $B_{signal}$ | Reach |
|---|---|---|---|---|
| 10 | 60 | 30 | 5.5 GHz | 120 km |
| 10 | 40 | 50 | 5 GHz | 100 km |
| 0 | 40 | 60 | 4.5 GHz | 70 km |
| 0 | 0 | 100 | 4 GHz | 70 km |

Analyzed BL schemes at the BVT DSP to obtain a net data rate of 10 Gb/s. The percentage of BPSK, 4PAM and 8PAM formats, and the bandwidth of the electrical OFDM signal and maximum are indicated. The maximum achievable SSMF link at $10^{-3}$ BER is also reported.

The sensitivity performance has been analyzed at the varying of the fiber length and the BL schemes. Uniform and adaptively non-uniform BL, are applied as defined in Table I to obtain a net bit rate $R_n$ of 10 Gb/s. The maximum SSMF link that can be reached at a target BER of $10^{-3}$ for each case is also reported. Using uniform 8PAM, $R_n$=10 Gb/s is obtained with $B_S$=4 GHz and the target BER is ensured up to 70 km. When all the subcarriers are mapped with 4PAM format, $R_n$=10 Gb/s cannot be achieved within a channel of 12.5 GHz, as it needs an electrical bandwidth of 6 GHz, and hence, considering the required guard band, an optical bandwidth of 13 GHz. On the other hand, a $R_g$=10 Gb/s, corresponding to a net data rate of 8.4 Gb/s, obtained with uniform 4PAM and $B_S$=5 GHz ($B_{opt}$=11 GHz), can be transmitted up to 150 km with a received power of -6 dBm [12]. In order to enhance the link length at a net data rate of 10 Gb/s, BL schemes, alternative to the case of using uniform bit loading, have been implemented for distance adaptive transmission. The largest link at $10^{-3}$ BER is 120 km, adaptively loading the subcarriers with 10% BPSK, 60% 4PAM and 30% 8PAM. Other BL schemes, combining two and three modulation formats, have also been tested. However, as they carry a higher percentage of 8PAM format, higher receiver sensitivity is required at the target BER and the achievable reach is reduced.

## IV. Experimental Assessment

For the experimental validation of the proposed data plane solution, we have considered the set-up described in Fig. 4. The maximum electrical signal bandwidth, which has been taken into account is $B_S$=5 GHz (due to hardware limitation) and the total electrical bandwidth including the guard band is $B_G+B_S$=5.5 GHz. Therefore, the corresponding DSB optical spectrum occupies $B_{opt}$=11 GHz, which perfectly fit within a 12.5 GHz flexi-grid channel.

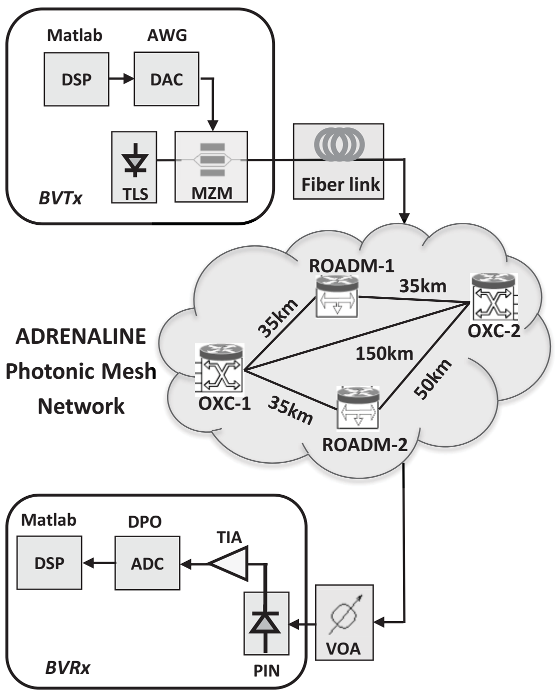


Fig. 4. Experimental set-up.

We assume that the rate/bandwidth variable transmitter (BVTx) is located at the BRAS and the receiver (BVRx) at a ROADM of the considered network. The performance has been first assessed in a back-to-back (B2B) configuration and then within the ADRENALINE mesh network [4, 7]. Furthermore, a fiber link of SSMF (G.652) of variable length (e.g. 10 km or 50 km) is also considered in order to emulate different BRAS locations.

A stream of randomly generated data is off-line mapped into 1D constellation and modulated by an FHT with $N$=64 subcarriers by using Matlab processing. The real-valued OFDM digital signal is loaded into an arbitrary waveform generator (AWG), which generates an analog signal at 12 GS/s. The analog OFDM signal modulates an external MZM biased at the quadrature point ($0.5V_\pi$) and driven by a tunable laser source at $\lambda$=1550.12 nm. A variable optical attenuator (VOA) is used for sensitivity measurements. At the receiver side, the transmitted signal is detected by a PIN photodiode and amplified by a trans-impedance amplifier (TIA). The data is captured by a real-time oscilloscope (labeled as DPO in Fig. 4) at a sampling rate of 50 GS/s and then down-converted, demodulated, equalized and demapped off-line with Matlab. According to the guidelines in Sec. III and [9], eight half-length training symbols are inserted every 512 OFDM frames, giving an overhead of 1.56%. Additionally, 10% CP is also considered. A FEC with 7% overhead is taken into account for assuming a target BER of $10^{-3}$. The total overhead is 19.54%.

TABLE II
Analyzed formats and bandwidth occupancy for BVT assessment

| Format | Bit Rate | $B_{signal}$ | $B_{optical}$ |
|---|---|---|---|
| BPSK | 5 Gb/s | 5 GHz | 11 GHz |
| 4PAM | 10 Gb/s | 5 GHz | 11 GHz |
| 4PAM | 8 Gb/s | 4 GHz | 9 GHz |
| BL | 8 Gb/s | 5 GHz | 11 GHz |

We assess the performance of the proposed BVT by varying the modulation format and bit loading scheme. For the experimental validation of the proposed BVT design, we analyze only two modulation formats (BPSK and 4PAM) at 5 GBaud/s ($B_S$=5 GHz), giving a gross rate of 5 Gb/s and 10 Gb/s, respectively. Fine bit rate selection is achieved with BL. For distance adaptive transmission assessment, we analyze the connection at 8 Gb/s. It is obtained by mapping the 40% of the subcarriers with BPSK and the 60% with 4PAM, according to the channel profile. Specifically, as the subcarriers at the edge of the signal present lower SNR (due to channel impairments), they are loaded with BPSK symbols. This intermediate target rate can either be obtained by reducing the electrical signal bandwidth to 4 GHz and using only 4PAM format. The analyzed cases are summarized in table II. In all the experiments, the BER is measured by error counting up to 1000 errors.

### A. *Back-to-back performance*

We have first analyzed the BVT of Fig. 4 in a B2B set-up and compared the obtained results with numerical simulations.

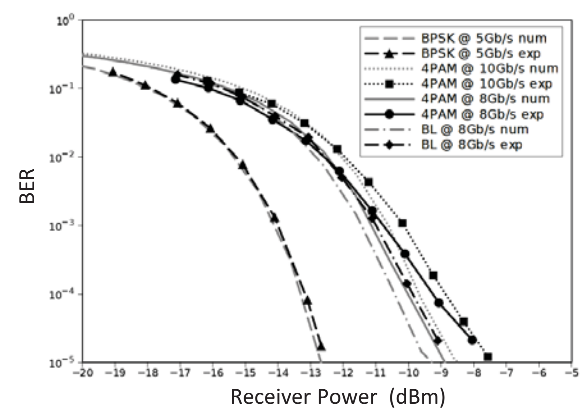


Fig. 5. Back-to-back performance. BPSK, 4PAM and BL are analyzed with numerical simulations (grey curves) and experiments (black curves).

For 5 Gb/s connections, using BPSK format, the experimental BER curves are in good agreement to the simulated ones, as shown in Fig. 5. At the target BER, the experimental curves present approximately 0.5 dB of penalty, with respect to the corresponding numerical curves, when multilevel modulation (either uniform or BL) is used. For uniform 4PAM format at 10 Gb/s and 8 Gb/s, the measured received power at $10^{-3}$ BER is -10.1 dBm and -10.6 dBm, respectively. At 8 Gb/s, the BL scheme shows better performance than uniform 4PAM with reduced bandwidth, requiring -10.9 dBm of receiver power.

### *B. Performance analysis in a photonic mesh network*

After the B2B case, we assess the BVT performance in the ADRENALINE photonic mesh network, which is considered for representing a 4-nodes metro network. Specifically, it consists of two optical cross-connects (OXCs) and two reconfigurable add-drop multiplexers (ROADMs), connected with links of 35 km, 50 km and 150 km, as shown in Fig. 4.

The optical OFDM signal generated at the source node (ideally the BRAS) is routed towards one of the network ROADM through optical paths with 2 hops. The first hop consists of a variable fiber link of either 10 km or 50 km. Optical paths of 45 km, 60 km, 85 km and 100 km are tested, considering the variable first hop and network links of 35 km and 50 km. Results in terms of receiver sensitivity at $10^{-3}$ BER are shown in Fig. 6. BPSK is the most robust modulation format. Thus, it is also successfully transmitted to ROADM-2 through a 3 hops path passing through OXC-2 and OXC-1 for a total length of 195 km, consisting of three links of 10 km, 150 km and 35 km, respectively. The required sensitivity measured at the target BER presents a penalty of only 0.45 dB compared to the case of 2 hops path with length 60 km, which is -13.26 dBm. Using 4PAM format at the same baud rate, the spectral efficiency doubles at the expense of receiver sensitivity and achievable reach. For example, for a path of 60 km with 2 hops, the required receiver power at $10^{-3}$ BER is -8.54 dBm.

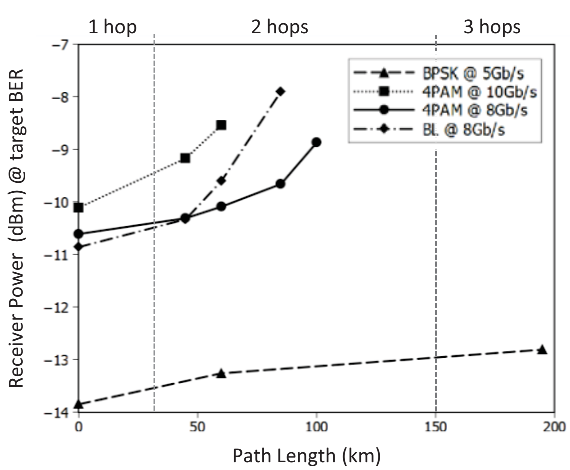


Fig. 6. BVT performance assessment in a photonic mesh network. The receiver power, as a function of the path length and the number of hops, is measured at the target BER of $10^{-3}$ (considering a 7% FEC).

We finally compare the connections at 8 Gb/s, obtained by either implementing adaptive BL scheme with $B_{opt}$=11 GHz, or uniform 4PAM format and reduced bandwidth occupancy ($B_{opt}$=9 GHz). The BL scheme outperforms the uniform approach up to a reach of 45 km with 2 hops. For longer optical path, in order to cope with the accumulated CD, it is convenient to set-up 8 Gb/s connections by reducing the signal bandwidth and select the same modulation format with higher-size constellation (4PAM) for all the subcarriers. In fact, as shown in Fig. 6, this connection can be successfully established through an optical path with 2 hops up to 100 km. In this longest path, a receiver sensitivity of -8.87 dBm is required. Whereas, the longest 2 hops path supporting adaptive BL at 8 Gb/s is 85 km, for which a BER of $10^{-3}$ is achieved with a receiver power of -7.9 dBm. A penalty of 1.76 dB compared to the sensitivity obtained using 4PAM format has been measured at the same bit rate.

## V. Sliceable BVT

The BVT described in Sec. III can be considered as a building block for designing a sliceable BVT (S-BVT). Thanks to this advanced functionality, the transponder consists of a set of virtual transponders able to generate a flow of great capacity [6], which can be suitably sliced as multiple flows direct towards different destination nodes and thus serving multiple MTUs in the evolutionary MAN scenario of Fig. 2.

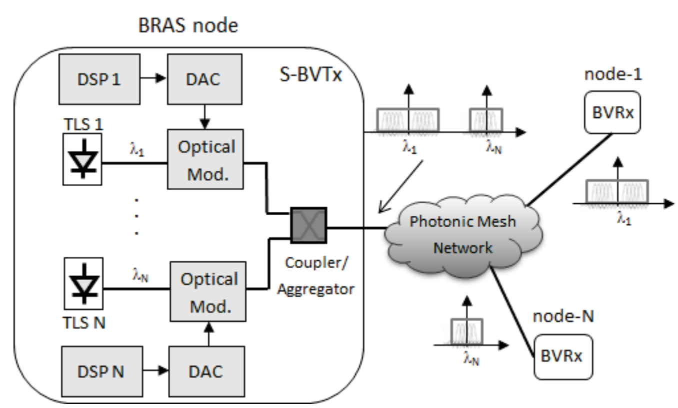


Fig. 7. S-BVT architecture.

A possible architecture that can be used at the BRAS node is described in Fig. 7, where an array of bandwidth variable sub-transmitters generate OFDM signals centered at different optical carriers, according to the wavelength selected at the TLS [13]. In the case of MTU connections, each sub-transmitter can be designed to have a capacity of 10 Gb/s, which can be varied (according to rate/distance adaptive strategy) with subwavelength granularity, thanks to the OFDM modulation. To further enhance the transponder capacity and reduce the number of optoelectronic devices, multi-band OFDM signals can be transmitted with cost-effective DD scheme [14]. The total S-BVT capacity is given by the contribution of all the rate/bandwidth variable sub-transmitters. The aggregated flow at the BRAS can be routed as sliced data flows with less capacity towards different destination nodes, as shown in Fig. 7.

At the destination node, the (sliced) data flow is received to be correctly demapped. In case of receiving an aggregated data flow (e.g. at the BRAS S-BVRx), it is distributed to the sub-receiver array and parallel processed [13].

### A. *Proof of concept*

In order to prove the sliceable capability of the proposed BVT, the set-up reported in Fig. 8 has been implemented. Specifically, two optical OFDM signals at half of the maximum rate capacity of the BVT are transmitted, selecting BPSK format and an electrical bandwidth of 5 GHz at the DSP. The two data flows are generated using two tunable laser sources at $\lambda_1$=1550.12 nm and $\lambda_2$=1550.92 nm, respectively. Since the modulation is performed by a single MZM, two identical signals at 5 Gb/s with optical bandwidth $B_{opt}$=11 GHz are obtained, as indicated in the inset of Fig. 8.

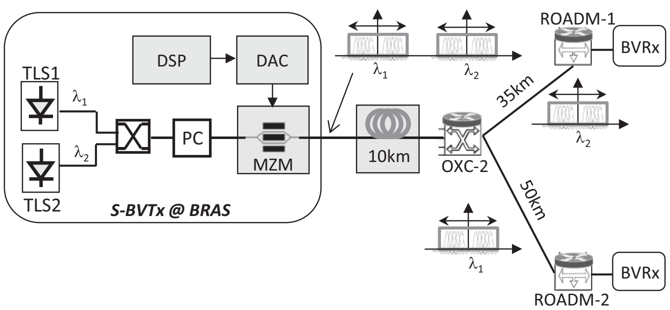


Fig. 8. Experimental set-up: the S-BVT is located at the source node (ideally the BRAS) and two slices of the aggregated flow are received at two destination nodes (ROADM nodes of the ADRENALINE network).

After passing the first hop, consisting of a fiber spool of 10 km (G.652), they are selectively switched at the OXC towards two different ROADMs of the ADRENALINE network. After a second hop of 35 km and 50 km, respectively, both signals have been correctly detected, considering a 7% FEC. In particular, for ensuring a BER of $10^{-3}$, at ROADM-1, the measured receiver power of the signal at $\lambda_2$ is -13.1 dBm. At ROADM-2, for obtaining the same target BER, the received power of the signal at $\lambda_1$ is -13.35 dBm.

Therefore, the proposed cost-effective BVT based on DD-OFDM can be a suitable solution for flexi-grid metro networks.

## VI. Conclusion

A cost-effective BVT design has been numerically and experimentally assessed for targeting flexi-grid metro networks. Limiting factors, such as PAPR, available bandwidth, dispersion impairments and linearity of the subsystem components have been taken into account in the BVT design guidelines. Bit loading schemes and guard band minimizing are proposed for distance adaptive transmission, considering up to 10 Gb/s connections and 12.5 GHz channels. To provide higher capacity and flexibility for serving several MTUs, the proposed BVT can be used as a building block for future sliceable transponder to be co-located at the BRAS node.

Towards a centralized BRAS scenario, for enabling more robust transmission along longer optical paths, advanced optical OFDM-based BVT architectures can be designed. Enhanced DSP can also be implemented, using for example optimized algorithm for bit and power loading. These improvements are at the expenses of increasing the S-BVT cost and complexity and should be carefully analyzed for future flexi-grid MAN.

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## References


[1] M. Jinno, H. Takara, B. Kozicki, Y. Tsukishima, Y. Sone, and S. Matsuoka, "Spectrum-efficient and scalable elastic optical path network: architecture, benefits, and enabling technologies," *IEEE Commun. Mag.*, vol. 47, no. 11, pp. 66–73, 2009.

[2] IDEALIST project deliverable D1.1: "Elastic optical network architecture: reference scenario, cost and planning," June 2013.

[3] C. Rottondi, M. Tornatore, F. Puleio, S. Raavi, A. Pattavina, and G. Gavioli, "On the benefits of elastic transponders in optical metro networks," in *Proc. OFC*, Mar. 2012.

[4] M. Svaluto Moreolo, J. M. Fàbrega, F. J. Vílchez, L. Nadal, V. López, G. Junyent, "Experimental validation of an elastic low-complex OFDM-based BVT for flexi-grid metro networks," in *Proc. ECOC*, paper We.C1.4, 2013.

[5] W. Shieh and I. Djordjevic, "Orthogonal Frequency Division Multiplexing For Optical Communications", Elsevier, 2010.

[6] O. Gerstel, et al., "Elastic optical networking: a new dawn for the optical layer?," *IEEE Commun. Mag.,* Vol. 50, s12-s20, Feb. 2012.

[7] R. Muñoz, et al. "The ADRENALINE Testbed: Integrating GMPLS, XML and SNMP in transparent DWDM networks," *IEEE Commun. Mag.*, Vol. 43, pp. s40-s48, Aug. 2005.

[8] "ITU-T Recommendation G.694.1, Spectral grids for WDM applications: DWDM frequency grid." Feb. 2012.

[9] M. Svaluto Moreolo, J. M. Fàbrega, J. Vílchez, L. Nadal, and G. Junyent, "Experimental Demonstration of a Cost-Effective Bit Rate Variable IM/DD Optical OFDM with Reduced Guard Band," *Opt. Express*, Vol. 20, B159-B164, 2012.

[10] L. Nadal, M. Svaluto Moreolo, J. M. Fabrega, and G. Junyent, "Clipping and quantization noise mitigation in intensity-modulated direct detection O-OFDM systems based on the FHT", in *Proc. ICTON*, paper We. B1.5, 2012.

[11] B. Lin, et al. "Comparison of DSB and SSB Transmission for OFDM-PON," *J. Opt. Commun. Netw.,* Vol. 4, pp. B94-B100, Nov. 2012.

[12] L. Nadal, M. Svaluto Moreolo, J. M. Fàbrega, G. Junyent, "Adaptive Bit Loading in FHT-based OFDM Transponder for Flexi-Grid Optical Networks", in *Proc. ICTON*, paper Tu.D1.5, 2013.

[13] M. Jinno, Y. Sone, H. Takara, A. Hirano, K. Yonenaga, and S. Kawai, "IP traffic offloading to elastic optical layer using multi-flow optical transponder", in *Proc. ECOC*, Paper Mo.2.k.2, 2011.

[14] W.-R. Peng, *et al*. "Transmission of high-speed (>100 Gb/s) direct-detection optical superchannel," *J. Lightw. Technol.,* Vol. 30, pp. 2025-2034, June 2012.