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Cost efficient traffic grooming and regenerator placement in impairment-aware optical WDM networks[☆]

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ABSTRACT

In this paper, we address the problem of traffic grooming and regenerator placement in a WDM optical network in which lightpaths are hop-constrained by physical impairments. The efficient placement of regenerators and electronic grooming equipment at ROADM nodes for a given network topology is required such that all traffic demands can be supported with minimum cost. We present a detailed ROADM node architecture together with an associated cost model. We model the problem by Integer Linear Programming (ILPs) and propose an auxiliary-graph-based heuristic for jointly placing regenerators and electronic grooming equipment in the network. To evaluate the performance of the proposed heuristic, we also derive a lower bound on the network cost. The numerical results show that combining the grooming problem with the placement of regenerators reduces the network cost significantly compared to the cases in which traffic grooming and regenerator placement are handled separately. The performance of the proposed polynomial-time heuristic is very close to the lower bound and approaches the bound as the network load increases.

1. Introduction

In optical networks, traffic grooming can be used to aggregate low-rate traffic onto high-rate lightpaths in order to utilize the wavelength resources efficiently. The optical signal in such lightpaths propagates through a number of fiber spans and ROADM nodes that can cause the degradation of the optical signal quality by introducing linear and nonlinear impairments [1], thus limiting the optical reachability of the lightpaths. Impairments may be addressed through the placement of signal regenerators, which convert the optical signals back to electronics and generate new optical signals without impairments.

Traditionally, the traffic grooming problem and the problem of regenerator placement for the impairment-aware network design have been solved sequentially. In traffic grooming, the problem is to find a logical topology consisting of lightpaths and to route the traffic over the logical topology while minimizing the use of network resources. The traffic grooming problem has been extensively studied in the literature, and a good overview of traffic grooming can be found in [2]. In [3], an auxiliary-graph-based heuristic is proposed for the traffic grooming network design problem in which various network design objects, such as minimization of the number of transponders, the number of wavelengths, cost of a network, and maximization of the network

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throughput, can be achieved by appropriately assigning costs to the auxiliary links; however, the authors neglect the effects of physical impairments on the optical signal.

In regenerator placement, the problem is to place regenerators throughout the network in order to ensure that the optical signal of a lightpath does not degrade beyond a certain level due to impairments. The problem has been studied in a number of works [4–7].

A few recent works have addressed the problem of impairment-aware traffic grooming in WDM networks [8–12]. These works consider the use of electronic grooming at a node to regenerate a signal in order to overcome impairments. In most cases, the impairment constraint is defined as the maximum number of physical hops that an optical signal can travel before requiring conversion back to electronics.

In [8], the authors propose an ILP for the design of traffic-grooming-capable optical Virtual Private Networks (oVPN). The objective of the network design problem is to minimize either wavelength resources or physical resources such that the constraint on reachability of a lightpath is satisfied. In [9], the authors propose a span-constrained traffic-grooming-capable impairment-aware network design problem with the objective of minimizing the number of wavelengths and transponders in the network. The authors propose a mathematical model and heuristics for the same problem. In [10], ILPs for transparent, semi-transparent, and opaque network design problems are proposed with the objective of minimizing the network cost. In their study, the authors have also considered network resilience. In [11], the authors propose a mathematical model for the semi-transparent impairment-aware network design problem. In their approach, the authors consider the routing and grooming problems as two independent problems in order to reduce complexity. In [12], the authors propose algorithms for the virtual topology design and traffic grooming problem under impairment constraints with the objective of maximizing the network throughput, where the impaired signal is regenerated through electronic switching at the IP layer.

In this paper, we investigate the combined traffic grooming and regenerator placement problem with the goal of minimizing cost for the first time. We provide a detailed ROADM node architecture, formulate the combined traffic grooming and regenerator placement problem [13], propose an auxiliary-graph-based heuristic [14], and evaluate the performance of the heuristic through simulation.

The detailed ROADM node architecture that we consider in this paper is shown in Section 2. An illustrative example showing the benefits of the combined regenerator placement and traffic grooming approach is given in Section 3. The network design problem is defined in Section 4. The problem is formulated as an Integer Linear Program in Section 5, and a heuristic is proposed in Section 6. Simulation results are presented in Section 7, and the paper is concluded in Section 8.

2. Node architecture

In this section we briefly describe the ROADM node architecture as shown in Fig. 1. Each ROADM node is equipped with an all-optical wavelength switch fabric where any wavelength on any ingress/egress port can be dropped/added (i.e., full flexibility). Transponder Cards (TC), Line Cards (LC), Grooming Cards (GC), Client Cards (CC), and Regenerator Cards (RC) are the five types of cards available at a ROADM node to provide various functionalities. A ROADM node can support multiple cards of each type. A TC has multiple client interfaces (ports) on the client side which are connected to client network elements, and a DWDM wavelength interface on the line side which is connected to the wavelength switch fabric. Therefore, it can take multiple lower rate client signals and multiplex them onto a single DWDM wavelength channel. A CC also has multiple client interfaces (ports) in the same way as a TC, however, the line side of a CC is a backplane interface designed to be plugged into ROADM nodes' electrical backplane. It takes multiple lower rate client signals and sends them to a GC through the backplane interface for grooming. A GC is only equipped with a backplane interface. It has a built-in electrical switching fabric. It is electrically connected with multiple CCs and LCs through the backplane. It performs grooming for the traffic received from CCs and LCs. After grooming, it forwards local drop traffic to the corresponding CC, and forwards outgoing traffic to the corresponding LC. A LC has a backplane interface on one side, and a DWDM wavelength interface on the other side that is connected to the wavelength switch fabric. It receives the groomed traffic from the GC and multiplexes them onto a single DWDM wavelength channel. A RC has a DWDM wavelength Interface on each side. It receives a DWDM wavelength channel signal from the wavelength switch fabric, performs O-E-O regeneration, and then sends the signal back to the wavelength switch fabric through the same or a different DWDM wavelength channel. Note in our architecture, both the wavelength switch fabric and all five types of cards support bidirectional traffic. Therefore, the description above also applies to the reverse direction. For example, the same TC can also receive traffic from the DWDM wavelength channel and forward it to multiple client ports, etc. Fig. 1 shows a two degree ROADM in which four wavelengths are multiplexed on a single fiber. As shown in the figure, a wavelength optically bypasses the node if it is not required to be regenerated or switched (groomed) at the node.

Traffic can be locally added or dropped using either a transponder card or a combination of a client card, a grooming card, and a line card. Traffic can be regenerated by either using a regenerator card or a combination of two line cards and a grooming card. Table 1 shows the cost of various network elements, where the capacity of the grooming card is assumed to be 240 Gbps and the capacity of other network elements is assumed to be the same as the capacity of the line rate. The capacity of a grooming card can also be defined in terms of number of interfaces for line cards and client cards. For example, a grooming card can support total 24, 6 and 2 interfaces for 10 Gbps, 40 Gbps and 100 Gbps line rate networks respectively. We classify lightpaths based on equipment used to establish them. In establishing a lightpath, if transponder cards are used at both ends then the lightpath is called a transponder card