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Analytical performance modeling of spectrum defragmentation in elastic optical link networks

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ABSTRACT

The spectrum efficiency and the connection blocking in Elastic Optical Networks (EONs) depend on how well the spectrum is managed by a spectrum allocation (SA) policy. Although spectrum fragmentation can be minimized by an efficient SA policy, it cannot be avoided. Moreover, heterogeneous bandwidth demands further exacerbate the detrimental effect of spectrum fragmentation in terms of spectrum efficiency and connection blocking probability. Recently, a few heuristic-based defragmentation (DF) schemes have been proposed to reconfigure some or all connections in the network. However, the analytical study of the effect of defragmentation on the connections' blocking probability is still under-explored. In this paper, we analyze the effect of defragmentation rate on different models depending on whether DF is proactively (Pro-DF) or reactively (Re-DF) performed. Additionally, a combined Proactive-Reactive-Delayed (Pro-Re-DL-DF) model is presented, which admits requests in a delayed fashion (similar to scheduled connections) that would have been blocked otherwise due to fragmentation. We analytically show that, under certain conditions, defragmentation process under different SA policies can reduce the overall connection blocking probability. We also illustrate that the model can be used in other scenarios, such as to increase security of optical link against eavesdropping. To this end, we model the busy/idle patterns of an elastic optical link (EOL) using a multi-class continuous-time Markov chain under two different SA approaches, first-fit and random-fit. Analytical and simulation results show the positive effect of defragmentation process depends on the rate at which it is performed, the link load and the EOL capacity.

1. Introduction

With the advent of the next generation flexible optical transponders, such as sliceable bandwidth variable transponders [1], the flexible-grid or the elastic optical network (EON) is going to replace sooner than later the fix-grid-based wavelength division multiplexing (WDM) networks. The reason is that the optical orthogonal frequency-division multiplexing or Nyquist-WDM based transponders together with the bandwidth-variable wavelength selective switches can be used in EONs to dynamically allocate spectrum to meet the demands of diverse applications [2,3]. Additionally, these transponders can be used to support a sub-channel or a super-channel data service applications by allocating the required number of the subcarrier spectrum slots. Unlike the traditional fixgrid (50 GHz)-based International Telecommunication Union-Telecom standard used in WDM networks, in EONs, the low attenuation fiber spectrum bandwidth in C-band (4.475 Tera Hertz) can be divided into smaller units (e.g., 6.25 or 12.5 GHz) [3]. Here, each subcarrier can support a fix or variable bit rates based on the modulation formats used. In addition to the spectrum (wavelength) continuity, a new constraint called spectrum contiguity should also be satisfied before an optical path is established in EONs. In other words, a connection can be established over an optical channel iff all subcarrier slots are adjacent on each link that it traverses.

The obvious gain of flexible spectrum allocation also brings new challenges in managing the spectrum occupancy in EONs [4,5]. In the dynamic connection set up and termination scenario, heterogeneous demands leave the gap between occupied spectrum slots, which is called spectrum fragmentation. Spectrum fragmentation, if not handled well, can lower the spectrum efficiency in EONs, which leads to higher connection blocking. To address this issue, a few efficient spectrum allocation policies have been proposed in EONs [6–8], which establish new requests such that the spectrum fragmentation is minimal. However, as network traffic varies with time, defragmentation (DF) as a connection reconfiguration scheme is desirable, since spectrum allocation might not be optimal. The defragmentation in general is an NP-hard problem in an EON [9]. Defragmentation process, which we coined as Defragmentation-as-a-Service (DaaS) in

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[10] is especially challenging to model and evaluate analytically, due to the spectrum continuity and spectrum contiguity constraints. To the best of our knowledge, there does not exist any performance evaluation frameworks to analyze how a state dependent defragmentation process, in addition to the data service arrival process, impacts the blocking performance of an EOL.

In this paper, we analyze the effect of defragmentation service process on blocking probability as a function of the rate at which it is performed, the link load, and the available resources. To understand the effect of defragmentation, we model an elastic optical link (EOL) using a multi-class continuous-time Markov chain (CTMC), and include DaaS states in addition to the regular (data) service states. Generally, requests are blocked either due to non-availability of resources, which is called Resource Blocking (RB) or due to spectrum fragmentation, called Fragmentation Blocking (FB). To this end, we consider three different scenarios: (i) a Proactive DF (Pro-DF) model, which performs DaaS operation proactively when system detects itself in a fragmentation state; (ii) a Reactive DF (Re-DF) model, which triggers DaaS operation when an incoming request cannot be admitted into the system due to the fragmentation of the spectrum resources; and (iii) a combined Proactive-Reactive-Delay DF (Pro-Re-DL-DF) model, which can perform DaaS either proactively by the system or reactively by the arrivals that can be admitted only after the reconfiguration of connections. We also illustrate that the model presented can be used in other scenarios, such as to increase security of optical link against eavesdropping with spectrum randomization, a case suitable for analytical evaluation. The results show that although defragmentation blocking (DB) is added in the overall blocking, the Pro-DF and Re-DF models can reduce the overall blocking (i.e. FB +RB +DB) in certain cases. The overall blocking in the Pro-Re-DL-DF model (i.e., RB + DB), on the other hand, can be much lower than the regular system, i.e., a system without reconfiguration, if the reconfiguration (defragmentation) service time is lower than the holding times of the connections. We also show that DaaS can be used for connection randomization and thus improving optical layer security.

The rest of the paper is organized as follows. Section 2 presents the related work and summary of our contribution. Our DF models are presented in Section 3. In that section, we present defragmentation models, assumptions and their limitations. The remaining sections analyze the benefits and drawbacks of these models in terms of connection blocking probability and interruption time. In Section 4, we analyze defragmentation blocking for our DF models. A use-case of randomized defragmentation to increase security of optical link against eavesdropping is presented in Section 5. We evaluate the performance in Section 6, and conclude the paper in Section 7.

2. Related work and our contribution

The spectrum assignment schemes to minimize fragmentation in EONs have been investigated extensively [6–8]. In [6], authors employ a metric to quantify the consecutiveness of the common available spectrum slots among all candidate as well as adjacent fiber links along a routing path. Yin et al. [7] proposed a “cut-based” metric to evaluate fragmentation on the links, and another metric named “alignment” considers the misalignment of the available spectral slots along a path when provisioning the connection requests. Chen et al. [8] allocate the resources based on the expected capacity that a spectrum block can accommodate considering the fragmentation. Defragmentation—as a proactive or a reactive reconfiguration scheme, has also been proposed [11,12,9,13–16] using ILP and heuristic-based approaches, where connections' reconfiguration are performed sequentially (i.e., connections are moved one-by-one) or in parallel. Recently, Zhang et al. in [9] proposed both proactive and reactive, sequential and parallel defragmentation schemes based on ILP in EONs. The trade-off between sequential and parallel defragmentation is also presented. The parallel defragmentation can reduce the traffic disruption and defragmentation latency at the cost of the higher connection blocking probability. The reason is that a sequential defragmentation method can reallocate connections with more freedom. However, the abovementioned works do not evaluate the effect of fragmentation or defragmentation analytically.

The analytical performance evaluation of fragmentation and connection blocking in EONs has started only recently [4,5,17–20]. The authors in [4] showed that the blocking probability due to bandwidth fragmentation in EONs depends on the size of the available spectrum blocks on a link, and their alignment over different links on the routing paths. In [5], authors used the Erlang-based loss model to calculate the blocking probability for different spectrum allocation policies under time-varying traffic conditions. In [17], exact blocking probability of an EOL was evaluated for the first time by modeling the bandwidth occupancy as continuous-time Markov chain under the first-fit (FF) and random-fit (RF) spectrum allocation methods. In addition to a link model, Beyranvand et al. [18] presented two approximation methods for large-scale networks. Recently, the same model was used in [19] to present resource blocking and fragmentation blocking separately. Vaezi and Akar [20] analytically evaluated a non-work-conserving spectrum allocation policy for an EOL, which allows demands to be allocated only in certain aligned spectral blocks. Since the exact stochastic models generally do not scale with the capacity of the EOL, authors used Markov Modulated Poison Process-based order reduction method to mitigate the dimensional complexity. However, the main drawback is that they do not allow all possible demands, instead only certain demands like (1, 2, 4) spectrum slots are admitted to the EOL. In [10], we modeled a reactive defragmentation for the first time, and showed that the overall blocking can be reduced if reconfiguration time is much lower than the connections' service times. The above mentioned works, however, are limited to the modeling of spectrum allocation in a single-hop or multi-hop networks, and do not model the defragmentation process in a generalized form that allows both proactive and reactive triggering mechanism for reconfiguration. In [21], we utilized the similar model to proactively randomize the spectrum reassignment to improve the data security in EOL networks. We observed that randomization improved the data security at the cost of a slight increase in blocking, therefore a combination of the proactive randomization and the reactive defragmentation is presented in [22] to show the trade-off between the security improvement and the blocking performance of connections. Recently, Liu et al. [23] showed that the security challenge can be mitigated in various ways, among others by data scrambling along the code, time and frequency domains. It has been also shown that channel (spectrum) fragmentation can be used for cognitive service disruption in radio networks [24], and it could also be exploited for out-of-band jamming attacks in optical networks [25]. The data scrambling along the multiple dimensions helps to resist the brute-force attacks, and makes it difficult for the attacker to decode the data. With the flexibility in assigning subcarriers, we believe that spectrum allocation in EONs also present a unique opportunity to provide optical layer security. Although the goal of this paper is not on optical layer security, but to analytically model the system, this paper shows that the models presented can be used for security as an example application.

This paper builds on our preliminary work [10] that models a reactive DF by assuming a constant mean reconfiguration time irrespective of the spectrum occupancy patterns (states). In extension of the preliminary work, this paper considers variable reconfiguration time based on the system states, and in addition to a proactive and a reactive DF models, we propose a new hybrid model, namely, Proactive-Reactive-Delayed (Pro-Re-DL)-DF model that can trigger DaaS proactively as well as reactively, and more importantly it admits the delayed requests which would have been blocked otherwise due to spectrum fragmentation. Notably, we present all models under two different spectrum allocation approaches, first-fit and random-fit, and try to answer the following questions.