Dynamic LSP Provisioning in Overlay, Augmented, and Peer Architectures for IP/MPLS over WDM Networks

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***Abstract*— We consider an IP/MPLS over WDM network, in which label switched routers (LSRs) in the IP/MPLS layer are interconnected through optical cross-connects (OXCs) in the optical core network (WDM layer) providing an end-to-end wavelength routing capability. In this paper, we study a dynamic label switched path (LSP) provisioning problem for the three different network models of the IP/MPLS over WDM network, namely, Overlay, Augmented, and Peer models. For the overlay model, we propose an algorithm, called MLH_OVLY, in which a network finds a path with the minimum number of logical hops for an LSP request. We also propose, for the augmented model, a simple and efficient dynamic LSP provisioning algorithm, called CAPA_AUG, utilizing summarized capacity information from the WDM layer. We compare the proposed algorithms with the existing algorithms available for the overlay [1] and peer [2], [3] models, and also provide an in-depth analysis of the algorithms in [2], [3]. The algorithms are compared and evaluated using two key performance measures: LSP blocking probability and network (lightpath) utilization. Simulation results show that at low loads with a limited number of ports available in the network, CAPA_AUG achieves an order of magnitude better blocking performance than the algorithm in [2] and outperforms the one in [3] by more than three times. It also achieves higher network utilization than the one in [2] by more than 10 % and the one in [3] by 2-7 % depending on the traffic load. Considering the small amount of information that is exchanged between the layers in the augmented model, these results suggest that the augmented model can be a practically good compromise between the overlay and peer models.**

I. Introduction

As communication networks have expanded to accommodate rapidly growing data traffic, the traditional network architecture with a full range of protocol stack (e.g., IP/ATM/SONET/WDM) has suffered from heavy network overheads and increasing management complexity. It is widely believed that a simpler network architecture of IP/MPLS directly over a WDM transport layer will be the most prominent network solution in the future. Emerging technologies and standardization activities on Multi-Protocol Label Switching (MPLS) [4], Generalized MPLS (GMPLS) [5], and User-Network Interface (UNI) [6] have been playing a key role in moving toward implementation of the IP/MPLS over WDM architecture. In this architecture, high-speed routers equipped with MPLS functions, called *label switched routers* (LSRs) are interconnected by intelligent optical core networks that provide dynamic point-to-point connectivity in the form of lightpaths. The resulting end-to-end path, which may traverse more than one lightpath, is referred to as a *label switched path* (LSP). In the IP/MPLS over WDM network, the *logical* topology seen by the IP/MPLS layer is the topology of the LSRs with logical links that are the lightpaths dynamically provided by the WDM layer with granularity of a whole wavelength. Note that a *logical edge* between two LSRs could comprise multiple *logical links* established on different wavelengths.[1]

In an IP/MPLS over WDM network, there are several architectural alternatives including overlay, augmented, and peer models [7], [8], [9]. As summarized in Table I, one of the key differences among the models is how much and what kind of network information can be exchanged between the two layers. In the peer model, the topology and other network information (e.g., routing and link state) are shared among all network elements across the layers by a unified signaling protocol and control plane. Such a model may be appropriate when the transport and service networks are operated by a single entity, whereas the overlay and augmented models are more suitable for the case with different management/ownership of each layer. In the overlay network model, there is no specific network information exchanged between the layers, since the routing in each layer is done separately with each layer's own signaling and control plane. The augmented model provides a compromise between the two extreme cases by allowing the exchange of some network information between the layers, such as reachability and/or summary of link state information (e.g., residual capacity), depending on a necessary and specific agreement between the two layers.

There are two different assumptions on the nature of network traffic that are often made in developing provisioning and routing algorithms: static and dynamic traffic. With static traffic, it is assumed that the traffic demands between all ingress-egress pairs are known at the time of initial provisioning. Then, one can formulate an optimization problem in order to make the

This work was supported in part by DARPA Grant N66001-00-18949 (co-funded by NSA) and by NSF Grants ANI-9973098 and ANI-9973111.

[1] In this paper, we use the terms *logical edge* and *logical link* interchangeably, unless it is necessary to distinguish one from the other.

TABLE I
NETWORK MODELS IN IP/MPLS OVER WDM NETWORK.

	Overlay	Augmented	Peer
Routing	Separated	Separated	Integrated
Network information exchanged	No information	Part or Summary	Full information
Signaling and control plane	Separated	Separated	Unified

most efficient use of network resources, as in [10] for example. The increasing agility of optical components, however, suggests that optical network traffic in the future is likely to be dynamic in nature with lightpaths signaled on demand. Typically, the bandwidth demand of LSP requests arriving at and departing from a network dynamically is smaller than that of a lightpath on a wavelength. Multiple sub-wavelength LSPs can possibly be groomed into a single lightpath at an edge LSR. Under the dynamic IP/MPLS traffic assumption, a network has to make a routing decision upon every new LSP request arrival without any *a priori* knowledge about future requests. Since any network reconfiguration would inevitably disrupt the existing LSP traffic, it may not be desirable or practical to reconfigure existing lightpaths and reroute existing LSPs upon every new LSP request arival. A more practical scenario would be to let the logical network evolve in response to LSP traffic demands, and re-optimize the entire network for more efficient use of network resources after some operational period.

In this paper, we study the dynamic LSP provisioning problem for the three different network models in IP/MPLS over WDM networks. Loosely speaking, this problem refers to the selection of an appropriate logical route for an arriving LSP request, including the opening of any new lightpaths at the optical layer. There are a few algorithms available for this problem that we are aware of – one for the overlay model [1] and two for the peer model [2], [3]. In this paper, we propose two algorithms, one for the overlay model, called MLH_OVLY, and the other, called CAPA_AUG, for the augmented model. As far as we are aware, no algorithms have been proposed and evaluated for the augmented model thus far. An observation worthy of note here is that all the previous algorithms assumed that there is no limit on the number of optical ports per LSR. As we will see later, the number of ports per LSR is a key determinant of the performance of the algorithms and the performances of the algorithms for the peer model deteriorate rapidly as the number of ports becomes more limited. Since a large majority of traffic at an OXC is likely to be pass-through traffic and optical ports tend to be expensive, the number of optical ports at an LSR is likely to be small, and therefore, the above result has serious practical implications. We present an analysis of this performance deterioration by using an integrated graph. In our simulations, our CAPA_AUG algorithm which uses a small amount of information about the WDM network gives better LSP blocking performance than [2], [3] in some cases when there are only a limited number of ports available in the network. In terms of network utilization (to be defined precisely later), CAPA_AUG outperforms the peer model algorithms in [2], [3] in all cases studied in this paper.

The rest of the paper is organized as follows. In Section II, we describe the problem with an illustrative example. We explain the differences in the problem for each model in terms of the available information regarding the WDM layer for LSP provisioning in the IP/MPLS layer. Our motivation and major contributions of the paper are summarized in Section III. Section IV provides the details of the previous work for the overlay [1] and peer [2], [3] models. Section V describes our two proposed algorithms – one for the overlay model and one for the augmented model. In Section VI, we present the performance evaluation results and compare the proposed algorithms with the existing algorithms. Section VII provides more observations and analysis on the peer model algorithms using an integrated graph. Section VIII concludes the paper.

II. DYNAMIC LSP PROVISIONING

A. Goals and Constraints

Consider an IP/MPLS over WDM network to which LSP requests arrive (and from which they depart) dynamically. The WDM network is capable of providing lightpaths between LSR pairs upon request, if sufficient resources (i.e., wavelengths) are available to satisfy the request. Wavelength conversion is assumed to be unavailable in this paper, though the work can be extended in a straightforward manner to networks with wavelength conversion. A lightpath may be requested between a pair of LSRs if there is an unused optical port available at both LSRs.

Upon the arrival of an LSP request for sub-wavelength bandwidth, the network has to decide how to accommodate/route it. The LSP request may be satisfied by routing the LSP over the existing logical network if it has sufficient capacity available, or one or more lightpaths may be signaled and set up, and used in combination with existing logical capacity to accommodate the new LSP request.

Such routing of an LSP request must be done without any a priori knowledge of future requests, such that two goals can be achieved at the same time, namely, (a) to accept as many LSP requests as possible over a period of time, and (b) utilize the lightpaths as efficiently as possible. The number of wavelengths per physical link in the WDM layer and the number of ports per LSR in the IP/MPLS layer are two major constraints on network resources to be considered to make a *good* routing decision. Opening a new lightpath between two LSRs in the IP/MPLS layer costs one port at both ingress and egress LSRs and one wavelength on the physical link(s) along the path in the WDM layer. Without wavelength conversion capability, the wavelength on all the physical links along a lightpath has to be same. An LSP request will be blocked if there is not enough capacity available on the current logical topology, and there is no wavelength and/or port available to open a new lightpath.

Depending on the network model, the LSRs receiving LSP requests in the IP/MPLS layer may have different information about the current status of the entire network. We look at each of the three network models below.

B. Overlay Model

In the overlay model, each LSR keeps only IP/MPLS layer information, such as residual capacity on all of the existing logical links and the number of ports available in the LSRs. The IP/MPLS layer only receives a response of whether a requested lightpath can be set up or not, from the WDM layer. Therefore, in the overlay model, a network has to decide whether it would use the existing logical links or open new lightpath(s) for a new arriving request. If it chooses to use the existing logical topology, then how to route the request over the existing logical topology has to be decided. If the network would open new lightpath(s), it has to decide the logical edge(s) (LSR pair(s)) on which to open the lightpaths, without any network information from the WDM layer.

C. Peer Model

In the peer model, on the other hand, each LSR keeps information about the topology and status of physical links (e.g., availability of each wavelength) in the WDM layer as well as logical links in the IP/MPLS layer. As often visualized, a network in the peer model can be seen as one graph with both LSRs and OXCs interconnected with physical and logical edges. In this case, an integrated routing can be done with a unified control plane, where an integrated routing scheme for both layers decides routing over existing logical links, and routing and wavelength assignment (RWA) in the WDM layer at the same time. Note that this is a fundamental difference in the dynamic LSP provisioning problem between the peer model and the other two models. In the overlay and augmented models, the RWA in the WDM layer is beyond the scope of the LSP provisioning problem in the IP/MPLS layer.[2]

D. Augmented Model

For the augmented model, however, the available information at LSRs in the IP/MPLS layer depends on a specific agreement between the two network entities. In this paper, we assume that the IP/MPLS layer may utilize a small amount of capacity information passed from the WDM layer. Specifically, we define the capacity information to be the number of lightpaths that the WDM layer can further provide between every LSR pair in the current state of the WDM network. Therefore, a network in the augmented model has to make the same provisioning decision as in the overlay model, except that it has more information about the status of the WDM layer.

[2]In this paper, we assume a fixed minimum-hop routing and the first-fit wavelength assignment in the WDM layer for the overlay and augmented model. Our focus here is the LSP provisioning problem at the IP/MPLS layer.

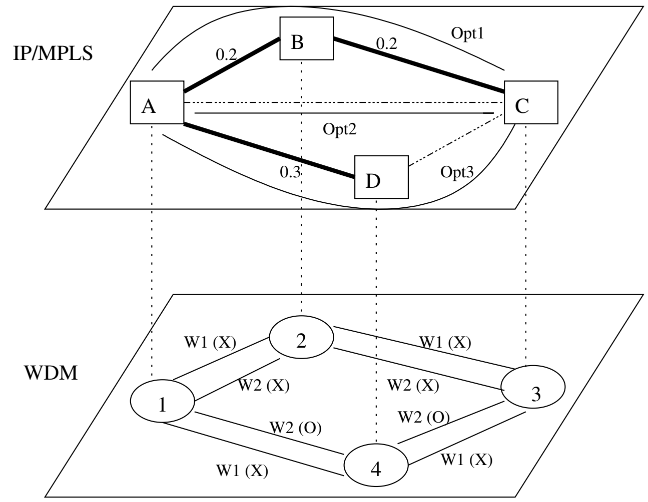

Fig. 1. An illustrative example of dynamic LSP provisioning.

E. An Illustrative Example

Let us illustrate the LSP provisioning problem using a simple illustrative example. Fig. 1 shows 4 LSRs in the IP/MPLS layer. In the WDM layer, 4 OXCs are connected by physical links with 2 wavelengths ($w1$, $w2$). In this example, each LSR in the IP/MPLS layer is connected to a corresponding OXC in the WDM layer. Assume that currently the network has the following residual capacity on the logical edges: A-B (0.2), B-C (0.2), and A-D (0.3)[3], which were already established using some of the wavelengths on the physical links (marked X). Now, let us say that a new LSP request for 0.2 units of bandwidth between LSRs A and C arrives. For this request, the IP/MPLS layer has three provisioning options: (1) routing over the existing logical links A-B and B-C without opening any new lightpath, (2) routing with a new lightpath between A and C using $w2$ available on both physical links 1-4 and 4-3, and (3) routing over the existing logical link A-D and a new lightpath between D and C. Depending on the choice, more or fewer LSP requests may be accommodated in the future.

III. Motivation And Contributions

In many instances in practice, there exists a separate management/ownership for each network layer that prefers to keep its network information (e.g., topology and/or routing) from other layers. It is also true in the case of the peer model that a significant number of control messages have to be flooded across the network layers frequently to keep all the information updated. On the other hand, in the overlay model, the entire network could be managed inefficiently due to the lack of information exchanged between the two layers. Even though it is believed that a suitable augmented model could benefit from the advantages of both overlay and peer models, there has been no provisioning algorithm proposed for this model, and there is little understanding of what kind of information would be most helpful in making LSP routing decisions. A

[3]The unit of LSP bandwidth request is normalized to the bandwidth of a lightpath for all examples in this paper.

major contribution of this paper is the presentation of a simple dynamic provisioning algorithm for the augmented model.

As mentioned earlier, one may expect that the number of optical ports at an LSR to be limited, and therefore, it may not be possible to open a lightpath between a pair of LSRs even if there are enough wavelengths on the physical links connecting the two LSRs. All previous provisioning algorithms in the literature assumed that the network was wavelength-limited, and as indicated earlier, the performances of some of those algorithms degrade rapidly as they become more port-constrained. Another main contribution of this paper is a thorough investigation of the effects of a limited number of ports on the performance of the dynamic LSP provisioning algorithms discussed in this paper.

We have implemented all the existing algorithms and our proposed algorithms, and present extensive simulation results comparing the performances of various algorithms under various network models. To the best of our knowledge, no such complete performance comparison of dynamic LSP provisioning algorithms across the different network models is available. We also provide additional observations and analysis on the algorithms for the peer model using an integrated graph.

IV. Previous Work

A. *Y_OVLY for Overlay Model*

In [1], Ye et al. presented a simple integrated provisioning/protection scheme to dynamically allocate restorable bandwidth-guaranteed paths in IP over WDM networks. Since our focus in this paper is provisioning primary LSPs, we take only the primary path provisioning part of their algorithm into consideration, which we refer to as Y_OVLY. In Y_OVLY, a network first tries to route the request over the residual capacity on existing logical links. If it finds the existing capacity in the logical layer insufficient for the arriving request, then it tries to add capacity by opening a new lightpath directly between the ingress and egress LSRs.

Let us consider the same example shown in Fig. 1. However, this time assume that the new LSP request requires 0.3 units of bandwidth, instead of 0.2 as in the previous case, and that $w1$, instead of $w2$, is available on the physical link between OXC1 and OXC4. As a result, the existing logical topology does not have enough capacity for a demand of 0.3 units between A and C, and a new lightpath on the direct logical edge between A and C cannot be established because no wavelength is available on both physical links 1-4 and 4-3. In this case, Y_OVLY will block the LSP request.

B. *K_PEER and Z_PEER for Peer Model*

In [2], Kodialam and Lakshman proposed an integrated dynamic IP and wavelength routing algorithm that utilizes the combined knowledge of resource and topology information in both layers, assuming a peer network model. We refer to their algorithm as K_PEER in this paper. In [3] Zheng and Mohan proposed a dynamic protection scheme in integrated IP/WDM networks. Since their scheme also considers provisioning primary as well as backup paths (LSPs), we consider only its primary path provisioning part, which is referred to as Z_PEER in this paper.

Both K_PEER and Z_PEER use an integrated graph, in which both the physical links and logical links (lightpaths shown as thick dashed lines) coexist as in Fig. 2. It is also a layered graph, where each wavelength is represented by a corresponding sub-node in the graph. When a new lightpath for a logical link is established using wavelength i, the corresponding physical link of the wavelength i is removed from the graph, and a logical link corresponding to the new lightpath is added between the LSRs. In Fig. 2, a logical link between A and B is created using $w2$, and say it has a residual bandwidth of 0.2 units. Likewise, 0.5 units of bandwidth is available on the logical link between B and C, using wavelength $w1$ on the physical links OXC3-OXC1 and OXC1-OXC2. Note that this lightpath between B and C does not use any port in LSR A because it by-passes that LSR.

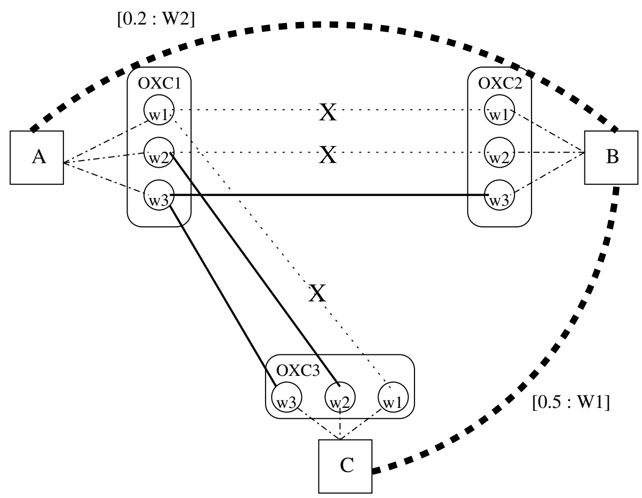

Fig. 2. An illustrative example of integrated graph.

In both algorithms, the basic procedure is to assign a cost to both the logical and physical edges first, and then find a minimum-cost path using a shortest path algorithm such as Dijkstra's algorithm. The resulting path may contain some logical links already established and/or new lightpath(s) to be opened for this LSP request. The main difference between the two algorithms lies in the way they assign cost to each edge in the graph. In K_PEER, all minimum-cut sets [11] for every ingress-egress LSR pair are first identified. All edges belonging to any minimum-cut set are defined to be *critical* for that ingress-egress LSR pair. Then, for each edge, the number of LSR pairs for which the edge is critical is noted, and is assigned as the cost of that edge. The idea behind this process is to find a route that would avoid using edges that are bottleneck edges for several ingress-egress LSR pairs. Note that the algorithm is rather complex and requires the computation of N^2 minimum-cut sets, where N is the number of LSRs.

In Z_PEER, the cost of an edge is assigned as the number of physical hops it uses. Therefore, the cost of a logical link is equal to the number of physical hops that it takes to establish that lightpath. For the example in Fig. 2, the cost of the logical edge between B and C is 2, whereas 1 is assigned as the cost for the edge between A and B. Z_PEER introduces a control parameter for the cost of a physical link. According to the numerical results in [3], the best value for the control parameter turned out to be 1, which implies that the cost of each physical edge is 1. This, in turn, means that the Z_PEER algorithm chooses the route with the minimum number of physical hops to satisfy the LSP request.

Note that a route that is chosen by these algorithms may consist of existing logical links as well as new physical links. The algorithms open a new lightpath between LSRs which are connected by the physical links that are part of the chosen route. Neither [2] nor [3] mentioned the cost of the cross-layer edges between an LSR and the sub-nodes representing wavelengths of the adjacent OXC in the integrated graph (shown as $- \cdot - \cdot -$ in Fig. 2). In general, they can simply be considered as virtual edges with infinite capacity or zero cost, when finding a maximum flow or minimum-cost path. We observed, however, that in this case they have a non-negligible effect on the performance as explained later in Section VII.

V. Proposed Algorithms

Before we proceed to present our algorithms for the overlay and augmented models, let us define the performance measures that are used to evaluate the algorithms. The main objective of all the algorithms studied in this paper is to minimize the probability of blocking an LSP request. Besides the blocking probability, we consider network (lightpath) utilization as another performance measure. To formally define utilization, let $B(t)$ be the total bandwidth of all the LSPs that are being served at time t. Correspondingly, let $C(t)$ be the total capacity of all the lightpaths that are operational at time t. Since the bandwidths are normalized to lightpath capacity, $C(t)$ is just the number of lightpaths that exist at time t. Then, the network or lightpath utilization at time t, denoted $U(t)$ is defined as $U(t) \stackrel{\text{def}}{=} \frac{B(t)}{C(t)}$. The time-average utilization, U, (which we simply call utilization) is then defined as

$$U \stackrel{\text{def}}{=} \lim_{T\to\infty} \frac{1}{T} \int_0^T U(t)dt.$$

It is obviously desirable that U be as high as possible while the main objective of minimizing blocking probability is achieved. We now present our algorithms.

A. MLH_OVLY for Overlay Model

We make the same assumption as in [1], where only one lightpath is allowed to be established per LSP request.[4] We do so for two reasons – one is to enable us to make a fair comparison between our MLH_OVLY and Y_OVLY, and the other is to ensure that the network utilization does not decrease very much. Note that the bandwidth of an LSP request is at most 1, and thus $B(t)$ can increase by at most 1, whereas each new lightpath that is opened increases $C(t)$ by 1. The objective of MLH_OVLY is to minimize the total number of logical hops that an LSP has to traverse. With the limited information about the residual capacity on the logical links only, the IP/MPLS layer in MLH_OVLY tries to save network resources for potential requests in the future by minimizing the number of logical hops.

In MLH_OVLY, the network first tries to route an arriving LSP request using a single hop on the direct logical edge between the ingress and egress LSRs, which means either using the residual capacity, or opening a new lightpath (logical link) on that direct edge. If the effort to accommodate the request on a single hop fails, the network checks all other LSR pairs (logical edges) between which it may open a new lightpath to find an end-to-end path with that new lightpath in place. If there are multiple candidate LSR pairs for a new lightpath, it chooses to open a new lightpath between an LSR pair, with which it would route the LSP request using the minimum number of logical hops.

Let us consider the same situation in Section IV-A, where Y_OVLY would have blocked the request because it could not open a direct lightpath between A and C. In MLH_OVLY, however, it would open a new lightpath between D and C using $w2$, then route the request for 0.3 units of bandwidth between A and C successfully, with the existing logical link (A-D) and the new logical link (D-C) as the two logical hops.

B. CAPA_AUG for Augmented Model

In this paper, we assume that only a summary of capacity information from the WDM layer is shared with the IP/MPLS layer in the augmented model. Regardless of the particular RWA scheme in the WDM layer, the WDM layer passes L_{ij}, the number of lightpaths that can be established between LSRs i and j, for all i and j, to the IP/MPLS layer. Without wavelength conversion capability,[5] L_{ij} is the number of common wavelengths that are available over every physical link on the path found by the routing algorithm in the WDM layer. This type of capacity information can be passed through a specifically designed UNI, or by the MPLS/GMPLS signaling mechanism such as RSVP-TE [12]. For a network with N ingress/egress LSRs, there are N^2 number of L_{ij}'s to be passed to the IP/MPLS layer from the WDM layer. We believe that this is a relatively small amount of information compared to the information that is flooded across the network layers in the peer model. The information that must be actually passed to the IP/MPLS layer may even be less than this, as the WDM network state changes only when a lightpath is set up or taken down, and even then, not all L_{ij}'s may change.

The IP/MPLS layer has its own limitation on the number of optical ports that are available on an LSR. Let P_i be the number of ports available in the LSR i. Then, C_{ij}, the number of lightpaths that can *actually* be established between LSRs i and j, considering both the number of wavelengths available in the WDM layer and ports in the IP/MPLS layer, can be found as follows:

$$C_{ij} = \min \{L_{ij}, P_i, P_j\}. \tag{1}$$

[4] In general, this kind of restriction on the number of lightpaths to be opened per LSP request is not necessary.

[5] Recall that we assume that the WDM transport network does not have wavelength conversion capability for all network models discussed.

Now, let r^w_{ij} be the residual capacity on the existing logical link established using wavelength w between LSR i and j. Then, R_{ij}, the total amount of residual capacity on the logical edge ij, is

$$R_{ij} = \sum_w r^w_{ij}. \quad (2)$$

The main idea of CAPA_AUG is to assign to each logical edge ij a cost that is inversely proportional to the total *potential* capacity between i and j, which is the sum of the existing logical capacity (R_{ij}) and the potential capacity available from the WDM layer (C_{ij}). In our algorithm, ϕ_{ij}, the cost of a logical edge between LSR i and j, is defined as follows:

$$\phi_{ij} = \begin{cases} \infty & \text{if} \quad C_{ij} = 0, \quad \text{and } r^w_{ij} < b \quad \forall\, w \\ \frac{1}{C_{ij}+R_{ij}} & \text{otherwise.} \end{cases} \quad (3)$$

In this paper, we assume that the entire traffic of a requested LSP has to be transmitted, without splitting it onto multiple logical links (lightpaths). Therefore, even for some edges for which $R_{ij} \geq b$, it could be true that $\phi_{ij} = \infty$ if $r^w_{ij} < b$, $\forall\ w$.

Once the costs of all logical edges are decided, one may find a minimum-cost path between an ingress and egress LSR. For each logical edge on the resulting path, CAPA_AUG always tries to use existing capacity first, if there is at least one lightpath with enough capacity, in order to keep network utilization as high as possible. If there is no existing logical link that has enough capacity for a logical edge on the path, then it opens a new lightpath (logical link) on that logical edge. There could be more than one logical link with enough capacity on a logical edge. In that case, CAPA_AUG picks the one with minimum capacity among them.

Note that L_{ij} depends on the RWA used in the WDM layer, and that it is not necessarily true that the WDM layer can establish L_{ij} lightpaths simultaneously for every pair ij. It is true that there are enough wavelengths in the WDM layer to establish L_{ij} lightpaths between LSRs i and j, but the actual establishment of one or more lightpaths between i and j may decrease the number of lightpaths that can be established between some other pair of LSRs m and n. In other words, the entries of the matrix $L \stackrel{\text{def}}{=} [L_{ij}]$ are not independent of each other. Therefore, even if the CAPA_AUG algorithm produces a minimum-cost path that requires more than one new lightpath to be established, it may not be possible to open all of them at the same time, even if $C_{ij} > 0$ for all the logical edges ij. In this case, CAPA_AUG will block the request.

Let us illustrate the working of the algorithm with an example. Fig. 3 shows the current capacity on logical edges, including the number of potential lightpaths (C_{ij}) and residual capacity of each logical link already established (r^w_{ij}).[6] On the logical edge between LSRs B and C, for example, there are two existing logical links with 0.4 and 0.5 units of residual bandwidth, respectively. $C_{BC} = 1$ means that another new lightpath can be opened on the logical edge B-C. Between C-E, there is one logical link opened, but it is fully used so that there is no residual capacity left on that logical link. Assume that there is a new LSP request between A and E for 0.2 units of bandwidth. Fig. 4 shows how to calculate the cost of each logical edge on the same example as in Fig. 3. It also shows the minimum cost path between A and E, which is A-B-C-E.

For the logical edges A-B and C-E, CAPA_AUG opens a new lightpath (logical link). For the edge B-C, however, it chooses to use the logical link with 0.4 units of residual bandwidth.

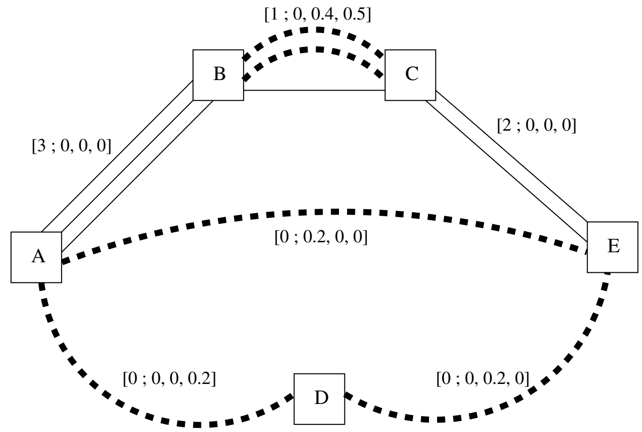

Fig. 3. Current capacity on logical edges [C_{ij} ; r^w_{ij}].

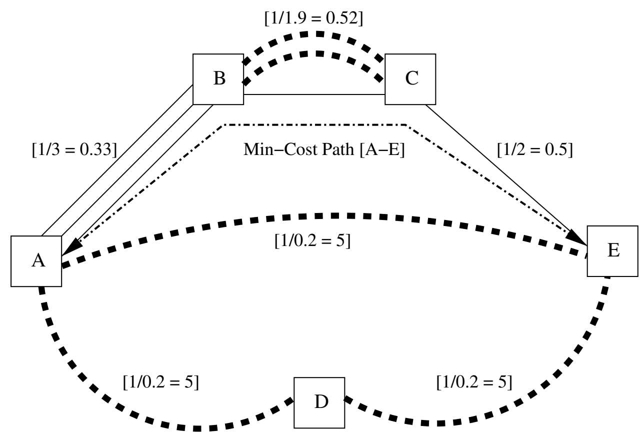

Fig. 4. Cost of logical edges [1 / total capacity = ϕ_{ij}].

As shown in Fig. 3 and Fig. 4, the idea in CAPA_AUG is to try to avoid using those logical edges with smaller total potential capacity. By doing so, it spreads out the traffic, thereby reducing potential bottleneck edges on the network for the future requests. We note that we attempt to reduce potential bottleneck edges at the expense of reducing network utilization in the CAPA_AUG algorithm. Alternatively, one could attempt to always use existing logical capacity first before opening any new lightpaths. Then, in the example above, the new request A-E would be routed over the existing logical edge A-E with residual bandwidth 0.2. Note, however, that this would mean that future requests cannot use logical edge A-E until some of the capacity is freed up. In our initial experimentation, we found that this latter algorithm performed similarly as the CAPA_AUG algorithm and, hence, we do not consider it further in this paper.

[6]Logical edges that have no capacity left ($C_{ij} = 0$, $r^w_{ij} = 0$, $\forall\ w$) do not appear in figures.

In all the algorithms, a lightpath is released as soon as the last LSP that uses the lightpath departs.

VI. Performance Evaluation

We evaluate the performance of the proposed algorithms through extensive simulations. We use the NSF network as our WDM transport layer topology, which includes 14 OXCs without wavelength conversion capability and 21 bi-directional links. All our experiments were performed assuming 8 wavelengths per physical link. We assume that one LSR in the IP/MPLS layer is connected to each OXC in the WDM layer as shown in Fig. 1, and every LSR is an ingress/egress LSR. These are assumptions used for generating results and are not assumptions needed by the algorithms themselves. We assume that LSP requests arrive according to a Poisson traffic model, and the ingress and egress LSRs for a request are uniformly distributed. We also assume that the bandwidth granularity of an LSP request is $\frac{1}{16}$, i.e., the normalized bandwidth of every LSP request is $\frac{i}{16}$ where i is an integer that is randomly (uniformly) chosen from the range [1, 16]. We calculate the blocking probability (P_b) and the utilization (U) for each algorithm.

A. No Port Limit

We first show the performance of the algorithms without any limit on the number of ports on the LSRs. We plot P_b and U in Fig. 5 and Fig. 6 against the network offered load measured in Erlangs. Without any limitation on the number of ports per LSR, Z_PEER shows the best performance, in which no request was blocked.[7] K_PEER shows the second best performance, suggesting the algorithms using the integrated graph in the peer model outperform the algorithms in the overlay and augmented model in the case with no port limits. However, this ceases to be the case when there is a limit on the number of LSR ports, as we will see soon.

Note that one of the reasons for having the worst blocking probabilities in Y_OVLY and MLH_OVLY, higher than those of the other algorithms by more than an order of magnitude, is the fact that only one new lightpath is allowed to be opened per request in Y_OVLY and MLH_OVLY, whereas there is no such restriction assumed by the other algorithms. It is interesting to note that the very same assumption leads to the two best network utilizations for Y_OVLY and MLH_OVLY, approximately 10-15% higher than the algorithms for the peer model, as shown in Fig. 6. They are restricted to open one lightpath per request, blocking some requests that would have been accepted with more than one new lightpath, which, in turn, would lower the network utilization. Between the two algorithms for the overlay model, however, our proposed MLH_OVLY shows as much as twice better P_b and 2-3% better U than Y_OVLY, depending on the traffic load. This comes from the additional step in MLH_OVLY of checking other logical edges for a new lightpath.

The proposed CAPA_AUG algorithm in the augmented model provides much lower P_b (by more than an order of

[7] Zero P_b is not shown in the figure.

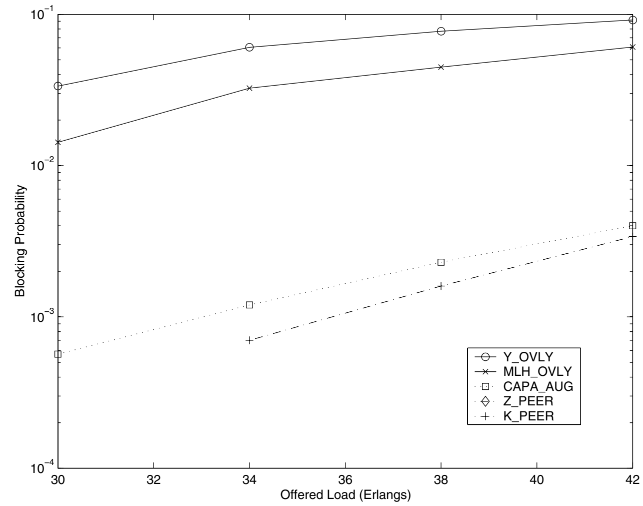

Fig. 5. Blocking probability vs. offered load with no port limit and 8 wavelengths.

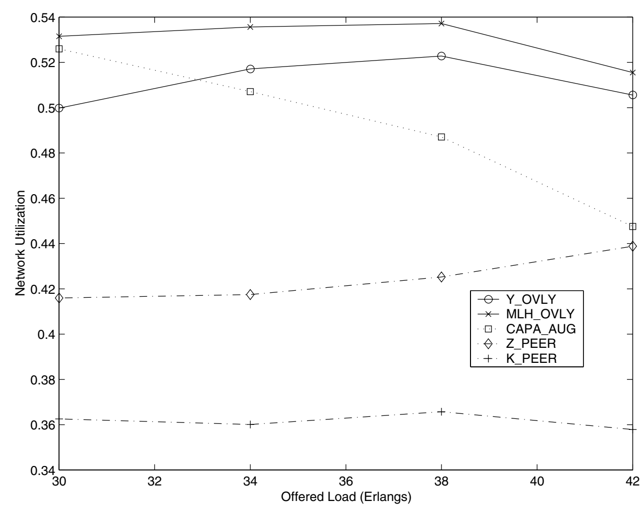

Fig. 6. Network utilization vs. offered load with no port limit and 8 wavelengths.

magnitude) than Y_OVLY and MLH_OVLY, but does not perform as well as K_PEER or Z_PEER. However, it also achieves approximately 5-10% higher network utilization than K_PEER and Z_PEER at low loads as shown in Fig. 6. This is because of its effort to use existing logical capacity whenever it finds enough capacity for a logical edge on the chosen minimum-cost path.

An important observation we made throughout this performance evaluation is that for the dynamic LSP provisioning problem, there exists a trade-off between blocking probability and network utilization. Y_OVLY and MLH_OVLY in the overlay model, for example, tend to open a new lightpath more conservatively than the other algorithms in the augmented and peer models. It is clearly shown that such a conservative approach leads to higher network utilization at the cost of higher blocking probability. This observation also implies that one can find an optimum point on the trade-off between P_b and U for given performance goals in a network model.

B. Limited Number of Ports

As mentioned earlier, we believe that the high cost of ports and the fact that a large majority of traffic is pass-through, would lead to a limit on the number of ports, in practice. In order to study the effects of a limited number of ports on the performance of the algorithms, we now plot the P_b and U against network offered load for the case of 8 wavelengths per physical link and 12 ports [8] per LSR in Fig. 7 and Fig. 8. Fig. 7 shows a relatively larger increase in P_b for K_PEER and Z_PEER than for CAPA_AUG, compared to the case with no port limit in Fig 5.

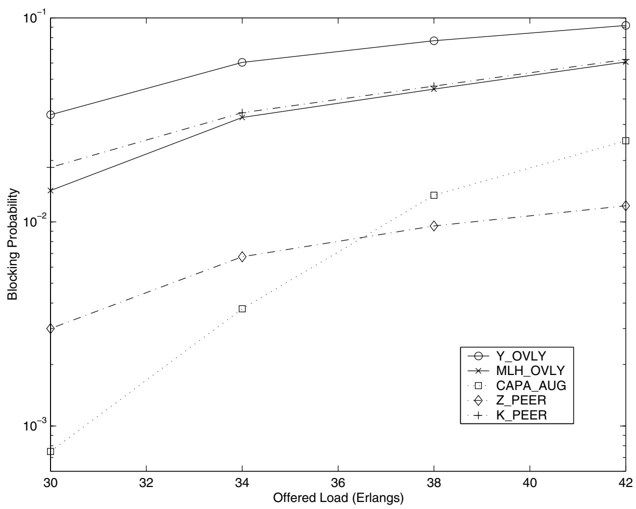

Fig. 7. Blocking probability vs. offered load with 8 wavelengths and 12 ports.

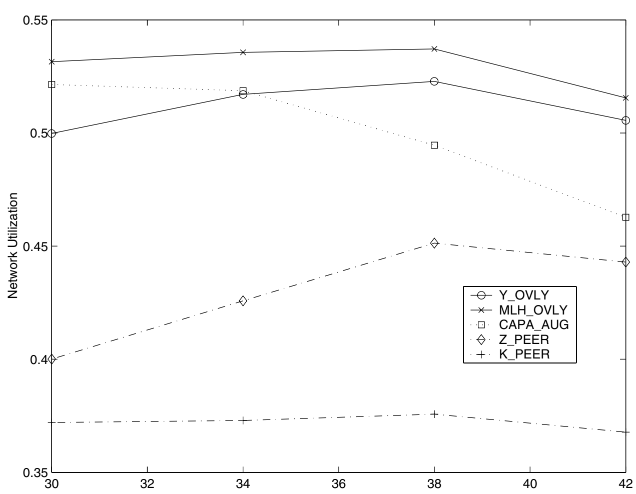

Fig. 8. Network utilization vs. offered load with 8 wavelengths and 12 ports.

Notice that there is no change in the blocking performances of Y_OVLY and MLH_OVLY from Fig. 5 and Fig. 6. This is because the performances of Y_OVLY and MLH_OVLY are limited by the number of wavelengths per link and are not port-limited.

[8] We assume that a lightpath on *any* wavelength may be terminated at a given port.

A very important observation from Fig. 7 is that the CAPA_AUG algorithm outperforms the Z_PEER algorithm at lower loads, and outperforms the K_PEER algorithm at all loads. In fact, even a simple overlay algorithm such as MLH_OVLY performs similarly to K_PEER. Besides, the utilization levels achievable by CAPA_AUG are higher than those achieved by Z_PEER and K_PEER at all loads. Considering the complexity of network management information to be exchanged between the network layers in the different models, it is significant that a simple algorithm such as CAPA_AUG designed for the augmented model can outperform the peer model algorithms K_PEER and Z_PEER. While an algorithm for the peer model can always be made to outperform a corresponding one for an augmented model (as the peer model algorithm has more information at its disposal than any algorithm for the augmented model), the above observation points out the importance of using the available information in a "correct" manner. This also shows the potential of an augmented model as a practical solution that could benefit from the advantages of both the peer and overlay models. We provide more insight into the apparent anomalous behavior of the peer model algorithms in Section VII.

C. Effect of Number of Ports

We next plot P_b and U against the number of ports per LSR in Fig. 9 and Fig. 10 to show how the performance improves as the number of ports increases. With 8 wavelengths on a physical link and a network load of 34 Erlangs, it is shown that Z_PEER's performance is the most sensitive to port limits. As the number of ports per LSR increases, P_b for Z_PEER drops faster than for any other algorithm, whereas in Y_OVLY and MLH_OVLY, it drops a little bit initially and then remains the same, due to the different cause of blocking as mentioned above.

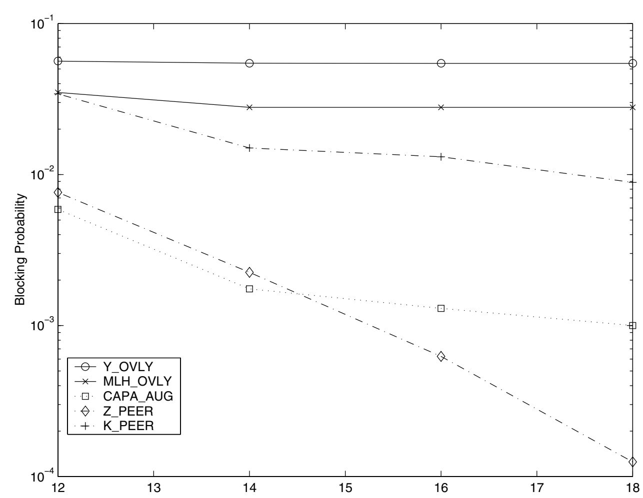

Fig. 9. Blocking probability vs. number of ports with 8 wavelengths, offered load = 34.

As the number of ports increases, CAPA_AUG also improves its P_b but not as much as Z_PEER or K_PEER. As we already

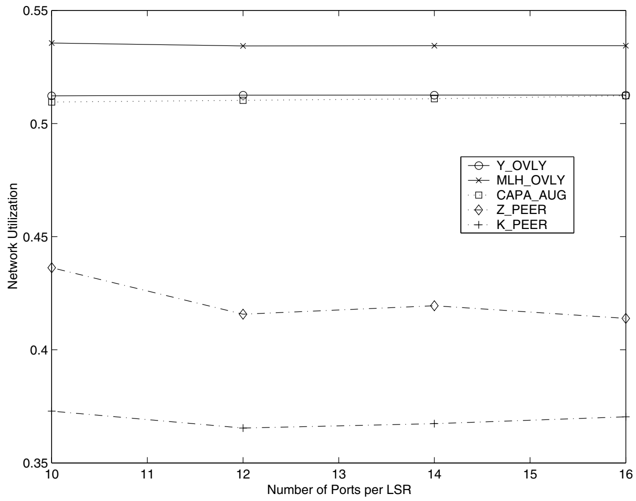

Fig. 10. Network utilization vs. number of ports with 8 wavelengths, offered load = 34.

showed in Fig. 5, if there is no limit on the number of ports, then Z_PEER and K_PEER outperform CAPA_AUG.

VII. More Analysis on Integrated Routing

In this section, we describe an observation we made regarding cost assignment in the integrated graph used by K_PEER and Z_PEER. As mentioned in Section IV-B, the cost of the cross-layer edges between an LSR and the sub-nodes for wavelengths in the corresponding OXC turned out to be an important factor in the performance of the two algorithms.

Let us consider the example in Fig. 11, where the costs of all physical edges are equal to 1 and only $w1$ between OXC1 and OXC2 is being fully used. Assume that the cross-layer edges have zero cost as was done in K_PEER and Z_PEER. Now, for a new request between LSRs C and B, there are several minimum-cost paths including the followings three: (1) $C - w1(OXC3) - w1(OXC1) - A - w2(OXC1) - w2(OXC2) - B$, (2) $C - w2(OXC3) - w2(OXC1) - A - w3(OXC1) - w3(OXC2) - B$, or (3) $C - w2(OXC3) - w2(OXC1) - w2(OXC2) - B$. In (1) and (2), two lightpaths are needed, C-A and A-B, which would use two ports in LSR A. In (3), however, there would only be one lightpath needed, which bypasses LSR A and does not use any of its ports, as in the cases of (1) and (2). In the K_PEER and Z_PEER algorithms, we chose one of the minimum-cost paths randomly. (In fact, we just chose the minimum-cost path selected by the shortest-path algorithm.) Therefore, there were instances when more than one lightpath was opened when one would have sufficed. When the number of ports is limited, this has the effect of unnecessarily consuming ports and blocking future requests.

The performance of the peer model algorithms can be improved by making a small modification that would eliminate the unnecessary use of ports. In the modified versions of the algorithms, called as MZ_PEER and MK_PEER, we assign a very small cost (e) to the cross-layer edges as shown in Fig. 11. The performances of the modified algorithms with $e = 0.1$ are shown in Fig. 12 and Fig. 13. Note that P_b of

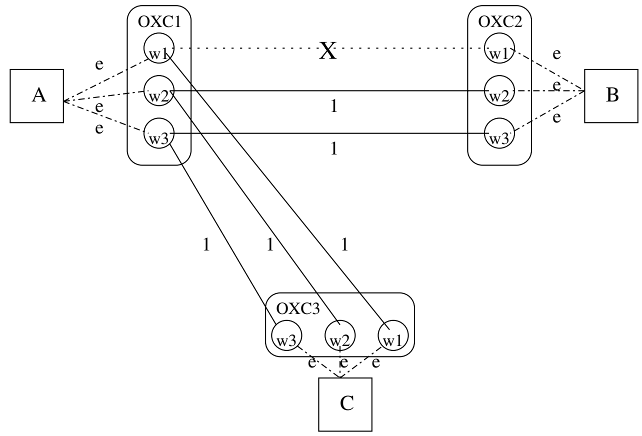

Fig. 11. Illustrative example of modified Z_PEER and K_PEER.

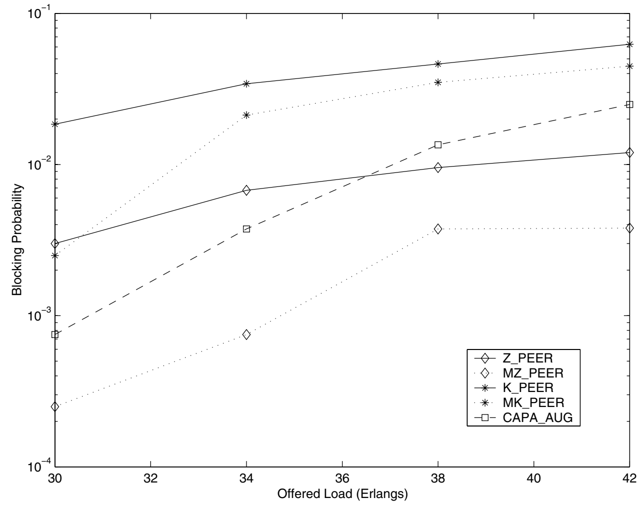

Fig. 12. Modified Z_PEER and K_PEER with $e = 0.1$. Blocking Probability vs. offered load with 8 wavelengths and 12 ports.

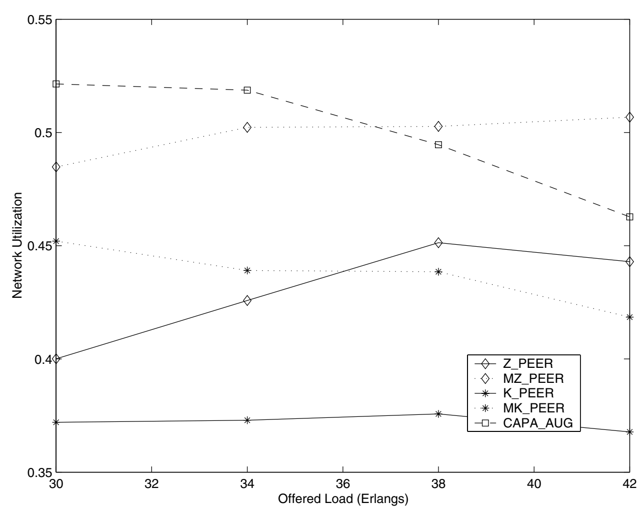

Fig. 13. Modified Z_PEER and K_PEER with $e = 0.1$. Network utilization vs. offered load with 8 wavelengths and 12 ports.

MZ_PEER is better than that of Z_PEER by almost an order of magnitude, and U improves by 7-9 % in MZ_PEER compared to Z_PEER. For comparison, we also show the performance of the CAPA_AUG algorithm. Notice now that MZ_PEER outperforms CAPA_AUG at all loads, while CAPA_AUG still outperforms MK_PEER at all loads.

VIII. Conclusions

In this paper, we studied the dynamic LSP provisioning problem for three different network models of IP/MPLS over WDM networks. While there have been algorithms proposed for the peer and overlay models, there has been no algorithm for the augmented model. We proposed a simple algorithm for the augmented model that achieves very good blocking performance and network utilization when compared to the peer and overlay model algorithms available in the literature. We also proposed a new algorithm for the overlay model, which performs better than the algorithm in [1], in terms of both blocking probability and network utilization.

While previous work assumed that the network is wavelength-limited in performance, we also considered a port-limited case which is likely to occur in practice due to the high cost of ports. We presented a comprehensive study of the performance of algorithms for the three network models for the first time, and showed the trade-off between network utilization and blocking probability.

An interesting observation we made was that our proposed augmented model algorithm outperformed both the peer model algorithms in terms of blocking probability over a wide range of network loads. An analysis of this phenomenon led to improved versions of the peer model algorithms. Nevertheless, we showed that it is possible to achieve very good performance using very limited information in the augmented model, when compared to the large amount of information that must be flooded across the network in the peer model. While we have presented an algorithm for the augmented model that shows good performance, more work remains to be done in quantifying the amount of network information that the various models use.

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