# Investigation of Spectrum Granularity for Performance Optimization of Flexible Nyquist-WDM-Based Optical Networks

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***Abstract*—The idea behind flexible optical transmission is to optimize the use of fiber capacity by flexibly assigning spectrum and data rate adapted to the needs of end-to-end connection requests. Several techniques have been proposed to this end. One such technique is based on the utilization of Nyquist-shaping filters with the aim of reducing the required channel spacing in flexible single-carrier and super-channel optical transmission systems. Nonetheless, the imperfect shape of the filters used at the bandwidth-variable transceivers and wavelength-selective switches compels the necessity to allocate a certain spectral guard band between (sub-)channels. Bearing this is mind, in this paper, we focus on the evaluation of the network-level performance, in terms of the filter characteristics and the WDM frequency-grid granularity, of flexible Nyquist-WDM-based transmission. We demonstrate that a granularity of 6.25 GHz offers a good compromise between network performance and filter requirements for spectrum assignment to single-carrier and super-channel signals. However, for sub-channel allocation within a super-channel, granularities as fine as 3.125 GHz are required to take advantage of filters with resolutions in the region of 1–1.2 GHz. Finer filter resolutions and frequency slot granularities provide negligible performance improvement.**

***Index Terms*—DWDM, elastic optical network, filtering, flexi-grid, network optimization.**

## I. Introduction

TRIGGERED by emerging services such as high-definition video distribution and social networking, the IP traffic volume has been exponentially increasing. The global IP traffic volume is expected to surpass the zettabyte threshold by the end of 2017 [1]. Furthermore, new hardware advances, such as multi-core processing, virtualization and network storage, are envisioned to support innovative e-Science and grid applications with data flows of 10 Gb/s up to the terabit level, making the traffic profile extremely diverse and time-varying. The predictable consequence is that the network operators will require a new generation of optical transport networks in the near future to serve this colossal and heterogeneous volume of traffic in a cost-effective and scalable manner. In response to these large capacity and diverse traffic granularity needs of the future Internet, the flexible optical network (FON) architecture has been proposed [2], [3], which increases the scalability in the connection provisioning by breaking the fixed-grid spectrum allocation limit of conventional wavelength division multiplexing (WDM) networks. To do so, depending on the traffic volume, an appropriately sized optical spectrum portion, data rate and modulation format is assigned to bandwidth adaptable (i.e. flexible) connections, with the aim of optimizing the use of the network resources.

To accommodate traffic, the available optical bandwidth is discretized in spectrum units, referred to as frequency slices (FS). According to the ITU-T 694.1 standard, the frequency slot granularity is 12.5 GHz —so that, e.g., 1, 1.5, and 2 THz optical bandwidths correspond to 80, 120, and 160 slices, respectively— and the spectrum variability of the connections is achieved by varying the number of allocated FSs. Despite the fact that the current spectrum discretization provides some benefits such as simpler connection labeling on the network control plane [2], there is a vivacious discussion in the research community about the effectiveness of this selection (in terms of spectrum utilization) and the possibility of moving to smaller FS sizes or even to gridless operation. For example in [4] it was demonstrated that, for mixed-rate signal transmission, an FS size calculated as the greatest common factor of the spectrum width of all signals would bring benefits in terms of network performance. Nevertheless, it did not address a scenario with fully flexible traffic accommodation and only evaluated the optimum FS size considering granularities down to 10 GHz. In [5] it was found that a gridless spectrum assignment achieved a performance similar to that of a 3-GHz grid in a CO-OFDM super-channel (Sp-Ch) transmission system, but an investigation on the impact of filter resolution for sub-channel (Sb-Ch) shaping and Sp-Ch switching upon Sp-Ch accommodation was not carried out. Recent developments in FON-enabling filtering technologies [6], [7] have made it possible to pack Nyquist-filtered Sb-Chs closer together (thereby reducing the inter-sub-channel guard band) while still obtaining a good transmission performance. Of course, dense packing of Sb-Chs may require

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a finer grid than the ITU-T 12.5-GHz grid, but moving to finer spectrum granularities might not be profitable unless the extra cost of developing these new filtering technologies translates into sufficient benefits with respect to the overall network performance and cost. Hence, it is important to find a suitable compromise between spectrum granularity, filter characteristics and network performance. Here, we aim at providing an answer to this conundrum.

Building on our previous studies [8] and [9] carried out under the framework of the EU ICT project FOX-C [10], in this paper we study the effect of the choice of frequency grid and filter resolution on the performance of flexible Nyquist-WDM transmission systems from a networking point of view. To provide a wider perspective, we divide the study into two flexible Nyquist-WDM transmission systems: single-carrier and super-channel transmission. Single-carrier transmission, due to current analog-to-digital/digital-to-analog (ADC/DAC) technology limitations, is more appropriate for low traffic volumes. Conversely, Sp-Ch transmission relying on Nyquist-shaped Sb-Ch multiplexing is capable of circumventing this problem through parallel processing of lower-bit-rate signals at the transceivers, thus becoming a powerful alternative technique to serve high traffic volumes. We initially detail each transmission system model and then investigate through extensive discrete event simulations the effect of filter sharpness on the performance of the transmission system models. Compared to [8] and [9], in this paper we include a more detailed transmitter description and present new simulation results to take into account several Sp-Ch level FS granularities and Sb-Ch baud rates.

The rest of the paper is organized as follows. Section II describes the transmission system models. Simulation results are showed in Section III. Finally, in Section IV we present our conclusions.

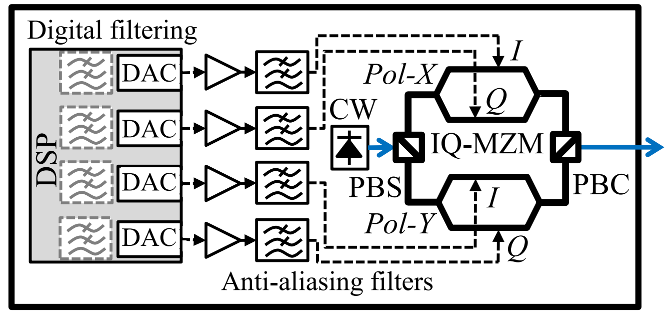
## II. Transmission System Models

### A. Flexible Single-Carrier Transmission System

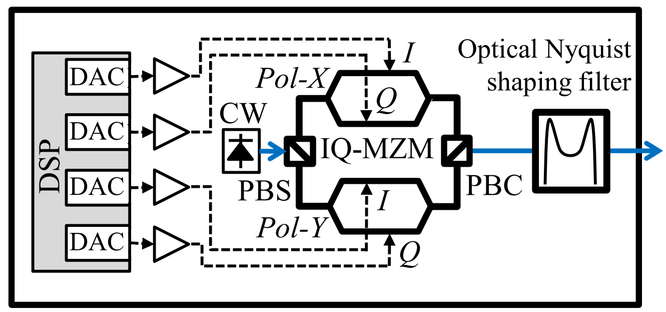
Nyquist-shaped signal transmission is one of a promising new generation of techniques for minimizing signal spectral occupancy, achieving square-like power spectrum with bandwidth matching the baud rate. In order to shape the signal spectrum, digital filtering (performed in the transmitter (Tx) DSP) is usually employed [6], although recent advances in filtering technology based on liquid crystal on silicon (LCoS) have also made it possible to implement high-spectral-resolution (HSR) optical Nyquist-shaping filters with resolutions of down to 0.8 GHz and spectral addressability of 400 MHz/pixel [7]. In Fig. 1 we depict two equivalent Tx implementations for Nyquist-shaped single-carrier dual-polarization (DP) phase-shift-keying (PSK) transmission relying on either digital or optical filters.

In practice, the signal square-like spectrum is slightly relaxed by shaping it with a raised-cosine filter [11] at the Tx. Thus, for a certain roll-off value, the total reserved spectrum after filtering ($BW_{\mathrm{Tx}}$) is given by [12]

$$BW_{\mathrm{Tx}} = (1+\beta)\, BW\ , \tag{1}$$




(a)




(b)

Fig. 1. Tx implementations for Nyquist-shaped signal transmission. Two equivalent filtering technologies are presented: (a) digital filtering performed in the DSP, and (b) optical filtering. PBS/PBC: Polarization Beam Splitter/Combiner. IQ-MZM: IQ Mach-Zehnder Modulator.

where $\beta$ is the filter roll-off factor and *BW* is equal to the signal baud rate. In this formulation, the spectral penalty due to the imperfect filter shape amounts to $\beta \cdot BW/2$ (on each side of the connection). For small $\beta$, these filters have therefore very sharp rising/falling edges.

At the intermediate nodes, we consider flex-grid LCoS-based WSS, whose spectral roll off at the filter edge can be modeled as an error function with sharpness defined by the optical resolution and position given by the spectral addressability of the filter [13]. In this study we have considered four different values for the optical resolution, namely, 2.5, 5.0, 7.5 and 10.0 GHz, such that the finer the resolution, the wider and flatter the passband characteristic across the allocated channel bandwidth. The spectral penalty —or guard band (GB) required on each side of the connection— due to the imperfect shape of the WSS filter was calculated as the extra spectrum required compared with the ideal Nyquist channel spectral width (i.e. *BW*) to achieve $-35$ dB transmissivity at the channel edge.

Fig. 2 shows the spectral penalty (or GB) as a function of the transmitter filter roll-off value (calculated according to (1)) and the intermediate-node WSS filter resolution for different signal baud rates (assuming future technology advances enabling single-carrier transmission at up to 125 GBaud. High symbol rates of 80 and 107 GBaud have already been reported in [14]). The gray area indicates the range of baud rates considered in this study, from which we have singled out three baud rates: 40, 50 and 60 GBaud. The Tx raised-cosine filters are load aware, while the LCoS-based WSS filters are load agnostic. The GB allocated to a certain channel is then dependent on which filter is dominant for a given baud rate, Tx-filter roll off, and

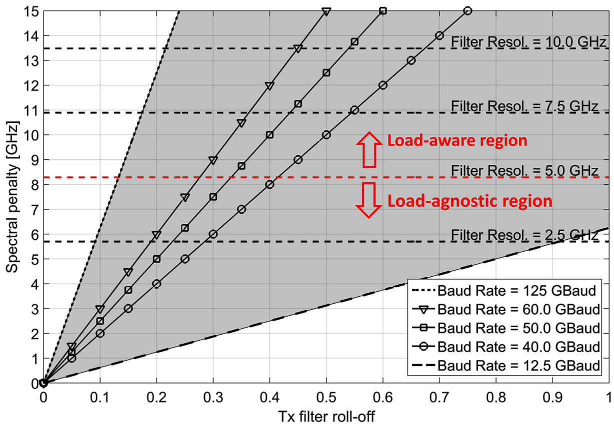



Fig. 2. Spectral penalty as a function of the Tx and WSS filter characteristics for single-carrier transmission with baud rates ranging from 12.5 to 125 GBaud (gray area). Load-agnostic and load-aware regions are shown (in red) for WSS filter resolution = 5.0 GHz.

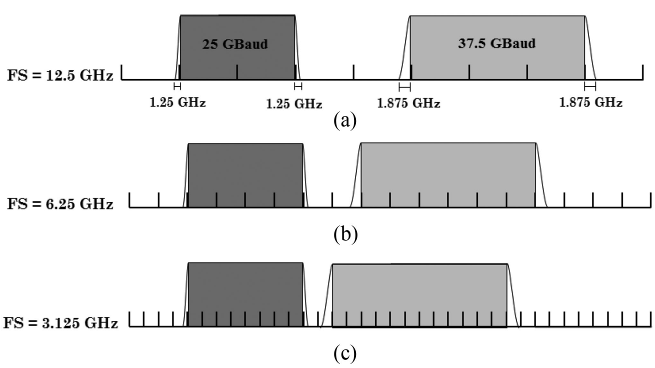



Fig. 3. GB assignment for two exemplary connections, considering FS size of (a) 12.5 GHz, (b) 6.25 GHz, and (c) 3.125 GHz.

WSS-filter optical resolution. Let us define a *load-agnostic region* as the area in the graph in which the WSS filter spectral penalty is dominant for a given optical resolution (and therefore the GB value must be equal to this spectral penalty value). Conversely, a *load-aware region* can be defined as the area in which the Tx raised-cosine filter penalty is dominant for a given WSS optical resolution and offered load. In both cases, the region reduces to a vertical line when a specific Tx-filter roll-off value is considered. These definitions will be used in discussing the simulation results.

To explain how the amount of reserved spectrum per connection request is influenced by the FS size, let us ignore for now the impact of the WSS filters (e.g. single-carrier transmission in a point-to-point configuration). If we consider two connections of 25 GBaud and 37.5 GBaud in a scenario with Tx roll-off factor of 0.10, a spectral penalty of 1.25 and 1.875 GHz, respectively, according to (1), is observed at each side of the connections, as shown in Fig. 3(a). Therefore, considering the conventional FS size, a spectrum portion equal to 25 GHz (12.5 GHz per connection) must be left unused between the two adjacent connections (worst case GB assignment) [15], [16]; alternatively, GBs can be assigned as explained in [17]. In this way, $\sim$22 GHz of spectrum are wasted ($25 - (1.25 + 1.875) = 21.875$ GHz). By moving

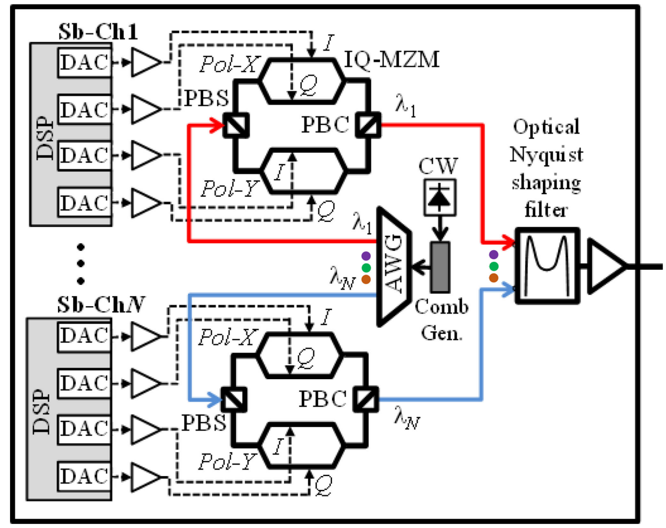



Fig. 4. Sp-Ch Tx based on optically filtered Nyquist-shaped Sb-Chs. Instead of $N$ lasers, this realization employs a comb generator and an arrayed waveguide grating (AWG).

to finer FS sizes, for instance, 6.25 GHz or 3.125 GHz, the spectrum utilization can be improved by reducing the amount of wasted spectrum. As depicted in Fig. 3(b), with FS size = 6.25 GHz, the wasted spectrum reduces to 9.375 GHz ($12.5 - 3.125 = 9.375$ GHz). In the same way, Fig. 3(c) indicates that a FS size equal to 3.125 GHz leads to almost 65% less wasted spectrum compared to the previous case. In light of this, it could be inferred that better spectrum utilization can be achieved by moving to finer FS granularities. This claim, nevertheless, needs to be examined for different filter characteristics and load profiles in order to quantify the gain obtained when moving toward lower granularities from a networking perspective.

## B. Flexible Super-Channel Transmission System

In this case, we consider a Nyquist-WDM-based Sp-Ch Tx. Fig. 4 presents an exemplary Tx implementation relying on a comb generator and a $1\times N$ optical Nyquist shaping filter, where $N$ is the number of Sb-Chs. In this study we assume that the $N$ Sb-Chs are DP-PSK-modulated by two IQ Mach-Zehnder modulators (MZM) and Nyquist-shaped by an inverse-Gaussian filter of order 2 with resolution ranging from 0.8 to 3.125 GHz. Fig. 5(a) shows the spectrum of a 25-GBaud signal at different stages within an optical-filter-based Sp-Ch Tx implementation with Sb-Ch Nyquist-shaping filter resolution of 0.8 GHz. Transmitters integrating digital filters with similar characteristics, albeit not shown here, yield equivalent results.

For Sb-Ch allocation, five different spectral grids are considered (12.5 GHz, 6.25 GHz, 3.125 GHz, 1.5625 GHz and gridless), so that the total Sb-Ch bandwidth, including the inter-Sb-Ch GB (calculated as twice the value given by Table I for different filter resolutions and two levels of crosstalk), is a multiple of the minimum slot width granularity in each case. Fig. 5(b) illustrates this point by depicting an exemplary Sp-Ch composed of five Nyquist-shaped Sb-Chs in two cases: the Sb-Chs comply with the ITU-T 12.5-GHz grid (top) and the Sb-Chs are

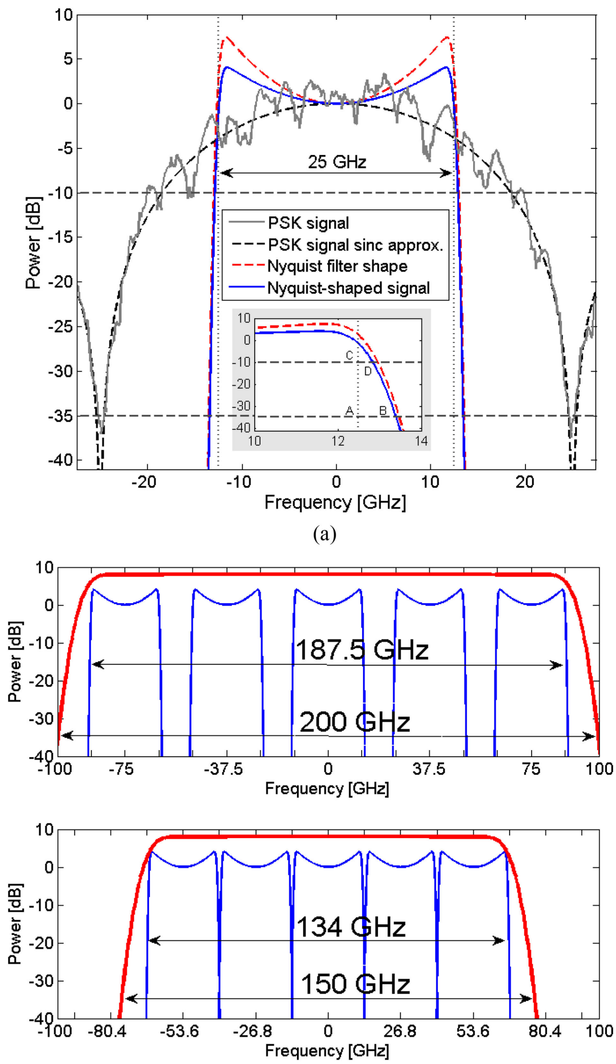



Fig. 5. (a) Simulated spectrum of the output signal of a MZM driven by a 25-GBaud square signal with rise time 0.32 ns (gray solid); approximation of the spectrum by a sinc function (black dashed); 0.8-GHz-resolution Nyquist-shaping filter transmissivity (red dashed); filter output spectrum (blue solid); inset: detail of falling edge of filter and output signal showing segments AB and BC along elevation lines for −35 and −10 dB block BWs used to calculate the GB between Sb-Chs. (b) Sp-Ch composed of 5 Sb-Ch spaced out according to the ITU-T 12.5-GHz grid (top) and based on gridless multiplexing (bottom). The Sp-Ch filter transmissivity is shown in red (shifted up for clarity).

multiplexed in a gridless scenario (bottom). In both cases, we have considered the spectral penalty incurred by the signal when a maximum level of crosstalk of −35 dB was allowed after Sb-Ch shaping by a 0.8-GHz-resolution filter. A significant spectral-occupancy difference (187.5 vs. 134 GHz) can be observed.

At the intermediate nodes, we assume in this case that the Sp-Chs go through flex-grid LCoS-based WSSs with 7.5-GHz resolution and 6.25-GHz spectral addressability. A 12.5-GHz GB between Sp-Chs is regarded to be sufficient to guarantee low impact of WSS cascading, especially when the level of crosstalk is low (e.g. −35 dB), in which case we mainly observe degradation due to ASE noise [18]. Furthermore, we initially require that the Sp-Chs comply with the ITU-T 12.5-GHz grid, so

TABLE I
SPECTRAL PENALTY FOR DIFFERENT NYQUIST-SHAPING FILTER RESOLUTIONS AND CROSSTALK VALUES

| Res. \ Xtalk | -10 dB | -35 dB |
|---|---|---|
| 0.8 GHz | 0.40 GHz | 0.90 GHz |
| 1.0 GHz | 0.42 GHz | 1.12 GHz |
| 1.2 GHz | 0.50 GHz | 1.34 GHz |
| 1.5 GHz | 0.61 GHz | 1.66 GHz |
| 2.0 GHz | 0.79 GHz | 2.19 GHz |
| 2.5 GHz | 0.95 GHz | 2.70 GHz |
| 2.75 GHz | 1.02 GHz | 2.95 GHz |
| 3.125 GHz | 1.13 GHz | 3.32 GHz |

their total bandwidth, including GB, is a multiple of 12.5 GHz. Therefore, in Fig. 5(b) the five-band Sp-Ch bandwidth subtends 200 and 150 GHz for the Sb-Ch-level 12.5-GHz-FS-size and gridless allocation scenarios, respectively.

### C. Filter Cascading

The transmitted optical signal may experience multiple optical filtering along its route. In this case, the effect of signal distortion due to cascaded optical filters has to be taken into account. The dominant signal distortion factor is unwanted spectral clipping arising from the narrowing of the filter passband [19], this effect being more destructive for lightpaths traveling through larger numbers of node hops [20]. In order to compensate for this degradation, filters with sufficiently large bandwidths are used to guarantee that the received signal is not distorted. From the networking point of view, this effect can be translated into more reserved spectrum for connections. In the single-carrier transmission system, given that the assigned GB is not enough to withstand the degradation brought on by a large cascade of filters, a quasi-dynamic scheme is introduced. We assume that for every lightpath with path length equal to $P$ (expressed as the number of transparent hops), the extra reserved spectrum for the connection due to the cascading effect (ERS) is given by $ERS = \lfloor (P-1)/4 \rfloor \times 6.25$ (GHz) [19], where $\lfloor \cdot \rfloor$ is the floor function. For example, if we have a connection traveling over six links, an extra portion of spectrum equal to 6.25 GHz is reserved for the connection in order to compensate for the effect of filter cascading.

Conversely, for the super-channel transmission system, on account of the considered WSS filtering characteristics and the sharp edges of the Sb-Chs, the 12.5-GHz GB between Sp-Chs is assumed to be sufficient to guarantee a good performance through a cascade of WSSs without the requirement of assigning extra spectrum.

## III. Simulation Results

Discrete event simulation studies have been carried out for performance evaluation purposes using the 34-node GÉANT2 pan-EU reference network topology with 54 links [21]. We assumed a total optical spectrum of 4 THz per link (C-band) and considered DP-BPSK as the modulation format due to its capability to support long reach optical transmission, which allows establishing all possible connections in the GÉANT2 pan-EU network [22]. To solve the routing and spectrum allocation (RSA) problem, a k-shortest path computation algorithm with a first-fit slot assignment starting with the shortest computed path was applied [23]. Additionally, unidirectional connections between end nodes were considered due to the asymmetric nature of today's Internet traffic. The load generation followed a Poisson distribution process, so that different offered loads could be obtained by keeping the mean holding time (HT) of the connections constant to 200 s, while their mean inter-arrival time (IAT) was modified according to the formula: offered load = HT/IAT. Traffic demands for each source-destination pair were randomly generated following a normal distribution over the range of study: (A) 25 Gbps to 250 Gbps for the flexible single-carrier transmission system and (B) 50 Gbps to 400 Gbps (corresponding to 1 to 8 Sb-Chs at 25 GBaud) for the flexible Sp-Ch transmission system. The average traffic demand of all generated connections in the simulation ($3 \times 10^5$) was used as a measure of the service granularity. The GB calculation and assignment policy, along with the effect of filter cascading, presented in Section II.C, were considered for all cases under study. The results have a confidence interval of 95% at all runs.

In a first study, we investigated the effect of the filter characteristics on the performance of the single-carrier transmission system in terms of the blocking probability (BP = total dropped traffic (Gbps) / total offered traffic (Gbps)). To do that, three optical resolution values (2.5, 5 and 7.5 GHz) for the WSS filters at the intermediate nodes and two roll-off values (0.05 and 0.3) for the Tx filters were considered. Regarding the offered load, the average number of connections per node was fixed at 8.5 for all cases under study (the total average number of connections in the network was therefore 289) and the simulations were run for three average bit rates per connection, namely, 80, 100 and 120 Gbps. Consequently, the total average traffic generated per node was 680, 850 and 1020 Gbps, respectively. Similarly, we evaluated the impact of using finer FS granularities on the BP performance of the network by running simulations with three FS sizes: 12.5, 6.25 and 3.125 GHz.

As can be seen in Fig. 6, a significant reduction in BP can be achieved by moving to sharper filters (e.g. with avg. bit rate = 120 Gbps and FS = 12.5 GHz, Tx roll off = 0.05 and WSS optical resolution = 2.5 GHz provide ~50% BP reduction compared to Tx roll off = 0.3 and same WSS optical resolution. Likewise, Tx roll off = 0.05 and WSS optical resolution = 2.5 GHz provide ~45% improvement in BP compared to Tx roll off = 0.05 and WSS optical resolution = 7.5 GHz). The remarkable difference (~65% BP reduction for avg. bit rate = 120 Gbps) between the network BP for the best (i.e. Tx roll off = 0.05 and WSS optical resolution = 2.5 GHz and FS = 3.125 GHz) and worst (i.e. Tx roll off = 0.3 and WSS optical resolution = 7.5 GHz and FS = 12.5 GHz) characteristics (for a given service granularity) is due to the fact that with better filter shapes connections can be allocated closer to one another without requiring a wide GB in between, and therefore the chances of finding free spectral resources for establishing new connections in the network improve. In addition, it is worth noting that in all cases under study with FS size = 12.5 GHz the network BP is higher than in the case of finer FS sizes. This

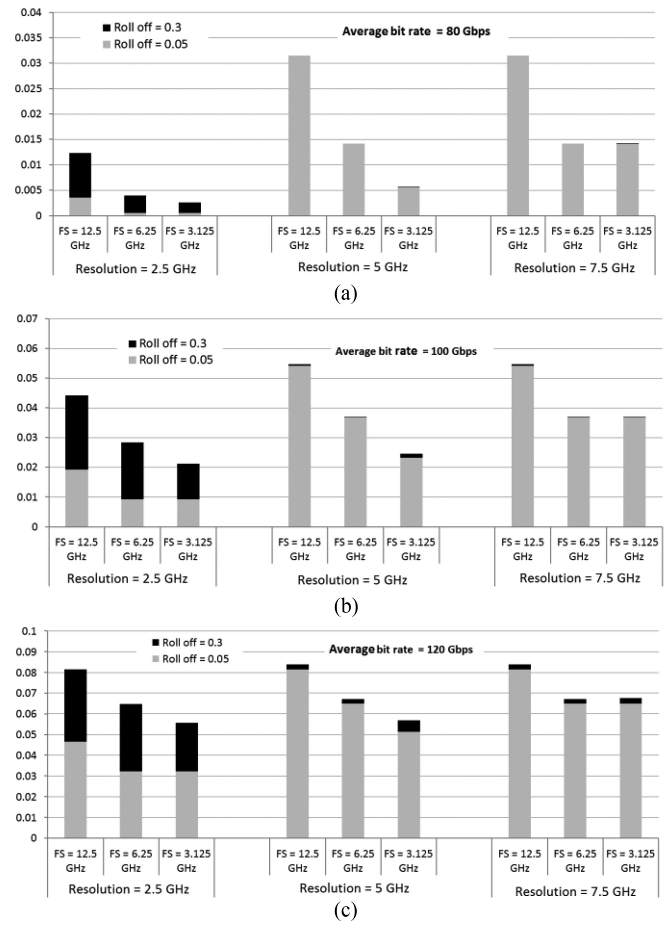



Fig. 6. Network BP for six filter characteristics (Tx filter roll off = 0.05 and 0.3, and WSS resolution = 2.5, 5 and 7.5 GHz) and three FS sizes (12.5, 6.25 and 3.125 GHz) for different offered loads. The average bit rate per connection is (a) 80 Gbps, (b) 100 Gbps, and (c) 120 Gbps.

result can be justified by virtue of the arguments given in the previous section: from a closer look at how the filter spectral penalty is calculated, we can easily deduce that in most cases the total spectral penalty is lower than 25 GHz and therefore it is possible to consider just one FS (12.5 GHz) as GB (on each side of a connection) to guarantee its quality of transmission –QoT– (conventional worst-case design). Hence, in general, by moving to finer FS granularities the amount of wasted spectrum for GB reduces.

However, this assertion needs to be qualified. To gain a better insight into this matter, let us investigate each of the filter characteristics individually. With a Tx filter roll-off value of 0.05, we find ourselves in the load-agnostic region, and therefore the GB value is given by the WSS filter spectral penalty. Since WSS optical resolutions of 2.5, 5.0 and 7.5 GHz lead to spectral penalties of ~6, 8 and 11 GHz, respectively, we observe that employing the finest FS size (3.125 GHz) can only provide benefits if the WSS optical resolution is set to 5 GHz, there being no reason to go for finer FS sizes than 6.25 GHz in any other case (for 5-GHz WSS resolution, the GB is 3·3.125 GHz with 3.125-GHz FS size, whereas 2·6.25 GHz are required with 6.25-GHz FS size). Similarly, with a Tx filter roll-off value of 0.3 and WSS optical resolution equal to 5 GHz, we are around

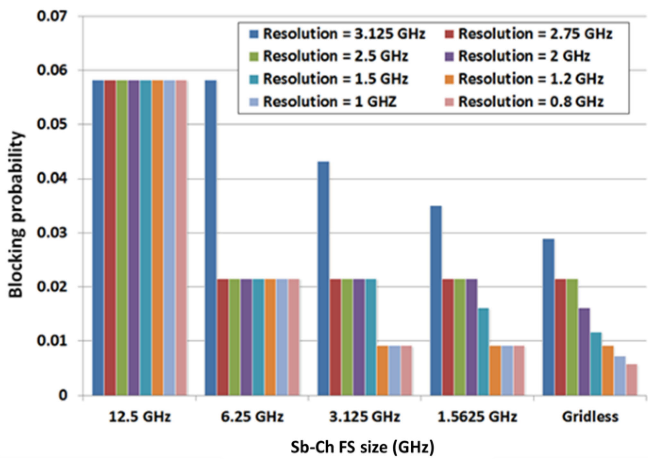



Fig. 7. Network BP for different Sb-Ch filter characteristics and Sb-Ch-level FS sizes.

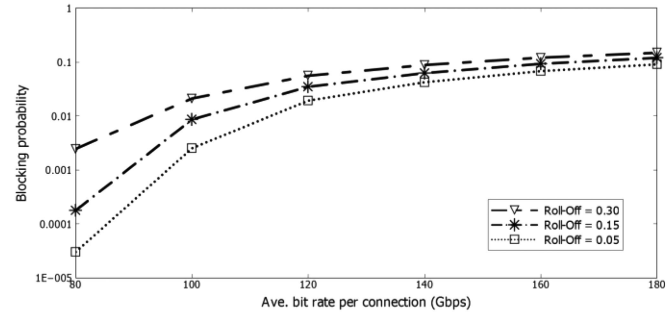



Fig. 8. Network BP for different roll-off values (considering ideal WSS filters). The offered traffic to the network ranges from 680 to 1530 Gbps per node (i.e. average number of connections per node 8.5 and average bit rate per connection ranging from 80 to 180 Gbps).

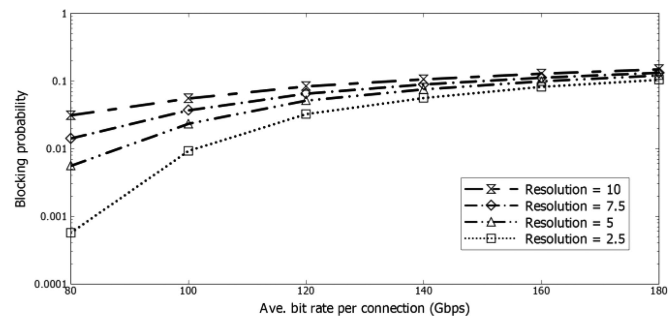



Fig. 9. Network BP for different resolutions (considering ideal Tx Nyquist filters). The offered traffic to the network ranges from 680 to 1530 Gbps per node (i.e. average number of connections per node 8.5 and average bit rate per connection ranging from 80 to 180 Gbps).

the edge of the load-agnostic region, so the GB value is either equal or very similar to the WSS filter penalty. In contrast, for a WSS resolution of 2.5 GHz (the most load-aware case under study), the BP performance of the network varies considerably with the Tx filter roll-off value and therefore a FS of 3.125 GHz can bring significant gain.

Following the same methodology, we also investigated the effect of the filter characteristics on the performance of the Sp-Ch transmission system in terms of the network BP. Here, we considered filter resolutions varying from 0.8 to 3.125 GHz. The average number of Sp-Chs per node was fixed at 5 for all cases under study (i.e. total average number of Sp-Chs in the network was 170) and the simulations were run for an average bit rate per Sp-Ch of 200 Gbps (i.e. total average traffic generated per node was 1 Tbps). We also evaluated the effect of using the Sb-Ch-level FS granularities mentioned in Section II.B on the BP performance of the network.

As can be seen in Fig. 7, a significant reduction in BP can be achieved by moving to finer Sb-Ch-level FS granularities (e.g. a vast reduction in the BP is experienced when moving from 12.5 GHz to 6.25 GHz FS size with a filter resolution of 2.75 GHz and below). The difference between the network BP for the finest and coarsest Sb-Ch-level FS granularities (especially for the finest filter resolutions) is due to the fact that with finer granularities Sb-Chs can be allocated closer to one another without wasting spectrum, and therefore the probability of finding free spectral resources for establishing new Sp-Chs in the network improves.

Let us now focus on the evaluation of the network BP performance for different offered load profiles. To begin with, we investigate the single-carrier transmission system, with an emphasis on the two limiting cases explained above: load-aware and load-agnostic filtering. Without loss of generality, the FS size in this first study is set to 3.125 GHz.

In the load-aware filtering region, we assumed a scenario with ideal WSS filters. The load profile is given by an average demand per connection request ranging from 80 to 180 Gbps, such that the total traffic generated per node ranged from 680 to 1530 Gbps, respectively (for the previously mentioned average number of connections per node of 8.5). The results presented in Fig. 8 quantify the benefit of employing sharper transmitter filters in terms of BP. As illustrated, by employing the best Tx filter roll-off under study (roll off = 0.05), the BP of the network can be improved by around 40% as compared with the worst case considered (roll off = 0.3) for high traffic. This improvement is even more significant for low traffic, amounting to around two orders of magnitude.

In the load-agnostic region, similar studies have been conducted in a scenario with ideal Tx filters (roll off = 0) and intermediate-node WSS filters with resolutions varying from 2.5 to 10 GHz. As shown in Fig. 9, a significant reduction in the BP of ∼30% can be achieved for high traffic and more than an order of magnitude for low traffic when the results for the best (2.5 GHz) and worst (10 GHz) resolutions are compared.

We also investigated the network BP vs. offered loads for Sp-Ch Tx Nyquist-shaping filter resolutions 0.8 and 1.2 GHz in two scenarios: Sb-Ch-level FS size of 3.125 GHz and gridless, and used Sb-Ch-level FS = 12.5 GHz as a benchmark. We considered an average demand per Sp-Ch request ranging from 150 to 300 Gbps, such that the total traffic generated per node ranged from 0.75 to 1.5 Tbps, respectively (for the above-mentioned fixed average number of Sp-Chs per node equal to 5). Fig. 10 shows that by employing the finest filter in a gridless scenario, the network BP can be improved by ∼10% compared with all other cases under study for high traffic. This improvement is more significant for low traffic, amounting in this case to ∼60%.

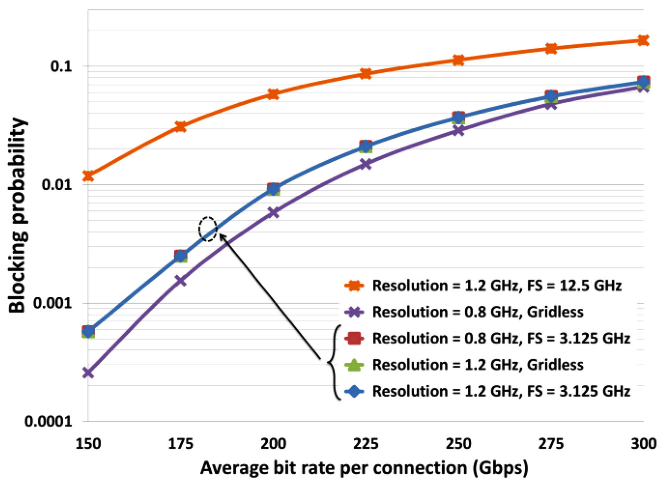



Fig. 10. Network BP for different filter characteristics and Sb-Ch-level FS sizes. Note that the cases with Sb-Ch-level FS size of 3.125 GHz and the gridless case with filter resolution 1.2 GHz overlap.

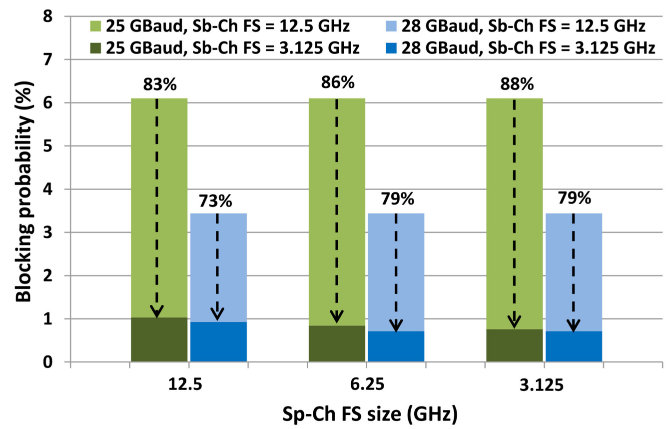



Fig. 12. BP for Sp-Ch transmission at 25 and 28 GBaud with Sb-Ch FS size of 12.5 and 3.125 GHz as a function of the Sp-Ch level FS granularity. Also shown is the blocking performance improvement for all baud rates and Sp-Ch FS sizes when the Sb-Ch FS size is reduced from 12.5 to 3.125 GHz. The Tx Nyquist-shaping filter resolution was set to 1.2 GHz.

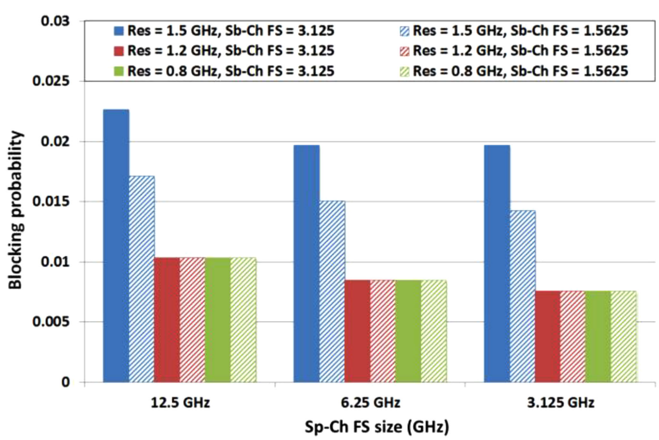



Fig. 11. Network BP vs. Sp-Ch-level FS sizes for different Sb-Ch filter resolutions and Sb-Ch-level FS sizes.

Furthermore, we analyzed the effect of the Sp-Ch-level FS granularity on the network BP. Thus far we have only assumed a Sp-Ch-level FS size of 12.5 GHz in the studies leading to Figs. 7 and 10. We now consider Sp-Ch-level FS sizes of 6.25 and 3.125 GHz to investigate whether reducing the granularity at the Sp-Ch level has an impact on the BP performance of the network. As explained above, we assumed an average bit rate per Sp-Ch of 200 Gbps and an average number of Sp-Chs per node of 5. Furthermore, we carried out the study for two Sb-Ch-level FS sizes: 3.125 GHz and 1.5625 GHz. Fig. 11 shows the network BP performance for Sp-Ch-level FS sizes of 12.5 (results already shown in Fig. 7), 6.25 and 3.125 GHz with three different Sb-Ch filter resolutions. As illustrated, by reducing the Sp-Ch-level FS size, an improvement in the BP performance is generally observed for a constant Sb-Ch FS size and filter resolution. However, this improvement is minimal when moving from Sp-Ch-level FS size of 6.25 GHz to 3.125 GHz. Similarly, the graph verifies that, regardless of the Sp-Ch-level FS size, a good compromise between network performance and hardware requirements is obtained for Sb-Ch-level FS size of 3.125 GHz and Nyquist-shaping filter resolution of 1.2 GHz.

Finally, to complete the study, we investigated the effect of the signal baud rate on the BP performance. We carried out the study with the baud rate used in the simulations presented so far in the paper (25 GBaud) and a baud rate of 28 GBaud, based on commercially available polarization-multiplexed phase-shift-keying transceivers with coherent receivers. Fig. 2 shows the BP for Sp-Ch transmission at 25 and 28 GBaud with Sb-Ch FS size of 12.5 and 3.125 GHz as a function of the Sp-Ch level FS granularity. The results —obtained for the same offered traffic as in Fig. 7 (total average number of Sp-Chs in the network = 170 and average bit rate per Sp-Ch = 200 Gbps) and a Tx Nyquist-shaping filter resolution equal to 1.2 GHz — show that 25 GBaud triggers a worse BP performance than 28 GBaud since the spectrum utilization of a 25-GBaud Sb-Ch (without GB) is a multiple of each of the FS sizes under consideration and therefore an entire FS needs to be assigned for GB in all cases. This is particularly noticeable for Sb-Ch FS size equal to 12.5 GHz, where the same number of Sb-Ch FSs is assigned per 25- and 28-GBaud Sb-Ch (as the spectral penalty incurred, given by Table I, is far less than 12.5 GHz), but the 28-GBaud Sb-Ch can accommodate more traffic (due to the increase in data capacity), which results in fewer allocated Sb-Chs and, consequently, a lower BP. For finer Sb-Ch FSs this divergence levels off, leading to a lower, yet significant (>70%, as can be observed in Fig. 12), BP improvement arising from the utilization of finer Sb-Ch FS sizes with industry-adopted baud rates such as 28 GBaud.

## IV. Conclusion

In this paper we presented a study to determine the optimum frequency slot width granularity for Nyquist-WDM single-carrier and super-channel transmission over flexible optical networks. To this end, we first reported on the impact of filter sharpness on the network-level performance of flex-grid single-carrier Nyquist-WDM systems taking into account the characteristics of the adopted optical filters at the transmitter (raised cosine filters with roll-off factors of up to 0.3) and at the WSSs (optical resolutions varying from 2.5 to 10 GHz) in a dynamic network scenario. After calculating the spectrum that needs to be reserved for each lightpath and the required guard band between neighboring connections according to the filter characteristics, we found that two limiting cases could be identified, which we referred to as load-agnostic and load-aware regions, depending on the source of the spectral penalty incurred by the connections. Through simulations, we showed that increasingly fine slot width granularities in the limit of the load-aware region lead to a blocking-probability decrease. However, in the load-agnostic region, because the WSS optical resolution dictates the spectral penalty (which is constant for all connections), a gridless scenario brings no benefit.

Similarly, for Nyquist-WDM super-channel transmission, we investigated the impact of the sub-channel-level and the super-channel-level frequency slot width granularities used to allocate sub-channels within a super-channel and super-channels on the flexible WDM grid, respectively. Super-channels were generated by bandwidth-variable transmitters incorporating sub-channel Nyquist-shaping filters with resolutions ranging from 0.8 GHz (the finest reported thus far for an optical filter [7]) to 3.125 GHz, and were routed across the network by WSSs at the intermediate nodes relying on commercially available filters with 7.5-GHz optical resolution.

From these studies we concluded that, in WDM networks based on currently deployed WSSs, finer frequency slot width granularities than 6.25 GHz offer no significant benefit in terms of network performance for both single-carrier and super-channel transmission (in the latter case, we refer here to the super-channel-level frequency slot width granularity). Regarding the sub-channel-level frequency slot width granularity (for sub-channel allocation within a super-channel), we demonstrated that a gridless scenario, despite showing a slightly better performance in terms of blocking probability than the 3.125-GHz sub-channel frequency slot width granularity when combined with Nyquist-shaping filters with resolutions ≤1 GHz, may only be justified if the additional investment in the required supporting technologies can be offset by a significant turnover increase. Otherwise, the results make a strong case for allocating sub-channels on the 3.125-GHz grid provided that filters with resolutions of at least 1.2 GHz are employed.

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Authors' biographies not available at the time of publication.