Optical Fiber Technology 34 (2017) 52–58

Contents lists available at ScienceDirect

Optical Fiber Technology

www.elsevier.com/locate/yofte

An auxiliary graph based dynamic traffic grooming algorithm in spatial division multiplexing enabled elastic optical networks with multi-core fibers

Yongli Zhao [a,b,*], Rui Tian [a], Xiaosong Yu [a], Jiawei Zhang [a], Jie Zhang [a]

[a] State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing 100876, China
[b] University of California, Davis, CA 95616, USA

ARTICLE INFO

Article history:
Received 10 September 2016
Revised 9 January 2017
Accepted 16 January 2017
Available online 25 January 2017

Keywords:
SDM-EON
Multi-core fiber
Traffic grooming
Auxiliary graph

ABSTRACT

A proper traffic grooming strategy in dynamic optical networks can improve the utilization of bandwidth resources. An auxiliary graph (AG) is designed to solve the traffic grooming problem under a dynamic traffic scenario in spatial division multiplexing enabled elastic optical networks (SDM-EON) with multi-core fibers. Five traffic grooming policies achieved by adjusting the edge weights of an AG are proposed and evaluated through simulation: maximal electrical grooming (MEG), maximal optical grooming (MOG), maximal SDM grooming (MSG), minimize virtual hops (MVH), and minimize physical hops (MPH). Numeric results show that each traffic grooming policy has its own features. Among different traffic grooming policies, an MPH policy can achieve the lowest bandwidth blocking ratio, MEG can save the most transponders, and MSG can obtain the fewest cores for each request.

1. Introduction

With the exponential growth of IP traffic, the transmission capacity of fiber links has increased by a hundredfold. However, for single-mode and single-core fibers, the total achievable capacity has almost reached its limit [1]. One approach to increase the link capacity further is to use spatial dimension resources. Spatial division multiplexing (SDM) can further scale the network capacities, using parallel strands of a single mode fiber (SMF), uncoupled or coupled cores of a multicore fiber, or even individual modes of a few-mode fiber in combination with multiple-input multiple-output (MIMO) digital signal processing [2,3]. Then, spatial division multiplexing enabled elastic optical networks (SDM-EON) will become the most important form of future optical transport networks or optical datacenter networks [4]. A multi-core fiber (MCF) and a multi-mode fiber (MMF) can be used with SDM technology to enhance the fiber capacity in proportion to the number of cores and modes per fiber. An MCF is mainly considered in the paper because it is more practical compared with an MMF [5]. A total capacity of 305 Tb/s has been demonstrated with a 19-core fiber [6].

Although the introduction of SDM-EON increases the capacity of the fibers, it is difficult to improve the utilization of the spectrum resources because of the complicated constraints, such as spectrum continuity and contiguity [7]. The problem of routing, space and spectrum allocation (RSSA) in SDM networks has been investigated, and a number of novel heuristic policies are proposed for solving the RSSA problem in SDM networks [8]. The problem of routing, spectrum and core assignment (RSCA) is modeled with the integer linear programming (ILP) formulation to optimally minimize the maximum number of spectrum slices required on any core of MCF of a flex-grid SDM network [9]. A routing, wavelength and mode assignment (RWMA) algorithm is proposed and evaluated in the SDM network with a multi-mode fiber [10]. In addition, there is serious crosstalk between the adjacent cores in one fiber [11]. The crosstalk may occur between adjacent cores, which severely impacts the signal quality during transmission. To decrease the crosstalk and achieve a dense core arrangement, a trench-assisted MCF (TA-MCF) was developed [12]. Additionally, crosstalk has been considered in RSCA algorithms [11,13] to reduce the inter-core crosstalk during lightpath provisioning. In addition to inter-core crosstalk, improving spectrum resource utilization is another important topic in SDM-EON.

Traffic grooming is an efficient method of improving the resource utilization by aggregating multiple traffic flows into a high bandwidth channel [14], which can be achieved by the controller in software-defined optical networks [15]. By a traffic

* Corresponding author at: State Key Laboratory of Information Photonics and Optical Communications, Beijing University of Posts and Telecommunications, Beijing 100876, China.
E-mail address: yonglizhao@bupt.edu.cn (Y. Zhao).

http://dx.doi.org/10.1016/j.yofte.2017.01.005
1068-5200/

grooming strategy, two service LSPs that have the same source or destination nodes can share the same physical links. Further, under the condition that the lightpath has enough bandwidth capacity, two service LSPs that have the same source or destination nodes can share the same lightpath to save IP router ports and optical transponders [16]. Actually, much research has been done for traffic grooming in elastic optical networks (EON) [14–18]. In EON, traffic grooming was first proposed for a static traffic scenario to save guard bands between two neighboring lightpaths [17]. The spectrum allocation sub-problem was simplified by ignoring spectrum continuity and spectrum contiguity constraints. As a network design problem, an OFDM-based optical-grooming scheme was proposed in [18], aiming to eliminate Optical-Electro-Optical (OEO) conversions and electrical processing. The grooming benefit is limited with respect to both spectrum and transponder utilization because traffic grooming is executed only at the source node. For dynamic traffic grooming, the authors in [19] extended the auxiliary graph model to be implemented in the EON. Based on this, they also proposed a spectrum reservation scheme by reserving more spectrum than the traffic demand when establishing a new lightpath. The impact of a series of factors, such as a different modulation format and physical impairment constraints, on the performance of traffic grooming in the EON, has been analyzed not only from a performance perspective, but also from the point of view of the operational costs [20].

Energy efficiency also has an important impact on dynamic traffic grooming. An energy efficient traffic grooming scheme is proposed for promoting greener optical networks, which considers a modular node architecture, reuses already active components during allocation requests, and conserves total energy consumption in the network [21]. A modified heuristic traffic grooming algorithm is proposed, which can improve the trade-off efficiency by approximately 20% compared with earlier algorithms [22]. A heuristic solution that provides an energy minimized design of long-haul optical networks is proposed by avoiding under-utilization of network resources such as optical fibers, transponders, and amplifiers [23]. The concept of stateful grooming is introduced to apply differentiated provisioning policies based on the state of the network nodes, on which an online traffic-aware intelligent differentiated allocation of lightpaths (TIDAL) algorithm is based to accommodate dynamic tidal traffic [24]. We studied energy-efficient traffic grooming with sliceable transponders, and compared three different elastic optical transponders based on their slice-ability. Significant power saving was achieved from the results of both ILP and heuristic algorithms [25]. An auxiliary graph (AG) model was introduced to address mixed-electrical-optical grooming under dynamic traffic scenario in the EON [26].

As the evolution from EON to SDM-EON occurred, requests in different cores of one fiber can be groomed by SDM grooming as shown in Fig. 1. This strategy not only aggregates IP packet flows to improve the utilization of the spectrum, but also reduces the influence of the crosstalk. However, in an SDM-EON with multi-core fibers, the traffic grooming problem will be more complicated because of the emergence of spatial dimensions. This paper is the first, to the best of our knowledge, to mainly focus on the traffic grooming problem in an SDM-EON with multi-core fibers. An AG is introduced for a traffic grooming solution in an SDM-EON with multi-core fibers. Five traffic grooming policies achieved by adjusting the edge weights of the AG are proposed and evaluated through simulation. Multi-core fibers here can be considered as bundles of single-core fibers, while inter-core crosstalk has not been considered here. Crosstalk aware traffic grooming in an SDM-EON will be considered in the future.

The rest of this article is organized as follows. In Section 2, a switching fabric is described in an SDM-EON with multi-core fibers. Then an auxiliary graph (AG) scheme is proposed to analyze the performance of the traffic grooming in Section 3. In Section 4, traffic-grooming policies based on the AG are proposed for different objectives. In Section 5, simulation results are presented to compare the performance of various traffic-grooming policies. Section 6 concludes the paper.

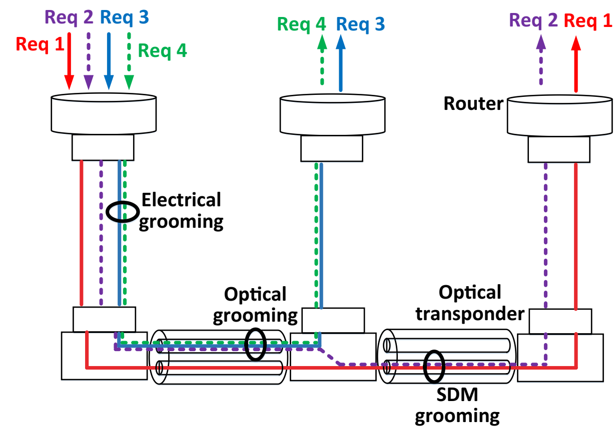

Fig. 1. Mixed electric-optic-SDM grooming with a sliceable transponder in an SDM-EON.

2. Switch fabric in SDM-EON with multi-core fiber

In addition to sliceable transponders which can support traffic grooming in an SDM-EON, the switch fabric is also important for the implementation of traffic grooming in an SDM-EON. A spatially and spectrally resolved optical switching fabric is designed as shown in Fig. 2. As the most important resource in the frequency domain, the spectrum slot is the basic bandwidth unit in the optical layer and spectrum continuity must follow. It means that an end-to-end lightpath must use the same spectrum slots from the source node to the destination node, unless wavelength converters or OEO units are deployed at the middle nodes. Meanwhile, the service can be carried by several spectrum slots within the same core. These spectrum slots must be continuous in the spectrum dimension, which is known as spectrum continuity. Of course, all the spectrum slots in one core channel should guarantee the orthogonality property.

Some optical switching fabrics of SDM networks have been proposed [27–29]. As shown in Fig. 2, the functions of fiber switching, core switching and spectrum switching can be achieved in the optical switching fabric [27], which allows the adding, dropping and switching of different flexible channels with granularity down to the wavelength level. The transceiver resources include a transceiver pool, which supplies the appropriate sub-transceivers according to the traffic requirement. In the switch fabric, different spectrum slots can be switched between different cores but must follow spectrum continuity as shown in Fig. 3.

3. Dynamic traffic grooming in SDM-EON

Traffic induced by various emerging services requires bandwidth-intensive transport networks to support dynamic connection setup and release. In this article, the network topology is defined as $G = (V, E)$, where v is a set of nodes with traffic-grooming capability and E is a set of bidirectional links. A connection request is labeled $r = (s, d, b)$, where s and d denote the source and destination nodes, and b is the requested bandwidth. When the request r arrives, the route of r is decided by going through existing lightpaths or new lightpaths. New lightpaths have to be established if the existing lightpaths are not sufficient. The new