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Dynamic traffic grooming with Spectrum Engineering (TG-SE) in flexible grid optical networks

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ABSTRACT

Flexible grid has emerged as an evolutionary technology to satisfy the ever increasing demand for higher spectrum efficiency and operational flexibility. To optimize the spectrum resource utilization, this paper introduces the concept of Spectrum Engineering in flex-grid optical networks. The sliceable optical transponder has been proposed to offload IP traffic to the optical layer and reduce the number of IP router ports and transponders. We discuss the impact of sliceable transponder in traffic grooming and propose several traffic-grooming schemes with Spectrum Engineering (TG-SE). Our results show that there is a tradeoff among different traffic grooming policies, which should be adopted based on the network operator's objectives. The proposed traffic grooming with Spectrum Engineering schemes can reduce OPEX as well as increase spectrum efficiency by efficiently utilizing the bandwidth variability and capability of sliceable optical transponders.

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1. Introduction

Optical networks have been widespread as important infrastructure in our information society, and over the past 30 years, the per-fiber capacity has doubled every two years by employing time-division multiplexing (TDM) and wavelength-division multiplexing (WDM) technologies [1]. In traditional WDM networks, multiple optical channels are multiplexed into a fiber following the ITU-T wavelength grid and spacing. Optical signals are transmitted over channels by transponders that support fixed line rates (typically 10, 40, or 100 Gbps). As the Internet traffic and applications growing fast, a spectrum-efficient, data-rate-flexible, and energy-efficient optical network architecture is needed for the future. Recently, flexible grid has been introduced in optical transport networks, which evolves the traditional ITU grid towards high flexibility with fine-grained spectrum slots (e.g., 6.25 GHz or 12.5 GHz vs. 50 GHz or 100 GHz) [2–5]. Advanced optical transmission technologies, such as coherent optical orthogonal frequency-division multiplexing (OFDM) [6], Nyquist WDM (N-WDM) [7], and optical arbitrary waveform generation (OAWG) [8] are identified as the enabling technologies for flexible-grid optical networks. This flexible architecture uses several key optical technologies, e.g., bandwidth-variable (BV) transponders at the network edge and bandwidth-variable optical cross-connects (BV-OXC) in the network core. BV-transponders support flexible central frequency tuning and elastic spectrum allocation, while BV-OXCs are critical for optically switching lightpaths with variable central frequencies and bandwidth.

Flexible grid optical network has been a relevant research subject in the past few years. In [9–11], the problem of designing an elastic network was mapped to a static routing and spectrum assignment (RSA) problem, which was formulated as a set of Integer Linear Programs (ILPs), and heuristics were also proposed. In [12], a distance-adaptive spectrum resource allocation scheme was proposed to allocate the minimum spectrum to a lightpath according to its physical condition. In [13], a policy to allocate subcarriers for time-varying traffic in a flexible OFDM optical network was proposed, and in [14], several dynamic RSA algorithms were proposed to achieve efficient spectrum utilization. In [15], survivable network design was proposed for elastic optical networks, while mechanisms exploiting adaptive bandwidth of elastic optical networks for restoration were discussed in [16].

Also, as services occupying different number of slots arrive and depart over time, the uneven usage of spectrum slots may cause spectrum fragmentations. These fragmentations make the spectrum state extraordinarily complex and are the main culprits for degradation in spectral efficiency. A number of spectrum defragmentation solutions in flex-grid optical networks also have been

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recently reported [17–22]. In [17], the network defragmentation problem was introduced, and two heuristics as its solutions were proposed. In [18], a spectrum compactness based defragmentation scheme was proposed to maximize the profitability of defragmentation. In [19], a make-before-break rerouting scheme was presented to minimize service disruptions. In [20], a dynamic lightpath frequency retuning based defragmentation technique was proposed. In [21], hitless spectrum defragmentation using the wavelength sweep capability of real-time digital coherent receivers was experimentally demonstrated. In [22], a defragmentation scheme using fast tunable laser with blanking and real-time wavelength tracking at the receiver was demonstrated.

In flex-grid optical networks, a connection's requested bandwidth can be much lower than the capacity of a lightpath (or transponder), and two lightpaths that go through one or more common fiber links must be separated by at least a guard band to avoid severe interference. So, provisioning each connection by a separate lightpath leads to high spectrum wastage by guard bands and low utilization of high-capacity transponders. Traffic grooming can increase transponder utilization and achieve higher spectrum efficiency by saving the spectrum usage of guard bands. In [23–26], the problem of traffic grooming was addressed to increase spectrum efficiency for elastic optical networks.

In this paper, we study traffic grooming issue with sliceable transponder in flex-grid optical networks. We propose a multilayer auxiliary graph to jointly solve the electrical-layer routing and optical-layer RSA, with the continuity and contiguity constraints. Various provisioning policies with different objectives can be achieved by properly adjusting the edge weights in the auxiliary graph. Also, we propose a spectrum-engineering-based scheme to efficiently utilize the bandwidth of fibers and transponders by defragmenting lightpaths and grooming incoming connections onto them. We show that there is a tradeoff among different traffic-grooming policies and our spectrum-engineering based schemes can lead to significant reduction in operational expenditure (OPEX), e.g., number of used transponders, and better spectrum efficiency.

The rest of this paper is organized as follows. In the second section, we introduce the concept of Spectrum Engineering. In the third section, traffic-grooming functions based on sliceable transponders are investigated, and a spectrum-engineering based grooming algorithm with different grooming policies is proposed. In Section 4, simulation results are presented to compare the performance of different grooming schemes. Finally the last section concludes the paper.

2. Spectrum Engineering

According to [27], there are three basic problems in communication networks: (1) *Traffic Engineering*, which is about putting the traffic where the bandwidth is; (2) *Network Engineering*, which is about putting the bandwidth where the traffic is; and (3) *Network planning*, which is about putting the bandwidth where the traffic is forecasted to be. While in flex-grid optical networks, there exists a very important problem named Routing and Spectrum Assignment (RSA). Note that (1) different connections co-existing in the network may follow different paths and ask for different number of frequency slots, (2) even for the same request, the number of frequency slots it requests may vary significantly with time, and (3) while establishing optical channels for an new incoming request, the assignment of frequency slots must obey not only wavelength continuity but also spectrum contiguity. So the available spectrum resources may develop many small noncontiguous spectral blocks after the process of RSA, and many unused spectrum resources may be wasted due to the low probability of usage.

To address those problems and optimize the spectrum resource utilization, we introduce a novel concept named Spectrum Engineering in flex-grid networks [28,29]. Spectrum Engineering is a series of methods used to improve the spectrum utilization in flexible grid optical networks, which can include planning, designing, operating and optimizing network spectrum resources. This optimization method can be used by network operators to save spectrum resources, decrease spectrum fragmentations, avoid link congestions, and improve network performance. It can maximize spectral efficiency in optical networks to increase number of channels in installed fibers and reduce connection blocking probability. As a tool in network control plane, Spectrum Engineering can include cognitive bandwidth-allocation algorithms, agile spectrum control and management strategies, elastic bandwidth adjustment operations, smart resource optimization schemes, and be a fundamental part of Cognitive Optical Networks (CON). Next are three sub-problems in flex-grid optical networks where we could use Spectrum Engineering.

2.1. Resource planning

Resource planning focuses on static planning problems. Here, a traffic matrix that includes the requested rates of connections is given, and spectrum resources should be planned to an optimal arrangement. Generally, this offline problem can be solved through Integer Linear Program (ILP) formulations. However, it is highly inefficient for larger networks since the ILP formulations cannot be solved in a tolerable running time. Usually, effective spectrum planning heuristic algorithms should also be developed. The objective of Spectrum Engineering in resource planning is to serve all connections and minimize the utilized spectrum resources.

2.2. Bandwidth assignment

Bandwidth assignment aims at dynamic RSA problems. When a request arrives and must be served in real time, we need to establish a flexible optical path for it using a bandwidth-assignment algorithm. This algorithm should (1) elastically allocate proper frequency slots based on the requested rate; (2) choose an appropriate modulation level, taking into account the transmission distance; and (3) be cognitive, e.g. physical-impairment-aware and client service aware. The goal of Spectrum Engineering in Bandwidth Assignment is to improve the utilization of spectrum resources and minimize the connection blocking probability.

2.3. Spectrum defragmentation

In a flex-grid optical network, setting up and tearing down connections with different bandwidths make the spectral resources into non-contiguous fragments, and may result in high blocking rates and low utilization of network capacity. Thus, network operators need to periodically re-optimize the network and return it to an optimal state under minimum cost, e.g., minimize interrupting services or affecting their QoS (i.e., delay, bandwidth, bitrate, etc.). This is defined as spectrum defragmentation. Here, Spectrum Engineering could be used to provide efficient spectrum defragmentation solutions.

3. Traffic grooming with Spectrum Engineering

In an optical WDM mesh network, the objective of traffic grooming is either to maximize network throughput or to minimize network cost in terms of optical transponders, electronic processing, or power consumption. In dynamic traffic grooming, connection requests arrive one at a time and hold for certain

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