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Statistical analysis of blocking probability and fragmentation based on Markov modeling of elastic spectrum allocation on fiber link

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ABSTRACT

In Elastic Optical Network (EON), spectrum fragmentation refers to the existence of non-aligned, small-sized blocks of free subcarrier slots in the optical spectrum. Several metrics have been proposed in order to quantify a level of spectrum fragmentation. Approximation methods might be used for estimating average blocking probability and some fragmentation measures, but are so far unable to accurately evaluate the influence of different sizes of connection requests and do not allow in-depth investigation of blocking events and their relation to fragmentation. The analytical study of the effect of fragmentation on requests' blocking probability is still under-explored. In this work, we introduce new definitions for blocking that differentiate between the reasons for the blocking events. We developed a framework based on Markov modeling to calculate steady-state probabilities for the different blocking events and to analyze fragmentation related problems in elastic optical links under dynamic traffic conditions. This framework can also be used for evaluation of different definitions of fragmentation in terms of their relation to the blocking probability. We investigate how different allocation request sizes contribute to fragmentation and blocking probability. Moreover, we show to which extend blocking events, due to insufficient amount of available resources, become inevitable and, compared to the amount of blocking events due to fragmented spectrum, we draw conclusions on the possible gains one can achieve by system defragmentation. We also show how efficient spectrum allocation policies really are in reducing the part of fragmentation that in particular leads to actual blocking events. Simulation experiments are carried out showing good match with our analytical results for blocking probability in a small scale scenario. Simulated blocking probabilities for the different blocking events are provided for a larger scale elastic optical link.

1. Introduction

Elastic Optical Network (EON) is a promising approach to meet the increasingly diverse traffic demands due to its ability to efficiently utilize spectral resources for communication over optical fiber [1]. In EON, modulation format and central frequencies are not fixed. To establish an optical channel each bandwidth variable optical cross connect (BV OXC) is able to allocate requested spectrum [2] with fine granularity, which allows for efficient spectrum utilization, in contrast to fixed-grid WDM networks [3].

Multicarrier solutions such as coherent optical orthogonal frequency division multiplexing (CO-OFDM) [4], as well as Nyquist WDM [3] have been proposed as viable techniques to enabling EONs. In this new context, the optical spectrum is considered to be divided into a number of frequency slots, with an appropriate width, in order to simplify the network design and modeling [5]. According to the ongoing standardization efforts in ITU-T, the minimum frequency slot unit that can be currently assigned is 12.5 GHz [6]. However, in the future the granularity can be scaled down to 6.25 GHz or below [7].

Although elastic optical networks present some similarities to

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wavelength routed WDM networks, the flexible properties of EONs raise new challenges from the network planning and resource provisioning point of view [8]; in EONs, the allocated spectrum is adapted according to the requested bit rate, transmission distance, and modulation format [9]. Furthermore, the evolution of resource units from an entire wavelength to a frequency slot leads to fundamentally new constraints in spectrum allocation practices [10], such as e.g., *spectrum contiguity*. Instead of one wavelength, a connection is now assigned one or several frequency slots, depending on whether the capacity requirement of a connection is larger than the capacity of one slot unit. If multiple slots are required, they have to be contiguous, i.e., a connection request can only be satisfied if a sufficient number of free and adjacent slots are available.

Recently, many works have investigated the possible advantages of using a flexible spectrum allocation (SA) concept, under both static and dynamic traffic conditions. The SA problem in EONs is analogous to the conventional wavelength allocation (WA) concept in wavelength routed WDM networks [11]. However, due to the new properties of EONs, WA algorithms cannot be directly applied. Static SA problem is considered for the network design or planning phase [10,12,13] where the objective is to minimize the number of necessary frequency slots while provisioning the given traffic demand. Dynamic SA problem, on the other hand, is applied during the network operation, when new lightpath requests should be served upon arrival [14–17]. Under these conditions, the heterogeneous bandwidth allocation may result in fragmentation of the spectral resources.

Spectrum fragmentation is an important aspect and inevitable problem, because it reduces the spectral efficiency. As a consequence, the blocking probability (BP) is increased due to scattered gaps in the spectrum, which result from the random release of dynamic heterogeneous connections.

As network traffic varies over time, the spectrum allocation might not be optimal. Thus, it is desirable for network operators to periodically re-optimize the network. In [18,19], authors addressed the defragmentation problem assuming full spectrum retuning. However, optical devices, which achieve such defragmentation cycle, can be quite expensive and even more importantly, defragmentation might interfere with existing traffic.

The statistical analysis of dynamic spectrum allocation was introduced only recently. Blocking probability, resource utilization as well as spectrum fragmentation are the common metrics of performance in EONs, which can be used to dimension network and link capacities while taking into account the dynamics of lightpath requests [5]. In [20], the authors proposed a birth–death model to analyze the blocking performance for three different spectrum allocation policies, under time-varying traffics in EONs. Although, by applying some relaxations assumptions, the dynamic SA problem is transformed into a static one. In [21], the authors presented an iterative procedure in order to estimate the blocking probability in EONs, with and without spectrum conversion, by approximating the bandwidth utilization ratio. In [5], the authors presented a continuous time Markov chain to calculate spectrum fragmentation and average blocking probability as well as resource utilization of a stand-alone EON link, considering *First-Fit* (*FF*) and *Random-Fit* (*RND*) SA approach. In [22], Beyranvand et al. presented the first attempt for performance evaluation of node- and network-wise operation scenarios in EONs. They developed an analytical framework and investigated average blocking-performance and spectrum fragmentation, in scenarios with and without spectrum conversion, considering *FF* and *RND* as spectrum allocation policies. The performance of the framework was compared to exact results for up to eight slots. The authors also show how elastic optical network performance modeling can be broken down to link modeling, in order to significantly reduce the complexity. Recently, in [23] was investigated the effect of spectrum fragmentation on the blocking probability of EONs under simplified model of EON operation with certain fragmentation and utilization. However, due to the high complexity of the model performance evaluation was only possible by using simulations.

In our study we noticed that the analysis of fragmentation is not sufficient to conclude on the network performance in terms of average BP. The majority of work available in the literature tends to assume that blocking probability for future requests should increase monotonically with increasing spectrum fragmentation [16,24]. Based on this, previous studies have tried to quantify the level of spectrum fragmentation by proposing various fragmentation formulas [24–27]. To the best of our knowledge, none of the previous works on statistical analysis of dynamic spectrum provisioning in the literature considers and investigates the reasons for blocking events, but rather the overall average blocking probability of the system. However, blocking can occur not only because of spectrum fragmentation, but in general due to lack of available resources to serve connection requests. It is usually not considered to which extent and why spectrum allocation policies proactively minimize the number of blocking events.

In [28], we proposed a novel spectrum allocation (SA) policy and Markov modeling of flexible spectrum allocation under dynamic traffic conditions, in order to compare it with existing policies in terms of average BP and fragmentation. In this paper, we introduce new definitions for blocking that differentiate between the reasons for the blocking events. We also introduce an accommodated fragmentation metric from the field of dynamic memory allocation research that allows differentiating between very small variations of spectrum occupancy, which can depend on different spectrum allocation strategies. Based on these new measures, we investigate how various request sizes contribute to fragmentation and blocking probability. Furthermore, we show to which extend blocking events, due to the fact of insufficient amount of resources, become inevitable and compare to the amount of blocking events due to fragmented spectrum. Based on this comparison, we draw conclusions on the possible gains one can achieve by system defragmentation. Analytical results are compared to the ones obtained by simulations. For a larger scale elastic optical link, when analytical results are not available, we provide results given by simulations.

On the other hand, our optical link analysis can give guidance for selection of the right SA policy in the network as well as providing the first step in network-wide evaluation. Moreover, the model can be easily adopted to evaluate networks based on broadcast-and-select architecture, i.e., without any switching nodes between the source and destination. Examples of such architecture are passive optical network (PON) in the access segment and so called filterless optical network (FON) in the core segment where active switching nodes are replaced by passive splitters/combiners. While different types of PONs are standardized and widely deployed in the fiber access networks, FONs concept has been recently proposed [29] as a cost-effective, energy-efficient and reliable alternative to the active optical switched core networks. The passive *gridless* architecture of FONs makes them naturally suitable for elastic optical networking without the need to replace the switching and filtering devices at nodes. Thanks to the above advantages, we expect that the filterless architecture will gain interest of the network providers in the future optical core and submarine network deployments and we believe that our elastic optical link model will be very useful for analysis of the network-wide performance of elastic FONs. However, an in-depth analysis of the network constraints as well as its main characteristics is not the scope of this work.

The remaining of this paper is organized as follows. In Section 2 we provide an overview of the spectrum fragmentation problem