

# Many-to-one Traffic Grooming in WDM Networks

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**Abstract**— This paper addresses the grooming of many-to-one traffic demands in WDM networks on arbitrary topologies. The problem is solved in an optimal way by developing an Integer Linear Program (ILP). The objective is to minimize the cost of the network, by minimizing the total number of higher layer components (e.g., electronic ADMs) and the total number of the wavelengths used in the network. The ILP formulation is generic and can handle varying amounts of traffic from each source to a common destination. The traffic delivery can be made over a single or multiple lightpaths in order to minimize the cost. Also, at each aggregation point in a many-to-one tree, an arbitrary fraction of the data coming from each source can be selected. This helps in reducing the bandwidth wastage, as redundant or duplicate data will not be propagated through the network.

Keywords: Wavelength Division Multiplexing (WDM) networks; traffic grooming; Add/Drop Multiplexers (ADM); IP routers, many-to-one traffic; data aggregation; Integer Linear Programming (ILP).

## I. INTRODUCTION

Wavelength Division Networks (WDM) provide high bandwidth, on the order of tens of Gigabits per second per wavelength. However, most of the applications' bandwidth requirements are subwavelength. For example, HDTV can work well with just 20 Mbps, while a normal TV channel typically requires less than 2 Mbps, when compressed using MPEG-2. Therefore, many such connections can be groomed together onto a single wavelength. Traffic grooming is thus defined as the intelligent allocation of the demands onto available wavelengths such that the cost of the network is minimized. The dominant cost factor in WDM networks, however, is not the number of wavelengths but rather the network components [2], specifically, higher layer equipment, such as SONET Add/Drop multiplexers (ADMs) or IP router ports. Therefore, while designing cost-effective WDM networks the emphasis should be on the minimization of the higher layer equipment over minimization of the other factors, such as total number of wavelengths used in the networks.

The traffic grooming problem with arbitrary traffic, even for simple topologies, has been proved to be NP-Complete [1]. In general the traffic grooming problem is regarded to be even harder than the combined virtual topology design, and Routing and Wavelength Assignment (RWA) problem [2]. To make the problem somewhat less difficult, many relaxations have been considered in the literature. For example, most of the

studies allow the traffic between each source-destination set to be (vertically) split over multiple wavelengths - a condition known as bifurcation. Due to bifurcation different components of the same traffic demand may traverse different links. This provision provides flexibility in traffic allocation, which may lead to a reduction in the number of wavelengths as well as the number of the ADMs. However, bifurcation increases the complexity and the cost of traffic reassembly, and may also introduce jitter at the application layer.

Most of the studies in traffic grooming have exclusively dealt with unicast traffic, except [3], in which the authors consider multicast traffic. However, as WDM networks are extending their presence from merely in backbone networks to metro and local area networks, there is a dire need to accommodate various existing applications onto WDM networks efficiently. In future a sizable portion of the traffic is foreseen to be multipoint, not just multicast, in nature, for example, multi-party conferencing, video distribution, network news distribution, collaborative processing, and web content distribution to proxies [4]. Multipoint traffic can take different forms, e.g., one-to-many, which is used in multicasting applications; and many-to-one, which can be used for resource discovery, service location, data collection, auctions, polling and audience to speaker communication [5]. Although both traffic types have the multipoint factor in common, each type has different characteristics, which warrants a separate study. The many-to-one traffic from a set of sources, making its way to a single common destination, may also share the very same lightpath(s) thus creating a routing tree. However, as compared to a typical multicast tree where a single stream of data coming from a source is split (at a splitting point) into multiple streams, the many-to-one tree aggregates the data coming from different sources (at an aggregation point). This drastically changes the bandwidth and equipment requirements for a many-to-one tree. Hence the algorithms developed for multicast trees are not very useful for designing the many-to-one trees. In this paper, our focus is to groom the many-to-one traffic onto WDM networks such that the number of the required SONET ADM (IP routers/ports) and the wavelengths be minimized.

Traffic grooming in WDM networks is comparatively a new field. Few survey papers have been published in this area [6], [7], [8]. Work on traffic grooming can be categorized based on the traffic patterns (uniform traffic, arbitrary/non-uniform traffic), network topology (unidirectional ring, bidirectional

ring, arbitrary topology) and solution approaches (heuristics, Integer Linear Programs, bounds). Most researchers developed heuristic approaches to the problem [9], [10], [11], [12], while many of them also focused on obtaining bounds on the number of ADMs required for specific topologies and traffic patterns [1], [2], [9], [13], [14]. Few researchers used stochastic combinatorial search techniques to explore the solution space [11]. Optimal approaches are developed in [2] for unidirectional rings, and in [11] for bidirectional rings. Only a few studies considered arbitrary mesh topologies [3], [15], [16], [17], [18]. The authors in [16], [18] developed Integer Linear Programs (ILPs) to determine the optimal solutions for (unicast) traffic grooming on mesh topologies. A number of researchers focused on optimizing factors other than static traffic conditions, and the cost of higher layer components, for example, [19], [20]. Currently, the traffic grooming literature is deficient of multipoint traffic considerations. In [3], the authors developed an ILP that handles multicast traffic, i.e., one-to-many, on random topologies. To the best of our knowledge, no work has been done that considers grooming many-to-one traffic streams on WDM networks.

In this paper, we develop an ILP to find an optimal network design for grooming of many-to-one traffic. As, optical networks are provisioned every few months [21], the traffic can be considered static, and hence optimal, though compute-intensive, approach can be taken. Many-to-one traffic grooming problem involves many difficult subproblems, e.g., routing and wavelength assignment, traffic grooming, traffic aggregation, and non-bifurcation, therefore, a linear formulation requires intelligent manipulation of the problem dynamics. This paper is the first to address grooming of many-to-one traffic in optical networks, and it has the following contributions:

- Our model handles many-to-one traffic on random topologies, and without bifurcation of traffic demands
- The introduced model provides the flexibility of choosing a fraction of the data when data is aggregated from more than one sources.
- The model optimally minimizes the cost of the WDM networks in terms of the number of required ADMs. The model simultaneously reduces the total number of the required wavelengths in the network.

The rest of the paper is organized as follows. In Section II, we present our model and the ILP formulation for the many-to-one traffic grooming problem. In Section III, we present few experimental results, while Section IV concludes the paper.

## II. PROBLEM FORMULATION

In this section we will introduce our model and formulate an ILP for the many-to-one traffic grooming problem on arbitrary network topologies.

### A. Model

We visualize the network at three different levels: the physical level, the lightpath level and the connection level. The physical level represents the topology made of physical

links between nodes, and is an input parameter. We assume that each physical link represents two fibers that are used to communicate in opposite direction and each fiber can support  $W$  wavelengths in only one direction. The lightpath level represents the virtual topology made of all-optical lightpaths, and is an output from the ILP. In our model each lightpath can span several physical links. Also, between any node pair more than one lightpath are allowed to exist, but if they use the same wavelength they must be routed on different physical routes. Connection level links between nodes represent the traffic demand between such nodes. Each link at the connection level is allowed to span multiple lightpaths.

As discussed earlier, in case of many-to-one traffic the bandwidth requirements of the routing tree is very different than that of a typical multicast tree. We define each such point on a many-to-one tree where the data streams, coming from different sources of the same session (and thus destined to a common destination) are aggregated as an *aggregation* point on that tree. We consider the case in which aggregation is implemented in the electronic domain, and requires an ADM. We will then minimize the number of the ADMs, thus leading to reduced network cost. Please note that once signals are available in electronic form, aggregation can be done at a negligible cost by some additional component. However, the aggregation function itself, in terms of bandwidth requirements, is application dependent. Few applications require that all the streams at aggregation points be fully aggregated, i.e., without losing any information. In this case, at an aggregation point, it is a simple addition of the data from all the incoming streams. However, in few applications streams of a same session have redundant or common data, like streams coming from geographically adjacent sensors, and hence a fraction of the data from each stream can be removed before aggregating them together. This helps in reducing the bandwidth wastage, as redundant or duplicate data need not be propagated through the network. Our model is generic and at each aggregation point allows selection of an arbitrary fraction of the data of each stream to be aggregated. We supply this arbitrary fraction as a constant input parameter, namely,  $r$ . The input parameter,  $r$  could be a function of applications' nature or their geographical distribution or both. Note that if  $r = 1$  then it is equivalent to the simple summation of the data from all the incoming streams at an aggregation point, while if  $r = 0.5$  then only half of the data of each incoming stream, at an aggregation point, would be aggregated. The rest of the data, being redundant, can simply be discarded. Thus the factor  $r$  essentially capture the amount of the correlation between the data streams destined to a common destination. Coming up with a linear formulation, in which the factor  $r$  depends on the number of the aggregating streams is even more challenging and is currently under investigation. However, the case of reducing  $n$  incoming streams, for  $n > 1$ , to just one stream is the inverse of multicasting and can be solved using the model developed by the author in [3].

Regarding notation, we will use  $s$  and  $d$  to represent source and destination of a connection,  $i$  and  $j$  to represent the source

and destination nodes of a lightpath,  $m$  and  $n$  to represent the source and destination nodes of a physical link, respectively. In order to simplify notation, we let  $K$  be the total number of sessions terminating at the destinations. Then, each connection  $c_a$ , where  $1 \leq a \leq K$ , corresponds to an ordered pair  $(d, k)$ , where  $d$  is the destination, and  $k$  represents the  $k^{th}$  (unicast or multicast) session terminating at  $d$ . The source set of session  $c_a$  is  $S_{c_a}$ , and  $s$  represents a source in the source set. The rest of the notations used in the paper are defined below.

- **Input parameters:**

- $N$  : total number of nodes in the network
- $W$  : number of wavelengths per fiber <sup>1</sup>
- $g$  : Capacity of a wavelength in terms of the number of basic units of traffic (also called grooming factor)
- $r$  : aggregation ratio; the fraction of the capacity selected of each aggregated stream when two or more streams of the same connection shares a lightpath
- $\alpha$  : cost of an ADM
- $\beta$  : cost of a wavelength
- $Q$ : A very large integer number,  $Q \geq N$
- $P_{mn}$  : physical fiber link (1 or 0) connecting nodes  $m$  and  $n$ .
- $m_{c_a, s}$  : number of basic units of traffic originating from source  $s$  in connection  $c_a$

- **Variables of the ILP:**

- $ADM_n$  : number of ADMs at node  $n$
- $L_{ij}^w$  : number of lightpaths from node  $i$  to node  $j$  on wavelength  $w$
- $L_{ij}$  : number of lightpaths from node  $i$  to node  $j$  on all the wavelengths,  $L_{ij} = \sum_w L_{ij}^w$
- $\psi$  : highest index of wavelength used over any fiber link in the network
- $y_w$  : a binary indicator; must be 1 if there is at least one lightpath in the network on wavelength  $w$
- $F_{mn}^{ij, w}$  : number of lightpaths between node pair  $(i, j)$  routed through fiber  $(m, n)$  on wavelength  $w$
- $Z_{ij}^{c_a, s}$  : a binary indicator; is 1 if and only if the traffic stream from source  $s$  in connection  $c_a$ , is employing a lightpath from  $i$  to  $j$  as an intermediate virtual link
- $M_{ij}^{c_a}$  : a binary indicator; is 1 if and only if at least one of the sources of connection  $c_a$  is using lightpath  $(i, j)$  to reach the destination, i.e,  $\exists s \in S_{c_a}$ , such that  $Z_{ij}^{c_a, s} = 1$
- $E_{ij}^{c_a}$  : a binary indicator; is 1 if and only if at least two of the sources of connection  $c_a$  are using lightpath  $(i, j)$  to reach the destination (the streams from each source need to be aggregated in this case)
- $J_{ij}^{c_a, c_b}$  : a binary indicator; is 1 if and only if connection  $c_a$  and  $c_b$  are groomed on the same lightpath from  $i$  to  $j$
- $G_{ij}^{c_a, s}$  : a binary indicator; conjunction of  $E_{ij}^{c_a}$  and  $Z_{ij}^{c_a, s}$  (i.e,  $E_{ij}^{c_a} \wedge Z_{ij}^{c_a, s}$ )
- $A_{ij}^{c_a, c_b, s}$  : a binary indicator; conjunction of  $J_{ij}^{c_a, c_b}$  and

$Z_{ij}^{c_a, s}$   
 $B_{ij}^{c_a, c_b, s}$  : a binary indicator; conjunction of  $J_{ij}^{c_a, c_b}$  and  
 $P_{ij}^{c_b, s}$

## B. The ILP Formulation

In this subsection we will present the ILP for the many-to-one grooming problem. Our objective is to minimize the total cost of the higher layer equipment by minimizing the total number of the required ADMs, as well the maximum number of different wavelengths on a fiber.

### Objective function:

$$\text{Minimize} : \alpha * \sum_n ADM_n + \beta * \psi \quad (1)$$

In the objective function,  $\alpha$  represents the cost of an ADM, while  $\beta$  represents the weight given to a wavelength, and is usually much smaller than  $\alpha$ .

### Subject to:

- **Number of ADMs:**

The following two constraints ensure that for each originating or terminating lightpath an ADM is present at a node

$$ADM_i \geq \sum_w \sum_{j, j \neq i} L_{ij}^w \quad \forall i \quad (2)$$

$$ADM_i \geq \sum_w \sum_{j, j \neq i} L_{ji}^w \quad \forall i \quad (3)$$

- **Number of wavelengths:**

The following two constraints ensure that  $\psi$  will be the index of the highest numbered wavelength used on any fiber link in the network. Notice that minimizing the  $\psi$  will minimize the total number of different wavelengths in the network and not just the total number of the wavelengths between each node pair

$$\psi \geq w * y_w \quad \forall w \quad (4)$$

$$y_w \geq \sum_i \sum_{j, j \neq i} L_{ij}^w / Q \quad \forall w \quad (5)$$

- **Lightpath level constraints:**

The following constraint ensures that the origin node,  $i$ , of lightpaths  $(i, j)$  has no incoming lightpaths between  $i$  and  $j$

$$\sum_{m, \text{for } P_{mi}=1} F_{mi}^{ij, w} = 0 \quad \forall i, j, w \quad (6)$$

Similarly, the following constraint ensures that the destination node,  $j$ , of lightpaths  $(i, j)$  has no outgoing lightpaths between  $i$  and  $j$

$$\sum_{n, \text{for } P_{in}=1} F_{jn}^{ij, w} = 0 \quad \forall i, j, w \quad (7)$$

<sup>1</sup>Although we start with  $W$  wavelengths, the ILP minimizes the total number of required wavelengths.

The following constraint preserves the wavelength continuity of lightpaths over multiple physical links

$$\sum_{m, \text{for } P_{m,x}=1} F_{mx}^{ij,w} = \sum_{n, \text{for } P_{x,n}=1} F_{xn}^{ij,w} \quad \forall w, i, j, x; x \neq i, j \quad (8)$$

Equations (9) and (10) compute the total number of the lightpaths on wavelength  $w$  between nodes  $i$  and  $j$ , supported by the underlying physical topology.

$$\sum_{m, \text{for } P_{m,j}=1} F_{mj}^{ij,w} = L_{ij}^w \quad \forall i, j, w \quad (9)$$

$$\sum_{n, \text{for } P_{i,n}=1} F_{in}^{ij,w} = L_{ij}^w \quad \forall i, j, w \quad (10)$$

Equations (8), (9) and (10) together ensure that for each lightpath there exists a corresponding physical path, while maintaining wavelength continuity over the physical path. Equation (11) below ensures that on a wavelength,  $w$ , on fiber  $(m, n)$ , only one lightpath is present.

$$\sum_i \sum_{j, \text{for } P_{m,n}=1} F_{mn}^{ij,w} \leq 1 \quad \forall m, n, w \quad (11)$$

- *Connection topology constraints:*

The following two constraints ensure that for the connection  $c_a$ , sourced at  $s$ , no traffic is coming in (going out) the source (destination), respectively

$$\sum_{i, i \neq s} Z_{is}^{c_a, s} = 0 \quad \forall c_a, s \in S_{c_a} \quad (12)$$

$$\sum_{j, j \neq d} Z_{dj}^{c_a, s} = 0 \quad \forall c_a, s \in S_{c_a} \quad (13)$$

The following two constraints ensure that the connection traffic between  $s$  and  $d$  is originating (terminating) at  $s$  ( $d$ ), respectively

$$\sum_{j, j \neq s} Z_{sj}^{c_a, s} = 1 \quad \forall c_a, s \in S_{c_a} \quad (14)$$

$$\sum_{i, i \neq d} Z_{id}^{c_a, s} = 1 \quad \forall c_a, s \in S_{c_a} \quad (15)$$

The following constraint preserves the continuity of connection traffic on multiple lightpaths

$$\sum_{i, i \neq x, i \neq d} Z_{ix}^{c_a, s} = \sum_{j, j \neq x, j \neq s} Z_{xj}^{c_a, s} \quad \forall c_a, s \in S_{c_a}, x, (x \neq s, d) \quad (16)$$

The following two constraints determine if more than one source, among the same source set, are using the lightpath(s) between nodes  $i$  and  $j$ .

$$M_{ij}^{c_a} \geq \sum_{s \in S_{c_a}} Z_{ij}^{c_a, s} / Q \quad \forall c_a, i, j \quad (17)$$

$$M_{ij}^{c_a} \leq \sum_{s \in S_{c_a}} Z_{ij}^{c_a, s} \quad \forall c_a, i, j \quad (18)$$

The following two constraints determine if at least two sources, among the same source set, are using the lightpath(s) between nodes  $i$  and  $j$ .

$$E_{ij}^{c_a} \geq (\sum_{s \in S_{c_a}} Z_{ij}^{c_a, s} - 1) / Q \quad \forall c_a, i, j \quad (19)$$

$$E_{ij}^{c_a} \leq \sum_{s \in S_{c_a}} Z_{ij}^{c_a, s} / 2 \quad \forall c_a, i, j \quad (20)$$

Note that if  $E_{ij}^{c_a}$  is 1, then this implies that data from sources in  $S_{c_a}$ , for which  $Z_{ij}^{c_a, s} = 1$  are aggregated on this lightpath between nodes  $i$  and  $j$ .

The following constraints ensure that the capacity of the streams on all the lightpaths from  $i$  to  $j$  do not exceed the lightpaths' physical capacity

$$G_{ij}^{c_a, s} = E_{ij}^{c_a} \wedge Z_{ij}^{c_a, s} \quad (21)$$

$$\sum_{c_a=1}^K \sum_{s \in S_{c_a}} (m_{c_a, s} Z_{ij}^{c_a, s} - [m_{c_a, s} * (1-r)] G_{ij}^{c_a, s}) \leq L_{ij} * g \quad \forall i, j \quad (22)$$

The first term on the left hand side of the inequality (22) computes the total capacity of all the connections present on the lightpath(s) between nodes  $i$  and  $j$  considering full capacity of each connection, while the second term subtracts the fraction of the capacity of each connection reduced due to the aggregation. Note that for every such connection for which there is no aggregated streams on the lightpath(s) between nodes  $i$  and  $j$ , the second term would equate to zero.

- *Non-Bifurcation:*

As mentioned earlier, there could exist more than one lightpath, between any two nodes  $i$  and  $j$ , even on the same wavelength, but using different physical routes. A demand can get bifurcated (vertically split) over multiple lightpaths between nodes  $i$  and  $j$ , because the above constraints restrict the traffic on all lightpaths between two nodes, without constraining the traffic on each lightpath. The following set of constraints will ensure, together with the above constraints, a non-bifurcated solution.

$$J_{ij}^{c_a, c_b} \leq (M_{ij}^{c_a} + M_{ij}^{c_b}) / 2 \quad \forall c_a, c_b, i, j \quad (23)$$

$$A_{ij}^{c_a, c_b, s} = J_{ij}^{c_a, c_b} \wedge Z_{ij}^{c_a, s} \quad (24)$$

$$B_{ij}^{c_a, c_b, s} = J_{ij}^{c_a, c_b} \wedge G_{ij}^{c_b, s} \quad (25)$$

$$\sum_{s \in S_{c_a}} (m_{c_a, s} Z_{ij}^{c_a, s} - [m_{c_a, s} * (1-r)] G_{ij}^{c_a, s}) + \sum_{c_b, c_b \neq c_a} \sum_{s \in S_{c_b}} (m_{c_b, s} A_{ij}^{c_a, c_b, s} - [m_{c_b, s} * (1-r)] B_{ij}^{c_a, c_b, s}) \leq g \quad \forall c_a, i, j \quad (26)$$

$$L_{ij} = J_{ij}^{c_1, c_1} + \sum_{a=2}^K (J_{ij}^{c_a, c_a} - \sqrt{a-1} J_{ij}^{c_b, c_a}) \quad \forall i, j \quad (27)$$

Equation (23) ensures that if  $J_{ij}^{c_a, c_b}$  is 1 (i.e., connections  $c_a$  and  $c_b$  share the same lightpath between nodes  $i$  and  $j$ ), then at least one stream of connection  $c_a$  and one stream of connection  $c_b$  must be utilizing the lightpath between nodes  $i$  and  $j$ . The equation (26) ensures that the capacity of each lightpath is not exceeded. The first term on the left hand side of the inequality 26 computes the effective bandwidth used by all the streams of the connection  $c_a$  that share the lightpath between nodes  $i$  and  $j$ , while the second term computes the effective bandwidth used by all such streams of all other connections ( $c_b, c_b \neq c_a$ ) that share the very same lightpath with streams of the connection  $c_a$ . Finally, equation (27) ensures that the total number of shared and unshared lightpaths between nodes  $(i, j)$  must be equal to the total number of lightpaths between these two nodes. The equation counts all the lightpaths between nodes  $(i, j)$  by counting all the connections sharing a lightpath only once.

Note that the constraint (22) ensures that the total capacity of all the connections groomed on the lightpaths between nodes  $i$  and  $j$  does not exceed the capacity of all those lightpaths. However, the constraint (26) ensures that all the aggregated streams of the same connection do not get split among the lightpaths between node  $i$  and  $j$ . This introduces a limitation to our formulation: the capacity of the aggregated streams should be less than or equal to the capacity of a lightpath (i.e.,  $\sum_{s \in S_{c_a}} m_{c_a, s} \leq g, \forall c_a$ ). If the value of the aggregated streams on a lightpath, say between node  $i$  and  $j$  is greater than  $g$ , then to ensure non-bifurcation the formulation will force the solution to aggregate, on lightpaths between node  $i$  and  $j$ , only that many streams whose capacity does not exceed  $g$ . The rest of the streams will then be routed and aggregated using lightpaths other than those between node  $i$  and  $j$ .

Finally, the disjunction operation, say,  $H = \vee_{i=1}^n U_i, H \in \{0, 1\}$ , is implemented using the following two constraints

$$H \leq \sum_{i=1}^n U_i \quad \text{and} \quad H \geq \sum_{i=1}^n U_i / n$$

While the conjunction operation, say,  $I = \wedge_{i=1}^n U_i, I \in \{0, 1\}$ , is implemented using the following two constraints

$$I \leq \sum_{i=1}^n U_i / n \quad \text{and} \quad I \geq \sum_{i=1}^n U_i - (n - 1)$$

### III. EXPERIMENTAL RESULTS

In this section we will present the results of the ILP model for many-to-one traffic grooming problem. Our purpose is to demonstrate the correctness of our model. The network used in the experiments consists of 6 nodes, and is shown in Figure 1. The traffic demands consist of integer multiples of OC-3 connections. The capacity of a wavelength is OC-48, and therefore, the grooming factor,  $g$ , is 16.

The ILP problem is solved using the CPLEX linear programming package [22]. The values of  $\alpha$  and  $\beta$  are selected to be 100 and 1, respectively. A sample traffic that consists of a mix of many-to-one and one-to-one sessions is generated

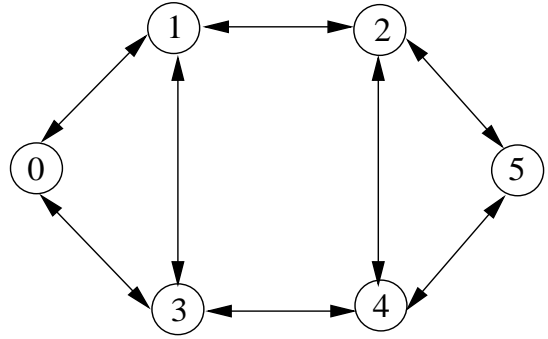


Fig. 1. A six node network

and is shown in Table I. We used the same traffic set to run three different experiments with  $r = 1$ , and  $r = 0.5$ , and  $r = 0.75$ , respectively. A higher value of  $r$  suggests a lesser correlation between the data streams destined to a common destination, and vice versa. In the Table I the last column lists the lightpaths employed by the many-to-one trees to deliver the traffic when  $r = 1$ . Shared usage of few lightpaths by more than one connection shows that these connections are groomed.

The problem is run using four wavelengths. However, the optimal solution always reduced the total number of wavelengths to two. When  $r = 1$ , the number of the ADMs and the number of the wavelengths required to accommodate the traffic set is 13 and 2, respectively. When  $r = 0.5$ , the required number of the ADMs are reduced to 11 while the required number of wavelengths are still 2. The higher amount of correlation in this case helped to remove the redundant data at each aggregation point, which in turn reduced the number of the ADMs required to terminate the traffic. When  $r = 0.75$ , the required number of the ADMs and wavelengths are same as that of  $r = 1$  case, however, the total number of the lightpaths in this case are lesser than that of  $r = 1$  case. This shows that even if one is able to achieve lesser number of lightpaths, this does not directly translates into reduction of the dominant cost factors of the network. Table II lists the number of the ADMs required at each node for different values of  $r$ . Finally, III lists all the lightpaths required to support the many-to-one traffic, for different values of  $r$ .

We run few experiments on the six node topology using large number of sessions. The results are omitted here due to space constraint. However, the complexity of the ILP does not warrant running it for large topologies within reasonable time. Therefore, one need to resort to the heuristic approaches. However, the above ILP can act as a benchmark to determine the performance of any heuristic designed for many-to-one traffic grooming problem.

### IV. CONCLUSION

In this paper we developed an ILP to optimally solve the many-to-one traffic grooming problem on arbitrary WDM networks. We exploited the specifics of the problem to have a linear formulation, of otherwise a non-linear problem. Also,

Destination	Source set	Traffic (multiples of OC-3)	Lightpaths
0	{1,2,4}	{6,4,6}	1-0, 2-0, 4-5, 5-0
1	{0}	{12}	0-1
	{3,5}	{8,6}	3-1, 5-1
2	{1}	{8}	1-2
	{0,3,5}	{3,8,4}	0-1, 1-2, 3-2, 5-1
3	{0}	{16}	0-3
	{0,1}	{12,3}	0-3, 1-0
5	{3}	{8}	3-1
	{1,4}	{3,8}	1-5, 4-5

TABLE I

MANY-TO-ONE AND ONE-TO-ONE TRAFFIC DEMANDS AND THE CORRESPONDING LIGHTPATHS OBTAINED BY THE ILP.

Node#	$r = 1$	$r = 0.5$	$r = 0.75$
0	3	3	4
1	3	2	2
2	2	1	2
3	2	3	2
4	1	1	1
5	2	1	2

TABLE II

NUMBER OF ADMs REQUIRED AT EACH NODE

we ensure non-bifurcation of the traffic. Our model and its formulation is generic, such that the full capacity of the streams aggregated at a common point (aggregation point) can be either fully summed together or a fraction of each stream be aggregated. The fractional factor used for aggregation is supplied as an input parameter and depends on the correlation among the data stream destined to a common destination. One of the limitations of the given formulation is that the fractional factor is independent of the number of the aggregated streams. Many-to-one traffic grooming in WDM networks is a totally new area and many future directions are possible. One of the future direction is to consider a fractional factor that depends on the number of the aggregating streams. Designing a linear formulation for such a scenario is a challenging task. Another future direction could be to develop heuristic approaches to handle many-to-one traffic on arbitrary topologies. Still another area is to investigate the heuristics that perform grooming while handling dynamic many-to-one traffic.

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$r = 1$	$r = 0.5$	$r = 0.75$
0-1 ( $\lambda_1$ )	0-1 ( $\lambda_2$ )	0-1 ( $\lambda_1$ )
0-3 ( $\lambda_1$ )	0-3 ( $\lambda_2$ )	0-3 ( $\lambda_1$ )
0-3 ( $\lambda_2$ )	0-3 ( $\lambda_1$ )	0-3 ( $\lambda_2$ )
1-0 ( $\lambda_1$ )	1-0 ( $\lambda_2$ )	0-5 ( $\lambda_2$ )
1-2 ( $\lambda_1$ )	1-2 ( $\lambda_1$ )	1-0 ( $\lambda_1$ )
1-5 ( $\lambda_2$ )	2-4 ( $\lambda_1$ )	1-2 ( $\lambda_1$ )
2-0 ( $\lambda_1$ )	3-1 ( $\lambda_1$ )	2-0 ( $\lambda_2$ )
3-1 ( $\lambda_2$ )	3-5 ( $\lambda_2$ )	3-2 ( $\lambda_1$ )
3-2 ( $\lambda_1$ )	4-0 ( $\lambda_1$ )	3-5 ( $\lambda_2$ )
4-5 ( $\lambda_1$ )	5-3 ( $\lambda_2$ )	4-0 ( $\lambda_1$ )
5-0 ( $\lambda_2$ )	-	5-1 ( $\lambda_1$ )
5-1 ( $\lambda_2$ )	-	-

TABLE III

LIGHTPATHS OBTAINED FOR  $r = 1$ ,  $r = 0.5$  AND  $r = 0.75$ , AND THEIR CORRESPONDING WAVELENGTHS

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