Traffic Grooming and Regenerator Placement in Impairment-Aware Optical WDM Networks

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***Abstract*—Traffic grooming aggregates low rate traffic on high rate lightpaths to utilize the wavelength resources efficiently: However all-optical lightpaths may be constrained by the physical impairments. To mitigate the effects of impairments, the optical signal in a lightpath needs to be regenerated. In this paper, we address the regenerator and electronic grooming placement problem from CAPEX point of view in designing of an impairment-aware network for the proposed detailed ROADM node architecture. We propose an auxiliary graph based heuristic for the placement of regenerators and electronic grooming in an impairment-aware network. The numerical results show that the placement of regenerator and electronic grooming together minimizes the network cost significantly compared to the placement of only regenerators or only electronic grooming.**

***Index Terms*—Traffic Grooming, Regenerator, Impairment-aware network, Optical WDM Network, ROADM, Aggregation**

I. Introduction

In optical networks, traffic grooming can be used to groom and aggregate low-rate traffic onto a high-rate lightpaths in order to utilize the wavelength resources efficiently. The optical signal in such lightpaths propagate 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 and thus limit optical reachability of the lightpaths. Impairments may be addressed through the placement of signal regenerators in the network. Regenerators convert the optical signal back to electronics and generate a new optical signal without impairments.

Traditionally, the traffic grooming problem and the problem of regenerator placement for the impairment-aware network design have been solved independently of one another. 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 [1]. In [2], an auxiliary graph based heuristic is proposed for the traffic grooming-capable network designing problem in which by choosing appropriate cost of the auxiliary links, various network design objectives can be achieve. In the network designing problem, the authors have neglected the effects of physical impairment on the optical signal. In the 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 [3], [4], and has been proved to be NP-complete.

A few recent work have addressed the problem of impairment-aware traffic grooming in WDM networks [5] - [8]. 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 [5], the authors have proposed mathematical model for designing of traffic grooming capable optical Virtual Private Networks (oVPN). The objective of the network designing problem is to minimize either wavelength resources or physical resources such that the constraint on reachability of a lightpath is satisfied. In [6], the authors have proposed span constraint traffic grooming capable impairment-aware network design problem with the objective of minimizing number of wavelengths and transponders in the network. The authors have proposed mathematical model and heuristics for the same problem. In [7], a mathematical models for transparent, semi-transparent, and opaque network designing problem have been proposed with the objective of minimizing the network designing cost. In their study, the authors have also considered the network with resilience. In [8], the authors have proposed mathematical model with a novel 'Path over Path' model for the semi-transparent impairment-aware network design. In their approach, authors have considered routing and grooming problem as two independent problems in order to reduce the complexity.

In previous works on impairment-aware traffic grooming, researchers have either considered only the placement of electronic grooming, or have treated the placement of regenerators separately from the grooming problem. While electronic grooming provides the benefit of regenerating a signal in addition to enabling the switching of groomed traffic, there may be situations in which placing regenerators alone is more cost efficient. For example, consider a 6-node network as shown in Fig 1(a). The capacity of each wavelength is assumed to be 10 Gbps. Assume that an optical signal can traverse

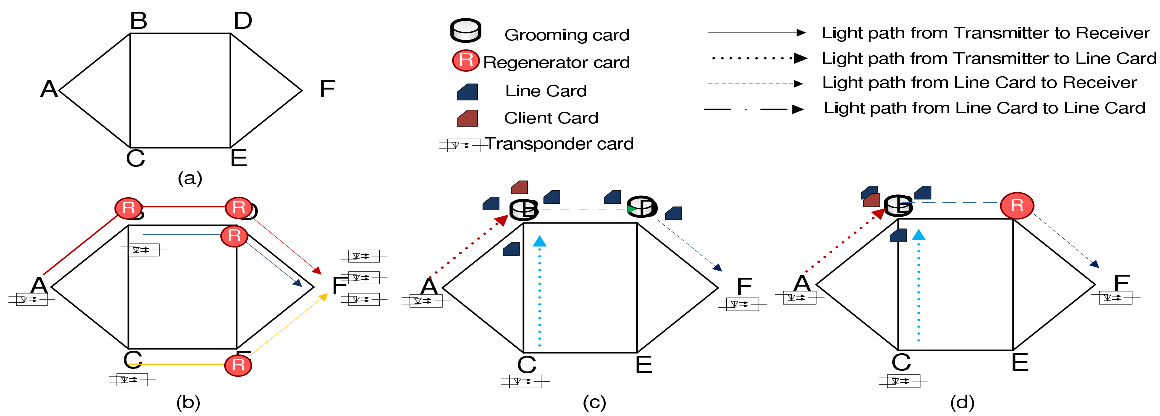

Fig. 1. Illustrative Example.

at most one hop without requiring regeneration. Consider the cost and capacity parameters for the equipment as shown in Table 1. Consider the following traffic demands: 1) 3 Gbps from A to F, 2) 5 Gpbs from B to F, and 3) 2 Gbps from C to F. If only regenerators are employed without electronic grooming to regenerate the traffic, then the optimal network design for the given traffic demands is shown in Fig. 1(b). This regenerator-only approach requires eight regenerator cards and six transponder cards to satisfy the traffic demands. The total cost of the network is $4(2) + 6(1) = 14$. On the other hand, if only traffic grooming is used to regenerate the signal at the intermediate nodes, then the optimal network design is as shown in Fig. 1(c). The traffic-grooming-only approach requires three tranponder cards, two grooming cards, five line cards, and one client card. The total network cost is $3(1) + 2(1.2) + 5(0.6) + 1(0.6) = 9$. If a combination of regenerators and traffic grooming is used to satisfy the traffic demands and to meet the impairment constraints, then the optimal network design is as shown in Fig. 1(d). The combined approach requires one grooming card, three transponder cards, three line cards, one client card, and one regenerator card for a total cost of $1(1.2) + 3(1) + 3(0.6) + 1(0.6) + 1(2) = 8.6$. The example shows that a combined regenerator and grooming approach for designing a network can result in lower cost than a regenerator-only approach and a grooming-only approach. In this paper, we consider the problem of traffic grooming jointly with the problem of regenerator placement, and we develop a heuristic that places grooming equipment and regenerators at nodes while attempting to minimize the network cost.

The detailed ROADM node architecture, considered in the network design is shown in Section II. The network design problem is defined in Section III and a heuristic is proposed in Section IV. Simulation results are analyzed in Section V and finally the paper is concluded in Section VI.

II. Node Architecture

In this section we briefly describe the ROADM node architecture as shown in Figure 2. 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 for 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 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 bi-directional 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. Figure 2 shows two degree ROADM in which four wavelengths are multiplexed on a single fiber. As shown in figure wavelength is optically bypassed if it is not required to be regenerated or switched (groomed) at the node. Traffic can be locally added or dropped using either 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.

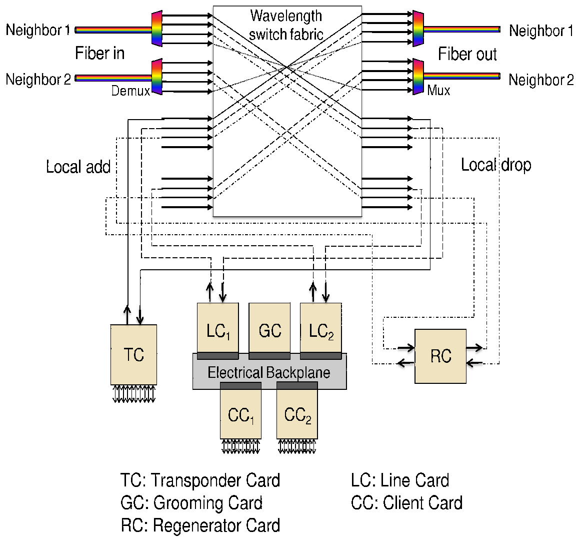

Fig. 2. Architecture of ROADM Node

Table 1. Cost and Reachability Assumptions for Various Cards

Rate (Gb)	Cost Ratio				
	Transponder	Regen	Grooming	Client	Line
10	1	2	1.2	0.6	0.6
40	2.5	5	3	1.5	1.5
100	5	10	6	3	3

Table 1 shows the cost and reachability assumptions of various network elements in which the capacity of the grooming card is assumed to be 240 Gbps and the capacity of the other network elements is assumed to be the same as the capacity of the line rate.

III. Problem Statement

We now define the traffic grooming and regenerator placement problem. For a given physical topology $G(\mathbf{V}, \mathbf{E})$, where $\mathbf{V}$ is a set of nodes, $\mathbf{E}$ is a set of fiber links, and a set of traffic demands $\mathbf{\Lambda}$ in which a request can be defined as $T(s, d, t, r)$, where s is a source, d is a destination, t is the number of client connections, and r is the requested bandwidth per connection, the problem is to place regenerators and electronic grooming equipment at ROADM nodes, such that total network cost, C_{min}, can be minimized subject to the constraint that the signal can propagate at most H hops. The problem can be stated formally as follows:

Given:

- physical topology $G(\mathbf{V}, \mathbf{E})$, where $\mathbf{V}$ is a set of nodes and $\mathbf{E}$ is a set of physical fibers between nodes $i, j \in \mathbf{V}$,
- W wavelength channels on each fiber with capacity R for each wavelength,
- cost of a transponder card C_{TC}, a line card C_{LC}, a regenerator card C_{RC}, and a client card C_{CC} for line rate R,
- cost of a grooming card, C_{GC} for switching granularity R_{GC},
- a set of traffic demands $\mathbf{\Lambda}$, in which a traffic demand is represented as $T(s, d, t, r)$, where s is a source, d is a destination, and t is the number of connections with requested bandwidth r,
- the distance in terms of hops, H, up to which an optical signal can be transmitted without any regeneration.

Find:

- virtual topology $G(\mathbf{N}, \mathbf{L})$, where $\mathbf{N} = \mathbf{V}$, and $\mathbf{L}$ represents a set of lightpaths between node $i \in \mathbf{N}$ and $j \in \mathbf{N}$,
- routing of the traffic demand over the virtual topology,
- routing and wavelength assignment of lightpaths over physical topology,
- placement of the network equipment.

Objective:

- Minimize the total network cost, C_{min}.

In this paper, we assume that all transponders and line interfaces operate at the same rate.

IV. Heuristic

We propose a heuristic which places regenerators and electronic grooming equipment at ROADM nodes such that total network cost is minimized. In the heuristic, we assume shortest path routing. The proposed heuristic is based on an auxiliary graph in which auxiliary links are constructed between pairs of nodes whose shortest path distance in terms of number of hops is smaller than the hop constraint due to impairments. If an auxiliary link exists between a pair of nodes, then those nodes are reachable without any signal regeneration. On the other hand, if two nodes are not directly connected by any auxiliary link, but are connected through some intermediate nodes in the auxiliary graph, then signal must be regenerated at those intermediate nodes either through the placement of grooming equipment or through the placement of regenerators. How to regenerate the signal at intermediate node is addressed by the algorithm, described in subsection IV-B, which determines the placement of regenerators and electronic grooming equipment based on the cost of equipment and resource utilization.

If the traffic demand between a source and destination is requesting an amount of bandwidth that occupies a majority of the wavelength capacity, then the advantage of switching the traffic via grooming at intermediate nodes may be low. On the other hand, if traffic demands require small amounts of bandwidth, then grooming may be more efficient because multiple demands that are groomed together may share common equipment. Based on this observation, the heuristic partitions the set of traffic demands into two sets based on whether the total bandwidth requested by all connections in a given demand is above or below a certain threshold parameter. Traffic demands that exceed the threshold parameter are regenerated using regenerators at intermediate nodes, and demands that fall below the threshold parameter are regenerated using electronic grooming at intermediate nodes. The heuristic solves the grooming and regenerator placement problem for several different threshold parameters and returns the result that yields the minimum network cost. The threshold parameters considered by the heuristic are integer multiples of the switching granularity of the grooming switch.

A. Construction of Auxiliary Graph

The impairment constraint can be addresses by an auxiliary graph, $G^{'}(\mathbf{N}, \mathbf{L})$, where $\mathbf{N}$ is a set of auxiliary nodes and $\mathbf{L}$ is a set of auxiliary links. In auxiliary graph, the set of nodes $\mathbf{N}$ is the same set of nodes $\mathbf{V}$ in the given physical topology $G(\mathbf{V}, \mathbf{E})$, $\mathbf{N} = \mathbf{V}$. The set of edges $\mathbf{L}$ in the auxiliary graph-I can be constructed as follow.

- **Step 1**: Find shortest path between all pair of nodes using BFS algorithm.
- **Step 2**: For all node pairs, **IF** the distance in terms of number of hops between a pair of nodes is smaller than the number of hops up to which signal can propagate without regeneration then establish an auxiliary link between pair of nodes,
  ELSE do nothing.

B. Pseudocode for Algorithm

Below we provide pseudocode for our proposed heuristic. We also define heuristics for the case in which only regenerators are used and the case in which only grooming is used. The latter two heuristics are used for comparison purposes.

Regenerator and Grooming:

INPUT: Graph $G(\mathbf{V}, \mathbf{E})$, traffic matrix Λ, hop distance H, cost of the equipment, capacity of the equipment,

OUTPUT: Virtual topology, Routing of traffic over virtual topology, routing and wavelength assignment of light path over physical topology, number of equipment at each node, and total network cost.

- **Step 1**: Generate the auxiliary graph-I, $G^{'}(\mathbf{N}, \mathbf{L})$ from the given graph $G(\mathbf{V}, \mathbf{E})$.
- **Step 2**: Find the shortest paths between each source- destination pairs in the auxiliary graph and record the paths.
- **Step 3**: Order the set of requests, Λ, in descending order of the total requested bandwidth by all connections in a given traffic demand.
- **Step 4**: Set the threshold, Thr, to be equal to line rate R.
- **Step 5**: Partition the set of traffic demands into two subsets, K_1 and K_2 based on whether the demand is above or below threshold, Thr.
- **Step 6**: For a set K_1, execute sub-routine **Regenerator-only**.
- **Step 7**: For a set K_2, execute sub-routine **Grooming-only**.
- **Step 8**: Record the cost of the network
  C_{Thr} = C_{Regen} + C_{Groom}.
- **Step 9**: Decrease the threshold, Thr, by the granularity rate, R_{GC}, and repeat Steps 5 to 8 until $Thr = 0$.
- **Step 10**: Select the solution of network, for which $C_{min} = Min_{Thr} C_{Thr}$.
  The heuristic keeps track of the virtual topology, traffic routing, and equipment placement for each value of Thr.

Regenerator-only:

INPUT: A set of demands, K_1, auxiliary graph $G^{'}(\mathbf{N}, \mathbf{L})$

OUTPUT:Total network cost C_{Regen},

- **Step 1**: Pick a traffic demand T(s, d, t, r) from the ordered set of traffic demands, K_1.
- **Step 2**: Delete the virtual edges from auxiliary graph-I whose capacity is less than the requested bandwidth r. and delete the physical edges whose all wavelengths are being used.
- **Step 3**: On the residual graph,
  IF the source is directly connected to the destination via virtual link (lightpath) then select it for the traffic demand,
  ELSE establish a new virtual link between source and destination (light path) by selecting wavelengths based on first-fit approach on each intermediate links on the shortest path from source s to destination d,
- **Step 4**: If a new light path is established between source and destination nodes in Step 3 then place regenerators at all intermediate nodes and place transponders at source and destination nodes.
- **Step 5**: Restore edges which are previously deleted in Step 5
- **Step 6**: Update the capacity of the equipment and light- paths.
- **Step 7**: Repeat Step 2 to Step 6 for t number of times.
- **Step 8**: Repeat Step 1 to Step 7 for all traffic demands.
- **Step 9**: Return the cost of the placed equipment, C_{Regen}.

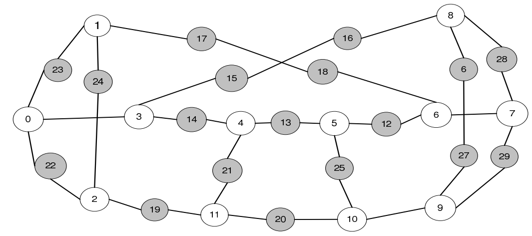

Fig. 3. 30-Node Network

Grooming-only:

INPUT: A set of demands, K_2, auxiliary graph $G^{'}(\mathbf{N}, \mathbf{L})$

OUTPUT:Total network cost C_{Groom},

- **Step 1**: Pick a traffic demand T(s, d, t, r) from the ordered set of traffic demands, K_2.
- **Step 2**: Delete the virtual edges from auxiliary graph-I whose capacity is less than the requested bandwidth r. and delete the physical edges whose all wavelengths are being used.
- **Step 3**: Along the shortest path, between intermediate nodes,
  IF the virtual link exist then select it for the traffic demand,
  ELSE Establish a new virtual link (light path) between intermediate nodes by selecting a wavelength based on first-fit approach.
- **Step 4**: **IF** a new light path is established between intermediate nodes in Step 3 then place line cards and/or grooming card at those intermediate nodes which does not have sufficient capacity for the traffic demand.
  ELSE If a new lightpath is generated at source node or terminated at the destination node then place transponder at source and destination if it is less expensive than a set of equipment such as client card, grooming card and line card, which does not have enough capacity for the traffic demand. Otherwise place the set of equipment.
- **Step 4**: Restore edges which are previously deleted in Step 5
- **Step 5**: Update the capacity of the equipment and light- paths
- **Step 6**: Repeat Step 2 and Step 5 for t number of times.
- **Step 7**: Repeat Step 1 to Step 6 for all traffic demands.
- **Step 8**: Return the cost of the placed equipment, C_{Groom}.

V. Simulation Results

We have implemented a simulator to compare the combined regenerator and grooming approach with a grooming-only approach and a regenerator-only approach. We consider the topology as shown in Figure 3.

Dark nodes in the figure indicate locations at which no traffic is added or dropped; thus, these are only potential locations for regenerating the optical signals. Each fiber link is bidirectional and has a capacity of 5 wavelengths. The capacity of each wavelength is assumed to be 10 Gbps. The source and destination of each traffic demand are uniformly distributed among all white nodes. Each traffic demand requests a finite number of connections in which each connection require 1 Gbps bandwidth. In this study, we analyze the network cost as a function of load for different values of the component costs. We also compare the cost of the impairment-aware network design for networks with various capacities such as 10 Gbps, 40 Gbps, and 100 Gbps. We assume that an optical signal operating at line rates of 10 Gpbs can travel at most 4 hops without regeneration, and that optical signals operating at line rates of 40 Gbps can travel at most 2 hops without regeneration. For a network operating at 100 Gbps line rates, we consider hop constraints of 1 hop and 3 hops.

Figure 4 compares the network cost of the regenerator and grooming-only approach with the the regenerator-only approach and the grooming-only approach as the network load increases. In this experiment, we assume that the costs of each regenerator is 1, while the other component costs are as specified in Table 1. At low load, the regenerator-only approach is costlier than the grooming-only approach and grooming-only approach is costlier than the regenerator and grooming approach. At low load, the requested bandwidth by the traffic demand is a fraction of the total wavelength capacity. The reason is that, since regenerator cannot take advantage of grooming the traffic at intermediate nodes, at low load, a large number of regenerators are placed to establish feasible connections between all source-destination pairs at intermediate nodes. On the other hand, at low load, the grooming-only approach aggregates low rate traffic demands on high bandwidth lightpaths and utilizes the existing network resources as much as possible, so grooming-only approach is less expensive than the regenerator-only approach. At high load, the grooming-only approach is costlier than the regenerator-only approach and the regenerator-only approach is costlier than the regenerator and grooming approach. At higher load, the requested bandwidth by the traffic demand occupies the entire wavelength capacity, so the grooming-only approach can not take advantage of grooming the traffic at intermediate node. In addition to that the regenerator cost is less expensive than the cost of a pair of line cards which are used to regenerate the signal in the grooming-only approach and thus the grooming-only approach is more costlier than the regenerator-only approach. In the regenerator-only approach, at low load, there is a sudden increase in the network cost and at higher load, the network cost increases linearly. At low load, large number of regenerators are placed to establish connections between all source-destination pairs. Once enough regenerators are placed at intermediate nodes, regenerators are only placed if the total traffic demand passing through the regenerator exceeds the capacity of the regenerator and thus the cost of the regenerator-only approach increases linearly. Since the regenerator and grooming approach can take an advantage of grooming the traffic at low load and less expensive regenerators at high load, it is the least expensive approach for all load values.

Figure 5 compares the network cost of all the three approaches for equipment costs as given in Table 1. In general, the grooming-only approach is less expensive than the regenerator-only approach, and the regenerator and grooming approach is similar as the grooming-only approach. At low load, the grooming-only approach is less expensive than the regenerator-only approach for the same reason as mentioned above. Since regenerator cost is higher than a pair of line cards cost, at higher load, even though the grooming-only approach can not take an advantage of grooming the traffic, it can be used to regenerate the signal using a pair of line cards. Since regenerator cost is high, the regenerator and grooming approach behaves the same as the grooming-only approach.

Figure 6 show the network cost if the line card cost is 1.8, and the other costs are as in Table 1. As the line card cost increases, the load after which the regenerator-only approach is less expensive than the grooming-only approach decreases. Also, a significant amount of cost improvement is observed in the regenerator-only approach. At high load, line cards at an intermediate node are only used for signal regeneration purpose, but not for traffic grooming purpose because the traffic demands are occupying the entire capacity of the wavelength. Also, the regenerator cost is lower than the pair of line card cost which reduces the network cost for employment of regenerators for regenerating the signal. The regenerator and grooming approach always has the lowest cost compared to the grooming-only approach and the regenerator-only approach for the same reason as mentioned above.

Figure 7 show the network cost as the load increases for all of the three network designing approaches, if the grooming card cost is 9.6 and the other costs are as in Table 1. As show in figure 7, at higher load, then regenerator-only approach has the lower cost compare to grooming-only approach. The reason is that expensive grooming cards are used at intermediate nodes which are not able to groom the traffic at higher load. Since regenerator and grooming-only approach places the equipment which minimizes the total network cost, for number of requests smaller than 350, it behaves the same as grooming-only approach and number of requests larger than 350, it behaves the same a regenerator-only approach.

Figure 8 compares the network designing cost for all the three approaches if the switching granularity of the grooming switch is increased from 1 Gbps to 2.5 Gbps. In this experiment, we assume that each connection requests 2.5 Gbps bandwidth. The cost of the regenerator is considered to be half of the given cost in Table 1. The load at which the regenerator-only approach becomes less expensive than the grooming-only approach decreases. The results demonstrate that even for course switching granularity, regenerator and grooming approach is the least expensive approach.

Figure 9 compares the cost of the network design for networks with capacity 10 Gbps, 40 Gbps, and 100 Gbps for the given cost parameters as shown in table 1. In the 100 Gbps network with an impairment constraint of a single hop, the network design cost is excessively high since the signal is required to be regenerated at every hop and network elements for 100 Gbps network are costlier than the 10 Gbps and 40 Gbps network elements. At low load, the 10 Gbps network is the least expensive network, while at higher load, the 10 Gbps network is the most expensive network. The reason is that at low load, the 10 Gbps network efficiently utilizes the wavelength resources, and 10 Gbps network elements are less expensive than in the 40 Gbps and 100 Gbps networks. As the

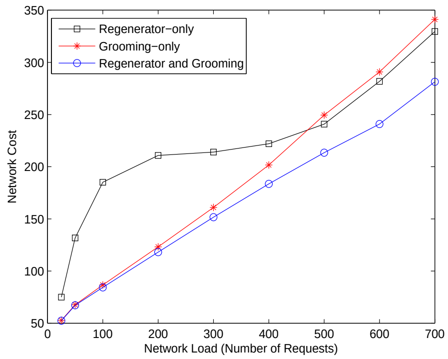

Fig. 4. Network Cost for RC=1

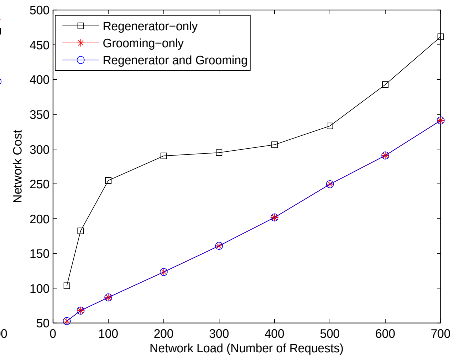

Fig. 5. Network Cost for the Given Cost Model

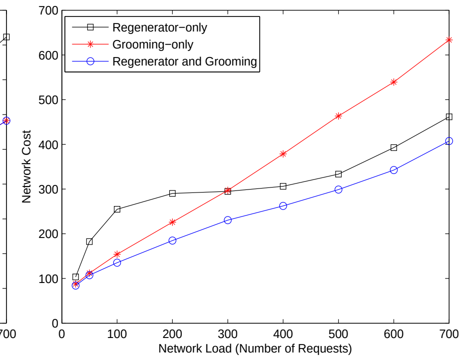

Fig. 6. Network Cost for LC=1.8

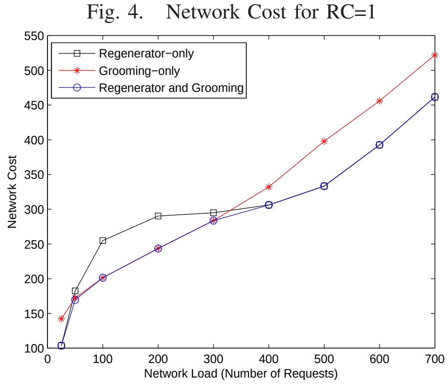

Fig. 7. Network Cost for GC=9.6

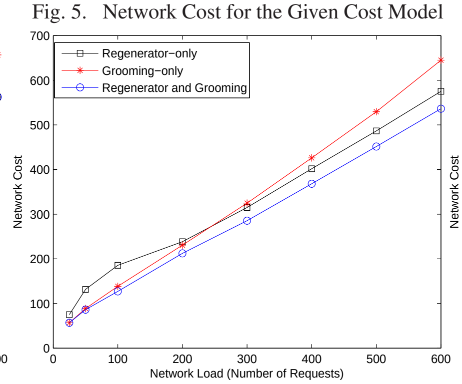

Fig. 8. Net. Cost for 2.5 Gbps Granularity

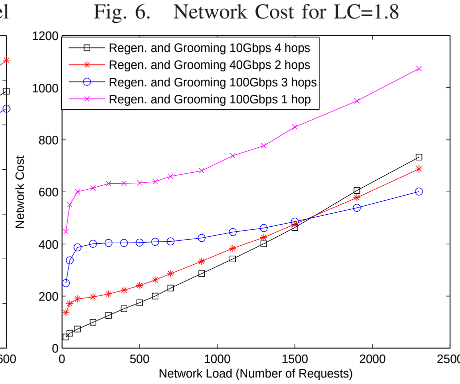

Fig. 9. Network Cost for Various Line Rates

load increases, the 40 Gbps network is getting cheaper than the 10 Gbps network and the 100 Gbps network is getting cheaper than the 40 Gbps network. The reason is that as the load increases, the 40 Gbps network elements are getting volume discount over the 10 Gbps network elements and the 100 Gbps network elements are getting volume discount over the 40 Gbps network elements. In addition to that network resource utilization increases in the 40 Gbps and 100 Gbps networks as the network load increases.

VI. Conclusion

In this paper, we have considered the impairment-aware grooming-capable optical WDM network design problem with the objective of minimizing the network cost. A detailed ROADM node architecture is considered for the network designing. At a ROADM node, optical signal can either be bypassed, groomed or regenerated. We propose an auxiliary graph based heuristic in which regenerators and grooming equipment are placed in such a way that the total network cost is minimized. The proposed heuristic is compared with network consisting only grooming nodes and network with only regenerators. The results show that the placement of regenerator and grooming together always minimizes the network designing cost compared to regenerator only and grooming only approaches.

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