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Article

Programmable Adaptive BVT for Future Optical Metro Networks Adopting SOA-Based Switching Nodes

Laura Martín González ^{1,*} , Sjoerd van der Heide ², Xuwei Xue ², John van Weerdenburg ², Nicola Calabretta ², Chigo Okonkwo ², Josep M. Fàbrega ¹ and Michela Svaluto Moreolo ^{1,*}

¹ Centre Tecnològic de Telecomunicacions de Catalunya (CTTC/CERCA), 08860 Castelldefels, Barcelona, Spain; jmfabrega@cttc.es

² Electrical Engineering Department, Technische Universiteit Eindhoven (TU/e), 5600 MB Eindhoven, The Netherlands; s.p.v.d.heide@tue.nl (S.v.d.H.); X.Xue.1@tue.nl (X.X.); J.J.A.v.Weerdenburg@tue.nl (J.v.W.); n.calabretta@tue.nl (N.C.); cokonkwo@tue.nl (C.O.)

* Correspondence: laura.martin@cttc.es (L.M.G.); msvaluto@cttc.es (M.S.M.)

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Abstract: Adaptive Sliceable-Bandwidth Variable Transceivers (S-BVTs) are key enablers for future optical networks. In particular, those based on Discrete MultiTone (DMT) modulation and Direct Detection (DD) can be considered a flexible solution suitable to address the cost efficiency requirement of optical metro networks. In this paper, we propose to use a cost-effective S-BVT option/implementation in optical metro networks adopting switching nodes based on Semiconductor Optical Amplifier (SOA) technology. Bit loading (BL) and power loading (PL) algorithms are applied to the Digital Signal Processing (DSP) modules, to maximize the performance and/or the capacity as well as enhance the flexibility and adaptability of the system. Our analysis considers switching nodes based on SOAs with and without filtering elements and fiber spans of 25 km. We present the results up to 100 km, with and without SOA-based nodes. Firstly, we analyze the adaptive BVT transmission using the Margin Adaptive (MA) BL/PL algorithm at a fixed bit rate of 28 Gb/s. The possibility of controlling the SOAs current is a key factor to face the transmission impairments due to the fiber and the filtering elements. We also analyze the system considering Rate Adaptive (RA) transmission at a fixed target Bit Error Rate (BER) of 3.8×10^{-3} , showing that a maximum capacity above 34 Gb/s can be achieved for a single span of 25 km. Although the cascading of filtering elements still constitutes a limiting factor, we show that an improvement of the net bit rate performance can be obtained thanks to the combined use of BVT and SOA technology at the switching nodes, resulting in a promising approach for designing future optical metro networks.

Keywords: optical metro networks; Bandwidth Variable Transceivers (BVT); Orthogonal Frequency Division Multiplexing (OFDM); Semiconductor Optical Amplifier (SOA)

1. Introduction

New challenges are envisioned for future optical networks to cope with the exponential and uncertain growth of internet traffic. In particular, the metro segment is emerging as the most challenging, due to the stringent requirements of cost efficiency and reduced power consumption, while offering very high capacity and dynamicity. To address these challenges, optical metro networks need to be equipped with flexible, adaptive, and programmable transmission and switching systems able to efficiently manage the available resources as well as the high peak of traffic and adaptive bit rates with cost- and power-efficient solutions [1,2].

In particular, to overcome the increasing traffic demand, programmable adaptive transceivers have been proposed as a suitable transmission technology [3]. In dynamic future optical networks, adaptability, flexibility, and programmability are of great importance, especially if deployed fiber infrastructure wants to be exploited. These requirements can be dealt with using Sliceable-Bandwidth Variable Transceivers (S-BVTs) [3]. They allow the generation of multiple flows while suitably and flexibly adapting the transmission in terms of bit rate, modulation formats, bandwidth, and reach. Multiple parameters and S-BVT components can be suitably configured on demand by means of an integration of the transceiver in a Software-Defined Networking (SDN) control plane, following the SDN principles [4]. In particular, an S-BVT based on Orthogonal Frequency Division Multiplexing (OFDM) offers the possibility to manage the capacity/spectrum at the subcarrier level [3,5,6]. The S-BVT architecture can be suitably tailored for the metro network segment [7]. For a cost-effective design Discrete MultiTone (DMT) modulation is preferred as the simplest OFDM implementation [5,6].

Optical networking based on Wavelength Selective Switch (WSS) technology has been studied in [8] for the future adoption of an elastic optical network. In fact, using flexi-WSS at the network nodes the optical spectrum can be used more flexibly and efficiently [8]. However, a significant source of penalty is caused by the transmission through a cascade of nodes. This effect, known as the filter narrowing effect, has been analyzed in [8,9]. In the context of elastic optical networks, Semiconductor Optical Amplifier (SOA) technology can be advantageously used, particularly for the metro segment, where the cost and power consumption are critical issues. In fact, the main advantages of using SOAs are the low power consumption, low cost, small size, and the possibility to be integrated with other optical components [10]. On the other hand, SOAs have high noise value compared to Erbium Doped Fiber Amplifier (EDFA) and have residual polarization-dependent operation <1 dB [11]. However, some studies focus on the reduction of these impairments, as in [12]. SOAs can be designed to deploy building blocks for optical switching as well as a booster amplifier, inline amplifier, or preamplifier [13,14]. By carefully adjusting the current injected into the SOA, it can be used as an optical amplifier; meanwhile, by turning on/off the electrical current, the SOA can act as a fast optical gate. Furthermore, SOAs can be used for wavelength selective applications by combining them with wavelength-filtering technologies [10]. In this work, we focus on the role of SOAs as building blocks in optical switching technologies [13]. In particular, we consider an SOA-based switching node with and without filtering elements. In the last case, the switching functionalities are performed by the SOAs and can also find application in filterless optical networks [15]. Filterless optical networks are simple network architectures based on passive splitters and combiners avoiding optical filters. Thus, they are more cost-effective than networks adopting filters; however, some functionalities are limited, such as wavelength reuse or capacity at high utilization rates [8,15]. In [15], a comparison between the filterless option and active switching, in terms of cost and performance, is provided. In the case where SOAs are combined with wavelength-filtering technologies, we consider SOA-based wavelength selectors as part of the Optical Add/Drop (OAD) nodes. These nodes have the capacity to insert or drop traffic to the optical network, by means of a SOA array with a splitter, a combiner and filtering elements based on Wavelength Division Multiplexing (WDM) technology [13]. WDM technology allows the multiplexing of multiple signals with different optical carrier wavelengths. In visible light communications, the performance of WDM technology is limited due to transmission losses [16,17]. Some studies propose the design of a novel 1×4 optical demultiplexer based on multimode interference [16] or the design of 1×4 silicon-alumina wavelength demultiplexer based on multimode interference [17], to overcome this problem. In the range of C band for optical communications, an 8-channel wavelength multimode demultiplexer is demonstrated to work with low cross-talk [18]. WDM cross-connect switches combined with SOA technology have been assessed in [10,19] for optical data center networks. The system is validated considering three different types of modulation formats, such as Non-Return Zero-On Off Keying (NRZ-OOK), Pulse Amplitude Modulation (PAM) and DMT. Potential lossless operation and low cross-talk (<-30 dB) has been

demonstrated. Using BVTs, the bandwidth and bit rate can be dynamically adjusted by adopting a modulation format per each subcarrier. Therefore, more flexibility and adaptability can be obtained [7].

In this paper, we propose a combined use of BVT and SOA technologies to design flexible and cost-effective solutions for future optical metro networks. Bit loading (BL) and power loading (PL) algorithms can be implemented in the transceiver Digital Signal Processing (DSP) module, to enhance the capacity, adaptability, and the resilience towards transmission impairments [5,6].

We will present preliminary results on the use of BVT in the context of elastic optical metro networks with switching nodes based on SOA technology, particularly analyzing the case of a cost-effective implementation of the BVT.

The paper is organized as follows. In Section 2, the S-BVT and its cost-effective implementation are described. Then, in Section 3 further details on optical metro network adopting switching nodes based on SOA technology are provided. In Section 4, we present the proposed system, adopting BVT and SOA technology. The experimental setup and system optimization are presented. In Section 5 the results obtained are discussed for the different analyzed scenarios and finally the conclusions are drawn in Section 6.

2. S-BVT Architectures Tailored for Optical Metro Networks

The S-BVT is a key element in elastic optical networks since it supports programmable functions and multi-adaptive, software-defined optical transmission. In fact, a multi-rate, multi-format, multi-reach, and multi-flow transmission is enabled on demand with sub- and super-wavelength granularity thanks to the SDN programmability and S-BVT functionalities/capabilities [6]. The slice-ability concept confers more flexibility to the BVT since it implies the capability of aggregating and distributing different flows. Furthermore, the adoption of OFDM at the DSP offers the possibility to load the subcarriers individually, according to the channel profile [3,5,6]. Hence, the spectrum can be optimized according to the traffic demand. Figure 1 shows a modular S-BVT architecture composed by N BVT modules. The multiple flows are aggregated/distributed at the output of the array of the N BVTs by an additional element using, for example, a bandwidth variable WSS, which can be implemented in Liquid Crystal on Silicon (LCoS) technology or can be a simple and cost-effective passive element, implemented for example in Planar Lightwave Circuit (PLC) [6,20].

To design the optoelectronic front-ends for an S-BVT, we can consider simple architectures using Direct Detection (DD) receivers. Several possibilities considering the DMT modulation can be used including Single Side Band (SSB) or Vestigial Side Band (VSB) modulations [5,21]. On the other hand, we can adopt more complex S-BVT using coherent detection, also combined with simple DMT transmission, as it has been demonstrated in [7]. For the experiments, we consider a single BVT. For a cost-effective solution, the BVT proposed is based on DMT, as the simplest version of the OFDM, and simple DD. Despite the simplicity of DMT, the Chromatic Dispersion (CD) can limit the system performance due to the transmission over the fiber [5]. At the increase of the fiber length, the impact of the CD is higher. As a result, various subcarriers, corresponding with certain frequencies, are highly attenuated. The frequencies where the attenuation peak appears, depends on the speed of light, the center wavelength, the fiber length, or the dispersion parameter as it is explained in Section 4. To mitigate this effect loading algorithms can be implemented to adapt the modulation format to the channel profile [5].

In DMT system, Hermitian Symmetry (HS) is forced on the input of the Inverse Fast Fourier Transform (IFFT) obtaining a real signal [5]. Thus, the complexity of the DSP module is reduced. The main building blocks of a DMT-based BVT are illustrated in Figure 1. At the Transmitter (Tx), the input data is parallelized. After that, the signal is mapped adapting loading using Binary Phase-Shift Keying (BPSK) and M-ary Quadrature Amplitude Modulation (M-QAM) or with uniform loading, using 4-QAM. According to the Signal-to-Noise Ratio (SNR) profile, estimated at the Receiver (Rx), with a uniform loaded probe signal, the DMT subcarriers are modulated at the transmitter side using BL and PL algorithms. The algorithms can be implemented under two criteria. The Margin

Adaptive (MA) criterion considers fixed bit rate and energy minimization and the Rate Adaptive (RA) criterion considers a fixed energy for bit rate maximization [5,22].

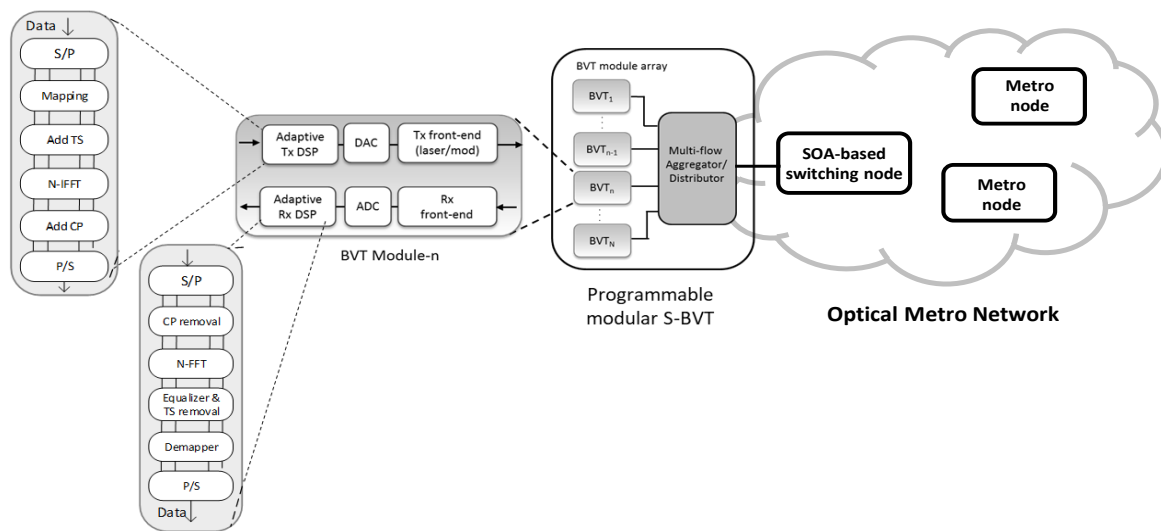


Figure 1. S-BVT architecture based on adaptive DSP using DMT for optical metro networks with SOA-based switching nodes. The S-BVT is programmable and composed by an array of BVT modules.

Training Symbols (TS) are added for zero-forcing equalization at the receiver side. Then, the IFFT is performed forcing the HS, the Cyclic Prefix (CP) is included, the signal is serialized (P/S) and finally it is symmetrically clipped (CLIP) [5]. After that, the digital signal is converted from digital to analog by means of a Digital to Analog Converter (DAC). The Tx optoelectronic front-end consists of an external modulator and a Tunable Laser Source (TLS), for arbitrary wavelength selection. At the Rx side, the signal is photo-detected by a DD optoelectronic front-end and converted from analog to digital by an Analog to Digital Converter (ADC). Finally, the signal is processed by the receiver DSP module. Thereby, the signal is firstly parallelized (S/P), then the CP is removed. After that, the Fast Fourier Transfer (FFT) is performed considering that the signal has HS, it is equalized, and the TS are removed. Finally, the signal is demodulated and serialized to obtain the original data.

3. SOA Technology for Optical Metro Network Nodes

SOA technology can be adopted for implementing switching devices. There are other optical switching technologies based on Electro-Optic, Acousto-Optic, Thermo-Optic or Opto-Mechanical switching. The main advantages of SOAs with respect to these other switching technologies are the loss compensation, the high speed, and the scalability [13]. When several switches are in cascade, SOAs can control the gain with the injected current and, depending on the node architecture, overcome the limitation due to the power decay. As losses due to the network elements can be compensated thanks to the presence of SOAs, this switching option can be envisioned also for applications in filterless optical networks. This would represent a cost-effective solution [15], as active reconfigurable components are eliminated or minimized using passive optical elements as combiners or /and splitters to interconnect the fiber links and to add or drop channel wavelengths at the nodes. Some advantages are expected for these networks such as simplified maintenance or reconfigurability. However, in a filterless optical network we must consider the related drawbacks and limitations. In this scenario, the use of SOA-based switching nodes combined with BVT technology can be advantageous. SOA-based switching nodes can be useful to compensate the attenuation, due to the passive elements and the transmission over the fiber, and BVT with loading capabilities, to combat the CD.

On the other hand, a generic filtered optical mesh network is equipped with OAD multiplexer, placed at the nodes, enabling to dynamically configure the dropping or adding of different wavelengths

through the fiber, remotely. Typically, the reconfigurable OAD nodes adopt WSS technology. Particularly, in the context of elastic optical networks, flexible WSS are needed to deploy a more flexible and bandwidth efficient network [8]. The main disadvantage of this solution is the penalties in signal degradation due to the filter narrowing effect caused by the crossing through a cascade of WSS [8], as it was mentioned in Section 1. The use of S-BVT can flexibly adapt the transmission.

In this work, SOA-based wavelength selectors are considered as the key element in OAD nodes to drop and add traffic in the network [13,23]. WDM optical cross-connect based on SOA has also been presented in [10] for interconnecting network elements, computing, or storage resources in a metro network architecture. It has been experimentally demonstrated the potential lossless, low cross-talk or multicasting operation of these network elements.

In our study, we analyze the performance when the OAD nodes with SOA-based wavelength selectors are included, being the target the metro segment. The OAD node consists of one splitter, one combiner, the SOA array for gating one or more wavelengths and two wavelength selectors. One acting as a demultiplexer and the other acting as a multiplexer. In the proposed system, the filter narrowing effect is also present due to the concatenation of the wavelength selectors [8]. The architecture of the SOA-based OAD node can be seen in Figure 2. In this case, losses are generated by the transmission over the fiber links and the filtering elements as well. Adjusting the SOA bias current, the filtering effects mainly due to the wavelength selectors and the losses due to the fiber, can be compensated.

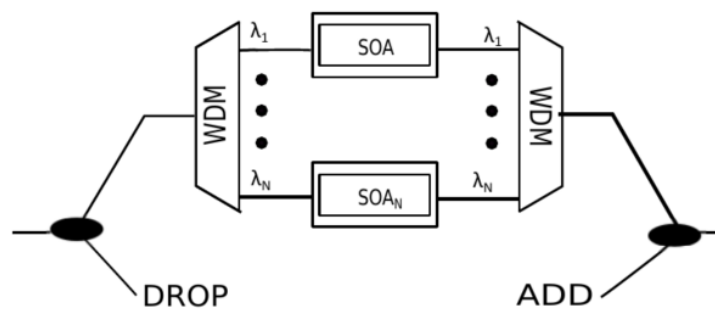


Figure 2. Architecture of a SOA-based OAD node.

4. BVT with Switching Nodes Adopting SOA Technology: Experimental Setup and Optimization

We propose to adopt the S-BVT described in Section 2 for optical metro networks adopting SOA-based switching nodes. In particular, for the experiments the simplest BVT architecture using DMT and DD is considered attractive for a cost-effective implementation and, thus, it is envisioned to be used when SOA technology is adopted for the switching nodes.

To analyze the performance of this approach, two scenarios are considered as shown in Figure 3. Both scenarios consider spans of 25 km of fiber and different cascading nodes; scenario (a) envisions the use of a simple SOA acting as switching node, while scenario (b) introduces OAD nodes based on SOA technology, as specified in Figure 2 and Section 3. As a reference, the case of multiple (up to 4) fiber spools of 25 km, without any SOA is analyzed as well. The scenario without considering filtering elements (filterless) is analyzed to study the impact on the system performance at different transmission distances with and without SOAs. Then, we analyze the case of SOA-based OAD nodes after each span of fiber. To evaluate the proposed system, the setup of Figure 2 has been considered. The WDM consists of 32 channels with a channel spacing of 100 GHz. However, for the experiments only the 1550.12 nm channel has been studied. It is marked by the red color in Figure 3. Thus, the signal traverses the first WDM acting as a demultiplexer, the SOA and finally the signal is multiplexed by the second WDM.

To experimentally analyze the proposed system, the setup of Figure 3 has been considered. A single BVT, based on DMT and DD, transmits over the cascading of fiber spools of 25 km and SOA-based switching nodes according to scenario (a) or scenario (b).

Python software has been used at the DSP module. The IFFT with 512 subcarriers modulates the mapped sequence. Due to the HS, only half of the IFFT subcarriers supports data. The total number of frames is 125 being 5 of them TS. The CP is 1.9% and the Forward Error Correction (FEC) considered is 7%. As it is well-known, the clipping factor can cause distortions and the degradation of the system performance. For this reason, the best clipping level should be selected according to the adopted constellation format. To estimate the channel profile, uniform loading is adopted, in particular 4-QAM. The clipping level recommended for this modulation format is 7 dB, which corresponds to a clipping factor of 2.24. When other modulation formats are used, 7 dB can be not enough. The clipping level must be selected according to the highest modulation format, when BL is used. In our case, the highest modulation format used in this experiment is 16-QAM. Accordingly, we have determined that the best clipping level is 8.5 dB giving a clipping factor of 2.6. The sample rate of the DAC is 28 GS/s.

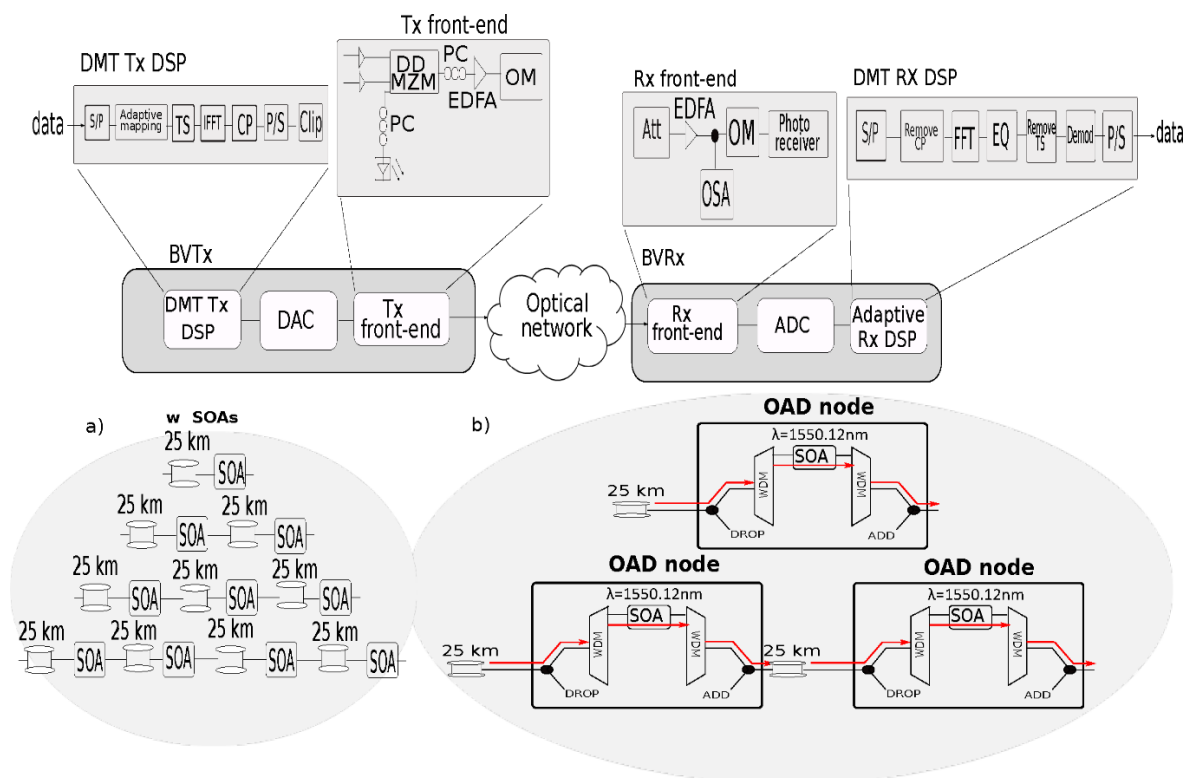


Figure 3. BVT architecture and experimental setup. OM: optical power monitoring, Att: Attenuator, OSA: Optical Spectrum Analyzer, EQ: Equalizer. The different analyzed scenarios for the optical metro network are indicated: (a) with SOAs and 25 km Single Standard Mode Fiber (SSMF) spools, and (b) with OAD nodes based on SOAs.

The obtained electrical signal is the input of a Dual Drive Mach-Zehnder Modulator (DD-MZM). The DD-MZM is working in the push-pull operation. The laser driving the DD-MZM is centered at 1550.12 nm with 13 dBm of output power. As the DD-MZM is polarization dependent, a Polarization Controller (PC) is needed to obtain the maximum power of the laser driving the DD-MZM. Another PC is at the output of the DD-MZM. With those PCs we can control the power at the input of the EDFA, obtaining a power value of 1.5 dBm at the input and 13 dBm at the output of the EDFA. Then, the power launched to the network is measured by an optical power monitor (OM). At the receiver, an attenuator followed by an EDFA is used to vary the Optical Signal-to-Noise Ratio (OSNR). After that, another OM

is placed for being able to ensure a constant power at the input of the photodetector. The sample rate of the ADC is 80 GS/s. The OSNR is measured within 0.1 nm and the target BER is set to 3.8×10^{-3} . The fiber spans are Single Standard Mode Fiber (SSMF) of 25 km each, with 0.2 dB/km of attenuation.

A probe signal modulated with uniform loading (4-QAM) is sent to the channel to estimate the SNR profile at the receiver side. To calculate the SNR, a sliding window method is used. We name the number of samples taken after or before the subcarrier considered, as Window Size (WS). The total number of the subcarriers considered for calculating the mean is given by $TW = WS \cdot 2 + 1$ where TW is the total size of the window. Figure 4 shows the optimization for 75 km (3 spans of 25 km of SSMF). We can see that the minimum BER is achieved by a WS of 4 (meaning 4 subcarriers taken after and 4 subcarriers taken before the subcarrier considered) that corresponds to a TW size of 9.

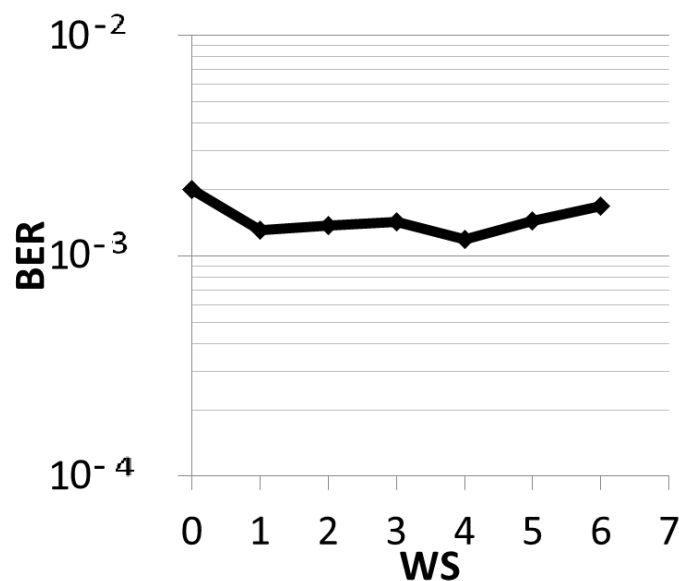


Figure 4. BER versus WS for 75 km (3 spans of 25 km of SSMF) and OSNR of 36 dB without considering any SOA placed inline.

As an example, the SNR estimation for the different scenarios with and without SOAs and with SOA-based OAD is shown in Figure 5a considering two spans of 25 km for a total of 50 km of fiber. There it is possible to observe a degradation of the SNR around the 156th subcarrier, which is due to the CD. This attenuation depends on the fiber length and appears at certain frequencies that are given by the expression

$$f^n = \sqrt{\frac{c(2n-1)}{2\lambda^2 LD}} \tag{1}$$

being c the speed of light, λ the center wavelength, L the fiber length, D the dispersion parameter and n the n -th attenuation peak (positive integer).

When the SOAs are included, this peak suffers a shift of around 10 subcarriers towards the lower frequencies. The maximum obtained SNR decreases 1 dB, but the SNR profile is similar. This frequency shift, with respect to the theoretical frequency, is due to the variation of the injected current of the SOAs to find the best working point. In our case study, the best conditions are achieved for a SOA input power of -8 dBm and an injected current within 60 mA and 80 mA.

When the SNR profile is estimated for the case using SOA-based OAD nodes, the maximum SNR decreases down to 14 dB, and the fading frequency peak is shifted to higher frequencies, where the minimum SNR is about 6.5 dB. In this case, the cascading of network elements, in particular the presence of filtering elements, causes the reduction of the obtained SNR for all the subcarriers and the shift of the fading peak. Indeed, for this case, the peak fading is not so pronounced as in the case

without filtering elements and it covers a greater number of subcarriers (from the 120th to the 200th approximately). According to the SNR profile, the subcarriers for each scenario are modulated at the transmitter side using BL/PL algorithms. Figure 5b shows the bit distribution according to the SNR estimation in Figure 5a and considering the MA criterion with a fixed gross bit rate of 28 Gb/s at 34 dB of OSNR. It can be seen that the modulation format order decreases with the reduction of the SNR values and increases with the increase of the SNR values. For the OAD scenario, since the SNR profile is more affected by the fiber impairments (CD) and the filtering elements, lower bits per symbol are loaded onto the subcarriers. In Figure 5c, the PL distribution according to the SNR profile is presented. It can be seen that the subcarriers corresponding to the lower SNR values for the case with SOAs do not have power assigned. For the OAD scenario, all the subcarriers have power assigned and the power variation corresponds to the change from one modulation format to another. In Figure 5d, the BER per subcarrier for the different analyzed cases is reported. We can observe that for the OAD scenario, the subcarriers affected by CD present high number of errors.

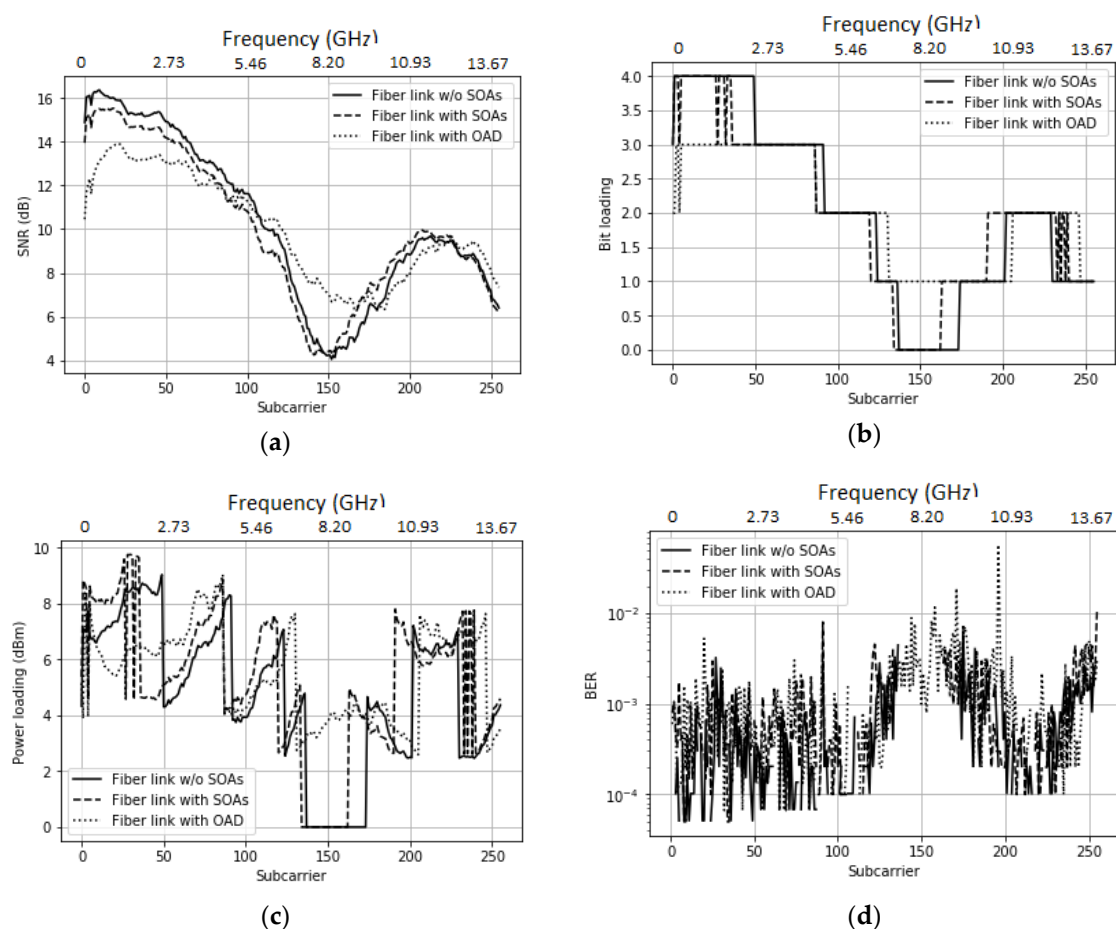


Figure 5. (a) SNR profile, (b) BL assignment, (c) PL assignment and (d) BER per DMT subcarrier considering MA transmission at 28 Gb/s over two SSMF spans of 25 km, with and without SOAs and for SOA-based OAD, at 34 dB of OSNR.

5. Results and Discussion

As shown in Figure 3 and detailed in Section 4, the experimental analysis considers two scenarios: the first using simple SOAs acting as switching nodes and the second adopting OAD nodes based on SOA technology. Fiber spans of 25 km until a maximum of 4, for a total path of 100 km, are considered. In particular, to observe the impact of adopting the SOAs in the system, we place an SOA after each

span of fiber and compare the results with the transmission over the fiber link without them. To analyze the second scenario, we consider SOA-based switching nodes based on the OAD node architecture of Figure 2. For both scenarios, the current injected into the SOA is properly varied to compensate the losses due to the fiber impairments or/and the different elements (splitters, combiners, filtering elements) of the OAD node.

First, we analyze the case at fixed bit rate (28 Gb/s) using the MA BL/PL algorithm for maximizing the performance. The BER performance at the varying of the OSNR is presented in Figure 6. It is interesting to observe that a similar behavior is obtained for 75 km (3 spans) of fiber without SOAs, 50 km (2 spans) of fiber with an SOA after each span and one fiber span of 25 km with an OAD node, being the difference between these cases lower than 1 dB at the target BER of 3.8×10^{-3} . Similar results are obtained when we compare the BER curves for 100 km (4 spans) of fiber, 75 km (3 spans) of fiber with an SOA per each span and 50 km (2 spans) of fiber including 2 OAD nodes (one after each span), being as well the penalty less than 1 dB, at the target BER. Up to 100 km (4 fiber spans) can be reached by cascading 4 SOAs with an OSNR value of 33 dB. It was not possible to retrieve results after 75 km (3 spans) with the OAD nodes because of the losses accumulation, mainly due to the filtering elements, and the noise introduced by the SOAs. The introduction of OAD nodes involves losses around 4 dBm per each WDM element and 1 dBm per each combiner/splitter.

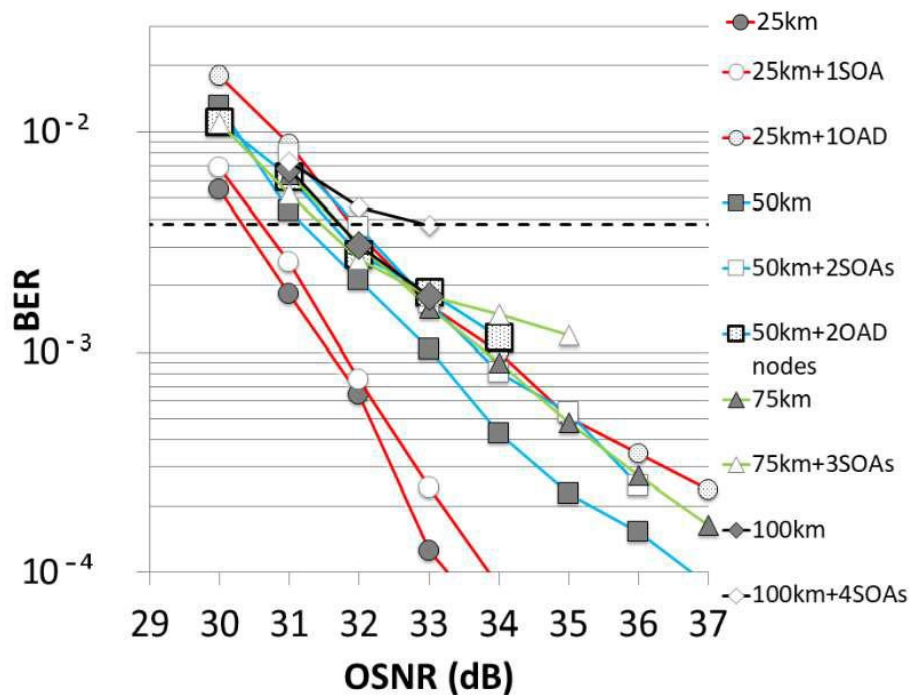


Figure 6. BER versus OSNR (with and without SOAs and including SOA-based OAD nodes) using BL and PL under the MA criteria for a fixed gross bit rate of 28 Gb/s.

Then, we have studied the maximum achievable net bit rate, adopting the RA BL/PL algorithm, for different transmission distances and scenarios considering at a fixed target BER of 3.8×10^{-3} . In Figure 7, the results at 33 dB of OSNR, are presented. We can see that, as the fiber length increases, the maximum net bit rate decreases, being more pronounced for the case of fiber transmission without SOAs. In fact, for the 50 km (2 spans) of fiber, the maximum net bit rate is obtained when 2 SOAs or 2 SOA-based OAD nodes are included in the optical path, obtaining 26.5 Gb/s. The value of the net bit rate when only 2 spans of fiber are placed inline, is lower, being its value 26.1 Gb/s. Therefore, the introduction of the SOAs, as switching nodes themselves or either as part of the OAD node, improves the net bit rate performance at least for fiber links higher than 50 km. In fact, there is an

improvement of 2 Gb/s when 75 km of fiber links and 3 SOAs are included, with respect to the case when the fiber links do not include the SOAs. This is due to the possibility of better optimizing the transmission by controlling the current injected into the SOAs, in combination to the transceiver adaptability by means of the BL/PL algorithm. According to the obtained results, a 26 Gb/s connection can be supported up to 50 km considering 2 cascading SOA-based OAD nodes and a maximum of 27 Gb/s for 75 km considering 3 cascading SOAs without filtering elements.

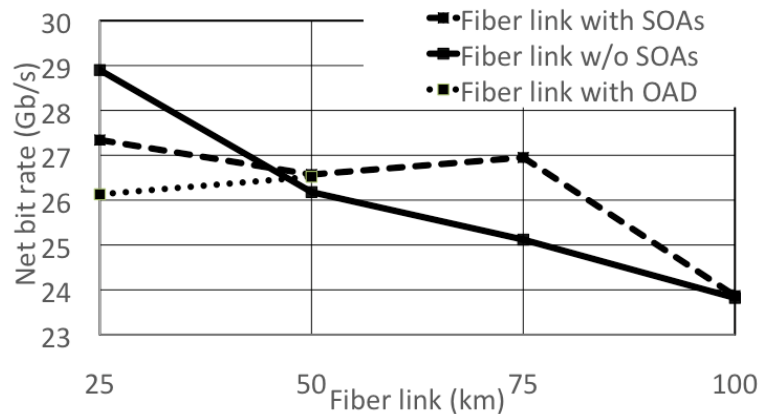


Figure 7. Net bit rate versus fiber link (with and without SOAs and including SOA-based OAD nodes), using RA BL/PL algorithm, for an OSNR of 33 dB at a target BER of 3.8×10^{-3} .

Table 1 shows the maximum achievable net data rate at different transmission distances for the considered scenarios adopting RA BL/PL. Please note that the maximum net bit rate of 37.32 Gb/s is achieved for 25 km of fiber when the SOAs are not included. On the other hand, the net bit rate penalty between the cases of 25 km of fiber and 100 km of fiber is greater (12.25 Gb/s of difference), when the SOAs are not included than when the SOAs are added (10.7 Gb/s of difference). Therefore, there is a reduction of the penalties, when SOAs are included. Therefore, also in this case, the current injected into the SOAs is a key factor to control the penalties when multiple fiber links and SOAs are in cascade.

Table 1. Achievable net bit rate and maximum OSNR for different transmission distances using RA BL/PL algorithm, for different fiber link with and without SOAs and considering SOA-based OAD.

Reach (km)	Fiber Link w/o SOAs	Fiber Link with SOAs	Fiber Link with OAD
	Net Bit Rate (Gb/s)	Net Bit Rate (Gb/s)	Net Bit Rate (Gb/s)
25	37.32	34.57	34.77
50	33	31.78	27.97
75	31.4	27.68	-
100	25.07	23.87	-

In case of considering SOA-based OAD nodes, the net bit rate decrease is greater than the case of using only SOAs. However, the maximum net bit rate achievable after 25 km of fiber is similar: 34.57 Gb/s and 34.77 Gb/s, with a simple additional SOA or including an OAD node, respectively. When 2 OAD nodes and 50 km of fiber links are included, the maximum net bit rate is 27.97 Gb/s that is similar to the maximum net bit rate obtained for 75 km of fiber link and 3 SOAs (the difference is 0.29 dB).

In Figure 8a,b the net bit rate versus the OSNR for 25 km and 50 km of fiber are presented. It can be observed that the overlapping between the results of the different scenarios is higher when 2 spans (50 km) of fiber are considered. This is due to the increase of the number of elements in the optical network, either SOAs acting as switching nodes or OAD nodes. In fact, this enables the possibility to

suitably manage (and carefully adjust) the SOAs bias current. Consequently, the system performance can be better optimized. For 50 km transmission distance, the penalties when the SOAs/OAD nodes are included, are minimum (<1 dB). Unfortunately, in this experiment, it has not been possible to further increase the cascading of more OAD nodes. Due to the different filtering elements and the associated noise accumulation, the maximum achievable OSNR was limited [21]. Thus, it was not possible to retrieve results after 75 km with the OAD nodes. However, to target metro network distances, the system can be improved considering other alternatives such as DMT with SSB or VSB modulation [20,21] with DD. In [24], a multi-band SSB-DD system has been studied for a metro-regional network. With this system, 545 km of transmission distance has been demonstrated. Furthermore, DD can be replaced with coherent detection for improving the performance. In [25], DMT transmission and coherent detection has been demonstrated in flexgrid metro networks covering distances up to 150 km. More recently, in [26] two different transceiver configurations have been experimentally validated. One is based on intensity modulation with DD and the other on amplitude modulation with coherent reception for the metro networks. Thus, in future work, different configurations would be addressed to improve the performance.

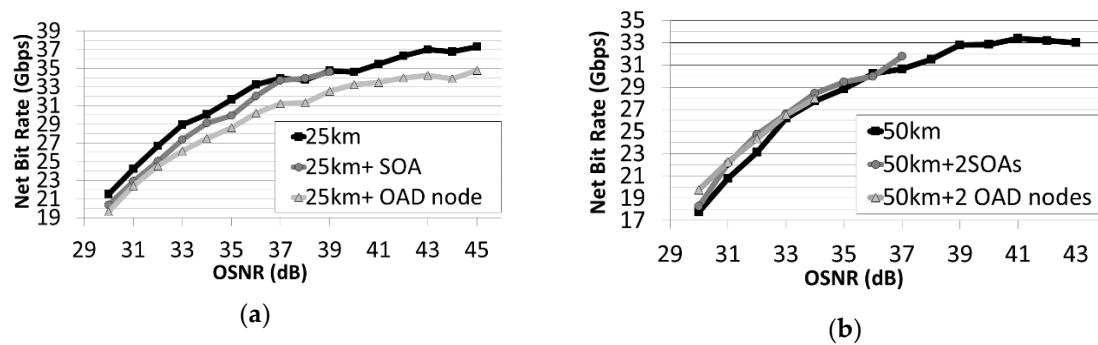


Figure 8. Net bit rate versus OSNR for (a) 25 km and (b) 50 km for the different scenarios at the target BER.

6. Conclusions

In this paper, the use of S-BVTs, based on DMT modulation and DD with adaptive loading capabilities has been proposed as a flexible and adaptive cost-effective solution for future optical metro networks adopting SOA-based switching nodes. A preliminary assessment of this system has been analyzed considering two scenarios: with or without filtering elements. Using loading algorithms for both scenarios, the limitations due to transmission impairments (caused by the CD, DAC bandwidth or the network elements) can be mitigated enabling higher transmission rates and reach.

When BL and PL algorithms are implemented using the MA criterion, the results show that the BER performance obtained for a 25 km of fiber link with an SOA-based OAD node has similar BER performance than the case of 50 km (2 spans of 25 km) of fiber with 2 SOAs acting as switching nodes, or the case of 75 km (3 spans) of fiber. Thus, the introduction of the SOAs or the OAD node, in terms of BER performance, results in an additional span of 25 km of fiber is included.

On the other hand, using the RA criterion, the net bit rate performance improves including SOA elements in the transmission system, compared to the case of simply adding fiber spans. This is due to the possibility of controlling the SOA current to face the transmission impairments. These impairments include the losses due to the fiber links, the SOAs as well as the WDM elements or the splitter/combiners used in the experiments [21]. These losses can be up to 4 dBm for each WDM element. Thus, as the number of SOA-based switching nodes increases, more SOA elements can be controlled, to ensure a better optimization of the system and an improvement of the performance overcoming the power losses due to the different elements in cascade. However, adding SOAs or/and filtering elements limits the maximum achievable OSNR and thus the number of cascading nodes that

can be traversed by the adaptive signal generated by the S-BVT. In particular, 27 Gb/s connections can be supported up to 75 km including 3 SOAs acting as switching nodes without any filtering element, and while 26 Gb/s for 50 km is the maximum achievable reach including 2 OAD nodes.

The experimental assessment demonstrates that thanks to the possibility of controlling the injected current to the SOAs and the application of loading schemes at the adaptive transceivers, high flexibility, scalability, and adaptability can be obtained. However, despite the possibility of compensating the losses thanks to the SOAs, the maximum transmission distance with 2 OAD nodes was 50 km, due to the introduction of the WDM elements and the splitters/combiners. These losses are around 4 dBm for each WDM element and 1 dBm considering each splitter/combiner, meaning that the current injected into the SOA needs to be efficiently controlled to avoid them. Different alternatives must be exploited for this setup to improve the attainable distance including the OAD nodes. OFDM based on SSB or VSB can be adopted with DD to simply maintain architecture [7,20,21,24]. To enhance the impairment tolerance and the achievable distance, coherent detection can also be used as in [25,26].

Monitoring techniques and the SDN paradigm play a key role in enabling these features. The combination of cost-effective implementation of programmable (SDN-enabled) BVT and SOA-based switching nodes seems to be promising for further investigation. In fact, future work in this direction will be carried out to improve the proposed system and target future optical metro networks.

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