

# Elastic Spectrum Allocation for Variable Traffic in Flexible-Grid Optical Networks

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**Abstract:** We focus on lightpath adaptation under variable traffic demands in flexible-grid optical networks. Specifically, we study three different adaptation schemes for the variable spectrum allocation. Illustrative numerical results show the benefits of the schemes.

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## 1. Introduction

The currently deployed wavelength division multiplexing (WDM) 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 QPSK, 16-QAM) in mixed-line-rate networks, the introduction of multi carrier modulation techniques (such as O-OFDM), and the elastic access to spectral resources within flexible frequency grids. Thanks to these advances, future elastic optical networks (EON) will utilize the spectral resources efficiently, according to the transmission path characteristics and bandwidth requirements [1, 2]; EON divide the spectrum into frequency slots which provides greater granularity than rigid networks based on WDM.

In EON operating within a flexible grid, 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 EON opens new functionalities to be developed at the optical layer, such as the adaptation of lightpaths through appropriate spectrum allocation in a response to bandwidth variations, in particular, expansion/reduction of the spectrum when the required bit rate of a demand increases/decreases [3].

In this paper, we define three schemes for variable spectrum allocation (SA) in EON, namely: 1) *Fixed SA*, 2) *Semi-elastic SA*, and 3) *Elastic SA*. We compare the performance of these schemes assuming a multi-hour traffic profile. The consideration of multiple time intervals results in the time-dependent routing with ELastic Spectrum Allocation (ELISA) problem.

## 2. The ELastic Spectrum Allocation (ELISA) problem

The ELISA problem can be formally stated as follows.

**Given:** 1) an EON represented by a graph  $G(V, E)$ , being  $V$  the set of optical nodes and  $E$  the set of fiber links connecting two nodes in  $V$ ; 2) an ordered set  $S$  of frequency slots in each link in  $E$ ; 3) a set of time intervals  $T$ ; 4) a set  $D$  of demands to be transported; each demand  $d$  is represented by a tuple  $(s_d, t_d, \{h_{dt} : \forall t \in T\}, h_d^{min})$ , where  $s_d$  and  $t_d$  are the source and the destination nodes respectively,  $h_{dt}$  is the requested bandwidth in time interval  $t$  ( $h_{dt} \leq h_d^{max}$ ), and  $h_d^{min}$  is the minimum bandwidth to be satisfied in every time interval, otherwise the demand will be rejected.

**Find** the route over the EON and the spectrum allocation of every transported demand in each interval time.

**Objective:** minimize the number of rejected demands (primary objective) and the amount of un-served bandwidth (secondary objective).

To solve the ELISA problem, we consider three schemes for variable in time SA (Fig. 1) that put some restrictions on the assigned CF and spectrum allocation:

- **Fixed SA** (Fig. 1a) both the assigned CF and spectrum allocation do not change in time; each slot is rigidly assigned to one demand at most and it is not shared between two demands. At each time period, demands can use all or only part of the allocated spectrum to convey the bandwidth requested for that period.
- **Semi-elastic SA** (Fig. 1b) the assigned CF is fixed but the spectrum width may vary; its total width is limited to a spectrum range. Here, half-slots are defined so increments/decrements of one slot are achieved by allocating/releasing one half-slot at each end of the already allocated spectrum while keeping invariant the

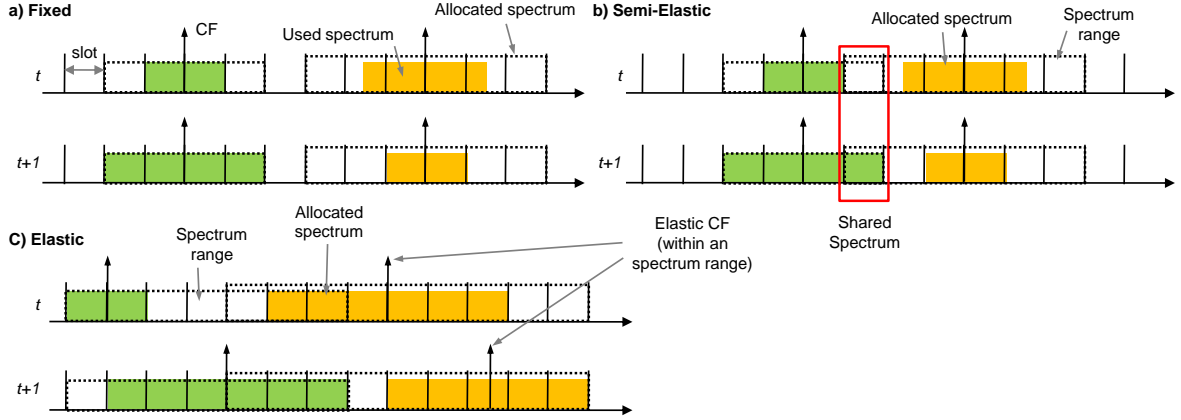


Fig. 1. Three schemes for variable spectrum allocation in a flexible-grid network (two time intervals are observed,  $t$  and  $t+1$ ).

CF. In this scheme, half-slots can be shared between two neighboring demands where its defined spectrum ranges overlap, but used by, at most, one demand in a time interval.

- **Elastic SA** (Fig. 1c) both the assigned CF and the allocated spectrum are flexibly selected at each time interval (the allocated spectrum can be flexibly moved within the spectrum range); a slot can be shared between two or more demands, but used by, at most, one demand in a time interval.

The problem concerns the resolution of the static RSA, based on [4], jointly, for each time period in which meaningful bandwidth variations are observed. Apart from the common RSA constraints, such as the spectrum continuity and contiguity, additional constraints related to the degree of flexibility in the spectrum allocation arise in the ELISA problem. Since Integer Linear Programming (ILP) formulations of ELISA are difficult to be solved, as an alternative we propose three heuristic algorithms based on the BRKGA meta-heuristic [5]. The performance of the proposed heuristics was validated against optimal solutions obtained with ILP models for small topologies. In all the tests performed, heuristic solutions were found within running times of some seconds, in contrast to several hours needed to find optimal solutions with the models.

### 3. Illustrative numerical results

This section evaluates the performance of ELISA implemented through each of the above SA schemes, considering a multi-hour traffic profile scenario when the spectral width of the slots was fixed to 12.5GHz. Three national optical network topologies were used: the 21-node and 35-link Spanish Telefónica (TEL) topology, the 20-node and 32-link British Telecom (BT) topology, and the 21-node and 31-link Deutsche Telecom (DT) topology. Fig. 2 shows such topologies.

A demands mix belonging to three different traffic profiles (TP) was used, where the bandwidth requested by each demand at each time period is randomly generated within the interval between the values  $h^{min}$  and  $h^{max}$  with a granularity of 10GHz. Specifically, we define the following intervals in Gb/s: TP-1 [10, 100], TP-2 [40, 200], and TP-3 [100, 400]. Note that, since the bandwidth of each demand at a given time period is not correlated with previous periods, high bandwidth fluctuations are expected between consecutive time periods. Moreover, high difference exists between  $h^{min}$  and  $h^{max}$  values (between 4 and 10 times higher). With these values, the on average bit rate per demand is in the order of 150 Gb/s. Finally, we considered an optical spectrum width of 600 GHz.

Fig. 1 shows the spectrum efficiency (used spectrum w.r.t. allocated spectrum) of the considered SA schemes as a function of the offered load in the TEL network. The efficiency of the Semi-Elastic and Elastic schemes is very similar, in the order to 95%, as a consequence of both schemes allocate spectrum for the bandwidth requested in each time period and the narrow slot width chosen. However, the spectrum efficiency of the Fixed SA scheme is in the order of 60-75% since the size of the allocated spectrum is statically computed. Besides, the spectrum efficiency increases with the offered load.

Fig. 4 shows the percentage of un-served bandwidth (UBw) as a function of the total requested one for the three considered schemes. Considering 1% as the target un-served bandwidth for each of the networks, increments in the order of 17-20% 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 adds equivalent increments (17-20%) 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.

In view of these results, and from the definition of the SA schemes where each scheme adds elasticity to the previous one, the following relation can be stated:  $UBw(\text{Fixed SA}) \geq UBw(\text{Semi-Elastic SA}) \geq UBw(\text{Elastic SA})$

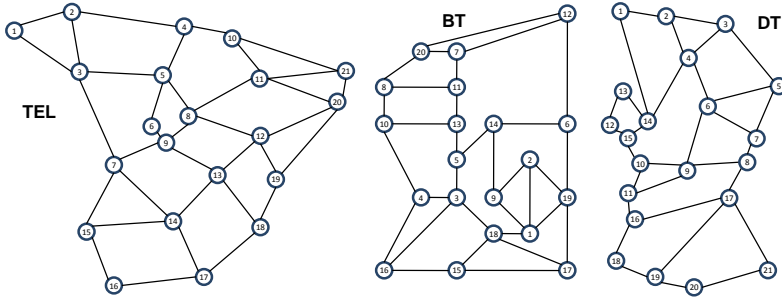


Fig. 2. Sample optical network topologies used in our tests: 21-node Spanish Telefónica (left), 20-node British Telecom (center), and 21-node Deutsche Telekom (right).

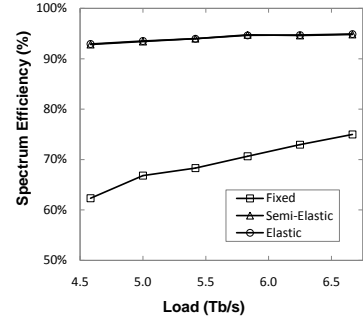


Fig. 3. Observed spectrum efficiency

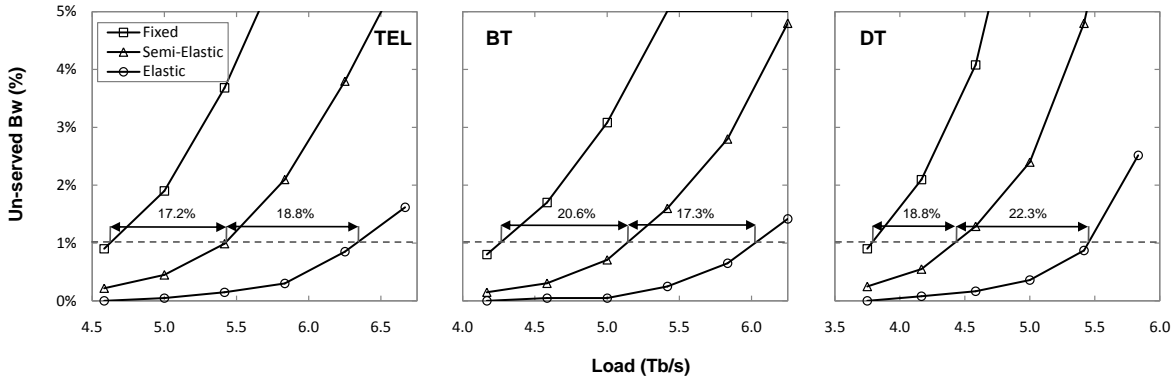


Fig. 4. Un-served bandwidth vs. offered load in TEL (left), BT (center), and DT (right) networks, for the three SA schemes considered. Relative gains are also highlighted.

SA). Note that in static scenarios where the requested bandwidth is constant with the time, that equality must be satisfied. Therefore, the gain of the Semi-Elastic and Elastic schemes is a function of the variability of the requested bandwidth in each time period.

#### 4. Conclusions

In this paper we investigated the performance of three spectrum allocation schemes under variable in time traffic demands in EON. 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.

As a final remark regarding the above-defined SA schemes, the complexity of EON operation increases when the flexibility degree is increased. Table 1 briefly summarizes each scheme.

Table 1. Summary

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

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