Lightpath Fragmentation for Efficient Spectrum Utilization in Dynamic Elastic Optical Networks

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***Abstract*—The spectrum-sliced elastic optical path network (SLICE) architecture has been presented as an efficient solution for flexible bandwidth allocation in optical networks. An homologous problem to the classical Routing and Wavelength Assignment (RWA) arises in such an architecture, called Routing and Spectrum Assignment (RSA). Imposed by current transmission technologies enabling the elastic optical network concept, the spectrum contiguity constraint must be ensured in the RSA problem, meaning that the bandwidth requested by any connection must be allocated over a contiguous portion of the spectrum along the path between source and destination nodes. In a dynamic network scenario, where incoming connections are established and disconnected in a quite random fashion, spectral resources tend to be highly fragmented, preventing the allocation of large contiguous spectrum portions for high data-rate connection requests. As a result, high data-rate connections experience unfairly increased bocking probability in contrast to low data-rate ones. In view of this, the present article proposes a lightpath fragmentation mechanism that makes use of the idle transponders in the source node of a high data-rate connection request to fragment it into multiple low data-rate ones, more easily allocable in the network. Besides, aiming to support such an operation, a light-weight RSA algorithm is also proposed so as to properly allocate the generated lightpath fragments over the spectrum. Benefits of the proposed approach are quantified through extensive simulations, showing drastically reduced high data-rate connection blocking probability compared to a usual contiguous bandwidth allocation, while keeping the performance of low data-rate requests to similar levels.**

***Index Terms*—Flexible optical networks, lightpath fragmentation.**

I. Introduction

Traditional Wavelength Division Multiplexing (WDM) networks rely on the fixed-size spectral grid standardized by the International Telecommunication Union (ITU), where the minimum granularity for provisioning traffic demands is a wavelength [1]. Although such networks enable the transmission of high bit-rates per optical channel, such a rigid and coarse resource allocation leads to a poor utilization of the spectrum, provided that the traffic between the remote endpoints of a connection is not enough to fill the entire wavelength capacity, which can rise up to 40 or 100 Gbps.

To overcome this drawback, the SLICE architecture has been recently proposed in [2]. SLICE aims to offer a flexible network environment suitable for providing sub-wavelength granularity for low data-rate transmissions and super-wavelength granularity for ultra-high capacity transmissions. The enabling technology for the SLICE architecture is Orthogonal Frequency Division Multiplexing (OFDM), jointly with the Bandwidth Variable Wavelength Cross Connects (BV-WXC) [3], [4]. Despite the many advantages of OFDM, and its widespread use in wireless communications, OFDM has been recently introduced as a modulation format in optical communications [5]. Through optical OFDM, data belonging to a single traffic demand is split in multiple lower bit-rate sub-carriers, providing fine-granularity capacity to the connections by elastically accommodating multiple sub-carriers according to the demands needs. Moreover, thanks to OFDM properties, it is possible to efficiently serve super-wavelength traffic demands that require multiple sub-carriers, by allocating consecutive sub-carriers in the spectrum domain.

Although optical OFDM provides SLICE with a highly spectrum-efficient and bandwidth-variable modulation format, it also poses new challenges to the resource assignment in the network. Indeed, classic Routing and Wavelength Assignment (RWA) solutions for WDM networks can not be directly applied here since, instead of wavelengths, an OFDM transmission requests a contiguous spectrum portion, over which the multiple contiguous sub-carriers required by the incoming traffic demand can be allocated. Moreover, given a lack of wavelength conversion capabilities in the network, the assigned spectrum portion must show a continuity between the remote endpoints of the incoming connection requests. Both spectrum contiguity and continuity constraints must be ensured by the Routing and Spectrum Assignment (RSA) algorithm in the network.

Looking at the literature, the RSA problem has been formulated both as an Integer Linear Programming (ILP) problem for the off-line planning scenario, or using lightweight heuristics for an on-line dynamic network scenario (e.g., see [6], [7]). In both scenarios, it is assumed that the useful bandwidth of an optical fiber can be discretized and divided into multiple Frequency Slots (FSs), being the width of a single FS much smaller than the width of the channels employed in a fixed-size grid scenario, such as the one defined by the ITU in [1]. Given these assumptions, and considering that the bit-rate requested by a traffic demand can be converted into particular spectrum bandwidth needs, each traffic demand can be understood as a requested number of FSs between a source and a destination node.

From the above, a demand must be accommodated on contiguous FSs. However, in dynamic scenarios, the available

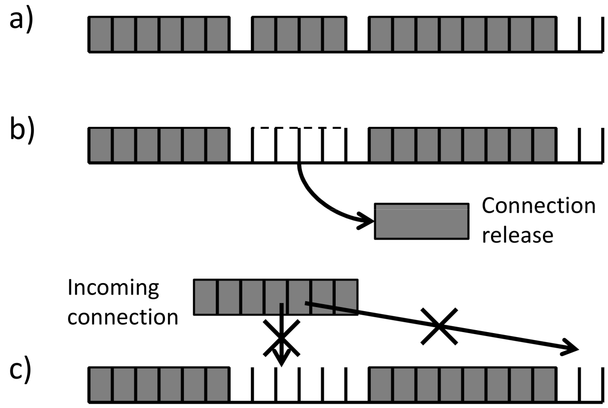

Fig. 1. Example of spectrum fragmentation in a dynamic scenario.

spectrum can be highly fragmented, mostly due to the randomness shown by those connection arrivals and disconnections in the network, which can highly penalize those connection requests demanding high data-rates (i.e., a significant number of contiguous FSs). Fig. 1 illustrates this situation. In Fig. 1.a, a certain number of connections, with different bandwidth requirements, is established over a given network link. After some time, in Fig. 1.b, one of these connections is released, thus freeing a portion of the spectrum in that link. Finally, in Fig. 1.c, a new high data-rate connection request arrives at the network and should be allocated on the link under study. Even though the total spectrum available on that link would be enough to allocate the new connection, such spectrum is fragmented into smaller portions than the contiguous spectrum requested by the incoming connection, which eventually causes its blocking.

To mitigate the spectrum fragmentation effects in elastic optical network, spectrum defragmentation strategies have been proposed in the literature [8]–[10]. Essentially, the rationale behind these strategies is to properly rearrange active connections in the network, so as to free as much contiguous spectrum as possible to be used by future connection requests. Note, however, that disruptions of active traffic caused by a reallocations is not admissible for certain classes of service, being hitless spectrum defragmentation of paramount importance in such a context. For these reason, make-before-break strategies are normally adopted in defragmentation mechanisms: before tearing down a lightpath, the new associated lightpath resulting from the defragmentation mechanisms is first created, so the traffic does not experience any disruption. However, this operation presents some drawbacks: note that to create the new ligthpath before tearing down the old one requires to allocate at a given time twice the resources needed to serve that ligthpath. This could lead to not having the sufficient resources to perform the make-before-break operation and, consequently, the traffic could experience some disruptions. Moreover, if there are enough spectral resources to perform this operation, during the time where both lighpaths, new and old, are present, it could happen that a possible incoming demand can not be served due the lack of spectral resources. Also, defragmentation techniques add an extra complexity to the control plane in order to perform and manage all the reallocations properly. On the other hand, equipping the nodes with spectrum conversion capabilities would allow to reduce the blocking of some demands through using not necessarily the same spectrum in all the links in the path from source to destination node. However, spectrum conversion devices are expensive and introduce some delay in the demands (due the conversion) that may not be admissible for certain classes of service.

Running away from the spectrum defragmentation or spectrum conversion approaches, this paper proposes a lightpath fragmentation mechanism that takes advantage of those idle transponders (TSPs) at the source node of a high data-rate connection request in order to fragment it into a number of slower data-rate connections and, thus, allowing them to fit more easily in the fragmented network spectrum. The remainder of this paper continues as follows. Section II presents the proposed lightpath fragmentation mechanism, as well as a light-weight RSA algorithm to properly allocate the lightpath fragments into the network. Section III evaluates the benefits of the proposed mechanism through simulations, while comparing its performance to usual RSA solutions aiming to allocate the entire demands requested bandwidth contiguously. Finally, Section IV draws up the main conclusions of the paper.

II. Proposed Mechanism

Before going into the details of our proposed mechanism, let us discuss how the requested bandwidth by a demand can be translated into a specific number of FSs. To this end, we assume that the requested bit-rate can be converted into a requested bandwidth (i.e., spectrum portion), whatever the specific modulation format used to reach the desired destination node would be. Then, the number of FSs needed by a demand is equal to the ceiling of the division between the bandwidth of the demand and the spectral width of a single FS. It shall be mentioned, though, that existent BV-WXC technologies require guard bands between signals to perform the switching adequately [3]. Hence, considering the presence of the guard bands as well, the number of FSs to allocate a demand is:

$$\#\text{ of FSs} = \left\lceil \frac{\text{Req. BW (GHz)} + \text{Guard band (GHz)}}{\text{FS width (GHz)}} \right\rceil \quad (1)$$

As expected, the guard band technological requirements may increase the number of FSs initially needed to allocate an incoming demand and, thus, the difficulty to allocate the demand on the fragmented network spectrum.

The proposed mechanism tries to take advantage of the available fragmented spectral resources, when a connection blocking situation may arise due the lack of enough contiguous FSs to serve its entire bandwidth requirements. With this in mind, the foundation of the mechanism is the following. If a traffic demand can not be served because the number of requested FSs exceeds the size of any available spectral gap in the candidate paths between the source and destination nodes, it may still be possible to accommodate it by splitting the demand into multiple independent lower data-rate signals, and allocate them into multiple non adjacent spectral gaps, assuming that enough spectral resources exist in any of those candidate paths.

This operation could be driven from the network control plane (e.g., based on Generalized Multi-Protocol Label Switching, GMPLS [11]), which could trigger the split of the incoming signal in the source node of the demand into multiple sub-signals, to be transmitted to the destination over separated lightpaths. The reconstruction of the original signal would be therefore performed on reception, by electrically multiplexing those incoming sub-signals belonging to the same demand. However, the analysis of how the additional hardware that would allow to perform correctly the splitting and the merging of the demands into the physical nodes could be implemented is out of the scope of this paper and left for future work.

In this process, the role of the control plane would be of key importance to manage the signaling and maintenance of the lightpath bundle [12] supporting a particular traffic demand which, in turn, would require an adequate configuration of the signal splitting and multiplexing operations at the source and destination nodes, respectively.

The establishment of multiple lightpaths for a single demand implies that a TSP at the source and destination must be allocated to each one of them. Hence, a trade-off exists between the number of lightpaths to which a demand is fragmented, which facilitates the allocation of a high data-rate demand over a highly fragmented network spectrum, and the cost (in terms of TSPs) required to allocate the split demand on the network. In this work, we aim at using idle TSPs at network nodes, that is, unused during low traffic periods, to allocate incoming demands that, otherwise, would be blocked due to the spectrum fragmentation in the candidate paths to the destination. One might argue that assigning multiple TSPs to a single demand could strongly impact on the blocking subsequent requests due to the unavailability of TSPs to allocate them on the network. As will be shown in Section III, though, by appropriately selecting the minimum number of TSPs to successfully allocate an incoming demand, important blocking probability improvements in the network operating range (i.e., blocking probability around 1%) can be achieved.

An additional argument to minimize the number of lightpaths required to allocate an incoming demand is the spectrum overhead that the guard bands needed by the BV-OXC introduce, as guard bands must be left to each lightpath allocated on the network. Therefore, it is of capital importance to decide how a demand is split and accommodated into multiple lightpaths, so as to avoid excessive guard band overheads and requested TSPs that will demerit the potential benefits of our proposal. Taking this into account, the flowchart in Figure 2 discloses the proposed mechanism's operation.

For an incoming demand, the mechanism firstly checks if there is any TSP available in both source and destination nodes. This verification allows blocking at the very beginning of the mechanism those demands for which the source node or the destination node do not have at least one TSP free, thus

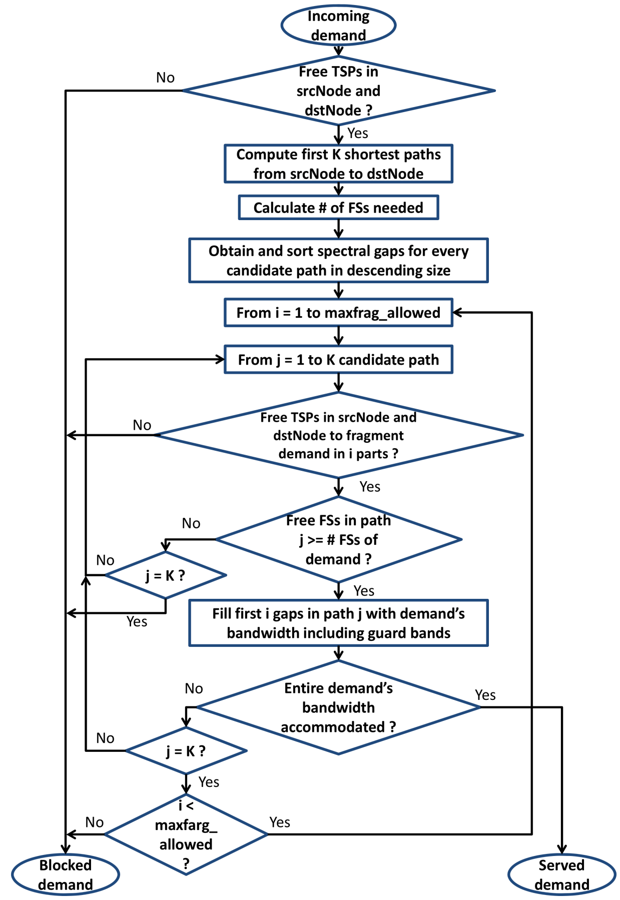

Fig. 2. Flow chart of the proposed mechanism.

skipping subsequent unnecessary steps. Once this verification is performed, and both source and destination nodes show TSP availability (at least one TSP is available), the mechanism calculates the first K shortest paths (e.g., in terms of number of hops) from source to destination. Next, it calculates the minimum number of FSs needed for accommodating the demand using the formula introduced in (1).

The next step consists in obtaining the spectral gaps for each of the K candidate paths. Specifically, a spectral gap is a contiguous number of FSs available from the source to the destination node, that is, in absence of wavelength converters in the network, the continuity of the FSs must be ensured along the end-to-end candidate path. Right after obtaining them, the mechanism sorts the available spectral gaps for every candidate path in descending order, starting from the one with the largest number of contiguous FSs to the one with the lowest number of them. The average complexity of an appropriate sorting algorithm stays commonly in $\mathcal{O}(n\log n)$, being n the number of elements to sort. Under this assumption, the average total complexity of the aforementioned operation in our algorithm will be $\mathcal{O}(Kn\log n)$, being K the number of candidate paths computed previously and n the number of spectral gaps in the paths, making our mechanism perfectly scalable if the number of candidate paths or FSs per fiber increases.

Once the spectral gaps in every candidate path are found and sorted, the mechanism checks if the demand can be allocated in any of the candidate paths starting as is, like in a usual RSA mechanism. Being the algorithm unsuccessful, it fragments the demand in two fragments (i.e., lightpaths) and checks if it can be allocated. Note that the bandwidth of each fragment is initially unspecified and will depend on the width of the available spectrum gaps on any candidate path. Being still unsuccessful, the algorithm repeats this operation by increasing the number of demand fragments by one each time, until $maxfarg\_allowed$ is reached. This field allows controlling the amount of splitting done to the demands, that will impact on the TSPs usage and the overhead of guard bands, by putting an upper limit of allowed parts per demand that can be adjusted depending on the bandwidth requested by the demand. This value is left to the network operator discretion.

The process of checking if a demand can be accommodated in a determined number of parts in any of the candidate paths entails multiple phases. First, the mechanism checks if both source and destination nodes have enough available TSPs to serve the demand into the desired number of fragments. Although at the beginning of the mechanism a TSP availability check was performed, at this point it is necessary to check it again as, even though both source and destination nodes have some free TSPs, it could be that one or neither of them have the sufficient available TSPs to serve the demand into the determined number of parts. If this happens, the demand is directly blocked. Otherwise, the mechanism verifies if the candidate path has, at least, a number of available FSs equal to the number of FSs determined through the formula in (1). This is done to ensure that the candidate path has a minimum capacity to potentially serve the demand. If the path does not have this minimum capacity, the next candidate path is explored.

The following stage of the mechanism involves how the bandwidth of the demand is accommodated into the spectral gaps of the candidate path without exceeding the number of allowed parts in the current iteration. From the sorted list of spectral gaps of the candidate path, the mechanism selects the first i gaps, being i the number of allowed parts in the current iteration, and tries to fit the bandwidth of the demand in those gaps. Because spectral gaps are sorted in descending order, the chances of fitting the entire demand bandwidth into the first i gaps increases, thus reducing the demand blocking probability. The distribution of the bandwidth of the demand into the i gaps goes as follows: if the size of the first gap is greater or equal than the number of FSs needed to accommodate the demand, all the bandwidth of the demand is accommodated in this gap, filling only a number of FSs as determined from (1). Conversely, if the size of the first gap is smaller, only part of the useful bandwidth of the demand is accommodated into the gap. Such an amount is determined through the following formula:

$$\begin{aligned} &\text{Amount of useful bandwidth accommodated} = \\ &= \text{Size of the gap in FSs} \times \text{FS width} - \text{Guard band} \qquad (2) \end{aligned}$$

The accommodated bandwidth is subtracted from the requested bandwidth by the demand. The remaining bandwidth is accommodated in the next $i-1$ gaps in a similar manner: if the size of the next gap is greater or equal than the number of needed FSs determined through (1), where the remaining unallocated bandwidth of the demand is considered, all the FSs are accommodated into this gap. Otherwise, the bandwidth that can be fit into the gap is calculated using formula (2) and subtracted from the remaining bandwidth. If using these i gaps the remaining bandwidth becomes 0, it means that the demand is successfully accommodated in the path using i different parts. Contrarily, the mechanism proceeds to the next iteration. Once all the candidate paths are explored using all the allowed values of parts, if it is not possible to accommodate the demand, it is finally blocked. Note that if a demand has to be split into multiple parts, the mechanism routes every of these parts through the same physical path. This is to avoid any delay between the parts that would difficult reordering the related data at the reception node, thus adding extra complexity to the control plane and the nodes to perform correctly this operation. With this mechanism, we are able to solve potential contention situation without penalizing future incoming demands due the over-usage of TSPs and guard bands.

A similar idea has been presented in [13] as inverse multiplexing. In this paper, the authors split high bit-rate demands into a bunch of lower bit-rate connections, each one of equal bandwidth, assigning the spectrum of these new connections in a Shortest-Path (SP) First-Fit (FF) basis to avoid contention situations. However, our mechanism differs in the sense that it does not restrict that each of the parts has to be of the same bandwidth, giving more flexibility in this regard. Moreover, it employs a better path and slot assignment mechanism than a simple SP-FF mechanism: it explores more than one candidate path and tries to assign the spectral resources using the regions of the spectrum with more available resources.

III. Results and Discussion

Aiming to quantify the benefits of the proposed mechanism, we have executed a series of simulations on the Deutsche Telekom network topology [14], composed of 14 nodes and 23 bidirectional links. Specifically, we assume that each fiber link provides a total usable bandwidth of 1 THz divided into FSs with a spectrum width of 6.25 GHz, which results in 160 FSs per fiber link. For all simulations we consider 13 TSPs per node, a value that allows a full-meshed virtual connectivity between nodes, and a guard band of 10 GHz. One might argue that the hereafter presented results would be affected by the number of TSPs per node. Indeed, in this sense, a small number of TSPs per node could lead to a significant number of demands being blocked due the unavailability of free TSPs, as it may seem in the presented scenario. However, we have observed in the executed simulations that in this scenario the percentage of demands blocked due the lack of free TSPs is significantly lower than the percentage of demands blocked due the lack of free spectral resources. In this regard, the presented results are not negatively influenced by the number of TSPs per node assumed.

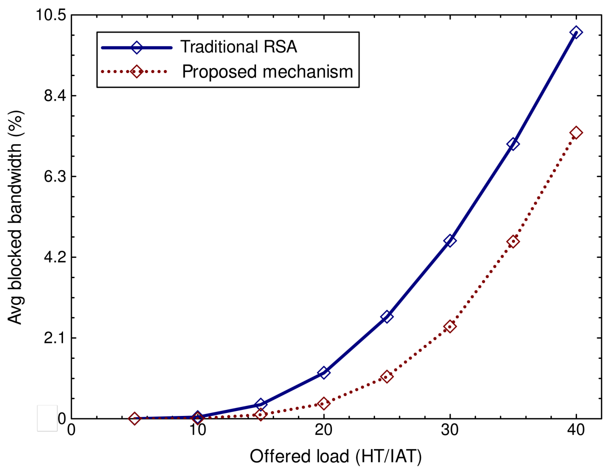

Fig. 3. Average blocked bandwidth as a function of the offered load.

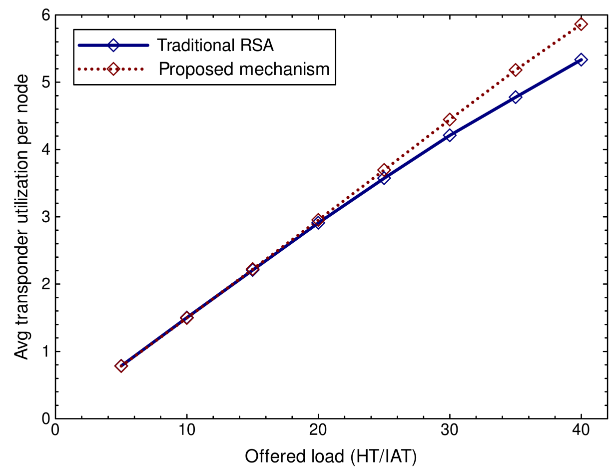

Fig. 5. Average TSPs utilization per node as a function of the offered load.

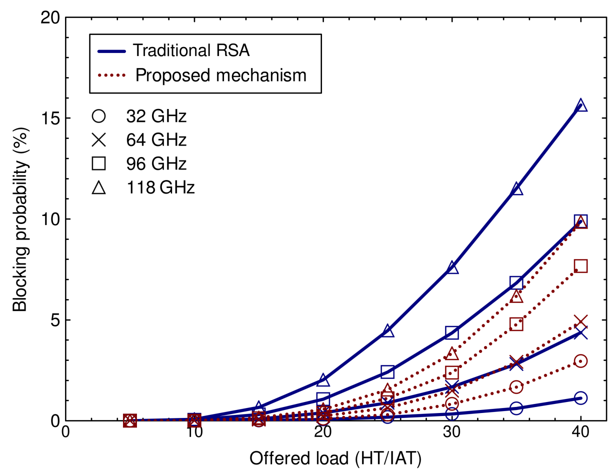

Fig. 4. Blocking probability per category as a function of the offered load.

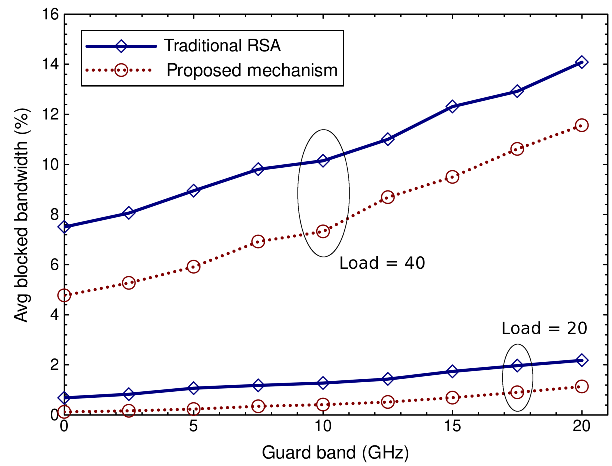

Fig. 6. Average blocked bandwidth as a function of the size of the guard band.

Simulation results have been extracted through the generation of 4×10^5 bidirectional demand requests per execution. Such requests arrive to the network following a Poisson process. Moreover, demand holding times (HTs) are exponentially distributed with mean 600 s. Different loads are thus generated by modifying the demand inter-arrival times (IATs) accordingly (load = HT/IAT). Bandwidth requirements of the demands in GHz are uniformly chosen among $\{32, 64, 96, 118\}$. Besides, the algorithm $maxfrag\_allowed$ field is set to $\{1, 2, 3, 4\}$, depending on the bandwidth requirements of the demands. Particularly, 1 fragment is allowed for the demands requesting a bandwidth of 32 GHz (i.e., fragmentation is not allowed for low data-rate demands), while 2, 3, and 4 fragments are allowed to the demands requesting 64, 96 and 118 GHz, respectively.

With comparison purposes, the performance of the proposed mechanism has been benchmarked against a traditional RSA mechanism, where the spectrum contiguity constraint must be ensured to all incoming demand requests. Particularly, a lightweight FF slot allocation strategy has been considered in this mechanism. In both mechanisms, K = 3 candidate paths for each demand are taken into consideration, using the distance in hops as the metric.

Figure 3 shows the average blocked bandwidth as a function of the offered load. By blocked bandwidth we are referring to the useful bandwidth of demands that are blocked, without the bandwidth allocated due the guard bands. From the results, we observe that our proposed mechanism yields significant improvements when compared against the traditional RSA mechanism. These benefits become more remarkable as the offered load to the network increases, which arises as a consequence of the high spectrum fragmentation preventing high data-rate demand requests to be allocated contiguously over the spectral resources. For example, the average blocked bandwidth differences stay around 0.8% for an offered load equal to 20, whereas they increase up to 2.6% for an offered load equal to 40.

In order to analyze the causes of such a behavior in more detail, Figure 4 depicts the Blocking Probability (BP) of the offered demand requests, based on their bandwidth requirements. Looking at the obtained results, a drastically reduced BP can be appreciated for the high data-rate demands when the proposed mechanism is employed. Indeed, thanks to the fragmentation of such demands into multiple lower data-rate ones, available spectral gaps can still be employed to allocate them. Focusing on the 118 GHz demands, for instance, the BP that they experience can be reduced from 2.02% to 0.56% for an offered load equal to 20. Even more pronounced differences can be identified for higher loads, such as a reduction from 7.61% to 3.33% when a load equal to 30 is offered to the network. It is interesting to note as well, that such a BP reduction for high data-rate demands does not entail a pernicious performance degradation of the low data-rate demands. From the figure, the only low data-rate demands experiencing slightly increased BP are those requesting 32 GHz. However, the performance deterioration is only remarkable in highly loaded scenarios, which would probably lay out of the network load operating range.

Heretofore, the obtained results highlight that our proposed mechanism succeeds in improving the BP figures in flexible optical networks, being high data-rate demands those experiencing the highest benefits. However, little attention has been paid to the real effects of the additional TSPs used at the source and destination nodes to enable the fragmentation of the incoming demands. To give insight into this effect, we have additionally computed the average number of TSP used per node, depending on whether the traditional RSA or the proposed mechanism is applied. The obtained results are shown in Figure 5 as a function of the offered load. As can be observed, up to a load equal to 20, the average number of TSPs used per node in our mechanism is practically identical as with the traditional RSA. Moreover, even for loads beyond this value, the average TSP utilization does not increase so notoriously, so as to imply a strong TSP unavailability in any network node. These results could be explained from the fact that, in the usual network operating range (e.g., offered loads resulting in BP around 1%), the fragmentation of the demands are only required in a small number of occasions. Avoiding these demand blocks, though, drastically impacts on the final network performance.

To complete our study, we have analyzed the effect of the guard band when accommodating the demands. To this goal, two different offered load scenarios have been considered, namely, 20 and 40. Then, in such scenarios, the size of the guard band has been modified from 0 (ideal situation) to 20 GHz. Figure 6 shows the average blocked bandwidth as a function of the size of the guard band. We can see that both traditional RSA and proposed mechanism show similar behaviors in this regard. As the size of the guard band increases, so it does the blocked bandwidth. Moreover, even though the proposed mechanism requires the allocation of an extra number of guard bands for those high data-rate demands that need to be split in multiple parts, the resulting behavior does not show a clear performance degradation, since the spectrum utilization still remains higher than in the traditional RSA.

IV. Conclusions and Future Work

This paper has proposed a novel lightpath fragmentation mechanism for dynamic scenarios in flexible spectrum networks. The proposed mechanism helps in avoiding potential blocking by permitting a demand to be split in multiple parts and served as multiple connections. The benefits of the proposed mechanism have been demonstrated through extensive simulation results, where a traditional RSA has been contemplated as a performance benchmark. From the results, drastic blocking probability improvements are observed for high data-rate demand requests. Moreover, it has been shown that such improvements do not entail neither significantly increased low data-rate demand blocking probability, nor an undesired increase of the node TSP usage.

As a future work, the analysis of the necessary control plane extensions and hardware modifications that would allow implementing the proposed solution will be investigated. Moreover, control-plane-driven mechanisms to dynamically merge the lightpath fragments again when spectral resources are available in the network will also be subject of study.

Acknowledgment

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