Proc. of IEEE Globecom'06, Nov 27 - Dec 1, 2006, San Francisco, CA.

Lightpath Topology Configuration for Wavelength-routed IP/MPLS Networks for Time-Dependent Traffic

Gaurav Agrawal, Deep Medhi
Computer Science & Electrical Engineering Department
University of Missouri–Kansas City, USA

***Abstract*— The integration of lightpath topology design and IP/MPLS traffic engineering provides greater flexibility for next generation networks. In this paper, we consider the integrated design problem of configuration of lightpath topology and optimal routing of IP/MPLS tunnels on this lightpath topology for time-varying traffic. A mixed integer linear programming model is proposed to design an optimal configuration of lightpath topology, which takes time-dependent traffic demand as an input to the model for IP/MPLS traffic engineering. We consider two variants of the problem: in the first variant, re-routing of IP/MPLS tunnels is not allowed from one-time period to another while reconfiguration rerouting is allowed in the second variation. We also consider various traffic engineering objectives and study their impact on different performance measures. In particular, we propose a composite objective function to combine the benefits of various objectives. Through computational results, we quantify the benefit of the configurable option over the static option.**

***Index Terms*— Lightpath, Lightpath Topology, Traffic Engineering, MPLS, WDM.**

I. INTRODUCTION

Wavelength division multiplexing (WDM) [1] is a promising technology for tapping the tremendous bandwidth of the optical fibers. With continuous increase in the amount of IP traffic, wavelength-routed optical networks using WDM approach are considered potential transport networks for carrying IP traffic. In addition, Multi-protocol Label Switching (MPLS) [2] addresses the traffic engineering needs of IP networks by allowing set up of explicit label switched paths (LSPs) between IP routers for each demand.

This paper considers integrated IP/MPLS over WDM networking paradigm. We refer to IP/MPLS routers as routers with integrated IP and label switching functionality. The WDM network consists of WDM-enabled nodes connected by fiber-optic links and IP/MPLS routers are connected to the ports of WDM cross connects. Optical nodes can be configured to setup wavelength channels or lightpaths between any two nodes. The set of all such lightpaths in the network constitutes a lightpath topology. IP traffic is carried by establishing label switched paths for each demand and these LSPs are then routed over lightpath topology. In this paper, we consider the combined problem of optimal configuration of lightpath topology and optimal routing of LSPs on this lightpath topology.

While conceptually, two geographically distant nodes in a physical topology can be directly connected by a lightpath, it may not be possible to do so between *every* node pair, primarily due to limits on the number of available transmitters and receivers at each optical node. In addition, lightpath topology connectivity needs to be optimized with respect to some performance measure. Similar problems have been addressed in several previous works [3]-[5]. In a previous work [6], we have proposed models to design lightpath topology for wavelength-routed IP/OSPF networks. All these works assume a *single* demand volume matrix.

In real networks, traffic demand do vary with time of the day. Moreover, if a network spans over multiple time zones as in continental U.S., different demands have peaks at different time of the day [7].Thus, it is worthwhile to consider time-dependent traffic matrices during the day in configuring lightpath topology, as a lightpath topology designed for a traffic demand at certain time may not respond well for traffic demand for another time of the day.

There are mainly two approaches proposed in the literature to address the lightpath topology design for time-dependent traffic. The first approach is to reconfigure the lightpath topology, every time the traffic demand matrix changes. Lightpath topology reconfiguration has been addressed by several previous studies. [5],[8] and [9] focus on minimizing the changes in lightpath topology from one time window to next. In [10], authors present a traffic-management framework for IP over reconfigurable WDM networks. The authors in [11] focus on minimizing the disruption to the ongoing traffic. While these dynamic configuration schemes allow more efficient use of network resources, they pose a significant overhead in terms of disrupting existing lightpaths and setting up new lightpaths.

The second approach is to configure a single static configuration of lightpath topology optimized by considering different traffic matrices that varies with time. This approach has the obvious advantage that there is no disruption to the ongoing traffic and no overhead in terms of tearing down and setting up lightpaths incurred. However, this comes at a cost of allocating network bandwidth at a high level without proper utilization. The work in [12] uses this approach to design a static configuration which minimizes the used network resources. This work provides solution that is static both at packet and

TABLE I

NOTATIONS USED IN FORMULATIONS FOR STATIC CONFIGURATION

Given:		
V	:	Set of nodes in the Network
T	:	Set of traffic busy hours (time windows)
$\mathcal{D}$	:	Set of origin-destination demand pairs in the network
$\mathcal{L}$	:	Set of candidate lightpaths in Lightpath Topology
h_{dt}	:	Traffic volume (Mbps) for demand $d \in \mathcal{D}$ at time $t \in T$
P_d	:	Set of candidate LSP paths in Lightpath Topology for $d \in \mathcal{D}$
$a_{\ell v}$	:	1 if link $\ell \in \mathcal{L}$ originates or terminates at node $v \in V$
δ^{ℓ}_{dp}	:	1 if path $p \in \mathcal{P}_d$ of demand $d \in \mathcal{D}$ uses link $\ell \in \mathcal{L}$, 0 otherwise
C_ℓ	:	Wavelength Transmission Capacity for $\ell \in \mathcal{L}$.
Δ_v	:	Number of transceivers at optical node $v \in V$
Variables:		
x_{dp}	:	Fractional flow allocated to path $p \in \mathcal{P}_d$ for demand $d \in \mathcal{D}$ (for Model-A)
x_{dpt}	:	Fractional flow allocated to path $p \in \mathcal{P}_d$ for demand $d \in \mathcal{D}$ at time $t \in T$ (for Model-B)
r_{max}	:	Maximum Lightpath utilization over all time windows
u_ℓ	:	1, if link $\ell \in \mathcal{L}$ is included in the lightpath topology and 0 otherwise

optical level (no re-routing of LSPs nor wavelength path is allowed). Our approach is somewhat different. We consider two routing options in this work. In first option, we assume that the LSPs cannot be re-routed on the lightpath topology from one time window to next. In the second option, we relax this restriction and allow the LSPs to take different routes in each time window, thus giving more flexibility to the network provider. Both these options are considered given limits on the number of incoming and outgoing lightpaths at an optical node. We also introduce a composite objective function.

II. PROBLEM FORMULATION

Consider N number of IP/MPLS nodes to be interconnected over an optical backbone by setting up bidirectional lightpaths between them. It is assumed that each optical node $v \in V$ has Δ_v optical transceivers; thus, each node can have at most Δ_v incoming and Δ_v outgoing lightpaths. We are given a set of traffic matrices h_{dt}, representative of the time-dependent traffic at time t for the IP network. This IP demand may be bifurcated in multiple LSPs and these LSPs are then to be routed over the lightpath topology. For example, a demand volume of 120 Mbps to be carried between two IP routers, router A and router B, may be split on multiple LSPs at MPLS level. These LSPs, in turn, are demands for lightpath topology and are independently routed over the lightpath topology. Note that this bifurcation at MPLS level does not impact at the IP level since IP routers see only a logical trunk between its routers. This however is transparent from the MPLS component of the router assigning specific IP flows on different LSPs at the time of flow arrival.

The notation for our problem formulation is listed in Table I. We assume that optical nodes are co-located with IP/MPLS routers. For N routers, there are $N(N-1)/2$ logical links possible in the lightpath topology which serve as candidate links in set $\mathcal{L}$. We then consider a set of candidate LSP paths in the MPLS level–some of the paths are valid if the lightpath is activated, while other aren't if the lightpath is not activated.

We generate candidate LSP paths in the set $\mathcal{P}_d$, such that one or more of the paths selected for each demand carries the optimal solution. A large number of paths are pre-computed as candidates using the k-shortest path algorithm. Note that $\mathcal{P}_d$ is a parameter in our model—a larger set can be generated if needed.

A. Model-A: Fixed routes to carry LSPs

In the first model, although the traffic is time-dependent, LSPs are routed over same paths in lightpath topology irrespective of the time of the day and the fraction of demand carried by each LSP does not change with time. We refer to this formulation as $\mathbf{VT}$.

$$\bar{F} = \min_{\{x,b\}} f(x,b) \tag{1}$$

subject to

$$\sum_{p \in \mathcal{P}_d} x_{dp} \;=\; 1.0, \quad d \in \mathcal{D} \tag{2a}$$

$$\sum_{d \in \mathcal{D}} \sum_{p \in \mathcal{P}_d} \delta^{\ell}_{dp} h_{dt} x_{dp} \;\leq\; C_\ell u_\ell, \quad \ell \in \mathcal{L} \;\; t \in T \tag{2b}$$

$$u_\ell + \epsilon \;\leq \sum_{d \in \mathcal{D}} \sum_{p \in \mathcal{P}_d} \delta^{\ell}_{dp} x_{dp} + 1, \quad \ell \in \mathcal{L} \;\; t \in T \tag{2c}$$

$$\sum_{\ell \in \mathcal{L}} a_{\ell v} u_\ell \;\leq\; \Delta_v, \quad v \in V \tag{2d}$$

$$0 \;\leq x_{dp} \;\leq 1, \;\; d \in \mathcal{D} \;\; p \in \mathcal{P}_d \tag{2e}$$

The goal of lightpath topology configuration problem ($\mathbf{VT}$) is to minimize a suitable objective function $f(x,b)$ (to be discussed in detail in next section). The first constraint refers that LSP paths are to carry all the demand volume for each demand in each time window. The second constraint ensures that the flow on any lightpath in any time window does not exceed the wavelength transmission capacity *if* this lightpath is activated (denoted by u_ℓ). Constraint (2c) refers to the condition that a lightpath is established, only if there is at least a minimum ϵ amount of flow on the lightpath in each time window; this avoids generating many LSPs with small flows. Here, ϵ is a parameter to the problem and we can study how network performance is impacted by varying the values of ϵ. The next constraint ensures that the number of lightpaths originating and terminating from a node do not exceed the number of transceivers, Δ_v, available at optical node $v \in V$.

B. Model-B: LSP Re-routing

We now relax the restriction of fixed paths spanning all time windows. That is, LSPs can be re-routed from one time window to next and also fraction of the IP demand carried on each LSP can vary with time. We refer to the formulation with LSP re-routing as $\mathbf{VT_r}$.

$$\bar{F_r} = \min_{\{x,b\}} f_r(x,b) \tag{3}$$

subject to

$$\sum_{p\in\mathcal{P}_d} x_{dpt} \;=\; 1.0, \quad d\in\mathcal{D}\;\; t\in T \tag{4a}$$

$$\sum_{d\in\mathcal{D}}\sum_{p\in\mathcal{P}_d} \delta^{\ell}_{dp} h_{dt} x_{dpt} \;\le\; C_\ell u_\ell, \quad \ell\in\mathcal{L}\;\; t\in T \tag{4b}$$

$$u_\ell + \epsilon \;\le \sum_{d\in\mathcal{D}}\sum_{p\in\mathcal{P}_d} \delta^{\ell}_{dp} x_{dpt} + 1, \quad \ell\in\mathcal{L}\;\; t\in T \tag{4c}$$

$$\sum_{\ell\in\mathcal{L}} a_{\ell v} u_\ell \;\le\; \Delta_v, \quad v\in V \tag{4d}$$

$$0 \;\le x_{dpt} \;\le 1, \;\; d\in\mathcal{D}\;\; p\in\mathcal{P}_d\;\; t\in T \tag{4e}$$

Note that by adding the subscript t to the flow variable x, we have tailored the formulation from $\mathbf{VT}$ to $\mathbf{VT_r}$. Note that the change of LSPs from one time window to another can conceivably have affect on IP traffic. However, if it is best-effort traffic, this effect is minimal. There is an LSP re-setup time-lag from one time window to another—this is also minimal without unduely affecting IP traffic.

III. OBJECTIVE FUNCTIONS

In this section, we consider four objective functions, which can address the goals of interest for service providers.

Objective Function-A:
One of the important criteria in the configuration of the lightpath topology is to reduce the electronic processing at intermediate IP routers—this can be accomplished by minimizing the average packet hop distance [5]. Average packet hop distance can be defined as total flow in the network divided by the sum of demand volumes for all the demands. Since, we are given demand volumes for all the time windows, minimization of the average packet hop distance is equivalent to minimization of the total flow in the network. Thus, we can write this objective for problem *Model-A* as:

$$f_1 = \sum_{t\in T}\sum_{\ell\in\mathcal{L}}\sum_{d\in\mathcal{D}}\sum_{p\in\mathcal{P}_d} \delta^{\ell}_{dp} h_{dt} x_{dp} \tag{5}$$

Similarly, by adding a subscript t to the flow variable x, we can write this objective for *Model-B* as:

$$f_{r1} = \sum_{t\in T}\sum_{\ell\in\mathcal{L}}\sum_{d\in\mathcal{D}}\sum_{p\in\mathcal{P}_d} \delta^{\ell}_{dp} h_{dt} x_{dpt} \tag{6}$$

We refer to the formulation incorporating this objective as $\mathbf{VT_1}$ for *Model-A* and as $\mathbf{VT_{r1}}$ for *Model-B*.

Objective Function-B:
Note that objective function-A above attempts to allocate the maximum possible volume of each demand on the minimum-hop path. This in turn can lead to some links with very high utilization and some links with negligible load. To address this issue, we consider minimization of maximum link utilization as the next objective function. This objective function for both *Model-A & Model-B* can be written as:

$$f_2 = f_{r2} = r_{max} \tag{7}$$

In order to consider this objective, we need to introduce an additional constraint (utilization constraint) for each link in the lightpath topology in each time window, such that utilization for any of the links does not exceed the maximum link utilization, r_{max}, over all time windows. For *Model-A*, this constraint can be written as follows:

$$\sum_{d\in\mathcal{D}}\sum_{p\in\mathcal{P}_d} \delta^{\ell}_{dp} h_{dt} x_{dp} \;\le\; C_\ell r_{max}, \quad \ell\in\mathcal{L}\;\; t\in T \tag{8}$$

Similarly, for *Model-B*, the utilization constraint for each link can be written as follows:

$$\sum_{d\in\mathcal{D}}\sum_{p\in\mathcal{P}_d} \delta^{\ell}_{dp} h_{dt} x_{dpt} \;\le\; C_\ell r_{max}, \quad \ell\in\mathcal{L}\;\; t\in T \tag{9}$$

We refer to the formulation incorporating this objective function as $\mathbf{VT_2}$ for *Model-A* and as $\mathbf{VT_{r2}}$ for *Model-B*.

Objective Function-C:
The above two objective functions do not take number of lightpaths into consideration. This can lead to increase in the number of lightpaths in the lightpath topology with negligible improvement in the network performance. On the other hand, adding each lightpath incurs a significant amount of signaling overhead, and also leads to increase in the required number of wavelengths. Therefore, some network providers might be interested in minimizing the total number of lightpaths in the lightpath topology. For both *Model-A & Model-B*, we can write this objective function as:

$$f_3 = f_{r3} = \sum_{\ell\in\mathcal{L}} u_\ell \tag{10}$$

We refer to the formulation incorporating this objective function as $\mathbf{VT_3}$ for *Model-A* and as $\mathbf{VT_{r3}}$ for *Model-B*.

Composite Objective Function:
Each of the objective functions considered above optimizes the network performance for a specific goal. By combining these objectives, we construct a composite objective, similar to the approach in [13]; that is, it combines the benefit of minimizing average packet-hop distance, minimization of maximum link utilization, and minimization of total number of lightpaths. In order to capture these three aspects, we introduce scaling factor α to objective function-A, β to objective function-B, and γ to objective function-C. For *Model-A*, we can write this combined objective as:

$$f_4 = \alpha\sum_{t\in T}\sum_{\ell\in\mathcal{L}}\sum_{d\in\mathcal{D}}\sum_{p\in\mathcal{P}_d} \delta^{\ell}_{dp} h_{dt} x_{dp} + \beta r_{max} + \gamma\sum_{\ell\in\mathcal{L}} u_\ell \tag{11}$$

Similarly, for *Model-B*, we can write the combined objective as:

$$f_{r4} = \alpha\sum_{t\in T}\sum_{\ell\in\mathcal{L}}\sum_{d\in\mathcal{D}}\sum_{p\in\mathcal{P}_d} \delta^{\ell}_{dp} h_{dt} x_{dp} + \beta r_{max} + \gamma\sum_{\ell\in\mathcal{L}} u_\ell \tag{12}$$

Note that for either composite objective, we need the additional utilization constraint for each link in each time window,

TABLE II

RESULTS FOR MODEL-A FOR DIFFERENT OBJECTIVES FOR EN-I

	$\mathbf{VT_1}$				$\mathbf{VT_2}$				$\mathbf{VT_3}$				$\mathbf{VT_4}$				
Δ	HD	NLP	ML	ALU	HD	NLP	ML	ALU	HD	NLP	ML	ALU	(α, β, γ)	HD	NLP	ML	ALU
4	1.27	13	1.00	0.40	1.58	14	0.92	0.50	1.44	11	1.00	0.45	(0.5, 4096, 64)	1.29	12	0.95	0.40
5	1.15	17	1.00	0.36	1.36	16	0.74	0.43	1.45	11	1.00	0.45	(0.5, 4096, 64)	1.22	16	0.74	0.38
6	1.06	21	1.00	0.33	1.40	21	0.61	0.44	1.41	11	1.00	0.44	(0.5, 4096, 64)	1.20	18	0.61	0.38

TABLE III

RESULTS FOR MODEL-A FOR DIFFERENT OBJECTIVES FOR EN-II

	$\mathbf{VT_1}$				$\mathbf{VT_2}$				$\mathbf{VT_3}$				$\mathbf{VT_4}$				
Δ	HD	NLP	ML	ALU	HD	NLP	ML	ALU	HD	NLP	ML	ALU	(α, β, γ)	HD	NLP	ML	ALU
5	1.34	25	1.00	0.34	1.66	25	0.91	0.43	1.49	20	1.00	0.38	(0.5, 4096, 64)	1.38	22	0.96	0.35
7	1.18	35	1.00	0.30	1.59	33	0.65	0.41	1.50	20	1.00	0.38	(0.5, 4096, 64)	1.31	27	0.69	0.34
9	1.05	45	1.00	0.27	1.62	44	0.51	0.42	1.45	19	1.00	0.37	(0.5, 4096, 64)	1.25	34	0.54	0.32

TABLE IV

COMPARATIVE STUDY OF $\mathbf{VT_4}$ AND $\mathbf{VT_{r4}}$

		$\mathbf{VT_4}$				$\mathbf{VT_{r4}}$			
ENs	(α, β, γ)	HD	NLP	ML	ALU	HD	NLP	ML	ALU
ENI($\Delta = 5$)	(0.5, 65536, 64)	1.221	16	0.736	0.384	1.205	15	0.736	0.379
ENII($\Delta = 7$)	(0.5, 65536, 64)	1.34	30	0.648	0.345	1.283	28	0.648	0.329

given by equations (8) and (9) for *Model-A and Model-B*, respectively. We refer to the formulation incorporating the combined objective function as $\mathbf{VT_4}$ for *Model-A* and as $\mathbf{VT_{r4}}$ for *Model-B*.

By tuning scaling values of α, β and γ, we can control the importance given to hop-count, link utilization or number of links in the lightpath topology. Therefore, in order to combine the benefits of all three objectives, values of α, β and γ need to be chosen appropriately.

IV. NUMERICAL RESULTS

We have implemented Model-A and Model-B for different objectives presented in section III using C^{++} and Cplex callable libraries. Note that a network provider is usually interested in a set of measures (rather than just the lowest objective function value) to see whether the network is engineered properly. The goal of this section is to see how various performance measures are impacted due to different objectives chosen, and if any of the objectives serves this goal more appropriately. Here, we consider the following performance measures:

- Average Packet Hop Distance (HD) captures the average number of hops taken by an IP packet from source to destination. A lower value of HD ensures minimal electronic processing at intermediate routers.
- Number of Lightpaths (NLP) captures the number of lightpaths in a lightpath topology. A higher value of NLP translates into more number of wavelengths.
- Maximum Link Utilization (ML) captures the utilization of the lightpath which is maximum loaded in the network.
- Average Link Utilization (ALU) captures the average utilization of a lightpath averaged over all time windows.

In our study, we use two networks, EN-I(7 Nodes) and EN-II(10 Nodes) with realistic traffic demand volumes between all node-pairs. The 3 time windows selected were 10:00 hr, 13:00 hr, and 16:00 hr -all US central time. We consider all $N(N-1)/2$ links as candidate links for lightpaths in the lightpath topology, where N is the number of nodes. We also assume that the wavelength transmission capacity for each lightpath as 2.5 Gbps. For each network, we generate 15 possible paths ($|\mathcal{P}_d| = 15$) for each demand d.

Next, we present values for different performance measures for these networks. First, we present results for Model-A for different objective functions in Tables II and III. We observe that $\mathbf{VT_1}$, $\mathbf{VT_2}$ and $\mathbf{VT_3}$ give the minimum values for HD, ML and NLP metrics respectively, but values of other performance metrics are very high. The results for $\mathbf{VT_4}$ show that the composite objective function was successful in getting values for HD, ML and ALU close to their respective optimal values. For most of the cases, we were able to get values for these metrics within 15% of the optimal values.

In our study, we kept Δ_v the same for all nodes for each scenario, i.e., $\Delta_v = \Delta$. With increasing values of Δ, we see a decrease in the values of HD, ML and ALU metrics for all the objectives except for $\mathbf{VT_3}$. With more number of transceivers available at each node, more number of lightpaths can be established; therefore more demands can be carried on direct paths. This in turn leads to decrease in the values of performance metrics. We do not see any improvement in performance metrics for $\mathbf{VT_3}$, which is not surprising, given the goal of this objective.

Next, we show the values of different performance metrics for the Model-A and Model-B for composite objective function in Table IV. The results show that Model-B results in significant improvement in values of all performance metrics, when compared to Model-A. This is expected, as relaxing the restriction of fixed paths during a day, gives more flexibility to carry demands in each time window. The results for other objective functions also followed a similar trend.

So far, we have reported results only for a certain combination of (α, β, γ) for $\mathbf{VT_4}$ and $\mathbf{VT_{r4}}$. In actuality, we have

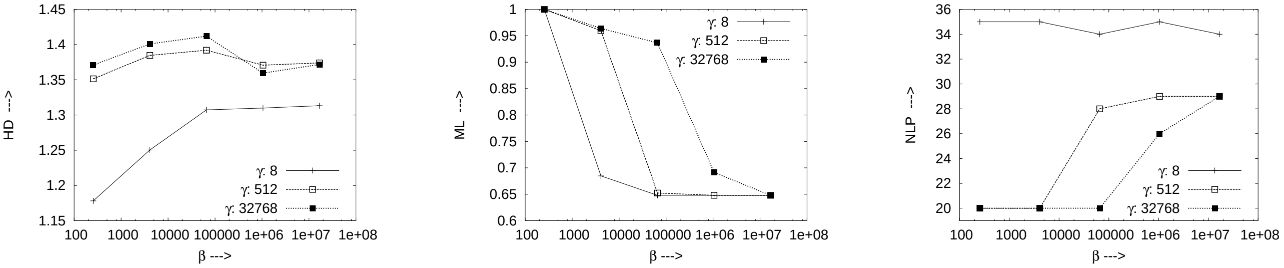

Fig. 1. Performance Metrics for EN-II for increasing β ($\alpha = 0.5$)

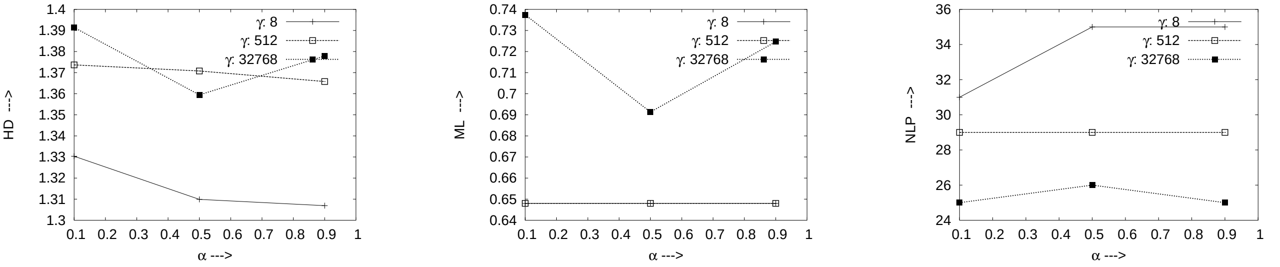

Fig. 2. Performance Metrics for EN-II for increasing α ($\beta = 1048580$)

tested a variety of combinations of (α, β, γ), and reported a specific combination to show that we observe a better behavior. Out of all runs for different values of (α, β, γ), we first picked the ones within 15% of optimal values of HD, ML and ALU metrics and then out of these, we picked the combination of (α, β, γ), which had the lowest value for NLP metric.

Figures 1- 2 show the pattern of performance metrics for *different* combinations of (α, β, γ) for for EN-II with $\Delta = 7$. These figures show the combined benefit in terms of improvement in all the performance measures for higher values of both β and γ. For this particular network (EN-II), we get acceptable values for all 3 performance measures for $\alpha = 0.5$, $\beta = 1048580$ and $\gamma = 32768$. However, the choice of (α, β, γ) might very well differ from one network to another.

V. CONCLUSION AND FUTURE WORK

In this work, we explore the problem of designing a static lightpath topology configuration for time-varying traffic during a day for different traffic engineering objectives. In addition to minimization of average packet-hop distance, minimization of maximum load and minimization of number of lightpaths, we proposed a composite objective function. We also presented a comparative study of the models with and without LSP re-routing. Our computational results show that the composite function was successful in getting values for all performance metric close to their optimal values and when LSP re-routing is allowed, values of performance measures show significant improvement. As ongoing research work, we are working on heuristic solutions to solve the problem for large networks.

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