Optical Fiber Technology 36 (2017) 297–305

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Regular Articles

Energy-efficient routing, modulation and spectrum allocation in elastic optical networks

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ARTICLE INFO

Article history:
Received 20 January 2017
Revised 27 April 2017
Accepted 1 May 2017

Keywords:
Energy consumption
Energy-efficient routing
Modulation and spectrum allocation
Traffic grooming

ABSTRACT

With tremendous growth in bandwidth demand, energy consumption problem in elastic optical networks (EONs) becomes a hot topic with wide concern. The sliceable bandwidth-variable transponder in EON, which can transmit/receive multiple optical flows, was recently proposed to improve a transponder's flexibility and save energy. In this paper, energy-efficient routing, modulation and spectrum allocation (EE-RMSA) in EONs with sliceable bandwidth-variable transponder is studied. To decrease the energy consumption, we develop a Mixed Integer Linear Programming (MILP) model with corresponding EE-RMSA algorithm for EONs. The MILP model jointly considers the modulation format and optical grooming in the process of routing and spectrum allocation with the objective of minimizing the energy consumption. With the help of genetic operators, the EE-RMSA algorithm iteratively optimizes the feasible routing path, modulation format and spectrum resources solutions by explore the whole search space. In order to save energy, the optical-layer grooming strategy is designed to transmit the lightpath requests. Finally, simulation results verify that the proposed scheme is able to reduce the energy consumption of the network while maintaining the blocking probability (BP) performance compare with the existing First-Fit-KSP algorithm, Iterative Flipping algorithm and EAMGSP algorithm especially in large network topology. Our results also demonstrate that the proposed EE-RMSA algorithm achieves almost the same performance as MILP on an 8-node network.

1. Introduction

With continuous development of Internet technology, huge volumes of traffic demands is explosive grows, which leads to the increase in energy consumption. Reducing energy consumption in optical network becomes a critical issue in recent years [1]. Therefore, many studies have been conducted to address the energy consumption of future optical transport networks [2–4]. The energy consumption issues in wavelength division multiplexing (WDM) based optical networks has been thoroughly investigated [5–8].

In elastic optical network (EON), optical orthogonal frequency division multiplexing (OOFDM) or Nyquist WDM technology is employed, it has been proposed as a promising all optical network (AON) architecture in the frequency domain [9]. OFDM is a multi-carrier transmission technology that slits high data rate channels into a number of orthogonal channels, called subcarriers, each with low data rates. EON uses subcarrier (e.g., 12.5 GHz) [10] as the minimal resource allocation granularity, which makes the optical fiber a sharable continuous spectrum resource pool [11]. Thanks to the fine grain and rate adaptation, EON shows great spectrum utilization efficiency than traditional WDM networks. Therefore, EON [12] should meet the constraints of spectrum continuity, spectrum contiguity and spectrum non-overlapping. Spectrum contiguity indicates that a contiguous fraction of frequency subcarriers is allocated to a lightpath request, while the spectrum continuity and spectrum non-overlapping means the same frequency slots is assigned in each link along the routing path and the assigned frequency subcarriers should not be overlapped when two routing paths share the common link. The energy-efficient routing, modulation and spectrum allocation (EE-RMSA) problem in EON could be considered as the problem that finds a proper energy-efficient end-to-end optical path which meet the traffic demand of each

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http://dx.doi.org/10.1016/j.yofte.2017.05.001
1068-5200/

lightpath request, and the energy consumption of the network devices during the routing path computation is considered. In previous studies, the problem has been extensively explored [13–25], and the problem has been proved to be NP-complete in [19].

Different solutions have been studied to reduce the energy consumption, they evaluate and compare the energy efficiency gains obtained through individual and joint application of these techniques (such as adaptive modulation and coding [11–17], flexible spectrum allocation [13–19], wavelength conversion [20–22], and traffic grooming [22,23]) [24]. Ref. [25] provided a framework for exploring the fundamental limits of energy consumption in optically amplified transport systems. In [13], Energy Aware Multigraph Shortest Path (EAMGSP), which extends the Multigraph Shortest Path (MGSP) to incorporate the modulation level choice as well as energy awareness is used. However, the algorithm does not consider the energy consumption of the optical transponder, which is an important energy equipment in EON. In [14], a heuristic method based on simulated annealing and k-shortest paths (KSP) is proposed to jointly solve the problem of laser transmit power, modulation level, number of subcarriers, and routing path of each node pair. To reduce computational complexity, a suboptimal Iterative Flipping (IF) method is proposed for solving the problem. In [18], a virtual graph is considered for a given network topology graph, and the cost functions of virtual graph is computed according to the energy consumption of the corresponding links and intermediates routers. The arrived traffic demands in this paper is served by finding the most energy-efficient path among the possible k candidate paths. Green grooming problem in EON with the integrated objective of minimizing the spectrum and power consumptions is investigated in [23], but it do not exploit variable modulation formats for different distances. Further, the research in [24] considered the shortest-path (SP) as the possible routing path, which imposed limits on the precision of the model and the performance of optimization results, i.e., the appropriate solution may not be included in the pre-calculated set of routing path. In previous studies, the common joint application of the above energy-efficient technologies was a simple combination of steps, and the optimal solution was usually chosen from the routing path set calculated in advance.

In this paper, we study EE-RMSA problem in EONs. To decrease the energy consumption in networks, a Mixed Integer Linear Programming (MILP) model with corresponding iterative heuristic algorithm is proposed. The MILP model and heuristic algorithm jointly considers the adaptive modulation format and optical grooming in the process of routing and spectrum resource allocation to satisfy the requirement of lightpath requests. With the help of genetic operators, we iteratively generate the feasible resource allocation solutions by serving lightpath requests which meets the quality of service (QoS) requirements and minimizes the energy consumption. In the process of iterative searching, all the possible routing path and modulation format allocation solutions is considered and then choose an optimum solution which consider both the energy consumption and the blocking probability (BP). By assuming that lightpath requests randomly generate between node pairs in a connected network, extensive simulations are conducted to validate the formulated MILP model and the iterative EE-RMSA algorithm, and compare the results with those of previously reported EE-RMSA schemes.

The rest of paper is organized as follows. Section 2 represents the major energy equipment and energy-efficient RMSA MILP model. The proposed iterative heuristic EE-RMSA schemes are analyzed in detail in Section 3. The energy consumption and the BP performance versus the average traffic rate of the proposed algorithm is evaluated in Section 4, where we validate the proposed algorithm by simulation in small and large networks. Finally, the main conclusions is described in Section 5.

2. Energy equipment and energy-efficient RMSA MILP model

In this section, the major energy equipment in elastic optical network and the energy-efficient MILP model is described. Fig. 1 shows an example of EON architecture. The main energy consumption equipment considered in this paper in EON consists of sliceable bandwidth-variable optical transponders (SBVTs), bandwidth-variable optical cross connect (BV-OXC), and Erbium Doped Fiber Amplifier (EDFA) optical amplifier. SBVTs contain multiple subcarrier modules to organize superchannels, which capable of transmitting/receiving signs with configurable physical parameters (i.e., bitrate, modulation format, Forward Error Correction (FEC), etc.) according to the client demand parameters such as the data rate or optical reach [26]. SBVTs enables transmitting from one node to multiple destination nodes by changing the traffic rate to each destination node. In addition, SBVTs can be used concurrently as a transmitter and a receiver. We assume that the SBVT resource is large enough to meet the traffic demands in the model. The main components that give the desired dynamic characteristics in current BV-OXC architectures are bandwidth-variable spectrum selective switches (BV-SSSs). BV-SSS can be used to exchange the no-overlapping arbitrary bandwidth frequency resources on any specified output lightpath. In this paper, the physical distance between two neighboring EDFA optical amplifiers is assumed to be 80 km, and there is always a pair of post- and pre-EFDA optical amplifiers at the two ends of each fiber link by default.

Client signals that come/go from/to the same source/destination but go/come to/from different destinations/sources can be distributed by the SBVT onto multiple optical flows that connect the source-destination pairs all optically, which is called "optical-layer grooming" [27]. To decrease the energy consumption of transponders, we implement optical-layer traffic grooming to minimize the number of active transponders for our heuristic solution by grooming low-capacity lightpath requests on active transponder which have extra resources.

Energy consumption model of the optical transponder, optical cross connect, and optical amplifier are stated below.

SBVT: For a sliceable bandwidth-variable transponder, the energy consumption model can be stated below according to [28], in which B_{sd} represents the number of finally decided frequency subcarriers for lightpath request T_{sd} and G_m^{sd} is a binary variable that equals 1 if lightpath request T_{sd} do not implement optical traffic grooming progress at node m, and 0 otherwise.

$$E_t(W) = 1.683 \cdot B_{sd} \cdot 12.5 + 91.333 \cdot G_m^{sd} \tag{1}$$

BV-OXC: We consider the power consumption of BV-OXC dependents on the node degree D_m and the add/drop degree α, as can be seen in the Eq. (2) according to [28,29], where an overhead of 150 W per node has been introduced to account for additional contributions to power consumption, such as fans, power supply, and control cards.

$$E_{oxc}(W) = D_m \cdot 85 + \alpha \cdot 100 + 150 \tag{2}$$

EDFA optical amplifier: One EDFA is assumed to be every 80 km on the optical fiber and consumes about 30 W, with an overhead contribution of 140 W per amplifier located at the end of a span, according to [30]. Additionally, the parameter A_{mn} stands for the number of amplifiers on fiber link l_{mn}, that is $\left\lceil \frac{L_{mn}}{80(km)} \right\rceil + 1$, where L_{mn} indicate the physical length of link l_{mn}.

$$E_a(W) = 30 \cdot A_{mn} + 140 \tag{3}$$

The issue of designing a mathematical MILP model for EON with minimum energy consumption is stated below. The network topology is represented by a connected graph $G(V, E, F)$, where V represents the set of physical nodes, E represents the set of