Benefits of Elastic Spectrum Allocation in Optical Networks with Dynamic Traffic

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Abstract — **Traditional optical core networks based on Wavelength Division Multiplexing (WDM) provide optical channels (wavelengths) rigidly allocated over the optical spectrum and separated by 50 or 100 GHz. The novel concept of Elastic Optical Network (EON) can help to improve network flexibility by allocating multiple sub-channels to incoming connection requests with finer bandwidth granularity (hence the term elastic) over a flexible spectrum grid. In this paper, we propose an algorithm for connection resource provisioning in EONs. We compare the performance of flexible-grid EONs to that of fixed-grid WDM networks under dynamic traffic, with and without grooming capability, in terms of blocking probability and network resource (i.e., overall spectrum) occupation, thus showing quantitatively the advantage of EON compared to grooming-based WDM networks.**

I. Introduction

Recent studies [1] confirm the exponential trend of growth of IP traffic routed by core networks. An evolution towards more flexible and scalable optical fiber systems is thus required to build next-generation optical core networks able to support such continuous traffic growth.

Currently deployed optical networks use Wavelength Division Multiplexing (WDM) systems operating over a rigid frequency grid with 50 or 100 GHz channels spacing. This rigid and coarse spectrum granularity causes inefficient capacity utilization. In fact, in current wavelength routed networks the allocation of an entire wavelength (also indicated with λ) is needed to route a connection, even when the required bandwidth is lower than the capacity of an entire λ channel. Moreover, with current WDM implementation, connections requiring bandwidth, which is an entire multiple of the wavelength capacity (e.g., multiple of 100 Gbit/s), cannot be efficiently provisioned from the spectrum occupation perspective, as the currently WDM grid implicitly assumes over-estimated spectral guard-bands between wavelengths (see Sec. II).

To cope with these issues, a finer sub-wavelength spectrum granularity can be identified within the optical spectrum, so that a series of contiguous *frequency slices* (FSs), having a spectral width of e.g. 12.5 GHz, 6.25 GHz or 5 GHz, can be exploited in order to create custom-size bandwidth channels [2]. The series of contiguous FSs used to serve a unique connection is typically referred to as *Spectrum Slot*. This technique provides higher flexibility in the bandwidth allocation, obtained by selecting a variable number of FSs according to the actual connection bandwidth requirements.

The implementation of the EON paradigm requires some novel enabling devices, such as Bandwidth-Variable (BV) Transponders and Cross-Connects, which must be capable of transmitting, receiving and switching optical signals at multiples of the FS intervals. With such constraints, the Routing and Wavelength Assignment (RWA) algorithms adopted in traditional WDM networks are no longer applicable to EONs.

In fact, connections provisioning in EONs introduces two specific constraints: spectrum contiguity and spectrum continuity. *Spectrum contiguity* means that, if a certain connection needs to be allocated in two or more FSs, these FSs must be adjacent on the optical spectrum. On the other hand, *spectrum continuity* means that a connection must occupy the same (set of) FS(s) along the whole route from the source to the destination node. Note that, while spectrum continuity has a correspondent constraint in the WDM case (the wavelength continuity constraint), the spectrum contiguity constraint is a specific characteristic of EON scenarios. Therefore, instead of the RWA, a more complex Routing and Spectrum Allocation (RSA) problem must be solved, whenever a connection needs to be provisioned in an EON.

Several papers in literature have addressed problems related to the efficiency, scalability and feasibility of the EON paradigm, for example [3]. The concept of EON was proposed for the first time in [4], where the authors referred to the concept of Spectrum sLICed Elastic optical path network (SLICE) and identify the Coherent Orthogonal Frequency Division Multiplexing (COOFDM) as an enabling technology towards higher flexibility in allocating spectral resources within optical networks. In [5], various traffic-grooming strategies and a spectrum reservation scheme were proposed for the dynamic connection provisioning in EONs, but only the benefits obtained when provisioning sub-wavelength demands were shown, without considering the provisioning of connections requiring higher bandwidth than that provided by one wavelength. In [6], various provisioning algorithms were proposed, which considered both fixed path routing and online paths computation, and the benefits provided by adopting multiple modulation formats for connections provisioning were also evaluated. In [7], the benefits of EONs under dynamic traffic conditions were evaluated from both the power consumption and blocking performance points of view. In [8], the effect of using multiple modulation formats in EON dynamic connection provisioning was studied.

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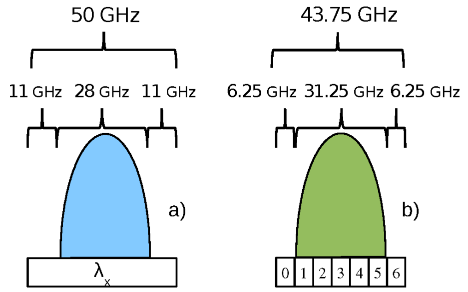

Fig. 1. Optical spectrum occupation with:
a) traditional WDM transponder; b) BV-transponder.

In this paper, we propose an RSA algorithm for EONs. We evaluate EON performance in terms of both blocking probability and network resources (i.e., overall spectrum) utilization under dynamic traffic, comparing EONs with current WDM networks, with and without grooming capability. Our results show quantitatively the advantage of EON compared to traditional grooming-based WDM networks.

Unlike previous works aimed at comparing EONs performance to traditional WDM, in our study we consider forming on-demand super-channels of any size (i.e., not necessarily as specified directly in the input traffic demand). We believe that allowing more flexibility in super-channel formation can better highlight EON benefits. To this regard, we will employ practical spectral occupation settings derived from the actual operation of current 100 Gb/s transponders.

II. Model of Elastic Optical Network

In this paper, we assume that the optical spectrum is divided into *M* FSs, indexed from 0 to (*M*-1) and each wide *T* GHz.

Current coherent PDM-QPSK (Polarization-Division-Multiplexed Quadrature Phase Shift Keying) transponders are able to transmit a 100 Gbit/s signal occupying about 28 GHz on the optical spectrum [9]. Therefore, considering traditional WDM systems with 50 GHz spaced channels (wavelengths), a bilateral guard-band of 11 GHz at each side is implicitly assumed to be used with current technology (see Fig. 1-a)), thus wasting spectral resources, since: i) a guard-band smaller than 22 GHz can be adopted; ii) if signals over adjacent wavelengths need to be switched/filtered together, no guard-band is strictly needed between them.

In the following, we assume that finer channel spacing can be adopted in EON. Recently, standard bodies worked on this direction: 12.5 GHz channel spacing has been adopted as a first step towards elastic-bandwidth allocation [10].

Assuming for the EON case that BV-transponders have approximately the same spectral efficiency as the aforementioned PDM-QPSK transponders, and given the width of each FS (e.g., 6.25 GHz), in the following we consider that one elastic transponder is able to transmit 100 Gbit/s over a 31.25 GHz spectrum (i.e., 5 FSs)[1]. Moreover, we assume that 1 FS per side is used as guard-band in EONs, as shown in Fig. 1-b).

Under these assumptions, one elastic transponder is able to transmit up to 20 Gbit/s in one FS (i.e., 6.25 GHz) and to flexibly tune its transmission rate with a granularity equal to one FS (we consider re-tuning the transponders symbol rate keeping constant the modulation format). When a connection is set-up, a number of FSs corresponding to the actually required bandwidth are allocated, and one additional FS per each side is assigned as guard-band.

In EONs, further spectral savings are also provided when accommodating connections requiring capacity higher than that provided by one transponder (such kind of connections is often referred to as *super-channels*). As an example, to setup a 200 Gbit/s connection, in current WDM networks two wavelengths (i.e., 100 GHz) are needed, as shown in Fig. 2-a). On the other hand, in the EON context, two transponders can be tuned to transmit on 10 adjacent FSs (we assume that 20 Gbit/s can be transmitted on one FS and that no guard-band is needed, if two signals have the same source and destination).

Therefore, we just have to consider two additional FSs as guard-bands, for a total of 12 FSs in the EON case. That is, an overall spectrum of 75 GHz is sufficient to transmit 200 Gbit/s (see Fig. 2-b)). Note that only an *intrachannel* guard-band (*IG*), much smaller than the guard-band used to separate the spectrum of different connections (*GB*), is needed to allow proper filtering[2] of the signals transmitted by the two elastic transponders used for a unique connection [11].

Fig. 2-b) shows the function of these guard-bands within EONs. In the example, *GB* is used to separate connections 1 and 2, whereas a smaller *IG* is used to separate the two signals composing the super-channel associated to connection 1. As already mentioned, we assume that the guard-band *GB* has a spectral width equal to one FS. On the other hand, in our model we set *IG* = *I-B*, where *I* is the subcarriers spacing (i.e., the spectral interval between the central frequencies of two signals transmitted by different transponders over adjacent FSs, belonging to the same super-channel) and *B* is the spectrum occupied by the transmitted signal.

In this study we do not explicitly model the intra-channel guard-band *IG*, but *we still catch its significance by over-dimensioning the overall spectrum occupied by one transponder* (we consider that a 28 GHz signal provided by one elastic transponder fits in a 31.25 GHz spectrum).

III. Provisioning Algorithm For EON

In this section, we describe the algorithm proposed in this paper for the dynamic connection provisioning in the EON scenario. The inputs of the RSA problem are the following.

- *G* = (*N, E, M*): graph representing the physical topology; where *N* is the set of nodes, *E* is the set of bidirectional fiber links and *M* is the number of FSs on each link.
- *c* = (*s, d, x*): connection request; where *s*, *d* ∈ *N* are the source and destination nodes, respectively, *x* is the number of FSs required by the connection (excluding guard-bands). For each request, a *bidirectional* connection must be set up between *s* and *d*.

[1] The lowest integer multiple of the number of FSs, where a 28 GHz spectrum fits corresponds to 5 FSs, i.e., 5·6.25 GHz = 31.25 GHz.

[2] Intra-channel filtering is needed only at the destination to separate signals to be received by different transponders. In intermediate nodes, only inter-channel guard bands are necessary to switch different flows via OXCs.

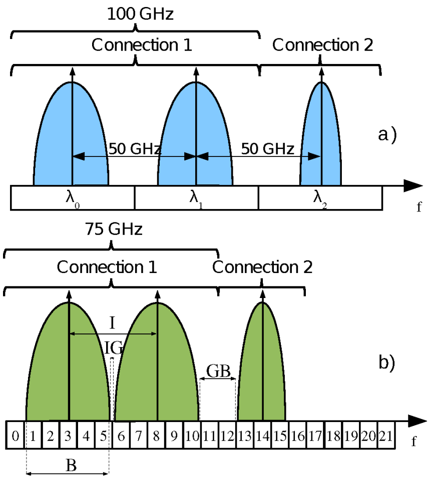

Fig. 2. An example of super-channel allocation: a) WDM, b) EONs.

- b: number of guard-bands placed at each side of the transmitted signals. Thus, the total number of FSs needed by connection c is $t = x+2b$. We will always assume $b = 1$.

Thus, given the graph G and the current network occupation state (i.e., the occupation state of every FS in every link of the network), for every incoming connection c, the provisioning algorithm aims at finding a minimum-cost RSA, subject to the following two main constraints:

i) spectrum contiguity: all the FSs allocated for c must be adjacent in spectrum;

ii) spectrum continuity: the same FSs must be allocated for c in each link on the path between source and destination nodes.

For each connection, if no feasible route (with enough available bandwidth) is found, then the connection is blocked, otherwise it is routed and spectral resources are allocated and successively released when the connection ends.

The following basic variables are also defined:

- w: the minimum-cost path computed for connection c; it consists of a set of links connecting nodes s and d, and the subset $\Phi \subseteq \{0, 1, \ldots, M\text{-}1\}$ of FSs allocated in w.
- w_c: the cost of path w.
- i_{FS}: the FS with lowest spectrum index for path w.

A. The Multi-Layer Graph Model

A common approach used to perform RWA in traditional WDM networks is based on the so-called Multi-Layer Graph (MLG) [12]. It consists in replicating the considered network topology as many times as the number of wavelengths per link, as shown in Fig. 3-a). Such graph-abstraction is useful when wavelength-continuity must be considered in computing a source-to-destination route, as it gives insight of the available routes over each wavelength.

A possible simple extension of this concept to the EON scenario is the MLG as in Fig. 3-b), where each layer corresponds to one FS. However, to catch the property of spectrum contiguity required in the RSA process, *an improved MLG can be obtained by associating one plane to every possible set of* t *adjacent FSs, where* t *is the total number of FSs required by a specific connection, including guard-bands.*

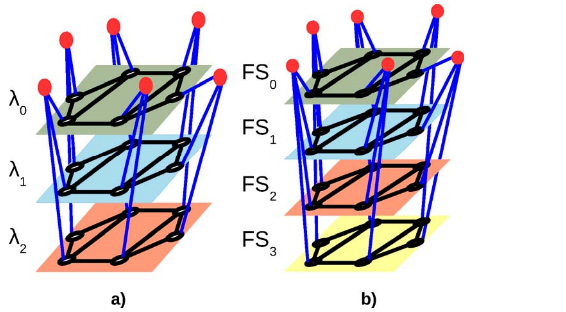

Fig. 3. a) The multi-layer graph model used in WDM networks: every plane corresponds to one wavelength. b) The multi layer-graph adapted to the EON context: every plane corresponds to a FS.

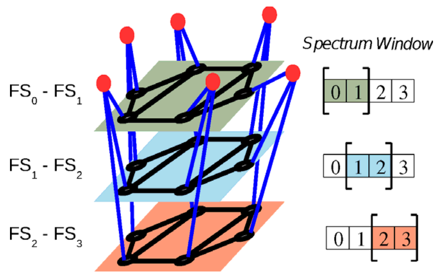

Fig. 4. The newly proposed multi-layer graph modified for EONs. Every plane represents the state of occupation of a set of adjacent frequency slots.

An example of the obtained MLG is shown in Fig. 4 for the case $t = 2$ (for the sake of simplicity, in the figure we assume that the optical spectrum is made up of 4 FSs, indexed from 0 to 3). In general, for a connection requiring t FSs within an optical spectrum constituted by M FSs, the MLG will be composed by M-(t-1) layers. Then, each of these layers is examined to compute, via Yen algorithm, the path (and the spectrum allocation) at minimum cost on every scanned layer.

The pseudo-code of the algorithm adopted to generate the auxiliary MLG is reported in Algorithm 1. Given the graph $G = (N, E, M)$, the connection request $c = (s, d, x)$, the number of guard-bands to be used b (then, $t = x+2b$ is the total number of FSs, including guard-bands, needed to allocate connection c), the algorithm creates the MLG layer by layer.

For a given layer i of the MLG, only the links (and the corresponding edge nodes) of G having at least t available FSs in spectrum adjacency are included. The auxiliary graph is initially set equal to the empty set. Then, for every layer i, i.e. for every possible FS to be allocated (note that the possible starting FSs are those from FS 0 to FS M-t), all the links $e \in E$ are examined, checking if at least t adjacent FSs, starting from the i-th FS, are available.

If all the FSs from i to i+t-1 are available on e, it is added to the layer i of *aux_graph* together with its edge nodes, and the cost of link e is computed as sum of the costs of all the FSs i, i+1, …, i+t-1, via the cost function $c_{\mathrm{FS}}(e, j)$, which gives the cost of FS j on link e. Specifically, the cost assigned to an unused FS is a low value (e.g., equal to 1), while the cost of an already allocated FS is set equal to ∞. Then, the total cost of link e is $c(e) = \sum_{j=i}^{i+t-1} c_{\mathrm{FS}}(e, j)$.

Algorithm 1 *Auxiliary Graph Generation*

Input: the graph $G = (N, E, M)$; the connection request $c = (s, d, x)$; the number of guard-bands to be used b (thus, $t = x+2b$ is the total number of FSs, including guard-bands, needed to allocate connection c).
Output: the auxiliary graph *aux_graph*.

```
aux_graph = 0;
for i = 0 → (M-t) do
    (i is the starting FS corresponding to the i-th layer of aux_graph)
    for all e ∈ E do
        usable = true;
        for j = i → (i + t-1) do
            if frequency slot j is already occupied then
                usable = false;
            end if
        end for
        if usable = true then
            add e to the i-th layer of aux_graph;
            add the edge nodes of e to the i-th layer of aux-graph;
            c(e) = 0;
            for j = i → (i + t-1) do
                c(e) = c(e) + c_FS(e, j);
            end for
        end if
    end for
end for
```

Algorithm 2 *Elastic Provisioning Algorithm*

Input: the auxiliary MLG *aux_graph*; the connection request $c = (s, d, x)$; the number of guard-bands to be used b (thus, $t = x+2b$); the number of shortest paths k to compute for each layer of the MLG.
Output: the minimum-cost path w, its cost w_c and the starting FS, i_{FS}, where to allocate the adjacent FSs for connection c.

```
w = NULL; w_c = UNREACHABLE; i_FS = -1;
Scan the layers of aux_graph:
for i = 0 → (M-t) do
    Find the shortest path p_i between s and d for layer i
    if c_pi < w_c then
        w = p_i;
        w_c = c_pi ;
        i_FS = i;
    end if
end for
if w_c = UNREACHABLE then
    the connection is dropped;
else
    set-up connection c allocating t FSs on w starting from i_FS;
end if
```

B. RSA Algorithm

For each connection to be provisioned, the RSA algorithm looks for the minimum-cost path between source and destination nodes. If such a path exists, the spectral resources are allocated and then released when the connection is torn down.

For every incoming connection, the algorithm tries to set-up a *new* lightpath between source and destination: i.e., it does not perform traffic grooming for different connections. Note that providing grooming capability to the EON would imply the adoption of a smart policy for resource (i.e., FSs) reservation, in order to reduce the spectrum fragmentation, which constitute a main problem in the context of EONs.

The RSA algorithm is shown in Algorithm 2. After variable initialization, the $(M\text{-}t\text{+}1)$ layers of the MLG are scanned. For each layer i, the minimum-cost path p_i between s and d is found and, if its cost c_{p_i} is lower than the cost of the current

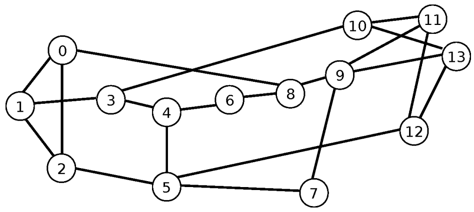

Fig. 5. NSFNET network topology used in this paper.

best path w, then the new minimum-cost path, its cost and the starting FS to be allocated are stored in w, w_p and i_{FS}, respectively. At the end of the MLG scanning, if no best path is found (i.e., if w_c has not been updated to a finite value), connection c is blocked; else, resources are allocated for the *bidirectional* connection, setting the costs of FSs from i_{FS} to $(i_{FS}+t-1)$ along w to infinite until the connection is not torn down.

IV. Case Study

The proposed RSA algorithm was tested on the NSFNET topology, consisting of 14 nodes and 21 bidirectional mono-fiber links, as shown in Fig. 5. Its flexibility and performance in allocating spectral resources in EON were evaluated.

We assumed that a 1 THz optical transmission spectrum is available on every fiber link. This spectrum is composed by 200 FSs, indexed from 0 to 199. Each FS is assumed having 5 GHz width. Moreover, we considered BV-transponders, which are able to transmit 100 Gbit/s over a 30-GHz spectrum (i.e., 6 FSs), so that each subcarrier (FS) supports a 16.7 Gbit/s capacity. Each BV-transponder is assumed to be able to transmit at variable rates, as summarized in Table I.

To evaluate the blocking probability P_b in this scenario, we developed an event-driven simulator implementing the RSA algorithm described in Sec. III for connection provisioning. The simulations were run on a workstation with a 3.1-GHz CPU and 8-GB RAM. Simulation runs with 10^4 connection requests were repeated until the estimated P_b had statistical confidence 95% and 5% error interval.

In our model, connections arrive as Poisson events and have duration distributed as a negative exponential function normalized to unity. The variable bandwidth required by the connections can be either below or above the transponder capacity ("sub-λ" and "super-λ" requests, respectively). These capacity values correspond to an integer number of FSs, which are then provisioned by the RSA algorithm of Sec. III.

We considered two traffic scenarios: the bandwidth required by connections can be either uniformly-distributed or not among all the allowed bit rates, as summarized in Table II. In this table, we indicate the "sub-λ" and "super-λ" transmission rates allowed, expressed in Gbit/s and number of FSs, and the corresponding probability values in the uniform (P_U) and non-uniform (P_{NU}) traffic scenarios. In the case of uniform traffic distribution, all possible capacity values can be required with equal probability. Otherwise, in case of non-uniform traffic distribution, the lower bit-rate requests are privileged.

As we will show in Sec. V, in the latter case the EON paradigm provides higher advantages with respect to traditional WDM solutions, thanks to its flexibility in provisioning spectral resources for incoming connections.

TABLE I: AVAILABLE DATA-RATE GRANULARITIES FOR BV-TRANSPONDERS.

Number of FSs	Transmission Bandwidth	Subcarrier Capacity
1	5 GHz	16.7 Gbit/s
2	10 GHz	33.3 Gbit/s
3	15 GHz	50.0 Gbit/s
4	20 GHz	66.7 Gbit/s
5	25 GHz	83.3 Gbit/s
6	30 GHz	100.0 Gbit/s

TABLE II: BANDWIDTH VALUES AVAILABLE FOR CONNECTION REQUESTS (EXPRESSED IN GBIT/S AND NR. OF FSS) AND THEIR RELATIVE PROBABILITIES IN UNIFORM AND NON-UNIFORM TRAFFIC SCENARIOS.

	Bit rate	No. of FSs	P_U	P_{NU}
Sub-wavelength requests	16.7 Gbit/s	1	1/8	8/39
	33.3 Gbit/s	2	1/8	8/39
	50.0 Gbit/s	3	1/8	8/39
	66.7 Gbit/s	4	1/8	4/39
	83.3 Gbit/s	5	1/8	4/39
	100 Gbit/s	6	1/8	4/39
Super-wavelength requests	200 Gbit/s	12	1/8	2/39
	300 Gbit/s	18	1/8	1/39

The performance of the RSA algorithm has been compared to three different possible operating strategies of the WDM network, considering the same traffic characterization as in the EON case. We assume that 100 Gbit/s PDM-QPSK transponders, transmitting over a 50 GHz spectrum, are deployed within the network, so 20 wavelengths are available over the 1 THz spectrum supported in every fiber link. Specifically, we consider the following WDM scenarios:

- *WDM*: the traditional WDM scenario, where each connection is provisioned by establishing one (or more) dedicated lightpaths. Depending on the allowed bit rate for each connection (Tab. II) one, two or three wavelengths can be used.
- *WDM with Single-Hop grooming (WDM-SHG):* in this scenario, if a connection c_1 between two nodes s and d arrives at the network while another connection c_2 *between the same nodes* s and d is still active, the residual capacity of the lightpaths used by c_2 can be utilized to accommodate c_1.
- *WDM with Multi-Hop grooming (WDM-MHG):* in this case, when a connection c_1 between two nodes s and d arrives at the network, the residual capacity of the other existing lightpaths can be used to accommodate c_1 via a concatenation of lightpaths between s and d.

Note that, given the allowed bit-rate requests (see Tab. II), in the WDM-SHG and WDM-MHG cases the grooming capability can be exploited only for sub-λ requests, as super-λ connections require the *entire* capacity of one (100 Gbit/s), two (200 Gbit/s) or three (300 Gbit/s) wavelengths.

V. RESULTS AND DISCUSSIONS

Figs. 6 and 7 show the values of P_b in four scenarios under uniform and non-uniform traffic distribution. For both traffic cases, the EON blocking probability is significantly lower than with WDM, even when traffic grooming is allowed.

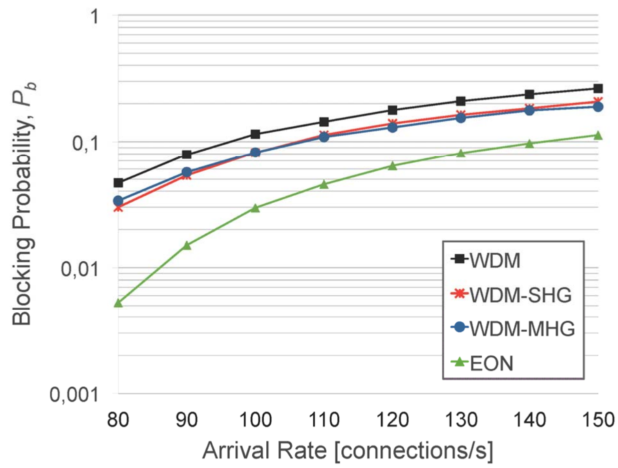

Fig. 6. Blocking probability for the different scenarios (uniform traffic).

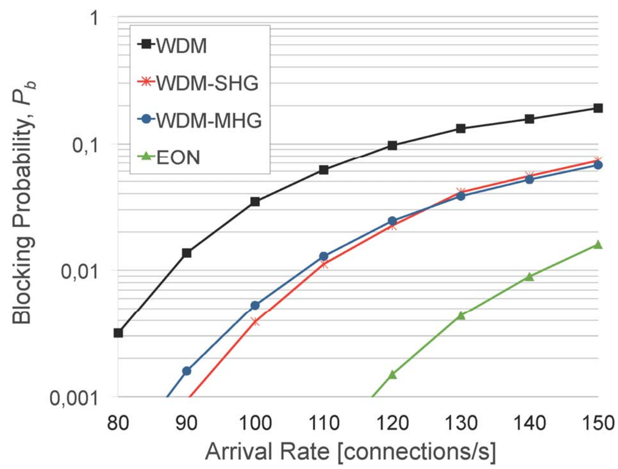

Fig. 7. Blocking probability for the different scenarios (non-uniform traffic).

Specifically, it can be observed that it is always more convenient to adopt the EON solution, rather then providing (either single- or multi-hop) grooming capabilities to the WDM network. In fact, the EON approach, besides the higher flexibility in accommodating connections over the available spectrum, offers the advantage of the guard-band saving, for both sub-wavelength or super-wavelength requests.

In the EON case with uniform traffic, the P_b values are about one order of magnitude lower than those obtained in the WDM case with low traffic (i.e., up to 100 connections/s), and at least 50% lower for higher loads (i.e., 150 connections/s).

The EON gain is even more relevant with non-uniform traffic, i.e., when sub-wavelength connections are privileged. Fig. 7 shows that EON outperforms WDM scenarios by at least one order of magnitude (two, in case of WDM with no grooming capability) in all cases, since for a given connection arrival rate finer bit-rate requests are more probable. The difference in blocking performance between EON and WDM (especially when no grooming is allowed) is much higher in the non-uniform traffic scenario, since when finer bit-rate connections are privileged, EONs take higher benefit from flexibility in allocating spectral resources.

Figs. 8 and 9 show the spectral resources occupation (either used for transmitting optical signals or as guard-bands) with uniform and non-uniform traffic distribution. Resource occupation is represented as percentage of the total available spectrum in all network links.

In general, adopting elastic bandwidth allocation allows large spectrum saving, compared to all WDM cases. In case of uniform traffic distribution, at least 20% spectrum saving is obtained in the EON case with respect to all WDM scenarios. The difference in resource occupation observed between various WDM scenarios is not evident, due to the lower impact provided by traffic grooming capabilities, which are not so relevant when high bit-rate connections are frequent.

On the other hand, for non-uniform traffic distribution, i.e., when finer bit-rate connections are privileged, higher spectrum savings (up to 25%) are obtained in EON compared to WDM networks. This is due to the higher flexibility of EON in accommodating fine bit-rate connections, which are the majority of connection arrivals when non-uniform traffic is considered.

Furthermore, we note that enabling traffic grooming in WDM networks provides higher advantage in the non-uniform traffic scenario, due to the higher spectrum waste in the case of traditional WDM in allocating fine bit-rate connections.

Finally, we note also that, in both uniform and non-uniform traffic scenarios, the resource occupation when doing multihop grooming is higher than in the case with single-hop grooming. This is due to the fact that when multi-hop grooming is accomplished, connections may tend to exploit longer paths, thus eventually occupying more resources unnecessarily.

VI. Conclusion

In this paper, we have compared the performance of EONs in comparison to traditional WDM networks, with or without grooming, under dynamic traffic conditions. We proposed an algorithm to accomplish the RSA for randomly arriving connections in the EON scenario. We compared the performance of the two paradigms in terms of blocking probability and network resources occupation.

We demonstrated that EON blocking probability can be several orders of magnitude lower than in WDM networks using practical values of spectral occupation derived from current 100Gb/s transponders. Moreover, up to 25% of spectrum savings can be obtained in EONs, especially if fine bit-rate connections are privileged.

The advantages of the EON paradigm over WDM are provided by a higher flexibility of the EON solution in allocating as much bandwidth as required by connections and by utilizing lower amount of spectrum as guard-bands, especially when provisioning super-channels connections.

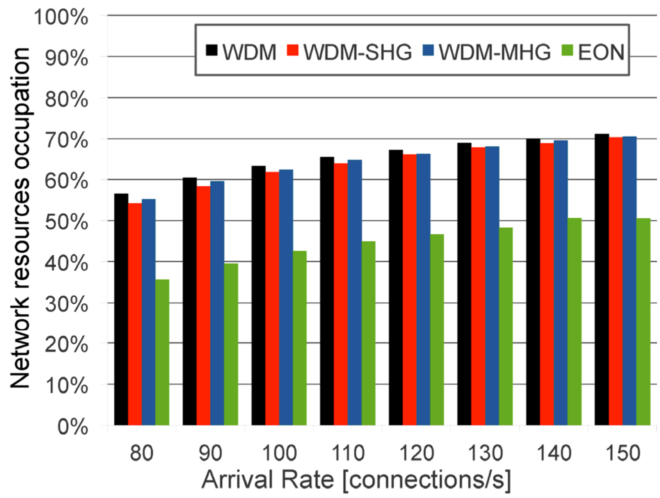

Fig. 8. Resources occupation for the different scenarios (uniform traffic).

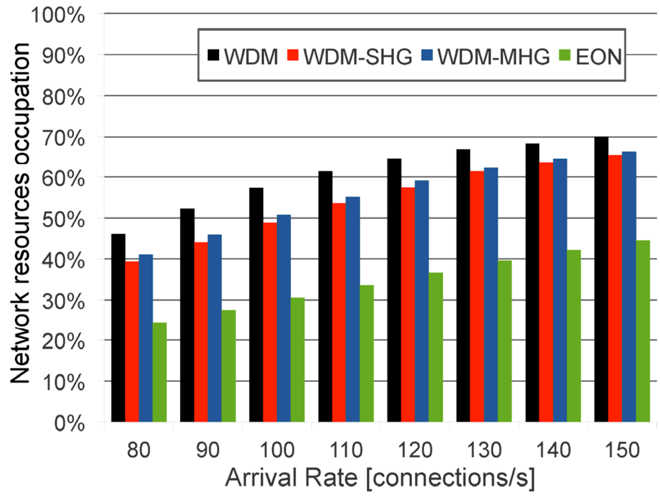

Fig. 9. Resources occupation for the different scenarios (non-uniform traffic).

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