MILP Formulations for Scheduling Lightpaths under Periodic Traffic

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ABSTRACT
This paper addresses offline virtual topology design in transparent optical networks under given periodic traffic. We call this planning problem "Scheduled Virtual Topology Design". Two problem variants are considered: for a network based on non-reconfigurable equipment and for a network based on reconfigurable equipment. Two MILP (Mixed Integer Linear Program) formulations are proposed, one for each alternative. The number of transceivers in the network is the selected cost figure to minimize. Tests are performed to evaluate the benefits of using reconfigurable equipment under different traffic conditions and network sizes. The reduction in the number of transceivers obtained by allowing temporal variations in the virtual topology seems low in all cases, indicating that using reconfigurable equipment may not be cost-effective for periodic traffic.
Keywords: All-optical networks, virtual topology design, multilayer optimization, scheduling.

1. INTRODUCTION

Transparent optical networks have been proposed to decrease costs and increase capacity in the Future Internet, i.e., "converged" multi-granular network architectures [1], [2]. In transparent optical networks, traffic is carried onto lightpaths which occupy one transmission wavelength in each traversed link. The carried traffic is electronically processed at the ingress and egress nodes of the lightpath, but not at intermediate transit nodes, saving electronic switching costs, and providing the data plane with a sort of traffic format transparency.

The Wavelength Switch Fabric (WSF) is the central optical part of a switching node in transparent optical networks. A WSF can have a fixed or reconfigurable structure. In non-reconfigurable switching fabrics, connections between the input and output ports of the WSF are manually hard-wired. However, if the WSF is a device implemented using reconfigurable optical add/drop multiplexers (R-OADM) or reconfigurable wavelength crossconnects (R-WXC), then connections from input to output ports can be dynamically reconfigured allowing lightpaths to change along the time.

In this paper, we focus on the offline planning of transparent optical networks for a given periodic traffic demand, which changes along a sequence of time intervals. The objective of our planning problem is to find the most cost-effective (i) scheduled virtual topology design, and (ii) routing of the electronic flows on top of the virtual topology.

Scheduled virtual topology design determines the number of lightpaths to be established between every input-output pair of nodes over time. This resolves the number of transceivers needed in the network, which is a common cost figure of interest. Naturally, in the lower layer, each lightpath in the virtual topology has to be routed over the physical topology and assigned a wavelength. This problem is called the Routing and Wavelength Assignment (RWA) problem [3]. In this paper, we assume that the network links support a sufficient number of wavelengths for any RWA scheme. Thus, the physical-layer constraints do not apply and we can remove the RWA subproblem from the global network planning optimization problem. This assumption realistically depicts several network scenarios, such as metro-area optical networks with an over-dimensioned fiber plant.

This paper proposes two MILP formulations to solve two variants of the "Scheduled Virtual Topology Design" problem (SVTD). The input data of a SVTD problem are a series of traffic matrices and a physical topology. The solution to a SVTD problem consists of one or more virtual topology designs, together with associated flow routings. The first problem variant is denoted as SVTD-NR (SVTD–Non-Reconfigurable). In this case, the WSFs are assumed to be non-reconfigurable or hard-wired. Hence, the virtual topology is constrained to be constant along time. In the second problem alternative, denoted as SVDT-R (SVTD-Reconfigurable), reconfigurable switching nodes are assumed, i.e., the virtual topology design can change along time. Intuitively, fewer transceivers should be necessary to carry a given periodic traffic demand with reconfigurable equipment.

We briefly summarize related contributions in this research field. Real traffic traces, such as the Abilene backbone network [4] suggest a periodic nature of traffic, making the expected traffic load in the network fairly predictable [5]. The first planning model to incorporate this phenomenon in transparent optical networks was the Scheduled Lightpath Demands (SLD) model from [5] where the set-up and tear-down times of lightpaths are

The work described in this paper was carried out with the support of the BONE-project ("Building the Future Optical Network in Europe"), a Network of Excellence funded by the European Commission through the 7th ICT-Framework Programme, the support of the MEC Spanish project TEC2007-67966-01/TCM CONPARTE-1, the support of the Fundación Séneca project FORMA 00002/CS/08, and developed in the framework of "Programa de Ayudas a Grupos de Excelencia de la Región de Murcia, de la Fundación Séneca (Plan Regional de Ciencia y Tecnología 2007/2010)".

known in advance. In [6] and [7], RWA heuristic approaches for a set of SLDs are proposed. A Simulated Annealing algorithm using channel re-use and back-up multiplexing for fault tolerant RWA is introduced in [6]. A more general model, called the sliding scheduled traffic model was proposed in [8], while fault tolerant RWA for this model was considered in [9]. However, all these approaches consider a *given* scheduled set of lightpaths, i.e. given scheduled virtual topologies, and solve their associated Routing and Wavelength Assignment problems. Conversely, we consider the problem of finding the scheduled virtual topologies themselves based on given periodic traffic, and determine the traffic flows therein.

The rest of the paper is organized as follows. In Section II we provide optimal MILP formulations for the SVDT-R and SVDT-NR problems. Section III presents the results of several cases studied and, finally, section IV concludes the paper.

2. MILP FORMULATIONS

In this section exact MILP formulations are presented for the two variations of the planning problem (SVTD-NR/R). Let N be the number of nodes in the network, and t=1,...,T be the set of time intervals for which the traffic is defined. Since we are dealing with periodic traffic, we assume that the last time interval t=T is followed by the first time interval t=1. Let $M(i,j,t)$, i,j=1,...,N, t=1,...,T denote the traffic demand (measured in Gbps) from node i to node j, during time interval t. Let C denote the lightpath capacity in Gbps. The cost of each transmitter and receiver is considered equal, and is represented by c_{TR}.

2.1 SVTD-NR formulation

The decision variables of the problem are:

- $p(i,j)$={0,1,2,...}, i,j=1,...,N. The number of lightpaths set from node i to node j.
- $f(i,j,s,d,t)$≥0, i,j,s,d=1,...,N, t=1,...,T. The amount in Gbps of the traffic flow (s,d) that traverses the lightpaths set from node i to node j.

The problem formulation is given by (1).

$$\min c_{TR} \sum_{i,j\in N} p(i,j) \qquad (1a)$$

subject to:

$$\sum_{s,d\in N} f(i,j,s,d,t) \le C\cdot p(i,j),\ \forall i,j=1,...,N,\ \forall t=1,...,T \qquad (1b)$$

$$\sum_{j\in N} f(n,j,s,d,t) - \sum_{i\in N} f(i,n,s,d,t) = \begin{cases} M(s,d,t), & if\ n=s \\ -M(s,d,t), & if\ n=d, \forall n,s,d=1,...,N,\ \ t=1,...,T \\ 0, & otherwise \end{cases} \qquad (1c)$$

The objective function (1a) minimizes the cost of the transceivers. Constraints (1b) represent the capacity constraints, and equations (1c) are the flow conservation restrictions for the link-flow formulation.

2.2 SVTD-R formulation

In this problem the variable $p(i,j)$ is replaced by $p(i,j,t)$ since the lighpaths can change along the time, and two new decision variables are added respect to the previous formulation (1). They are:

- $T(i)$={0,1,2,...}, i=1,...,N. The number of transmitters available in node i.
- $R(i)$={0,1,2,...}, i=1,...,N. The number of receivers available in node i.

$T(i)$ and $R(i)$ represent the requirements in the number of transmitters, receivers and electronic switching capacity in node i=1,...,N .

The objective function (2a) minimizes the cost of the transmitters and receivers.

$$\min c_{TR} \sum_{i\in N} \left(T(i)+R(i)\right) \qquad (2a)$$

The constraint (1b) is replaced by constraint (2b) with the new variable $p(i,j,t)$, meanwhile the constraint (1c) is also valid in this problem. Moreover, two new constraints are added with respect to the previous formulation (1).

$$\sum_{s,d \in N} f(i,j,s,d,t) \le C \cdot p(i,j,t), \ \forall i, j = 1,...., N, \ \forall t = 1,..., T \quad (2b)$$

$$T(n) \ge \sum_{j=1}^{N} p(n,j,t), \forall n = 1,..., N, t = 1,..., T \quad (2c)$$

$$R(n) \ge \sum_{i=1}^{N} p(i,n,t), \forall n = 1,..., N, t = 1,..., T \quad (2d)$$

Constraints (2c) and (2d) ensure that the number of lightpaths originating (terminating) at a given node at any time must be lower than the number of transmitters (receivers) installed at that node.

3. RESULTS

The SVTD-R and SVTD-NR formulations have been utilized to assess the benefits of using reconfigurable equipment under time-variant traffic conditions. The formulations were implemented in the MatPlanWDM tool [10] which links to the TOMLAB/CPLEX library [11] to solve MILP problems. Four network sizes were considered with N={4,6,8,10} nodes.

Each planning problem is fed by a series of T=12 traffic matrices. $M(i,j,t)$ denotes the traffic in Gbps from node i to node j during time interval t, i,j=1,...,N, t=1,...,T:

$$\mathbf{M}(i,j,t) = \mathbf{M}_{\mathbf{Base}} \cdot nf \cdot \text{activity}(t) \cdot rf(R), \quad nf = \frac{N \cdot M_{node}}{\sum_{i,j} \mathbf{M}_{\mathbf{base}}(i,j)}, \quad (3)$$

$\mathbf{M}_{\mathbf{Base}}$ is a base traffic matrix where the 50% of the values (randomly chosen) equal to 1 and the remaining 50% equal to 2. The normalization factor (nf) is a value calculated to satisfy that the total offered traffic in the base traffic matrix matches a desired value. Two load conditions are tested. In the medium (high) load condition, the nf factor is calculated so that the average traffic generated by each node equals M_{node}=100 Gbps (M_{node}=500 Gbps).

Factor *activity(t)* in equation (3) represents the activity function, which intends to capture the effect of traffic intensity variation along the day. Our intensity variation model is described by equation (4), based on the intensity model presented in [12].

$$\text{activity}(t) = \begin{cases} 0.1 \text{ if } t \in [1,6] \\ 1 - 0.9 \cdot \left(\cos\left(\frac{\text{mod}(t,T) - 6}{18} \cdot \pi \right) \right)^{10} \text{ otherwise} \end{cases}, \text{ where } t = 1,..., T \quad (4)$$

Function *rf(R)* computes a matrix where each coordinate is random, uniformly distributed over interval [1-R,1+R]. The object of the *rf* matrix is to capture a randomness effect in traffic intensity. The random factors used are R={0.1,0.2,0.5}, which correspond to low, medium and high random variation scenarios.

The solutions were obtained by solving both proposed variants of the MILP formulations for the mentioned network and traffic scenarios and evaluated with respect to the total number of transceivers needed. Table 1 shows the results of all the tested experiments. Each experiment was repeated 5 times to average the random effect introduced in the traffic model. The values written in the table are the mean of these five experiments. In parenthesis, the increase in the number of transceivers obtained by using non-reconfigurable equipment is also shown.

As expected, for both reconfigurable and non-reconfigurable networks, the number of transceivers necessary was higher for series of traffic matrices with higher traffic variability factors R. This increase is more significant at higher loads. The penalty (in terms of the number of transceivers required) incurred by using non-reconfigurable equipment respect to the reconfigurable case was shown to be (i) slightly greater for higher loads and (ii) greater for higher variability factor R, but (iii) mostly independent of the number of nodes. However, it is clear that this penalty is quite low in all cases. Considering that reconfigurable equipment is significantly more expensive, these results indicate that using non-reconfigurable equipment may be a cheaper option for virtual topology design under periodic traffic.

4. CONCLUSIONS

In this paper, we suggest a new planning problem in optical networks, which we call “Scheduled Virtual Topology Design”, aimed to schedule lightpaths according to given periodic traffic patterns. Two variants of the problem are solved, assuming a network based on non-reconfigurable and reconfigurable equipment. The aim of the SVTD problem is to minimize the number of transceivers needed to handle the given periodic traffic. We formulate both problem alternatives as exact MILPs (Mixed Integer Linear Programs). Our results reveal that the increase in the number of transceivers required by using non-reconfigurable equipment with respect to the reconfigurable option is not significant and therefore, this last option may not be cost-effective. For future work, we plan to extend these results with a detailed cost-benefit analysis, as well as an investigation of the frequency of reconfiguration disruptions for the reconfigurable case.

Table 1.Total number of transceivers for all the experiments (average values taken over 5 samples).

		N=4		**N=6**	
M_{node}	**R**	**SVTD-R**	**SVTD-NR**	**SVTD-R**	**SVTD-NR**
100 Gbps	10 %	87.8	88 (+0.23%)	132.6	132.8 (+0.15%)
	20%	89.4	90.4 (+1.12%)	135.4	136 (+0.44%)
	50%	99.8	101.6 (+1.80%)	141.6	144.4 (+1.98%)
500 Gbps	10 %	418	421.6 (+0.86%)	626.4	631.6 (+0.83%)
	20%	432.6	436.8 (+0.97%)	644.6	653.6 (+1.40%)
	50%	485.2	495.6 (+2.14%)	700	712.8 (1.83%)
		N=8		**N=10**	
M_{node}	**R**	**SVTD-R**	**SVTD-NR**	**SVTD-R**	**SVTD-NR**
100 Gbps	10 %	170.2	170.4 (+0.12%)	225.2	226 (+0.36%)
	20%	175.8	177.2 (+0.80%)	227	227.6 (+0.26%)
	50%	189.8	192.4 (+1.37%)	234	238 (+1.71%)
500 Gbps	10 %	830	840.4 (+1.25%)	1032.6	1046.8 (+1.38%)
	20%	851	860.4 (+1.10%)	1050	1067.2 (+1.64%)
	50%	905	929.2 (+2.67%)	1130.2	1159.6 (+2.60%)

REFERENCES

[1] Berthold, A. A. M. Saleh, L. Blair, and J. M. Simmons, "Optical Networking: Past, Present, and Future," IEEE Journal of Lightwave Technology, vol. 26, no. 9, pp.1104-1118, May 2008.

[2] S. Sygletos, I. Tomkos, and J. Leuthold, "Technological challenges on the road toward transparent networking," OSA Journal of Optical Networking, vol. 7, no. 4, pp. 321-350, Apr. 2008.

[3] H. Zang, J. P. Jue, and B. Mukherjee, "A Review of Routing and Wavelength Assignment Approaches for Wavelength-Routed Optical WDM Networks," Optical Network Magazine, pp. 47-59, Jan. 2000.

[4] TOTEM Project: Toolbox for Traffic Engineering Methods [Online]. Available: http://totem.run.montefiore.ulg.ac.be/datatools.html

[5] J. Kuri, N. Puech, M. Gagnaire, E. Dotaro, and R. Douville, "Routing and wavelength assignment of scheduled lightpath demands," IEEE J. Select. Areas Commun., vol. 21, pp. 1231–1240, Oct. 2003.

[6] J. Kuri, N. Puech, and M. Gagnaire, "Diverse routing of scheduled lightpath demands in an optical transport network," in Proc. Design of Reliable Communication Networks (DCRN2003), pp. 69–76, Oct. 2003.

[7] N. Skorin-Kapov, "Heuristic algorithms for the routing and wavelength assignment of scheduled lightpath demands in optical networks," *IEEE J. Select. Areas Commun.*, vol. 24, pp. 2–15, 2006.

[8] B.,Wang, T. Li, X. Luo, Y. Fan, and C. Xin, "On service provisioning under a scheduled traffic model in reconfigurable WDM optical networks" in Proc. Of BroadNets 2005, Boston, USA, pp 13-22, Oct. 2005.

[9] C. V. Saradhi, M. Gurusamy,and R. Piesiewicz, "Routing fault-tolerant sliding scheduled traffic in WDM optical mesh networks" in Proc. of Broadnets 2008, London, UK, pp.197-202, Sept. 2008.

[10] P. Pavon-Mariño, R. Aparicio-Pardo, G. Moreno-Muñoz, J. Garcia-Haro, J. Veiga-Gontan, "MatPlanWDM: An educational tool for network planning in wavelength-routing networks", *Proc. IFIP Int. Conf. Optical Network Design and Modelling*, Athens, Greece, 2007, pp. 58-67.

[11] TOMLAB Optimization. Available: http://tomopt.com/

[12] J. Milbrandt, M. Menth, S. Kopf: Adaptive Bandwidth Allocation: Impact of Traffic Demand Models for Wide Area Networks, *in 19th International Teletraffic Congress (ITC19)*, Beijing, China, 2005.