LSP and λSP Setup in GMPLS Networks

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***Abstract*— In this paper, a new optimal policy is introduced to determine and adapt the Generalized MultiProtocol Label Switching (GMPLS) network topology based on the current traffic load. The Integrated Traffic Engineering paradigm provides mechanisms for dynamic addition of physical capacity to optical networks. In the absence of such mechanisms, the rejection of incoming requests will be higher. The objective of the proposed policy is to minimize the costs involving bandwidth, switching and signaling. The policy is derived by utilizing the Markov Decision Process theory. The new policy is split into two levels: the MPLS network level and the optical network level. In addition to the optimal policy, a sub-optimal policy and a threshold-based policy are also proposed which are less computationally intensive but have comparable performance to the optimal policy. The proposed policies have been evaluated by simulation and compared to some heuristics. Numerical results, which show their effectiveness and the achieved performance improvement, are presented.**

***Index Terms*— Optical networks, Stochastic processes, Markov Decision Process theory, Optimization, GMPLS, Topology adaptation**

I. INTRODUCTION

A multi-service IP network should provide Quality of Service (QoS) to different applications and users. Such IP networks are becoming more feasible with the current advancements in the technology. These advancements include various QoS mechanisms, *e.g.* Differentiated Services (DiffServ) architecture, MultiProtocol Label Switching (MPLS) etc., the underlying physical network components, *i.e.* optical networking technology, and their integration in the form of the multipurpose control plane paradigm of Generalized MPLS (GMPLS).

GMPLS is the proposed control plane solution for next generation optical networking. It is an extension to MPLS that enables Generalized Label Switched Paths (G-LSPs) such as lightpaths [1], to be automatically setup and torn down by means of a signaling protocol [2]. GMPLS differs from traditional MPLS because of its added switching capabilities for lambda, fiber etc. It is the first step towards the integration of data and optical network architectures. It reduces network operational costs with easier network management and operation. The traditional MPLS is defined for packet switching networks only. It provides the advantage of Traffic Engineering (TE) when compared to other routing mechanisms, added to the improved forwarding performance. In other words, MPLS mainly focuses on the data plane as opposed to GMPLS' focus on control plane. GMPLS extends the concept of LSP setup beyond the Label Switched Routers (LSRs) to wavelength/fiber switching capable systems. Thus, GMPLS allows LSP hierarchy (one LSP inside another) at different layers in the network architecture. This concept is illustrated in Fig. 1. In this hierarchy, the packet switched link is nested inside a lambda switched link inside a fiber switched link. GMPLS also performs connection management in optical networks. It provides end-to-end service provisioning for different services belonging to different classes. Its management functionalities include connection creation, connection provisioning, connection modification, and connection deletion.

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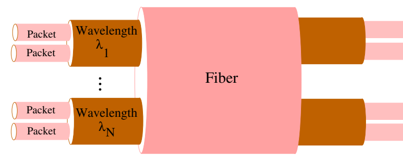

Fig. 1. Link Hierarchy.

WDM is an optical multiplexing technique that allows better exploitation of the fiber capacity by simultaneously transmitting data packets over multiple wavelengths. IP-over-WDM networks can be wavelength routed (WR) networks. In WR networks, an all-optical wavelength path is established between edges of the network. This optical path is called a λ Switched Path (λSP) and it is created by reserving a dedicated wavelength channel on every link along the path. However WR networks do not use statistical sharing of resources, and therefore provide low bandwidth utilization. To overcome this problem we consider a network architecture where different MPLS networks (for different traffic classes) will be built over the WR network. So each λSP will be assigned to LSPs carrying an aggregation of traffic flows in the same traffic class.

Many virtual topology design algorithms [3], [4], [5] for wavelength routed optical networks have been proposed in literature. A survey of many more such algorithms is given in [6]. A scheme for optical network design with lightpath protection is given in [7]. A wavelength routing and assignment algorithm for optical networks with focus on maximizing the wavelength utilization at the switches is given in [8]. However, all these algorithms design the network off-line with a given traffic matrix for the network. An on-line virtual-topology adaptation approach is suggested in [9]. This approach is concerned only with the optical network and does not relate the optical topology to the MPLS network topology. In this paper, we propose an online dynamic algorithm for topology adaptation in wavelength routed optical networks that is based on bandwidth request events as they occur. We consider GM-PLS networks, and thus the bandwidth requests are handled at two separate levels: the MPLS level and the optical level.

The motivation for the development of a combined method to control the topological structure of both the optical network and the MPLS networks is based on the concept of Integrated Traffic Engineering (ITE) proposed in [10]. It is a new holistic paradigm for network performance improvement, which consists of viewing the network as an integrated and cohesive system rather then a collection of independent layers. ITE attempts to tie together the key technical activities associated with network performance improvement, by taking a broad view of network performance optimization to encompass domain specific traffic routing and control, resource and capacity management, and economic considerations. The advantages of ITE include cost reduction, greater network adaptability and responsiveness to changing traffic demands, higher quality of service to end users of network services, increased efficiency of network asset utilization, and increased competitiveness. One of the objectives of ITE is to increase resource utilization, efficiency, and responsiveness by eliminating information gaps in the management of heterogeneous networks such as an IP-MPLS-over-optical network. The coordinated control and management of network resources is conducted to satisfy traffic performance requirements, improve network efficiency and reduce long term average network capital and operational costs. In particular, in the case of IP-MPLS-over-optical networks, costs can be further reduced and traffic performance enhanced by establishing direct optical connections between IP routers where substantial traffic demand exists to minimize multi-routing in the IP domain. In this way, the problem of network dimensioning, which traditionally is viewed as a long term planning problem, can be treated as a dynamical operational problem.

The contribution of this paper is a method to dynamically setup and tear-down LSPs and λSPs in response to new traffic demands in order to operate the Internet backbone networks more efficiently. In our previous papers [11], [12], we introduced a traffic-driven decision policy for on-line design of MPLS network. The policies proposed here will allow to adjust the virtual topologies both at the MPLS level and the optical level. The ITE approach is crucial to the dynamic topology adaptation of optical networks. ITE provides the capability to dynamically add capacity to the optical network when necessary. This adaptability leads to better QoS satisfaction and negligent request rejection. The proposed optimal policy is derived based on the Markov Decision Process theory and a sub-optimal policy is obtained by some simplifications to the optimal policy. In addition, a threshold-based policy is also proposed where the threshold is derived from economic considerations related to bandwidth reservation/utilization, switching and signaling the new LSP/λSP information to the relevant nodes. The threshold calculation requires knowledge of only few network-wide constant parameters along with local node state. Thus, this method is highly scalable and easy to implement.

This paper is organized as follows. In section II, the hierarchical LSP setup problem is formulated and solved, and the policy structure is described. In Section III, we detail the optimal policy followed by the sub-optimal policy in Section IV. The policies are tested by simulation and the numerical examples are shown in Section V. Conclusions are given in Section VI.

II. Hierarchical LSP and Lightpath Setup Problem

In this formulation, we are handling the problem of LSP creation at three levels, namely the MPLS, optical and fiber levels. Since similar variables will be used for each level, we use superscript to distinguish between the different levels. We define:

- $G^F(N, L^F)$: (Physical) Topology of fibers
- $G^\lambda(N, L^\lambda)$: (Virtual) Topology of λSPs
- $G^{LSP}(N, L^{LSP})$: (Virtual) Topology of LSPs

Here, N is the set of nodes in the network and is common between the physical and virtual topologies. L^F denotes the set of links F_{ij} in the fiber network. Each $LP^\lambda_{ij} \in L^\lambda$ is a λSP between the nodes i and j (using wavelength λ), and each $LSP_{ij} \in L^{LSP}$ is an LSP between the nodes i and j. We assume that there are no wavelength converters in the network. In other words, a λSP occupies the same wavelength on all the fibers through which it passes. We define a default λSP (LSP) as the λSP (LSP) between two nodes when they are physically connected with a fiber. Thus, the default λSPs and LSPs are mapped onto the fiber network *i.e.* each fiber in L^F contains one default λSP and one default LSP and the default λSPs and LSPs are exactly one fiber length long. We do not place any restriction on the wavelength used by the default λSPs *i.e.* different default λSPs can be created using different wavelengths. We use the notation LSP^0_{ij} for the default LSP routed on the default λSP between the node pair. The defaults LSPs and λSPs are not a subject of consideration in the following because they are always established and can not be torn-down. We will only consider the non-default LSPs (LSP^k_{ij}) and λSPs since they are candidates for redimensioning etc.

For each fiber/λSP/LSP, we define:

- $C^F_{ij}/C^\lambda_{ij}/C^{LSP}_{ij}$: Capacity of fiber, λSP, LSP between nodes i and j, respectively

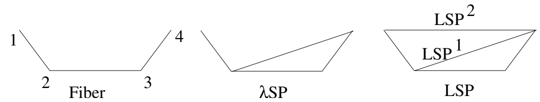

Fig. 2. Topologies

- $A_{ij}^F/A_{ij}^\lambda/A_{ij}^{LSP}$: Available capacity on fiber, λSP, LSP between nodes i and j, respectively

There may exist multiple λSPs between a node pair. There capacities and available capacities are distinguished by putting their wavelength specification in the superscript. We define B_{ij} as the total bandwidth reserved between routers i and j. Fractions of this reservation will be occupying different paths in the topology, as explained later. We define the following path variables:

- P_{ij}^F : Minimum hop path between i and j on G^F
- P_{ij}^λ : Minimum hop path between i and j on G^λ
- P_{ij}^{LSP}: Concatenation of LSPs overlaying P_{ij}^λ.

We assume that there is only one fiber between the nodes that are connected. We also assume that the minimum hop path P_{ij}^F between any two nodes i and j stays constant during our analysis. This assumption is valid because addition/deletion of fibers is a part of network planning which is performed on a long-term basis. We also assume that a suitable WDM technology is employed and it provides M distinct wavelengths for simultaneous use on a fiber. M is assumed constant throughout the network. The WDM technology assigns a capacity of W capacity units to each of these M wavelengths.

There exists only a single direct LSP between any node pair. This direct LSP can be routed either on a direct λSP or on the multi-λSP route. In the former case, it is denoted by LSP_{ij}^1, and in the latter by by LSP_{ij}^2. This is illustrated by the example in Fig. 2. In the first figure is the fiber topology for a small network. The λSP topology is shown in the second figure. The λSP from node 2 to node 4 is routed along fibers 2-3 and 3-4. The LSP topology in the third figure shows two LSPs for nodes 1-4 and 2-4. The LSP 1-4 shown in the figure is of type 2 since it is not routed on the direct λSP, rather it is routed on the multi-λSP route 1-2, 2-3, and 3-4. We can expand the minimum hop path on the fiber network between nodes i and j as a concatenation of the fiber links between the intermediate nodes *i.e.* $P_{ij}^F = \{F_{im}, \ldots, F_{nj}\}$. Similarly, we can write for the minimum hop path between nodes i and j on G^λ as : $P_{ij}^\lambda = \{LP_{ih}^{\lambda i}, \ldots, LP_{kj}^{\lambda k}\}$, a concatenation of λSPs between the intermediate nodes, and for P_{ij}^{LSP} as: $P_{ij}^{LSP} = \{LSP_{ih}^0, \ldots, LSP_{kj}^0\}$. The default LSPs are used to route MPLS traffic between two nodes when there is no direct LSP or not enough available bandwidth on the direct LSP. Thus, in an MPLS network, the bandwidth requests between i and j are routed either on a direct LSP LSP_{ij}^k or on P_{ij}^{LSP}, a concatenation of default LSPs overlaying P_{ij}^λ. We assume that P_{ij}^λ stays constant during the analysis. This implies that a λSP is used only to route LSPs with the same end-points as the λSP and a new LSP can not utilize a previously established non-default λSP for its routing. This assumption is illustrated in Fig. 2. The LSP 1-4 is routed over λSPs 1-2, 2-3 and 3-4 rather than 1-2 and 2-4. This assumption is made to approximate a decentralized management architecture. The decentralized approach is widely used in the current networks and has its advantages of scalability and ease of operation. With this assumption, events in other parts of the network do not affect the local network state.

When a new bandwidth request b_{ij} arrives between routers i and j in the MPLS network, the existence of a direct LSP between i and j is checked initially. For direct LSP between i and j, the available capacity A_{ij}^{LSP} is then compared with the request b_{ij}. If $A_{ij}^{LSP} > b_{ij}$, then the requested bandwidth is allocated on that LSP and the available capacity is reduced accordingly. Otherwise, C_{ij}^{LSP} can be increased subject to bandwidth allocation constraints (such as Russian Doll [13], Maximum Allocation Model [14]) in order to satisfy the bandwidth request. If there exists no direct LSP between i and j, then we need to decide whether to setup a new LSP and its according C_{ij}^{LSP}. Each time a new LSP is setup, the previously granted bandwidth allocation requests between i and j are rerouted on the new LSP. If we are not able to satisfy the request on the direct LSP, the request will be routed on P_{ij}^{LSP}, if there is enough available capacity on each default LSP in P_{ij}^{LSP}. If any of the default LSPs does not have the required available bandwidth, we redimension them. For this redimensioning, we borrow capacity from the corresponding λSP, LP_{hk}. Since the present day λSPs are normally allocated capacities in the order of OC-192c (10Gbps), in most cases there will be enough available capacity and the bandwidth requests can be satisfied by this part of the method. However, since Internet traffic is growing exponentially and new applications are developed on a day-to-day basis, we foresee a scenario where the OC-192c capacities will be fully occupied. While adding new physical capacity to the traditional networks was part of the long-term network planning, with the advancement in the optical technology and the integration of the MPLS and optical control planes, the capacity addition has become a more dynamic and on-demand process. Thus, we propose the second part of our method for setting up and tearing down λSPs depending on the bandwidth need, network performance and economic considerations. This part of our method is applied if the direct LSP capacity exceeds a threshold. We decide whether or not to setup a new direct λSP between i and j.

At the time of the departure of a bandwidth request, we check if the LSP where the request was routed is a candidate for being torn down. If the request was routed on LSP_{ij}^2, we decide whether to teardown the LSP. However, if the request is routed on LSP_{ij}^1, we have to consider the option of tearing down the LSP as well as the λSP. The default LSPs and default λSPs overlaying the fiber links in L^F are never torn down.

We describe the events, states, actions, and cost functions for the description of our method. The following definitions are provided for a node pair i, j. We assume that the definitions can be extended to other node pairs independently. This assumption is valid because the events for each node pair are assumed to be independent. Thus, we will drop the subscript in the definitions henceforth.

Definition 1: Bandwidth requests

We denote bandwidth requests by b. A request specifies the amount of bandwidth requested and the origin and destination end-points. We associate events with the arrival and departures of the requests, as explained next.

Definition 2: Events and decision instants

For each router pair i and j in the MPLS network, we define the following events e^{MPLS}:

- $e^{MPLS} = 0$: Arrival of a bandwidth request b
- $e^{MPLS} = 1$: Departure of request from LSP^1
- $e^{MPLS} = 2$: Departure of request from LSP^2
- $e^{MPLS} = 3$: Departure of request from P^{LSP}

In the optical network, the events are generated by actions at the MPLS network. We define the events as:

- $e^\lambda = 0$: Arrival of LSP setup or capacity increment
- $e^\lambda = 1$: Departure of LSP or capacity decrement

The occurrence of each event is a decision instant. The decision rules are explained later.

Definition 3: States

The MPLS state vector s^{MPLS} at a given time instant for a node pair in the MPLS network is defined as

$$s^{MPLS} = [A^{LSP},\, B^L,\, B^P]. \tag{1}$$

Here, B^L is the part of B that is routed on the direct LSP $LSP^k, k \in \{1, 2\}$ and B^P is the part that is routed on P^{LSP}, the concatenation of the default LSPs.

The λSP state vector s^λ at a given time instant for a node pair in the optical network is defined as

$$s^\lambda = [A^\lambda,\, B^\lambda, B^F, k], \tag{2}$$

Here, k denotes the number of λSPs between the node pair. If the capacity of the direct LSP increases beyond the λSP capacity, then another λSP is created to route the additional LSP capacity. Thus, there may exist multiple λSPs between the node pair. The first fit algorithm is used for λ assignment to the λSP. A^λ is the total available bandwidth on all the λSPs between the node pair, B^λ is the part of B that is routed on the direct λSPs between the node pair, B^F is the part of B that is routed on the λSPs in P^λ. Note that we only consider the state of the direct λSP between the node pair and not other λSPs. This is because of the assumption that the direct λSP is used only for LSPs with the same end-points.

The fiber state vector s^F at a given time instant for a node pair in the fiber network is defined as

$$s^F = [\Omega]. \tag{3}$$

where Ω denotes the set of wavelengths still available on the fiber and not being used by any λSP. We use the notation $\#(\Omega)$ to denote the cardinality of Ω. Thus, $A^F = \#(\Omega) * W$ where W is the capacity assigned to each wavelength by the deployed WDM technique. This constraint is obtained because the WDM technique introduces a granularity in the capacity allocation.

Even though we have split the system state into three separate levels, the state of the system is expressed as a combination of state at all the levels. This division among the state variables has been made because the decisions (as explained later) are made independently at each level and require only the state information at that level. Note that the system state is unchanged unless an event occurs. The occurrence of an event triggers our decision policy which provides a suitable action to handle the event. Execution of the action changes the network state. Next, we describe the actions, followed by the decision rules.

Definition 4: Extended States

The MPLS and the optical state space can be extended by the coupling of the current state and the event.

$$\begin{aligned} S^{MPLS} &= \langle s^{MPLS}, e^{MPLS} \rangle \\ S^\lambda &= \langle s^\lambda, e^\lambda \rangle \end{aligned}$$

This extended state space $\bar{S}$ is the basis for determining the decisions.

Definition 5: Actions

Assume that at time instant t, the event e occurs which has to be handled by the network. The network decides its action at both the MPLS (a^{MPLS}) and the optical (a^λ) levels. $a^{MPLS} = 1$ means that the direct LSP will be redimensioned and $a^{MPLS} = 0$ means that no action will be taken and the request is routed either on a existing direct LSP or on P^{LSP}. $a^\lambda = 1$ means that the λSP will be setup/torn-down and $a^\lambda = 0$ means that no new λSP will be setup. We denote the combined actions at the two levels by a, i.e., $a = \langle a^{MPLS}, a^\lambda \rangle$.

Definition 6: Decision rules and policies

A decision rule d_i provides an action selection for each state at a given decision instant t_i. A decision policy π specifies the decision rules to be used in the complete time horizon where the problem is considered, i.e., $\pi = \{d_0(\bar{S}), d_1(\bar{S}), d_2(\bar{S}), \ldots\}$. A decision policy is called stationary if the decision is solely dependent on the network state and not the time instant, i.e., for such a policy $d_i(\bar{S}) = d_j(\bar{S})$ for $i \neq j$.

Definition 7: Cost function

The cost is split into two levels for the MPLS network and the optical network. The cost at each level is the sum of three components: the bandwidth cost $W_b(S, a)$, the switching cost $W_{sw}(S, a)$, and the signaling cost $W_{sign}(S, a)$:

$$W(S, a) = W_b(S, a) + W_{sw}(S, a) + W_{sign}(S, a) \tag{4}$$

with appropriate superscripts for the two levels. The bandwidth and switching costs depend on the time for which the system stays in that state. Thus, $W_b(S, a) = \int_0^T w_b(S, a)dt$ and $W_{sw}(S, a) = \int_0^T w_{sw}(S, a)dt$ where T is the time till the next event. The signaling cost is incurred instantaneously when action $a = 1$ is chosen.

We assume that the rate at which MPLS bandwidth cost is incurred depends linearly on the bandwidth required and the number of hops h^λ in the shortest path P^λ on the optical network.

$$w_b^{MPLS}(S,a) = c_b\ h^\lambda\ B, \tag{5}$$

where c_b is the bandwidth cost coefficient per capacity unit (c.u.) for the MPLS network and the cost is incurred for the total traffic B between the node pair. Note that, in our model the physical path is inherently the same irrespective of the actual path taken by the request. Thus, the bandwidth cost incurred is the same irrespective of the decision and so we do not show the dependence of the bandwidth cost on the decision variable.

The switching cost depends linearly on the number of switching operations in the MPLS network and the switched bandwidth. Part of the switching operations will be in MPLS and the rest in IP mode depending on the existence of the direct LSP. The total number of switching operations is always h^λ (the number of hops in P^λ) since the physical path is fixed. Whether these switching operations are IP or MPLS depends on the path chosen in the MPLS network. If the direct LSP exists, we have 1 router performing IP switching and $[h^\lambda(i,j)-1]$ routers performing MPLS switching. If no direct LSP exists, $h^\lambda(i,j)$ routers perform IP switching. Thus, the rate at which switching cost is incurred is given as:

$$w_{sw}^{MPLS}(S,a) = \begin{cases} D(B^L + B^P + b) & a = 1 \\ DB^L + h^\lambda c_{ip}(B^P + b) & a = 0 \end{cases} \tag{6}$$

where $D = c_{ip} + c_{mpls}(h^\lambda - 1)$ and c_{ip} and c_{mpls} are the switching cost coefficients per c.u. in IP and MPLS mode respectively.

The signaling cost is incurred when an LSP is setup or redimensioned. We consider that this cost depends linearly on the number of hops h^λ in the shortest path in the optical network over which the LSP is setup, plus a constant component to take into account the notification of the LSP to the network.

$$W_{sign}^{MPLS}(S,a) = a^{MPLS}[c_s\ h^\lambda + c_a], \tag{7}$$

where c_s is the signaling cost coefficient per hop and c_a is the fixed notification cost coefficient. This cost is not incurred if $a = 0$.

Next, we explain the cost components at the optical network level. The rate of bandwidth cost $w_b^\lambda(S,a)$ incurred depends linearly on the number of hops h^F in P^F and the capacity of the λSP.

$$w_b^\lambda(S,a) = c_{cap} k\ W\ h^F, \tag{8}$$

where c_{cap} is the bandwidth cost coefficient per capacity unit (c.u.) for the optical network. The cost is incurred for the whole capacity allocated to the k λSPs because of the large modularity in capacity allocation by the current WDM technologies.

The switching cost in the optical network depends on the number of switching operations in the optical and opto-electronic switches. The total number of switching operations is always h^F, since the physical path is fixed. The type of

TABLE I

SET OF POSSIBLE STATES

Old state $\overset{Action}{\rightarrow}$ New state $(e \in \{0,1\})$
$\langle 0,0,B^F,0,0\rangle \overset{0}{\rightarrow} \langle 0,0,B^F+b,0,e\rangle$
$\langle 0,0,B^F,0,0\rangle \overset{1}{\rightarrow} \langle W-B^F-b,B^F+b,0,1,e\rangle$
$\langle 0,0,B^F,0,1\rangle \overset{0}{\rightarrow} \langle 0,0,B^F-b,0,e\rangle$
$\langle A^\lambda,B^\lambda,B^F,k,0\rangle \overset{0}{\rightarrow} \langle A^\lambda-b-B^F,B^\lambda+B^F+b,0,k,e\rangle$ where $k>0$ and $A^\lambda \geq b+B^F$
$\langle A^\lambda,B^\lambda,B^F,k,0\rangle \overset{1}{\rightarrow} \langle A^\lambda+W-b-B^F,B^\lambda+B^F+b,0,k+1,e\rangle$ where $k>0$ and $A^\lambda < b+B^F$
$\langle A^\lambda,B^\lambda,B^F,k,1\rangle \overset{0}{\rightarrow} \langle A^\lambda+b,B^\lambda-b,B^F,k,e\rangle$ where $k>0$ and $A^\lambda < W-b-B^F$
$\langle A^\lambda,B^\lambda,B^F,k,1\rangle \overset{1}{\rightarrow} \langle A^\lambda+b-W-B^F,B^\lambda-b+B^F,0,k-1,e\rangle$ where $k>0$ and $A^\lambda \geq W-b-B^F$

these operations depends on the path chosen in the optical network. Thus, the rate of switching cost is given as

$$w_{sw}^\lambda(S,a) = \begin{cases} E(B^\lambda + B^F + b) & a^\lambda = 1 \\ EB^\lambda + c_\lambda h^F(B^F + b) & a^\lambda = 0 \end{cases} \tag{9}$$

where $E = (h^F - 1)c_{opt} + c_\lambda$, c_{opt} is the cost coefficient for the switching of the λSP in the optical switches on the path and c_λ is the cost coefficient for the opto-electronic switching at the head-end of the λSP. Since the λSPs are assumed to be always formed over the physical shortest path in P^F (which stays constant), the optical switching cost coefficient is multiplied by $(h^F - 1)$, the number of successive hops with optical switching.

The signaling cost of a λSP is made up of many components. As for the MPLS network, the signaling cost is incurred only when a new λSP is being created or an old one being destroyed. The components of the signaling cost include c_{sign} (the cost for signaling the information to all the relevant nodes) among others. This cost component is fixed in nature and does not depend on the network topology. The other two components of the signaling cost are proportional to h^F, the number of hops on the physical path between the nodes. They are $c_{find\lambda}$ (the cost for finding the common wavelength to be used on the fibers in P^F) and $c_{allocate}$ (the cost of allocating that wavelength to the λSP). The last component c_{moving} relates to the cost of moving the existing traffic from one λSP to another. Note that the signaling cost is instantaneous and not time-dependent. Grouping together terms, we obtain:

$$W_{sign}^\lambda(S,a) = a^\lambda[c_x + c_y h^F] \tag{10}$$

The set of system states, events, and actions at the MPLS level can be deduced similar to [12]. In Table I, we provide these information for the optical level.

III. Optimal LSP and Lightpath Setup Policy

We propose a stochastic model to determine the optimal decision policy for LSP and λSP set-up. The optimization problem is formulated as a Continuous-Time Markov Decision Process (CTMDP) [15]. The cost functions for the MDP theory have been defined in Definition 7. Following the theory of MDPs, we define the expected infinite-horizon discounted total cost, $v^{\pi}(S_0)$, with discounting rate α, given that the process occupies state S_0 at the first decision instant and the decision policy is π by:

$$v_{\alpha}^{\pi}(S_0) = E_{S_0}^{\pi}\left\{\sum_{m=0}^{\infty} e^{-\alpha t_m}\left[W_{sign}(S_m,a) + \int_{t_m}^{t_{m+1}} e^{-\alpha(t-t_m)}[w_b(S_m,a)+w_{sw}(S_m,a)]dt\right]\right\}. \quad (11)$$

where t_i represents the time of events and $W_{sign}(S_m,a)$ represents the fixed part of the cost incurred whereas $[w_b(S_m,a)+w_{sw}(S_m,a)]$ represents the continuous part of the cost between times t_m and t_{m+1}. This definition can be applied to both the LSP and λSP levels. The *optimization objective* is to find a policy π^* such that:

$$v_{\alpha}^{\pi^*}(s) = \inf_{\pi\in\Pi} v_{\alpha}^{\pi}(s).$$

The optimal decision policy can be found by solving the optimality equations for each initial state S. We assume that the bandwidth requests arrive in the MPLS network according to a Poisson process with rate λ and the request durations are exponentially distributed with mean μ. Only some of these requests are relayed to the underlying optical network when λSP states need to be modified. Since the sampling of a Poisson process leads to another Poisson process, we assume that the λSP requests in the optical network arrive according to a Poisson process with rate λ' and are valid for exponentially distributed durations with mean μ'. With our assumptions of a discounted infinite-horizon CTMDP, the optimality equations for the MPLS network can be written as:

$$v(S) = \min_{a\in A}\left\{r(S,a) + \frac{\lambda+\mu}{\lambda+\mu+\alpha}\sum_{j\in\overline{S}} q(j\,|S,a)v(j)\right\} \quad (12)$$

where $r(S,a)$ is the expected discounted cost between two decision instants and $q(j\,|S,a)$ is the probability that the system occupies state j at the subsequent decision instant, given that the system is in state S at the earlier decision instant and action a is chosen.

Following an approach similar to [12], we obtain the optimal LSP setup decision policy as $\pi^* = \{d^*, d^*, d^*, \ldots\}$ and the decision rule is given by

$$d^* = \begin{cases} 0 & S=\langle A,B^L,B^P,0\rangle \;\; A\geq b \\ a^*\langle A,B^L,B^P,0\rangle & S=\langle A,B^L,B^P,0\rangle \;\; A<b \\ a^*\langle A,B^L,B^P,1\rangle & S=\langle A,B^L,B^P,1\rangle \\ a^*\langle A,B^L,B^P,2\rangle & S=\langle A,B^L,B^P,2\rangle \\ 0 & S=\langle A,B^L,B^P,3\rangle \end{cases} \quad (13)$$

where

$$a^*\langle A,B^L,B^P,0\rangle = \begin{cases} 1 & c_s h^{\lambda}+c_a < v^*\left(A,B^L,B^P+2b,3\right) - v^*\left(0,B^L+B^P+b,b,3\right), \\ 0 & \text{otherwise,} \end{cases}$$

$$a^*\langle A,B^L,B^P,1\rangle = a^*\langle A,B^L,B^P,2\rangle = \begin{cases} 1 & c_s h^{\lambda}+c_a < v^*\left(A+b,B^L-b,B^P+b,3\right) - v^*\left(0,B^L+B^P-b,b,3\right), \\ 0 & \text{otherwise.} \end{cases}$$

For the optical network, the optimality equations are:

$$v(S)=\min_{a\in A}\left\{r(S,a) + \frac{\lambda'+\mu'}{\lambda'+\mu'+\alpha}\sum_{j\in\overline{S}} q(j\,|S,a)v(j)\right\} \quad (14)$$

Here $r(S,a)$ can be written as

$$r(S,a) = W_{sign}^{\lambda}(S,a) + \frac{w_b^{\lambda}(S,a)+w_{sw}^{\lambda}(S,a)}{\alpha+\lambda'+\mu'} \quad (15)$$

Since the set of possible actions is finite and $r(S,a)$ is bounded, it can be proved that the optimal policy π^* is stationary and deterministic [15]. The solution of the optimality equations (given in Appendix) gives the optimal values of the expected infinite-horizon discounted total costs. The optimality equations can be solved using value iteration approach. The decision rule for the optimal policy at the optical level is given as

$$d^* = \begin{cases} a^* & S=\langle 0,0,B^F,0,0\rangle \\ 0 & S=\langle 0,0,B^F,0,1\rangle \\ 0 & S=\langle A^{\lambda},B^{\lambda},B^F,k,0\rangle \;\; k>0, A^{\lambda}\geq b+B^F \\ 1 & S=\langle A^{\lambda},B^{\lambda},B^F,k,0\rangle \;\; k>0, A^{\lambda}<b+B^F \\ 0 & S=\langle A^{\lambda},B^{\lambda},B^F,k,1\rangle \;\; k>0, A^{\lambda}<W-b-B^F \\ 1 & S=\langle A^{\lambda},B^{\lambda},B^F,k,1\rangle \;\; k>0, A^{\lambda}\geq W-b-B^F \end{cases} \quad (16)$$

where

$$a^* = \begin{cases} 1 & c_x+c_y h^F + \dfrac{c_{cap}Wh^F}{\alpha+\lambda'+\mu'} < v^*\left(0,0,B^F+2b,0,1\right) - v^*\left(W-B^F-2b,B^F+2b,0,1,1\right), \\ 0 & \text{otherwise,} \end{cases}$$

The threshold structure of the optimal policy facilitates the solution of the optimality equations but still it is difficult to pre-calculate and store the solution because of the large number of possible system states. In a large network, the application of this optimal policy will no more be real-time since solving the infinite-horizon MDP problem is a time-intensive process. So, we propose a sub-optimal policy that is easy and fast to calculate and implement in large realistic scenarios.

IV. Sub-optimal Setup Policy

The proposed sub-optimal policy is an approximation to the solution of the optimality equations. It minimizes the cost incurred between two decision instants, rather than the whole infinite horizon cost. Instead of going through all the iterations of the value iteration algorithm, we perform the first iteration with the assumption that $v^0(\cdot) = 0$. Thus, for the MPLS network we obtain the sub-optimal LSP setup decision policy as $\pi^{\#} = \{d^{\#}, d^{\#}, d^{\#}, \ldots\}$ and the decision rule is given by

$$d^{\#} = \begin{cases} 0 & S = \langle A, B^L, B^P, 0\rangle \;\; A \geq b \\ a^1\langle A, B^L, B^P, 0\rangle & S = \langle A, B^L, B^P, 0\rangle \;\; A < b \\ a^1\langle A, B^L, B^P, 1\rangle & S = \langle A, B^L, B^P, 1\rangle \\ a^1\langle A, B^L, B^P, 2\rangle & S = \langle A, B^L, B^P, 2\rangle \\ 0 & S = \langle A, B^L, B^P, 3\rangle \end{cases} \quad (17)$$

where

$$a^1\langle A, B^L, B^P, 0\rangle = \begin{cases} 1 & B^P + b > \frac{(c_s h + c_a)(\alpha+\lambda+\mu)}{(h-1)(c_{ip} - c_{mpls})} \\ 0 & \text{otherwise,} \end{cases}$$

$$a^1\langle A, B^L, B^P, 1\rangle = a^1\langle A, B^L, B^P, 2\rangle = \begin{cases} 1 & B^P > \frac{(c_s h + c_a)(\alpha+\lambda+\mu)}{(h-1)(c_{ip} - c_{mpls})} \\ 0 & \text{otherwise.} \end{cases}$$

We obtain the sub-optimal policy for optical network as $\pi^{\#} = \{d^{\#}, d^{\#}, d^{\#}, \ldots\}$ and the decision rule is given by

$$d^{\#} = \begin{cases} a^1 & S = \langle 0, 0, B^F, 0, 0\rangle \\ 0 & S = \langle 0, 0, B^F, 0, 1\rangle \\ 0 & S = \langle A^\lambda, B^\lambda, B^F, k, 0\rangle \;\; k > 0, A^\lambda \geq b + B^F \\ 1 & S = \langle A^\lambda, B^\lambda, B^F, k, 0\rangle \;\; k > 0, A^\lambda < b + B^F \\ 0 & S = \langle A^\lambda, B^\lambda, B^F, k, 1\rangle \;\; k > 0, A^\lambda < W - b - B^F \\ 1 & S = \langle A^\lambda, B^\lambda, B^F, k, 1\rangle \;\; k > 0, A^\lambda \geq W - b - B^F \end{cases} \quad (18)$$

where

$$a^1 = \begin{cases} 1 & B^F + b > \frac{(c_x + c_y h^F)(\alpha+\lambda'+\mu') + c_{cap} W h^F}{(h^F - 1)(c_\lambda - c_{opt})} \\ 0 & \text{otherwise,} \end{cases} \quad (19)$$

This sub-optimal policy is easy to implement in a real-time manner for a large network since it is a simple threshold-based policy where the thresholds are dependent on the network costs which are known and constant during the analysis. Thus, the thresholds can be calculated and stored apriori and and the application of the sub-optimal policy becomes a simple comparison check for the network state. Though this sub-optimal policy is easy to implement, it is still restricted in its physical application because of the assumption that a λSP can only be used by LSPs with same end-points. An improvement to this policy can be achieved with a centralized approach where information is available about the whole network. Thus, we propose another policy for λSP establishment which is sub-optimal. In this policy, we remove the aforementioned assumption and intermediate λSPs are used for longer LSPs. The algorithm for this threshold-based sub-optimal policy for LSP and λSP topology adaptation is given in Fig. 3. This policy achieves lower overall operational cost at the expense of increased management effort for maintaining the global network state. In this policy, B_{Th}^{MPLS} is equal to the threshold in (18) and B_{Th}^{λ} is given as:

$$B_{Th}^{\lambda} = \frac{(c_x + c_y h^F - c_x\beta - c_y \sum_{i\in\beta} h_i^F)(\alpha + \lambda' + \mu')}{(h^\lambda - 1)(c_\lambda - c_{opt}) + c_{cap}\sum_{i\in\eta} h_i^F} + \frac{c_{cap} W (h^F - \sum_{i\in\beta} h_i^F)}{(h^\lambda - 1)(c_\lambda - c_{opt}) + c_{cap}\sum_{i\in\eta} h_i^F} \quad (20)$$

where β is the total number of λSPs in P^λ that do not have enough available bandwidth and η is the number of λSPs that do not need modification. Also, h_i^F denotes the number of fibers corresponding to the λSP i among the β λSPs to be redimensioned. We used the relations $\beta + \eta = h^\lambda$ and $\sum_{i\in\beta,\eta} h_i^F = h^F$ to derive the threshold. This threshold has been calculated by a cost comparison among the options of creating a direct λSP and redimensioning intermediate λSPs for LSP request. On close observation, this threshold is similar to the threshold in (19).

V. Numerical Results and Discussions

In this section, we compare and evaluate the proposed topology adaptation policies, along with other well-known algorithms, from the viewpoint of performance and robustness. We first present a simple analytical example, followed by experiments with a more complex network.

We have introduced the cost coefficients in the cost definitions to provide a relative weight to each of the cost components. A network operator can decide these coefficients based on the fraction of the total cost that is attributed to each cost component. For example, if the bandwidth is a scarce resource in the network, then the bandwidth cost coefficients c_b and c_{cap} can be assigned larger values to ensure that bandwidth wastage in minimized in the network. A study to assign values to these cost coefficients based on network characteristics is out of the scope of this paper. However, in the following, we have assigned values to these coefficients that we deemed appropriate. In our model, the cost functions are assumed to be linear with respect to the bandwidth requirements of the requests. By keeping a history of user requests, the average inter-arrival time and connection duration can be estimated. The value for the time duration of the LSP can be obtained from past statistics of the traffic and the network. Note that we assume no wavelength converters are available in our optical network.

The optimal policy decisions can be stored a-priori for all possible events for all possible node pairs of the network. Whenever there is a bandwidth request arrival or departure, the network performs a table lookup at the corresponding node pair entry. For networks of considerable size, the storage of the optimal policy for each node pair can be very resource-consuming. In such cases the proposed threshold-based policy, given in Section 4, can be applied. This policy computes the decision upon arrival of each request and does not involve storage of the whole policy. This policy is control-theoretic, i.e., it compares the total traffic between the node pair with a threshold to decide how to handle the request.

LSP & Lightpath Setup/Redimensioning Policy
At time t, $\mathbf{s^{MPLS}} = [\mathbf{A^{LSP}}, \mathbf{B^{L}}, \mathbf{B^{P}}]$, $\mathbf{A}^{\lambda}, \mathbf{B}^{\lambda}, \mathbf{B^{F}}, \mathbf{k}]$ and event $\mathbf{e^{MPLS}}$ occurs
Case 0: $\mathbf{e^{MPLS}}$ = **Arrival of request b**
If direct $LSP^k, k \in \{1, 2\}$ exists with enough available bandwidth
Request is accepted and routed on LSP^k
Else
If all LSPs $\in P^{LSP}$ have enough available capacity
LSP Check: If total traffic between nodes exceeds B_{Th}^{MPLS}
If direct LSP^1 exists
If LP does not have enough available capacity, LP is redimensioned
LSP^1 is redimensioned and request is accepted and routed on LSP^1
If direct LSP^2 exists
If total traffic between nodes exceeds threshold in (19)
LP and LSP^1 are created and request is accepted and routed on LSP^1
If LSP^k does not exist, new LSP^2 is created and request is accepted and routed on LSP^2
Else request is accepted and routed on P^{LSP}
Else
Identify all default $LSP_{hk}^0 \in P^{LSP}$ without enough available capacity. Let α be the number of such LSPs
For each such LSP_{hk}^0
If the corresponding λSP has enough available capacity LSP_{hk}^0 is redimensioned
Else identify λSP LP_{hk}
Let β be the total number of λSPs without enough available capacity
Let η be the number of λSPs with enough available capacity ,i.e., $\beta + \eta = h^{\lambda}$
If total traffic on LSP^k exceeds B_{Th}^{λ}
New direct LP and LSP^1 are created. Request accepted and routed on LSP^1
Topologies P^{λ} and P^{LSP} are modified
Else
Create β new λSPs LP_{hk}
β default LSP_{hk}^0 are redimensioned
Jump to LSP Check
Case 1: $\mathbf{e^{MPLS}}$ = **Departure of b from** $\mathbf{LSP^1}$
If $B^L = b$ and $B^P = 0$ and F not exists
LSP^1 and LP are torn-down
Case 2: $\mathbf{e^{MPLS}}$ = **Departure of b from** $\mathbf{LSP^2}$
If $B^L = b$ and $B^P = 0$ and F not exists
LSP^2 is torn-down
Case 3: $\mathbf{e^{MPLS}}$ = **Departure of b from** $\mathbf{P^{LSP}}$
Adjust B^P accordingly

Fig. 3. Threshold-Based Setup/Redimensioning Policy.

A. Analytical Example

Let us apply the threshold-based policy to a network where no additional λSPs have been added yet. Thus, all the λSPs correspond to a single fiber and $h^{\lambda} = h^F = h$ and $h_i^F = 1$. When a new LSP setup request arrives, if only one out of the h λSPs needs redimensioning, the threshold for creation of a direct λSP becomes $\{c_y(\alpha + \lambda + \mu) + c_{cap}W\}/\{c_{\lambda} - c_{opt} + c_{cap}\}$. If two λSPs need redimensioning, the threshold becomes $\{c_y(\alpha+\lambda+\mu)c_{cap}W - \frac{c_x}{h-2}\}/\{\frac{h-1}{h-2}(c_{\lambda} - c_{opt}) + c_{cap}\}$. It is easy to see that the former expression is larger than the latter. Thus, it is faster to create a new direct λSP if more λSPs need redimensioning. This observation is very intuitive as redimensioning larger number of λSPs implies larger signaling cost. Let us consider a case when all the λSPs need to be redimensioned to accommodate the LSP, i.e., $\beta = h^{\lambda}$. In this case, the threshold for creation of a direct λSP becomes $-c_x/(c_{\lambda} - c_{opt})$. As this value is less than zero, it implies that the direct λSP will be created even for a very small bandwidth request.

B. Experimental Results

For the simulations, we used the physical topology of Fig. 4. Each node represents an LSR and each edge represents a fiber link connecting two LSRs. We assign a capacity of 10Gbps to each λSP. The cost coefficients are chosen as $c_s = c_y = 2.5, c_a = c_x = 2.5, c_b = c_{cap} = 1, c_{ip} = c_{\lambda} = 0.35, c_{mpls} = c_{opt} = 0.25$. Equal values were chosen for the MPLS and optical network. Note that we have assigned values such that $c_{ip} > c_{mpls}$ and $c_{\lambda} > c_{opt}$ and the signaling costs are larger than any of the other costs. The values for λ and μ are chosen such that the traffic in the network is increasing. The values of λ' and μ' are obtained by observing the statistics of the MPLS network operation under the optimal policy for LSP setup.

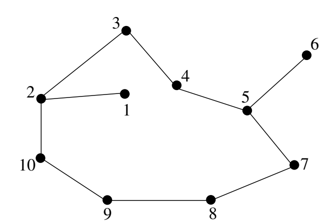

Fig. 4. Network Topology.

We start the experiment for the threshold-based policy such that the three topologies G^F, G^{λ} and G^{LSP} coincide. We present homogeneously increasing amount of traffic to the

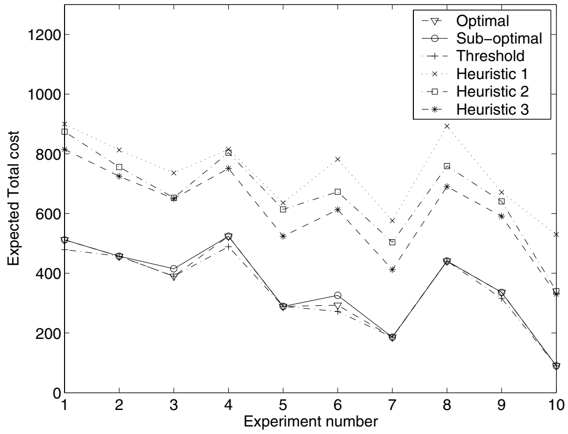

Fig. 5. Total expected cost.

node pairs 2-5, 2-6, 2-7, 2-8, 10-5, 10-6, 10-7, and 10-8. We observe the network topology over time. The LSP evolution profile shows that the longer LSPs tend to be established first. From the λSP evolution, we observe that for a given h^λ, the setup threshold decreases with increasing β. The second observation states that for a given β, the threshold increases with increasing h^λ.

If the capability to add physical capacity on demand was not available, then the rejection of bandwidth requests would be very high in current networks as the traffic continues to grow. To put the performance of the proposed policies (13, 16, 17, 18, Fig.3) in perspective, we compare their performances with three well-known simple heuristics. In all the heuristics considered, a fully connected λSP network is pre-established. Thus, there is no need for λSP topology adaptation. Heuristic 1 also establishes a fully connected LSP network before the network is operational. In this way, all the virtual topologies are fixed a-priori and can not be adjusted to the traffic demands. This heuristic leads to resource wastage as the reserved resources are not necessarily utilized. Heuristic 2 redimensions the LSPs every time there is a bandwidth request. The redimensioning is such that the the LSP size exactly fits the bandwidth request. This heuristic leads to large number of topology modifications. Heuristic 3 tries to reduce the number of modifications by redimensioning the LSPs such that there is a cushion. Thus, the LSPs are redimensioned, when necessary, to $\Delta\%$ ($\Delta > 100$) of their capacity. These three heuristics are simple to implement and are currently in use by network operators.

In the following, we present the metric comparison results for independent experiments. For each figure, different experiments are considered to reflect appropriate behaviors. First, we compare the total expected cost (II) of the six policies in Fig. 5. As expected, the cost for the heuristics are much higher when compared to the proposed policies. Heuristic 1 has a lot of wasted bandwidth whereas heuristic 2 has very high signaling costs. Heuristic 3 also has a higher cost due to the combination of wasted bandwidth and frequent bandwidth adjustments. On the other hand, the three proposed policies have comparatively lower costs. Among the three policies, the sub-optimal policy has a higher cost than the optimal policy as expected. However, the threshold-based policy has an even lower cost than the optimal policy. This results from the removal of the limitation that an intermediate λSP can be used only for LSP with the same end-points. By removing this limitation, the number of λSPs to be created reduces and thus the total cost reduces. Note that this limitation can only be removed in centralized network operation because information is required about the state of the intermediate λSPs which is not available in the decentralized scenario. Thus, the cost reduction has been obtained at the expense of the added network management effort.

We can use many other metrics to compare the performance of the proposed policies. One such metric can be the number of LSPs in the MPLS topology that were created to handle the traffic requests. For heuristic 1, the number is always 8 because all the LSPs are pre-established. The results for heuristic 2 and 3 are comparable to the proposed sub-optimal policy. They differ in only one experiment. In this case, the sub-optimal policy is waiting to create the direct LSP since the traffic has not exceeded the threshold but the two heuristics have created the LSP as soon as any traffic is encountered between the node pair. Next, we compare the number of λSPs created by the different policies. All the three heuristics have pre-established λSPs, so they show a constant 8 λSPs. The sub-optimal and the threshold-based policies establish and delete λSPs as needed. Thus, they have a lesser number of λSPs. In most of the experiments, the two policies have similar performances except three cases when the threshold-based policy has a lower number of λSPs established than the sub-optimal policy. These cases reflect the scenario where the threshold-based policy decided to use the λSPs in P^λ instead of creating a direct λSP. A metric that is more reflective of the operations is the number of modifications to the LSPs and λSPs. In Fig. 6, we plot the number of modifications for LSPs.

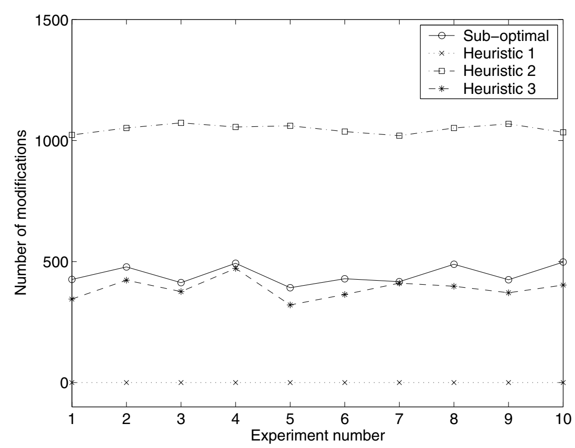

Fig. 6. Number of modifications in the LSP topology .

Another metric for comparison is the bandwidth wastage in the LSP and the λSP. We can look at the mean and max wastage. The mean wastage considers all the LSPs or λSPs whereas the max value gives a worst-case scenario picture of the bandwidth wastage. In Figs. 7 and 8, we plot the max bandwidth wastage for the LSPs and λSPs, respectively. As is noticeable, the heuristics perform worse than the proposed policies. In Fig. 7, the results for Heuristic 1 have been clipped at 800 to show the results for other policies at a reasonable scale. The actual results for Heuristic 1 are very large which show the inefficiency of the heuristic.

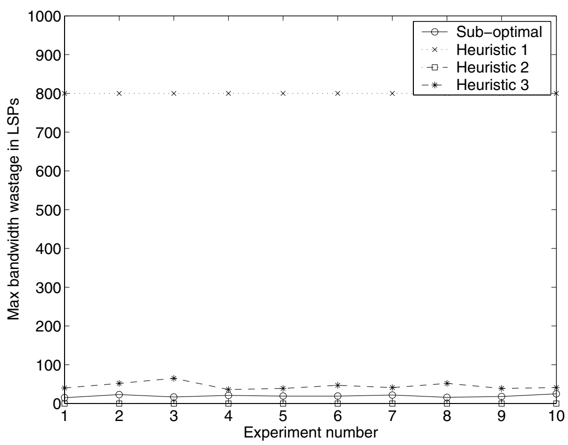

Fig. 7. Max bandwidth wastage in MPLS network

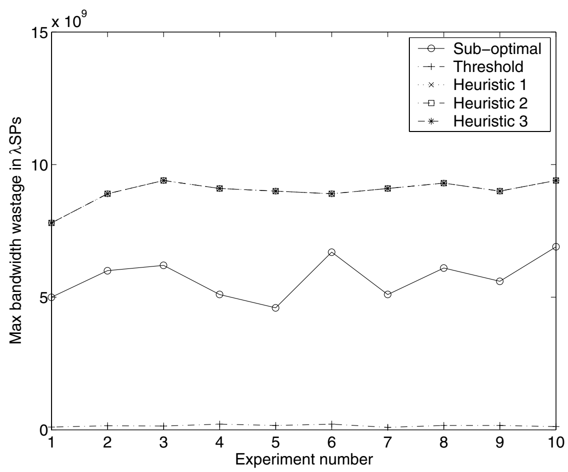

Fig. 8. Max bandwidth wastage in optical network

VI. CONCLUSIONS

In this paper, we presented a new decision policy that provides the on-line design of a GMPLS network topology for the current traffic load and pattern. An optimal policy has been proposed that has been derived based on the Markov Decision Process theory. A sub-optimal policy has also been obtained by simplifying the solutions of the optimality equations. Finally a threshold policy is proposed that is based on the network load, which is part of the defined network state, via a threshold criterion. The threshold calculation takes into account the bandwidth, switching and signaling costs. The proposed methods were tested by simulation. Several examples were considered. The results confirm that the proposed policy is effective and improves network performance by reducing the cost incurred.

The use of ITE in the GMPLS networks provides a high degree of flexibility for topology adaptation to traffic variations. This dynamic setup of adding capacity to the links is advantageous in real scenarios as it can obtain capacity when needed and release when it is not needed. The advancement of ITE has motivated this work for on-line optical network topology design.

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APPENDIX

For the optical network, the optimality equations are:

$$v(S)=\min_{a\in A}\left\{r(S,a)+\frac{\lambda'+\mu'}{\lambda'+\mu'+\alpha}\sum_{j\in\overline{S}}q(j\,|S,a)v(j)\right\} \quad \text{(A-1)}$$

Here $r(S,a)$ can be written as

$$r(S,a)=W^{\lambda}_{sign}(S,a)+\frac{w^{\lambda}_{b}(S,a)+w^{\lambda}_{sw}(S,a)}{\alpha+\lambda'+\mu'} \quad \text{(A-2)}$$

The transition probabilities $q(j\,|S,a)$ can be elaborated from Table I. Note that the probability of event $e=0$ is $\lambda'/(\lambda'+\mu')$ and event $e=1$ is $\mu'/(\lambda'+\mu')$. By substituting $r(S,a)$ and $q(j\,|S,a)$ into the optimality equations (14), we can write:

$$v\left(0,0,B^F,0,0\right)=\min\left\{\frac{c_\lambda h^F(B^F+b)}{\alpha+\lambda'+\mu'}+\frac{\lambda'+\mu'}{\alpha+\lambda'+\mu'}J,\, c_x+c_y h^F+\frac{c_{cap}Wh^F+E(B^F+b)}{\alpha+\lambda'+\mu'}+\frac{\lambda'+\mu'}{\alpha+\lambda'+\mu'}K\right\} \quad \text{(A-3)}$$

$$v\left(0,0,B^F,0,1\right)=\frac{c_\lambda h^F(B^F-b)}{\alpha+\lambda'+\mu'}+\frac{\lambda'+\mu'}{\alpha+\lambda'+\mu'}L, \quad \text{(A-4)}$$

$$v\left(A^\lambda,B^\lambda,B^F,k,0\right)\qquad k>0,\, A^\lambda\geq b+B^F$$
$$=\frac{EB^\lambda+c_\lambda h^F(B^F+b)}{\alpha+\lambda'+\mu'}+\frac{\lambda'+\mu'}{\alpha+\lambda'+\mu'}M, \quad \text{(A-5)}$$

$$v\left(A^\lambda,B^\lambda,B^F,k,0\right)\qquad k>0,\, A^\lambda< b+B^F$$
$$=c_x+c_y h^F+\frac{c_{cap}Wh^F+E(B^\lambda+B^F+b)}{\alpha+\lambda'+\mu'}+\frac{\lambda'+\mu'}{\alpha+\lambda'+\mu'}X, \quad \text{(A-6)}$$

$$v\left(A^\lambda,B^\lambda,B^F,k,1\right)\qquad k>0,\, A^\lambda< W-b-B^F$$
$$=\frac{E(B^\lambda-b)+c_\lambda h^F B^F}{\alpha+\lambda'+\mu'}+\frac{\lambda'+\mu'}{\alpha+\lambda'+\mu'}Y \quad \text{(A-7)}$$

$$v\left(A^\lambda,B^\lambda,B^F,k,1\right)\qquad k>0,\, A^\lambda\geq W-b-B^F$$
$$=c_x+c_y h^F+\frac{-c_{cap}Wh^F+E(B^\lambda+B^F+b)}{\alpha+\lambda'+\mu'}+\frac{\lambda'+\mu'}{\alpha+\lambda'+\mu'}Z, \quad \text{(A-8)}$$

where

$$E=(h^F-1)c_{opt}+c_\lambda$$

$$J=\frac{\lambda'}{\lambda'+\mu'}v(0,0,B^F+b,0,0)+\frac{\mu'}{\lambda'+\mu'}v(0,0,B^F+b,0,1)$$

$$K=\frac{\lambda'}{\lambda'+\mu'}v(W-B^F-b,B^F+b,0,1,0)+\frac{\mu'}{\lambda'+\mu'}v(W-B^F-b,B^F+b,0,1,1)$$

$$L=\frac{\lambda'}{\lambda'+\mu'}v(0,0,B^F-b,0,0)+\frac{\mu'}{\lambda'+\mu'}v(0,0,B^F-b,0,1)$$

$$M=\frac{\lambda'}{\lambda'+\mu'}v(A^\lambda-B^F-b,B^\lambda+B^F+b,0,k,0)+\frac{\mu'}{\lambda'+\mu'}v(A^\lambda-B^F-b,B^\lambda+B^F+b,0,k,1)$$

$$X=\frac{\lambda'}{\lambda'+\mu'}v(A^\lambda+W-B^F-b,B^\lambda+B^F+b,0,k+1,0)+\frac{\mu'}{\lambda'+\mu'}v(A^\lambda+W-B^F-b,B^\lambda+B^F+b,0,k+1,1)$$

$$Y=\frac{\lambda'}{\lambda'+\mu'}v(A^\lambda+b,B^\lambda-b,B^F,k,0)+\frac{\mu'}{\lambda'+\mu'}v(A^\lambda+b,B^\lambda-b,B^F,k,1)$$

$$Z=\frac{\lambda'}{\lambda'+\mu'}v(A^\lambda+b-W-B^F,B^\lambda-b+B^F,0,k-1,0)+\frac{\mu'}{\lambda'+\mu'}v(A^\lambda+b-W-B^F,B^\lambda-b+B^F,0,k-1,1)$$

Equation (A-3) can be simplified as

$$v\left(0,0,B^F,0,0\right)=\min\left\{v(0,0,B^F+2b,0,1),\, c_x+c_y h^F+\frac{c_{cap}Wh^F}{\alpha+\lambda'+\mu'}+v(W-B^F-2b,B^F+2b,0,1,1)\right\}$$