A Dynamic Traffic Grooming Algorithm in Multi-granularity Heterogeneous Optical WDM Mesh Networks

Lin Zhang and Gee-Swee Poo

Network Technology Research Center, School of EEE
Nanyang Technological University, Singapore
{ezhangl, egspoo} @ntu.edu.sg

Abstract

We consider the problem of traffic grooming in wavelength division multiplexing networks. Our objective is to minimize the required number of electronic add-drop multiplexers. We investigate the problem of efficiently provisioning connections of different bandwidth granularities in a heterogeneous WDM mesh network through dynamic traffic grooming schemes under traffic engineering principles. We first formulate the problem as an integer linear programming (ILP) problem, and then we derive the optimal solution under all-to-all uniform traffic in WDM ring networks using optimization tools.

1. Introduction

In recent years, the pervasive use of Internet services has significantly increased the volume of Internet traffic. Due to the popularity of emerging Internet-based real-time applications and services, the network will become much more congested unless appropriate techniques are designed. Traffic engineering (TE) is an effective solution to control network congestion and optimize network performance. As stated in [1, 2], TE encompasses the application of technology and scientific principles to the measurement, modeling, characterization, and control of Internet traffic. The purpose of TE is to facilitate efficient and reliable network operations while simultaneously optimizing network resource utilization and traffic performance.

It has been well recognized that optical wavelength-division multiplexing (WDM) networks will become the dominant transport infrastructure for Internet traffic. A lightpath provides a basic communication mechanism between two nodes in WDM networks. A lightpath is a wavelength circuit, which may span multiple fiber links and be routed by the intermediate optical switches between a given node pair. Although the bandwidth of a lightpath (i.e., a wavelength channel) in an optical WDM backbone network is quite high (10 Gb/s, OC-192, today; expected to grow to 40 Gb/s, OC-768, soon), only a fraction of customers are expected to have a need for such high bandwidth. Many will be content with lower bandwidth, say, STS-1 (51.84 Mb/s), OC-3, OC-12, or OC-48, for backbone applications. Since high-bandwidth wavelength channels will be filled up by many low-speed traffic streams, efficiently provisioning customer connections with such diverse bandwidth needs is a very important problem and is known as the traffic grooming problem. Due to the large cost of the optical backbone infrastructure and enormous WDM link capacity, provisioning inefficiency can cause significant capital overhead and a large amount of bandwidth waste. Therefore, traffic grooming is one of the most important TE issues in optical WDM mesh networks. It enables a network operator to increase capacity utilization, minimize network cost, and optimize potential network revenue.

In this article we investigate the problem of efficiently provisioning connections of different bandwidth granularities in a heterogeneous WDM mesh network through dynamic traffic grooming schemes under traffic engineering principles. Due to the huge amount of traffic a WDM backbone network can support and the large geographic area it can cover, constructing and upgrading such an optical WDM network can be costly. Hence, it is extremely important for network operators to apply traffic engineering strategies to cost-effectively support different bandwidth granularity services using only the appropriate amount of network resources. This requires an optical WDM network to have multi-granularity switching capability, and such a network tends to be a multi-vendor heterogeneous network. However, WDM network heterogeneity increases the difficulty and challenge of efficient traffic provisioning. In this article, we first formulate the problem as an integer linear programming (ILP) problem, and then we derive the optimal solution under all-to-all uniform traffic in WDM ring networks using optimization tools.

2. Related works

Recently, traffic grooming has been a hot topic for optical WDM networks, and most of the previous research [3–6] has focused on synchronous digital hierarchy (SDH)/WDM ring networks. In long-haul backbone networks, the mesh network is preferred because of its rapid and effective capacity configuration, so traffic grooming is essential to WDM mesh networks [7–10]. This issue is discussed in Refs. [7] and [8] for WDM mesh networks with a static traffic pattern (i.e., the low-rate traffic demands are fixed and known a priori). However, in the operational networks,
the traffic pattern most likely changes over time; i.e., traffic demands might come and go. In Ref. [9] the routing problem for traffic grooming was studied, but constraints on the number of transceivers were not considered. In Ref. [10] it was assumed that all the nodes in the network have the full ability of wavelength conversion, and the dynamic routing problem was solved on the basis of the so-called reachability graph. As mentioned above, the cost of transceivers cannot be ignored, and because of the limitation of technology and the high price of wavelength converters, it is impractical to equip all nodes with wavelength converters at this point in time. For these reasons we investigate the adaptive traffic-grooming algorithm, which assumes wavelength continuity.

3. Problem formulation

We consider a unidirectional ring \( R \) with \( N \) nodes, numbered from 0 to \( N - 1 \). The fiber link between each pair of nodes can support \( W \) wavelengths and carries traffic in the clockwise direction; in other words, data flows from a node \( i \) to the next node \((i + 1) \mod N\). The links of \( R \) are numbered from 0 to \( N - 1 \), such that the link from node \( i \) to node \((i + 1) \mod N \) is numbered \( i \). The traffic demands between pairs of nodes in the ring are given in the traffic matrix \( T = [t^{(sd)}] \). We assume this traffic demands are a multiple of some basic rate and let \( C \) denote the capacity of each wavelength expressed in units of this basic rate. Each quantity \( t^{(sd)} \in \{0,1,2,\ldots,C\} \) denotes the traffic demand originating from node \( s \) and terminating at node \( d \), also expressed in units of this basic rate.

An important problem to satisfy this traffic demand by the ring network is the design of traffic grooming scheme that optimize a certain performance metric. Our interest is to minimize the number of electronic add-drop multiplexers (ADMs). Fig.1 shows the architecture of a typical node in a SONET-WDM ring network. For some wavelength \( \lambda_1 \) in fig. 1), because there is no need to add or drop any of its timeslots, they can be optically bypassed at the node. For other wavelengths \( \lambda_2 \) and \( \lambda_3 \) where at least one timeslot needs to be added or dropped, an electronic ADM is used.

![Fig. 1. Architecture of a WDM ring network node.](image)

Instead of having an ADM on every wavelength at every node, it may be possible to have some nodes on some wavelength where no add-drop is needed on any timeslot; thus, the total number of ADMs in the network and hence the network cost can be reduced. Under the static traffic pattern, the savings can be maximized by carefully packing the lightpaths.

Let \( t(l) \) denote the aggregate traffic load on the physical link \( l \) of the ring. The component of the traffic load \( t(l) \) due to the traffic from source \( s \) to destination \( d \) is denoted by \( t^{(sd)}(l) \). We denote the lightpath count from node \( i \) to node \( j \) by \( b_{ij} \), taking its value from \( \{0,1,2,\ldots,W\} \) if multiple lightpaths with the same source and destination exist. Let \( c_{ij} \) be the lightpath wavelength indicator, i.e., \( c_{ij} = 1 \) if a lightpath between node \( i \) and node \( j \) uses wavelength \( k \), 0 otherwise. The traffic on the lightpath between node \( i \) and node \( j \) due to traffic from \( s \) to \( d \) is denoted as \( t^{(sd)}_y \). The set of lightpaths that pass through link \( l \) is defined as \( B(l) = \{(i,j)| \text{lightpath } (i,j) \text{ pass through link } l\} \).

So the optimization problem can be organized as follows:

Find the solution set of the lightpath indicator \( b_{ij} \), lightpath wavelength indicator \( c_{ij} \), and traffic routing variables \( t^{(sd)}_y \), to optimize:

\[
\min \sum_{i} \sum_{y} ADMI_i
\]

(1)

Given the physical topology as a unidirectional ring \( R \) with \( N \) nodes, the traffic matrix \( T = [t^{(sd)}] \), \( s,d \in \{0,\ldots,(N-1)\} \), \( t^{(sd)} \in \{0,1,2,\ldots,C\} \), \( C = 0,\forall s \), and the wavelength limit \( W \) which is the number of distinct wavelength each link can carry.

Subject to:

Traffic constraints

\[
t^{(sd)}_y \leq t^{(sd)}(i), \forall (i,j),(s,d)
\]

(2)

\[
t^{(sd)}_y \in \{0,1,2,\ldots,C\}, \forall (i,j)
\]

(3)

\[
\sum_{(i,j) \in B(l)} t^{(sd)}_y = t^{(sd)}(l), \forall (s,d),l
\]

(4)

\[
t^{(sd)}_y = \sum_{i} t^{(sd)}_y, \forall (i,j)
\]

(5)

\[
t^{(sd)}_y \leq b_{ij} \times C, \forall (i,j)
\]

(6)

\[
\sum_{j} t^{(sd)}_y - \sum_{j} t^{(sd)}_y = \begin{cases} t^{(sd)}_y, & s = i \\ -t^{(sd)}_y, & d = i \\ 0, & s \neq i, d \neq i \end{cases}, \forall i,(s,d)
\]

(7)

Wavelength constraints

\[
\sum_{(i,j) \in B(l)} b_{ij} \leq W, \forall l
\]

(8)

\[
\sum_{k=1}^{W} c_{ij}^{(k)} = b_{ij}, \forall (i,j)
\]

(9)

\[
\sum_{(i,j) \in B(l)} c_{ij}^{(k)} = 1, \forall l,k
\]

(10)

The traffic constraint (2) ensures that a lightpath can carry traffic for a source-destination node pair only if it is in the
physical route of the traffic component. Constraint (4) states that the physical traffic on a link due to a source-destination node pair must be equal to the sum of the traffic on all lightpaths passing through that link due to that node pair. Constraints (5) and (6) define the total traffic on a lightpath and relate it to the lightpath count, respectively. Because of the definition of the quantities $t^{(sd)}(l)$, constraints (2) and (4) together ensure that no traffic component can be routed completely around the ring before being delivered at the destination node. Constraint (7) is the expression of traffic flow conservation at lightpath endpoints. Among the wavelength constraints, constraint (8) expresses the bound imposed by the number of wavelength available, (9) relates the wavelength indicators to the lightpath counts, and (10) ensures that no wavelength clash can occur.

4. Simulation Analysis on All-to-all Uniform Traffic

Since the solution to the general problem in NP-complete, we consider a more limited case of uniform traffic. That is, $r_{ij} = r$ for all $i \neq j$, where $r$ is some positive integer representing the number of basic rate between each pair of nodes. The traffic granularity, $g$, is equal to the number of the basic rate that can fit on a wavelength. In this case, an interesting observation that significantly simplifies the solution for unidirectional rings is that the routing problem is eliminated. We choose this traffic setting in ring network for testing, since its optimal solution can be obtained analytically. From Ref [8], we have:

Lemma 1: let $A^*$ denote the minimum number of ADMs required. $A^* = \frac{N(N-1)}{2}$ when $N \geq 5$ and $g=4$.

Lemma 2: when $g=4$ the minimum number of ADMs, $\frac{N(N-1)}{2}$, can be achieved with the minimum number of wavelength, which is equal to $\left\lceil \frac{N(N-1)}{8} \right\rceil$.

We examine the effect of the traffic granularity $g$ on the minimum number of ADMs required in ring networks by use of CPLEX 7.0 optimization tools on PC. In all the cases when the number of nodes in the ring network is smaller than 15, we forced the CPLEX program to terminate after 100s if it is still running; for the number of the ring network is no less than 15, the termination time is set to 1000s. For different number of nodes in ring network and the traffic granularity, the best solution found when the CPLEX program was terminated is provided in Table 1.

From the results in Table 1, one can observe that as the traffic granularity quadruples in size, the number of ADMs required is reduced by approximate half. Even for $N=7$ the CPLEX program was still running after 100s. Hence it is computationally infeasible to run the CPLEX program when the size of the ring network is big.

5. Conclusion

In this paper, we have studied the traffic grooming problem for WDM ring networks. An ILP formulation was proposed for the problem and a simulation analysis is given to an all-to-all traffic case in WDM ring networks to study the influence of traffic granularity to the minimum ADMs required to support this all-to-all traffic.

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<th>Table 1: Number of ADMs required</th>
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References
