Optical Fiber Technology 36 (2017) 353–365

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

Regular Articles

Spectrum-efficient multipath provisioning with content connectivity for the survivability of elastic optical datacenter networks

Tao Gao, Xin Li, Bingli Guo, Shan Yin, Wenzhe Li, Shanguo Huang *

State Key Laboratory of Information Photonics and Optical Communication, Beijing University of Posts and Telecommunications (BUPT), Beijing 100876, China

ARTICLE INFO

Article history:
Received 26 December 2016
Revised 4 May 2017
Accepted 14 May 2017

Keywords:
Survivability
Elastic optical datacenter networks
Content connectivity
Multipath provisioning
Distance adaptive modulation
Dynamic content placement

ABSTRACT

Multipath provisioning is a survivable and resource efficient solution against increasing link failures caused by natural or man-made disasters in elastic optical datacenter networks (EODNs). Nevertheless, the conventional multipath provisioning scheme is designed only for connecting a specific node pair. Also, it is obvious that the number of node-disjoint paths between any two nodes is restricted to network connectivity, which has a fixed value for a given topology. Recently, the concept of content connectivity in EODNs has been proposed, which guarantees that a user can be served by any datacenter hosting the required content regardless of where it is located. From this new perspective, we propose a survivable multipath provisioning with content connectivity (MPCC) scheme, which is expected to improve the spectrum efficiency and the whole system survivability. We formulate the MPCC scheme with Integer Linear Program (ILP) in static traffic scenario and a heuristic approach is proposed for dynamic traffic scenario. Furthermore, to adapt MPCC to the variation of network state in dynamic traffic scenario, we propose a dynamic content placement (DCP) strategy in the MPCC scheme for detecting the variation of the distribution of user requests and adjusting the content location dynamically. Simulation results indicate that the MPCC scheme can reduce over 20% spectrum consumption than conventional multipath provisioning scheme in static traffic scenario. And in dynamic traffic scenario, the MPCC scheme can reduce over 20% spectrum consumption and over 50% blocking probability than conventional multipath provisioning scheme. Meanwhile, benefiting from the DCP strategy, the MPCC scheme has a good adaption to the variation of the distribution of user requests.

1. Introduction

Emerging applications such as cloud computing and online video game dramatically promote the increase of IP traffic and accelerate the development of advanced all-optical interconnection technology in datacenter networks. To achieve high spectrum efficiency, multi-carrier modulation techniques such as optically generated orthogonal frequency-division multiplexing (OFDM), Nyquist-WDM, and so on [1–3] are applied for next-generation optical networks, especially for the newly build optical interconnected datacenter networks, which is referred as elastic optical datacenter networks (EODNs). However, optical network is fragile and easy to be broken by natural or man-made disasters such as earthquake, hurricane, and weapons of mass destruction [4,5]. Especially when the capacity of one single fiber increase to Pb/s (for example by using low-crosstalk one-ring-structured 12-core fiber [6]), any fiber failure could cause a great loss of data and revenue. Consequently, improving the survivability of optical networks is crucially important and has been studied extensively [7–9]. Traditional single-path protection schemes reserve backup resource for an end-to-end connection so that the interrupted traffic can be switched over to the backup path when any failure occurs [10–12]. However, all these single-path protection schemes obviously deteriorate network spectrum efficiency due to large amount of backup spectrum resource reserving.

Compared with the single-path protection, the multipath provisioning scheme has higher spectrum efficiency, in which traffic is transmitted through multiple node-disjoint paths. If a failure occurs on one path, the affected data stream can be transmitted through other paths and the service will not be interrupted. Multipath protection scheme for the end-to-end connection has been well studied in conventional wavelength-switched optical networks and elastic optical networks (EON). The authors in [13] developed an Integer Linear Program (ILP) model for optimally realizing static multipath routing and resource allocation while guaranteeing the required protection level. In [14], a dynamic multipath provisioning scheme supporting full and partial protection was proposed in elastic optical networks. In [15], a shared-protection multipath scheme was proposed to improve the survivability against multiple failures in

* Corresponding author.
E-mail address: shghuang@bupt.edu.cn (S. Huang).

http://dx.doi.org/10.1016/j.yofte.2017.05.008
1068-5200/

flexible-grid optical networks. These studies improve the network survivability against single or multiple link failures and guarantee the flexible protection requirement of the traffic. Moreover, improving the spectrum efficiency is also an important issue in multipath protection scheme. The authors in [16] proposed a novel multipath routing and spectrum allocated (RSA) algorithm with distance-adaptive modulation format assignment in dynamic traffic scenario. In [17], to solve the problem of spectrum waste caused by the guard bandwidth in multipath protection scheme, a dynamic multipath routing algorithm with traffic grooming was proposed. By aggregating small-size connections originated from the same source node and sharing common fiber links, the scheme improves the spectrum efficiency and enhances the network throughout. To solve the spectrum fragmentation issue caused by spectrum contiguity and continuity constraints, the authors in [18] proposed a novel multipath de-fragmentation method, which aggregates spectrum fragments instead of reconfiguring existing spectrum paths. This scheme achieves high spectrum efficiency and reduces blocking probability in dynamic traffic conditions. A spectrum-efficient multipath routing scheme in elastic optical networks that supported simultaneously anycast and unicast traffic demands was proposed in [19]. However, multipath protection scheme for end-to-end connection relies on network connectivity, which has a fixed value for a given topology. In practical scenarios, sometimes it is hard to find sufficient node-disjoint paths for every source-destination node pair.

Fortunately, most of services and data can be replicated and maintained in multiple datacenters such that any user can obtain the required content as long as one of these datacenters is reachable. Consequently, the spectrum efficiency and the survivability of EODNs can be further improved. In [20], the authors proposed a joint anycast and unicast routing scheme considering content distribution in elastic optical networks, which brought significant spectrum savings. From the perspective of network survivability, the authors in [21] first proposed the concept of content connectivity, which is defined as the reachability of every content from any point of an optical network. Considering content connectivity, the research for the survivability of EODNs has entered a new stage. In [22], the authors proposed the concept of k-node (edge) content connectivity and designed the k-node (edge) content connected optical datacenter networks against multiple failures, which had high spectrum efficiency. A novel perfect matching based sharing principle among multiple end-to-content paths was proposed to reduce the spectrum consumption while ensuring the survivability in [23]. The authors in [24] proposed a bandwidth-adaptive protection scheme where the backup path employed distance-adaptive modulation level in content connected EODNs. However, there are few researches jointly considering multipath provisioning and content connectivity. Meantime, all of above researches either focused on the static traffic scenario or focused on the dynamic traffic scenario without considering the practical network environment where network state such as disaster probability or the distribution of user requests is time-varying. To reduce the content loss caused by disasters of which probability changes as time passes in nature, the authors in [25,26] studied the dynamic content placement based on risk analysis in a cloud network. Nevertheless, compared with the changing frequency of disaster probability, the changing frequency of the distribution of user requests is higher [27,28]. Thus, dynamically readjusting the content placement among multiple datacenters according to the variation of user requests is meaningful to improve the spectrum efficiency.

In this paper, we jointly consider multipath provisioning and content connectivity in EODNs. The impact of time-varying distribution of user requests is also taken into account. A novel survivable multipath provisioning with content connectivity (MPCC) scheme is proposed, which focuses on reducing the spectrum consumption as well as improving the survivability of EODNs. Considering content connectivity, a user can be served by multiple datacenters, so that the number of node-disjoint end-to-content paths in the MPCC scheme will increase. Meantime, this scheme can achieve higher spectrum efficiency since the average length of end-to-content paths is shorter than that of end-to-end paths in the conventional multipath provisioning scheme. When addressing the routing, modulation level, and spectrum allocation (RMLSA) problem for each end-to-content path, the distance-adaptive spectrum allocation [29,30] is adopted by the MPCC scheme. Besides, since full replication of content where all content is replicated to each datacenter is not reasonable due to various cost such as storage cost and synchronization cost, there should be a trade-off between the spectrum efficiency and the cost of the content. In the MPCC scheme, under the limitation of the number of the content replicas, the spectrum consumption is minimized and the optimal content placement is achieved. We develop an ILP model for the MPCC scheme with the objective of minimizing the total spectrum consumption and optimizing content placement among multiple datacenters. We also design a heuristic algorithm for the MPCC scheme based on dynamic content placement (DCP) strategy in dynamic traffic scenario. In the DCP strategy, the distribution of user requests is periodically detected to determine whether the content placement algorithm is triggered or not. Simulation results indicate that the MPCC scheme can reduce the spectrum consumption and blocking probability dramatically compared with the full protection with content connectivity scheme (FPCC) and the multipath protection for end-to-end connection scheme (MPEE) in both static and dynamic traffic scenarios. The survivable provisioning scheme FPCC is based on the scheme proposed for anycast in content delivery networks in [20], and meanwhile, full protection is introduced. The MPEE scheme is a conventional multipath scheme [13,14], which is widely used for protecting end-to-end connections.

The rest of this paper is organized as follows. In Section 2, the concept of content connectivity, the MPCC scheme, and the DCP strategy are stated. The ILP model and the heuristic algorithms are presented in Section 3 and Section 4 respectively. Section 5 presents the numeric results of our proposed MPCC scheme. Finally, Section 6 concludes this paper.

2. DCP based MPCC scheme

In this section, we first introduce the concept of content connectivity. Then, the MPCC scheme is presented and compared with the traditional multipath provisioning scheme. Moreover, the DCP strategy, which readjusts the position of each content according to the current distribution of user requests, is also elaborated.

2.1. Content connectivity

Content connectivity guarantees that the content is still available for users even if the disaster destroys the networks into multiple segregated parts. As presented in Fig. 1(a) and (b), the network has 8 optical nodes and 2 datacenters (node 2 and node 6). We assume that there are 5 user requests with different source nodes. In traditional datacenter networks as shown in Fig. 1(a), each content is only placed in one single datacenter (without content connectivity), and when two disasters destroy the networks into two segregated parts, requests r_3 along light-path $4 \rightarrow 5 \rightarrow 6$ and r_4 along light-path $3 \rightarrow 6$ are both interrupted. While in datacenter networks with content connectivity as shown in Fig. 1(b), the content is placed in multiple datacenters (Without loss of generality, we assume there is only one kind of content). In this case, even if the EODNs are disconnected, content placed in datacenter 2 and 6 is still available in both parts. In addition, the total spectrum consumption is reduced by serving the users through