Computer Networks 112 (2017) 223–236

Contents lists available at ScienceDirect

Computer Networks

journal homepage: www.elsevier.com/locate/comnet

Energy-efficient virtual topology design in IP over WDM mesh networks☆

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ARTICLE INFO

Article history:
Received 13 June 2016
Revised 19 October 2016
Accepted 22 November 2016
Available online 23 November 2016

Keywords:
IP over WDM
Energy efficiency
Virtual topology
Survivability

ABSTRACT

Energy efficiency has been well recognized as an important objective in design of IP over WDM mesh networks. While previous works always focus on energy minimization through green routing and resource provisioning, the comprehensive performances of the two-layer network cannot be guaranteed. This would be not good for realization of energy-efficient networking methods.

In this paper, we first study the problem of getting a good tradeoff between the three-part network comprehensive performances: energy efficiency, resource efficiency and cross-layer survivability efficiency for IP over WDM mesh networks under the static traffic demand. We present the virtual-link energy model for two-layer networks. The energy model is computed from the power consumption value of commercial network devices. Based on the energy-aware two-layer auxiliary graph, we propose a new Energy-Efficient Virtual Topology Design (E^2VTD) scheme. The novelty of our proposed E^2VTD scheme is mainly twofold as following: the first is the energy-efficient virtual link direct mapping and rerouting and the second is the cross-layer survivability improvement for energy-efficient virtual topology. We use extensive simulations to demonstrate the efficiency of our proposed E^2VTD scheme. It is shown that the network comprehensive performances are significantly improved for two-layer networks. Compared with the previous algorithms, network energy consumption is reduced by about 39.8%, network resource is reduced by about 28.2%, and cross-layer topology survivability can be enhanced by about 35.7% in average.

1. Introduction

The traffic volume that needs to be transported by communication networks is growing very fast due to the continuously increasing number of end-users and to the new emerging application services that can be accessed to the network. This reflects into a need for increased network capacity, which in turn results in higher energy consumption [1]. This contributes to the increasing energy consumption of the ICT (Information and Communication Technology) field which currently represents about 8% [2] of the total electricity consumption all over the world. It becomes evident that research on technologies, methodologies and approaches that can offer energy efficiency are of the utmost importance. In this paper, we concentrate on problem of energy-efficient core networks. It is widely accepted that optical transmission technologies [3–5] will have a central role in the formation and the support of the core network of the future. Thus it is necessary to explore new solutions with respect to optical network's energy efficiency.

Compared with the research of one-layer green optical networks, the energy minimization of two-layer IP over WDM mesh networks is more important because the energy of IP/MPLS router port is far greater than that of optical transmission equipments [6–8]. In our opinion, it should not only emphasize energy efficiency for IP over WDM mesh networks. In networks some links are turned into sleep status during non-peak time for energy-saving purpose, which inevitably decreases the survivability of topology.

☆ This work is partially supported by China's 973 Program (2013CB329103), NSFC Fund (61271165, 61301153), Program for Changjiang Scholars and Innovative Research Team in University (PCSIRT), the 111 Project (B14039), Shanghai Oriental Scholar Program, Science and Technology Program of Sichuan Province (2016GZ0138, 2016GZ0107) and The National Natural Science Foundation of China (NSFC) under Grant 61671124.

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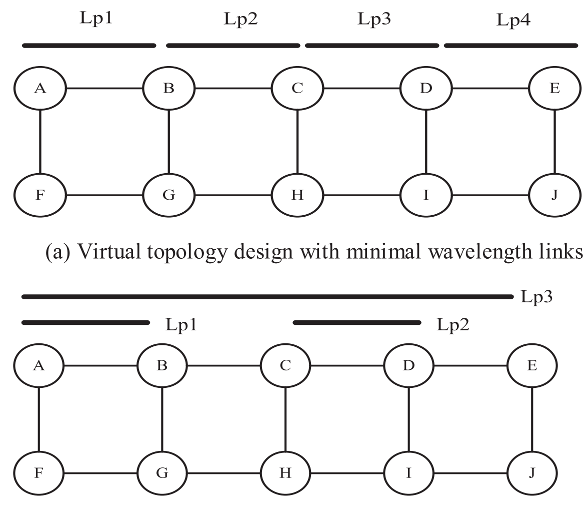
http://dx.doi.org/10.1016/j.comnet.2016.11.016
1389-1286/

Moreover, traditional research works on IP over WDM mesh networks is always to minimizing network resource (i.e., improving resource efficiency). This objective seems to be similar with energy efficiency from some aspect, but not completely identical. The relationship between energy efficiency and resource efficiency needs to be analyzed in detail. In this paper we first research the problem of how to balance the three-part network comprehensive performances: energy efficiency, resource efficiency and cross-layer survivability efficiency in two-layer networks. In what follows, we will outline previous work and motivate our study.

1.1. Previous work

The problem of energy-efficient IP over WDM mesh networks under the static traffic demand has been studied by several researches in the literature. In [8], the concept of energy-efficient IP over WDM mesh networks is first introduced. The authors of [8] presented the energy consumption minimization mathematic model, and propose two heuristics based on lightpath strategy: Direct Bypass and Multi-hop Bypass. While the heuristics of [8] select the shortest path on the virtual topology to improve capacity utilization, the authors of [9] analyze the layered architecture of IP over WDM mesh networks and present Auxiliary Graph (AG) model. Two energy-aware heuristics are proposed: Request Size Based (RSB) and Link Utilized Based (LUB) which find the shortest path from (*s, d*) node pair on AG model. Similar with [9], the authors of [10] propose three categories of heuristics: path based, link based and flow deviation which are all based on *Dijkstra*'s shortest path algorithm. The authors of [11] analyze transport architectures of IP over WDM mesh networks, and find that IP with Bypass and Grooming (IP-BG) performs best in energy efficiency and network cost. The works of [8–11] perform energy minimization in IP over WDM mesh networks from the respect of resource optimization. When routing connections and resource allocation in two-layer networks, these works do not consider energy consuming factor, but resource factors (e.g., hop minimization or distance minimization). The authors of [12] present operational energy model of IP over WDM mesh networks, and propose power-aware provisioning algorithm based on the energy-aware link weights. In [12], when deploying connection request into the network, the newly increased of energy consumption is minimized. But the whole network energy consumption cannot guarantee the global optimum. Ricciardi et al. [13,14] try to reduce both the energy cost and Green House Gases (GHG) emission by leveraging renewable energy sources. However, they consider these two objectives separately, rather than pursue them as an joint optimization. Mandal et al. [15] presents another algorithm to reduce both the energy consumption and the workload on the CDN based on a hybrid CDN-P2P system in an IP-over-WDM network. In fact, it exploits P2P system to reduce workload on the CDN, but not dealing with the energy consumption directly. In [16], an energy model is proposed with the concept that the consumption will scale with the traffic speeds and volumes processed and also depend on the type of processing required. Similarly, Ricciardi et al. [17] presents a hybrid routing and wavelength assignment algorithm to make the switching decision among load-balancing and energy-awareness. Ricciardi et al. [16,17] focus on single network performance, rather than multiple objectives as in our work.

While the above studies always focus on energy minimization of two-layer networks, but how to guarantee comprehensive performances of energy-efficient IP over WDM mesh networks is an open issue for future investigation. Sleeping low loaded network equipment and reroutes the traversing traffic to other areas is a fundamental method for reducing energy consumption of networks. Since traffic demands always change in different time periods, the energy-efficient network design is to determine the effective routing and optimal topology in order to minimize the nonnecessary links or nodes, which means the traffic is aggregated in residual links. This would decrease the topology connectivity. Careful attention should be paid onto the tradeoff between energy consumption and network survivability performance. On the other hand, in general decreasing the network resource in IP over WDM mesh networks may also reduce the network energy consumption. This indicates that power efficiency can be improved by smart virtual topology design and traffic grooming method. But the grooming policy in previous works focuses on two-layer network resource utilization improvement, not directly considers energy consumption factor. The two objectives do not completely coincide.



(b) Virtual topology design with minimal virtual links/energy

Fig. 1. Virtual topology design example 1.

1.2. Motivation

In this paper, we study the problem of getting a good tradeoff between three main comprehensive performances in IP over WDM mesh networks: energy efficiency, resource efficiency and cross-layer survivability efficiency. The definition of energy efficiency is the minimization of network energy consumption; the definition of resource efficiency is the minimization of network resource, which means that the number of virtual links (i.e., lightpaths) or wavelength links in the network is minimized; the definition of cross-layer survivability efficiency is to maximize virtual topology survivability, which means the single physical link failure on bottom layer induces the minimum number of connection requests' disruption on top layer. To illustrate the importance of virtual topology design in energy-efficient IP over WDM mesh networks, we give two examples in Figs. 1 and 2.

In Fig. 1, we assume there are three connection requests to be deployed in the network: C_1 (A-B), C_2 (C-D), and C_3 (A-E). Fig. 1(a) illustrates virtual topology design results with minimal wavelength links: Lighpath 1 (in the following part of the paper, we abbreviate Lightpath as Lp) carries connection C_1. Lp3 carries connection C_2, and C_3 is groomed into Lp1-4.

The virtual topology of Fig. 1(a) occupies four wavelength links and four Lps. Fig. 1(b) illustrates virtual topology design results with minimal virtual links: Lp1 carries connection C_1, Lp2 carries connection C_2, and Lp3 carries connection C_3. The virtual topology of Fig. 1(b) occupies 6 wavelength links and three Lps, and the virtual links is minimized. As the energy consumption of electronic port (i.e., the transceiver port of virtual link) is much higher than