New Techniques for Efficient Traffic Grooming in WDM Mesh Networks

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Abstract—Traffic grooming techniques are used to combine low-speed data streams onto high-speed lightpaths with the objective of minimizing the network cost, or maximizing the network throughput. In this paper, we first present an efficient Integer Linear Program (ILP) formulation for traffic grooming on mesh WDM networks. Our formulation can be easily modified to implement different objective functions. Unlike previous formulations, our ILP formulation can be used for practical sized networks with several hundred requests. We then propose a second ILP for traffic grooming, with the simplifying assumption that RWA is not an issue. This second formulation is able to generate, in a reasonable time, grooming strategies for networks with over 30 nodes, with hundreds and even thousands of low-speed data streams. Finally, we introduce a set of ILP formulations for traffic grooming, where the logical topology is specified. We have studied, using simulation, the time needed to determine grooming strategies, using the different ILP formulations.

I. INTRODUCTION

Wavelength Division Multiplexing (WDM) in optical networks has made possible high throughput backbone networks [16], [19]. The physical topology of a wavelength routed WDM network is often depicted by a graph $G_P = (V_P, E_P)$ where $V_P$ is a set of nodes, each representing a router node, or an end-node (a potential source or destination of data communication). A lightpath [19] in an optical network is a point-to-point communication path supporting a data rate of 2.5, 10 or even 40 giga-bits per second (Gbps) that optically connects a transmitter at a source end-node to a receiver at a destination end-node with no opto-electronic conversion at any intermediate node in the route from the source to the destination of the communication. The logical topology (also called the virtual topology) [19], [20] of a WDM network is represented by a graph $G_L = (V_L, E_L)$ where the set of nodes, $V_L$, is the set of all end-nodes in the set $V_P$ of graph $G_P$. If there is a lightpath from end-node $i$ to end-node $j$, there is a directed edge, often called logical (or virtual) edge, $i \rightarrow j$, from $i$ to $j$, in the logical topology. Lightpaths between every pairs of end nodes are not, in general, feasible. To service a request for a data stream from a source node $s$ to a destination node $d$, $s$ communicates with $d$, typically using a directed multi-hop [19] path, called a logical path, from $s$ to $d$ in the graph $G_L$.

As compared to the huge bandwidth of a lightpath, individual requests for connections are typically for data streams at a much lower data communication rate, of the order of megabits per second (Mbps). Traffic Grooming in WDM can be defined as a family of techniques for combining a number of low-speed data streams from users so that the high capacity of each lightpath may be used as efficiently as possible [4], [5], [8], [10], [15], [23], [25], [26]. There are two basic approaches [23] in traffic grooming:

Approach i) for a given set of traffic requests, minimize the total network cost, with the condition that all traffic requests are satisfied.

Approach ii) for given resource limitations and traffic demands, maximize the network throughput, measured by the total amount of traffic that is successfully carried by the network.

The complete logical topology design and traffic grooming problem has the following subproblems that have to be solved simultaneously for optimizing the network cost or the resource utilization:

Subproblem i) Topology Design (TD): find the logical topology of the network,

Subproblem ii) Route and Wavelength Assignment (RWA): ensure that a feasible RWA, to realize each logical edge, is possible,

Subproblem iii) Traffic Routing (TR): decide which logical path(s) should be used for each data stream so that the total payload of each edge in the logical topology never exceeds the capacity of a lightpath.

Integer linear program (ILP) formulations to solve the combined logical topology design and traffic grooming problem for mesh networks have been proposed in the literature [19], [20]. Such ILP formulations become computationally intractable, even for moderate sized networks, and heuristics are typically proposed for such problems. For example in [25], the ILP formulation fails to obtain an optimal solution, even for a small network with 6 node and 8 links. In [24], the author has obtained a solution of up to 14 nodes, after applying the Lagrangian Relaxation.

In this paper we have:

- proposed an efficient ILP formulation, that addresses the combined logical topology design, RWA and traffic grooming problem for mesh networks,
- shown that our formulation is able to generate optimal solutions for practical networks, with up to 20 nodes and hundreds of traffic requests,
- proposed a simplified formulation, by removing the RWA
requirements from our initial formulation. These formulations optimally solve the combined topology design and traffic routing problems. We have shown that networks, with 30 nodes and thousands of requests, can be effectively handled using the simplified formulation.

- presented optimal formulations for the traffic routing problem, in situations where the logical topology is already specified. These formulations can handle large networks with thousands of requests.
- made a comparative study, of the time required to solve the traffic grooming problem, using different formulations, and made the observation that the objective function can affect the solution time very significantly.

In Section II we have proposed the formulations for topology design and traffic grooming. In Section III, we have proposed the set of formulations for traffic routing over a given topology. In Section IV, we describe our experimental results and present our conclusions in Section V.

II. ILP Formulations for Traffic Grooming

In this section we first present a formulation that addresses the complete traffic grooming problem, including topology design as well as routing and wavelength assignment (RWA) of lightpaths, for WDM mesh networks. We then propose a simplified formulation, that does not consider RWA. For the RWA problem, we do not search for all possible paths over the physical topology. Instead we pre-compute a set of \( \mathbb{R} \) “promising” routes over the physical topology, for each pair of end-nodes. If a lightpath is to be established from a source node \( s \) to a destination node \( d \), we select one of the \( \mathbb{R} \) routes between \( s \) and \( d \) as the physical route for the lightpath. In our experiments, we have used \( \mathbb{R} = 3 \). If possible, we generate 3 edge-disjoint paths between each pair of end-nodes. If this is not possible, for a given pair of nodes, we generate three distinct paths over the physical topology in a way that minimizes the number of common links.

In our formulations we have a set \( Q \) of requests. Each request is characterized by its source, its destination and its data communication rate, using the OC-\( n \) notation. In general, there are a number of requests from a given source, to any given destination.

Each of our formulations can easily be adapted to consider different objective functions as follows:

i) Minimize the total weighted hop count corresponding to the logical paths used to route each traffic request. A similar objective was used in [13]. However, the formulation in [13] only considered a single aggregated data stream between each pair of end-nodes. The heuristic proposed in [25], where the single hop communication was favored over multi-hop communication, captures the same idea.

ii) Minimize the number of lightpaths in the network. This objective function is directly related to the cost of the transceivers. It has been used in [12] (without considering RWA), and in [9] (with fixed routes) for mesh networks.

Similar objectives have been proposed in [3], [7], [8], [11] for ring networks.

iii) Maximize the weighted sum of requests that may be handled by the network, for a specified set of network resources. Here, the weight of a request is the required data communication rate, in OC-\( n \) notations. This addresses the same problem as the formulation in [25], which also considers the full RWA problem. However, our formulation requires significantly fewer integer variables compared to [25]. This objective was also considered in [14], [24].

A. Notation used

In our sets of formulations we will use the following symbols\(^1\) to represent input data:

- \( V_L \): Set of end-nodes in the network.
- \( n \): Number of end-nodes in the network.
- \( E_P \): Set of directed edges in the physical topology, each edge representing a fiber in the network.
- \( m \): Cardinality of set \( E_P \).
- \( E_L \): Set of directed edges in the logical topology, each edge representing a lightpath.
- \( n_{ch} \): Number of channels supported by each fiber in the network. The allowed channel numbers on any fiber will be 1, 2, ..., \( n_{ch} \).
- \( K \): Set \( \{1, 2, ..., n_{ch}\} \) of channels numbers on each fiber.
- \( P \): Set of potential lightpaths to be considered for inclusion in the network. Each lightpath, selected using any one of our formulations, will constitute an edge in the logical topology. Since all possible potential lightpaths in the network has to be considered, the set \( P \) has \( n(n-1) \) elements.
- \( o(p) \) (\( l(p) \)): Originating (Terminating) node of lightpath \( p \).
- \( q \): Capacity of lightpath \( p \) using the OC-\( n \) notation.
- \( Q \): Set of all traffic requests.
- \( n_q \): Number of elements, \(|Q|\), in \( Q \).
- \( \mathcal{P} \): The cardinality, \(|\mathcal{P}|\), of \( \mathcal{P} \).
- \( s_q \) (\( d_q \)): Source (Destination) node of traffic request \( q \).
- \( t_q \): Data communication rate for traffic request \( q \) using the OC-\( n \) notation.
- \( T^X_q \) (\( R^X_q \)): Number of transmitters (receivers) at end-node \( i \).
- \( \mathbb{R} \): Number of “promising” routes through the physical topology to be considered for RWA between each ordered pair of end-nodes.
- \( D \): Fiber-lightpath incidence matrix with \(|E_P|\) rows and \( \mathbb{R} \times \mathbb{R} \) columns.
- \( d^r_{p,e} \): The element of matrix \( D \) in row \( e \in E_P \) and the column corresponding to lightpath \( p \in \mathcal{P} \) and route \( r, 1 \leq r \leq \mathbb{R} \). The element is defined as follows:

\(^1\)Some of the symbols described here will be used only in some of the formulations.
\[ d^e_{p,r} = \begin{cases} 
1 & \text{if the } p^{th} \text{ physical route for lightpath } p \\
0 & \text{otherwise.}
\end{cases} \]

We also define the following variables:

- \( b_p \): Binary variable defined as follows:
  \[
b_p = \begin{cases} 
1 & \text{if lightpath } p \in \mathcal{P} \text{ is selected to constitute an edge in the logical topology,} \\
0 & \text{otherwise.}
\end{cases}
\]

- \( f_{p,q} \): Binary variable defined as follows:
  \[
f_{p,q} = \begin{cases} 
1 & \text{if request } q \text{ is routed over lightpath } p, \\
0 & \text{otherwise.}
\end{cases}
\]

- \( y_q \): Binary variable defined as follows:
  \[
y_q = \begin{cases} 
1 & \text{if request } q \text{ is not blocked,} \\
0 & \text{otherwise.}
\end{cases}
\]

- \( x_{r,p} \): Binary variable defined as follows:
  \[
x_{r,p} = \begin{cases} 
1 & \text{if the } p^{th} \text{ physical route is selected for the } r^{th} \text{ lightpath,} \\
0 & \text{otherwise.}
\end{cases}
\]

- \( w_{k,p} \): Binary variable defined as follows:
  \[
w_{k,p} = \begin{cases} 
1 & \text{if channel } k \text{ is assigned to the } p^{th} \text{ lightpath,} \\
0 & \text{otherwise.}
\end{cases}
\]

- \( \delta^e_{k,p} \): A continuous variable, whose value is restricted, using the constraints in our formulations, as follows:
  \[
\delta^e_{k,p} = \begin{cases} 
1 & \text{if the } p^{th} \text{ lightpath uses physical edge } e \text{ and channel } k, \\
0 & \text{otherwise.}
\end{cases}
\]

- \( \lambda_{\text{max}} \): The maximum amount of traffic, using the OC-\(n\) notation, on any lightpath.

**B. Formulation for Minimizing Resource Requirement (ILP1a)**

Minimize \[ \sum_{p \in \mathcal{P}} \sum_{q \in \mathcal{Q}} f_{p,q} t_q \] (1)

Subject to:

a) Flow constraints:

\[ \sum_{q:(p) = i} f_{p,q} - \sum_{p:(l) = i} f_{p,q} = \begin{cases} 
1 & \text{if } i = s_q, \\
-1 & \text{if } i = d_q, \\
0 & \text{otherwise.}
\end{cases} \] (2)

Constraint (2) has to be repeated for all \( q \in \mathcal{Q} \) and for all \( i \in V_L \).

b) Capacity constraint for each lightpath:

\[ \sum_{q \in \mathcal{Q}} f_{p,q} t_q \leq g \cdot b_p, \quad \forall p \in \mathcal{P} \] (3)

c) Transceiver constraints at each node:

\[ \sum_{p:(o(p) = i)} b_p \leq T^i_{X}, \quad \forall i \in V_L \] (4)

d) RWA constraints:

\[ \sum_{r=1}^{\mathbb{R}} x_{r,p} = b_p, \quad \forall p \in \mathcal{P} \] (6)

\[ \sum_{k=1}^{\mathbb{N}_p} w_{k,p} = b_p, \quad \forall p \in \mathcal{P} \] (7)

\[ \sum_{r=1}^{\mathbb{R}} x_{r,p} \cdot d^e_{p,r} + w_{k,p} - \delta^e_{k,p} \leq 1, \quad \forall k \in \mathcal{K}, \quad \forall e \in \mathcal{E}_p, \] (8)

\[ \sum_{r=1}^{\mathbb{R}} x_{r,p} \cdot d^e_{p,r} - \delta^e_{k,p} \geq 0, \quad \forall k \in \mathcal{K}, \quad \forall e \in \mathcal{E}_p, \] (8a)

\[ w_{k,p} - \delta^e_{k,p} \geq 0, \quad \forall k \in \mathcal{K}, \quad \forall e \in \mathcal{E}_p, \quad \forall p \in \mathcal{P} \] (8b)

\[ \sum_{p \in \mathcal{P}} \delta^e_{k,p} \leq 1, \quad \forall k \in \mathcal{K}, \forall e \in \mathcal{E}_p \] (9)

Equation (1) is the objective function that minimizes the total amount of optical resources used to accommodate a given set of traffic requests, by minimizing the weighted hop count. This approach attempts to maximize the total amount of spare capacity available on all the lightpaths. This increases the chances of new requests being accommodated successfully, without requiring a change in the logical topology. The solutions generated by ILP1a typically use up all available transceivers at each node. The solutions also favor single-hop communications for larger traffic requests. This objective can be easily changed to minimize the total number of lightpaths, \[ \sum_{p \in \mathcal{P}} b_p, \] needed to accommodate all the traffic requests. Since each lightpath requires one transmitter and one receiver, the objective minimizes the cost of the network, by minimizing the number of costly optical transceivers.

Constraint (2) is the standard flow constraint [2], and is used to route each request over the logical topology, using a single multi-hop logical path, in accordance with the non-bifurcation model used in this paper. Constraint (3) ensures that no traffic is routed on lightpath \( p \), if the lightpath is not included in the logical topology (i.e. \( b_p = 0 \)). It also ensures that the total traffic on lightpath \( p \) does not exceed the capacity \( g \) of the lightpath. Constraint (4) ((5)) ensures that the total number of lightpaths originating from (terminating at) any end-node does not exceed the number of transmitters (receivers) available at that node. Constraints (6) - (9) are used to perform RWA for each selected lightpath. Constraint (6) ensures that, if the \( p^{th} \) lightpath is included in the logical topology, then it is allocated exactly one route over the physical topology. Constraint (7)
enforces the wavelength continuity constraint and ensures that exactly one wavelength is assigned to each selected lightpath. If a lightpath is not selected (\( b_{p} = 0 \)) then no route or wavelength is assigned to the lightpath.

Constraint (8) - (8b) are used to set \( \delta_{k,p} \) if:

\[
\begin{align*}
& \sum_{r=1}^{R} x_{r,p} \cdot d_{r,p}^{e} = 1 \\
& b_{p} = 1.
\end{align*}
\]

If the above conditions are not satisfied, \( \delta_{k,p}^{e} = 0. \)

If \( \sum_{r=1}^{R} x_{r,p} \cdot d_{r,p}^{e} = 0 \) (\( w_{k,p} = 0 \)), constraints (8a), (8b) become \( \delta_{k,p}^{e} \geq 1, 1 \leq \delta_{k,p}^{e} \) and \( 1 \geq \delta_{k,p}^{e} \) respectively.

We note that \( \delta_{k,p}^{e} \) is defined as a continuous variable, even though it is constrained to take on integer values of 0 or 1 only. The use of this technique significantly reduces the number of integer variables in this formulation and hence the time needed to solve it [18]. Finally, constraint (9) ensures that a particular channel \( k \) on a physical edge \( e \) cannot be assigned to more than one lightpath.

C. Formulation for Maximizing Throughput (ILP1b)

The previous formulation assumes that the entire set of traffic requests can be accommodated in the network. If this is not the case, our formulation can be modified slightly, as shown below, to maximize the amount of traffic that can be successfully handled by the network.

Maximize \( \sum_{q \in Q} y_{q} \cdot t_{q} \) \hspace{1cm} (10)

Subject to:

a) Flow constraint.

\[
\sum_{p: \sigma(p) = i} f_{p,q} - \sum_{p: \pi(p) = i} f_{p,q} = \begin{cases} y_{q} & \text{if } i = s_{q}, \\
-y_{q} & \text{if } i = d_{q}, \\
0 & \text{otherwise}. \end{cases}
\]

Constraint (11) has to be repeated for all \( q \in Q \) and for all \( i \in V_{L}. \)

b - d) Constraints 3 - 9.

e) Blocked request constraints:

\[
f_{p,q} \leq y_{q} \hspace{1cm} \forall p \in P
\]

The above formulation uses a new type of integer variables \( y_{q} \), which specifies whether traffic request \( q \) can be accommodated in the network. Equation (10) is the objective function that maximizes the weighted sum of traffic requests, \( \sum_{q \in Q} y_{q} \cdot t_{q} \), which can be handled by the network. This value depends on available resources such as the number of transceivers per node, the capacity of a lightpath and the number of available channels per fiber. Constraint (2) in ILP1a is replaced by constraint (11). This enforces the flow constraints only for commodities that are accommodated in the network (i.e., \( y_{q} = 1 \)). Constraint (12) ensures that if a request \( q \) is blocked, (i.e., \( y_{q} = 0 \)), then it is not allocated any bandwidth on any lightpath (\( f_{p,q} \leq y_{q}, \forall p, p \in P \)).

D. Topology Design and Traffic Routing

In recent years, the number of lightpaths on a single fiber has increased tremendously, accommodating up to 160 WDM channels [17], [19]. In many cases, WDM channels are no longer the scarce resources to be the primary targets of optimization. It is reasonable to assume that RWA may be solved in a separate step [12], [19] or simplified considerably - in [9], for instance, the route is specified, leaving only the channels to be determined. In this section, we propose a simplified formulation ILP2a, which considers the integrated topology design and traffic routing problems, without considering RWA. This is accomplished simply by removing the RWA constraints (constraints 6 - 9) from the complete formulation given in ILP1a. In cases where it is appropriate to ignore RWA, due to the availability of a large number of channels per fiber, ILP2a can be used to quickly generate solutions for the static traffic grooming problem.

III. ILP FORMULATIONS FOR TRAFFIC ROUTING

The formulations presented in this section assume that the logical topology is already known and focuses on routing the traffic over the logical topology. The traffic routing problem (TR) for the bifurcated model is relatively easier and may be solved using standard multi-commodity network flow techniques [19]. For the non-bifurcated model, which we consider in this paper, traffic routing itself has been recognized as an inherently difficult problem [6], and can become computationally intractable, particularly when considering hundreds, or even thousands of low-speed traffic requests.

We have considered three possible objectives for the traffic routing problem. Formulation ILP3a (ILP3b) has exactly the same objective as formulation ILP1a (ILP1b). The objective of ILP3c is to minimize the congestion of the network, defined as the maximum traffic load on a logical link. This is a well-known objective that has been used for traffic routing, for the bifurcated grooming model [19]. The flow constraints for ILP3a, ILP3c (ILP3b) remain the same as those given in ILP1a (ILP1b). The transceiver and RWA constraints (constraints (4) - (9)) are not needed and the capacity constraints need to be modified slightly as indicated below.

A. Formulation for ILP3a

Minimize \( \sum_{p} \sum_{q} f_{p,q} \cdot t_{q} \) \hspace{1cm} (13)

Subject to:

a) Constraint (2).

b) Ensure that total demand on a lightpath does not exceed the congestion.

\[
\sum_{q} f_{p,q} \cdot t_{q} \leq g \hspace{1cm} \forall p \in E_{L}
\]
Equation (13) minimizes the weighted hop count, similar to ILP1a. Constraint (14) ensures that the total load on each lightpath is less than the capacity of the lightpath.

B. Formulation for ILP3b

\[
\text{Maximize } \sum_q y_q \cdot t_q \quad (15)
\]

Subject to:

a) - b) Constraint (11) - (12).

c) Constraint (14).

For ILP3b, the objective function, flow constraints and blocking constraints are identical to those given in ILP1b. The capacity constraint is modified to (14), used in ILP3a.

C. Formulation for ILP3c

\[
\text{Minimize } \lambda_{\text{max}} \quad (16)
\]

Subject to:

a) Constraint (2).

b) Compute total demand on a lightpath.

\[
\sum_q f_{p,q} t_q \leq \lambda_{\text{max}} \quad \forall p \in E_L \quad (17)
\]

c) Capacity constraint.

\[
\lambda_{\text{max}} \leq g \quad \forall p \in E_L \quad (18)
\]

Equation (16) is the objective function that minimizes the maximum load, \( \lambda_{\text{max}} \), on any given lightpath, and hence minimizes the congestion. Constraint (17) computes the total load on each lightpath and ensures that this load is less than \( \lambda_{\text{max}} \). Constraint (18) is used to enforce the capacity constraint on each lightpath, by ensuring that the maximum load \( \lambda_{\text{max}} \) is less than the lightpath capacity \( g \).

IV. EXPERIMENTAL RESULTS

In this section, we present and analyze our experimental results. We have considered a number of networks of different sizes, ranging from 6 nodes to 30 nodes. The average number of traffic requests varied, from about 60 for a 6 node network to over 1800 for a 30 node network. The experiments were carried out on a 900 MHz processor, using CPLEX 9.1 [1].

A. Performance Evaluation

In our first set of experiments, we addressed the complete topology design and traffic grooming problem, including RWA. We considered several physical networks including the well-known NSFNET topology and the 20 node ARPANET topology [22]. The number of available channels per fiber were given by \( n_{ch} = 16, 32, 64 \). Our formulation, presented in ILP1a, performed quite well. We were able to generate optimal solutions for networks of up to 20 nodes, with 64 channels per fiber and over 800 demands. This is significant since previous formulations reported in the literature, for mesh networks, can only handle very small networks with relatively few demands [9], [12], [25]. As expected, the solution times increased with the size of the network and the number of demands. Fig. 1 shows the increase in solution time, and Fig. 2 shows the resource requirements (measured in terms of the number of wavelength links [21]) with network size, assuming \( n_{ch} = 32 \) and an average of 60, 112, 385, and 805 traffic requests for networks with 6, 10, 14 and 20 end-nodes respectively.

For problems where the RWA can be ignored, we can use ILP2a to quickly generate solutions, even for larger networks. A comparative analysis of the solution times for the formulations ILP1a and ILP2a, is provided in Table I, for various network sizes . Note that ILP2a is the the similar to formulation ILP1a, except the requirements for the RWA constraints are removed. We see that ILP2a leads to a significant speedup and can quickly generate solutions for networks of up to 30 nodes and over 1800 traffic requests. This means that, if the objective function of ILP2a is acceptable, heuristics are not needed for practical sized networks and we may use ILP2a to get an optimized solution.

The formulations ILP3a, ILP3b and ILP3c assume that the logical topology is given and are concerned with aggregating low-speed data streams efficiently onto high bandwidth lightpaths. Table II shows the solution times required for ILP3a and ILP3b for various network sizes. As expected, ILP3 formulations are much faster compared to both ILP1a and ILP2a formulations. Both ILP3a and ILP3b can easily handle networks of 30 nodes. In our experiments, ILP3c is able

Fig. 1. The solution time using ILP1a for various sizes of network.

Fig. 2. The resource requirement for various sizes of network, using ILP1a.


<table>
<thead>
<tr>
<th>Number of Nodes</th>
<th>Execution time in Sec.</th>
<th>ILP1a</th>
<th>ILP2a</th>
<th>% Impv.</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>35</td>
<td>1.07</td>
<td>0.22</td>
<td>79</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>12.61</td>
<td>1.97</td>
<td>95</td>
</tr>
<tr>
<td>14</td>
<td>5</td>
<td>866</td>
<td>52</td>
<td>94</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
<td>1314</td>
<td>85</td>
<td>94</td>
</tr>
<tr>
<td>30</td>
<td>15</td>
<td>1842</td>
<td>836</td>
<td>94</td>
</tr>
</tbody>
</table>

**Table I**

**Comparison of execution times for ILP1a and ILP2a.**

to generate solutions for networks of up to 8 nodes. Again, as with the previous formulations, ILP3a clearly outperforms both ILP3b and ILP3c. If the objective function used in ILP3a (ILP3b) is acceptable to the user, heuristics are not needed for practical sized networks for grooming, and we may use ILP3a (ILP3b) for optimized grooming.

**V. CONCLUSIONS**

In this paper we have presented a number of efficient ILP formulations for traffic grooming in WDM mesh networks. The first formulation addresses the complete traffic grooming problem, including topology design and RWA. We then propose a formulation that performs topology design and traffic routing, without considering RWA. Finally, we present a set of formulations to address the traffic routing problem, for a given logical topology. We have shown that, unlike previous formulations presented in the literature, our formulation is able to generate optimal solutions for the complete traffic grooming problem (including RWA) for practical networks with hundreds of traffic demands, in a reasonable amount of time. We have also shown how different objective functions can be easily implemented, in our formulations, and have performed a comparison of the different formulations, using similar experiments. Our results indicate that the objective function has a significant impact on the speed of the formulation.

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