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Survivable Impairment-Aware Traffic Grooming

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***Abstract*—Traffic grooming allows efficient utilization of network capacity by aggregating several independent traffic streams into a wavelength. In addition, survivability and impairment-awareness (i.e., taking into account the effect of physical impairments) are two important issues that have gained a lot of research interest in the area of optical networks. In this paper, we consider the survivable impairment-aware traffic grooming problem in Wavelength Division Multiplexing (WDM) optical networks, where the objective is to minimize the cost of traffic grooming and regeneration. Our approach to solve this problem is shown, using data obtained from a realistic network, to significantly outperform a sequential approach, which is usually used by practitioners.**

I. INTRODUCTION

In optical networks employing Wavelength Division Multiplexing (WDM), the capacity of a fiber is divided into several non-overlapping wavelength channels that can transport data independently. The wavelength channels make up *lightpaths*, which are used to establish optical connections that may span several fiber links. With current commercial technology, each lightpath can be independently operated at a data rate ranging up to 100 Gb/s [3]. Since traffic between a pair of nodes may not fill up the available bandwidth of a lightpath, several independent traffic streams can be aggregated to share the capacity of a lightpath. This is known as *traffic grooming*, and allows efficient utilization of the network capacity.

Since lightpaths may carry a large amount of data, survivability, which is the ability to reconfigure and retransmit data after failure, is vital. It is usually achieved by computing a link/node-disjoint backup lightpath that will take over after failure of the primary lightpath [4]. In addition, physical impairments caused by noise and signal distortions affect the quality of an optical signal. The effect of physical impairments becomes more significant with an increase in distance and bit rates. In order to minimize the bit error rate (BER), an optical signal may need to be regenerated at intermediate nodes. The *impairment threshold* of a lightpath is the maximum amount of impairment tolerated before the quality of the signal reaches an unacceptable level. A routing of lightpaths that takes into account physical impairments is known as *impairment-aware routing* [7].

In this paper, we study *survivable impairment-aware traffic grooming* in WDM networks. Nodes are assumed to be equipped with an optical add/drop multiplexer (OADM) to add/drop wavelengths. There can be two types of OADMs in the network: fixed OADMs and Reconfigurable OADMs (ROADMs) [1]. In fixed OADMs, wavelengths that are added/dropped at a given node are fixed and reconfiguration requires human intervention. On the other hand, in ROADMs, one or more wavelengths can be added/dropped automatically with minimal user intervention. The key enabling component in ROADM configuration is the Wavelength Selective Switch (WSS), which allows for individual wavelengths on a common input fiber to be selectively switched to any of multiple output fibers [6]. Even though ROADMs are flexible and efficient, the initial cost of ROADM components is higher than that of OADM components. Thus, not all nodes may be equipped with ROADMs. Amplifiers at nodes, which are required to compensate for transmission fiber loss and the loss of passive optical components, add noise and contribute to signal distortions. The impairment value of a node depends on the type of OADM used at the node.

Most previous traffic grooming studies focused on ring topologies, and did not consider survivability and impairment-aware routing. Sankaranarayanan *et al.* [11] considered survivable traffic grooming in unidirectional WDM rings under uniform traffic with a mix of protected and unprotected requests. Ou *et al.* [8] gave heuristic algorithms for the survivable grooming in mesh networks, while Yao and Ramamurthy [14] considered the same problem under shared risk link group (SRLG) constraints, and provided heuristic algorithms. Unlike [8], [11] and [14], *we consider both survivability and impairment-aware routing*, and give a heuristic approach for solving the problem. Patel *et al.* [9] considered impairment-aware traffic grooming, where regeneration is performed through regenerator cards. In this approach, there is a distinction between add/drop nodes and regeneration nodes, since regenerator cards are not capable of adding/dropping traffic. However, regeneration can also be achieved using back-to-back transceivers [12], in which case, regeneration nodes can also be used as add/drop nodes, and vice versa. In this paper, we follow the second approach since it allows the use of the same type of devices for both add/drop and regeneration, and the regenerators may also be used as wavelength converters [12]. In addition, unlike most previous studies, we not only consider impairments associated with links, but also nodal impairments. We also take into account the types of nodes, which determines the impairment value associated with it.

In Section II, we give a formal definition of the survivable impairment-aware traffic grooming problem. We provide a heuristic approach for solving the problem in Section III and study its performance in Section IV. We finally conclude in Section V.

II. Problem Definition

For a given wavelength, a *regenerator node* is a node where the wavelength is regenerated, whereas an *add/drop node* is a node where traffic is added/dropped from the wavelength. Since a wavelength is regenerated when traffic is added/dropped from it, an add/drop node is also a regenerator node. Thus, a wavelength can be regenerated under two scenarios: (1) when regeneration is required so that the impairment threshold is not exceeded, and (2) when traffic carried by the wavelength is added/dropped. We refer to the former as simply *regeneration*, while to the latter as *add/drop regeneration*. A *regeneration segment* is a segment of a lightpath between two consecutive add/drop or regenerator nodes, i.e., there is no other add/drop or regenerator node in this segment. Associated with each link and node is an additive impairment value. The impairment value of a given path is the sum of the impairment values of its links and nodes. A path is said to be *feasible*, if the impairment value of any of its regeneration segments does not exceed the impairment threshold.

Splitting traffic of a single request might cause reordering problems at the receiving end as some higher-layer protocols may not be able to deal with it. Since the regenerator nodes as well as links that the signals go through may be different, it may also lead to different signal quality. Therefore, we assume that the traffic of a given request is not split unless its demand exceeds the full capacity of a wavelength. In addition, in order to facilitate control, the primary and backup lightpaths of a given request are assumed to be on the same wavelength. The network cost mainly comprises of the electronic and opto-electronic cost associated with grooming and regeneration (i.e., cost of transceivers), and the number of wavelengths. In practice, the cost of transceivers dominates that of the number of wavelengths [5]. Hence, we minimize the total number of transceivers under the assumption that there are enough wavelengths to accommodate all the requests.

Survivable impairment-aware traffic grooming problem Given is an optical network $G(\mathcal{N},\mathcal{L})$, where $\mathcal{N}$ is the set of nodes, $\mathcal{L}$ is the set of links. Associated with each link $l \in \mathcal{L}$ is an impairment value $r(l)$, and with each node $u \in \mathcal{N}$ is an impairment value $r(u)$. The impairment threshold is Δ and a wavelength has a capacity C. Also given are a set $\mathcal{F}$ of F requests. Each request $f \in \mathcal{F}$ is represented by the tuple (s_f, d_f, δ_f), where s_f and d_f are the source and destination nodes, respectively, and δ_f is the amount of demand of request f. The problem is to minimize the total number of transceivers needed in the network so that (1) each request is assigned a pair of disjoint lightpaths; (2) the capacity of each wavelength in a link is not exceeded; and (3) for any lightpath, the impairment value of any of its regeneration segments should not exceed the impairment threshold.

III. Heuristic Approach

Since the traffic grooming problem is NP-hard even in such simple topologies as ring topologies [2], it follows that the survivable impairment-aware traffic grooming problem, which contains the traffic grooming problem, is NP-hard as well. Thus, we propose a heuristic approach for solving it. The complexity of the problem can be reduced by limiting the number of paths that are considered for each request. However, since it is a design problem, time is of less importance as the algorithm needs to run only once. We provide a two-phase heuristic approach that uses a precomputed set of paths.

A. *Phase 1: Precomputed Paths*

In the first phase, K pairs of (shortest) disjoint paths are pre-computed for each request (using an algorithm given in [10]), and the solution will be selected from these pairs of paths using an Integer Linear Programming (ILP) formulation, which can be solved by ILP solvers such as CPLEX. In this phase, the objective is to minimize the number of transceivers required for adding/dropping (grooming traffic on) the wavelengths (i.e., regeneration is not considered). It is based on the assumption that aggregating requests that originate or end at a given node in the same wavelength minimizes the total number of transceivers needed. This approach has also an additional advantage in that the total number of used wavelengths is minimized, since it tends to aggregate (groom) traffic in a smaller number of wavelengths. Let W be the number of wavelengths, and all the requests can be accommodated. We assume that each request has a demand that is less than the capacity of a wavelength, otherwise a full wavelength is independently assigned for the request and the remaining amount is considered as its demand.

Indices, constants, variables:

- $P_{f,k}$ A set of K precomputed pairs of disjoint paths for request f.
- $\alpha_{f,k,w}$ is 1 if the k^{th} disjoint path pair is selected and uses wavelength w; 0 otherwise.
- $a_{f,k,l}$ is 1 if either the primary or the backup of the k^{th} disjoint path pair uses link l; 0 otherwise.

Objective:

Minimize the total number of add/drop nodes:

$$\text{Minimize:} \qquad \sum_u \sum_w x_{u,w}. \tag{1}$$

Constraints:

For each request, only one pair of disjoint paths is selected:

$$\sum_k \sum_w \alpha_{f,k,w} = 1 \quad \text{for } f = 1, \ldots, F. \tag{2}$$

The capacity of each wavelength on each link should not be exceeded:

$$\sum_f \sum_k \delta_f \cdot a_{f,k,l} \cdot \alpha_{f,k,w} \leq C \quad \forall l \in \mathcal{L}; w. \tag{3}$$

A given node is an add/drop node for a given wavelength if traffic is added/dropped (groomed) on this wavelength at the node:

$$\sum_{f \in \{f | s_f = u \text{ or } d_f = u\}} \sum_{k} \alpha_{f,k,w} \leq F \cdot x_{u,w} \ \forall u \in \mathcal{N}; w. \quad (4)$$

B. *Phase 2: Rerouting Lightpaths*

In phase 1, the objective is to reduce the number of transceivers needed for adding/dropping (grooming) the given set of requests at the source and destination nodes. However, some of the lightpaths obtained in phase 1 may not be feasible, thus require the placement of extra transceivers. Algorithm $Reroute$ (see Algorithm 1) minimizes the additional number of regenerations by rerouting requests whose lightpaths are infeasible. A request needs extra regeneration if its primary or backup lightpath has an infeasible segment (i.e., its impairment value exceeds Δ) in the current setup. Let $\mathcal{P}$ be the set of requests that need extra regeneration, and $\mathcal{N}_w$ be the set of regenerator nodes for wavelength w in the given network.

Algorithm 1 $Reroute$

1) While $\mathcal{P}$ is not empty, pick a request $f \in \mathcal{P}$. Let its assigned disjoint pair of lightpaths be $\{P_{f,1}, P_{f,2}\}$.
2) For each wavelength w for which s_f and d_f are add/drop nodes, let $B'_{l,w}$ be the residual capacity of wavelength w on link l. Let $G_w = (\mathcal{N}, \mathcal{L}_w)$, where $\mathcal{L}_w = \{l \in \mathcal{L} | B'_{l,w} \geq \delta_f \text{ or } l \in P_{f,1} \text{ or } l \in P_{f,2}\}$. Let $\mathcal{N}'_w$ be the set of nodes on which w is add/dropped or regenerated.
   a) For any $u, v \in \mathcal{N}'_w$, let $r_w(P_{u-v})$ be the length of the shortest path (in terms of impairment values) between nodes u and v in G_w.
   b) Create graph $G'_w = (\mathcal{N}'_w, \mathcal{L}'_w)$, where $\mathcal{L}'_w = \{(u,v) | u, v \in \mathcal{N}'_w \text{ and } r_w(P_{u-v}) \leq \Delta\}$. Assign a cost of 1 to each link in G'_w.
   c) Find two disjoint paths P'_1 and P'_2 in graph G'_w.
   d) For P'_1 and P'_2, find their corresponding paths P_1 and P_2 in G_w.
   e) If P_1 and P_2 are simple and disjoint lightpaths:
      i) Assign them to request f.
      ii) Remove f from $\mathcal{P}$ and update the residual capacities of all links that belong to the old and new lightpaths of f.
      iii) Go to Step 1.
   f) Else, go to Step 2 for the next wavelength.
3) If all wavelengths are exhausted and no feasible lightpaths are found,
   a) Place the minimum number of regenerators needed to make $P_{f,1}, P_{f,2}$ feasible.
   b) Remove f from $\mathcal{P}$.
   c) Remove all requests in $\mathcal{P}$ whose lightpaths are now feasible.
   d) Go to Step 1.

Algorithm $Reroute$ works as follows. In Step 1, it (randomly) chooses a request f from the requests in $\mathcal{P}$. In the next steps, it tries to find a feasible pair of disjoint lightpaths using only the existing regenerator nodes. This is done by constructing a new graph on each wavelength that s_f and d_f are add/drop nodes. In Step 2, graph G_w represents a graph on wavelength w, and is made up of links with enough residual capacity on wavelength w to support request f or belong to the primary or backup lightpaths of request f. In Step $2b$, a new graph G'_w is obtained from graph G_w as follows. Its nodes are the add/drop or regenerator nodes of wavelength w (including the source and destination nodes of request f), and a link exists between two nodes if they are directly reachable (i.e., without regeneration). Then in Step $2c$, two disjoint paths are computed using Suurballe's algorithm [13] in graph G'_w. These paths are then translated to their equivalent paths in G_w by replacing the links in G'_w with the corresponding subpaths in G_w. If the paths are simple and feasible, they are accepted as a solution. Otherwise, we add extra regenerator nodes to make the original lightpaths of f feasible. Adding extra regenerator nodes, however, may render some of the requests in $\mathcal{P}$ feasible. These requests are removed from $\mathcal{P}$ before the next iteration.

IV. Simulation Results

In this section, we compare our heuristic approach with a sequential approach. In the sequential approach, each request is assigned the shortest link-disjoint pair of paths between its source and destination nodes. Then, the lightpaths are sequentially allocated wavelengths in such a way that a lightpath is assigned to the lowest-indexed wavelength that has sufficient capacity for its traffic. We first provide a description of the physical impairment considered in these simulations.

A. *Figure of Merit (FoM)*

Amplifiers are placed at several points along a fiber-link to overcome fiber losses. The segment of a link between two consecutive amplifiers is known as a *fiber span*. However, each amplifier adds noise, which is referred to as *Amplifier Spontaneous Emission (ASE)*, along the fiber. ASE degrades the optical signal to noise ratio (OSNR) and is an important physical impairment, especially when the power levels are low enough to ignore non-linearities [12]. In most WDM systems, the net gain of a link is set to unity so that the total amplification cancels out the total loss. Under such scenario, the noise figure of a link, which is the ratio of the OSNR at the start of a link to that at the end of a link, is the sum of the noise figures of its spans. The noise figure of a system is usually given in *dB*. Since the typical noise figure of amplifiers in commercial systems is fairly constant in the range of operation and similar among the different system vendors, we introduce the following formula to quantify the quality of an optical fiber link, which we refer to as the *Figure of Merit (FoM)*.

$$FoM = \sum_{j=1}^{H} 10^{\left(\frac{L_j}{10}\right)}, \quad (5)$$

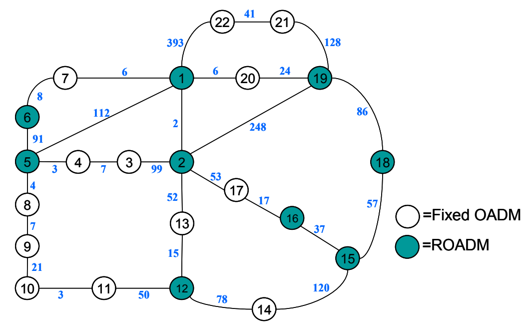

Fig. 1. The SURFnet6 network. Shown are the different types of nodes and the FoM values of the links in the network (for a fiber loss of 25 dB/km).

TABLE I
RESULTS COMPARING OUR APPROACH AND A SEQUENTIAL APPROACH.

Total Amount of Traffic (Gb/s)					
	TM1	**TM2**	**TM3**	**TM4**	**TM5**
	106	130	144	162	180
Number of Transceivers					
Our Approach	158	170	178	196	206
A Sequential Approach	232	284	300	294	318
Number of Wavelengths					
Our Approach	5	7	8	9	12
A Sequential Approach	8	11	12	13	15

where L_j is the fiber loss of span j in *dB* (it is the same as the gain of amplifier j when the net gain of the amplified link is unity), and H is the number of spans.

B. Results and Discussion

We have performed simulations on the SURFnet6 network, which connects research and educational institutes in the Netherlands using lightpaths, shown in Figure 1. There are two types of nodes in the network: Fixed OADM and ROADM nodes. The FoM value of a fixed OADM node is 65, while that of a ROADM node is 37. The FoM values of the links are shown in the figure. We have considered five traffic matrices (TMs) that represent synchronous digital hierarchy (SDH) data over the WDM network. One of the traffic matrices (TM1) represents a realistic traffic matrix of the SURFnet6 network, while the others represent predicted traffic scenarios of this traffic matrix. The impairment (FoM) threshold for the 10Gb/s WDM interfaces that we considered is equal to 600.

Table I compares our approach (for $K = 3$ pairs of disjoint paths per request) with the sequential approach in terms of the total number of transceivers and wavelengths required in the network for five different traffic matrices. The results show that both the number of transceivers and wavelengths required by our heuristic approach are significantly less than those of the sequential approach. Additionally, in our approach, all the regenerations for the given traffic matrices are handled using add/drop regenerations, i.e., no extra transceivers are needed for only regeneration. This is achieved through rerouting of the lightpaths in the second phase of our approach. We have also developed an exact ILP for the problem, but it was too complex to return solutions in a reasonable time frame (within a few weeks). We have, therefore, compared our approach only to the sequential approach, which is often used by practitioners.

V. CONCLUSIONS

In this paper, we have studied the survivable impairment-aware traffic grooming problem, where given a network and a set of requests, the problem is to assign link-disjoint primary and backup lightpaths for each request such that the total number of transceivers required (for adding/dropping traffic as well as regeneration) in the network is minimized. We have provided a heuristic approach for solving this NP-hard problem. We have performed simulations on a realistic network comparing our approach with a greedy sequential approach. The simulation results have shown that the number of transceivers and wavelengths required by our heuristic approach are significantly less than those of the sequential approach. Minimizing the number of transceivers will not only lead to a significant reduction in the capital expenditure (CAPEX), but also results in a reduced operational expenditure (OPEX) because of the significant decrease in power consumption and heat dissipation. In addition, the reduced number of wavelengths decreases the operating cost (OPEX) associated with each wavelength.

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