Design and Control in Elastic Optical Networks: Issues, Challenges, and Research Directions

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***Abstract*—The rapid growth in world-wide communications and the rapid adoption of the Internet has significantly modified our way of life. The traffic behavior is changing rapidly and the increasing mobility of traffic sources makes grooming more complex. To fulfill the needs of the future Internet, optical transmission and networking technologies are moving toward to the goals of greater efficiency, flexibility, and scalability. Recently, elastic optical networks (EONs), which adopt flexgrid technology, have been shown to be a promising candidate for future high-speed optical communication. An EON has the potential to allocate spectrum to lightpaths according to the bandwidth requirements of clients. This paper presents the EON, and provides possible scopes for the future research. Finally, the paper addresses a number of research challenges and open issues presented by elastic networks.**

***Index Terms*—Elastic optical networks, flexgrid, lightpaths, spectrum allocation**

I. Introduction

Internet traffic volume is outpacing the technology advancements in networking. Network operators [1], [2] expect that the worldwide internet protocol (IP) traffic hit 20.2 Exabytes per month in year of 2020. Therefore, we need optical networks that supports Tb/s class of transmission in upcoming years [3]. Unluckily, the conventional optical network is unable to fulfill the huge bandwidth requirement of clients as it undergoes the electrical bandwidth bottleneck. The impairments of physical layer, such as four-wave mixing, dispersion, attenuation, and cross-talk, become a serious issue as the transmission speed of optical networks increases [4]. In addition, the traffic behavior is changing very quickly, and the mobility of traffic sources becomes increasing, which makes grooming [5] difficult. Thus, innovative technologies of optical networks, which support high-speed and flexible communications, are required.

To fulfill the huge bandwidth requirements of clients, optical transmission systems need to be more scalable, efficient, reliable and flexible. Presently, the flexgrid technology or elastic optical network (EON) [6]–[10] has been considered one of the auspicious candidates for high-speed communications. EONs have the ability to assign lightpaths flexibly according to the bandwidth requirement of clients. The spectrum resources are separated into thin spectrum slots that support fine granularity, and a number of contiguous slots are required for establishing an optical connection. As a result, the efficiency of spectrum utilization in EONS is significantly enhanced compared to wavelength-division multiplexing (WDM) optical networks. In EONs, the system parameters, such as modulation technique, channel spacing, and bit rate, will be made tunable for each connection; these parameters are fixed in presently deployed optical networks. Thus, EONs are considered as a possible solution to overcome the shortcomings of conventional optical networks.

As EONs have been broadly accepted as the next generation transport network, researchers have move forwarded their works from fixed-grid technology to flexgrid technology. Taking this direction, G. Zhang et al. [9] presented a survey on orthogonal frequency-division multiplexing (OFDM) based flexible optical networks. A tutorial on routing and spectrum allocation (RSA) for EONs was provided by B.C. Chatterjee et al. A comprehensive study on spectrum management techniques for EONs was presented by S. Talebi et al. [11]. Recently, a survey of the ongoing research regarding the control plane architectures of EONs was provided in [12]. With the time, research directions and technologies are being rapidly changing in order to satisfy the users' requirements, which introduce new challenges for optical networks. This paper is aimed to highlight current research areas and scopes, and addresses a number of challenging issues posed by EONs.

The reminder of the paper is structured as follows. Section II provides the background of the EON. Section III presents the current research areas of EONs. Section IV presents research issues and directions. Finally, the conclusions are drawn in section V.

II. Background of EONs

The conventional optical network splits the spectrum into wavelength channels. The spacing between two contiguous wavelength channels is either 50 GHz or 100 GHz, defined by the international telecommunication union (ITU)-T, which is relatively large. The channel spacing between two contiguous wavelength is depicted in Fig. 1(a). If the low bandwidth is carried out by a wavelength channel, a large portion of the spectrum are unused (see Fig. 1(b)), which decreases the spectrum efficiency.

To alleviate the shortcoming of conventional optical networks, M. Jinno et al. [7] presented an architecture for spectrum efficient EONs based on the OFDM technology [9], [13], which assigns the data to several subcarrier channels that support fine-granularity. The OFDM technology allow the adjacent subcarrier channels to overlap each other, as shown in Fig. 2. As a result, it increases transmission spectral efficiency. A bandwidth-variable OFDM transponder produces an optical

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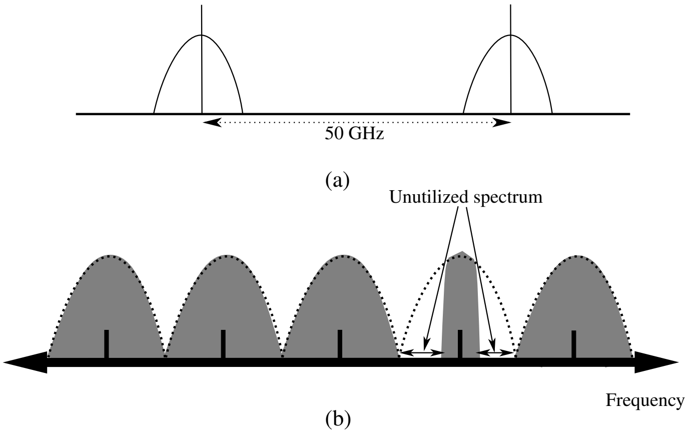

Fig. 1. (a) ITU-T fixed-grid and (b) Spectrum allocation in ITU-T fixed-grid.

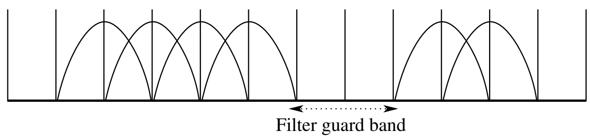

Fig. 2. Overlying subcarriers introduced by OFDM.

signal using just enough spectrum resources to satisfy the client's requirements. To setup an optical connection, each bandwidth variable cross-connect on the route allocates a cross-connection in order to create a proper sized lightpath from source to destination; this lightpath is contracted and expanded based on the user requirements.

The main properties of an EON, such as aggregation and segmentation of bandwidth, efficient accommodation of different data rates, and flexible variation of allocated resources, are explained in the following. An EON has the ability to enable the bandwidth aggregation (sometimes referred as super-wavelength) feature in order to create a super-wavelength optical lightpath by contiguously combining low speed optical bandwidths, thus guaranteeing high utilization of spectrum resources. These properties are captured in Fig. 3; three 60 Gb/s optical connections are aggregated in order to create a super-wavelength of 180 Gb/s. EONs support the feature of a spectrum bandwidth segmentation (sometimes referred

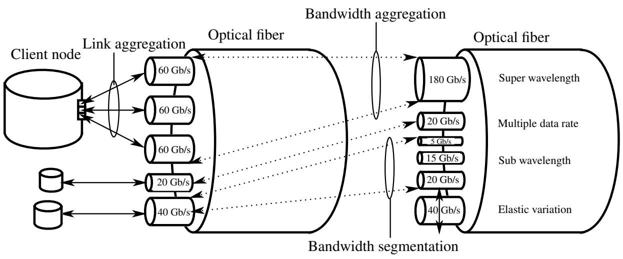

Fig. 3. Unique properties of EONS [6].

as sub-wavelength), which provides low bandwidth services according to clients' demand. This property of EONs is shown in Fig. 3; a 50 Gb/s optical connection is divided into three connections in order to make sub-wavelengths. As EON supports flexible spectrum assignment, it has the capability to provide the spectrum-efficient direct accommodation of different data rates in the optical domain, as depicted in Fig. 3. It provides distance-adaptable line rate, as well as dynamic bandwidth enlargement and reduction, by automatically adapting the number of subcarriers and modulation formats. The EON supports energy-efficient facilities in order to reduce the energy consumption by turning off unnecessary OFDM subcarriers while traffic is relaxed. It also supports optical network visualization.

III. Research on EONs and Scope for Future Research

This section presents the current research on EONs, and provides the scope for future research. As the EON is an emerging technology for future high-speed communications, its architecture and working principles need to be explored. The performance of an EON not only depends on its physical resources but also how the resources are used and controlled. The objective of a resource allocation and control algorithm is to obtain the best performance within the limited resources. Recently, several studies have been introduced to focus on various aspects of RSA, which are fragmentation, modulation, quality-of-transmission, traffic grooming, survivability, energy saving, and networking cost. These studies are summarized in Table I; the detail information regarding the various aspects of RSA can be found in [6], [14], [15]. In the following, we provide the basic skeleton and possible research areas in EONs.

TABLE I
Research works on various aspects of RSA approach

Various issues		Reference
Fragmentation	Proactive	[16], [17]
	Reactive	[18], [19]
Quality of transmission		[20], [21]
Survivability	Protection	[22], [23]
	Restoration	[24], [25]
Energy saving		[26], [27]
Modulation	Online	[28], [29]
	Offline	[30]
Traffic grooming		[31], [32]
Networking cost		[33], [34]

The development of high-performance-sophisticated devices and optical components is essential in order to implement the high-speed communication system. In addition, bandwidth-variable optical switches and filtering components need to be developed to execute the efficient protocols and schemes. Therefore, development of hardware and optical devices is one of essential research topics, which needs to be emphasized.

Considering the present and past works in EONs, we still need to focus on resource allocation policies and approaches as the performance of conventional routing and spectrum allocation approaches is not optimum; there is a huge scope to improve the performance. Fragmentation is one of the key problems in EONs due to the constraints of spectrum contiguity and continuity. Defragmentation approaches are used to suppress the fragmentation problem, and hence the accommodated traffic in the network is increased. Recently, hitless defragmentation approaches have been considered to suppress the fragmentation. Still, suppressing fragmentation is a challenging issue, and this area needs to be explored. Recently, routing and spectrum allocation approaches considering effective modulation have been introduced. Spectrum allocation considering physical layer impairments with appropriate modulation technique uses spectrum resources efficiently, which needs further research. Quality of transmission in EONs is the ultimate importance to satisfy the required signal quality threshold level, which needs to be explored. To use spectrum resources efficiently, traffic grooming mechanism in EONs needs to be investigated. As EONs have the ability to make a super-wavelength channel that carries a huge amount of information in the order of Tb/s range, the survivability against the failures of network components is an essential requirement, which is considered as a hot research topic in the optical domain.

To enhance the performances of EONs, network operators consider planning and designing phases. Mathematical modeling approaches [35], such as integer linear programming and mixed integer linear programming, are normally used to obtain the optimum output. When network size and input increase, mathematical approaches are not tractable within a practical time. In that situation, heuristic approaches are one of the possible solutions. In that case, optimality cannot be achieved, but we reduce the computation time. Therefore, designing efficient heuristic algorithms considering both computational time and accuracy is a challenging issue.

Recently, green computing or energy saving is a hot research topic due to environmental consciousness and reduce the operational cost. Therefore, the work on energy saving in EONs need to be investigated.

IV. Research issues and challenges

The EON is an emerging technology; its execution is under development. Several challenges and open issues exist in EONS, which require further research to overcome the shortcomings. This subsection addresses a number of research issues and open challenges encountered by EONs.

One of the most significant problems in EONs is bandwidth fragmentation, which occurs due to the constraints of spectrum contiguity and continuity. Some proposals [36], [37] presented in the literature, which divides the whole spectrum block in an advance by assuming known traffic demand in order to manage spectrum resources efficiently. Considering the unknown traffic condition, it may happen that the connection with a large number of required slots may not be adapted by a partition; in this situation, the connection request is rejected. As a result, the call blocking in the network is increased. Partitioning the whole spectrum considering the unknown traffic condition is a challenging issue, which may be overcome by further research.

Robustness against traffic uncertainty is one of the key requirements for EONs. Several ongoing researches have been carried out to reduce the energy consumption according to shortest path first protocol and known traffic demand. Some proposals [38] are found, which focuses on dynamic voltage scaling considering adaptive link rate in order to reduce energy consumption. However, under traffic uncertainty, energy saving in EONs is a challenging issue; most of the previous researches minimize the energy consumption under given traffic demand.

The EON has the ability to maximize the performance in terms of processing time in a distributed environment considering cloud infrastructures; multiple clients and a server located different parts of the world can be used for job processing in order to enhance the performances. However, the bandwidth-variable elastic virtual path setup between master and slaves and allocate the job considering both computer processing performance and network resource availability are challenging issue in the optical domain.

To enhance the capacity of optical transport systems, multi-core fiber technology or space division multiplexing (SDM) has been incorporated with EONs. To amplify the multi-core optical signal without fan-in and fan-out mechanism, multi-core transient-suppressed erbium-doped fiber amplifiers (TS-EDFAs) are required. However, multi-core TS-EDFAs are under development. As a result, the lightpath activation and releasing times in SDM technology become longer, which increase both delay and call blocking in the network. Therefore, we need to develop a scheme, which rapidly activates and deactivates the lightpaths in EONs.

V. Conclusions

The elastic optical network (EON) is a promising technology for future high-speed communications due to its flexible characteristic. This paper presented EONs and provided possible scopes and directions for the future research. Finally, a number of research issues and open challenges presented by EONs were addressed.

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