SDN control of optical nodes in metro networks for high capacity inter-datacentre links

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SDN control of optical nodes in metro networks for high capacity inter-datacentre links

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ABSTRACT

Worldwide demand for bandwidth has been growing fast for some years and continues to do so. To cover this, mega datacentres need scalable connectivity to provide rich connectivity to handle the heavy traffic across them. Therefore, hardware infrastructures must be able to play different roles according to service and traffic requirements. In this context, software defined networking (SDN) decouples the network control and forwarding functions enabling the network control to become directly programmable and the underlying infrastructure to be abstracted for applications and network services. In addition, elastic optical networking (EON) technologies enable efficient spectrum utilization by allocating variable bandwidth to each user according to their actual needs. In particular, flexible transponders and reconfigurable optical add/drop multiplexers (ROADMs) are key elements since they can offer degrees of freedom to self adapt accordingly. Thus, it is crucial to design control methods in order to optimize the hardware utilization and offer high reconfigurability, flexibility and adaptability. In this paper, we propose and analyze, using a simulation framework, a method of capacity maximization through optical power profile manipulation for inter datacentre links that use existing metropolitan optical networks by exploiting the global network view afforded by SDN. Results show that manipulating the loss profiles of the ROADMs in the metro-network can yield optical signal-to-noise ratio (OSNR) improvements up to 10 dB leading to an increase in 112% in total capacity.

1. Introduction

The unprecedented amount of data that needs to be transferred between datacentres imposes new requirements and challenges on inter-datacentre optical networks. Most of inter-datacentre networks require global reach, large capacity, and inherent redundancy [1]. In this work it is assumed that the datacentres are located within the same metropolitan area and that the datacentre operators may not own their own inter-datacentre links. There is therefore a need for low latency all-optical paths to be established through existing third party optical networks that include switching nodes that can add or drop channels on other wavelengths within the network. Such nodes can have a detrimental impact on the all-optical paths between the datacentres so it is interesting to explore how such impacts can be minimized. The end to end links considered here are also expected to be relatively short lived (of the order of minutes) so that frequent reconfiguration and optimization of the link capacity is envisaged.

To fulfill this network demand, a number of approaches have been proposed, including Bandwidth Variable Transponders (BVTs) that can support multiple bit-rates and/or modulation formats according to traffic demands and the heterogeneity of the network endpoints [2,3]. Through the latest innovations in photonics (such as flexible rate coherent transceivers and flexible grid Colorless, Directionless, and/or Contentionless configurations [CD/CDC]), network operators have the powerful ability to re-purpose existing network resources to adapt to network growth, avoiding stranded investment. The result is the ability to continuously optimize system capacity and resiliency of equipment already deployed for specific reach, wavelength fill, and link margin parameters reducing capital expenditure (CAPEX) [4]. A sliceable BVT architecture can obtain granularity, flexibility and grid adaption suitable for metro/regional elastic networks and highly scalable datacentre applications [5]. With these programmable, multi-modulation transponders, carriers can adjust the transponder capacity to the physical characteristics of an optical path enabling them to maximize network capacity and efficiency on each route.

On the networking side, software-defined networking (SDN) enables a global network view for monitoring and actuation allowing the use of

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autonomous applications that enhance network performance in terms of capacity and quality [6]. This global perspective enables the operating points for Erbium Doped-Fiber Amplifiers (EDFAs) and wavelength selective switch (WSS)-based equalization strategies for end-to-end OSNR improvements [7–11].

The OSNR limit assumed so far has arisen from basic assumptions concerning fibers, Reconfigurable Optical Add/Drop Multiplexer (ROADM) losses and EDFA features [12]. It is therefore interesting to explore the possibility of increasing network capacity by using the global view to further improve the overall OSNR for optical paths, so that higher order modulation formats can be used [13]. Furthermore, with flexible transceivers, margins can be converted into capacity by choosing appropriate data rates for each link. Moreover, in the 'bandwidth on demand' scenario, tunable data rates and tunable bandwidth transceivers enhance the agility of a dynamically provisioned optical connection [4].

This work is based on experimental results reported in [9,10]. In [9] we introduced a global (end-to-end) ROADM-based spectrum equalizer algorithm running over DWDM networks on SDN architecture. Moreover, in [10] we experimentally demonstrate the benefits of global WSS-based spectrum equalization for multiple ROADMs in cascade and introduced three equalization strategies to enable OSNR enhancement in a SDN metropolitan mesh optical network test-bed.

Here, we propose for the first time, to the authors' knowledge, an end-to-end OSNR optimization through global ROADM-equalization in order to increase the aggregated capacity. To address this issue, we use a simulation framework to analyze the proposed method. Our major contribution is the proposal of a dynamic adaptive method that finds the highest OSNR per channel that fits the best modulation format ensuring end-to-end capacity maximization. Results show aggregate capacity improvements up to 112% when compared to other standalone methods [10].

The remainder of the paper is organized as follows. Section 2 reviews related works in the literature on the topic. Sections 3 and 4 details an optical power profile manipulation methodology to achieve higher aggregated capacity. Section 5 describes the simulation modeling environment used to evaluate the main goal of this work. Section 6 explain the results of the capacity maximization method. Finally, Section 7 concludes the paper and outlines potential future work directions.

2. Background

2.1. Problem statement

In the physical transmission layer, an optical signal accumulates attenuation due to fiber and ROADM losses. Optical amplifiers are inserted to recover these losses, but at the cost of introducing noise and reducing the OSNR. When considering an ensemble of dense wavelength division multiplexed (DWDM) channels, the spectral response of these cascaded EDFAs results in variations in signal and noise levels across the channels. The most affected channel due to the spectral non-uniformity is that which experiences the lowest gain of the amplifier, and consequently, this will have an OSNR value much smaller than the other channels. Thus, at the end of these cascaded amplifiers, the ensemble of DWDM channels will each experience very different OSNR values and the overall performance tends to be limited by the channel with the worst OSNR at the destination node [14].

Typically, this signal power variation is corrected by using power equalization in the WSS's in a ROADM. However, these consecutive mitigations along the path can lead to unequal OSNR degradation [12]. Other solutions include hybrid amplifiers using distributed Raman amplification and EDFA gain media together to eliminate the gain tilt [15]. However, results indicate that increasing the distributed gain to avoid losing OSNR on the shorter wavelengths increases the accumulated nonlinearity of the channels where the Raman gain is maximum, which leads to spectral broadening of the channels at longer wavelengths.

Our previous works include the experimental demonstration of an SDN-based method that adjusted the attenuation profile of each ROADM to achieve a power-equalized comb of signals at the path end [9,10]. That method decreases the total attenuation applied in each channel along the path, improving the OSNR. Additionally, if power tilt is accepted at the receiver then the method offers even higher OSNR values. The work presented here builds upon that method to include multiple modulation formats that can exploit the OSNR improvement on a per-channel basis.

2.2. Related works

In the literature, several studies have focused on developing methods to improve OSNR in optical networks [16–20]. Some studies attempt to enhance OSNR as a throughput parameter of optical network [21–26]. On the one hand, in [16], the OSNR optimization problem with the total power constraint on a single point-to-point optical link was formulated as a Nash game. The OSNR optimization problem is formulated as an m-player no cooperative game, based on a network OSNR model, developed for a general multi-link configuration.

On the other hand, others studies focused on minimizing the nonlinear interference effect and thus increasing network throughput by adjusting channel launch power and optimizing spectral resources using several modulation formats [27,28]. Similarly, [24] proposed a BVT adjustment scheme in which OSNR gains provided by Architecture on Demand (AoD) raise the modulation format order leading to higher network capacity or improved spectral efficiency. Additionally, [25] presents a power control process that takes advantage of link optical power and channel OSNR margins to allow network operators to support this optical power increase while maintaining the use of legacy optical amplifiers. All these studies, in addition to those dealing with digital signal processing techniques [26], have only considered the power resources as a limitation without taking into account the attenuation resource limits due to equalization process of optical links (which depend on the amplifier spectrum profile and induce higher noise figure).

For all these mentioned reasons, in this work, and unlike the current paradigm, we take into account attenuation resource limits afforded by power equalization. The proposed method adapts the attenuation per channel to their minimum required in order have a higher OSNR fitting the best modulation guaranteeing error-free operation at the endpoint.

2.3. Enabling technologies

SDN is emerging as a strong candidate to improve the control of telecommunication networks. Indeed, among other aspects, SDN enables the control of multiple specific node parameters which may be unsuitable for advertisement in a fully unified distributed control plane involving different technologies and telecommunication areas [29]. This SDN paradigm also enables network automation that was previously not possible with a traditional system where the control software was embedded and coupled with a specific hardware implementation [6].

Traditionally, transceivers had a fixed performance based on the optical components that were selected. With the introduction of digital signal processing and SDN in the new generation of coherent transceivers, it is now possible to design flexible hardware that will support trade-offs between parameters such as optical reach, bit rate, and spectral efficiency under software control [30,31]. In [32] a sliceable bandwidth-variable transponder (SBV-T) is proposed as a transponder that can include multiple subtransponders. Similarly, in [33] is proposed a novel multirate, multimodulation, and code-rate adaptive sliceable bandwidth variable transponders (SBV-Ts) architecture. The proposed architecture presented enables sliceability and multirate capability and supports optical reach adaptation while preserving the bit rate.

In the data plane, ROADMs usually based on wavelength selective switches (WSSs), are key elements since they route the signals directly

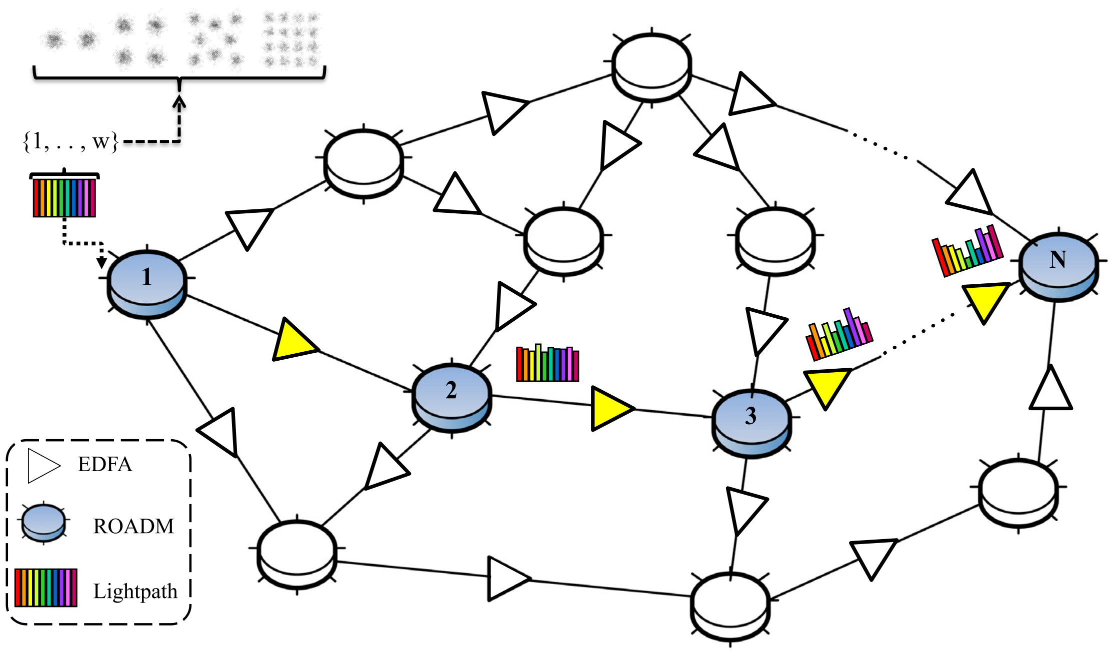

Fig. 1. Example of an optical network with multiple modulation format (BPSK/QPSK/8QAM/16QAM) carriers facing tilt degradation.

in the optical domain. WSS are key components in dynamic optical networks, they allow the consolidation of optical dynamic networks in the telecom scenario, especially for complex mesh topologies in particular with optical spectrum equalization. It is worth mentioning that [9] can be considered as the first work showing the benefits of global operation of ROADMs under a SDN controller may provide benefits in terms of OSNR, allowing longer transmission reaches and flattened spectral characteristics for proper system operation. Similarly, in [10] three equalization strategies are proposed to offer high OSNR enhancement and longer reach suitable for high SE transmission systems. Further details will be discussed in the next section.

Relevant to SDN control of hardware elements, works in the literature include local adaptive and cognitive gain control for EDFAs [8,34], and the later method that relies on case based reasoning showed OSNR improvements over time demonstrating the ability of cognition process regardless of the employed amplifier type or network topology. Further, in [11] is proposed a simultaneous optimization of EDFAs' gain operation point and WSSs' spectrum tilt correction, and an OSNR improvement up to 5.7 dB at the receiver is presented for different lightpath conditions. However, when the equalization is locally applied to every node in a path, the attenuation in each channel results in optical signal power reduction and, consequently, OSNR degradation [11].

3. Global WSS-based equalization

Consider the optical network shown in Fig. 1 and the optical path composed by nodes 1 to N. Additionally, also consider that we have access to read and control the network elements (NEs) parameters, e.g., by a SDN controller. The optical amplifiers placed along the path can provide different profiles, leading to non-equalized channels on the destination node. We denote the attenuation at each ROADM $i \in (1, \ldots, N-1)$ of the lightpath by a vector $A_i = [A_i(1), \ldots, A_i(\lambda)]$, where $A_i(\lambda)$ is the optical attenuation given at wavelength λ. Similarly, we denote the spectrum tilt at the receiver by a vector $T = [T(1), \ldots, T(\lambda)]$, where $T(\lambda)$ is the difference between the optical power of channel λ and the minimum channel power of the aggregate W at the receiver. First, the global attenuation vector (AG) is obtained as the sum of all attenuations applied at each ROADM of the lightpath $A_{(1,\ldots,N-1)}$ plus the tilt at the receiver T:

$$AG_j(\lambda) = \sum_{i}^{N-1} A_i(\lambda)|_j + T(\lambda)|_j. \tag{1}$$

The last ROADM N is not considered because the broadcast-and-select (B&S) structure prevents equalization for dropped lightpaths. Note that AG stores attenuations applied in previous iterations. Second, the minimum global attenuation vector (Γ) is obtained as the difference between the total attenuation applied to channel λ (i.e., $AG_j(\lambda)$) and the minimum total attenuation of the aggregate W:

$$\Gamma_j(\lambda) = AG_j(\lambda) - min(AG_j(\lambda)). \tag{2}$$

Third, Γ is applied from the last ROADMs of the lighpath until the first (i.e., in the inverse direction of the signal propagation):

$$A_i(\lambda)|_j = \Gamma_j(\lambda) - \sum_{k=i+1}^{N-1} A_k(\lambda)|_j. \tag{3}$$

By doing so, high OSNR values are expected since noise contribution of the first EDFAs in the lightpath is reduced [10]. Finally, these three steps are executed recursively until the minimum allowed spectrum tilt T at the receiver is achieved.

4. Capacity maximization method

Fig. 2 shows the capacity maximization procedure flowchart. Consider the same optical network presented in Fig. 1. We start from the assumption that a global equalization algorithm is already applied. We denote $OSNR_{th}$ as the vector of the threshold OSNR required per modulation format and baudrate corresponding to the FEC limit (BER below 3.8×10^{-3}). A hard-decision FEC (HD-FEC) with fixed 7% overhead is assumed in this work [35]. We also assume that the system uses a total of W channels and then define three vectors of size W: $OSNR_i$ is the current OSNR measured (at the receiver) in the channels at the i_{th} iteration of the algorithm, Γ is the global attenuation for each ROADM and T is the spectrum tilt at the receiver calculated as the difference between the optical power of channel λ and the minimum channel power.

Initially, the current OSNR for each channel ($OSNR_i$) is compared with the OSNR threshold vector ($OSNR_{th}$) to select the modulation format with the greatest spectral efficiency (SE) that can be supported. Next, the attenuation (Γ) of each channel is adjusted in proportion to the difference (*diff*) between the measured OSNR value and the threshold for the current modulation format chosen for that channel. If

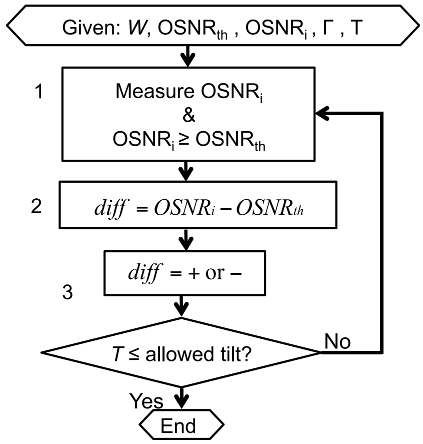

Fig. 2. Capacity maximization procedure flowchart.

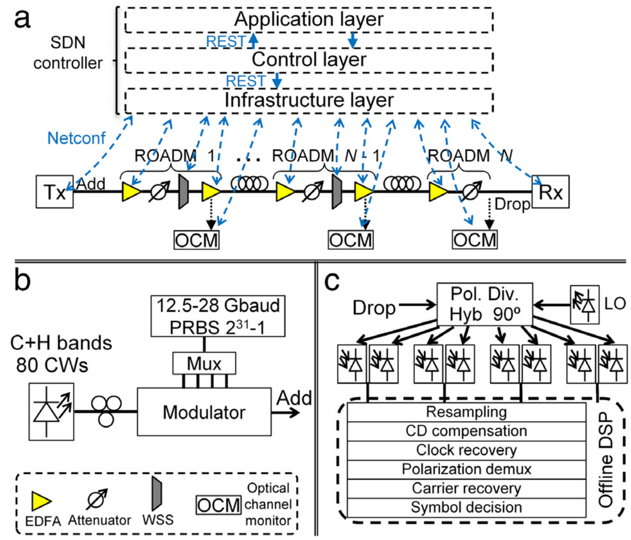

Fig. 3. (a) Simulation setup, (b) flex transmitter and (c) flex receiver.

the difference between Γ and *diff* is positive the attenuation is reduced for that channel (provided that the channel has an attenuation margin), otherwise the same attenuation profile is kept.

It is important to point out that applying less attenuation impacts the power tilt as compared to the limited strategy in [10], i.e., this method will typically not offer a flat spectrum at the receiver, but rather, exploits the tolerance of commercial coherent receivers which can accommodate up to 18 dB of sensitivity range [36]. Finally, these three steps are executed recursively until the maximum allowed spectrum tilt at the receiver is achieved (i.e. the aggregate of channels W is optimized). If there is no change in current $OSNR_i$ (i.e., *diff* = 0), and additionally, the maximum value of T (λ) is less than the allowed value, the application converges.

For example, consider 2 channels, λ_1 and λ_2 with their respective OSNR measured at receiver. If channel λ_1 has an initial received OSNR of 20 dB and the threshold for the chosen modulation format is 25 dB, then we have a *diff* of 5 dB. If channel λ_2 has an OSNR of 20 dB it also has a *diff* of 5 dB. In both cases, the *diff* is positive, so we can reduce the total attenuation (Γ) on both wavelengths as this will improve the OSNR [10]. Since higher total attenuation values (Γ) are distributed in the latest network nodes [10], it is expected that the noise contribution of the first amplifier is reduced, thus ensuring a better OSNR per channel on the destination node. As a result, at the next iteration, λ_1 and/or λ_2 may have an OSNR that allows a more spectrally efficient modulation scheme to be used which yields a new value for *diff*. The algorithm continues until:

1. the tilt constraint is reached, or
2. the maximum power (0 dbm/channel) constraint is reached, or
3. the condition where there is no more benefit is to be achieved (*diff* = 0) has been reached.

This proposed end-to-end OSNR optimization outperforms our previous algorithm [9,10] because it considers the transmitters with multiple baudrate and modulations formats maintaining its complexity Θ(W,N). In more detail, in [9] the global equalization was developed and reported for a fixed number of ROADMs (N = 4). Further, in [10] the algorithm was analyzed and discussed with different equalization strategy.

5. Simulation setup

5.1. Data-plane

Fig. 3(a) depicts the simulation setup used to evaluate the proposed method. The amplifier model used in this work to simulate the accumulated tilt effect along a cascade of amplifiers [8] is restricted to the following assumptions, based on the characterization outcome: NF depends only on the overall gain setting, while the gain for each channel will depend on the wavelength.

The optical fiber model assumes fixed attenuation independent of wavelength (α = 0.20 dB/km). Considerations of non-linear effects are neglected here as the launch power is constrained to 0 dBm per channel. Two EDFAs per link are used to compensate for the 100-km single mode fiber links and ROADM losses (20 dB and 14 dB, respectively). The ROADMs are composed of two EDFAs, optical attenuators, wavelength selective switches (WSSs) and optical channel monitors (OCMs) that simulate the broadcast and select (B&S) stages respectively. The last ROADM of the cascade consists of a single EDFA and an attenuator to simulate the dropped lightpath.

The flex transmitter, in Fig. 3(b), is composed of 80 continuous wave (CW) lasers (C-band) with 50-GHz channel spacing. Each carrier is modulated by four multiplexed lines of 12.5 or 28 Gbps (PRBS 2^{15}-1) data. Each PRBS was also uncorrelated among the different channels and modulation format. This generates channels with different dual-polarization (DP) modulation formats (BPSK, QPSK, 8-QAM, 16-QAM and 32-QAM). Each modulation format leads to a different OSNR and reach requirements and filtering impact [37,38]. At the flex receiver (see Fig. 3(c)), each channel is combined with an local oscillator (LO) in a polarization-diversity 90-degree optical hybrid and digital signal processing algorithms are used offline to recover the data stream [10].

We carried out the analysis of aggregated capacity considering $SE = 2.M.R_s/\Delta f$, where M is the number of bits/symbol of the constellation on each polarization, R_s is the baudrate and Δf is the channel spacing fixed at 50 GHz and the aggregate capacity is thus considered as $C = \sum_{i=1}^{W} SE(i).\Delta f$.

5.2. SDN controller

To provide access to and control of the NEs via the application, a SDN controller is used. The SDN controller can be viewed as a logically centralized single control entity that appears as the directly controlling entity to the NEs [39,40]. In the following we describe the SDN controller used in this work with a bottom-to-top approach.

The main components of the proposed architecture are depicted in Fig. 3(a). It is composed of three layers: infrastructure, control and application layer [41]. The infrastructure layer (infra-layer) is responsible for sending commands to each NE and receiving information from the physical layer. The infra-layer communicates with the control

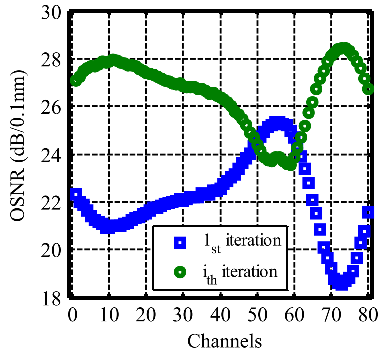

Fig. 4. Initial and optimized OSNR for four cascaded ROADMs.

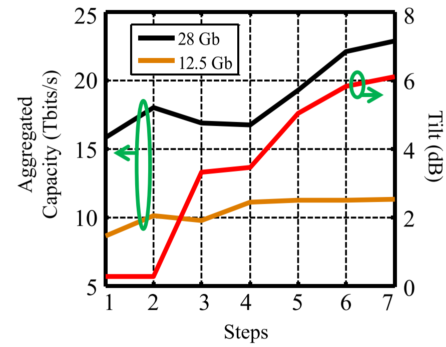

Fig. 6. Aggregated capacity (12.5 / 28 Gbaud) and tilt for four cascaded ROADMs.

layer using NETCONF protocol to share information and send commands to the application. The NETCONF protocol [42] provides mechanisms to configure, modify, and delete configurations on a network device. The control layer receives instructions to configure the network infrastructure based on application layer requirements. In addition, it communicates with the application layer using the REST protocol. Lastly, the application layer comprises network applications and services that utilize the control plane to realize network functions over the physical or virtual infrastructure. Considerations of latency are outside the scope of this paper [43,44].

It is important to point that, it is possible to implement the system in many other environments with the main differences being the communications message formatting and the message exchange protocols used. Clear examples are Open Daylight [45] and ONOS [46]. On the one hand, since the northbound interface of every SDN controller has some peculiarities, it is necessary to tailor any northbound application to the controller in question. On the other hand, although the southbound interface is implemented with NETCONF, it is believed that other implementations are possible. For example, an OpenFlow [47] implementation would use its ability to embed non-standard messages and commands within an OpenFlow message. OpenROADM [48] would be a good approach to be considered since the device models are based in YANG data models. By modeling these devices using the NETCONF-modeling language YANG, we gain the possibility to export or transform the data that is needed for their configuration, as well as to model their interconnections and restrictions.

6. Results and discussion

The results shown in Fig. 4 are achieved in a number of different steady-state conditions (i.e. when the allowed tilt condition is verified). It is important to point out that, in each iteration, the equalizers should take into account at least one previous state of attenuation, acting as a proportional controller [49]. Fig. 4 shows the OSNR per channel at the initial state when our proposed method is applied and the results after the i_{th} iteration for four cascaded ROADMs, showing a significant gain in OSNR for some wavelengths.

Initially, high attenuation values are applied to high wavelengths by the local equalization algorithm. Indeed, the cascaded effect of 7 EDFAs without a gain flatness filter (GFF) leads to 40 dB of attenuation to locally compensate for spectrum tilt. This level of attenuation leads to poor OSNR values for some channels as shown in Fig. 4. However, an improvement is obtained when comparing the initial conditions against the steady-state of the capacity maximization method thanks to the global coordination of the attenuation profiles that yields an overall reduction in attenuation of up to 85%.

This OSNR improvement arises due to the attenuation being reduced up to 85% with the capacity maximization method. Thus, by adjusting the attenuation profile in the link to power tilt between the channels, different input powers will be experienced by EDFAs, i.e., by modifying the input power to the EDFAs, its performance is also modified. For example, the channels around channel 70 have improved OSNR from 18.5 dB to 28.4 dB, i.e., a gain of 9.9 dB. As a result, it is possible to change the modulation schemes from QPSK and 8-QAM to 8-QAM and 16-QAM as shown in Fig. 5(a) and (b). However, the power tilt has degraded to 6 dB (see Fig. 6). Additionally, Fig. 6 shows the aggregated capacity for 12.5 Gbaud and 28 Gbaud scenarios. In the 28 Gbaud case, the total capacity increases from 15.8 to 22.82 Tb/s — an improvement of 44.43%.

The same analysis was performed for other cases from 2 to 8 cascaded ROADMs. Fig. 7(a) shows the obtained OSNR values as a function of the number of ROADMs in the lightpath. Both curves show the OSNR reducing as the number of cascaded ROADMs increases, as expected [10].

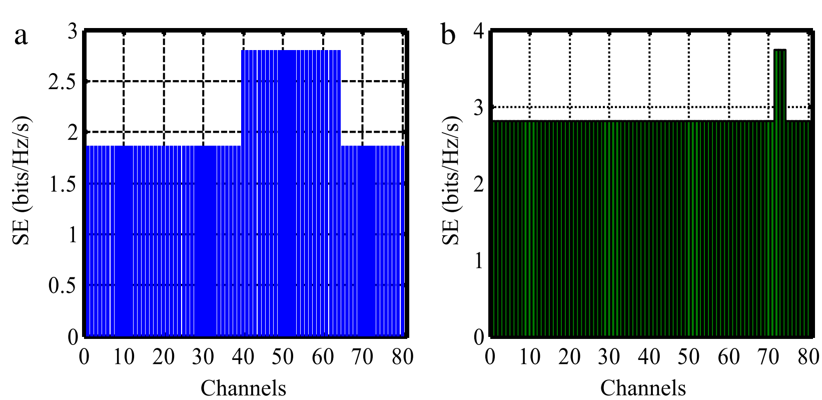

Fig. 5. (a) Initial and (b) optimized spectral efficiency with 12.5 Gbaud for four cascaded ROADMs.

Table 1
Results for aggregated capacity ratio between the proposed method and the initial conditions.

Cascaded ROADMs		2	3	4	5	6	7	8
Baudrate (Gb)	12.5	10.5%	12%	30.5%	40.7%	71.3%	**112.1%**	101.1%
	28	2.1%	35.6%	44.4%	**85.7%**	85.3%	80.9%	63.9%

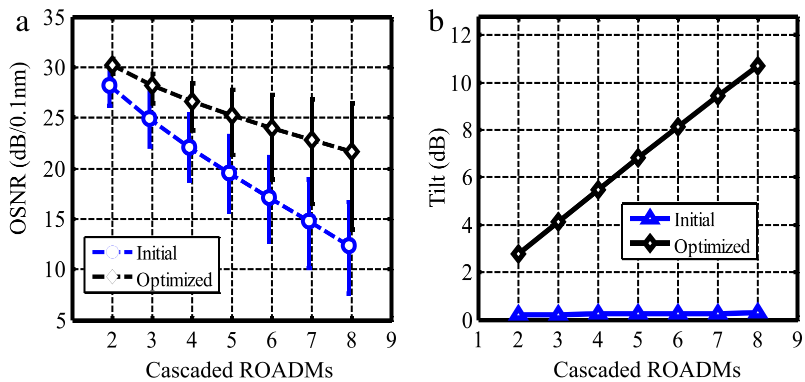

Fig. 7. (a) Average OSNR and (b) spectrum tilt as a function of cascaded ROADMs, respectively.

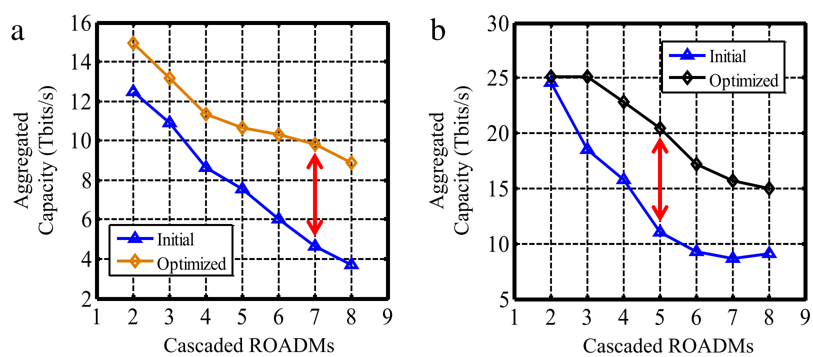

Fig. 8. Aggregated capacity for (a) 12.5 and (b) 28 Gbaud cases, respectively.

In general, both curves show the reduction in OSNR value of the number of cascaded ROADMs thus to longer reaches, more amplifiers are required to surmount losses leading to further degradation of the OSNR. The results for the proposed method show average OSNR values that are significantly higher than the initial condition which allows modulation formats with higher spectral efficiency to be used resulting in higher aggregated capacity.

Fig. 7(b) shows the results for the tilt levels at the receiver input. Note that, the residual tilt increases with the number of cascaded ROADMs but never exceeds the 18 dB margin allowed in commercial receivers. Indeed, the proposed method results in 10.6 dB power tilt after 8 ROADMs, i.e., 15 cascaded EDFAs.

Finally, Fig. 8(a) and (b) show the aggregated capacity values for the different baud rates as a function of cascaded ROADMs. Note that, in Fig. 8(a) shorter links exhibit higher aggregated capacity values since higher OSNR values (see Fig. 7(a)) means that using higher order modulation formats can be applied. These results show that after 7 cascaded ROADMs the new technique has yielded a 112% increase in the aggregated capacity as shown in Fig. 8(a). Additionally, in Fig. 8(b), note that, using 28 Gb yields a 85.7% capacity improvement after 5 cascaded ROADMs. Table 1 summarizes the results for different Baudrates (12.5 and 28 Gb) as a function of cascaded ROADMs. Compared to current approaches, our proposed method improves optical link capacity utilization in the metro network which is suitable for enhancing inter data-center networking.

7. Conclusion

In this work, we have used SDN's global view of network monitoring and control to enable end-to-end performance improvement for flexible inter-datacentre links through third party networks. The SDN control is used within a simulation framework to dynamically adapt the power equalization process and modulation format to significantly increase the link capacity through OSNR optimization.

Results showed that it is possible to increase the network capacity by 112% with a residual tilt of 10.6 dB. Thus the technique has been shown to improve the capacity of all-optical links through a metropolitan area network which will be useful for inter-datacentre links. Furthermore, enabling dynamic adaptive capacity maximization adds robustness and intelligence to WDM optical networks without the need for replacing any device. Future works include different exploration alternatives for national and continental network topologies, as well as dynamic and flexible spectrum analysis additionally with different ROADM architecture and optical amplifiers models.

Acknowledgments

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