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Brief Overview of Elastic Optical Networks

-- A Promising Transmission Network Technology

Xiangsheng Zeng [1] *, Shen Liu [2]

[1] College of Electronic and Information, Southwest Minzu University, Chengdu 610041, China
[2] Faculty of Business, Lingnan University, New Territories, Hong Kong, China

* **Corresponding author**: Xiangsheng Zeng (Email: zengxiangsheng@stu.swun.edu.cn)

Abstract: With the rapid development of information technology, the Internet of Things industry and E-Commerce industry has become increasingly mature, and topics such as cloud-computing and edge-computing have become hot topics. In these fields, the rapid growth of terminal devices and the significant increase in user communication service demands have led to higher requirements for optic fiber networks in terms of bandwidth, cost-effectiveness, and protection. Elastic optical networks technology has emerged as a standout solution due to its ability to improve performance through optimizations in modulation formats, routing, and spectrum allocation. Over the past decade, EONs have experienced substantial development. This article provides a concise tutorial on EONs, covering its characteristics, architecture, principles, and reviewing some technical details. Lastly, the article discusses the research challenges and issues posed by EONs.

Keywords: Elastic optical networks; Routing and spectrum allocation.

1. Introduction

The rapid development of communication technologies worldwide, such as fiber optics and 5G, has greatly transformed people's lives. For instance, the Internet of Things (IoT) services have penetrated into various aspects of production and daily life, aiming to connect a wide range of terminals, sensors, and servers to collect, interact, and process information, providing efficient production and life services with self-awareness, adaptability, and self-organization. In the field of IoT, to meet the enormous computing demands, concepts like cloud computing, edge computing, and fog computing have been proposed [1,2]. However, all of these pose demands on the development of IoT services, including large-scale connectivity, reliability, energy efficiency, among others. These technical metrics are crucial for ensuring the quality of services.

Similarly, the E-Commerce industry has a growing demand for transmission speed, troubleshooting, and timeliness. Modern E-Commerce requires cross continent communication and is highly sensitive to the timeliness of financial transactions [3]. The response speed needs to reach the microsecond standard, which requires efficient transmission methods. Only fiber optic communication can meet this requirement. The modern online trading business volume is huge, especially in the financial industry. Every second interruption of communication lines will cause huge economic losses, which puts forward high requirements for the reliability and recovery ability of the network [4]. This is something that ordinary network architectures find difficult to meet.

In laboratory environments, research achievements based on fiber optics and 5G communication technologies have demonstrated the capability of achieving a single-channel transmission rate of 1.6 Tbps in distributed computing networks. In real-world engineering applications, successful transmissions have been achieved with a baud rate of 128 GBd, QPSK modulation format, and a total distance of 1900 km, enabling a transmission speed of 80×400Gbps in the C+L band. These achievements provide high-bandwidth transmission capabilities for the development of the Internet of Things. However, challenges still remain, such as dynamic traffic, diverse types of services, and fault protection.

The emergence of elastic optical networks has garnered significant attention as it offers solutions to address these challenges. Elastic Optical Networks (EONs) can optimize optical networks in terms of modulation formats, routing, spectrum allocation, traffic grooming, survivability, energy efficiency, and multipath utilization [5,6,11]. Notably, its flexible grid feature allows for higher resource utilization efficiency and greater adaptability to diverse services compared to traditional dense Dense Wavelength Division Multiplexing (DWDM) optical networks [7]. As of today, EONs continue to hold immense research value and promising prospects.

This article provides a concise tutorial on Elastic Optical Networks to help researchers gain a more intuitive understanding of this topic. The remaining sections of this article are organized as follows. In Section 2, an overview of the characteristics and architecture of EONs will be presented. Section 3 will delve into the technical details of Routing and Spectrum Allocation, as well as other related issues. Finally, in Section 4, we will explore the challenges and open questions in EONs research, concluding the article.

2. The Features and Architecture of EONs

Traditional optical networks have the advantages of high transmission speed and low cost, making them the standard for backbone networks. However, they do not perform well when facing the complex and ever-changing business demands of today. To meet the diverse requirements of dynamic traffic and various services, flexible, scalable, and efficient EONs have emerged as the future direction of optical communication development. They have already been preliminarily applied in the industry.

2.1. EONs Features

Traditional Wavelength-Division Multiplexing (WDM) based optical networks use fixed grids with a bandwidth of typically 50GHz or 100GHz. In contrast, EONs that emphasize spectral efficiency employ Orthogonal Frequency-Division Multiplexing (OFDM) technology. In EONs, each Bandwidth-Variable Cross-Connection (BV-WXC) in the optical path establishes an end-to-end cross-connection with a spectrum size that is sufficient and suitable. It offers higher spectral granularity and can use a flexible grid to achieve more efficient spectrum utilization.

Elastic optical networks typically exhibit six main features: Bandwidth segmentation, Bandwidth aggregation, Effective adaptation to multiple data rates, Reach adaptability to different rates, Energy efficiency, and Network virtualization.

2.2. EONs Main Hardware Architecture

The main components of an Elastic Optical Network include Bandwidth-Variable Transponder (BVT) and Bandwidth-Variable Cross-Connects (BV-WXC). BVTs enable high-speed transmission using spectrum-efficient modulation formats, such as 64-QAM, QPSK, BPSK, and others. The development of Sliceable Bandwidth-Variable Transponder (SBVT) allows for the partitioning and aggregation of specified spectrums. BV-WXCs provide appropriate-sized cross-connections for elastic optical paths by assigning corresponding optical spectrum bandwidth. Both components are critical for achieving "elasticity" in the network.

2.3. The Architecture of Optical Nodes

The architecture of optical nodes in EONs has evolved through four stages:

(1) Broadcast and Select: Initially used in high-speed local area networks and metropolitan area networks.

(2) Spectrum Routing: Introduced the use of Spectrum Selective Switches (SSS), which brought additional costs.

(3) Switch and Select With Dynamic Functionality: Introduced larger port optical switches and Spectrum Selective Switches at the expense of higher port counts.

(4) Architecture on Demand: Consists of an optical backplane that connects multiple processing modules with high-port optical switches, including Spectrum Selective Switches, Fast Switches, Erbium-Doped Fiber Amplifiers (EDFA), Spectrum Defragmenters, and splitters, among others. Different components can be interconnected in any desired way, and the number of devices is determined based on specific functional requirements. This type of architecture provides a cost-effective solution.

The Architecture on Demand is currently a popular development direction [10]. The number of Spectrum Selective Switch ports is not strictly related to the node degree, making it convenient to implement alternate paths for flexible protection. It also allows for time multiplexing through synchronous switching, supports full optical 3R signal regeneration, and facilitates spectrum defragmentation.

3. Issues in EONs

3.1. Basic Concepts of RSA

The main objectives of Routing and Spectrum Allocation (RSA) are twofold:

1)To find suitable paths for a pair of source and destination nodes.

2)To allocate appropriate frequency slots for the requested light paths.

During the spectrum allocation process, two constraints need to be satisfied:

Constraint 1: Spectrum Continuity Constraint - For transmission between a pair of source and destination nodes, the allocated frequency slots along each link of the path should be consistent.

Constraint 2: Spectrum Compactness Constraint - The numerous frequency slots allocated along the links of the path should be as contiguous and adjacent as possible.

3.2. The Development of Routing Methods

Methods used to address the routing subproblems in EONs can be categorized into two types: Non-Elastic routing and Elastic routing.

Non-Elastic routing methods include Fixed Routing, Fixed Alternate Routing, Least Congested Routing, and Adaptive Routing. Among them, Fixed Routing has the lowest algorithm complexity and the fastest path selection speed, but it also exhibits the highest blocking rate. Fixed Alternate Routing and Least Congested Routing show similar performance in various aspects. On the other hand, Adaptive Routing performs opposite to Fixed Routing.

Elastic routing refers to the routing method that can flexibly select the optimal path based on network demands and conditions. It allows dynamic path selection based on real-time network status and traffic requirements to maximize resource utilization and meet quality of service requirements. Elastic routing makes intelligent decisions based on real-time network topology, link status, bandwidth utilization, and other information, enabling efficient data transmission and flexible network configuration. The advantages of elastic routing lie in its ability to provide better performance, higher reliability, and adaptability, allowing the network to cope with dynamic changes and uncertainties.

3.3. The Development of Spectrum Allocation Methods

In EONs, spectrum allocation can be categorized into three scenarios.

(1) Spectrum Range Allocation for Connection Groups: In this case, the optical spectrum resources are divided into multiple connection groups, with each group containing multiple optical channels or light paths. An appropriate spectrum range is then allocated to each connection group to meet its communication requirements. This method is suitable for scenarios where spectrum resources are managed in groups, allowing flexible spectrum allocation based on the characteristics of each connection group.

(2) Spectrum Slot Allocation for Individual Connection Requests: In this scenario, the optical spectrum resources are partitioned into a series of contiguous spectrum slots or time slots. Each connection request is assigned one or more slots to transmit data. The number of spectrum slots allocated to each connection request is dynamically determined based on its bandwidth requirements [8]. This approach is suitable for scenarios requiring fine-grained control, allowing flexible spectrum allocation based on the specific needs of each connection request.

(3) Joint Routing and Spectrum Allocation Algorithm: In this case, the spectrum range allocation for connection groups and the spectrum slot allocation for individual connection requests are considered together. By jointly considering the

spectrum allocation at both the connection group and connection request levels, the goal is to maximize the utilization of spectrum resources and meet the demands of each connection. This method enables resource sharing and coordination between connection groups and connection requests to optimize overall spectrum allocation performance. Concepts such as fragment awareness and congestion avoidance can also be incorporated into the joint consideration process [9].

3.4. Other Issues

The other issues in elastic optical networks include, but are not limited to, the following four common examples due to space constraints.

3.4.1. Modulation Format

In EONs, the selection of modulation formats requires a comprehensive consideration of factors such as transmission distance, bandwidth requirements, fiber characteristics, and network topology. Moreover, a balance needs to be struck between modulation complexity and transmission performance to achieve efficient data transmission and spectral utilization. As a result, the modulation format problem remains an important topic worth researching and optimizing in EONs.

3.4.2. Traffic Grooming

In EONs, traffic grooming is a significant problem that involves efficiently directing and aggregating traffic flows to optimize network resources and improve overall performance. The traffic grooming problem becomes more challenging due to the heterogeneous nature of traffic demands and the varying requirements of different services.

Overall, traffic grooming is a critical issue in EONs, as it directly impacts the network's capacity, efficiency, and ability to handle diverse and dynamic traffic demands effectively. Therefore, ongoing research efforts focus on developing advanced traffic grooming algorithms to meet the evolving requirements and Quality of Service (QoS) of modern communication networks.

3.4.3. Survivability

The survivability problem in EONs involves effectively setting up backup paths and spectrum resources so that data can be rerouted through backup paths or channels when the primary path or channel experiences a failure [12]. To achieve survivability, the network needs to quickly detect failures and switch to backup paths to minimize data loss and service interruption.

Solutions to the survivability problem include pre-establishing backup paths and spectrum resources, employing fast failure detection and switching mechanisms, and optimizing the allocation of backup paths and spectrum resources. Additionally, it is necessary to balance the trade-off between survivability and resource utilization, ensuring that the network provides high reliability without excessive resource waste.

3.4.4. Energy Efficiency

The energy efficiency problem in EONs involves finding ways to reduce the power consumption of network elements, such as transceivers, amplifiers, and switches, while still meeting the required data transmission and service demands. This is particularly important as data centers and communication networks consume a considerable amount of energy, and optimizing energy efficiency can lead to cost savings and environmental benefits.

Several approaches can be employed to address the energy efficiency problem in EONs. For instance, using advanced energy-efficient transceivers and components, implementing dynamic sleep modes for network devices during periods of low traffic, and optimizing routing and spectrum allocation to minimize the number of active network elements.

Energy-Aware network management and resource allocation strategies can also play a crucial role in achieving energy efficiency. By monitoring network traffic and dynamically adjusting the usage of network resources, energy consumption can be optimized based on real-time traffic demands.

4. Challenges and Opportunities

This article provides a concise overview of Elastic Optical Networks, comprehensively introducing the fundamental concepts of EONs. It is evident that EONs with flexible grid offer unparalleled advantages compared to traditional fixed-grid optical networks. Thanks to its unique structure and technological features, EONs show significant improvements in flexibility, survivability, and cost-effectiveness.

Moreover, there are still substantial research opportunities in various aspects of EONs, such as routing and spectrum allocation, traffic grooming, and multicast. Each year, numerous studies propose novel ideas and strategies in these areas. Additionally, the rapid development of Machine Learning (ML) has captured the attention of researchers, with various techniques like Deep Reinforcement Learning (DRL) and Transfer Learning (TL) being introduced into the study of EONs [13-16]. This brings new challenges but also provides new opportunities. We look forward to seeing further achievements in this direction from the industry and research community.

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