On the Filter Narrowing Issues in Elastic Optical Networks

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Abstract—**This paper describes the problematic of filter narrowing effect in the context of next generation elastic optical networks. First, three possible scenarios are introduced: the transition from actual fixed-grid to a flexi-grid network; the generic full flexi-grid network; and a proposal for filterless optical network. Next, we investigate different transmission techniques and evaluate the penalty introduced by the filtering effect when considering: Nyquist WDM, SSB DD-OFDM and symbol-rate variable DP-4QAM. Also, different approaches to compensate for the filter narrowing effect are discussed. Results show that the specific needs per each scenario can be fulfilled by the aforementioned technologies and techniques, or a combination of them, when balancing performance, network reach and cost.**

Index Terms— **Networks, optical communications, elastic optical networks, flexi-grid, WSS.**

I. Introduction

The future adoption of elastic optical network (EON), mainly fostered by the advent of next technologies (e.g., media, HDTV, 5G, Internet of Things, etc.) and backed by the considerable advances of transmission techniques in terms of flexibility and capacity, is heading to undertake new challenges and goals. In fact, when adopting the flexi-grid paradigm [1], optical channels with different bandwidth occupation can coexist within the same fiber. Some of these channels, denominated as super-channels, are wider in frequency and comprise multiple sub-channels transmitted together tightly; while others are narrower in frequency and specifically tailored for low bit/symbol rate connections. For an efficient fitting of them all, ITU-T has recently standardized the flexible wavelength division multiplexing (WDM) grid, where optical frequency slots, of different size, can be allocated by employing variable bandwidths in steps of 12.5 GHz [2]. Consequently, new flexible wavelength selective switches (flexi-WSSes) at the network nodes are needed to support this bandwidth elasticity. Such flexi-WSSes are manufactured employing suitable technologies, e.g. liquid crystal on silicon (LCoS) [3]. These devices present enhanced performance and advanced features when compared to conventional WSSes used in fixed-grid, In fact, the latter can provide only fixed width frequency slots (50 or 100 GHz) evenly spaced. Employing flexi-WSSes the optical spectrum can be used more flexibly and efficiently, being not restricted to operating within approximately 90 slots of 50 GHz. This allows, for example, a new 37.5 GHz slot size, providing an additional 33% of aggregated throughput when comparing to the legacy 50 GHz networks [4]. Moreover, the flexible frequency slot size supports the transmission of super-channels, giving a further spectral efficiency enhancement thanks to the tight spectral packing of the optical sub-channels.

The transceivers envisioned for EONs, implement a range of advanced functionalities that include the support of multiple flows or spectrum slices, different bit rates and a dynamic variation and adaptation of modulation format and symbol rate [5]. Thus, these transceivers are often referred as sliceable bandwidth/bitrate variable transceivers (BVTs). These transceivers have capabilities to generate multiple slices that can be grouped in super-channels of different sizes, enabling increased optical spectrum efficiency thanks to a tight spectral packing. Also, the inherent flexibility of EON transceivers allows the optimization of the network capacity by configuring them to transmit the most spectrally efficient format for the required performance.

Optical networks entirely based on EON paradigm are not expected to be widely deployed soon. More realistically, a coexistence of fixed and flexi-grid networks is expected with flexi-grid dominating in the backbone network segment. In this context a significant source of penalty is caused by the transmission through a cascade of nodes. Indeed, these nodes contain non-ideal optical filters and, when the optical signals traverse several of them, the resulting equivalent channel bandwidth may be significantly decreased, entailing spectral distortions and optical signal to noise (OSNR) penalty. This

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effect is usually referred to as filter narrowing effect, being the source of non-negligible performance degradation [4]. This penalty is more likely to be present in transparent aggregation networks (typically covering the metropolitan and regional segments) where signals are expected to pass through a high number of nodes and low symbol rate connection may force the use of the smallest available slots sizes. Moreover interoperability issues arise when transparent optical connections pass through fixed filters (mainly in the metro area) and flexi-WSSes.

This paper is organized as follows. First, three reference networks, including system scenarios and use cases, are described to address the topic of the imminent deployment of next generation EONs. Following, the filter narrowing impact is discussed for different technologies and general recommendations are derived. Next, experiments addressing approaches to mitigate that effect are detailed. The last section on discussion and conclusion provides guidelines for systems and network design.

II. Reference Scenarios

We present three possible reference network scenarios where filter narrowing effect is of different concern. The first two address different level of EON deployment: subsection A discusses the transition case, where the problematic arising while deploying flexi-grid network aside of current fixed-grid one are discussed. In subsection B we present the case of full flexi-grid network. Finally, subsection C considers the so-called filterless optical network (FON), where the penalty caused by filtering does not exist.

A. Hybrid Fixed-/Flexi-Grid Optical Network

Although flexi-grid optical networking present several benefits when compared to actual fixed-grid networking, a

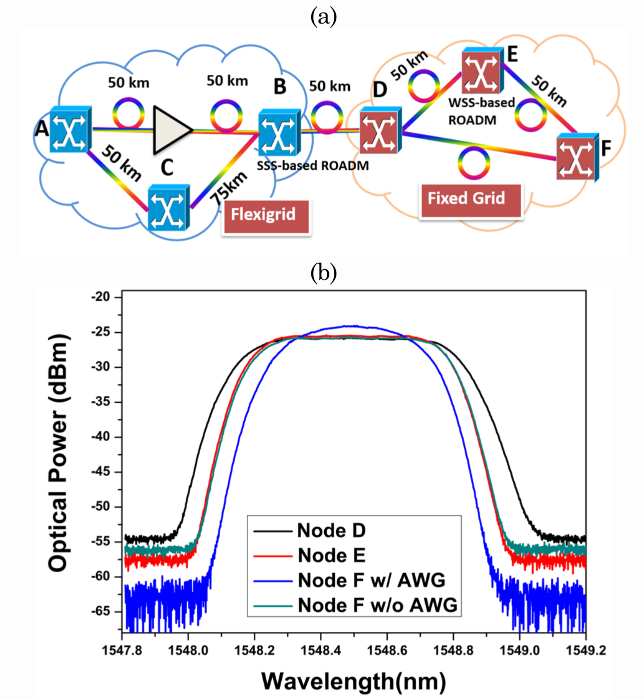

Fig. 1: (a) Fixed- and flexi-grid optical network experimental test-bed (b) Channel profiles for links with variable number of hops.

gradual migration process from fixed-grid to flexi-grid can be envisioned in order to smoothly upgrade the existing infrastructure. Thus, during the initial period of transition the current widely-deployed fixed-grid optical networks will coexist with the emerging flexi-grid optical networks.

To take full use of the available network infrastructure, optical transparent interconnection should be setup across both fixed- and flexi-grid optical network domains. Such interoperability is critical for enabling the foreseen gradual migration [6].

Within the fixed-grid domain, conventional WSS-based reconfigurable optical add/drop multiplexers (ROADMs) are widespread in regional or backbone areas; while legacy (and low-cost) fixed filters, e.g. based on arrayed waveguide gratings (AWGs), are extensively employed in metro and access network segments or in some add&drop block (A&D) of ROADMs. Since their spectral characteristics are far from being flat, the filter narrowing effect would be relevant when optical channels are routed through these nodes. On the contrary, flexi-WSSes based on LCoS have a sufficient wide flat-top spectral behavior with affordable insertion losses suitable for flexi-grid slots of 37.5 GHz and beyond [3]. Thus, the filter narrowing effect of the fixed-grid domain is expected to dominate the spectrum profile of a cross-domain path, entailing an increase of signal degradation. Fig.1a shows a network test-bed, representing a hybrid fixed- and flexi-grid metro optical network, used for running experimental tests for the mentioned interoperability scenario. Fig.1b shows the measured spectral transfer function of a generic cross-domain path from A towards F. After few hops in fixed-grid domain, the accumulated filtering effect dramatically reduces the channel optical bandwidth. In this particular case, the actual 3 dB bandwidth of a nominal 100 GHz wide channel, decreases from 0.649 nm (81.1 GHz) at node D to 0.457 nm (57.1 GHz) at node F; a 29.6% bandwidth shrink caused by the AWG-based A&D employed in the fixed-grid domain.

B. Flexi-Grid Elastic Optical Network

Once the migration is completed, the EON paradigm will be fully adopted, and a generic flexi-grid meshed network can be deployed. In this context, the nodes are expected to adopt a switch-and-select internal architecture with colorless and directionless A&Ds in order to prevent channel crosstalk [4]. This architecture involves the crossing of several filtering elements, even for pass-through flows, representing a challenge for the performance of flexi-WSSes. As mentioned before, a popular choice are WSSes based on LCoS that fully support the flexible grid as specified by the ITU-T [2]. Such solution is envisioned to be efficient with media-channels at least 3 elementary slots wide (37.5 GHz). However, for channels fitting into 1-2 elementary slots (12.5 GHz, 25 GHz), these devices increase the passband insertion losses and exhibit a non-flat behavior [3], which translates into severe bandwidth shrinking. The consequent performance degradation is a concern only in future all optical metro and metro aggregation scenarios where low bit rate connections are expected to be quite common.

Considering the aforementioned node architecture, the total number of traversed WSSes by an optical path is 3 for each A&D node, and 2 per pass-through node. Thus, a total number of filters $n = 2(3 + k)$ are crossed, being k the number of pass-through nodes [4] [6]. For example in a large regional network, 12 transparent crossed nodes are more than sufficient to include the longest conceivable protection or restoration path, giving a maximum $n = 30$.

Special consideration should be made for a flexi-grid optical network that aggregates low bit rate traffic. First, node architectures can be tailored to the employed transmission techniques, operating at low bandwidth [7][8]. This means that the adopted WSSes are expected to have a clearly non-flat behavior and exhibit substantially increased insertion losses and reduced selectivity. This fact poses a balance to be traded when considering the node architecture. On the one hand, the number of traversed WSSes should be minimized in order not to have excessive spectrum distortion due to the non-flat behavior. On the other hand, the selectivity of the WSSes is also a critical point. Thus, a reasonable compromise could be to reduce the number of components by restricting the node capabilities to implement wavelength contention [6]. So, the number of filters to be traversed at the A&D nodes would be reduced to 2; and the total number of filters would be $n = 2(2 + k)$. Since k=5 is a reasonable number of intermediate nodes for this specific use case [7], the maximum n to be considered is 14.

C. *Filterless Optical Network*

While today's ROADM-based DWDM networks use fixed optical filters or adaptive WSSes to route wavelengths through an extended optical domain, FONs have been recently proposed as disruptive alternative [9]. They simply utilize passive splitters and combiners, avoiding optical filters and thus the signal degradation associated to the filter narrowing effect. FONs behave like a radio ether, now being transferred to the optical domain, i.e. an optical signal is broadcasted over the entire connected fiber network. Thus, FONs provide no means to steer a wavelength from a source to a destination. Instead, a single bidirectional signal occupies the entire domain's wavelength resource so that this wavelength cannot be reused anywhere else. That is why FONs are said to follow the so-called "drop&waste" paradigm.

The FON node architecture is illustrated in Fig. 2a. In the express path, splitters are used to replicate the WDM combs forwarding them to the combiners which are connected to the outgoing fibers. As power levels of the involved incoming channels might exceed the allowed boundaries, an optical channel equalizer might be used. Though this is actually an adaptive optical filtering device, it does not violate the FON paradigm as it does not route any wavelength to a specific direction. Instead it only compensates power imperfections.

In the A&D part, optical filters are banned as well. Thus, transmitted power adjustment is done by variable attenuators on a per-channel base at each add port. Lightpath extraction is performed by the transceivers, at the receiver side. i.e. only coherent receivers are compatible with this approach. Their inherently sharp channel separation is the key FON enabler.

Topologically, FONs rely on one or multiple loop-free fiber trees, see Fig. 2, in order to prevent from both destructive superposition of WDM signals and lasering effects. A comprehensive study on how to derive a reasonable set of

(a) (b)

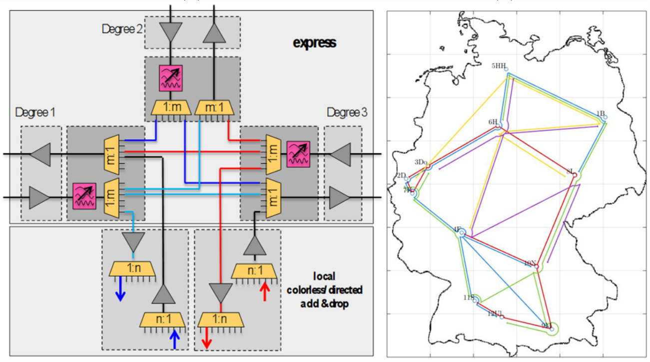

Fig. 2: Example of a 3-degree FON node (a) consisting of splitters, couplers (both in yellow), amplifiers (grey) and even potentially optical equalizers (purple). Fiber tree topology (b)

fiber trees can be found in [10].

Though it still seems premature to finally judge on the FON paradigm, the following pros and cons can already be summarized. The main promise is their supposed conceptual and operational simplicity. In the planning phase, this may avoid any kind of wavelength assignment effort. Secondly, all incoming signals are available at all receivers and thus any wavelength re-assignment is needless during the FON lifetime. Next, the absence of optical band-pass filters enables to transmit DWDM signals with any modulation format and spectral width. Thus, FONs are inherently compliant to the spirit of flexi-grid networking. Finally, the technology purely based on passive elements is expected to be more cost-efficient than actively controlled optical filters.

Opposed to those advantages stands quite a long list of challenging issues. A first fundamental challenge is to meet the receiving power levels for all channels concurrently active in the FON. The lower power boundary might be tackled by selective equalization and an optimized placement of amplifiers. Depending on the specific FON tree topology and fiber type, high-quality gain-flattened and low-noise amplifiers might be required. An even pretty small gain profile imperfection of a single amplifier type might sum up across the link to quite a substantial channel power imbalance at the receivers' sides. The upper power boundary occurs due to the comparably high number of incident channels interfering at the receiver. This sets quite a restrictive upper limit to the channel powers, mainly when the system gets fully loaded.

In current or soon available coherent transceivers, several vendors integrate an inner amplification stage behind the modulator to keep the transmitter's output power high enough [12]. Traditionally, this does not represent a problem as the respective broadband noise is suppressed by filtering. Within a FON, however, this effect might be detrimental because every channel contributes a noise floor to all others. Therefore, the OSNR at the transmitter is critical and should stay well above 45 dB.

Similarly, the linear inter-channel crosstalk generated at the transmitter side impacts the physical reach. Out-of-band crosstalk suppression should be above 25 dB for a practical FON deployment.

If a perfectly balanced receiver were employed, all coincident-channel beating terms would be suppressed inside the receiver. However, any real implementation shows a limited common mode rejection ratio (CMRR) [13][14]. Following the derivations published in [12], the total OSNR contribution induced by an insufficient CMRR scales quadratically with the coincidently beating channel power. As an example, the electrical CMRR should be at least 18 dB for a local oscillator power of 10 dBm, a flat signal channel power of -14 dBm and signal-signal current variance scale $\gamma = 0.5$ in order to achieve an $OSNR_{CMRR}$ of at least 25 dB.

Conceptually, the maximum capacity of a “drop&waste” architecture is limited to the number of wavelengths available for the system. Thus, compared to WSS-based state-of-the-art architectures offering the ability for wavelengths reuse, FONs tend to exhaust much earlier. Finally, optical resiliency is more difficult to be implemented compared to traditional approaches. While the latter are able to re-route a lightpath in case of an optical failure, FON resilience usually relies on a set of mutually disjoint fiber trees [10]. Fig. 2b depicts five trees serving together for full FON survivability. For protection purposes, the optical signal might be launched into two trees and is selectively extracted at the receiver side.

Practically, FONs have already been subjected to several experimental evaluations. For example, Deutsche Telekom (DT) conducted a first trial in a Croatian pilot network in 2012 [15]. Two years later, DT built a laboratory pilot test emulating a so-called horseshoe within the German aggregation network. A horseshoe is an open ring-like chain of regional add/drop sites connected to two end nodes at backbone sites. Maximum FON reach in these experiments was about 1600 km [11]. This was achieved with interoperable coherent 100 Gb/s transceivers stemming from four different system vendors. Currently, further interworking tests are underway before actually deploying the FON technology in the outside field.

III. Assessment of Filter Narrowing Effect on Different Technologies

This section reports the investigations of filter narrowing impact on different technologies and approaches to mitigate and compensate that effect. The transmission technologies investigated in the upcoming subsections are assessed either considering a soft-decision forward error correction (SD-FEC) coding, with target BER set a 10^{-2}; or a hard-decision (HD-) FEC; this last with $3.8 \cdot 10^{-3}$ target BER and 7% overhead. Additionally, and unless otherwise is stated, the OSNR is referred to 0.1 nm bandwidth.

A. Nyquist WDM

Nyquist WDM uses digital spectral pulse shaping to reduce the spectral width of the signals, allowing for channel spacing almost equal to the symbol rate and tight spectral packing of sub-channels inside a super-channel. Nyquist WDM is expected to be the first transmission technique to be deployed in next generation network [1][5].

Here its performance degradation due to the filter narrowing effect is discussed, considering both single optical channels and super-channels, in a fully EON scenario with flexi-WSS based ROADMs.

Extensive simulations have been carried out to address

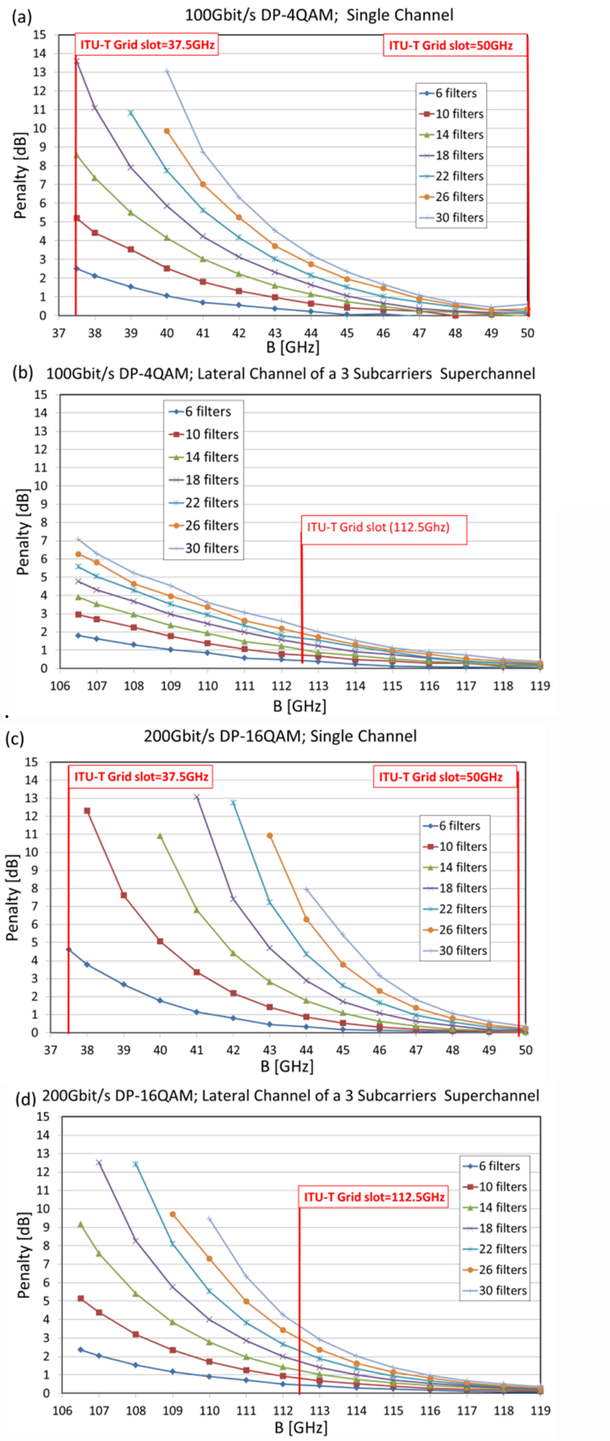

Fig. 3: Penalty versus WSS filters bandwidth for different number of filters.

performance degradation as a function of the number of crossed filters. Cumulative filtering penalty has been evaluated against an unfiltered setup, adding, noise just before the receiver, resulting in a worst-case configuration. Transmitter and receiver were kept ideal, in order to isolate the contribution of cumulative filtering. The sub-channels spectral shaping was given by a square root raised cosine (RRC) electrical filter with roll-off equal to 0.1. For the flexi-WSSes, a realistic optical filter model has been

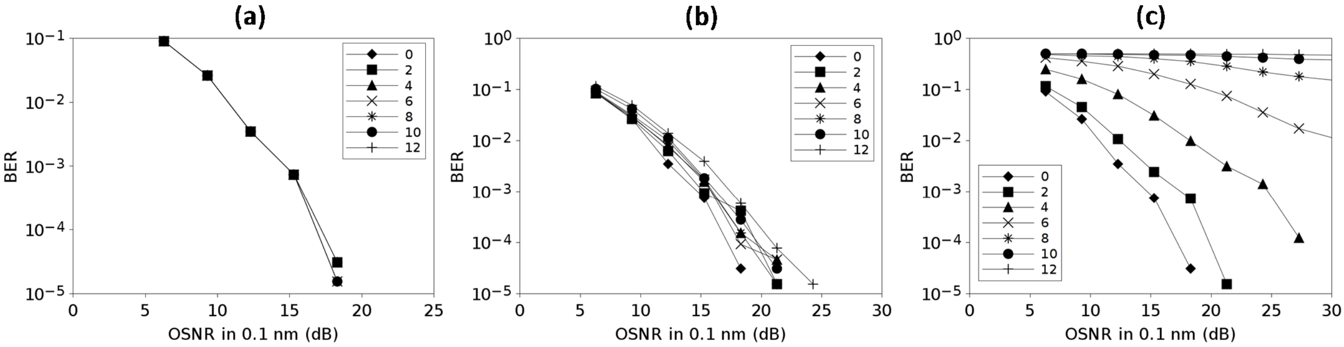

Fig. 4: BER versus OSNR for DD-OFDM SSB transceiver with bit loading after concatenation of different intermediate filters featuring bandwidths of 50 GHz (a), 25 GHz (b and 12.5 GHz (c).

implemented, characterized by a transfer function obtained according to [3]. A number of crossed filters ranging from 6 to 30 has been considered. Fig 3 shows the results in terms of OSNR penalties, taking into account the SD-FEC threshold, with respect to unfiltered back-to-back (B2B). It compares the performance of the single channel case (a) with the one of a lateral carrier of a 3 sub-channel super-channel (b) for a 100 Gb/s DP-4QAM modulation format, while (c) and (d) show the same comparison for a 200 Gb/s DP-16QAM. The bandwidth of the flexi-WSS filters for the single-carrier case ranges from 37.5 GHz to 50 GHz. To make a fair comparison the bandwidth of the super-channel has been chosen as:

$$BW_{SuperChannel} = BW_{SingleChannel} + (N-1)\Delta f \quad (1)$$

where N is the number of sub-channels and Δf the frequency spacing between adjacent sub-channels, set at 34.5 GHz. Thus the total filter bandwidth ranges from 106.5 GHz to 119 GHz for $N = 3$.

For both transmission formats the central carrier of the super-channel is not affected by the cumulative filtering; on the other hand, the impact on the edge sub-channels is lower and less dependent on the number on filters with respect to the single-channel case. These results can be generalized to super-channels carrying more than 3 sub-channels. In fact we repeated the simulation with a 5 sub-channels super-channel, where the bandwidth of the filters was calculated according to Eq. (1), and the results matched the ones of the 3 sub-channels case, both for the inner sub-channels and for the edge ones. Summarizing, cumulative filtering strongly degrades the transmission performance for narrow flexi-WSS bandwidths. However, the impairment appears to be less severe on super-channels, in comparison to single channels.

B. OFDM with bit/power loading

An alternative approach for the metro/regional segment is the direct detection (DD)-OFDM transceiver, which is a cost-effective solution including DSP, approaching the BVT concept when targeting low bit-rate connections in a flexi-grid network. One of the relevant DD-OFDM capabilities is that its individual digital sub-carriers can be arbitrarily set with different bit/power loads, enabling optical spectrum manipulation with sub-wavelength granularity. This is an interesting aspect, as it enables the possibility of adaptively modulating each OFDM sub-carrier according to the measured SNR profile. This can be performed either at the receiver side or employing advanced monitoring techniques as reported in [17] and in [18] for the case of digital sub-carrier multiplexing. Additionally, no dispersion compensation is needed by the DD-OFDM transceiver, at the expense of including a single side band (SSB) filter at the transmitter; whereas OOK is heavily affected by chromatic dispersion, requiring compensation modules at the nodes.

The performance of the SSB DD-OFDM system is here assessed by means of numerical simulation assuming a HD-FEC coding scheme. Further details of the simulation parameters can be found in [16]. Bit-loading is implemented with a Levin-Campello margin adaptive algorithm as in [19].

The performance of the proposed systems is assessed in B2B. Similarly to the OOK case, we carry out the study considering for the concatenation of up to 12 intermediate filters with nominal bandwidth of 50 GHz, 25 GHz and 12.5 GHz. Results are shown in Fig. 4. The 50 GHz case is depicted in Fig 4d. There it can be observed that the required OSNR for the HD-FEC target BER is 12.3 dB for all the examined filter stages. The required OSNR ranges from 12.3 dB up to 15.0 dB when considering 25 GHz filters Finally, the worst case (12.5 GHz) analysis shows that the SSB DD-OFDM system meets the HD-FEC target BER for 2 and 4 intermediate filtering stages requiring 14.6 dB and 20.7 dB OSNR, respectively.

C. Bandwidth variable transmitter for hybrid fixed-/flexi-grid optical networks

We have seen that filter narrowing penalties may be considerable when envisioning low bandwidth connections. Thus, an alternative solution to overcome the narrowing effect can be to adapt the net capacity of the channel. This requires BVT with symbol-rate variability (with the corresponding digital OTN hierarchy to support it). This results to a suitable solution for hybrid fixed-/flexi-grid scenarios in metro/regional areas. In a fixed-grid scenario, DP-4QAM signals have been favored at symbol rates of 28 GBaud or 32 GBaud for a 50 GHz frequency slot for channel with 100 Gb/s line rates [20]. Due to the flexible spectrum allocation in EON networks, these signals can be fitted in a 37.5 GHz channel to increase spectral efficiency. Fig. 5 shows the B2B performance for 28 GBaud DP-4QAM signal with different channel bandwidth. The 28 Gbaud DP-4QAM signal can be more tolerant to filtering effect due to its lower spectral occupation comparing to 32 GBaud; and no significant penalty is observed for channel bandwidth

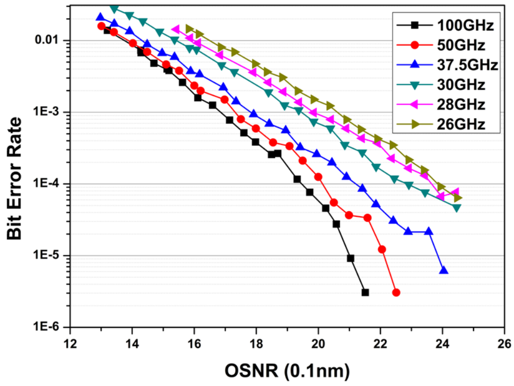

Fig. 5: Back-to-back performance for 28 GBaud DP-4QAM signals with different filter-bandwidth

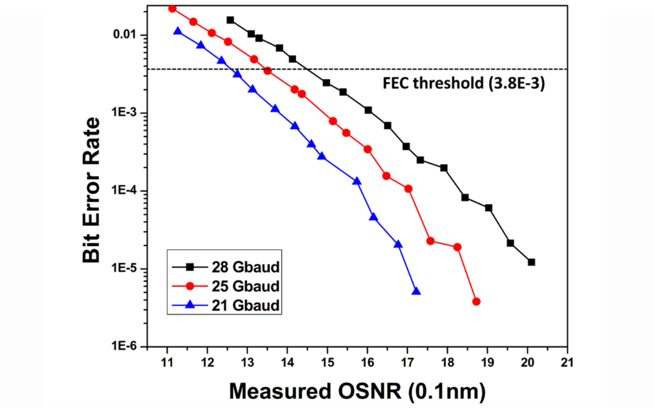

Fig. 6: Back-to-back performance for DP-4QAM signals with different symbol rates in a fixed 37.5 GHz optical channel.

shrinking from 100 GHz to 37.5 GHz. If the channel bandwidth is further reduced, the over-filtering leads to high penalties. The over-filtering tolerance of a 28 GBaud DP-4QAM channel can be used to mitigate the filtering effect. However, as shown in Fig.1b, in hybrid fixed-/flexi-grid optical networks, the compact spectrum signals coming from the flexi-grid domain experience higher degradation due to filtering effect in the fixed-grid domain. Especially, the channels close to the edge of the equivalent channel filter might degrade their performance, leading some optical channel to fail to reach its destination. Thus, this effect should be considered during network planning.

As the occupied optical bandwidth is proportional to the symbol rate, bandwidth variable transmitter can adjust its operation symbol rate to mitigate the filtering effect. In [21], a symbol rate variable transmitter is demonstrated by aggregating the incoming OTN tributaries onto an optical signal supporting just-enough data rate. The symbol rate can be varied from 2.67 GBaud up to 26.7 GBaud in steps of about 2.67 GBaud. By adjusting the operation symbol rate, the occupied optical bandwidth can be suitably set to the signal spectra, mitigating the over-filtering in the link at the expense of a net capacity shrinking.

Fig. 6 shows the B2B performance for DP-4QAM signals with different symbol rates in a 37.5 GHz channel bandwidth. As indicated, the transmitter with a reduced symbol rate can improve its performance for fixed channel width; demonstrating that the severe filtering effect of a hybrid flexi-/fixed-grid optical interconnection can be

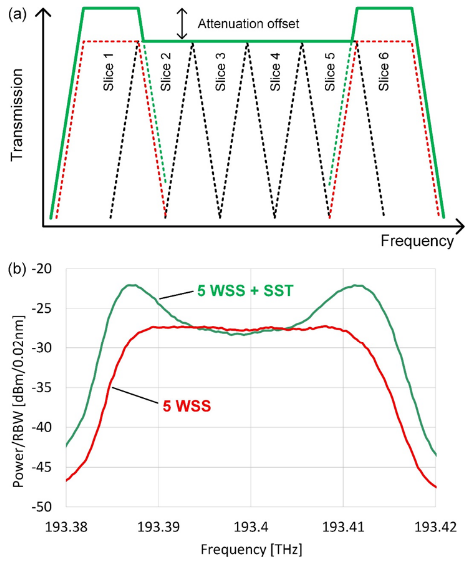

Fig. 7 (a) WSS transfer function with 6.25 GHz grid for routing a 37.5 GHz channel. An attenuation offset between outer and inner slices can intentionally be set (green curve) to enhance the effective bandwidth of the filter. (b) Measured WSS spectra without and with spectral shaping technique (SST).

reduced by suitably configuring the operation symbol rate of DP-4QAM transmitters [22].

D. *Optical Spectrum Shaping*

A method to compensate for narrow filtering is to optically shape the spectrum of the channel, for instance, after a cascade of ROADMs [23]. The optical shaping can be applied at different positions of the link: beginning, end, and distributedly, with the last being the most effective. The latter is at the cost of requiring an optical equalizer per filter [23]. The principles described in [23] have been experimentally validated in [24]. Although the gain provided by the optical shaping is significantly reduced, as a consequence of the frequency offset (between transmitter laser and WSS are not considered in [23]) and of the increased OSNR degradation due to the filter losses. In fact in [23] and [24] it has been employed a wave-shaper (WS) as optical equalizer; a device that introduces high losses in the pass-band, in comparison to a flexi-WSS. A similar solution to [23] and [24] has been presented in [25] where the WS is replaced by a flexi-WSS with similar granularity in attenuation, but not in frequency. The results reported in [25] are in agreement with [24]. This section analyzes a simplified node structure where one device (the WS or the flexi-WSS in [24] and in [25], respectively) is removed, yielding a cost-effective solution.

We consider a 1×20 flexi-WSS, configured with a 6.25 GHz switching granularity for both routing and spectral shaping. In order to create a 37.5 GHz (50 GHz) channel, 6 (8) neighboring spectral slices of the flexi-WSS need to be activated. By reducing the attenuation of the outer slices 1 and 6, the effective bandwidth of the filter can be slightly increased as shown by the green curve in Fig. 7a. When cascading several flexi-WSSes, filtering penalties arise and the benefit of spectral shaping become more important. Fig. 7b depicts the transmission characteristic of 5

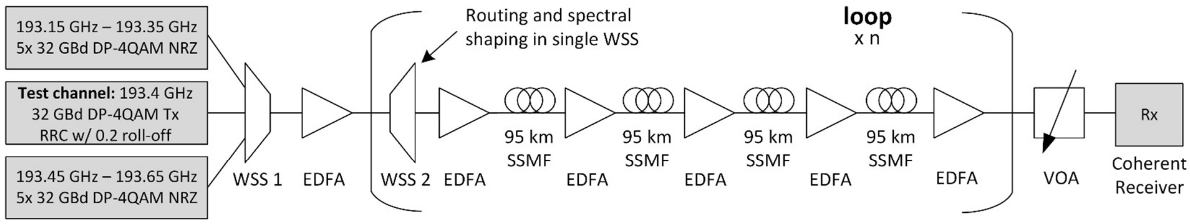

Fig. 8: Experimental setup. A 128 Gb/s 4QAM channel and 10 adjacent 32 GBaud, NRZ 4QAM channels are combined using *WSS 1*, amplified and coupled into a recirculating loop. The loop include *WSS 2* with 6.25 GHz granularity, followed by 4×95 km of standard single mode fiber (SSMF). After the loop, the channel power is set to -10 dBm using a variable optical attenuator (VOA) and received by a coherent receiver.

subsequent 37.5 GHz filters, for the case without (w/o, red) and with (w/, green) spectral shaping technique (SST).

Fig. 8 depicts the experimental setup. The transmitter of the channel under test consists of a digital-to-analog converter with 64 GSa/s, a linear quad-driver amplifier and a dual polarization IQ-modulator. This generates a DP-4QAM signal at a symbol rate of 32 GBaud. A RRC filter with 0.2 roll-off is used for confining the signal spectrum within 38 GHz. The channel under test and 10 adjacent channels (e.g., at 32 GBaud, DP-4QAM, NRZ) are combined on a 50 GHz grid WSS and are subsequently amplified using an Erbium-doped fiber amplifier (EDFA) and sent into a recirculating loop. The loop consists of the investigated flexi-WSS followed by 4×95 km single mode fiber. The launch power into each span is 2 dBm per channel using dedicated EDFAs. After n round-trips, the signal is received by an intra-dyne coherent receiver with off-line digital signal processing. The received channel power is -10 dBm.

In the scope of this work three different settings of the flexi-WSS are investigated: (I) a standard 50 GHz filter bandwidth (w/o SST); (II) a 37.5 GHz bandwidth (w/o SST), and (III) a 37.5 GHz bandwidth (w/ SST) with optimized attenuation of the outer slices for spectral shaping of the channel. We measure the BER of the channel under test as a function of reach or number of loops. The blue curve in Fig. 9a depicts the case of a 50 GHz transmission characteristic. When reducing the filter bandwidth to 37.5 GHz (red) a significant reach penalty is observed. For instance, at BER = 2 10^{-3} we lose 33% (~1100 km) when switching from a 50 GHz grid to a 37.5 GHz grid w/o employing SST.

The spectrum of the signal after traversing the flexi-WSS, for 5 times, is depicted in Fig. 9b. The signal fits into the 50 GHz channel (blue) and the 3 dB signal bandwidth of 32 GHz is preserved. In case of a 37.5 GHz channel (red), the signal suffers from the non-ideal filtering-shape and frequency offset (~1.5 GHz) between filter and signal, and its bandwidth is reduced to 26.5 GHz. The filtering penalty can be reduced when using the SST capabilities of the employed flexi-*WSS* (green). A 3 dB signal bandwidth of 29.6 GHz is measured after 5 flexi-WSSes, see fig. 9b, proving that spectral clipping of high frequencies is reduced. In this configuration, a 24% reach improvement (compared to the case without SST) is achieved when targeting BER = $2{\cdot}10^{-3}$ (green curve in Fig. 9a). When accepting a BER ≤ $3{\cdot}10^{-2}$, the maximum transmittable number of loops increases from 7 (2660 km) to 10 (3800 km).

Next, we investigate the attenuation offset between inner and outer slices of the flexi-WSS with 37.5 GHz channels and its impact on the link performance when traversing 8 flexi-WSSes (8 loops), see Fig. 10a. Without setting an attenuation offset, which corresponds to the red line in Fig. 9a, the signal cannot be recovered after 8 loops. SST enables to detect the signal at a BER of $1.8{\cdot}10^{-3}$ when setting an optimum attenuation offset of 2 dB (see Fig. 9a). When reducing the attenuation offset below 2 dB, spectral clipping of high frequencies increases, resulting in a higher BER. Conversely, an attenuation offset above 2.5 dB also increases the BER. The reason for this is that spectral shaping does not only reduce spectral clipping, but also distorts the signal spectrum, which leads to performance degradation. Therefore a compromise is needed between reducing spectral clipping and restricting signal distortion to a moderate level. In fact, the optimum spectral attenuation parameter

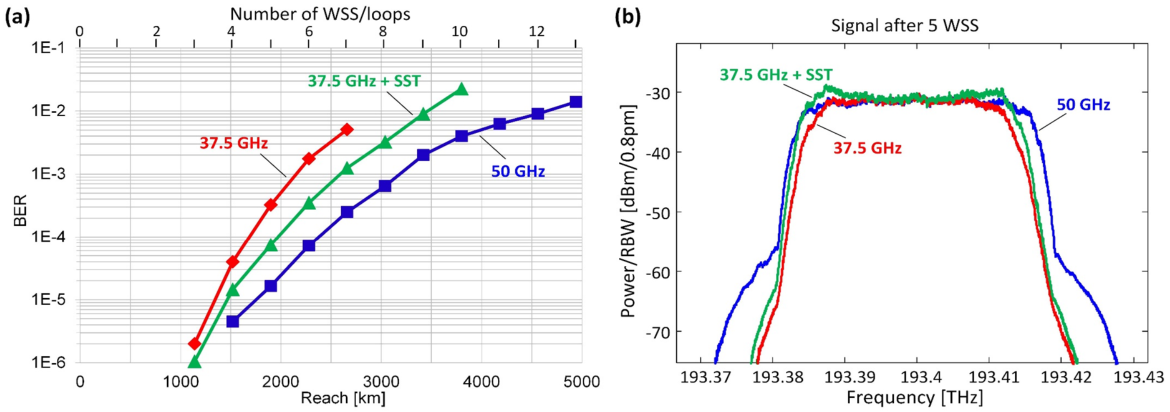

Fig. 9: (a) Loop experiment. (b) Signal spectra after passing 5 flexi-WSS for 50 GHz (blue), 37.5 GHz (red), or 37.5 GHz with spectral shaping (green). SST effectively increases the pass-band width of the WSS channel.

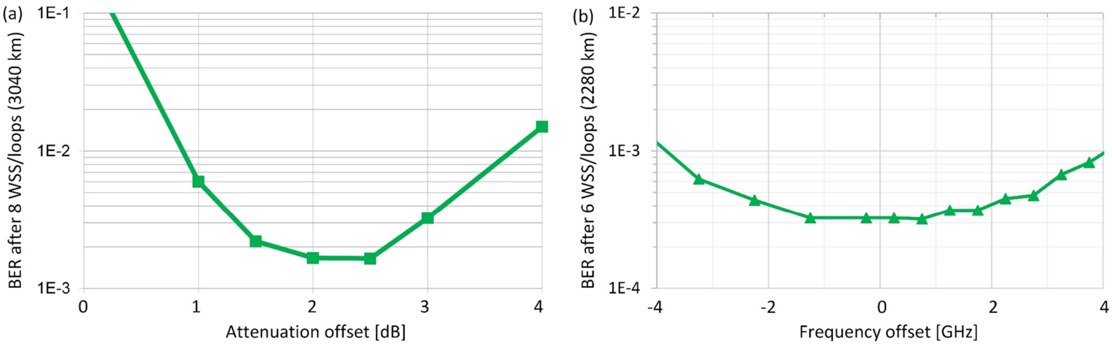

Fig. 10 (a) Optimization of the attenuation offset of the flexi-WSS slices for a 37.5 GHz channel after 8 flexi-WSSes. (b) Impact of relative frequency offset between flexi-WSS filter and signal laser on transmission performance for a series of 6 flexi-WSS.

depends on the number of cascaded flexi-WSSes.

Lastly, we investigate the impact on link performance of a frequency offset between flexi-WSS channel and the signal carrier frequency. According to ITU standards, the frequency offset of the WSS channel and of the signal carrier from the defined ITU grid is ≤ 1.5 GHz. Therefore, the worst case for the relative offset between carrier and flexi-WSS channel is 3 GHz. We measure the BER of the test channel after 6 flexi-WSS loops with SST as a function of this relative frequency offset as reported in Fig. 10b. In our tests, we find that a 3 GHz offset increases the BER from $3\cdot10^{-4}$ to $6\cdot10^{-4}$.

E. Differentiated/enlarged filter bandwidth

Lastly, a selection of network level techniques to mitigate filtering effect is here considered. Such techniques can be applied alone or in conjunction with the transmission approaches previously discussed.

Among them, differentiated filter configuration (DFC) [26] can be an effective solution to trade-off between spectral efficiency and detrimental filtering effect. According to DFC, the pass-band of the filters traversed by the same connection can be configured to different values (as shown in Fig. 11a). Specifically the bandwidth of each filter along the path, in term of number m of elementary ITU-T slots, can be set to different values. Acting this way, m can be set to low values (e.g., $m = 4$) in specific nodes to occupy a low amount of spectrum along the outgoing links. Then, it can be set to higher values (e.g., $m = 5$) to avoid an excessive accumulation of filtering effect that could degrade the signal. As a result, spectrum reservation can be minimized on a per node basis according to the expected quality of transmission, improving the overall spectrum utilization. Such a technique can be applied to both, single channel and super-channel.

A particular case of DFC is the super-filtering technique [27], consisting in the aggregation of several independent super-channels (or either single channels) within the same filter pass-band along common links. An example is shown in Fig. 11b, where three channels sharing adjacent spectrum and links A-B and B-C are collected under the same pass-band in nodes A and B (and related outgoing links), while are associated to individual pass-band in the other links. The super-filtering solution limits the filtering effect. In fact, when collected under the same pass-band, central channel avoid filter transition bands and external channels are impacted only for one side of the spectrum.

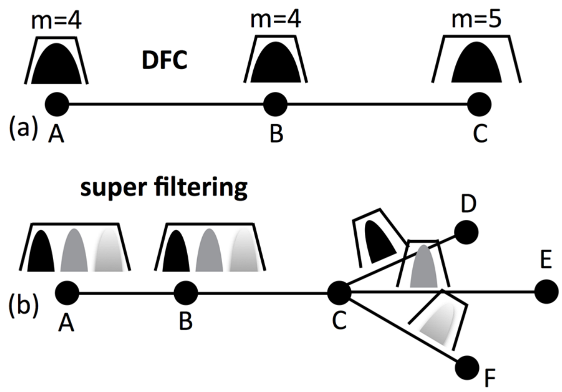

Fig. 11: (a) DFC; (b) super-filtering DFC.

IV. Discussion and Conclusion

Filter narrowing effect in EON presents different aspects that are mutually related. First, it is bounded by the given networking scenario. According to the use cases introduced in Sec. II, both the hybrid fixed-/flexi-grid optical network and the full flexi-grid optical network suffer the filter narrowing effect. On the contrary, the filterless optical network is a simple cost effective approach that is not affected by filtering effect; but at the expense of other issues detailed in Sec. II, such as the bandwidth limit and the strict requirements for implementing resiliency.

We have seen that when tackling a hybrid fixed-/flexi-grid optical network, the effects that predominate are those related to WSSes employed in the legacy part of the scenario. Thus, the use of BVT has been proposed as a solution. In fact, the filtering effect cannot be compensated with currently available technologies. However, it is related to the devices used and, thus, it can be predicted and managed. The BVT based solution uses filtering-tolerant signal, such as a symbol rate adjustable DP-4QAM, to tolerate small filtering effect. When filtering effect occurs, the BVT configures its optical bandwidth to reduce the penalty on the signal performance at the expense of the net capacity. This solution requires network planning and BVT capable to provide a fine granularity of symbol rate to combat the filtering effect.

Next, we have seen that for a pure flexi-grid approach, the filtering effect depends on (I) the transmission technologies, (II) the internal architecture of the nodes, (III) the type of flexi-WSSes employed, and (IV) how the optical channels are set-up and routed. These four points are deeply interrelated

Table I: Comparison between the different transmission technologies investigated. Additional data (including reach, target OSNR and capacity) is extracted from previous works [7][16][28] and commercial datasheets [29]. NWDM: Nyquist WDM.

Technology	Modulation Format	Symbol rate [GBaud]	Number of optical sub-carriers	Net Capacity [Gb/s]	Target OSNR [dB]	Unfiltered Reach [km]	Filtering penalty [dB]	Number of ITU-T slots	Number of filters	Application
NWDM	DP-QPSK	32.5	1	100	11.5	2400	3	3 (37.5 GHz)	6	M-R
NWDM	DP-QPSK	32.5	1	100	11.5	2400	3	4 (50 GHz)	>30	M-R-LH
NWDM	DP-16QAM	32.5	1	200	20.0	360	3	3 (37.5 GHz)	3	M-R
NWDM	DP-16QAM	32.5	1	200	20.0	360	3	4 (50 GHz)	>30	M-R-LH
NWDM	DP-QPSK	32.5	3	300	11.5	2400	1	9 (112.5 GHz)	14	M-R
NWDM	DP-QPSK	32.5	3	300	11.5	2400	1	10 (125 GHz)	>30	M-R-LH
NWDM	DP-QPSK	32.5	4	400	11.5	2400	1	12 (150 GHz)	14	M-R
NWDM	DP-QPSK	32.5	4	400	11.5	2400	1	13 (162.5 GHz)	>30	M-R
NWDM	DP-16QAM	32.5	2	400	20.0	360	1	7 (87.5 GHz)	>30	M-R-LH
NWDM	DP-16QAM	32.5	3	600	20.0	360	1	9 (112.5 GHz)	10	M-R
NWDM	DP-16QAM	32.5	3	600	20.0	360	1	10 (125 GHz)	>30	M-R-LH
OOK	OOK	10.7	1	10	9.8	80	15.3	1(12.5 GHz)	4	M-R
OOK	OOK	10.7	1	10	10.7	80	5.9	2 (25 GHz)	>12	M-R
OOK	OOK	10.7	1	10	10.7	80	0	4 (50 GHz)	>12	M-R
OFDM	Adaptive ≤256 QAM	6.11	1	10	15	>200	8.4	1 (12.5 GHz)	4	M-R
OFDM	Adaptive ≤256 QAM	6.11	1	10	15	>200	2.7	2 (25 GHz)	>12	M-R
OFDM	Adaptive ≤256 QAM	6.11	1	10	15	>200	0	4 (50 GHz)	>12	M-R

and should be regarded as a whole.

The transmission technologies suitable for the full flexi-grid network scenario are several [4]. In this work, we consider the Nyquist WDM transmission of super-channels for establishing high symbol rate connections and targeting an extended reach. Alternatively, for the use case of aggregating low bit rate traffic, we investigated SSB DD-OFDM systems and here we include the legacy 10G OOK, reported in [16], for the sake of comparison.

All their performance are summarized in Table I. The values reported in Table I show that Nyquist WDM, featuring coherent detection, can cover transmission distances between 360 km and 2400 km (considering reasonable system margins) with OSNR penalties of up to 3 dB due to filtering issues. Opposed to the Nyquist WDM coherent transmission, legacy 10G OOK and SSB DD-OFDM can be considered for a cost-effective aggregation of low bit rate connections. As it can be observed in Table I, filtering penalties are severe when employing a single ITU-T elementary slot (12.5 GHz) for both transmission technologies, and the maximum number of intermediate nodes to be traversed is limited to 2. Nevertheless, in case of employing 2 elementary slots (25 GHz), the filtering penalties are limited to 5.9 dB for OOK and 2.7 dB for SSB DD-OFDM. Thus, results show that SSB DD-OFDM provides increased flexibility and robustness to transmission impairments without dispersion compensation (and regeneration stages), thanks to its ability to set different performance target.

The role of the internal ROADM architecture and the flexi-WSSes functionalities also are to be considered. First, the type of traffic to aggregate may condition the features to implement at each node and, thus, their architecture. This is strongly related to the behavior of the flexi-WSSes employed. In case of incorporating advanced flexi-WSSes capable to route and conveniently shape the spectrum of the optical signal, adverse filtering effect can be mitigated using SST. SST has shown to be a powerful technique that envisions optical wave-shaping for the mitigation of filtering penalties originating from the cascade of (flexi-) WSSes.

Finally, the way channels are set-up and routed is also critical. As shown in Table I, the transmission penalties of Nyquist WDM are substantially decreased (from 3 dB down to 1 dB) when packing several wavelengths in the same super-channel. Indeed, the optical sub-channels that fall in the central part of the super-channel do not show any substantial penalty, while the sub-channels that are in sub-carriers at the edges suffer a partial degradation. Another possibility would be to use digital subcarrier multiplexing, where the edge subcarriers present more robust modulation format compared to the central ones, as reported in [30].On the other hand, in case of single-channel transmission, we showed that when approaching 3 spectral slots (37.5 GHz) and below, the filter narrowing effect becomes more important. In order to overcome this, a possible mitigation technique is based on the optical spectral shaping, achieving a 24% reach improvement for the Nyquist WDM case. A similar principle is also exploited in super-filtering technique in order to limit the filtering penalties by aggregating several independent (super-) channels within the same filter pass-band along common links. Such a methodology, as well as DFC, is independent from transmission technologies. Thus, filters along the path can be differentially configured node by node by limiting detrimental filtering effect while minimizing the occupied spectrum along the network. This reflects in the reduction of connection blocking probability or, conversely, on the increase of accepted network load. Studies in [31] have shown that the adoption of both DFC and super-filtering can increase the network load by 15% with respect to a network applying traditional filtering, given the improvements on spectrum utilization.

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