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Leveraging adaptive modulation with multi-hop routing in elastic optical networks

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ABSTRACT

The technology used for data transmission in optical networks is going through significant changes in response to the rapid growth of Internet traffic and emerging high performance applications, boosting research on how to satisfy the increasing demands with the available resources. In this scenario, the elastic optical networks paradigm enables improved provisioning through flexibility and scalability in spectrum assignment. This work proposes data and optical grooming and the use of spectral modulation control as a solution to the Routing, Modulation Level, and Spectrum Allocation problem in a dynamic traffic context. The proposed algorithm obtains the greatest spectrum aggregation possible using higher modulation levels through multiple hops in the virtual topology. Experiments show that this approach results in reduced blocking without impacting the use of the network's resources.

1. Introduction

Internet traffic has been growing exponentially and tends to continue doing so due to emerging applications such as high definition TV, cloud computing, multimedia applications, and real-time networks [1]. Current optical networks, which are based on the *Wavelength Division Multiplexing* (WDM) paradigm, can establish connections with a fixed bit rate (10Gb/s, 40Gb/s, or 100Gb/s) where the channels are modulated in a single format and equally spaced by 50 GHz [2].

Currently, Internet traffic demands increasingly different granularity levels with more flexible bit rates and unpredictable geographical transit patterns [3]. The conventional optical transmission technology is unable to satisfy these growing demands since it has physical limitations which impose fixed transmission rates in each wavelength, hindering the use of the network resources [4]. Additionally, new researches show that the WDM networks are approaching their limits due to the increase in traffic and growing mobility of its sources [5].

Adapting this technology to the recent demands is one of the challenges of the Future Internet. These issues require scalable optical network infrastructure and efforts to increase the network transport capacity, improving its efficiency using the resources, and allowing traffic with different granularities and flexible bit rates.

An *Elastic Optical Network* (EON) can dynamically adjust resources, such as optical bandwidth and modulation format, according to the requirements of each demand [6]. This flexibility is mostly due to the *Orthogonal frequency-division multiplexing* (OFDM), especially in wireless networks (802.11a/g *Wi-Fi*, 802.16 *WiMAX*, and *LTE*) [7]. OFDM improves efficiency of spectral resources via super-channels which provide an adaptable bit rate to ideally satisfy the band requirements, creating channels with the bandwidth required by the data flows to be transmitted.

The allocation strategies for satisfying the call requests determine the resources usage. In WDM, this is the *Routing and Wavelength Assignment* (RWA) problem, and the goal is to allocate the best pairing of route and wavelength for a given traffic demand. In EON, it is the *Routing and Spectrum Assignment* (RSA) problem, and the objective is to find a path and give it a contiguous amount of spectrum slots [2]. This problem has evolved into the *Routing, Modulation Level, and Spectrum Allocation* (RMLSA) problem [8], which includes the attribution of the modulation format to be used. These are NP-Hard problems [8,9] to which several algorithmic solutions for elastic networks have been successfully applied [2].

Similar to WDM technology, the EON networks also allow flow aggregation onto one optical channel through (electrical) traffic grooming [10]. This technique results in higher spectral efficiency since it enables low capacity demands to be grouped and, at the same time, minimizes guard band usage by electrically aggregating traffic [11].

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To further improve flexibility, EON technology provides support for optical grooming [2], which enables transport from a single source to different destinations without having to establish more than one optical channel, using only one transponder at the source [12]. This dispenses guard bands between optical paths with identical routes, resulting in better spectral efficiency. Additionally, traffic grooming and distribution can be done directly in the optical layer [13], which significantly increases spectral efficiency and reduces the network operational costs.

Several works approach traffic and optical grooming concepts for handling the RSA problem, but these have not yet been fully investigated in the RMLSA context, especially in a scenario with dynamic traffic, in which it also important to explore multi-hopping routing in a virtual topology [12].

Considering the current state-of-the-art and unanswered questions related to this problem, this works proposes a solution for RMLSA in dynamic traffic scenario by using spectral modulation control and traffic and optical grooming. The idea behind joining these techniques is to better exploit the optical network resources to provide greater bandwidth by obtaining greater optical grooming using higher modulation levels through multiple hops in the virtual topology. Simulation results show reduced blocking, with gains up to 81%, with no impact on the use of the network resources.

The rest of the paper is organized as follows. Section 2 introduces elastic optical networks architectures and their elements. Section 3 presents the algorithms, techniques, and the state-of-the-art in EON literature. Section 4 shows the proposed approach for solving the RMLSA problem. Section 5 presents numerical results for applying the proposal in standard tests. Finally, concluding remarks are given in Section 6.

2. Elastic optical networks

EONs based on OFDM are characterized for dividing spectral resources into frequency *slots* as subcarriers, allowing multiple modulation formats and different data rates and spectra sizes. An EON's goal is to allocate a demand to an optical path with bandwidth of adequate size, so the optical path can be expanded or contracted as needed, according to traffic fluctuations or new connection demands [14].

Fig. 1 illustrates the differences between optical paths with fixed and flexible grids. In a fixed grid, a single frequency bandwidth of the spectrum is used, regardless of the client's demand; in a flexible grid, the bandwidth adapts to the demand. The architecture of an EON based on OFDM is composed of *bandwidth-variable transponders* (BVTs) and *bandwidth-variable Wavelength Cross-Connects* (BV-WXC), which enable lightpaths in flexible grids to be established.

Several OFDM subcarriers can be joined into a superchannel, transporting data without any guard bands. So the BVTs create the lightpaths with flexible bandwidth, allowing the resources to be adjusted to the current demand [7]. Since an elastic lightpath is allocated as required, it can transmit multiple bit rates, as illustrated in Fig. 1 where the use of a fixed grid's fiber's spectral resources are adapted to a flexible grid. The figure also presents gain with this spectrum variation.

The BV-WXCs are responsible for establishing an end-to-end path with enough bandwidth to accommodate the spectral resources defined by the BVTs. When the BVTs increase traffic, each BV-WXC in the route must expand its switching window, allowing a variable data rate in each lightpath [7]. This OFDM based EON architecture is illustrated in Fig. 2, where the BVTs are located in the network's edge and the BV-WXCs in its core [14].

The modulation format used in each subcarrier of EONs also allows flexible adjustment of bandwidth. Since every lightpath is composed of an arbitrary number of OFDM subcarriers, each can be individually modulated (with a different BVT) for a transmission [15]. For example, single bit per symbol *binary phase shift keying* (BPSK), QPSK (2 bits per symbol), 8QAM (3 bits per symbol) or 16QAM (4 bits per symbol). The number of subcarriers and the modulation format are adjusted to the amount of traffic and optical reach requested [7]. The choice of modulation level should consider the *quality-of-transmission* (QoT) and, consequently, the *optical signal-to-noise ratio* (OSNR) [7,8].

Even though physical impairments, such as crosstalk, affect OSNR and thus, the QoT [16,17], in EON literature the transmission distance of the lightpath is claimed to be the most relevant factor in QoT [18–20]. Therefore, given the size of the path, the modulation level that provides the best spectrum efficiency without hindering the QoT can be found. This allows shorter paths to use higher modulation levels, as illustrated in Fig. 3.

An important issue is the choice of the spectral and capacity characteristics of the subcarriers. As per the International Telecommunication Union's Recommendation G.694.1, conventional fixed grid networks channel spacings of 50 GHz on a fiber [21], but EONs have more flexibility, using a spectrum granularity of 12,5 GHz per subcarrier [2]. The passband is, therefore, closely related to the size of the spectrum allocated by each OFDM subcarrier and its modulation format. This is represented by Eq. (1),

$$B = \frac{C}{log_2 M} \tag{1}$$

where B is the subcarrier's spectrum capacity in GHz, C is the data rate in Gbps, and M is the modulation level being used, *Quadrature Amplitude Modulation* (QAM) or *Phase-Shift Keying* (PSK) [7]. In other words, M is the number of phases used for coding a number of bits per symbol, so the higher the modulation level, the greater the subcarrier's passband and the shorter its reach (according to the QoT factor).

This kind of lightpath with flexible spectrum bandwidth cannot be found by traditional RWA algorithms, commonly used in conventional optical networks [7,8], so new mechanisms for routing and spectrum allocation are needed. In usual RSA algorithms, subcarriers in the same optical path must be routed contiguously using the same spectrum band throughout the route, and distinct lightpaths must be spaced by a guard band to attend OFDM restrictions.

These RSA limitations are illustrated in Fig. 4, which considers an EON with four nodes and the arrival of a request for connection with bit rate equivalent to three OFDM subcarriers (shown as slots). Assuming this request source is node a and its destination is node d, the connection cannot be established through the shortest path (via nodes a–c–d) because links 1 and 2 do not have three contiguous slots which are continuous along the links. These requirements, however, are met by a connection through the a–c–b–d route using slots 5, 6, and 7 through links 1, 3, and 4.

The complexity of the RSA problem can be deduced by reduction of the RWA problem. If the number of OFDM subcarriers in the channel is equal to the number of wavelengths in the fiber, the creation of a new lightpath in the RWA algorithm is equivalent to that in the RSA algorithm, i.e. for conventional optical networks, the RSA problem is a reduction of the RWA problem [8]. Since this reduction is done in polynomial time, the RWA problem has a solution if and only if the RSA is solvable; thus, the RSA problem is also of the NP-Hard class [9].

One of the issues of RSA algorithms is satisfying traffic demands with low bit rates. A connection requested bandwidth can be much lower than the capacity of a lightpath, and two lightpaths that go through one or more common fiber links must be separated by at least one guard band to avoid severe interference [11]. Though BVTs can dynamically adjust the offered bandwidth in an EON, if