Traffic Grooming in WDM Mesh Networks with Loop-Free Paths

Kwok Shing Ho[1]**, Victor Yu Liu**[2]
[1]*Huawei Technologies Limited, Shenzhen, China,* [2]*Huawei Technologies, Santa Clara, CA, USA,*
Email: (kwokshing.ho@huawei.com, victor.liu@huawei.com)

Abstract: A solution framework for the traffic grooming problem with physical loop-free end-to-end paths is proposed and its impacts in terms of network resource efficiency and installation cost is analyzed.

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1. Introduction

Architecturally speaking, an optical WDM mesh network has two topologies: 1) the physical topology with a set of cross-connect nodes N, connected by a fiber link set E, and 2) the logical topology formed by a lightpath set L for that each may span several fiber links and use a wavelength available to carry traffic. The traffic grooming problem here includes a logical topology design problem with the primary goal of finding the minimum number of lightpaths. That is equivalent to the dominating cost – the total number of transponders needed. The logical topology is carried by the fiber network so that all traffic can be groomed and routed onto the available wavelengths, see [1], [2] and references therein. Currently, the operational network is able to support a hundred of 40-Gbps (i.e. STM-256) wavelengths per fiber while a large fraction of total traffic is at much smaller granularities, such as 2.5Gbps (i.e. STM-16). How to perform traffic grooming is critical for building a cost effective network.

In this paper, we study the problem of Grooming with Loop-Free Routing (GLFR). With traffic grooming, the physical path of a demand may pass through a node or a physical link more than once. Fig.1 gives an example. There is a demand *a* flowing from node *1* to node *4*. The logical route of this demand consists of lightpaths *1-6* and *6-4* without loop. However, as both ligthpaths *1-6* and *6-4* traverses node *7* in fiber network, the physical route of demand *a* will pass through node *7* twice and form a backhaul. As the objective is minimizing the lightpath count and lightpaths can only be installed in integer multiples, such backhaul routing helps save cost by allowing slack capacities on the existing logical links to be fully exploited for grooming. That is why such a seemingly weird routing will happen when traffic grooming is implemented. Because allowing backhaul may save the overall network cost and the corresponding traffic grooming problem gets lower complexity, sometimes it is better to practice the backhaul routing. However, there is a trade-off that the network resource (wavelengths in fiber network) is used in an inefficient way because demands are carried by unnecessarily longer paths. It can be 7 or 8 times longer than the shortest path according to our experimental results. Furthermore, the transmission delay and the chance to link or node failure can be greatly increased when backhaul routing is implemented. Consequently, the network operational cost may grow, especially in case of transporting the real-time traffic that desires low latency and the critical demands that requires reliable transmission. That is why whenever it is possible, the network operators are always seeking for a cost-effective solution to avoid physical loops. This is our motivation to study the GLFR problem.

There are only few works discuss the loop-free routing in the area of traffic grooming. In [3], the solution approach only prevents the source or destination to be traversed twice. In [4], a link cannot be used twice on the same path. In this paper, we provide a general solution framework for efficient traffic grooming with loop-free routing that avoids any node or link to be used twice or more.we also discuss the effect of implementing physical loop-free routing in terms of network resources, efficiency, and installation cost that network operators always concern.

2. Problem Statement, Formulation, Complexity and Solution Method

The GLFR problem considered in this work can be addressed as follows. Given a fiber network F=(N,E) with a finite wavelength set W of same capacity (say 40Gbps) on each fiber and a set of symmetric traffic demands R, we want to find a way to route and groom these demands in the logical network (formed by the lightpaths) with the objective of minimizing the total number of lightpaths. In the obtained solution, the end-to-end paths of the demands are required to be loop-free.

The GLFR problem can be formulated in an integer linear programming (ILP) model. The ILP model will consists of two sets of binary variables: 1) lightpath routing variable x_{rl} which is equal to 1 if demand r traverses lightpath l, and 0 otherwise; 2) wavelength assignment variable y_{lw} which is equal to 1 if wavelength w is assigned to ligthpath l, and 0 otherwise. The ILP model will have an objective function $\min \sum_{w\in W, l\in L} y_{lw}$ that minimizes the total number of lightpaths. The objective function is subject to four sets of constraints. Interested reader can find the equations for the first three sets of constraints in [2]. We omit them here due to space limit. The equation for the fourth constraint set is a unique point of this work and given in (1) below. The four constraints are described as follows:

1) Logical Routing Constraints: Classical flow balance constraints that ensure logical routing of each demand.
2) Wavelength Continuity Constraints: Constraints that ensure a specific wavelength is assigned to only one lightpath on a specific fiber because we assume that wavelength convertors are not available in the network.
3) Lightpath Capacity Constraints: Constraints that guarantee the capacity installed on each lightpath is enough for carrying all the demands that traverse it.
4) Loop-Free End-to-End Routing Constraints: Constraints that make sure the physical paths of all specific demands cannot pass through any node more than twice. Under this condition, it will surely not pass through any link more than twice and must be loop free.

$$\sum_{l\in L}\sum_{e\in E} x_{rl}\, h_{le}\, a_{en} \le 2, \forall n \in N, r \in R \qquad (1)$$

where h_{le} = 1 if fiber link e is on lightpath l and 0 otherwise, a_{en} = 1 if n is the end node of fiber span e and 0 otherwise.

The traffic grooming problem has been shown as NP-hard in ring topology [1]. In ring network, we shall always find a loop-free path for each demand. That implies that the GLFR problem for the special instance of ring network is equivalent to the NP-hard traffic grooming problem. Because the GLFR problem is NP-hard for the special instance of ring topology, we know that the general GLFR problem is also NP-hard.

We propose a decomposition approach to efficiently solve the NP-hard GLFR problem which is likely to be computationally complex. As the experimental result shown, our approach can solve the GLFR problem on a large scale practical network with more than 100 nodes. It should be noted that our method is a general method that can be applied to the GLFR problem with other objectives such as maximizing network throughput. Our approach has four steps. In step 1, we remove the wavelength continuity constraints from the ILP model and reserve them for separate treatment in later step. Moreover, instead of considering all possible lightpaths and all their corresponding routes in fiber network, we use only a finite number of these candidate paths. The key idea of this step is to make the ILP model more computationally efficient by reducing its complexity and candidate solution pool. Otherwise, the scale of the model will exponentially explode that a solution cannot be obtained in a reasonable time for even medium scale practical network. In step 2, we use the Branch & Cut method that is built in typical ILP solvers such as CPLEX to obtain the solution for the reduced ILP model within limited time or when the solution falls within a specific optimality gap. Next, we check the solution for the wavelength continuity violations in step 3. In this step, we need to solve a typical wavelength assignment feasibility problem for which we have several efficient methods to tackle with. In this work, we use the method listed in [2]. If we can find a feasible wavelength assignment in the previous solution, we end this step. Otherwise, we go to step 4 and take the repairing procedure - breaking the most utilized lightpaths one by one into two or more lightpaths. Because this procedure is equivalent to a virtual wavelength conversion, the wavelength continuity constraints can be satisfied after a certain number of iterations. In the end of the repairing procedure, the repaired solution is taken as the final solution.

3. Experimental Results and Analysis

In this section, based on the proposed solution framework, we conduct experiments to study how the loop-free routing affects traffic grooming performance in terms of resources efficiency and network installation cost. We consider the 14-node 21-link and 140-demand NSFNET and a 103-node 194-link and 577-demand real network *D*. The demand node pairs for the NSFNET are randomly generated but those for the real networks are collected from network operator in reality. The available wavelengths on each fiber for all the networks are assumed to be 80 according to today's technology. Only 2.5-Gbps (i.e. STM-16) traffic demands that are groomed to 40-Gbps (i.e. STM-256) wavelength capacity are considered in this paper. Other traffic combinations will be considered in the future. The demand node pair set is read as the candidate lightpaths set and the shortest path is set as the candidate physical path for each lightpath. It is found that such combination can achieve good quality solution in reasonable time after many tests. Fig. 2 and 3 show the results for the two test networks and all results are obtained within two hours. In both figures, $P_{loop\text{-}free}$ represents the portion of traffic demands required to have loop-free end-to-end routing. $P_{loop\text{-}free}=0$ is the extreme case that all demands can be carried by backhaul routing while $P_{loop\text{-}free}=1$ represents another extreme case that we always use loop-free paths to transport demands.

Fig. 2 shows how the Link Capacity Over-use (LCO) ratio changes with $P_{loop\text{-}free}$. The LCO ratio is equal to the total bandwidth-distance product (in Gbps*hops) for those demands with loops in their paths to the total bandwidth-distance product for all demands in the network. LCO ratio is an indicator of how many network resources are inefficiently used due to backhauls in the network. It numerically measures how our algorithm improves the network efficiency. While the portion of demands transported with loop-free routing increases with $P_{loop\text{-}free}$, the network resources efficiency increases with $P_{loop\text{-}free}$ as shown in Fig.2. It is observed that the network efficiency can be enhanced up to 19% in NSFNET and 26% in real network *D* respectively with our algorithm. Though there are some fluctuations in the curves, caused by the inherent heuristic characteristic of our algorithm whose performance can vary according to the topology, traffic demand distribution and input parameters of the ILP model, it is still sound to draw a conclusion that our algorithm improves the network efficiency quite significantly on the test real networks, based on the overall trend shown in Fig. 2.

Fig. 3 shows how the network installation cost (the number of lightpaths) changes with $P_{loop\text{-}free}$. The network installation cost is normalized with the basic cost set to the cost obtained in case of $P_{loop\text{-}free}=0$. It is observed in Fig.3 that the network installation cost increases slightly with $P_{loop\text{-}free}$. As explained in section 1, implementing loop-free routing can increase the network efficiency, but with a trade-off of decreasing the grooming efficiency, because this will restrict slack capacities on the existing logical links to be fully exploited for grooming. As a result, more lightpaths may be added to satisfy all the demands when $P_{loop\text{-}free}$ increases. However, such increment of the network installation cost is relatively small for the test networks, only at most 6% in NSFNET and 5% in real network *D* respectively. Furthermore, there are some cases that the network installation cost does not decrease even though $P_{loop\text{-}free}$ decreases. This implies that, by modifying our algorithm suitably according to the network parameters such as topology and traffic demand distribution, we may find a routing and grooming solution with loop-free routing implemented, and it will not be more expensive than one with the backhaul routing. This is for future analysis.

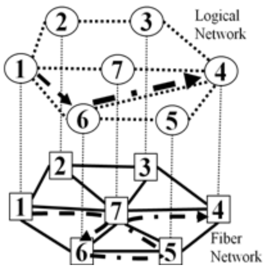

Fig.1. Physical end-to-end routing contains loop

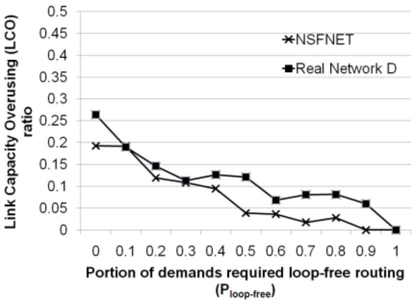

Fig.2. Change of LCO ratio with $P_{loop\text{-}free}$

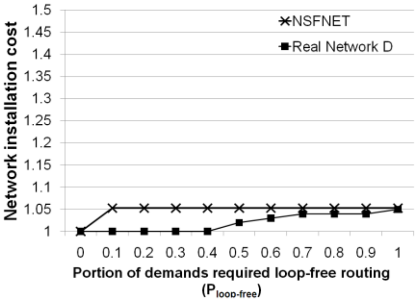

Fig.3. Change of installation cost with $P_{loop\text{-}free}$

4. Conclusions

We study the traffic grooming problem with loop-free routing constraints. We present a solution framework that can efficiently tackle the problem on real network instances with more than 100 nodes. Based on our numerical study, it is found that enforcing physical loop-free routing can improve the network efficiency of real networks up to 26% with a trade-off of less than 6% increase in the network installation cost.

5. References

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