Quantifying Spectrum, Cost, and Energy Efficiency in Fixed-Grid and Flex-Grid Networks [Invited]

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***Abstract*—Single and multi-carrier networks offering channel rates up to 400 Gb/s are evaluated under realistic reach parameters. It is found that efficient spectrum utilization and fine bit-rate granularity are essential to achieve cost and energy efficiency. Additionally, the break-even cost of flexible orthogonal frequency division multiplexing transponders is examined under different settings. The break-even cost of a flexible transponder corresponds to the cost value for which the total cost of the network is equal to that of the related single-line-rate network. The impact of the traffic load, the additional cost required for flex-grid optical cross connects, the cost of spectrum, as well as the cost of fixed-grid transponders is examined.**

***Index Terms*—Cost analysis; Energy efficiency; Flexible optical networking; Optical OFDM.**

I. Introduction

In the pursuit of the technologies to be adopted by the next-generation core networks it is vital to be able to support channel rates beyond 100 Gb/s. Concurrent research efforts are focused on advanced transmission methods that achieve long reach and high spectral efficiencies either employing fixed-grid [1] or flex-grid [2] systems. Optical networks that rely on the ITU-T fixed grid need to accommodate all channels inside a fixed channel spacing, which may not be sufficient for the future 400 Gb/s channels or under-utilize the spectrum for the low-rate demands. On the other hand, flex-grid networks which are able to adapt the bandwidth utilization to the demands entail a significant capital investment over the existing infrastructure. Bandwidth-flexible nodes [3] and software-defined transponders [4] are required to realize the vision of spectrum-and-rate flexible networking. In [5] an excellent overview of the drivers, the building blocks, the architecture, the enabling technologies, as well as the early standardization efforts is provided.

Operators seeking to migrate to the next-generation core are likely to select the winning solution by taking into account the capital investment that it requires together with its performance. However, in addition to the capital cost of the future core network, power consumption is another parameter that becomes relevant, mainly due to the operational economic implications, considering the pace at which traffic is increasing annually. This work aims to evaluate emerging technologies in core networks from a cost, spectral, and energy perspective and give a comprehensive view of the potential of each solution. Recent works that have attempted a similar comparison between the proposed technologies that will support the future optical transport network focused their studies on the spectrum and cost efficiency [6–9]. In [8] fixed-grid network architectures are compared with variable-spacing orthogonal frequency division multiplexing (OFDM) based solutions. An impairment-aware routing and spectral allocation algorithm is proposed and it is shown how the advantages of elastic-OFDM depend on transparent routing constraints and on the traffic matrix characteristics. Additionally, in [9] the cost efficiencies of optical networks based on mixed data rates (10 Gb/s, 40 Gb/s, 100 Gb/s) and elastic technologies (25 Gb/s, 50 Gb/s, 100 Gb/s) are compared for translucent transport networks. In [9] only the cost of optoelectronic interfaces (emitters, receivers, and regenerators) is considered.

In this work we consider networking solutions that can deliver up to 400 Gb/s per channel in a fixed or flexible spectrum grid and utilized physical-layer aware algorithms to route and allocate the available spectrum [10,11]. The methodology introduced in [12] is used to investigate the requirements in capital expenditures of the flex-grid networks over the fixed-grid solutions in correlation with the gained spectrum optimization. We extend the work presented in [13] by conducting a more in-depth study of the requirements in capital expenditures for emerging flex-grid networking solutions. Special attention is given to the impact of different cost values of the flex-grid optical cross connects (OXCs) in conjunction with the cost for spectrum. Additionally, the impact of the cost of fixed-grid transponders is examined. Following the resource allocation of the different networking

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solutions, the energy efficiency is estimated considering the power consumption needs of the associated networking elements. It is shown that a transition to a flex-grid network can overcome the added cost of the equipment due to the minimized spectrum utilization. In addition, we find that solutions offering finer bit-rate granularity achieve low energy per transported bit.

II. Network Planning in Fixed-Grid and Flex-Grid Networks

In the following we discuss the applied network planning methodology along with the assumptions considered in this work.

A. Methodology

During the network planning procedure, resources—such as transponders and spectrum slots—are appropriately assigned to connections in order to satisfy a defined optimization objective. We consider as input the network topology, the set of traffic demands that have to be accommodated, and the capabilities that are offered by the considered network equipment.

Conventional fixed-grid networking solutions require the application of routing and wavelength assignment (RWA) algorithms. These algorithms guarantee that the traffic demand is appropriately routed between all source–destination node-pairs. RWA algorithms also impose constraints that are required in the network planning process, such as wavelength continuity (i.e., imposing that the same wavelength is used in all of the links traversed by the connection) and single wavelength assignment (i.e., imposing that on each link each wavelength can be used by only one connection). In this work the reach-adapting routing and resource allocation algorithms developed in [11] are applied for the considered fixed-grid networking solutions for both single-line-rate (SLR) networks, that is, fixed-grid networks that employ only a single type of transponder, and multi-line-rate (MLR) networks, where more than one type of transponder is employed. The optimization objective is set to minimizing the spectrum utilization (in terms of the 50 GHz wavelengths that are used) or to minimizing the cost of the transponders.

For the flex-grid networking solutions, the RWA algorithms are not applicable. Instead of assigning a certain wavelength to each connection, a number of contiguous spectrum slots, which have a finer granularity than the 50 GHz wavelengths, are now to be assigned. Moreover, the continuity of these spectrum slots should be guaranteed in a similar manner to that in which the wavelength continuity constraint is imposed in fixed-grid networks. This leads to the development of routing modulation level and spectrum allocation (RMLSA) algorithms. In this work we apply the RMLSA simulated-annealing-based algorithm, which is presented in detail in [10]. In all cases the optimization objective is set to the minimization of the utilized spectrum.

B. Assumptions

In the following we discuss the considered networking solutions. The study includes fixed-grid WDM SLR networks that deliver either 40 Gb/s or 100 Gb/s per wavelength channel and MLR [1] networks with data rates of 10 Gb/s, 40 Gb/s, 100 Gb/s, and 400 Gb/s. Regarding the flex-grid solutions, two multi-carrier solutions have been considered: one refers to the case where subcarriers are electrically OFDM modulated [14] offering ultra-fine sub-wavelength granularity (denoted as E-OFDM), while the other refers to the case where a comb of frequency-locked subcarriers are conventionally modulated at the baud rate of the subcarrier spacing [15] (denoted as O-OFDM). The transmitted bit rate can be adapted from 10 Gb/s to 400 Gb/s by modulating subcarriers with the necessary modulation level that varies between BPSK, QPSK, and n-QAM (quadrature amplitude modulation) ($n = 8, 16, 32, 64$).

In the fixed-grid cases a 50 GHz channel spacing is assumed. The transmission reach is set to 3200 km, 2300 km, 2100 km, and 790 km for the fixed-grid signals of 10 Gb/s, 40 Gb/s, 100 Gb/s, and 400 Gb/s, respectively, which is considered to take into account the interference effects between different modulation formats/rates used in an MLR system. In E-OFDM, superchannels are assigned a variable bandwidth depending on the selected symbol rate and format and the reach-adaptive model presented in [14] is employed. O-OFDM superchannels are generated with a group of subcarriers spaced at 12.5 GHz and the reach depends on the modulation level selected, i.e., 3000 km, 1500 km, 750 km, 800 km, or 375 km for 2, 4, 6, or 8 bits per symbol, respectively. These cases respectively correspond to polarization-multiplexed binary phase-shift keying (PM-BPSK), polarization-multiplexed quadrature phase-shift keying (PM-QPSK), PM-8-QAM, and PM-16-QAM.

In the presented studies the Deutsche Telekom core network (14 nodes, 23 bidirectional links) and the corresponding traffic matrix for reference year 2010 is used [10]. It is noted that the traffic demand values for the given reference year range between 5 Gb/s and 48 Gb/s, with an average of approximately 15 Gb/s. All node-pairs, that is, a total of 182 node-pairs, are actively communicating in this scenario. In order to obtain future traffic demands the traffic matrix is uniformly scaled assuming an annual growth rate of 34%. Thus, various traffic load settings are examined corresponding to different reference years. For example, reference years 2014 and 2020 have average traffic values of approximately 50 Gb/s and 300 Gb/s, respectively.

In the conducted case studies the required resources in terms of spectrum and network equipment are calculated in order for the requested traffic demand to be fully accommodated. Note that no additional optical grooming functionality is assumed to be available. The assumed cost and power consumption models are discussed in the relevant sections.

III. Spectrum Efficiency

In the following we examine the requirements in terms of spectrum that are imposed by the different networking

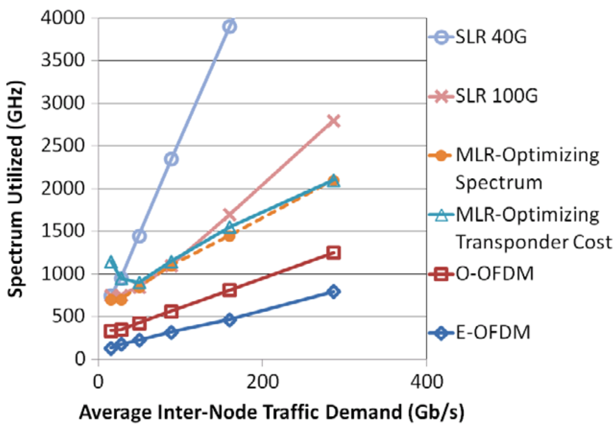


Fig. 1. (Color online) The spectrum utilization is presented for different networking solutions as a function of the average inter-node traffic demand.

solutions. In Fig. 1 the utilized spectrum is presented as a function of the average traffic demand. The utilized spectrum in this case corresponds to the maximum amount of spectrum that is required over all links in the network. As different spectrum slots are allocated to different connections over different links, "gaps"—consisting of unoccupied spectrum slots—are unavoidably introduced. Note that these unoccupied spectrum slots are included in the calculation of the total utilized spectrum if there are higher spectrum slots that are occupied in the considered link.

As expected, the SLR case deploying 40 Gb/s transponders has the worst performance in terms of spectrum utilization. This is caused by the low spectral efficiency of the utilized transponders, at 0.8 b/s/Hz. The SLR case deploying 100 Gb/s transponders yields an improved performance, requiring in some cases less than half of the spectral resources of the 40 Gb/s case. Note that the maximum transparent reach obtained for the SLR case, which deploys only 400 Gb/s transponders, is not sufficient to provide transparent connections between all node-pairs. Thus, 400 Gb/s transponders are included only in the MLR case to serve connections with short paths which require no additional regeneration—in order to provide a fair comparison.

For the MLR case two different optimization objectives are examined: (i) minimization of utilized spectrum and (ii) minimization of transponder cost. The cost values assumed for the minimization of transponder cost are discussed in more detail in Section IV.

It is observed that the utilized spectrum increases almost linearly with the average inter-node traffic demand—with the exception of the MLR case where the optimization objective is set to the minimization of transponder cost. Note that the spectrum utilization in this case initially decreases as the average inter-node traffic demand increases. The reason behind this is that for low inter-node traffic demands it is more cost efficient to deploy 10 Gb/s transponders than to deploy underutilized 40 Gb/s or higher rate transponders. Comparing between the two MLR variants (cost and spectrum optimization), we find that up to 8 times more 10 Gb/s transponders are deployed when the primary optimization objective is set to the minimization of transponder cost. However, this cost efficiency comes at the expense of spectrum utilization, as the 10 Gb/s transponders have the lowest spectral efficiency. As the traffic demand increases the higher rate transponders become more cost efficient, and there are no significant trade-offs occurring between spectrum utilization and MLR transponder cost. When the average inter-node traffic demand is above 50 Gb/s, both variants of the MLR case achieve the same performance in terms of spectrum utilization.

We now proceed to compare the MLR case with the SLR variants. In cases where the average inter-node traffic demand is lower than 100 Gb/s, the MLR solution yields no additional benefits in terms of spectrum efficiency compared to the SLR case deploying 100 Gb/s transponders. However, as the average inter-node traffic demand increases, the MLR case offers significant savings in spectrum utilization. These savings can reach 33% of the spectrum required for the SLR case deploying 100 Gb/s transponders.

Under the given assumptions, the flexible multi-carrier solutions offer the most efficient spectrum allocation, as expected from the optimized packing of the connections in the frequency domain, with E-OFDM outperforming all of the examined cases. The performance of O-OFDM is constrained by the 12.5 GHz subcarrier spacing assumed.

IV. Cost Efficiency

In [12] a methodology is introduced that explores the conditions under which the vision of flexible networking makes a good business case. This methodology is applied here in order to investigate how spectrum savings can potentially counterbalance the added cost of the capital expenditures for flexible network equipment. It is expected that spectrum savings can be utilized for the provisioning of new traffic and/or revenue generating services. To translate the spectrum savings to a measurable entity, the cost of a "dark" 50 GHz channel slot wavelength is introduced. This definition of a 50 GHz channel slot corresponds only to the cost of the link infrastructure (equipment/fiber) to support a 50 GHz channel and excludes any cost associated with "lighting up" this channel. Based on this methodology we model the total cost of a system considering three cost parameters: the cost of transponders, the cost of node equipment, and the third is related to the number of "dark" 50 GHz channel slots that are utilized.

Among the fixed-grid networks the distinctive component that determines the capital requirements is the type of the transponders. The relative cost values are set at 1, 2.5, 3.75, and 5.5 for the 10 Gb/s, 40 Gb/s, 100 Gb/s, and 400 Gb/s transponders, respectively [16].

Figure 2 illustrates the absolute number of transponders per networking solution as a function of the inter-node traffic demand. The SLR case deploying 40 Gb/s transponders has the worst performance in terms of the number of required transponders—with the SLR 100 Gb/s case following. We now focus on the MLR solution with the primary optimization objective set at minimizing the transponder cost. As observed for the utilized spectrum (see Fig. 1), the number of required transponders initially decreases with increase of the traffic

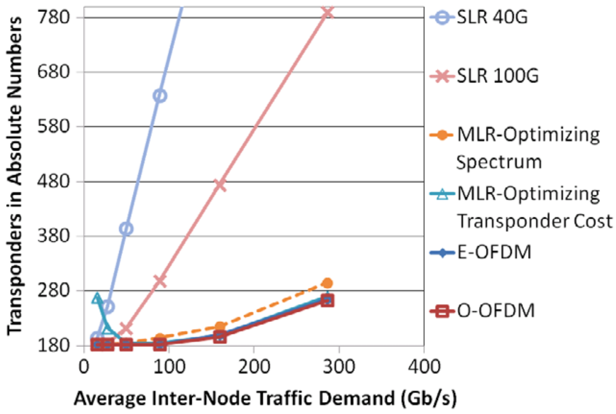


Fig. 2. (Color online) The required number of transponders is presented for different networking solutions as a function of the average inter-node traffic demand (in absolute numbers).

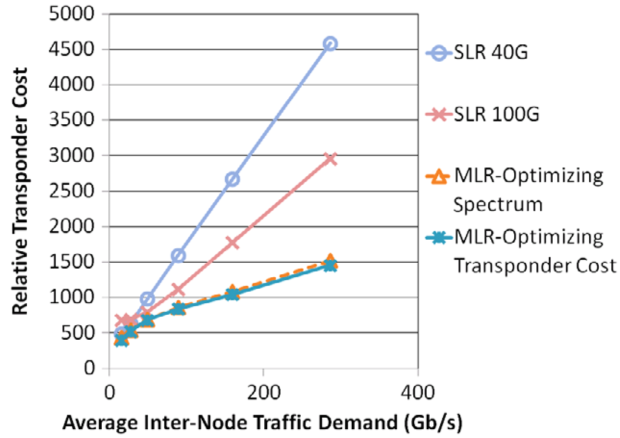


Fig. 3. (Color online) The relative transponder cost for the fixed-grid networking solutions is presented as a function of the average inter-node traffic demand. Costs are normalized to the value of one 10 Gb/s transponder.

demand. However, for average inter-node traffic demands of around 50 Gb/s, the number of transponders starts to increase. As already discussed, the reason for this is that after a point 40 Gb/s transponders that would be underutilized at lower rates become more cost efficient (as opposed to multiple 10 Gb/s transponders). In contrast to the conclusions drawn for the spectrum utilization, we observe that for average inter-node traffic demands above 50 Gb/s, the E-OFDM, O-OFDM, and both MLR variants have similar requirements in terms of the total number of required transponders.

Figure 3 shows the relative transponder cost for all fixed-grid solutions as a function of the average inter-node traffic demand. Comparing the two variants of the MLR case, we find relative differences in the range between 3% and 11%. This means that by setting the optimization objective to minimizing costs, up to 11% transponder cost savings can be achieved. These savings come at the expense of additional requirements in terms of utilized spectrum—as shown in Fig. 1.

One challenging aspect in evaluating the overall cost efficiency that can be achieved by flexible optical networking is the lack of reliable data for the cost of the flex-grid network components (i.e., the software-defined transponders and bandwidth-variable optical switches). To overcome this, we estimate the additional cost of the E-OFDM and O-OFDM transponders over the cost of a 100 Gb/s transponder, in order to achieve a total network cost equal to that of the related SLR network.

In the following, we describe how different cost values are considered for the optical switches. In [17] a generic equipment model along with a set of realistic cost values for different technologies is presented. Different architectures for optical switches performing switching of wavelength channels without o-e-o conversion are presented. In [17] optical switches are divided into optical add drop multiplexers (OADMs) and OXCs depending on the number of fiber ports. OXCs provide more than two fiber ports, whereas OADMs are restricted to two fiber ports. In the scope of this work, both variants of optical switches are referred to as OXCs. Optical switches are further characterized by (i) their pass-through capacity, (ii) their add–drop capacity, and (iii) their reconfigurability.

In this study, we consider for the fixed-grid case optical switches with a pass-through capacity of 80 channels and an add–drop capacity of 100% (corresponding to the case in which all channels can be added–dropped). The reconfigurable option is selected—providing automatic switching of wavelengths. It is noted that the OXCs incur a fixed cost and an additional cost related to the number of bidirectional fiber line ports connected. As for the bandwidth-variable nodes for the flex-grid case, we examine the effect of different cost values—assuming an overhead that is relative to the cost value of the fixed-grid case.

The resource allocation algorithms are applied to calculate the required transponders and the spectrum savings under different traffic demand settings. Figure 4 presents the "break-even" cost for E-OFDM and O-OFDM transponders compared to the SLR case deploying 100 Gb/s transponders. The break-even cost of the flexible E-OFDM or O-OFDM transponders corresponds to the cost value for which the total cost of the network is equal to that of the related SLR network. In other words, if a flexible transponder costs more than the break-even cost, then the SLR network is more cost efficient. If the flexible transponder costs less than the break-even cost, then it is beneficial to deploy flexible networking solutions.

The break-even cost is presented as a function of the normalized cost per 50 GHz channel slot. Note that all costs are normalized to the value of a 10G transponder, that is, 1 (reference) cost unit corresponds to the cost of a 10 Gb/s transponder. We examine two different values for the cost of the 100 Gb/s transponder: options A and B correspond to a cost value for a 100 Gb/s transponder of 5.5 and 3.75 cost units, respectively. Unless explicitly stated otherwise (that is, except for Subsection IV.C), the additional cost of a flex-grid OXC over a fixed-grid OXC is set to 10%. Various traffic load settings are examined corresponding to different reference years—considering an annual traffic growth rate of 34%.

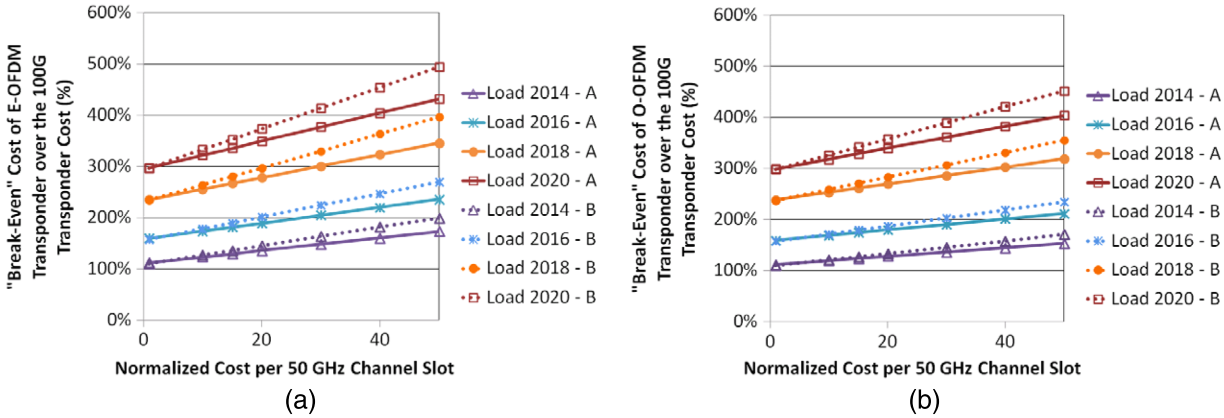


Fig. 4. (Color online) The "break-even" cost for (a) E-OFDM and (b) O-OFDM transponders compared to the SLR 100G case is presented as a function of the normalized cost per 50 GHz channel slot under different traffic load settings. Costs are normalized to the value of a 10G transponder. Options A (solid line) and B (broken line) correspond to a cost value for a 100G transponder of 5.5 and 3.75 cost units, respectively. The additional cost of a flex-grid OXC over a fixed-grid OXC is set to 10%. Reference years 2014 and 2020 have average traffic values of approximately 50 Gb/s and 300 Gb/s, respectively. An annual growth rate of 34% is assumed for the traffic demand.

In the following we examine the effect of the traffic load, the cost of the spectrum, the cost of the flex-grid OXCs, and the cost of the fixed-grid transponders on the break-even cost of flexible transponders. Note that the effects of these parameters are to a certain degree intertwined.

A. Impact of the Traffic Load

We first focus on option A of the E-OFDM case (option A corresponds to 100 Gb/s transponder cost equal to 5.5), which is shown in Fig. 4(a). It is interesting to observe that there is a significant dependence of the break-even cost on the traffic load. For a low traffic load (corresponding to reference year 2014) the break-even cost is 109% of the cost of a 100 Gb/s transponder, whereas for a high traffic load (corresponding to reference year 2020) the break-even cost reaches 296% of the cost of a 100 Gb/s transponder—for a 50-GHz-channel cost equal to one unit.

Thus, it is observed that as the traffic load becomes higher, the break-even cost for the E-OFDM transponder increases. There are three reasons contributing to this effect. The first one is related to the savings achieved in terms of spectrum slots. These savings, which are enabled by the higher spectral efficiency of E-OFDM, are more pronounced for higher traffic loads. The second reason is related to the number of required E-OFDM transponders. As the traffic demand increases, the higher capacities offered by E-OFDM transponders can be better utilized. Thus, the relative difference in the number of E-OFDM transponders compared to the number of 100 Gb/s transponders increases. The third reason is that the required additional investment for flexible OXCs becomes less significant when it is distributed over a larger traffic load. Similar observations hold for the O-OFDM case, which is shown in Fig. 4(b), and for both options A and B.

B. Impact of the Cost of Spectrum

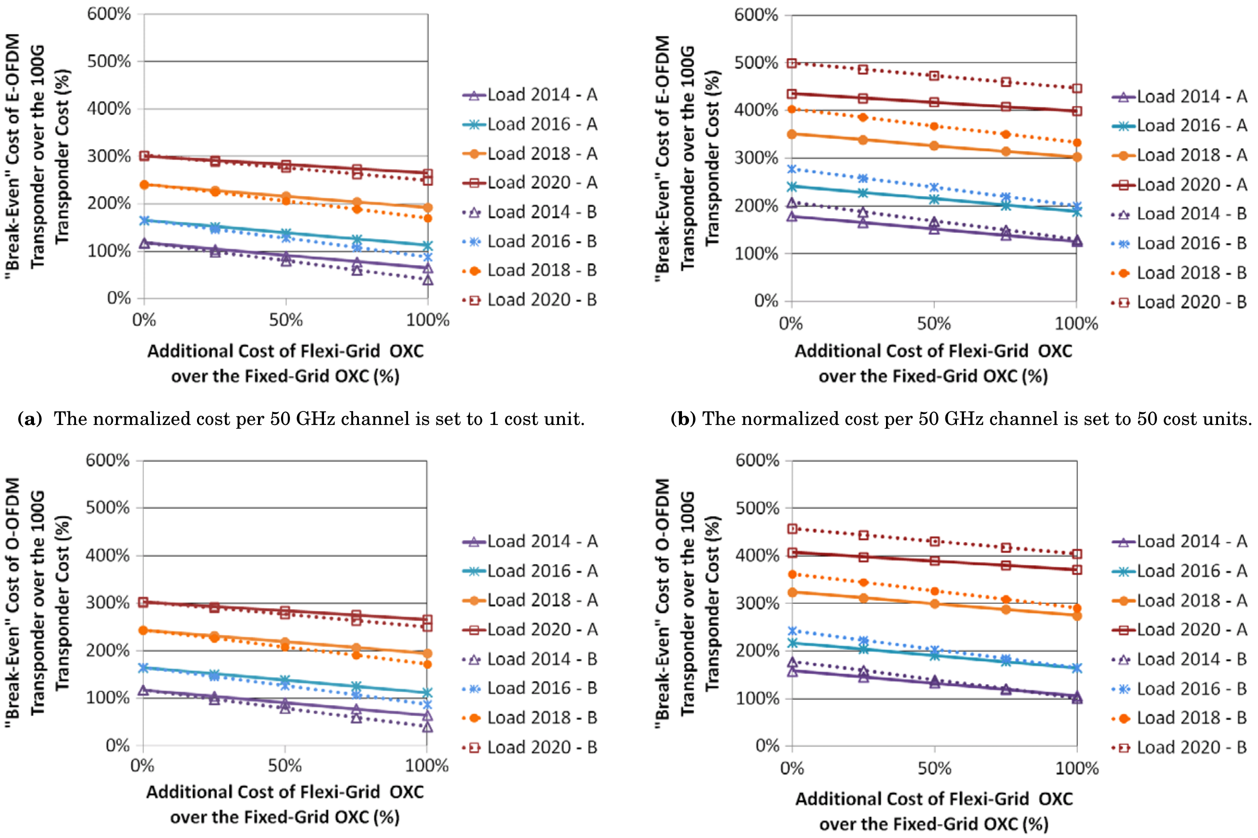
We now proceed to examine the effect of the cost per 50 GHz channel slot (x-axis of Fig. 4). As expected, we find that as the cost of the spectrum rises, the break-even cost of the E-OFDM transponder increases. For a low traffic load (corresponding to reference year 2014) the break-even cost ranges between 109% and 200% of the cost of a 100 Gb/s transponder—for a 50-GHz-channel cost ranging between 1 and 50 cost units. For a high traffic load (corresponding to reference year 2020) the break-even cost ranges between 296% and 494% of the cost of a 100 Gb/s transponder. Remember that the higher the break-even cost is, the easier it becomes to introduce spectrum flexible networking—since if a flexible transponder costs less than the break-even cost, cost savings are yielded compared to the related fixed-grid solutions.

From the operators' perspective, these results indicate how the spectrum savings of the flex-grid networks can be used to mitigate the additional cost of the new spectrum flexible transponders. Similar conclusions can be drawn for the O-OFDM case. However, the break-even cost in this case is less than that of the E-OFDM transponder due to the reduced savings in terms of spectrum slots (as shown in Fig. 1).

C. Impact of the Cost of Flex-Grid OXCs

In our previous analysis the additional cost of a flex-grid OXC over a fixed-grid OXC was set to 10%. In the following we examine the effect of this additional cost. In Fig. 5 the break-even cost for E-OFDM and O-OFDM transponders compared to the SLR 100G case is presented as a function of the additional cost of a flex-grid OXC over a fixed-grid OXC—under different traffic load settings.

Different cases are examined for the cost of a 50 GHz spectrum slot, in order to consider the combined effects of these two parameters. In Figs. 5(a) and 5(c) the normalized cost per 50 GHz channel is set to 1 cost unit (1 cost unit corresponds



(a) The normalized cost per 50 GHz channel is set to 1 cost unit.

(b) The normalized cost per 50 GHz channel is set to 50 cost units.

(c) The normalized cost per 50 GHz channel is set to 1 cost unit.

(d) The normalized cost per 50 GHz channel is set to 50 cost units.

Fig. 5. (Color online) The "break-even"cost for (a, b) E-OFDM and (c, d) O-OFDM transponders compared to the SLR 100G case is presented as a function of the additional cost of a flex-grid OXC over a fixed-grid OXC—under different traffic load settings. Options A (solid line) and B (broken line) correspond to a cost value for a 100G transponder of 5.5 and 3.75 cost units, respectively. Reference years 2014 and 2020 have average traffic values of approximately 50 Gb/s and 300 Gb/s, respectively. An annual growth rate of 34% is assumed for the traffic demand.

to the cost of a 10 Gb/s transponder), whereas in Figs. 5(b) and 5(d) the cost per 50 GHz channel is set to 50 cost units. In all cases, increases in the cost of a flex-grid OXC over a fixed-grid OXC lead to lower break-even costs for the flexible transponders. However, the impact of this factor is significantly smaller than the effect of the traffic load.

For example, we examine the break-even cost of an O-OFDM transponder for the case in which the normalized cost per 50 GHz channel is set to 1 cost unit (Fig. 5(c)). The additional cost required for flex-grid OXCs compared to fixed-grid OXCs is varied from the extreme case in which no additional premium is required to the case in which double the costs are required (i.e., for an additional cost of a flex-grid OXC ranging between 0% and 100% of the cost of fixed-grid OXC). It is observed that the break-even cost in this case varies between 304% and 266% of the cost of a 100 Gb/s transponder for option A and between 304% and 250% for option B for a high traffic load (corresponding to reference year 2020). It is noted that OXCs providing switching at a different bandwidth granularity may incur different costs. If this is the case, then it is possible to perform the comparison of E-OFDM and O-OFDM solutions via examining the break-even cost at different values of the additional cost of flex-grid OXCs compared to fixed-grid OXCs (x-axis of Fig. 5). For example, the E-OFDM and O-OFDM solutions may require the deployment of OXCs costing 10% and 5% more than the fixed-grid OXCs, respectively. In this case the break-even costs of the E-OFDM and O-OFDM transponders will be determined by considering different points of the x-axis of Fig. 5 for each case (i.e., the break-even costs at 10% and 5% for the E-OFDM and O-OFDM transponders, respectively).

D. Impact of the Cost of Fixed-Grid Transponders

In the following we discuss how the break-even cost of flexible transponders is affected by the cost of fixed-grid transponders. When the cost of a 100 Gb/s transponder is reduced, the total network cost is reduced for the SLR case. At the break-even point, we assume that the total network cost of the flexible networking solution is equal to the total cost of the 100 Gb/s SLR case. Thus, the total network cost of the flexible networking solution is also reduced. As a result, the absolute cost of the flexible E-OFDM or O-OFDM transponders will be less at the break-even point. Note that in Figs. 4 and 5 we normalize the break-even cost to the value of a 100 Gb/s transponder. As a result, it is not straightforward to determine whether lower costs for a 100 Gb/s transponder lead to lower break-even costs for the flexible transponders (as the metric used is normalized and a lower absolute cost value of the flexible transponder is divided by the lower cost value of a 100 Gb/s transponder) In the following we describe the effects taking place in more detail.

As discussed, options A and B correspond to a cost value for a 100 Gb/s transponder of 5.5 and 3.75 cost units, respectively. In Fig. 4(a), we observe that option A requires lower break-even costs than option B. Thus, as the relative cost of a 100 Gb/s transponder decreases, the break-even cost of an E-OFDM transponder increases. This is more pronounced for higher traffic loads. We additionally find that it is not always the case that a lower relative cost of a 100 Gb/s transponder leads to higher break-even costs of flexible transponders. In Figs. 5(a) and 5(c) it is observed that option A allows higher break-even costs than option B for the E-OFDM and O-OFDM transponders, respectively.

In the following we analyze this behavior. There are two antagonizing effects taking place. The first one is related to the cost savings achieved in terms of spectrum slots. The second one is related to the "penalties" imposed via the additional required investment for flexible OXCs. If the relative cost benefits gained from the spectrum savings are less than the additional costs required for the flex-grid OXCs, then higher 100 Gb/s transponder costs lead to relatively higher break-even costs for the flexible transponders. If these benefits are more than the additional costs imposed by the flex-grid OXCs, then higher 100 Gb/s transponder costs lead to relatively lower break-even costs for the flexible transponders.

As discussed, in Figs. 5(a) and 5(c) the normalized cost per 50 GHz channel is set to 1 cost unit, whereas in Figs. 5(b) and 5(d) this cost is set to 50 cost units. Thus, the same amount of spectrum saving (in GHz) translates into lower cost savings for Figs. 5(a) and 5(c). As a result, the additional costs required for the flexible OXCs outweigh the cost benefits gained from the spectrum savings.

V. Energy Efficiency

In the following, the considered solutions are compared with respect to their power consumption. The network planning procedure is as previously described—with the optimization objective set to either the minimization of the utilized spectrum or the minimization of the cost of the transponders. Thus, the basis is provided to perform a comparison between the different networking solutions. Note that there is a direct correspondence between the utilized spectrum, the required transponders, and the total power consumption of the different networking solutions presented in Figs. 1, 2 and 6.

The transponders of the fixed-grid solutions are assumed to require 47 W, 125 W, 215 W, and 330 W for the 10 Gb/s, 40 Gb/s, 100 Gb/s, and 400 Gb/s transponders, respectively [16]. In the flex-grid solutions, E-OFDM and O-OFDM have transmitters with similar power consumption characteristics, yet they differ in the receiver part. E-OFDM requires an IFFT/FFT DSP module and digital-to-analog converters (DACs) at both ends, while in O-OFDM the FFT process is performed passively at the receiver and the demultiplexed carriers are then processed separately with an equal number of coherent receivers.

With respect to E-OFDM, a DSP complexity analysis reported in [18] has shown that E-OFDM has the same DSP complexity as a coherent 400 Gb/s QPSK. Since the DSP complexity is related with the processes that are implemented electronically, it can be concluded that the associated power consumptions for the two cases are similar. In this study, in order to have a fairer comparison and also to indirectly account for the DACs, two power consumption levels were assumed for the E-OFDM transponder according to the processed data rate. Therefore, for rates of 10–100 Gb/s E-OFDM is assumed to consume power equal to that of a 100 Gb/s coherent transponder (i.e., 215 W), and for bit rates of 100–400 Gb/s power equal to that of a 400 Gb/s transponder (i.e., 330 W). As opposed to this conservative assumption, a linear function may prove more suitable, as the power consumption of DSP has been reported to scale linearly with the bit rate.

With respect to the flex-grid O-OFDM transponder, the power consumption is calculated based on the power consumption per active subcarrier, which is in turn extracted by the values shown for the fixed-grid solution according to the modulation level. Note that at the O-OFDM receiver the all-optical FFT module separates the subcarriers which are then processed independently by an equal number of coherent receivers. The difference is evident at the transmitter side, where the source laser is shared among the subcarriers that are modulated at low baud rates (in fixed grid all transponders are independent). For example, a 6-subcarrier O-OFDM connection at 12.5 Gbaud with PM-16QAM per subcarrier (i.e., 100 Gb/s per subcarrier) has almost similar power consumption to that of six 100 Gb/s coherent transponders. Therefore, the power consumption per 12.5 Gbaud subcarrier of the O-OFDM transmitter is assumed to require 86 W for PM-BPSK (which is equal to almost twice the power consumption of a 10G fixed-grid transponder), 125 W for PM-QPSK (which is equal to a 40G fixed-grid transponder), and 215 W for PM-16QAM subcarriers (which is equal to a 100G fixed-grid transponder).

Finally, with respect to the transmission system, the OXCs and optical line amplifiers (OLAs) are considered to consume an equal amount of power for all cases. The power consumption of the OXCs is set to 430 W, including control overhead, for the node degree of the DT topology. The OLAs are set to 145 W per direction of a double-stage erbium-doped fiber amplifier, including control overhead. A total of 120 OLAs is assumed for the entire DT topology. In addition, a cooling factor equal to two is assumed for all considered components.

According to the aforementioned analysis, the estimated energy efficiency (in Gb/s/W) for the various traffic loads has been calculated for the SLR, MLR, and flexible OFDM system cases and is illustrated in Fig. 6. The energy efficiency is defined here as the aggregated traffic demand accommodated by the network, divided by the network-wide power consumption. Thus, a metric is provided as to how efficiently each unit of power is used by the network in order to transport traffic.

The results in Fig. 6 show that the SLR solutions at both 40 Gb/s and 100 Gb/s appear to be less energy efficient compared to the MLR and OFDM cases. The 100 Gb/s SLR

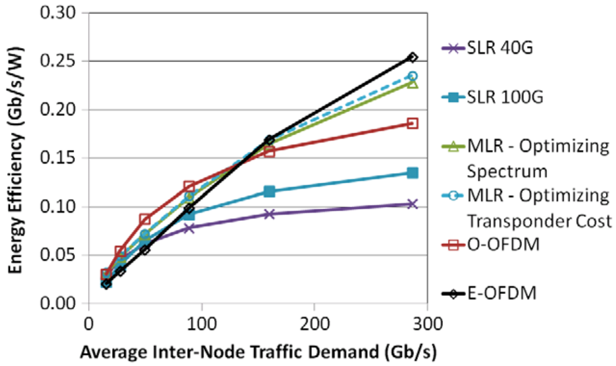


Fig. 6. (Color online) The energy efficiency achieved for different networking solutions as a function of the average inter-node traffic demand.

shows a better performance than the 40 Gb/s SLR variant as it requires a reduced number of transponders (see Fig. 2) especially at higher traffic loads. Note that as the traffic load increases, the power consumption overhead introduced for the OXCs and the OLAs is distributed over a larger traffic load.

Also in Fig. 6 it is observed that both MLR variants (with the optimization objective set at minimizing the spectrum utilization or the transponder cost) have a similar performance in terms of power consumption. For high traffic loads the MLR solutions display good performance in terms of energy efficiency because higher capacity transponders are assumed to have better power consumption per bit than lower capacity ones. Thus, as the traffic load increases, more high capacity transponders are deployed, and therefore the energy efficiency is improved.

Finally, focusing on the two flexible OFDM solutions it is observed that for an average inter-node traffic demand below 150 Gb/s, the O-OFDM case shows the best energy efficiency. This in turn deteriorates for higher traffic demands, where the E-OFDM case displays increased energy efficiency characteristics. This is attributed to the fact that the flexible O-OFDM solution allocates the required number of subcarriers and their modulation level adaptively according to the demand. As the traffic load increases, a larger number of subcarriers and therefore independent power-consuming coherent receivers are allocated in order to meet the increased demands, resulting in an overall increased power consumption. On the other hand, the E-OFDM model has fixed power consumption for bit rates between 100 Gb/s and 400 Gb/s and equal to that of a 400 Gb/s transponder—since it is assumed to operate based on the maximum allocated capacity that it can handle. Moreover, the power consumption of a single 400 Gb/s transponder is much less than that of an equivalent 400 Gb/s transponder that is composed of several lower rate transponders for each subcarrier as in the case of O-OFDM. Thus, at high traffic loads, where the maximum capacity of E-OFDM transponders is utilized, the energy efficiency increases. Finally, it is worth mentioning that for average inter-node traffic demands above 150 Gb/s the O-OFDM energy efficiency is even less than that of the MLR cases, since the MLR systems start utilizing a larger number of higher data rate (100 Gb/s and 400 Gb/s) transponders.

VI. Conclusion

Focusing on spectrum as a resource, we have studied how bandwidth allocation in fixed-grid and flex-grid core networks with up to 400 Gb/s channel rates affects the requirements in capital expenditures and power consumption. The capability of a flex-grid network to allocate efficiently the available spectrum counterbalances the additional capital expenditures that is required to migrate to a multi-carrier system.

More specifically, the break-even cost of the flexible E-OFDM and O-OFDM transponders was examined under different settings. The break-even cost of a flexible transponder corresponds to the cost value for which the total cost of the network is equal to that of the related SLR network. We found that the traffic load has a great impact on the break-even cost, with higher traffic demands leading to greater break-even costs for the flexible transponders. More specifically, we found that the break-even cost of an E-OFDM transponder ranges between approximately 110% and 300% of the cost of a 100 Gb/s transponder as the traffic demand varies from low to high traffic loads. This holds for a 50 GHz channel cost equal to one unit (in the assumed cost model one cost unit corresponds to the cost of a 10 Gb/s transponder). When higher cost values are assumed for a 50 GHz channel slot, the break-even cost of an E-OFDM transponder ranges between approximately 170% and 500% of the cost of a 100 Gb/s transponder as the traffic demand varies from low to high traffic loads.

It was additionally shown that increases in the cost of a flex-grid OXC over a fixed-grid OXC lead to lower break-even costs for the flexible transponders. However, the impact of this factor is significantly smaller than the effect of the traffic load. This became clearer when examining two extreme cases: (i) no additional cost premium is required for flexible OXCs and (ii) a flexible OXC requires double the costs of a fixed-grid OXC. We found that the break-even cost of a flexible transponder may vary by approximately 40%. Similar observations hold for the cost of spectrum, with higher costs per 50 GHz spectrum slot leading to greater break-even costs for flexible transponders.

We additionally investigated how the break-even cost of flexible transponders is affected by the cost of fixed-grid transponders. We found that if the relative cost benefits gained from the spectrum savings are less than the additional costs required for the flex-grid OXCs, then higher 100 Gb/s transponder costs lead to relatively higher break-even costs for the flexible transponders. Finally, we found that the overall network energy efficiency may be optimized by offering finer bit-rate granularity.

In this work we focused on static network planning. It is expected that when considering the dynamic operation of networks, additional benefits will be yielded via the deployment of flexible networking.

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