

On the Performance of Flexgrid-based Optical Networks

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ABSTRACT

The ever increasing IP traffic volume has finally brought to light the high inefficiency of current wavelength-routed rigid-grid networks in matching the client layer requirements. Such an issue results in the deployment of large-size, expensive and power-consuming IP/MPLS layers to perform the required grooming/aggregation functionality. To deal with this problem, the emerging flexgrid technology, allowing for reduced size frequency grids, usually referred to as frequency slot, has recently attracted great attention among network operators, component and equipment suppliers, and the research community. In this paper, we report the main contributions performed in the context of EU STRONGEST project regarding flexgrid optical networks.

Keywords: Flexgrid Optical Networks, Multilayer IP/MPLS-over-Flexgrid, Elastic Spectrum Allocation.

1. INTRODUCTION

The emergence of new disruptive bandwidth intensive services and applications has led to a huge surge of IP traffic which, ultimately, has brought to light the clear granularity mismatch between the client layer and current wavelength-routed optical layer. This issue results in a highly inefficient use of the network capacity, and consequently, in multi-layer networks requiring a large amount of highly expensive, power-consuming IP/MPLS equipment to be installed for grooming/aggregation purposes. In this context, flexgrid optical networks [1], [2], which provide a highly flexible, spectrally efficient use of resources, have emerged as a potential candidate for next-generation optical transport networks. The flexgrid technology, which leverage upon key advances in optical multi-level modulation techniques and the design of both Bandwidth-Variable Transponders (BV-Ts) and Bandwidth-Variable Wavelength Selective Switch (BV-WSS), are regarded as a viable alternative to the not yet mature Optical Packet Switching (OPS) technology enabling both sub- and super-wavelength traffic accommodation.

In flexgrid optical networks, the available optical spectrum is divided into a set of frequency slots (FSs) of a fixed (finer) spectral width, e.g. 25GHz, 12.5GHz or even 6.25GHz, in comparison to the current ITU-T Dense Wavelength Division Multiplexing (DWDM) rigid frequency grid (e.g. 50GHz) [3]. The number of contiguous FSs an optical demand occupies depends on the requested bit-rate, the modulation technique and the frequency grid [2]. Thus, such narrower grids allow for efficient spectrum utilization and favor grooming data directly at the optical layer instead of requiring costly IP/MPLS equipment for such functionality. Since network Capital Expenditures (CAPEX) is a figure network operators are always striving to reduce, the introduction of flexgrid technology is of paramount importance for future multi-layer networks. However, while reducing the need for grooming at the IP/MPLS layer, this more advanced optical technology will also imply higher costs at the optical layer given the highly demanding (grid-dependent) filtering characteristics required in each BV-WSS.

The currently deployed DWDM optical networks operate within a rigid frequency grid and with single-line-rate transponders making use of single carrier modulation techniques. The evolution path of optical transport networks can be translated to the application of advanced single-carrier modulation formats (such as the quadrature phase shift keying (QPSK), 16-ary quadrature-amplitude modulation (16-QAM)) in mixed-line-rate networks, the introduction of multi carrier modulation techniques (such as optical OFDM (O-OFDM) which again can be differentiated in an all-optically generated orthogonal-band-multiplexed O-OFDM with a few, e.g. 4, orthogonal carriers modulated compared to an IFFT-based synthesis of the O-OFDM signal by a digital signal processing (DSP) with several hundreds of subcarriers), and the elastic access to spectral resources within flexible frequency grids. Thanks to these advances, future flexgrid optical networks will utilize the spectral resources efficiently, according to the transmission path characteristics and bandwidth requirements [1], [2].

In flexgrid optical networks, the optical path (*lightpath*) is determined by its routing path and the allocated fraction of frequency spectrum (i.e., the subset of frequency slots allocated) around a central frequency (CF). The introduction of the flexgrid technology opens new functionalities to be developed at the optical layer, such as the adaptation of lightpaths through appropriate spectrum allocation (SA) in a response to bandwidth

variation, in particular, expansion/reduction of the spectrum when the required bit rate of a demand increases/decreases [4].

The contributions of STRONGEST project [5] in flexgrid networks are multifold:

1. In the context of dynamic scenarios, where a RSA algorithm is specially designed to cope with the large amount of frequency slots foreseen in future flexgrid optical networks is proposed. The optimal frequency slot width is analyzed as a function of the traffic profile (TP) to be served by the optical network under consideration.
2. In multilayer IP/MPLS-over-Flexgrid, the CAPEX needed to deploy a multilayer architecture is analyzed for a number of candidate slot widths. It is clear that finer grids will allow for more efficient spectrum utilization, and as a result, favor grooming data directly at the optical layer instead of requiring costly IP/MPLS equipment for such functionality. Thus, given the fact that the network CAPEX, that is, those costs related to purchasing and installing fixed infrastructures, is a figure network operators are always striving to reduce, the introduction of flexgrid technology is of paramount importance for future multi-layer networks. However, it must be noted that while reducing the need for grooming at the IP/MPLS layer, this more advanced optical technology will also imply higher costs at the optical layer given the highly demanding (grid-dependent) filtering characteristics that BV-WSSs are required to have. Due to the fact that exact costs for such components are still not available, we considered a relative cost value so as to effectively determine which frequency grid will better address network operator's needs for cost-effective, spectrum-efficient network architectures [6].
3. In variable traffic scenarios, where the use of OFDM to add elasticity allows flexgrid optical networks to accommodate higher amounts of traffic. In this context, three schemes for variable SA are defined and their performance compared assuming a multi-hour traffic profile [7].

Next Sections detail the above studies and provide the obtained results. All the studies started modeling each problem as Mixed Integer Linear Problems (MILP) using the using the formulation proposed in [8]. Next, heuristic algorithms were developed to obtain near-optimal solutions and validated against the optimal values obtaining solving the MILP models for small instances.

2. FLEXGRID vs. FIXED-GRID

The influence of the flexgrid slot width on the performance of the network has been studied and Routing and Spectrum Allocation (RSA) algorithms have been developed. Simulation experiments were carried out using those algorithms considering the evolution in the expected bandwidth necessities for the years to come, where the bit rate demanded by each connection request is 10, 40, 100 or 400Gb/s.

Results clearly shown that as soon as the frequency slot width is reduced, the amount of traffic served for a given blocking probability (P_b) notably increases. This is a consequence of the fact that more efficient spectrum utilization is achieved by reducing the slot width for this traffic profile. Table 1 summarizes gains in terms of total transported bandwidth at $P_b=1\%$ when the width of the used slots is reduced, with respect to using the DWDM fixed 50GHz width.

Table 1 Average gains of using different flexgrid slot width w.r.t. DWDM

Average bit rate (Gb/s)	50GHz	25GHz	12.5GHz	6.25GHz
22.2	0%	112%	260%	416%
24.1	2%	99%	247%	354%
38.4	2%	92%	208%	276%
52.0	11%	105%	187%	213%
66.1	16%	105%	180%	182%
80.0	15%	92%	131%	133%

As shown, increments of 5 times can be obtained using the 6.25GHz grid, when the traffic to be transported has low average bit rate. In addition, reducing slot width improves the obtained performance. When, the on average bit rate increases the gains are not as high as before, although allow for increments higher than 2 times w.r.t the DWDM technology. However, the benefits of using extremely narrow slot widths disappear. The reasons for that are: on the one hand, the effect of the more efficient spectrum utilization obtained for low on-average bit rate traffic is gradually reduced and on the other hand, spectrum fragmentation increases as a consequence of requesting connections for a larger amount of frequency slots. In view of the effects of spectrum fragmentation, new strategies for spectrum reallocation have been devised. The performance gains obtained show an improvement in the range of 20% to 35%.

Therefore, the slot width used in a given flexgrid optical network should be selected on the basis of the traffic to be served by that network. Since that traffic is as a consequence of client layer connection requests, the CAPEX costs needed to deploy a multi-layer IP/MPLS-over-Flexgrid architecture need to be also analyzed.

3. MULTI-LAYER IP/MPLS-OVER-FLEXGRID

It is clear that finer grids will allow for more efficient spectrum utilization, and as a result, favor grooming data directly at the optical layer instead of requiring costly IP/MPLS equipment for such functionality. Thus, given the fact that the network CAPEX is a figure network operators are always striving to reduce, the introduction of flexgrid technology is of paramount importance for future multi-layer networks. However, it must be noted that while reducing the need for grooming at the IP/MPLS layer, this more advanced optical technology will also imply higher costs at the optical layer given the highly demanding (grid-dependent) filtering characteristics that BV-WSSs are required to have.

Table 2 reports the average number and bitrate of the installed BV-Ts, and the average reduction in both IP/MPLS node switching capacity and actual amount of traffic switched (flow switched) compared with the 50GHz grid. As expected, these values are strongly dependent on both the frequency grid and on-average bit rate traffic evaluated. As long as the on-average bit rate analyzed allows for it, the use of finer frequency grids entails a higher number of BV-Ts but with a considerably lower average bit-rate per BV-T, a fact which leads to lower switching capacity, and therefore, to cheaper IP/MPLS equipment.

Table 2 Avg. BV-T number and Bitrate and Node and Flow Switching

Grid (Ghz)	#BV-T			BV-T bitrate		
	24.1Gb/s	52Gb/s	80Gb/s	24.1Gb/s	52Gb/s	80Gb/s
25	23.1%	21.5%	0.6%	-20.8%	-21.9%	-2.6%
12.5	54.0%	38.9%	0%	-38.2%	-33.2%	-6.1%
6.25	78.9%	53.9%	0%	-51.1%	-40.1%	-6.1%
Grid (Ghz)	Switching Capacity			Flow Switched		
	24.1Gb/s	52Gb/s	80Gb/s	24.1Gb/s	52Gb/s	80Gb/s
25	7.3%	7.3%	7.0%	3.3%	6.3%	8.3%
12.5	13.0%	13.0%	10.0%	3.7%	11.3%	9.7%
6.25	18.3%	18.3%	11.3%	3.7%	18.3%	11.0%

From a temporal perspective, an increment of 56.6% in the cost of BV-WSS can be assumed for a 6.25GHz grid for low on-average bit-rate traffic, decreasing to 37.7% and 14.4% when medium and high, respectively on-average bit-rate traffic is considered. Then, as a result of the expected traffic evolution these investments will not be profitable.

Therefore, it can be concluded that investments in flexgrid optical networks using the 12.5GHz, or even the 25GHz grid, are cheaper in the short-term and more appropriated for medium and long-term scenarios.

4. ELASTIC SPECTRUM ALLOCATION

The introduction of the flexgrid technology opens new functionalities to be developed at the optical layer, such as the adaptation of lightpaths through appropriate Spectrum Allocation (SA) schemes in a response to bandwidth variations, in particular, expansion/reduction of the spectrum when the required bit rate of a demand increases/decreases, respectively.

Three schemes for time-varying SA that put some restrictions on the assigned CF and SA are being considered:

- in the *Fixed* SA both the assigned CF and SA do not change in time;
- in the *Semi-elastic* SA the assigned CF is fixed but the spectrum width may vary;
- in the *Elastic* SA both the assigned CF and the allocated spectra are flexibly selected at each time interval.

Considering 1% as the target un-served bandwidth, increments in the order of 6.5% of offered load can be obtained by applying the Semi-Elastic SA scheme with respect to the Fixed SA one. This is as a consequence of the elasticity that adding/releasing operations add to the former. Interestingly, the Elastic SA scheme provides much higher increments (25%) to the traffic server by the Semi-Elastic SA one, as a result of not only provide elastic spectrum allocation, but also dynamically changing the CF of the lightpaths.

As a final remark regarding the above-defined SA schemes, the complexity of flexgrid operation increases when the flexibility degree is increased. Table 3 briefly summarizes each scheme.

Table 3. Summary of the schemes proposed for time-varying SA

Spectrum Allocation	Requirements	Performance w.r.t the Fixed SA
Fixed	No special requirements.	--
Semi-Elastic	<ul style="list-style-type: none"> Control plane protocols to allow dynamically modify the allocated spectrum. Optical transponders and filters to on-demand increase/decrease the used spectrum. 	6.44%
Elastic	<ul style="list-style-type: none"> Control plane protocols to allow dynamically modifying the allocated spectrum and the CF. Optical filters to on-demand increase/decrease the used spectrum and modify the CF. Optical transponders to on-demand modify the CF and/or increase/decrease the used spectrum. Network management system to manage various demand changes in the network simultaneously. 	24.78%

5. CONCLUDING REMARKS

In this paper the contributions in flexgrid networks performed in the framework of the STRONGEST project have been presented.

The optimal frequency slot width was analyzed as a function of the traffic profile to be served by each of the optical networks under consideration. Interestingly, the narrowest slot width (6.25GHz) provided the highest performance when the traffic profile requested to the network included high amount of low bit rate connection requests. However, when the relative weight of low bit rate (10Gb/s) connection requests decreased with respect to the weight of high bit rate (>100Gb/s) connection requests, the effectiveness of the narrowest slot width was canceled, providing then the same performance than that of 12.5GHz.

Regarding the design of multilayer IP/MPLS-over-flexgrid networks, the cost implications that the frequency grid (slot width) has on this emerging multilayer network planning problem was analyzed through extensive numerical experiments. For the sake of a comprehensive study, a set of realistic network topologies, equipment costs, and traffic instances was considered.

The results showed that the benefits that can be achieved through the use of finer slot widths are strongly dependent on the actual TP under which the network is operating. Whilst investments in costly BV-WSS (finer grid) devices are very well motivated under traffic conditions reporting a high number of light bit-rate demands, which represent short-term traffic scenarios, do not seem profitable in the long-term, where a reduced number of higher bit-rate demands are expected. Consequently, both the 12.5GHz and the 25GHz slot widths are reported as potential candidates for the deployment of future multilayer networks based on flexgrid technology.

Finally, regarding time variable traffic, we investigated the performance of three spectrum allocation schemes. Obtained results show that the application of elastic spectrum allocation leads to a significant improvement in the network throughput with respect to fixed spectrum allocation when multi-hour traffic scenario are considered. Since bit rate increments provided by the Elastic SA scheme are in the range 16%-29%, research in suitable methods, including signaling protocols, to implement that SA scheme should be promoted.

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