Spectrum, Cost and Energy Efficiency in Fixed-Grid and Flex-Grid Networks

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Abstract: Single and multi-carrier networks offering channel rates up to 400Gb/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.

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1. 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. 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 the new 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 [5,6].

In this work we considered 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 [7,8]. The methodology introduced in [9] is used to investigate the requirements in capital of the flex-grid networks over the fixed-grid solutions in correlation with the gained spectrum optimization. Following the resource allocation of all solutions, the energy efficiency was finally 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. In addition solutions that offer finer bit-rate granularity and efficient spectrum allocation achieve low energy per bit as they use just the amount of network resources needed for given input traffic.

2. Spectrum allocation in Fixed-Grid and Flex-Grid Networks

The study includes fixed WDM single line rate networks (SLR) that deliver either 40 Gb/s, 100 Gb/s or 400 Gb/s per channel and mixed line rate (MLR) [1] networks with data rates of 10Gb/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 (Orthogonal Frequency Division Multiplexing) OFDM modulated [10] 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 [11] (denoted as O-OFDM). Both multi-carrier solutions can adapt the transmitted bit-rate from 10Gb/s-400Gb/s by modulating subcarriers with the necessary modulation level that varies between BPSK, QPSK and n-QAM (n=16, 32, 64).

Reach-adapting routing and resource allocation algorithms with realistic transmission reach data [10] developed for both flex-grid [7] and fixed-grid [8] networks are utilized to minimize the spectrum utilization and the number of transponders. In the fixed-grid cases a 50 GHz channel-spacing has been assumed. The transmission reach is set to 3200km, 2300km, 2100km and 790 km for the fixed-grid signals of 10Gb/s, 40 Gb/s, 100 Gb/s and 400 Gb/s respectively. In E-OFDM, superchannels are assigned a variable bandwidth depending on the selected symbol rate and format and the reach-adaptive model presented in [10] 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. 4000 km, 2500 km, 1200 km, 800 km and 400 km for 1, 2, 4, 5 or 6 bits per symbol respectively.

To calculate the bandwidth utilized by the various solutions we have used the Deutsche Telekom core network (14 nodes, 23 bidirectional links) [7] and the realistic traffic matrix of the DT network for 2010 scaled up to 11 times to obtain traffic ranging from 3.6 Tb/s up to 39.6 Tb/s (Fig. 1). 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 ourperforming all. The performance of O-OFDM is constrained by the 12.5 GHz subcarrier spacing assumed here. It is should be noted that in the 400 Gb/s SLR network, regenerators are required for the connections with longer paths than its maximum transmission reach.

3. Cost Efficiency

Spectrum utilization is presented not only as a way to evaluate the networking solutions but also in the form of spectrum savings (considered here in 50GHz slots) that can be utilized for the provisioning of new traffic. Based on the methodology introduced in [9] 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” 50GHz channel slots that are utilized and are associated only with the link infrastructure cost.

Among the fixed-grid networks the distinctive component that determines the capital requirements is the type of the transponders. Fig. 2 illustrates the absolute number of transponders per networking solution and Fig. 3 shows the relative transponder cost of all fixed-grid solutions. The relative cost values are set at 1/2.5/3.75/5.5 for the 10 Gb/s, 40 Gb/s, 100 Gb/s and 400 Gb/s transponders respectively [12]. For MLR systems, two variations of the planning algorithm are reported; the first one seeks to minimize the number of utilized wavelengths, and the second plans the network optimizing the transponder cost.

However, reliable data for the cost of the flex-grid networks components i.e. the software-defined transponders and bandwidth-variable nodes, are currently not available. To overcome this, we estimate the additional cost of the E-OFDM and O-OFDM transponders cost over the cost of a 100 Gb/s transponder, in order to achieve total network cost equal to that of the related SLR network. The comparison was focused on the cost of the E-OFDM and O-OFDM transponders as those rely on electronics for DSP. We set the corresponding cost of a fixed-grid wavelength selective switch (WSS) at 12 K€ and the cost of the 100 Gb/s transponder at 12 K€. Directionless, colorless, and contention-less nodes were assumed that require 92 WSS elements for the pass-through traffic of the DT topology, which in the case of the flex-grid networks it is assumed to cost 1.25 times the conventional fixed-grid WSS. The resource allocation algorithms were utilized to calculate the required transponders and the spectrum savings for the different traffic matrices. Fig. 4 presents the allowable additional cost for the E-OFDM transponder compared to the SLR 100Gb/s transponder for different traffic loads. For a 50-GHz-channel cost that ranges from 10K€ to 100K€, an E-OFDM transponder may cost 3 to 5 times more when the traffic load is equal to 11 so as to achieve total network cost equal to that of the SLR network. For the lowest traffic scenario (load=1), where the spectrum savings of the flex-grid solution compared to the 100G SLR are less pronounced, the E-OFDM solution is preferable over the SLR network when the additional cost that is tolerable ranges between 6% to 50%. In a similar manner, Fig. 5 presents the results for the comparison between O-OFDM and 100G SLR. The O-OFDM transponder may cost approximately 2-3 times more for the highest traffic load scenario. The difference with the O-OFDM case is justified by its higher spectrum utilization as shown in Fig. 1. 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.

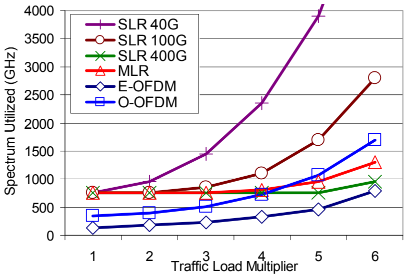

Fig. 1: Spectrum utilization for all solutions and different traffic loads.

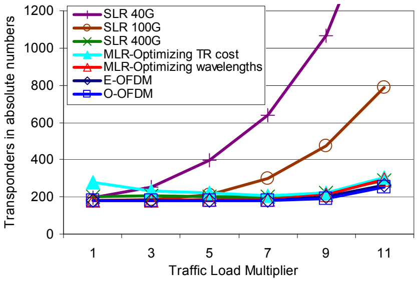

Fig. 2: Required number of transponders for all solutions to serve the different traffic matrices (in absolute numbers).

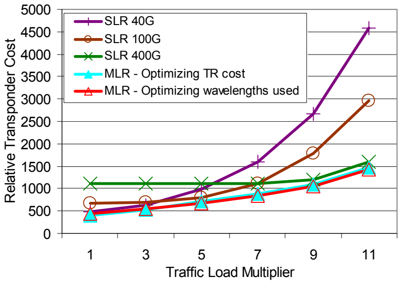

Fig. 3: Relative transponder cost for the fixed-grid networking solutions

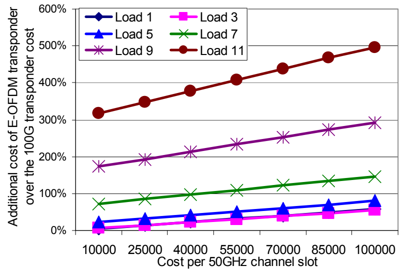

Fig. 4: Allowable additional cost for E-OFDM transponder compared to SLR 100G from spectrum savings for different traffic loads.

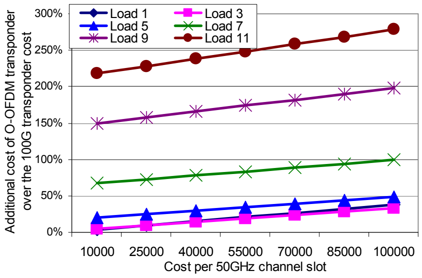

Fig. 5: Allowable additional cost for O-OFDM transponder compared to SLR 100G from spectrum savings for different traffic loads.

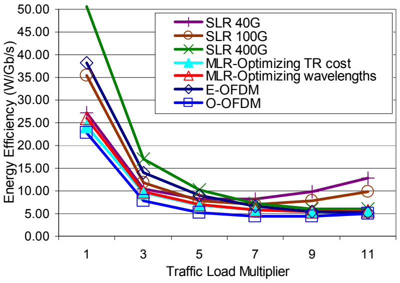

Fig. 6: Energy Efficiency achieved for all solutions and different traffic loads.

4. Energy Efficiency

Next, the considered solutions were compared with respect to their power consumption. The transponders of the fixed-grid solutions were assumed to require 47W, 125W, 215W, and 330W for the 10 Gb/s, 40 Gb/s, 100 Gb/s and 400 Gb/s transponders [12]. In the flex-grid solutions, E-OFDM and O-OFDM have similar receiver architectures, yet they differ in the transmitter part. E-OFDM requires a DSP module and digital-to-analog converters (DACs) at both ends while in O-OFDM these are present only at the receiver part, similar to a commercial coherent transponder. Nevertheless, as reported in [13] E-OFDM has the same DSP complexity as a coherent 40Gb/s QPSK, giving insight into the associated power consumption. In this study we have assumed that the E-OFDM transponder consumes power equal to that of a 100 Gb/s transponder for bit rates from 10-100Gb/s and equal to a 400Gb/s transponder for bit rates 100-400Gb/s, to also indirectly account for the DACs. As opposed to this conservative assumption, a linear function may be proven more suitable as DSP has been reported to scale linearly with bit-rate. At the O-OFDM transmitter, the source laser is shared among the subcarriers that are modulated at low baud-rates. Therefore, it is assumed that its power consumption per subcarrier matches that of a 10 Gb/s transponder. OXCs and optical line amplifiers (OLAs) are considered to consume an equal amount of power for all cases. Bandwidth-variable WSSs are expected to require the same amount of power to operate as the conventional WSSs. The power consumption of OXCs was set to 430W, including control overhead, for the node degree of the DT topology. OLAs were set to 145W per direction of a double-stage EDFA, including control overhead. 120 OLAs were assumed for the entire DT topology. In addition a cooling factor equal to 2 has been assumed for all considered components.

The estimated energy efficiency (in W/Gb/s) for the various traffic loads is illustrated in Fig. 6. 400G SLR appears to be the least efficient for traffic load up to 5 although it tends to improve for higher loads. The other SLR solutions achieve better efficiency that increases for high loads justified by the great number of transponders as depicted in Fig. 2. On the other hand the granularity of 10G/40G/100G/400G in MLR and of the low-rate subcarriers in O-OFDM, appears to be sufficient for the entire range of traffic loads optimizing the number and type of transponders and leading to low power consumption. Under the given assumptions, E-OFDM appears to consume more than what it would be expected for load up to 5 considering that they offer a finer granularity than MLR. Moving up in traffic load, the transponders assumed run at higher bit rates with better energy efficiency.

5. Conclusions

Focusing on spectrum as a resource, we study how bandwidth allocation in fixed-grid and flex-grid core networks with up to 400 Gb/s channel rates affects the requirements in capital and power. The capability of the flex-grid networks to allocate efficiently the available spectrum counterbalances the additional capital expenditures that are required to migrate to a multi-carrier system. Overall network energy efficiency may be optimized by offering finer bit rate granularity and minimizing the utilized spectrum.

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