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Spectrum efficient distance-adaptive paths for fixed and fixed-alternate routing in elastic optical networks

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ABSTRACT

Efficient utilization of spectrum is a key concern in the soon to be deployed elastic optical networks (EONs). To perform routing in EONs, various fixed routing (FR), and fixed-alternate routing (FAR) schemes are ubiquitously used. FR, and FAR schemes calculate a fixed route, and a prioritized list of a number of alternate routes, respectively, between different pairs of origin o and target t nodes in the network. The route calculation performed using FR and FAR schemes is predominantly based on either the physical distance, known as k-shortest paths (KSP), or on the hop count (HC). For survivable optical networks, FAR usually calculates link-disjoint (LD) paths. These conventional routing schemes have been efficiently used for decades in communication networks. However, in this paper, it has been demonstrated that these commonly used routing schemes cannot utilize the network spectral resources optimally in the newly introduced EONs. Thus, we propose a new routing scheme for EON, namely, k-distance adaptive paths (KDAP) that efficiently utilizes the benefit of distance-adaptive modulation, and bit rate-adaptive superchannel capability inherited by EON to improve spectrum utilization. In the proposed KDAP, routes are found and prioritized on the basis of bit rate, distance, spectrum granularity, and the number of links used for a particular route. To evaluate the performance of KSP, HC, LD, and the proposed KDAP, simulations have been performed for three different sized networks, namely, 7-node test network (TEST7), NSFNET, and 24-node US backbone network (UBN24). We comprehensively assess the performance of various conventional, and the proposed routing schemes by solving both the RSA and the dual RSA problems under homogeneous and heterogeneous traffic requirements. Simulation results demonstrate that there is a variation amongst the performance of KSP, HC, and LD, depending on the $o-t$ pair, and the network topology and its connectivity. However, the proposed KDAP always performs better for all the considered networks and traffic scenarios, as compared to the conventional routing schemes, namely, KSP, HC, and LD. The proposed KDAP achieves up to 60%, and 10.46% improvement in terms of spectrum utilization, and resource utilization ratio, respectively, over the conventional routing schemes.

1. Introduction

Global IP traffic has recently crossed the Zettabyte threshold, and it is predicted that it will reach an annual rate of 2.3 Zettabytes by 2020 with a compound annual growth rate of 22% [1]. This incessant growth in IP traffic is continuously imposing new challenges on the communication network operators to increase the network capacity. It is widely known that increasing the number of fiber cables in the long haul core networks (that enable the Internet) is not a feasible solution to this capacity crunch. The primary reason for this infeasibility is not the cost of the fiber, but the increased cost and difficulty associated with the excavation and installation [2]. Hence, efforts are required to utilize the deployed network spectrum resources as efficiently as possible. In this Zettabyte era, the major line rates in core backbone optical networks are above 100 Gbps [3], which the currently deployed dense wavelength division multiplexed (DWDM) optical networks are not able to satisfy [4]. The reason for this bottleneck is the rigidity and homogeneity of DWDM optical networks where optical C-band is subdivided into a number of wavelengths with fixed frequency grids. These wavelengths are modulated with a single modulation format (MF), and support only a fixed line rate. However, in transport networks, the traffic demands are heterogeneous. Thus, DWDM networks are not capable to match with these line rates of heterogeneous traffic, consequently resulting in inefficient optical network spectrum utilization. Elastic optical network (EON), also referred as flexible grid network, has been introduced as a promising solution to replace the DWDM

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networks, and has been widely accepted by both academia and industry [3]. EON is capable of supporting heterogeneous traffic demands by adaptively allocating minimum necessary spectral resources to the lightpath demands, which in turn increases the spectrum utilization efficiency. The main features of EON, among others, are distance-adaptive modulation (DAM) and bit rate-adaptive superchannels [5]. Moreover, overlapping subcarrier allocation using optical orthogonal frequency division multiplexing (O-OFDM) can further improve spectrum utilization in EON.

With a view to meet the predicted ever increasing bandwidth demands, efficient spectrum allocation has emerged as a key issue in EONs. Significant improvement in spectrum utilization has already been achieved in EON as compared to DWDM network architecture, due to the DAM feature of EON. Using DAM, it is possible to use different MFs for different lightpaths based on the physical distance of the selected route between origin o and target t nodes while ensuring the sufficient signal quality requirements at t. That is, the most spectral efficient MF that fulfills the optical signal to noise ratio (OSNR) requirement at t for transmission distance of the chosen route is selected. In this manner, minimum necessary spectrum is allocated to the lightpath demands in EON, which is not possible in DWDM networks that are designed for worst case transmission conditions [3].

The problem of assigning a suitable route to the lightpath demands and allocating spectrum on the selected route, is known as routing and spectrum allocation (RSA) [6]. RSA is analogous to routing and wavelength assignment (RWA) problem in DWDM networks. However, RSA in EON is subject to the additional constraints of spectrum contiguity, and non-overlapping spectrum assignment, along with spectrum continuity constraint which is analogous to wavelength continuity constraint in RWA [7]. In the network planning problem, also referred as offline RSA/RWA, a set of lightpath demands to be established is known in advance, and the objective is to establish all the demands using a suitable route so that the spectrum utilization is minimized [4,8–10]. In the dual RSA/RWA problem, the objective is to maximize the number of lightpath demands that can be established using a limited amount of spectrum available per fiber in the network [8]. The most commonly used routing approach to perform RSA/RWA is fixed-alternate routing (FAR) for both offline planning, and dynamic service provisioning [9–24]. In FAR, a number of routes, known as 'alternate routes', are calculated and prioritized for each $o-t$ pair of nodes in the given network. In the literature [9–24], the alternate routes are calculated in optical networks either on the basis of physical distance between o and t, known as k-shortest paths (KSP); on the basis of hop count (HC) between o and t; or link-disjoint (LD) paths. In the literature, the most commonly used routing scheme is KSP [9,11,14–22], where the routes are first found on the basis of physical distance, and then the modulation format with highest spectral efficiency is chosen as per DAM while ensuring the transmission reach.

A simpler approach than FAR is fixed routing (FR) in which only a fixed route is calculated for each $o-t$ pair in the network, and if the resources are not available on that route, the lightpath demand is rejected. The route calculated using FR is usually the most preferred route amongst the alternate routes obtained for an $o-t$ pair using an FAR scheme. For instance, the fixed route calculated on the basis of smallest physical distance is the same as the most preferred route amongst the alternate routes calculated using KSP. Fig. 1 shows the possible routes obtained using FR, and FAR approach for a lightpath demand between node A, and node E. In Fig. 1(a), a possible fixed route (ACE) obtained using FR is shown. In Fig. 1(b), four possible alternate routes obtained using FAR are shown. The alternate routes are calculated offline, and during lightpath establishment, one of these possible routes is selected on a pre-determined priority basis, or on-the-fly selected during dynamic service provisioning [9–21]. In Fig. 1(c), link-disjoint alternate routes are shown, where no common link is present amongst the three possible alternate routes. This type of routing is preferable for survivable optical network design [18,23–24]. In this paper, it has been demonstrated that the above conventional routing schemes do not utilize the EON spectrum efficiently. That is, the preferred route obtained using HC, KSP, or LD may consume more spectral resources than the other possible routes for an $o-t$ pair. Thus, we propose a new routing scheme, namely, k-distance adaptive paths (KDAP) to perform FR and FAR in EON that utilizes the spectrum more efficiently as compared to the conventional routing schemes. It is worth mentioning that this work is focused on routing in EONs only, and does not deal with spectrum allocation (SA) part of the RSA problem. We have compared the spectrum utilization efficiency of the proposed KDAP routing with the widely used HC, KSP, and LD routing schemes. However, various SA policies present in the literature can be used along with the proposed KDAP routing to further improve the spectrum utilization by means of different approaches such as spectrum defragmentation, first-last fit SA, spectrum partitioning, etc.

In Section 2, we present the motivation for the proposed routing scheme, and summarize the conventional FR and FAR schemes used in optical networks, and the related work done in EON to improve spectrum utilization through several RSA schemes. In Section 3, we present the network model employed, and different notations used in this paper. Section 4 describes the proposed KDAP routing, and the difference in spectrum consumption to perform RSA using the proposed, and the conventional routing schemes. In Section 5, evaluation of the performance of different conventional routing schemes in comparison with the proposed KDAP routing scheme is done under different traffic patterns and networks. Conclusions are drawn in Section 6.

2. Related work and motivation

Various aspects of RSA schemes have been researched since the introduction of EONs to improve spectrum utilization. A number of ways to perform SA in EONs have been presented in the literature. SA approaches such as first-last fit, spectrum sharing, spectrum partitioning, fragmentation-aware SA, etc., have been proposed to improve the performance of RSA [7,14,16,17,25–27]. However, to perform route calculation in EONs, the conventional approaches of HC, KSP, and LD routing have been widely employed in the literature [9–24]. In case of FR, the calculated route is always selected for lightpath establishment in offline networks, as well as during dynamic service provisioning. However, using FAR, a set of possible alternate routes is calculated offline. A route is then selected for lightpath establishment from the set of alternate routes; either on a pre-determined priority basis (e.g., shortest path first), or on-the-fly evaluation of each of the alternate paths is performed, as per the objective of the problem [9–24]. The routing schemes that have been used for FR and FAR in optical networks are described below.

FR calculates fixed routes for each $o-t$ pair of nodes in a given optical network on the basis of minimum hop count, or on the basis of smallest physical distance between o and t [8]. Amongst the FAR schemes, HC has been advantageous, and has been widely used for DWDM networks where the MF is fixed as per the worst case transmission requirements [3]. In this case, it is not possible to adjust the MF as per the individual distances to be traversed by different lightpaths. Thus, in DWDM networks, the number of links utilized in a route from o to t is directly proportional to the spectrum consumed in the network. Hence, HC is preferred for being simple and appropriate routing scheme in DWDM networks [22]. However, in EON, it is possible to perform DAM, where the spectral resource consumption can be reduced by adjusting the MF according to the actual physical distance between o and t. Hence, calculating routes on the basis of physical distance between o and t using KSP is advantageous in EON, and has been widely used in the literature, e.g., in [9,11–21]. LD routing [12,23–24] is commonly preferred for fault-tolerant networks, so that connections may survive in the events of failures via link-disjoint backup paths, e.g., using Suurballe's algorithm in [23–24]. Using LD, maximum possible link-disjoint paths between $o-t$ pair are calculated with the shortest path