Cross-Layer Traffic Grooming for Optical Networks with Hybrid Layer-One and Layer-Zero Signal Regeneration

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Abstract: We present a cross-layer traffic grooming algorithm that balances layer-one and layer-zero signal regeneration capability to achieve the lowest network design cost. The cross-layer approach shows good cost reduction compared to the traditional non-cross-layer approach.

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1. Introduction

Traffic grooming is important for optical transport networks. Most of studies in this area have focused on minimizing total network capacity or maximizing total served traffic demand subject to predefined network capacity [1][2]. When planning lightpath demand, the existing traffic grooming studies often ignored the impairments in the physical layer. However, it is well-understood that an optical signal suffers from impairments in the physical layer, ranging from linear factors, such as ASE noise and residual dispersion, to nonlinear factors, such as self-phase modulation, cross-phase modulation, and four-wave mixing [3][4]. These factors limit an optical signal to be transmitted a certain distance before 3R signal regeneration is necessary. Such a distance is called *optical transparent reach limit* [4].

This paper presents an efficient cross-layer traffic grooming algorithm that takes into account the physical layer impairments. We evaluate how the physical layer impairments show their impacts on traffic grooming. For simplicity, we use *optical transparent reach limit* to approximately but validly set a signal quality limit in the physical layer. In addition to minimizing a total number of end-to-end lightpaths that corresponds to the number of switch line modules, we minimize a total number of 3R OEO regenerators, which relay lightpaths in layer zero. The proposed approach is expected to be easily extended to the case that accurately evaluates OSNR and non-linear effects to decide an optical reach limit.

2. Cross-layer traffic grooming

Traffic grooming can be divided into two categories, namely single-hop grooming and multi-hop grooming [1]. Single-hop grooming directly establishes sufficient lightpath capacity between a pair of nodes to support all the traffic demand between the node pair. Multi-hop grooming employs the remaining capacity on other established lightpaths to serve traffic demand between a pair of nodes. A good traffic grooming algorithm generally combines the single-hop grooming and multi-hop grooming modes. Specifically, the single-hop grooming mode is first employed to serve the most traffic demand between a pair of nodes, and then the multi-hop grooming mode is applied to serve the remaining fractural demand between the node pair by using free capacity on other established lightpaths that are however not directly established between the node pair. When planning a lightpath between a pair of nodes, the traditional grooming approaches often ignored the physical distance between the node pair. In contrast, under cross-layer grooming, we consider the physical distance when planning a lightpath. Specifically, if the distance is longer than a predefined transparent reach limit, we deploy intermediate 3R regeneration for the lightpath.

There are two possible ways to support 3R regeneration, namely (i) a pure layer-zero 3R regenerator, and (ii) a pair of layer-one switch line modules. In general, a pair of layer-one switch line modules is more expensive than a pure OEO 3R regenerator. This is because in addition to the hardware cost for optical transceivers, the switch line modules require advanced electrical signal processing parts for packet switching. The switch line modules however allow for adding/dropping and re-grooming traffic demand onto under-utilized lightpaths so as to improve capacity efficiency. Thus, the switch line module tradeoffs the traffic grooming capability and a higher hardware cost. In general, it is preferred to use a pure 3R regenerator to relay a lightpath signal if the lightpath capacity has been fully- or well-utilized. Only when the capacity of a lightpath is under-utilized, would a switch line module be used such that more traffic demand can be added onto the lightpath for better capacity utilization. Fig. 1 shows an example for the two different types of 3R regeneration. For a 30%-utilized lightpath, we use a switch line module to regenerate the signal, which allows to add 70% more traffic on the lightpath. However, for a 100%-utilized lightpath, we always use a pure 3R regenerator for a lower cost.

3. Grooming algorithm

We developed a cross-layer grooming algorithm that takes into account the physical-layer transparent reach limit. The algorithm is shown in Fig. 2, in which the left hand side is the major flowchart of the algorithm. Step 1 inputs a physical topology and traffic demand. Step 2 employs the single-hop grooming strategy to plan lightpaths and serve all the traffic demands between node pairs. It then removes the wavelength capacity units on the established virtual links if the capacity units are under-utilized. Specifically, if the utilization level of a capacity unit is lower than a predefined threshold level ($U_{thresh1}$), we remove the capacity unit from its virtual link and recover all the served demands by the capacity unit as *un-served*.

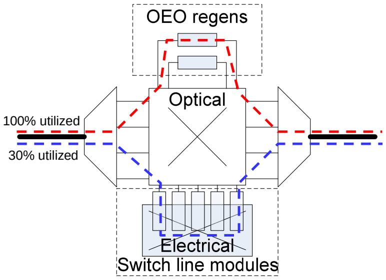

Figure 1: Two signal regeneration scenarios.

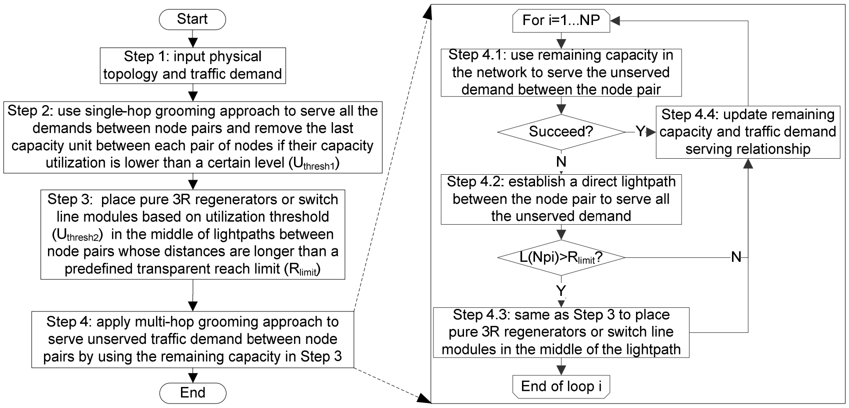

Figure 2: Flowchart of the proposed cross-layer traffic grooming approach.

In Step 3, we deploy signal regeneration capability in the middle of the lightpaths (planned in Step 2) whose distances are longer than transparent reach limit (R_{limit}). Specifically, if the capacity utilization of a lightpath channel is greater than a certain threshold level ($U_{thresh2}$), we place pure 3R regenerators; otherwise, we place switch line modules to allow for more traffic demand added to the lightpath. Moreover, if the distance between a pair of nodes is so long to require more than one intermediate 3R regenerations, we employ a recursive process to determine the best locations of 3R regeneration. Specifically, from a source node, we find the farthest intermediate node *N1*, whose distance is within R_{limit} from the source node, and deploy regeneration capability on *N1*. Next, starting from node *N1*, we repeat the same regeneration placement process until the destination node is reached.

Step 3 leads to a network that has unused capacity on some virtual links and un-served traffic demands between some node pairs. Based on such a network, Step 4 employs the multi-hop grooming strategy to serve all the un-served traffic demands by either using the existing free capacity or adding more lightpaths. The flowchart on the right-hand side in Fig. 2 shows the detail of Step 4.

Specifically, in Step 4.1, we use the free capacity in the current network to serve the un-served demand between each node pair. If successful, we update the remaining capacity and move to the next node pair; otherwise, we establish new lightpath capacity between the node pair to serve the un-served demand. When establishing a new lightpath, we need to check whether the physical distance of the lightpath is longer than R_{limit}. If not, we serve the demand and update the remaining capacity on the new established lightpath; otherwise, we move to Step 4.3 to deploy 3R regenerators or switch line modules in the middle of the lightpath. This step is the same as Step 3. The loop will stop when all the un-served demands are served.

4. Simulation Results

Based on the proposed grooming algorithm, we conducted simulations to evaluate how the physical-layer transparent reach limit can affect traffic grooming performance in terms of total network design cost. Here the total network cost is defined to be the sum of the costs of switch line modules and pure 3R regenerators. This approach is justified since at a high bit rates (40 Gb/s and above), transponder costs are much higher than those of the optical line system (including amplifiers, optical power monitors, filters etc), and dominate the total network cost. The test networks include a 21-node and 43-link USNET [3] and a real network X with more than one hundred nodes and more than one hundred links. For the USNET network, each node pair has a traffic demand randomly within a range from 1 to 10 STM-16s. These demands are assumed to be groomed to 10-Gb/s wavelength capacity (i.e., STM-64). The real network X has 2.5-Gb/s and 10-Gb/s traffic demands, and they are groomed onto 40-Gb/s wavelength capacity. The related thresholds in the grooming algorithm are set as follows: $U_{thresh1}$=0.3, $U_{thresh2}$ ranges from 0 to 1.0 increased by 0.1 in each step, R_{limit}=3000 km (USNET) and R_{limit}=2000 km (the real network X). Fig. 3 shows the results of cross-layer traffic grooming for (a) the USNET network and (b) the real network X. In the figures, $U_{thresh2}$=0 corresponds to an extreme case that we always use pure 3R regenerators for signal regeneration no matter how low the capacity utilization of a lightpath is; in contrast, $U_{thresh2}$=1.0 corresponds to another extreme case that we always use switch line modules for signal regeneration as long as a lightpath is not 100% utilized. The $U_{thresh2}$=0 case can essentially be considered as a *non-cross-layer* design, in which all traffic demands are first groomed into lightpath demands and then 3R regenerators are placed for groomed lightpaths.

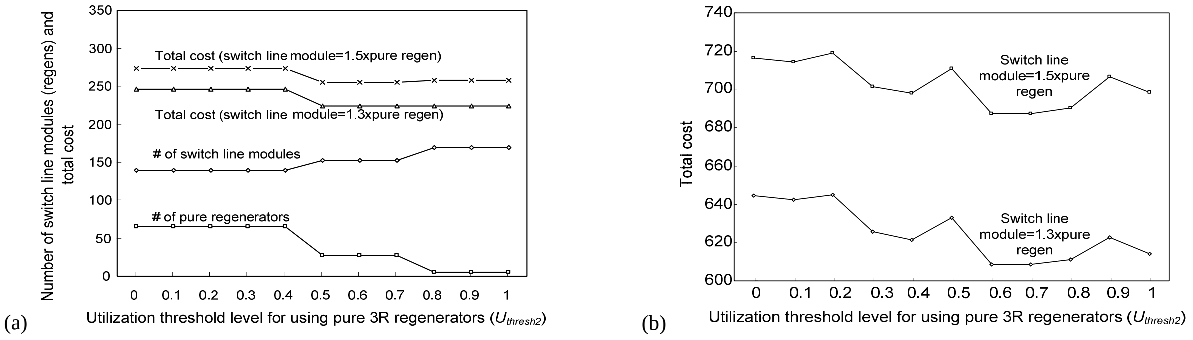

Figure 3: (a) Results of USNET, (b) Results of the real network X.

Fig. 3(a) shows how many pure OEO regenerators and switch line modules are required with the increase of $U_{thresh2}$. As a large $U_{thresh2}$ requires high capacity utilization for a lightpath to be eligible for being deployed with pure 3R regenerators, it is found that an increase of $U_{thresh2}$ leads to an increasing number of switch line modules and a decreasing number of pure 3R regenerators. In addition, given a certain cost ratio between a switch line module and a pure 3R regenerator (for example, "switch line module=1.3×pure regen" in the legend means that a pair of switch line modules is 1.3 times as expensive as a pure 3R regenerator), the total network cost is found to drop when $U_{thresh2}$ reaches 0.5, and there is a (minor) increase in the total cost when $U_{thresh2}$ is greater than 0.7. The results imply that there exists an optimal $U_{thresh2}$ that ensures the total network cost to be minimal. For the USNET network, such a threshold is within a range from 0.5 to 0.7. For a cost ratio of "switch line module=1.3×pure regen," the total network cost under an optimal $U_{thresh2}$ is found to be 8.6% lower than the non-cross-layer design with $U_{thresh2}$=0. The same observation can be found for cost ratio 1.5 in Fig. 3(a). For the real network X, similar optimal threshold level $U_{thresh2}$ is found to be within a range from 0.6 to 0.8 and the optimal cross-layer design can reduce the cost by 4.0% and 5.6% compared to the non-cross-layer design respectively for cost ratios 1.5 and 1.3. Note that the non-smoothness of the curves in Fig. 3(b) is due to the inherent heuristic characteristic of the grooming algorithm, whose performance can be affected by various factors such as topology, traffic demand distribution, etc.

The above cost analyses are based on the hardware costs. Under some situations, when determining whether to use a pure 3R regenerator or a switch line module, we are also interested in another type of costs called *opportunity cost*. The opportunity cost considers the maximal number of allowed switch line modules on a switch node. Reserving more switch line module space at a node means more *opportunity* for future layer-one traffic grooming. In general, when the number of allowed switch line modules is small, we should set a large opportunity cost for the addition of a switch line module, and vice versa. In addition, the opportunity cost can be *adaptive*, which for example can be gradually increased with the reduction of the remaining switch line module space at a node. For an opportunity cost-based design, the same approach as proposed in the paper can be applied.

5. Conclusion

We presented a cross-layer traffic grooming algorithm that considers the physical transparent reach limit. The algorithm optimally places regeneration capability and is efficient to reduce the total network design costs by 4.0%~8.6% compared to the simple non-cross-layer designs in the simulations studies. This cost savings come with no disadvantage to robustness of system design. We also identified the optimal utilization threshold level for using pure 3R regenerators or switch line modules when regenerating lightpath signals. When the utilization level on a capacity unit is higher than 0.5~0.6, it is more cost-effective to place pure 3R regenerators than switch line modules.

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