Reconfigurable Optical Networks: Is It Worth?

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Abstract: A fundamental question to address is what levels of traffic fluctuations may justify the deployment of reconfigurable optical networks. Based on a flow model, this study provides a preliminary answer for IP/MPLS over WDM networks.

OCIS codes: (060.4250) Networks; (060.4251) Networks, assignment and routing algorithms.

1. Introduction

Reconfigurable optical networks have gained increasing attention among researchers. It is argued that reconfigurable optical networks may yield improved network utilization when the offered traffic is by its nature fluctuating over time. For example, noticeable traffic fluctuations are reported in IP/MPLS networks throughout the day [1]. The intensity of traffic fluctuations may be expected to arise as new services are being added to the network, e.g., TV-over-IP and IPTV.

Time variability of traffic patterns usually tends to fall into predictable and quasi-synchronous categories, e.g, the bandwidth requirement of groups of label switched paths (LSP) happens to either increase or decrease in a short time interval. As a result, a fixed reservation of the network resources, which is optimized for the traffic pattern at one given time, may be far from optimal at some other time.

This problem is addressed in a recent study [2] by designing a virtual topology that is robust to traffic fluctuations. A mixed objective function is used to compute the virtual topology, which provides best performance over a number of metrics. An alternative approach is to re-optimize the LSP's in the network, to account for the traffic fluctuations [1]. In this latter solution, the individual LSP routing and/or reserved bandwidth are changed over time using a distributed procedure. Both of these solutions assume a fixed virtual topology, i.e., a fixed set of optical circuits (or lightpaths [3]), which connects the routers.

The concept of network re-optimization can be pushed to the next level by adopting a reconfigurable optical layer. The lightpaths in the optical layer may be switched over time, thus offering varying virtual topologies to the routers. Changes in the virtual topology offer an additional dimension to exploit when re-optimizing LSP's. A fundamental question to address at this point is what level of traffic fluctuations may justify the deployment of reconfigurable optical networks.

The study presented in this paper compares the network utilization, achieved in a centrally controlled network, considering two alternative scenarios: (a) LSP's re-routing (RR) in a fixed virtual topology, and (b) LSP's re-routing in a dynamic virtual topology, which is obtained by switching lightpaths (LPS-RR) in the optical layer.

2. Problem Definition

Consider a network where each node comprises both an IP/MPLS router and an optical cross-connect (OXC). The OXC's are used to establish lightpaths, which in turn provide virtual connectivity to the routers. The virtual topology is modeled as a graph $G(\mathcal{N}, \mathcal{A})$, where $\mathcal{N}$ is the set of routers in the network and $\mathcal{A}$ is the set of virtual links connecting the routers. The following assumptions are made: (i) the number of wavelengths is unbounded, (ii) traffic is symmetric, i.e., for a LSP from node i to node j there is a LSP from node j node i with the same bandwidth requirement of the former LSP, and the two LSP's follow the same path in reverse order, and (iii) LSP's may be split and carried over multiple paths on the virtual topology.

Network utilization is measured in terms of *total residual bandwidth* (*TRB*), i.e, the total bandwidth in the virtual topology, which is not reserved to carry any LSP. The problem of maximizing the total residual bandwidth, while (a) designing the virtual topology and (b) routing the LSP's, is formulated as a flow model that relies on the following input parameters and variables.

Input parameters. C: lightpath capacity; Tx_i: total number of transmitters at node i; Rx_i: total number of receivers at node i; $\lambda_{(i,j)}$: required bandwidth for the LSP from node i to node j.

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Variables. *TRB*: total residual bandwidth; $y_{(i,j)}$: binary, 1 if there is a lightpath connecting node i and node j,0 otherwise; $x_{(i,j)}^{(s,d)}$: portion of the required bandwidth for all LSP's from node s to node d, which are routed using the lightpath from node i to node j. For a given traffic matrix $[\lambda_{(i,j)}]$ the value of the residual bandwidth is maximized as follows:

$$TRB = max : \sum_{i,j} \left(C \cdot y_{(i,j)} - \sum_{s,d} x_{(i,j)}^{(s,d)} \right),$$

subject to:

$$\sum_{j} y_{(i,j)} \leq Tx_i, \quad \forall i \in \mathcal{N}, \tag{1}$$

$$\sum_{i} y_{(i,j)} \leq Rx_j, \quad \forall j \in \mathcal{N}, \tag{2}$$

$$\sum_{i} x_{(s,i)}^{(s,d)} = \lambda_{(s,d)}, \quad \forall (s,d) \in \mathcal{N}, \tag{3}$$

$$\sum_{i} x_{(i,d)}^{(s,d)} = \lambda_{(s,d)}, \quad \forall (s,d) \in \mathcal{N}, \tag{4}$$

$$\sum_{j} x_{(i,j)}^{(s,d)} = \sum_{k} x_{(k,j)}^{(s,d)}, \quad \forall (i,s,d) \in \mathcal{N}, i \neq s, k \neq d, \tag{5}$$

$$\sum_{s,d} x_{(i,j)}^{(s,d)} \leq C \cdot y_{(i,j)}, \quad \forall (i,j) \in \mathcal{N}, y \in \{0,1\}, \tag{6}$$

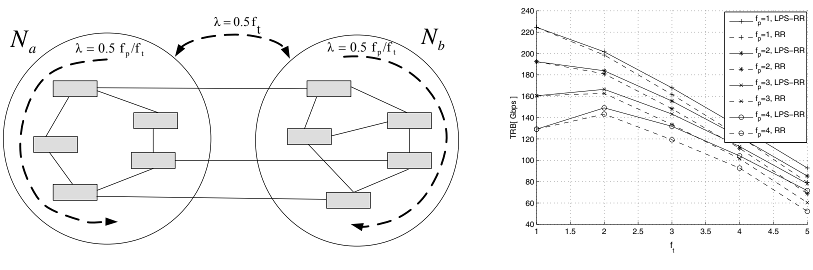
$$y_{(i,j)} = y_{(j,i)}, \quad \forall (i,j) \in \mathcal{N}, \tag{7}$$

$$x_{(i,j)}^{(s,d)} = x_{(j,i)}^{(d,s)}, \forall (i,j,s,d) \in \mathcal{N}. \tag{8}$$

Equations (1), (2) and (6) ensure that the transmitter/receiver constraints and the lightpath capacity constraint are satisfied. Equations (3)-(5) are flow conservation constraints. Equations (7) and (8) are traffic symmetry constraints.

3. Simulation Results

Numerical results are obtained for a network of 10 nodes. Transmission impairments limit the number of lightpaths that can be established as follows. It is assumed that each node i can reach all-optically up to 5 other nodes, i.e., the neighboring node set V_i. $Tx_i = Rx_i = 3$ for every node, i.e, at most three lightpaths can originate and terminate at each node at any given time. $C = 10$ Gbps, i.e., established lightpaths between IP/MPLS routers, have a capacity of 10 Gbps. Traffic fluctuations are modeled as follows. Network nodes are partitioned into 2 sets, N_a



(a) (b)

Fig. 1. (a) Network partitions and traffic fluctuation, (b) total residual bandwidth (TRB) as a function of f_p and f_t

and N_b (Fig. 1(a)). Each set contains 5 nodes. $\lambda_{(s,d)} = \lambda_{(d,s)} = 0.5 \cdot \frac{f_p}{f_t}$ Gbps, if $(s,d) \in N_a$ or $(s,d) \in N_b$. $\lambda_{(s,d)} = \lambda_{(d,s)} = 0.5 \cdot f_t$ Gbps, if $s \in N_a$, $d \in N_b$ or $s \in N_b$, $d \in N_a$. The values for f_p and f_t are chosen in such

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Table 1. Performance metrics as a function of f_p and f_t

RR																				
	f_p=1					f_p=2					f_p=3					f_p=4				
	TRB	*AHC*	*NRR*	*ALL*	*INF*	*TRB*	*AHC*	*NRR*	*ALL*	*INF*	*TRB*	*AHC*	*NRR*	*ALL*	*INF*	*TRB*	*AHC*	*NRR*	*ALL*	*INF*
$f_t = 1$	224.5	1.68	0.0	2.51	0	192.4	1.66	0.0	3.59	0	160.4	1.64	0.0	4.65	0	129.1	1.63	0.0	5.69	0
$f_t = 2$	198.6	1.69	0.2	3.38	0	181.0	1.70	0.3	3.97	0	162.7	1.72	0.9	4.57	0	143.3	1.74	2.0	5.22	0
$f_t = 3$	161.7	1.69	0.3	4.61	0	148.3	1.72	0.5	5.06	0	133.5	1.75	1.6	5.55	2	119.2	1.78	3.2	6.02	85
$f_t = 4$	122.4	1.69	0.4	5.92	17	111.3	1.72	0.5	6.29	41	101.4	1.72	1.0	6.62	186	92.7	1.73	1.4	6.91	382
$f_t = 5$	79.3	1.71	8.5	7.36	71	68.8	1.74	8.8	7.71	169	60.4	1.75	9.3	7.99	334	52.2	1.76	10.3	8.26	509
LPS-RR																				
	f_p=1					f_p=2					f_p=3					f_p=4				
	TRB	*AHC*	*NRR*	*ALL*	*INF*	*TRB*	*AHC*	*NRR*	*ALL*	*INF*	*TRB*	*AHC*	*NRR*	*ALL*	*INF*	*TRB*	*AHC*	*NRR*	*ALL*	*INF*
$f_t = 1$	224.5	1.68	0.0	2.51	0	192.4	1.66	0.0	3.59	0	160.4	1.64	0.0	4.65	0	129.1	1.63	0.0	5.69	0
$f_t = 2$	201.6	1.64	44.0	3.28	0	183.8	1.66	44.6	3.87	0	166.4	1.67	49.5	4.45	0	149.1	1.68	39.6	5.03	0
$f_t = 3$	167.8	1.62	47.2	4.41	0	155.5	1.64	53.5	4.81	0	143.3	1.65	53.6	5.22	0	131.8	1.65	56.0	5.60	0
$f_t = 4$	131.1	1.61	48.0	5.63	0	121.9	1.62	54.0	5.94	0	112.9	1.63	55.7	6.24	0	104.1	1.63	56.3	6.53	0
$f_t = 5$	92.8	1.61	48.5	6.91	0	85.3	1.61	54.2	7.16	0	78.0	1.62	55.7	7.40	0	71.6	1.62	55.7	7.60	0

a way that either traffic among node pairs in the same set, i.e., N_a or N_b, is predominant, or traffic among node pairs across the two sets is predominant.

Results for RR are obtained as follows. For each value of f_p, the configuration for the virtual topology is determined running the flow model presented in Section 2 with $f_t = 1$. Such (fixed) virtual topology is then used to obtain the results for other values of f_t. Results for LSP-RR are obtained by solving the flow model in Section 2 anew, for each pair of values f_t and f_p.

For each pair of values f_t and f_p results are averaged over 800 experiments. For each experiment, set N_a, set N_b and traffic values $\lambda_{(s,d)}$ are left unchanged. For each node i, set V_i is randomly generated.

Fig. 1(b) shows the value of *TRB* for a number of configurations. The figure shows that LPS-RR is more effective than RR only when traffic changes are more pronounced. For each pair of values f_t and f_p, Table 1 reports additional performance metrics. *AHC* is the weighted average hop count for each LSP, i.e., the average number of lightpaths an LSP goes through, weighted by the required bandwidth for the LSP. For each value of f_p, *NRR* is the average number of LSP's that must be rerouted when compared to the case $f_t = 1$. *ALL* is the average lightpath load, i.e., the average amount of aggregate bandwidth reserved on each lightpath for the LSP's. *INF* is the number of problem instances for which a solution was not found, i.e., there is not enough capacity in the network to carry all the LSP's while meeting their respective required bandwidth. The table shows that, when comparing LPS-RR to RR, a gain in terms of *TRB* corresponds to a gain in terms of *AHC*. However, those gains come at the expense of a larger number of LSP's that must be rerouted in order to take advantage of the changing virtual topology. Another important finding shown in the table is that, for each possible combination of f_p and f_t LPS-RR is always able to obtain a solution, while RR might not find a solution due to the wide traffic fluctuation, e.g., when $f_p = 4$ and $f_t = 5$, RR cannot find a solution in more than 60% of the instances.

4. Conclusion

From a pure network utilization perspective, reconfigurable optical networks appear to provide tangible advantages when the levels of traffic fluctuations exceed some threshold value. The threshold value is quantified in this study for a small (10 node) network. Below that threshold value, re-optimization of LSP's alone may suffice to efficiently cope with the traffic changes, as also suggested in a recent work [1]. Further investigation is however needed to answer additional questions, e.g., what threshold values should be used in larger networks, and what is the performance disruption incurred by the traffic during the transient, which takes place while the lightpaths are being switched off and back on.

Acknowledgments

This research was supported in part by NSF Grant No. CNS-0435393.

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