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Review

Spectrum management techniques for elastic optical networks: A survey ☆

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ABSTRACT

In recent years, OFDM has been the focus of extensive research efforts in optical transmission and networking, initially as a means to overcome physical impairments in optical communications. However, unlike, say, in wireless LANs or xDSL systems where OFDM is deployed as a transmission technology in a *single link*, in optical networks it is being considered as the technology underlying the novel elastic network paradigm. Consequently, *network-wide spectrum management* arises as the key challenge to be addressed in network design and control. In this work, we review and classify a range of spectrum management techniques for elastic optical networks, including offline and online routing and spectrum assignment (RSA), distance-adaptive RSA, fragmentation-aware RSA, traffic grooming, and survivability.

Contents

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1. Introduction

Optical networking technologies are crucial to the operation of the global Internet and its ability to support critical and reliable communication services. In response to rapidly growing IP traffic demands, 40 and 100 Gbps line rates over long distances have been deployed, while there is substantial research and development activity targeted to commercializing 400 and 1000 Gbps rates [1]. On the other hand, emerging applications, including IPTV, video-on-demand, and inter-datacenter networking, have heterogeneous bandwidth demand granularities that may change dynamically over time. Accordingly, mixed line rate (MLR) networks [2] have been proposed to accommodate variable traffic demands. Nevertheless, optical networks operating on a fixed wavelength grid [3] necessarily allocate a full wavelength even to traffic demands that do not fill its entire capacity [4]. This inefficient utilization of spectral resources is expected to become an even more serious issue with the deployment of higher data rates [5,6].

Elastic optical networks [7,8] have the potential to overcome the fixed, coarse granularity of existing WDM technology and are expected to support flexible data rates, adapt dynamically to variable bandwidth demands by applications, and utilize the available spectrum more efficiently [6]. The enabling technology for such an agile network infrastructure is orthogonal frequency division multiplexing (OFDM), and other efficient transmission techniques including Nyquist WDM and low-density parity-check (LDPC) based transmission [7]. OFDM, a modulation format that has been widely adopted in broadband wireless and copper-based communication systems, is a promising candidate for high-speed (i.e., beyond 100 Gbps) optical transmission [9]. Other key technologies include distance-adaptive modulation, bandwidth-variable transponders and flexible spectrum selective switches; for a recent survey of optical OFDM and related technologies, and how they impact network and control algorithm design, we refer the reader to [9].

OFDM is a multiple-carrier modulation scheme that splits a data stream into a large number of sub-streams [10]. Each data sub-stream is carried on a narrowband sub-channel created by modulating a corresponding carrier with a conventional scheme such as quadrature amplitude modulation (QAM) or quadrature phase shift keying (QPSK). The modulated signals are further multiplexed by frequency division multiplexing to form what is referred to as multicarrier transmission. The composite signal is a broadband signal that is more immune to multipath fading (in wireless communications) and inter-symbol interference. The main feature of OFDM is the orthogonality of subcarriers that allows data to travel in parallel, over sub-channels constituted by these orthogonal subcarriers, in a tight frequency space without interference from each other. Consequently, OFDM has found many applications, including in ADSL and VDSL broadband access, power line communications, wireless LANs (IEEE 802.11 a/g/n), WiMAX, and terrestrial digital TV systems.

In recent years, OFDM has been the focus of extensive research efforts in optical transmission and networking, initially as a means to overcome physical impairments in optical communications [11,12]. However, unlike, say, in wireless LANs or xDSL systems where OFDM is deployed as a transmission technology in a *single link*, in optical networks it is being considered as the technology underlying the novel elastic network paradigm [6]. Consequently, in the quest for a truly agile, resource-efficient optical infrastructure, *network-wide spectrum management* arises as the key challenge to be addressed in network design and control.

In this work we review and classify recent work in spectrum management in elastic optical networks. The paper is organized as follows. In Section 2, we discuss the advantages of, and challenges associated with, elastic optical networks. In Section 3 we define the offline routing and spectrum assignment (RSA) problem, and we discuss its complexity and various ILP formulations and heuristics. In Section 4 we describe and classify algorithms for the online RSA problem, and discuss performance modeling techniques. In Sections 5 and 6 we examine and categorize solution approaches based on distance-adaptive RSA (DA-RSA) and fragmentation-aware RSA (FA-RSA), respectively. In Section 7 we present traffic grooming techniques for RSA, in Section 8 we review survivability mechanisms for elastic optical networks, and in Section 9 we discuss multi-path variants of RSA. We conclude the paper in Section 10.

2. OFDM-based elastic optical networks

OFDM technology is the foundation of the elastic optical network (EON) concept [7], also referred to as "spectrum-sliced elastic optical path network" or *SLICE* [13]. The major difference between RWA and RSA lies in the SLICE network architecture as it flexibly adjusts to the format of the modulation [14]. The main driver of the EON architecture is the ability to allocate bandwidth at the granularity of an OFDM subcarrier rather than at the coarse unit of a wavelength in a fixed-grid network, using bandwidth-variable and format-agile transponders that may be reconfigured dynamically via software [10]. Optical signals are routed along the path to the destination by multi-granular optical switches that adapt to the data rate and center frequency of incoming channels via software control [15,16]. Bandwidth-variable transponders and switches make it possible to support efficiently a range of traffic demands, from sub- to super-wavelength, by *slicing off* just a sufficient amount of spectral