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Design of virtual topologies for large optical networks through an efficient MILP formulation

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Abstract

In this paper we propose a Mixed-Integer Linear Programming (MILP) formulation for designing virtual topologies of wavelength-routed optical networks, considering as objective function the minimization of the traffic electronically forwarded at the network nodes. Our goal is twofold. Firstly, to reduce packet router processing requirements of the electronic routers, and secondly, to get the most transparent traffic distribution for a given traffic matrix, using the available optical resources at the nodes. The proposed formulation was applied successfully to reasonable sized networks yielding optimal solutions in a few minutes. To the best knowledge of the authors, this is the first report on optimizing virtual topology and traffic routing of large optical networks with a low computational cost MILP formulation.

Keywords: Optical networks; WDM networks electronic bottleneck; Topology design

1. Introduction

The rapid growth of traffic demand has led to a paradigm shift in the telecommunication industry from voice-optimized to data-centric networks. Currently, it is a common thought that, in the near future, data communications will be based on Optical Transportation Networks (OTN).

The first generation of optical networks was developed to overcome limitations imposed by physical impairment on transmission links of the high-speed communication networks. The design of advanced types of fibers, with low attenuation and dispersion, and the advent of optical devices such as optical amplifiers and dispersion compensators were determinant to define the optical network as the best choice to implement broadband data transport links.

Wavelength Division Multiplexing (WDM) has emerged as a dominant trend to provide future OTN services. It increases significantly the optical fiber capacity utilization by dividing the available bandwidth into wavelength channels that matches the peak electronic processing speed. Connections among users are supported by establishing all optical channels, or lightpaths, among end nodes.

In wavelength-routing networks, the lightpath topology, also known as logical or virtual topology [1,2], is detached from the physical topology. The virtual

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topology provides a set of transparent routes, where the transported traffic is not routed electronically. The limited optical resources at the nodes define important constraints to the virtual topology design. These resources are basically WDM multiplexers and demultiplexers, optical switches and transceivers, but can also include wavelength converters and tunable optical devices.

The development of wavelength-routing introduced the concept of transparent traffic routing in optical data transport networks, reducing the limitations imposed by the electronic bottleneck [1,3]. Traffic congestion at electronic routers causes packet loss, delay and jitter. The discussion about techniques and protocols to control these impairment [4] concentrates on how the packets are electronically switched at the edge and inside the network, seeking for a more efficient way to route packets than the best-effort criterion of traditional IP routing. For that, new functions are incorporated into electronic routers to process packets more efficiently [5] and therefore, electronic traffic processing becomes the central function of the node in the network, by which all packet-level routing services are implemented, with great influence on traffic routing impairment that impacts on quality of service [4].

Electronic traffic routing could be eliminated in an all-optical network, with lightpaths available for each traffic demand, but it is not an efficient design choice in terms of the optical resources required at network nodes [1]. A semi-transparent architecture offers, therefore, a better trade-off between the number of lightpaths and the amount of electronic processing, where a given traffic demand is likely to be transmitted through a few concatenated hops. Each one of these hops corresponds to a lightpath in the route between source and destination nodes. At the end of each lightpath, an electronic router processes the carried traffic to perform forwarding to another node or to deliver packets locally.

The virtual topology design problem was earlier [6] subdivided into four subproblems: determining lightpath configuration, routing traffic over lightpaths, routing lightpaths over physical links and assigning wavelengths to lightpaths. We focused, in this paper, on solving the combined subproblems of traffic routing and lightpath configuration. Our purpose is to analyze the trade-off between the traffic routing performance and the cost of the network routers.

In order to get the best performance on traffic routing, we propose the minimization of the electronic traffic processing at the routers subjected to cost constraints. The cost of a router is defined basically by the number and capacity of its line cards. On the other hand, the traffic routing performance is strongly dependent on the traffic load delivered to the router switch fabric, where packet routing contention may cause queuing delay, jitter and packet loss due to buffer overflow.

Other researchers have studied the problem of designing virtual topologies. The traffic routing subproblem can be easily solved by a Linear Programming (LP) model [1,2,7–11]. On the contrary, the lightpath configuration subproblem requires combinatorial optimization to reach the optimal solution, which can be very complex and time consuming. As a consequence of that, heuristic algorithms such as genetic algorithms [12], simulated-annealing [7], tabu search [13], search space dimensionality reduction techniques [14] and branch-exchange [15] have been applied to find good solutions. A detailed survey of heuristics is available in [16]. These approaches have an important shortcoming, as they can not guarantee the optimal solution.

Exact formulations to solve the combined problems of lightpath configuration and traffic routing, using linear [17] and nonlinear [7,15] objective functions, were proposed earlier. In this paper we will use the formulation presented in [17] as a basis for comparison. Linear formulations to solve the complete virtual topology design problem were also presented, as in [7], which was applied only to networks with 4 and 6 node networks. In [9], suitable simplifications in the problem, such as search space reduction and the assumption of wavelength changers at all nodes, allowed the analysis of networks up to 20 nodes. The exact MILP formulation proposed in this paper presents an incremental advance, reducing the optimization time requirements and rapidly providing optimal solutions for networks sized up to 30 nodes. Moreover, we study the trade-off between the required lightpath capacity and the amount of electronic traffic forwarding.

Survivability is another problem related to traffic routing in wavelength-routed networks, consisting in the definition of backup routes in case of failures at the nodes and also in fiber links. The problem of survivable traffic routing would increase the computational complexity of the optimization process because of the additional set of integer variables necessary to control traffic routing in the linear formulation. In order to perform non-bifurcated traffic routing, this additional set of integer variables is also necessary and the correspondent increase in the computational complexity was already discussed in [9] and [7]. We consider that survivable traffic routing is outside the scope of this work, since failures in the optical layer, such as fiber cuts, cannot be considered without handling the routing and wavelength assignment problem.

The rest of the paper is organized as follows: Section 2 discusses the virtual topology optimization criteria considered in this work. Section 3 presents our MILP model, and in Section 4 we evaluate the performance of the proposed formulation. Finally, conclusions are given in Section 5.

2. Virtual topology optimization criteria

Past research on the topological design of distributed computer networks [10] has modeled a packet switched network as a network of independent $M/M/1$ queues, following the basic scheme shown in Fig. 1 for each communication channel [18,19].

The average delay Q_{ij} in a channel between nodes i and j with traffic load L_{ij}, in packets per second, and capacity C_{ij}, in bits per second, given an average packet length $\frac{1}{\mu}$, in bits per packet, is defined as

$$Q_{ij} = \frac{1}{\mu C_{ij} - L_{ij}}. \quad (1)$$

As long as the link utilization L_{ij} remains lower than the link capacity C_{ij}, the queuing delay can be kept low, improving the network throughput [1]. The average queuing delay issue was considered in many related works [1,2,7] to define congestion minimization as the optimization criterion of the virtual topology design problem. However, observing the architecture of backbone IP routers [5], we can see a multi-stage service-intelligent switch fabric with aggregate capacity of 92 Tbps in the core, supporting up to 1152 slots for 40 Gpbs line cards with 1xSTM-256 up to 16xSTM-16 bidirectional ports each one. These differences between the IP router architecture and the $M/M/1$ queuing model, along with the goal of getting the minimum electronic traffic routing, has driven us to propose a paradigm shift for the virtual topology and traffic routing optimization problem.

The following optimization criterion is proposed in our model: minimization of the forwarded traffic in the network FT_{NET}, subjected to constraints on lightpath capacity and number of transceivers at the nodes. This formulation will be called in the future as the Min[FT_{NET}] model. We consider that the best solution is a virtual topology that minimizes the electronic processing overhead caused by its semi-transparent architecture. This optimization criterion provides a traffic routing solution close to the all-optical case, as long as more transceivers and lightpath capacity are available. The constraints on lightpath capacity

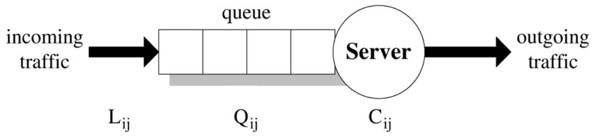

Fig. 1. Queuing system representing the routing of a single channel traffic load of L_{ij} packets per second received in a queue placed before a router server with capacity C_{ij} bits per second. The average queuing delay is represented by Q_{ij}.

and number of transceivers limit the cost of the routers. By varying these constraints, we can solve the combined problem of lightpath configuration and traffic routing with a multiobjective approach, to define a reasonable balance between cost and performance. The traffic forwarding minimization is indeed equivalent to minimizing the traffic weighted hop count from source to destination. Nevertheless, the formulation presented in [9] defined the traffic weighted hop count as the sum of all traffic components, divided by the sum of all traffic demands. In that case, there was unnecessary counting of traffic components already transported through a single hop.

Virtual topology optimization through MILP formulations taking congestion minimization as the objective function are well known as hard problems to solve, and not suitable to large networks [1,2,8,20]. Such a type of formulation will be referred to as the Min[λ_{MAX}] model, where λ_{MAX} is the network congestion.

3. Virtual topology design formulation

In this section we present the Min[FT_{NET}] model, considering an optical network with N nodes. Let Λ denote the input traffic matrix and Δ_l the input and the output logical degree, i.e., the number of transceivers at each node. Lightpaths are set between pairs of nodes (i, j) with traffic load $\lambda(i, j)$. A given traffic demand from a source s to a destination d, $\Lambda(s, d)$, is transmitted through one or more concatenated lightpaths. The portion of the traffic carried out by a certain lightpath connecting (i, j) that is part of the demand $\Lambda(s, d)$ is represented by $\lambda(i, j, s, d)$. The electronic traffic forwarding in a certain node j, FT_j, is the portion of the traffic arriving at j to be processed and forwarded to another node.

The results for the MILP formulation are the virtual topology matrix, B, the optimal electronic traffic forwarding in the network, FT_{NET}, the traffic routing solution $\lambda(i, j, s, d)$, and the network congestion. The elements of the virtual topology matrix B are binary variables, where $B(i, j) = 1$ if there is a lightpath between the nodes i and j, or $B(i, j) = 0$ otherwise. Then the MILP formulation is as follows:

- *Objective function*

$$Minimize[FT_{\text{NET}}] \tag{2}$$

Subject to the following:

- *Traffic flow conservation*

$$\sum_j \lambda(i, j, s, d) - \sum_j \lambda(j, i, s, d) = \begin{cases} \Lambda(s, d); s = i \\ -\Lambda(s, d); d = i, \quad \forall(s, d) \\ 0; s \neq i, d \neq i \end{cases} \tag{3}$$

$$\lambda(i, j, s, d) \leq B(i, j), \quad \forall(s, d). \tag{4}$$

- *Logical degree constraints*

$$\sum_i B(i, j) = \Delta_l; \quad \forall j \tag{5}$$

$$\sum_j B(i, j) = \Delta_l; \quad \forall i. \tag{6}$$

- *Multi-hop traffic definition*

$$FT_j(j) = \sum_{s,d} \sum_i \lambda(i, j, s, d), d \neq j. \tag{7}$$

- *Network traffic forwarding definition*

$$FT_{\text{NET}} = \sum_j FT_j. \tag{8}$$

Traffic flow conservation constraints given by Eq. (3) guarantee the conservation of the traffic demands $\Lambda(s, d)$ along the routes between source and destination. Eq. (4) defines the dependence of the virtual topology matrix components $B(i, j)$ and the traffic components $\lambda(i, j, s, d)$. Logical degree constraints are defined in Eqs. (5) and (6). The traffic to be processed and forwarded at each node, FT_j, is given by Eq. (7). The entire network traffic routing processing load FT_{NET}, is defined in Eq. (8). The objective function shown in Eq. (2) minimizes traffic routing processing in the network.

The electronic processing load at the nodes, EP_j, has two components. The first one is the traffic that will be forwarded to another node FT_j. The second component is the traffic that is dropped at the node, which defines the lower bound on electronic processing at the nodes EP_j^{LB}, determined by

$$EP_j^{LB} = \sum_i \Lambda(i, j). \tag{9}$$

The electronic processing lower bound of the network EP_{NET}^{LB} is

$$EP_{\text{NET}}^{LB} = \sum_j EP_j^{LB}. \tag{10}$$

In order to balance the required lightpath capacity and the amount of electronic traffic forwarding, we have imposed a limit on the maximum lightpath occupation λ_{MAX}. For that, two groups of constraints are necessary to define the traffic load assigned to the lightpaths $\lambda(i, j)$ and to limit them to at most λ_{MAX} as follows

$$\lambda_{ij} = \sum_{s,d} \lambda_{ijsd}, \tag{11}$$

$$\lambda_{ij} \leq \lambda_{\text{MAX}}. \tag{12}$$

4. Numerical examples

This section presents numerical examples for the virtual topology design problem. Section 4.1 shows a study of the computational complexity of the proposed formulation considering a set of networks. In Section 4.2 we compare the electronic processing requirements and the achievable congestion with the Min[λ_{MAX}] and Min[FT_{NET}] models. For that, the exact algorithm proposed by Ramaswami in [17] was re-implemented and some experiments were done to validate our approach, including a reproduction of the results presented in [17] for the Min[λ_{MAX}] model. Finally, in Section 4.3, we present the results for congestion limitation in the Min[FT_{NET}] model, showing the possibility to make the trade-off between transparency on traffic routing and the number and maximum required capacity of the router interfaces.

4.1. Optimization time analysis

In order to evaluate the performance of our MILP formulation with a larger set of networks than those presented in [7,17,9], we have considered networks ranging from 14 to 30 nodes, traffic demands uniformly distributed within (0, 100), and different values of logical degree. These results were obtained running ILOG CPLEX 7.0 [21] in a personal computer with a PENTIUM IV 2.8 GHz processor.

Fig. 2 depicts the running time required to find the optimal solution as a function of the logical degree. As expected, the optimization time increases with the network size. These results also show that the performance is nearly constant along all variations of $\Delta_l > 8$. It is important to notice that for values close to $N/\Delta_l < 3$, the optimization time can be considered negligible [14].

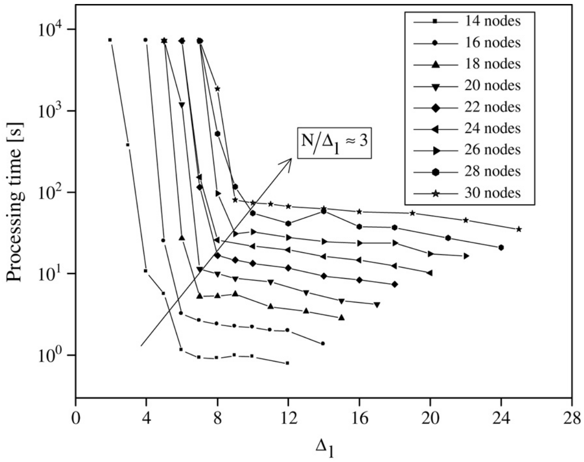

Fig. 2. Running time as a function of the logical degree for networks ranging from 14 to 30 nodes.

4.2. Electronic processing minimization efficiency

In this section we make a comparison among the Min $[FT_{\mathrm{NET}}]$ model and Min $[\lambda_{\mathrm{MAX}}]$ models, regarding FT_j. For that, we consider two different traffic matrices, namely Λ_1 and Λ_2. The traffic pattern Λ_1 has 42 traffic demands $\Lambda(s, d)$, chosen from a uniform distribution in (0, 100), and the remaining traffic demands from a uniform distribution in (0, 1), representing a situation where traffic is concentrated among 42 node pairs. The traffic pattern Λ_2 was obtained by measurements in the NSF Network, with traffic distributed more evenly among all (s, d) pairs.

Similarly to the experiments carried out by Ramaswami [17] with the NSFNET, we also had to interrupt the optimization process reaching only sub-optimal solutions for the Min$[\lambda_{\mathrm{MAX}}]$ model. We expect that a good sub-optimal solution for this problem is close enough to a known lower bound. In our experiments, the first integer solution was yielded and its congestion was very close to the lower bounds in all the cases.

These results are shown in the boxes near the nodes of the network drawn in Fig. 3. The FT_j obtained with the Min$[\lambda_{\mathrm{MAX}}]$ model are in the shaded boxes. We can see that the solutions obtained with the Min$[FT_{\mathrm{NET}}]$ model, placed under the Min$[\lambda_{\mathrm{MAX}}]$ results, are much more efficient in terms of the traffic forwarding at the electronic routers. Another important result is the total amount of traffic forwarded in the network FT_{NET}, which is, for the Min$[FT_{\mathrm{NET}}]$ model, two orders of magnitude lower than that required by the Min$[\lambda_{\mathrm{MAX}}]$ model solution. Similar results were obtained for traffic patterns Λ_1 and Λ_2, and also with other logical degrees, 4 and 8.

In Figs. 4 and 5, one can see the difference between the lower bound on electronic processing at each node EP_j^{LB} and the EP_j obtained with Min$[\lambda_{\mathrm{MAX}}]$ and Min$[FT_{\mathrm{NET}}]$ models. These results represents the overhead on electronic processing caused by the semitransparency of the virtual topology, compared with the all-optical routing, subject to different optimization criteria.

The efficiency of the Min$[FT_{\mathrm{NET}}]$ model is asserted, given the proximity of the results from the lower bound, despite the considerable logical degree reduction, from 8 to 4. The main benefit of the Min$[FT_{\mathrm{NET}}]$ model is to provide optimal solutions with electronic processing very close to that yielded by an all-optical traffic routing solution, even considering a progressive limitation of the optical resources at the nodes, represented in the formulation as the logical degree constraints.

Fig. 6 shows, for the Min$[FT_{\mathrm{NET}}]$ and Min$[\lambda_{\mathrm{MAX}}]$ models, the traffic forwarded in the network, as defined in Eq. (8). The Min$[FT_{\mathrm{NET}}]$ obviously resulted in lower traffic forwarding, from just 1.61% ($\Lambda_1, \Delta_l = 8$) to 22.16% ($\Lambda_1, \Delta_2 = 4$) of the FT_{NET} required by the Min$[\lambda_{\mathrm{MAX}}]$ solutions.

As shown in the results for electronic processing at the nodes, logical degree increase did not imply forwarding reduction for the Min$[\lambda_{\mathrm{MAX}}]$ model, then we can conclude that a substantial increase in the number of lightpaths in a network designed with the Min$[\lambda_{\mathrm{MAX}}]$ model does not imply more transparency in the traffic routing solution.

Without any limitation on the lightpath capacity, the FT_{NET} minimization results in congestion about 75% to 231% over the lower bounds presented in [17], as shown in Table 1. It can be easily explained by looking at the traffic component distribution over the virtual topology. Generally, the most occupied lightpaths are used as single hop routes to transport the highest traffic demands. Although congestion is that high for the proposed model, we observed that this increase in the required capacity occurs in a few lightpaths.

According to the results shown in Table 1, the total required lightpath bandwidth in the network, $\sum_{ij} \lambda_{ij}$, remains 40% to 50% lower with the proposed model in comparison with the Min$[\lambda_{\mathrm{MAX}}]$ model. We can also observe that the mean lightpath load required with congestion minimization is about 84% to 105% higher than that obtained with the Min$[FT_{\mathrm{NET}}]$ model.

4.3. Bounds on congestion

We have observed in Section 4.2 that FT_{NET} minimization causes congestion increase. Since load-balancing among lightpaths is desirable, we deal

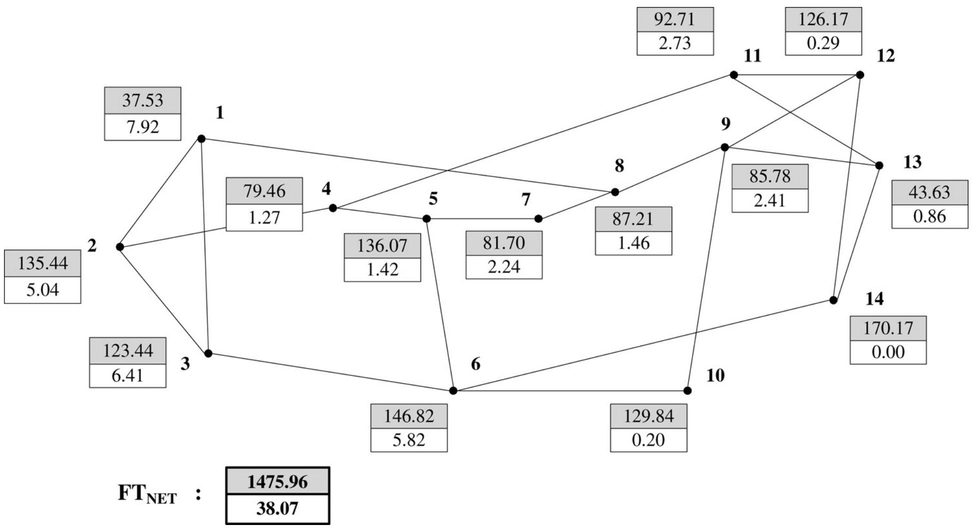

Fig. 3. Traffic routing processing distribution among the network nodes (FT_j) for traffic matrix Λ_1 and $\Delta_l = 6$ obtained for congestion minimization (Min[λ_{MAX}]) (gray boxes) and electronic traffic forwarding minimization (Min[FT_{NET}]) (white boxes).

Table 1
Congestion increase with forwarded traffic minimization and comparison with lower bounds on congestion for different traffic matrices, varying the logical degree

Traffic matrix	Δ_l	λ_{max}		$\sum_{i,j} \lambda_{i,j}$		$\frac{\sum_{i,j} \lambda_{i,j}}{\sum_{i,j} b_{i,j}}$	
		Lower bound	Min[FT_{NET}]	Min[λ_{max}]	Min[FT_{NET}]	Min[λ_{max}]	Min[FT_{NET}]
Λ_1	4	63.43	111.61	3327.21	1991.79	65.24	34.94
	6	42.29	98.72	3348.60	1911.61	41.86	22.76
	8	31.72	97.75	3595.78	1779.91	34.58	16.92
Λ_2	4	142.32	270.200	6061.26	3234.68	114.36	58.81
	6	94.89	235.720	5223.16	2830.65	68.73	36.76
	8	71.17	235.720	5594.37	2596.43	55.39	27.05

with the variations in lightpath capacity requirements imposing a limit on channel capacity.

A progressive congestion limitation increases the electronic traffic forwarding, as shown in Fig. 7 for traffic matrices Λ_1 (squares) and Λ_2 (triangles), with $\Delta_l = 8$. Optimal solutions were reached even with congestion limited to the theoretical lower bound of 71.17 for traffic matrix Λ_2, represented with the vertical dashed line. For traffic matrix Λ_1 congestion could be limited to 34.00, very close to the theoretical lower bound of 31.72. As long as the limits on λ_{MAX} approximates to its theoretical lower bound, the optimization time was found considerably longer, reaching up to tens of hours, but a good trade-off between λ_{MAX} and FT_{NET} could be obtained with minor computational effort.

The differences on FT_{NET} with about the same congestion for both models indicates that the proposed model offers a considerably better trade-off between congestion and electronic traffic forwarding, despite the great differences between traffic matrices Λ_1 and Λ_2. For example, the Min[λ_{MAX}] strategy resulted in sub-optimal solutions with $\lambda_{MAX} = 34.75$ and $FT_{NET} = 1322.72$ for traffic matrix Λ_1 and with $\lambda_{MAX} = 71.17$ and $FT_{NET} = 3164.34$ for traffic matrix Λ_2 ($\Delta_l = 8$). The proposed model provided $FT_{NET} = 749.21$ with congestion limited to $\lambda_{MAX} = 34.00$ for traffic matrix Λ_1 and $FT_{NET} = 469.94$ with congestion limited to $\lambda_{MAX} = 71.17$ for traffic matrix Λ_2 ($\Delta_l = 8$).

5. Conclusions

In this paper we presented a new mixed-integer linear programming model for the design of virtual topologies, where the goal is to minimize the electronic traffic forwarding. Despite past reports on the infeasibility of MILP models applied to the virtual topology design of

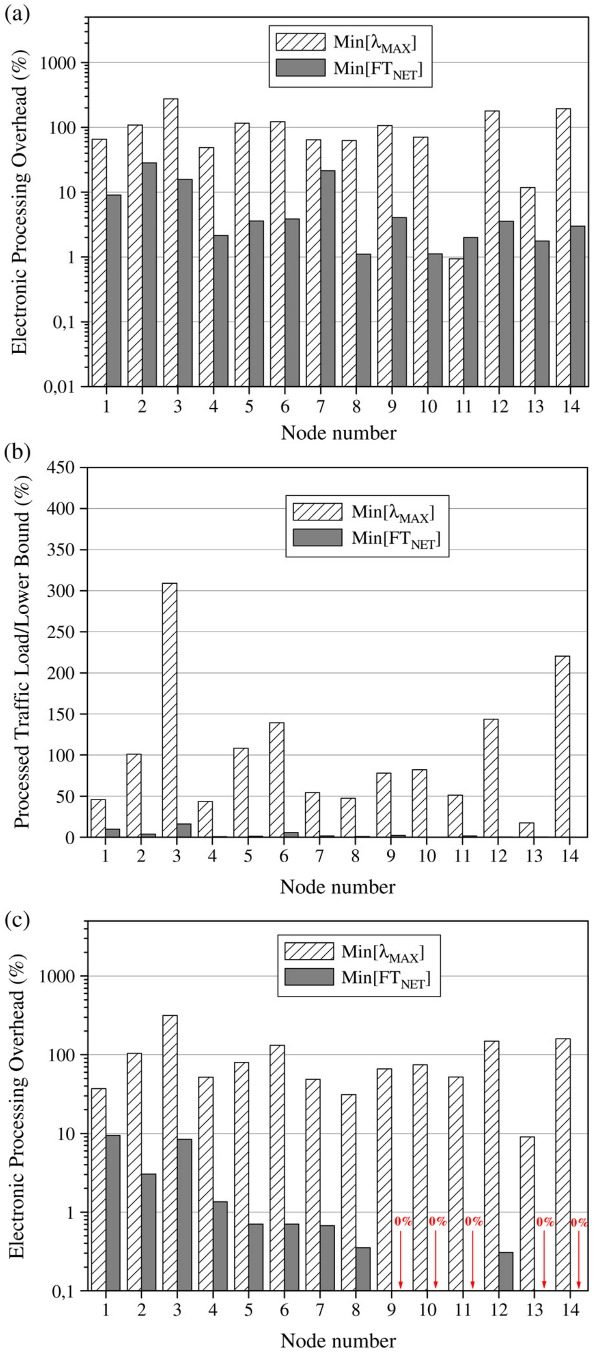

Fig. 4. Electronic processing overhead for Λ_1. (a) $\Delta_l = 4$ and (b) $\Delta_l = 8$.

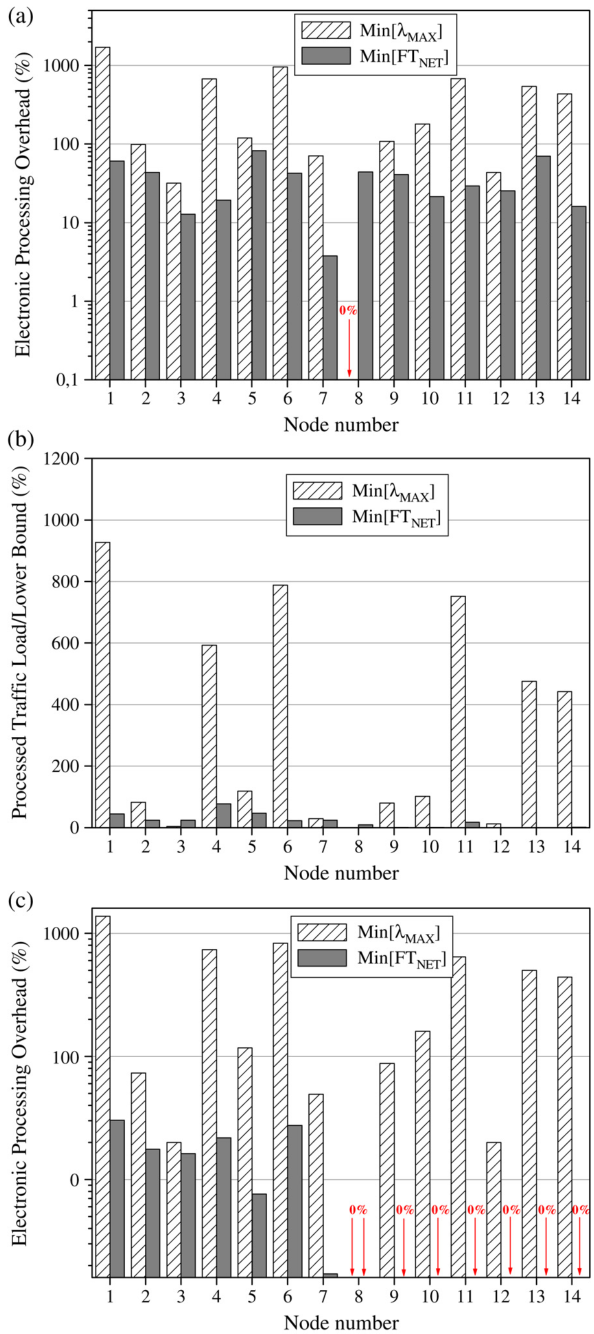

Fig. 5. Electronic processing overhead for Λ_2. (a) $\Delta_l = 4$ and (b)$\Delta_l = 8$.

large networks [1,2,8,20], our model provided optimal solutions in less than one second for a 14-node network.

We carried out experiments with networks up to 30 nodes, and the minimum optimization time for the largest network in the case of study remained within 2 min. An important matter concerning the computational cost of the Min[FT_{NET}] model is that it decreases as the logical degree increases. A threshold for the optimization time increase was found: for networks with $N/\Delta_l < 3$, the computational effort is small and nearly constant. In contrast, the Min[λ_{MAX}] model always requires exhaustive optimization.

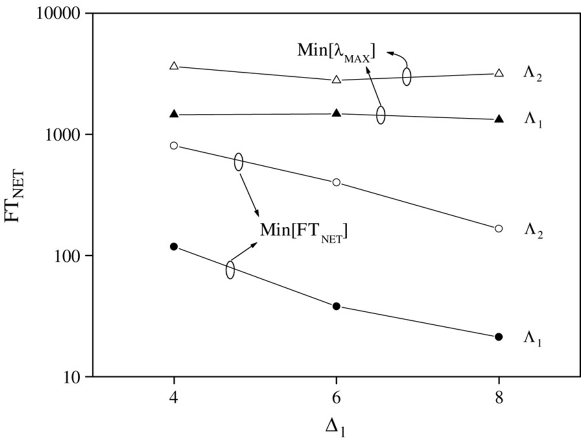

Fig. 6. Electronically forwarded traffic in the network for each model.

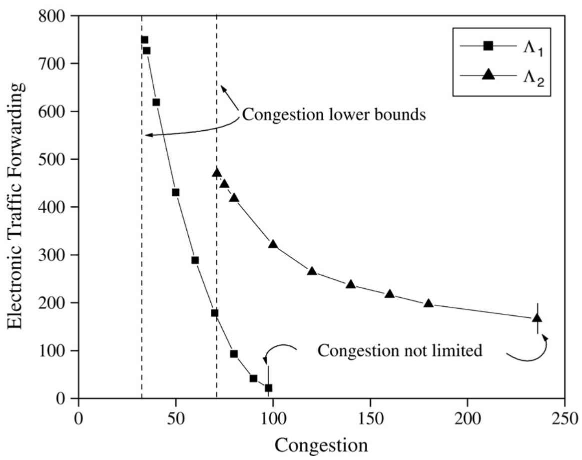

Fig. 7. Influence of congestion limitation on electronic traffic forwarding FT_{NET} for traffic matrix Λ_1 (squares) and Λ_2 (triangles).

Without limits on the lightpath capacity, the proposed model provides an electronic processing load close to that required in the all-optical solution, however, fewer lightpaths are required. The increase in congestion due to forwarded traffic minimization justifies the utilization of constraints on the maximum lightpath capacity. Nevertheless, even with tight bounds on the maximum lightpath capacity, the proposed model results in less electronic processing than the (Min[λ_{MAX}]). Thus, we can conclude that the proposed model is capable of optimizing electronic traffic processing and congestion simultaneously, offering a better trade-off between the required lightpath capacity and the transparency on traffic routing than other MILP formulations.

Further studies on this topic include the evaluation of non-bifurcated traffic routing, the integration of the routing and wavelength assignment subproblems to the proposed model, considering survivable traffic routing.

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