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Efficient routing and spectrum assignment in elastic optical networks with time scheduled traffic

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ABSTRACT

Elastic optical networks (EONs) employ dynamic routing and spectrum assignment (RSA) algorithms to support diverse services and heterogeneous requests. However, these RSA algorithms may possibly induce spectrum fragments when allocating spectrum to accommodate different service requests. Therefore, such induced spectrum fragments should also be regarded as spectrum consumption besides the allocated spectrum by RSA algorithms. In this paper, by additionally considering the holding times of lightpaths and service connections, we first introduce a comprehensive spectrum consumption model to simultaneously investigate both the allocated and the fragmented spectrum consumptions. Then we solve this model in both static and dynamic traffic scenarios, by either formulating the RSA problem with time-scheduled traffic or introducing a time-aware spectrum-efficient heuristics algorithm. Since no defragmentation is executed in spectrum allocation, the proposed RSA algorithm requires no traffic disruption and can be realized more easily in reality. Simulation results show that the proposed algorithm reduces the comprehensive spectrum consumption and has lower bandwidth blocking probability than the typical first-fit RSA algorithm.

1. Introduction

Elastic optical networks (EONs) have attracted much attention ever since they were first proposed due to their obvious advantage in spectrum provisioning [1]. Different from traditional wave length-division-multiplexing (WDM) [2] and multi-granularity grooming optical networks [3,4], EONs employ a finer spectrum allocation granularity, known as frequency slot (FS), and are able to assign spectrum to different services adaptively according to their bandwidth requirements with variable number of contiguous FSs. Thanks to the finer granularity, FS, employed in spectrum assignment, the flexibility of spectrum allocation and the efficiency of resource utilization have been remarkably improved, although it may also require some expensive components, such as bandwidth-variable optical cross-connects [5]. But their high cost may be reduced with the development and maturity of optical integration and wavelength selective switch technologies. Therefore, elastic optical networks are now considered a promising candidate solution to the next-generation high-speed optical networks.

Routing and spectrum assignment (RSA) algorithm [6], which seeks a transmission path for a service request and assigns spectrum on the sought path to the service, is the key enabling technology to realize dynamic spectrum allocation in elastic optical networks. Therefore, various RSA schemes for EONs [7–9], have been proposed recently, including the shortest path routing and first-fit spectrum allocation algorithm [7], and the distance-adaptive modulation formats allocation algorithms [8,9]. However, if a spectrum band is successfully assigned to a service by the aforementioned RSA algorithms, the assigned spectrum band cannot be re-used or changed on the transmission path, until the service expires. This is known as spectrum continuity constraints. Since practical networks always have limited capacity of spectrum conversion due to its high complexity and cost, this continuity constraint may induce spectrum fragmentation in network evolutions, connection tear-down operations, or some network maintenance procedures. Besides the spectrum continuity constraint, spectrum contiguity constraint is another important constraint in spectrum assignment, which requires that the spectrum band assigned to one service should be composed of multiple contiguous FSs. But such spectrum contiguous constraint may possibly leave some tiny spectrum fragments due to the finer spectrum granularity, FS, employed in spectrum assignment. If such tiny fragments are

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accumulated before being properly handled, the available spectrum resource decreases and the networking performance deteriorates, because these tiny fragments cannot be used by any kind of services. Therefore, spectrum fragmentation [10,11] has become a serious issue in EONs and many schemes, known as defragmentation, have been proposed on it [12–22]. A make-before-break rerouting algorithm was proposed in [12] to reduce the generated spectrum fragments by rerouting the lightpaths for the existing services, but extra free spectrum and multiplexer/de-multiplexer may be required to create an alternative lightpath. In [13–17], spectrum retuning based algorithms were proposed to reduce the generated fragments in time-varying traffic, employing either spectrum expansion, contraction, reallocation policies [13–16], or hot-tuning technique [17]. Defragmentation algorithms with both rerouting and retuning were proposed in [18,19]. Although these defragmentation algorithms can successfully reduce the generated spectrum fragments by re-optimizing the spectrum resource, the traffic of the existing services may possibly be disrupted in lightpath rerouting or spectrum retuning procedures, which may lead to a large mount of loss in data and business, especially in high-speed transmissions. Regarding such traffic disruption in spectrum defragmentation, an auxiliary graph and maximum independent sets were introduced into spectrum retuning to minimize the traffic disruption [20,21]. In [22,17], defragmentation algorithms employing push–pull technique were proposed to avoid traffic disruption. However, in order not to disrupt the traffic, the whole spectral band in the spectrum retuning range is required vacant in push–pull technique to guarantee non-disruptive spectrum shifting. For instance, if the allocated spectrum of a service connection (assuming the service connection requiring one FS) is to be retuned from FS_m to FS_n (m and n are the indices of the FSs on a fiber link) by the push–pull defragmentation algorithm, all the FSs between FS_m and FS_n (including FS_n) need to be vacant for spectrum shifting in push–pull technique. If any FS between FS_m and FS_n is occupied, it should be shifted to the spectrum outside the band from FS_m to FS_n by the same technique (push–pull technique) so as to create the vacant spectrum band from FS_m to FS_n. This requires that there should have enough vacant spectrum outside the spectrum band from FS_m to FS_n on the fiber link for the occupied FSs between FS_m and FS_n. And this additional requirement for spectrum will reduce the successful probability of spectrum shifting in push–pull technique and thus reduces its effectiveness. In addition, fast tunable lasers are always needed for spectrum shifting in push–pull technique, which may increase the cost and the complexity of the system. In [23,24], fragmentation-aware spectrum assignment algorithms were introduced into EONs to solve spectrum fragmentation problem. By employing the parameter "cut" to calculate the number of spectrum blocks a provisioning scheme would break, fragmentation-aware algorithms increased the number of contiguous FSs in available spectrum bands when choosing the provisioning scheme with the least or no broken spectrum blocks. However, even with no broken spectrum blocks, an available spectrum band should be recognized as fragments if it had no enough contiguous FSs for any kind of services.

Previous investigations on RSA algorithms are focus on the allocated spectrum resources or the generated spectrum fragments. But, actually, both the allocated spectrum and the generated fragments are the spectrum consumption to accommodate service connections. Therefore, the two kinds of spectrum consumptions should be comprehensively considered in RSA algorithms, although they have different timing characteristics (i.e., the timing characteristics of the allocation spectrum depends on the holding-time of its served service connection, while the timing characteristics of the generated fragments depends on the adjacent allocated spectrum). In this paper, with the additional consideration of the holding times of lightpaths and connection requests, we introduce a comprehensive spectrum consumption model to simultaneously investigate both the allocated and the fragmented spectrum consumptions, and then try to solve this model in both static and dynamic traffic scenarios. In static case, in which all connection requests with their setup and tear-down times are known in advance, we formulate the RSA problem with time-scheduled traffic via Integer Linear Programming (ILP) to minimize the comprehensive spectrum consumption. In dynamic case, we propose a time-aware spectrum-efficient heuristics algorithm which takes the holding time of a new arrival connection request and the remaining holding time of existing lightpaths into consideration to minimize the comprehensive spectrum consumption. Simulation results show that the proposed algorithm can reduce the comprehensive spectrum consumption with no traffic disruption, while having lower bandwidth blocking probability than the typical first-fit RSA algorithm.

The rest of the paper is organized as follows. In Section 2, we introduce the comprehensive spectrum consumption model to simultaneously investigate both the allocated and fragmented spectrum consumptions. In Section 3, the ILP formulation for the RSA problem with time-scheduled traffic is introduced to solve the comprehensive spectrum consumption model in static traffic scenario. In Section 4, a time-aware spectrum-efficient heuristics algorithm is proposed to solve the comprehensive spectrum consumption model in dynamic traffic scenario. In Section 5, simulation results are presented to compare the performance of different RSA algorithms. Section 6 concludes this paper.

2. Comprehensive spectrum consumption model

In this section, a comprehensive spectrum consumption model is introduced to characterize both the allocated spectrum and the fragmented spectrum, via additionally considering the holding times of lightpaths and service connections. Although distance-adaptive modulation format allocation can further improve the spectral utilization efficiency by choosing more effective modulation format according to the transmission distance, bandwidth variable transponders are usually required in these systems to generate a large set of modulation formats and vary data-, symbol-, and code-rate according to actual traffic conditions [25]. Therefore, bandwidth variable transponders always require high-quality components and advanced DSP to meet the requirements of different modulation formats (MF) and transmission reach. In addition, bandwidth variable transponders may require multiple carriers (which can be realized by multiple lasers or subcarrier generation) for very high-rate transmissions [26]. All these may increase the cost and the complexity of a bandwidth variable transponder, especially for future ultra high-speed service connections. Thus, in this model, we use determined MFs for different kinds of service connections instead of considering distance-adaptive modulation format allocation, and the elasticity of the network is mainly from the used flex-grid switches in the network. As for the MF selection, we use the MF with low spectral efficiency for the current frequently-used low-speed service connections (e.g. 100 Gb/s) to meet the requirement of long transmission reach and system complexity, since these service connections have higher possibility to be requested in the whole network and are quite sensitive to the transmission reach and system complexity. But for the future ultra high-speed service connections (e.g. 1 Tb/s), the MF with high spectral efficiency is employed for them, since they are more bandwidth-hungry than the low-speed service connections. Considering the limited transmission range for different MFs and the existing physical impairments (e.g. transmission loss, dispersion and nonlinear impairments) in reality, we assume that optical amplifiers (e.g. EDFA) and some novel techniques (such as digital