

Integrated Dynamic IP and Wavelength Routing in IP over WDM Networks

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Abstract

This paper develops an algorithm for integrated dynamic routing of bandwidth guaranteed paths in IP over WDM networks. By integrated routing, we mean routing taking into account the combined topology and resource usage information at the IP and optical layers. Typically, routing in IP over WDM networks has been separated into routing at the IP layer taking only IP layer information into account, and wavelength routing at the optical layer taking only optical network information into account. The motivation for integrated routing is the potential for better network usage, and this is a topic which has not been studied extensively. We develop an integrated routing algorithm that determines (1) whether to route an arriving request over the existing topology or whether it is better to open new wavelength paths. Sometimes it is better to open new wavelength paths even if it is feasible to route the current demand over the existing IP topology due to previously set-up wavelength paths. (2) For routing over the existing IP-level topology, compute "good" routes. (3) If new wavelength paths are to be set-up, determine the routers amongst which new wavelength paths are to be set-up and compute "good" routes for these new wavelength paths. The performance objective is the accommodation of as many requests as possible without requiring any a priori knowledge regarding future arrivals. The route computations account for the presence or absence of wavelength conversion capabilities at optical crossconnects. We show that the developed scheme performs very well in terms of performance metrics such as the number of rejected demands.

I. INTRODUCTION

We develop an algorithm for integrated online routing of bandwidth guaranteed paths in IP over WDM networks. The problem we consider is motivated by service provider needs for fast deployment of bandwidth guaranteed services which imply the need to dynamically set-up bandwidth guaranteed paths between a network's ingress-egress routers. Though bandwidth guaranteed paths can be set-up in a variety of ways, for ease of explanation we assume an MPLS network. Bandwidth guaranteed paths in this case are MPLS bandwidth guaranteed label switched paths (hereafter referred to merely as LSPs). Since all potential LSP requests are not known a priori, offline LSP routing algorithms cannot be

used. Instead, on-line algorithms that handle requests arriving one-by-one and that satisfy as many potential future demands as possible are needed.

The typical approach to routing LSPs is to separate the routing at each layer, i.e., routing at the IP/MPLS layer is independent of routing of wavelengths at the optical layer. Wavelength-routing at the optical layer is used to set-up a quasi-static logical topology which is then used at the IP layer for IP routing. Algorithms for routing bandwidth guaranteed paths considering only the IP layer topology and resource information have been extensively studied. Some examples are widest-shortest path routing [9], minimum-interference routing [11], and shortest-path routing with load-dependent weighting [15]. Wavelength routing at the optical layer has also been extensively studied [12]. A key difference, in an algorithmic sense, between IP layer LSP routing and wavelength routing is that in the optical network some network elements may not be able to perform wavelength conversion and this has to be taken into account by the routing algorithm.

The prime difference between these previously considered routing problems, and the problem considered in this paper is that instead of separating routing at each layer we consider the routing of LSPs taking into account the combined knowledge of resource and topology information in both the IP and optical layers. Clearly, this extra knowledge that is available to an integrated routing algorithm can be exploited so that the integrated routing algorithm can extract better network efficiencies than is possible with separated routing. An integrated dynamic routing scheme will be more robust to changing traffic patterns at the IP layer, than a scheme which uses dynamic routing at the IP layer only and uses a static wavelength topology determined by some a priori assumed traffic distribution. The key issues in integrated routing, which the algorithm that we develop addresses, are the following: (1) When a new request arrives, is this request to be routed over the existing topology due to previously set-up wavelength paths? If it is to be routed over the existing topology, then what is a "good" path? The measure of goodness is the selection of a path that permits as many future requests to be routed as possible. (2) If new wavelength paths are to be set-up then which are the routers amongst which new wavelength paths are to be set-up? (3) What are "good" routes in the optical network for these new wavelength paths?

We develop a new integrated on-line routing algorithm which performs better than separated routing, and takes into account all of the above issues. Also, it can take into account router capacities and the presence or absence of wavelength conversion capabilities at each of the optical network elements. We show by simulation studies that the developed integrated on-line routing scheme performs very well in terms of performance metrics such as the number of rejected demands.

II. MOTIVATION FOR INTEGRATED ROUTING

The network we consider consists of network elements which are either routers with WDM interfaces or optical cross connects (OXC). At the network edges, there are a set of routers which we call ingress-egress routers. For our purposes, the optical network can be thought of as a fiber network with each fiber carrying multiple wavelengths, and where each network element is either an optical cross-connect (OXC) or a backbone router. Whereas a router can handle traffic at any granularity and perform wavelength conversion (i.e., route traffic from any incoming interface to any outgoing interface regardless of incoming and outgoing wavelengths), an OXC is a wavelength switch which can only switch traffic at wavelength granularities. An OXC can switch any wavelength from any input fiber link to any outgoing link. Depending on the technology used, an OXC may or may not be able to perform wavelength conversion¹.

The main motivation for integrated routing in these networks, is the possibility of achieving better network usage efficiencies than is possible with separate routing at the IP and optical layers. Recently, proposals have been made to use OSPF-like link-state discovery and MPLS signaling (RSVP or LDP), in the optical network, to dynamically set-up wavelength paths [4]. The motivation for this is the use a single control-plane for MPLS and optical channel routing, and to extend the traffic engineering framework of MPLS [2] to the optical network as well. Also, proposals have been made to define a standard interface permitting routers to exchange information and to dynamically request wavelength paths from the optical network [6]. This makes it is feasible to consider integrated online routing of bandwidth guaranteed paths where an arriving bandwidth request can either be routed over the existing logical (IP-level) topology (due to previously set-up wavelength paths) or can be routed by setting up new wavelength paths.

To obtain topology and resource usage information for such integrated routing, one possibility is to consider both routers and OXCs as being in the same domain, and to run an OSPF-like protocol on both routers and OXCs. This protocol distributes both link-state and resource usage information to all network elements. For the IP layer, OSPF (or ISIS) extensions similar to those proposed in [8], [10], [13] can be used to distribute bandwidth usage information. For

the optical layer similar extensions can be used to distribute wavelength usage information for each link. Additional extensions to indicate properties of OXCs (such as wavelength conversion capability) may also be needed.

The only dynamic information used by our routing algorithm are the link residual capacities (available bandwidth at the IP layer, and available wavelengths at the optical layer). Also, quasi-static information such as the ingress-egress nodes in the network are known. This knowledge of the ingress-egress nodes should be exploited to reduce the number of request rejections due to insufficient network capacity. Even when all nodes are ingress-egress nodes, it is likely that some subset of ingress-egress nodes are more important and so requests between them will be required to have a lower probability of being rejected. The algorithm should be able to protect such important ingress-egress pairs.

III. OBJECTIVES FOR INTEGRATED IP OPTICAL-LAYER ROUTING ALGORITHMS

We first identify the design objectives that an integrated routing algorithm must satisfy in order to be useful in practice.

1. *Necessity to use on-line algorithms:* For traffic engineering purposes, it is usually assumed that all point-to-point demands are known. While this is a valid assumption for network design, for provisioning of bandwidth guaranteed services this implies that all LSPs that traverse the network are known at the time of initial routing. This is unlikely to be the case in practice. Furthermore, in this offline (all LSPs are known) model the objective usually is to make the most efficient use of the network, i.e., to minimize the resource usage for the LSPs that are being routed. Note that with this objective, it may happen that after the routing has been done there may no available capacity between certain ingress-egress routers (even though a different routing may have resulted in some available capacity between those routers). In the offline model, this lack of residual capacity between certain ingress-egress pairs is not relevant since all LSPs that need to be routed are known and no future routing requests are expected. If any new LSPs are to be routed, this may require re-routing of existing LSPs. It is unlikely that existing LSPs will be re-routed except upon link failures (and perhaps for relatively rare network re-optimization). In practice, since the possibility of having to route future LSP demands cannot be excluded, the routing algorithm must be an on-line algorithm capable of routing requests in an "optimal" manner when the requests are not all presented at once and re-routing of existing LSPs is not allowed.
2. *Use knowledge of ingress-egress points of LSPs:* Even though future demands may be completely unknown, the routers where LSPs can potentially originate and terminate are known since these are the network's edge routers. The algorithm must be able to use any available knowledge regarding ingress-egress pairs and must not

¹OXC's implemented using an electrical crossconnect, are likely to have wavelength conversion capability. All-optical OXC's, such as those based on MEMS technology may not have wavelength conversion capability.

always assume that every network element can potentially be an ingress and egress point (though this may be the case sometimes).

3. *Efficient network usage:* The performance objective for our algorithm is the accommodation of as many requests as possible without making any assumptions regarding future arrivals.
4. *Good re-routing performance upon link failure:* This is clearly an important performance metric. When a link fails, it must be possible to find alternate routes for as many LSPs as possible. If before failure, certain ingress-egress pairs have no residual capacity available between them then re-routing LSPs between these pairs after link failure is not possible. Our algorithm tries to maximize a surrogate measure of the residual capacity between all ingress-egress pairs and this makes it perform well upon link failure.
5. *Routing without traffic splitting:* Though splitting is used for load balancing purposes (by routing demands over multiple LSPs at the ingress point), it is not permissible for the routing algorithm to always split traffic in an arbitrary manner since the traffic being routed may be inherently unsplitable. Hence, the algorithm must be able to route a desired amount of bandwidth between a given ingress-egress pair without being able to split traffic onto multiple paths in an arbitrary way at every potential router in the path even though such splitting could permit better network usage.
6. *Computational requirements:* The routing problem is NP-hard considering just the IP layer [11]. Any heuristic or approximation algorithm must be implementable on routers and route servers and must execute within a reasonable time-budget for networks with a few thousand ingress-egress pairs.
7. *Feasibility of distributed implementation:* It is desirable that the algorithm be amenable to distributed implementation where each LSP's explicit route is computed at the local ingress router without communication with a domain or area wide route-server. Hence, it is desirable for the algorithm to restrict its use of dynamic information to information derivable from current routing protocols or their extensions. The algorithm we propose uses topology information and residual capacities on links. This is the same information that even min-hop routing with bandwidth guarantees will require. Within an OSPF-area, the topology information can be derived from the link state database and residual capacities can be obtained if extensions such as those suggested in [8], [13], [10], and similar extensions for distributing optical channel information are implemented. We also use the possible set of ingress-egress pairs. This information is quasi-static and we take that to be provisioned information (note that the algorithm is applicable even if this information is unavailable because then every router can be assumed to be a potential ingress and egress).

8. *Information useful for aggregation:* When routing over multiple areas or multiple domains, the algorithm if possible should generate information that can be useful for aggregation of bandwidth availability between ingress-egress pairs. Though this is not a necessity, it is a desirable feature and our algorithm takes this into account.
9. *Re-Optimization:* The on-line routing objective must permit optimization of existing LSPs' routes by using the same objective. Though frequent re-routing (as would happen with offline algorithms) is not permissible, it may be acceptable to occasionally re-route existing LSPs to optimize routing so as to carry more traffic. This optimization is possible because the on-line route selection happened with less information than that available during optimization since the optimizer knows the set of LSPs which have been set-up. Note that this optimization cannot use an offline algorithm since it still has to account for future arrivals. If occasional optimization is desired, the on-line algorithm's path selection objective must be such that a consistent optimization is possible.
10. *Policy constraints:* The algorithm must be able to incorporate common policy constraints such as policy restrictions on the type of links or routers that are permissible for routing a given LSP.
11. *Other requirements:* The algorithm must be able to accommodate requirements such as pre-emption and set-up priorities. A detailed discussion of these types of requirements is in [3].

IV. PROBLEM DEFINITION AND SYSTEM MODEL

We consider a network of n nodes interconnected by optical links. let m be the number of links in the network. For the ease of explanation we assume that each optical link supports k wavelengths. Each node is either a router, an OXC with wavelength conversion or an OXC without wavelength conversion. Let R refer to the set of nodes which are routers, S the set of nodes which are OXCs with wavelengths conversion, and T the set of nodes which are OXCs without wavelength conversion (MEMS based all optical switches, for example). Therefore, at a node belonging to set R it is possible to multiplex or demultiplex bandwidths at any granularity and also do wavelength conversion. We assume that the routers have enough interfaces and process all the traffic that can potentially flow through it. This assumption can be relaxed to account for the case where the router has limited processing power. At the nodes belonging to set S it is possible to do wavelength conversion and to switch a wavelength on an incoming link to a wavelength on any outgoing link. Nodes belonging to set T can do pure optical switching of wavelengths without wavelength conversion. A subset of the set R are ingress-egress nodes between which LSPs are to be set up dynamically. It is not necessary that there be a potential LSP between every ingress and every egress. Instead, from a certain ingress, LSPs may be allowable only

to certain egresses. This may be because of policy or service constraints (such as certain VPN traffic may only originate and exit at certain ingress-egress pairs). We assume that any such information is known, changes not very frequently and is made available to the route server (we describe for simplicity only a centralized route computation in the paper) by a provisioning or administrative mechanism. Therefore, we assume that there is a set of distinguished router pairs $\mathcal{P} \subseteq \mathcal{R} \times \mathcal{R}$. These can be thought of as the set of potential ingress-egress router pairs. All LSP set-up requests (demands) are assumed to occur between these pairs. Each request for an LSP set-up arrives at a route server which determines the explicit-route for the LSP. The request either arrives directly to the route server (if the LSPs are being set-up manually) or may first arrive at ingress routers which then query the route server to generate the explicit route (details of protocols that may be used for this interaction are left out for conciseness). The explicit route is then communicated back to the ingress router which then uses a signaling mechanism such as RSVP or LDP to set-up the path to the egress and to reserve bandwidth on each link on the path. With MPLS integration into the optical layer the same protocols should be able to set-up wavelength paths in the optical layer as needed. For calculating the explicit route, the route server needs to know the current topology and available capacities at both the IP and optical layers. This is obtained by potentially running a link-state protocol with appropriate extensions on all the network elements as mentioned before. Failures of LSPs due to link failures is detected from signaling protocol (LDP or RSVP) information by the edge routers. They can request a re-routing of the LSPs after the link-state database has been updated by routing protocols or by other means. (An alternative not studied in the paper for LSP's which require fast re-route is to set-up a disjoint path backup LSP so that failures can be accommodated by activating this pre-established backup path.)

We consider the request for an LSP i to be defined by a triple (o_i, t_i, b_i) . The first field $o_i \in R$, specifies the ingress router, the second field $t_i \in R$ specifies the egress router and the third b_i specifies the amount of bandwidth required for LSP i . Without loss of generality, the unit for the bandwidth request is assumed to be the transmission rate for one wavelength. Therefore, typical bandwidth requests will be fractional. We assume that the QoS requirements have been translated into an effective bandwidth requirement. We assume that requests for LSPs come in one at a time and there is no knowledge of the characteristics of future demands. The objective is to determine a path (if one exists) along which each demand for an LSP is routed so as to make "optimal" use of network infrastructure.

V. SETTING UP NETWORK FOR INTEGRATED ROUTING

We use Figure 1 to outline the key distinguishing feature of setting up the network for integrated IP and optical routing. There are 4 nodes connected by optical links. Each link is assumed to have two wavelengths, λ_1 and λ_2 . Nodes 1 and

4 are routers, node 2 is an OXC with wavelength conversion and node 3 is an OXC without wavelength conversion. (The symbols for the different elements used in this figure are used in the rest of the paper). Consider a request for 0.1 units from node 1 to node 4 in Figure 1. Assume that there are no other requests in the network. Let this demand be routed from node 1 to node 3 to node 4 using λ_1 . Once this demand is routed, note that node 3 cannot use λ_1 to route traffic along the path 2-3-4. This is because node 3 is an OXC and can only switch wavelengths. It cannot multiplex traffic coming from node 2 onto the unused λ_1 capacity between 3 and 4. Therefore, once traffic is routed on a particular wavelength from a node in $r_1 \in R$ through a set of nodes in $S \cup T$ to another node in $r_2 \in R$, then this wavelength acts a direct connect between r_1 and r_2 . This direct connection can be viewed as a logical link in the IP layer.

A. Modeling Routers and Optical Cross Connects

In this section we outline the fundamental difference between modeling routers and modeling optical cross connects. Consider any flow that can be established in the network between nodes $a \in R$ and $b \in R$. This flow may be actual demands that have been routed, or potential demands that can be routed from a to b . Let y_{ij}^k represent the amount of flow on link (i, j) over wavelength k . Since all flows go between nodes a and b at each node in the network, excepting a and b , the amount of flow into the node should equal the amount of flow out of the node. If node $p \in R \cup S$ then this flow balance can be written as

$$\sum_k \sum_i y_{ip}^k - \sum_k \sum_i y_{pi}^k = 0 \quad \forall p \in R \cup S.$$

If node p is an OXC without wavelength conversion, then it is not possible to go from one wavelength to another at this node. Therefore, the flow balance has to hold for each wavelength. In this case, the flow balance can be written as

$$\sum_i y_{ip}^k - \sum_i y_{pi}^k = 0 \quad \forall k \quad \forall p \in T.$$

Therefore there is a fundamental difference in modeling the nodes which can do wavelength conversion versus the nodes that cannot. From the perspective of representing the flows, the routers and OXCs with wavelength conversion behave identically.

Figure 2 shows the network representation for the graph shown in Figure 1. This representation is used by the routing algorithm to compute routes taking into account the capabilities of the different types of network elements. We expand each node into a number of sub-nodes, one per wavelength. For OXCs without wavelength conversion, each subnode is connected to a wavelength on each incoming or outgoing link as shown in Figure 2. For OXCs with wavelength conversion and for routers, we introduce a super-node that is connected to all the subnodes by infinite capacity links. Wavelength conversion is achieved by traversing this super-node. For the 2-wavelength example network of Figure 1,

there are two subnodes at each node without wavelength conversion, and two subnodes and a super-node at each node capable of wavelength conversion.

B. Modeling Logical links in the IP network

Assume that a demand of $r \leq 1$ units is to be routed from node $a \in R$ to node $b \in R$. Assume that this is the first demand in the network. Assume that the path that this demand takes has been determined. This path, in general will pass through a sequence of routers and OXCs (with or without wavelength conversion). An example of one such path is shown in Figure 3. The routers are represented by shaded circles and the other nodes are OXCs. Note that r units of a particular wavelength is consumed by this demand. The residual capacity of $1 - r$ units of bandwidth is available for future demands. The OXCs (with or without wavelength conversion) cannot do any sub-wavelength granularity bandwidth switching or multiplexing. Therefore, if the path passes through some OXCs between routers, the residual bandwidth of $1 - r$ units is modeled by introducing a cut-through arc between the routers and eliminating the links in the original graph. This cut-through arc is a logical link in the IP layer. All the non cut-through arcs are links in the physical (optical) layer. If the path has two routers that are adjacent then the residual capacity of the wavelength that is used to route this demand is reduced by r units. This is illustrated in Figure 4. The logical IP links are represented by the curved lines in Figure 4. All future demands are routed on this new network. If the residual capacity of the logical link reaches one unit on any LSP departure (i.e., the logical IP link is not being used by any LSP), then the logical IP link is eliminated and the original physical (optical) links in the network that constituted the logical IP link are re-established with unit capacity. This is equivalent to removing the cut-through wavelength path from the system.

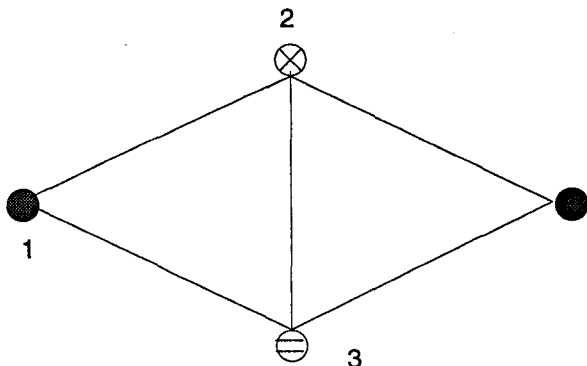


Fig. 1. Integrated IP-Optical network routing: Example Network

VI. KEY IDEAS FOR MAXIMAL OPEN CAPACITY ROUTING ALGORITHM

In this section, we give a description of the key ideas used in our routing algorithm. There are several existing schemes that take into account the topology of the network and the

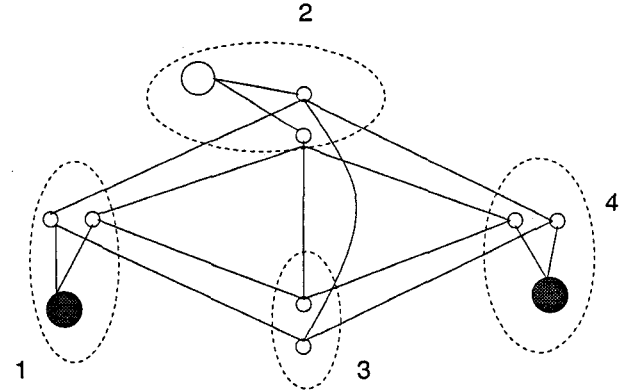


Fig. 2. Network representation for integrated routing computation

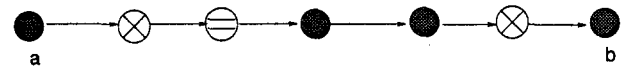


Fig. 3. An example LSP path encompassing routers and OXCs

residual capacities on the links, but do not take into account the location of the ingress/egress routers. These routers serve as ingress and egress of future traffic. If routing is done oblivious to the location of these ingress and egress points of traffic then we may “interfere” with the routing of some future demands. We illustrate this with a simple example. Consider the network shown in Figure 5. The dark nodes represent nodes that are routers and the light node represents a node that does not have a router. Each link is assumed to carry two wavelengths, λ_1 and λ_2 . As outlined in Section V, the network corresponding to this case is shown in Figure 6. There are three potential ingress egress pairs, $(1, 2)$, $(1, 3)$, $(4, 3)$, $(4, 2)$. We now have a request for 0.2 wavelengths for the ingress egress pair $(4, 3)$. Assume that this demand is routed along the wavelength λ_1 (represented by the dotted line in Figure 6). Note that at the end of the routing, there will be 0.8 units of residual bandwidth on the cut-through arc between nodes 4 and 3. Figure 7 shows the graph used by the routing algorithm to represent the combined state of the IP and optical layers after the demand of 0.2 wavelengths has been routed. Note the addition of the cut-through arc with 0.8 residual capacity (available at the IP layer) and the deletion of some wavelength capacity from the optical layer. Next there is a demand of 0.3 units from node 1 to node 2. Note that this demand can take the wavelength corresponding to the dotted line or the solid line. If min-hop routing is used, then either of these options appears the same. However, if λ_2 (solid line) is used for this demand, then nodes 1 and 3 will be disconnected. Therefore it

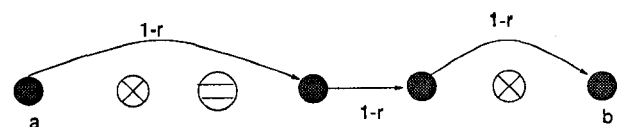


Fig. 4. Cut-through arcs modeling path with routers and OXCs

is better to use λ_1 (dotted line) to route this demand. Similarly it is easy to come up with illustrations where routing along the existing logical links in the IP layer is less preferable to opening new paths in the physical layer and routing along this path. The main point that we want to illustrate with this example is that there are some paths that interfere with potential future demands more than others. Therefore it is better to route along paths which minimizes the “interference” or maximizes the residual or open capacity between the ingress-egress pairs.

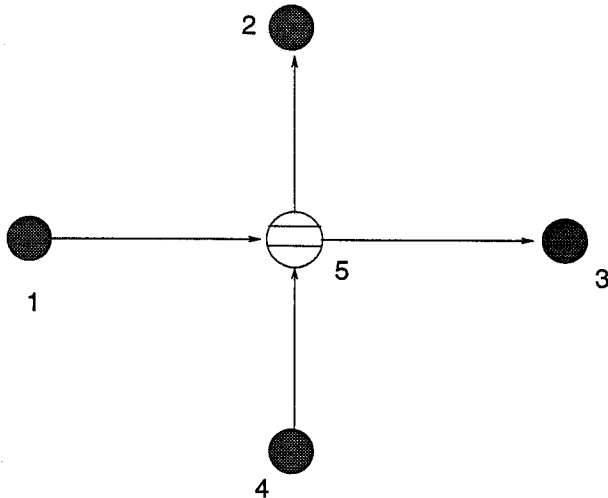


Fig. 5. Illustrative Example Network

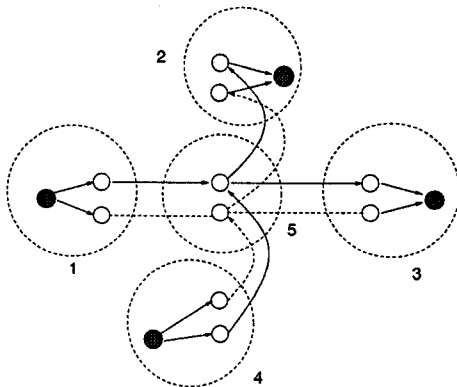


Fig. 6. Illustrative Example: Representation of Network

Interference and Maximizing Open Capacity

The key idea is to pick paths that do not interfere too much with potential future set-up requests (demands) between other ingress egress pairs such that the open capacity is maximized. We now make these concepts of interference and open capacity more rigorous.

A. Modeling the Open Capacity Between the “Edge” Nodes

After some demands have been routed, we would like to estimate the available open capacity between the different ingress-egress pairs. We capture this open capacity by computing the maximum flow that can be sent from the ingress

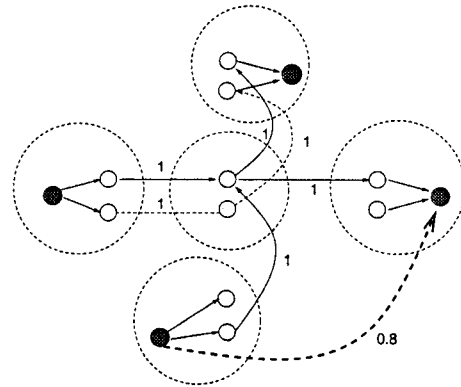


Fig. 7. Graph (with residual capacities) after routing $4 \rightarrow 3$

to the egress over the network where the capacity of a link is the current residual capacity. *The maximum flow is computed on the network with both the logical IP links and the optical links.* The maximum flow provides an upper bound on the amount of demand that can be routed between the ingress-egress pair since we insist that a given demand cannot be split across multiple paths. Nevertheless the maximum flow provides a good estimate of the available capacity between different ingress-egress pairs. In fact, if the maximum flow between a given ingress-egress pair is zero then no demand can be routed between that ingress-egress pair.

B. Modeling the Importance or “Criticality” of each link

The maximum flow depends on the residual capacity of the links in the network. Consider a particular ingress-egress pair. From linear programming duality [1], corresponding the maximum flow is the minimum cut. If the capacity of any of the links in the minimum cut is decreased, the maximum flow value between that ingress-egress pair decreases. This means that the number of demands which can be routed between this ingress-egress pair in the future decreases. Therefore, we define all the links that belong in the minimum cut for an ingress egress pair to be critical to that ingress egress pair. Since there may be more than one mincut for a ingress egress pair, all arcs belonging to any mincut are defined to be critical for that ingress egress pair. This is done with the same scheme as is given in [11]. With interference defined as above, we can think of a path that maximizes open capacity as one that maximizes the sum of the maxflows between all other ingress-egress pairs. Figure 8 shows the graph for the illustrative example given in Figure 5, with the number next to each arc being its weight (number of ingress-egress pairs for which that arc is critical). Note that the shortest path for the route from node 1 to node 2 uses λ_1 and hence does not choke off all the paths between nodes 1 and 3.

Path Selection by Shortest Path Computation

Once the critical links are identified, we would like to avoid routing LSPs on critical links to the extent possible. We do this by generating a weighted graph where the critical links have weights that are an increasing function of their “critical-

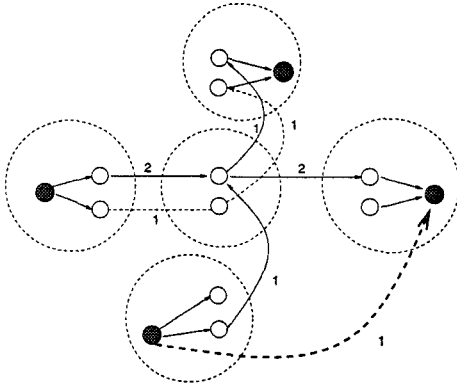


Fig. 8. Graph (with link weights) after routing $4 \rightarrow 3$

ity” The increasing weight function is picked to defer loading of critical links whenever possible. The actual explicit route is calculated using a shortest path computation (using Dijkstra’s algorithm) as in other routing schemes. *The shortest path is computed in the network with both the logical IP links and the optical links* Therefore, a path in general will use some logical IP links and then might create additional logical IP links (but opening a new cut-through path). In fact, even if there are paths in the logical IP network that go from the ingress to the egress of the current demand, if these paths are “long”, then the algorithm will create additional logical links from the IP layer. Thus the maxflow computation as well as the path computation steps take advantage of the fact that the routing is done jointly.

VII. OUTLINE OF MAXIMUM OPEN CAPACITY ROUTING ALGORITHM (MOCA)

In this section, we outline the different steps of the algorithm for integrated IP and wavelength routing. The algorithm is used to route demands dynamically. It automatically opens wavelength paths on an as needed basis and opens these paths in a such a way that the open capacity between ingress-egress pairs is maintained at a large value. As outlined in the earlier sections, the path is the shortest path in a modified network where the link weights are proportional to the criticality of the links. It can be shown that the determining the maximum flow is the dominant computational step in the determination of the critical links [11]. Once the demand is routed, the network is modified with the addition of cut-through arcs as outlined in Section V-B. It should be pointed out that it is also possible to weight the critical links for different source-destination pairs differently. For example, in order to protect the source-destination pairs for which the current maximum flow value is low, the critical links for this source-destination pair can be made higher. This will tend to keep the smallest maximum flow value high. The following gives a high level view of the Maximum Open Capacity routing Algorithm (MOCA). Note that the algorithm description is for the addition of a demand. When a demand leaves the system, then the algorithm is reversed, the residual capacities are increased and when a logical IP link’s residual capacity

is one unit, then the logical link is removed and the optical links that make up the logical link are introduced back into the network with unit residual capacity.

MAXIMUM OPEN CAPACITY ROUTING ALGORITHM (MOCA)

INPUT:

A graph $G(N, L)$ the cut-through arcs and the residual capacities of all the links.
An ingress node a and an egress node b between which a flow of D units have to routed.

OUTPUT:

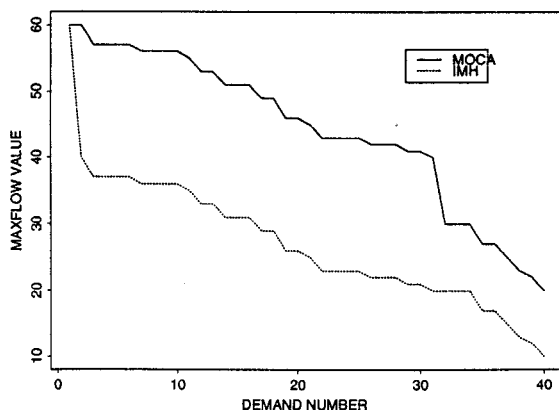
A route between a and b having a capacity of D units of bandwidth.

ALGORITHM:

1. Compute the critical links for $(s, d) \in \mathcal{P} \setminus (a, b)$.
 2. Compute the weight of all the links in the network (including the cut-through arcs).
 3. Eliminate all links which have residual bandwidth less than D and form a reduced network.
 4. Using Dijkstra’s algorithm compute the minimum weight path in the reduced network.
 5. Form the cut-through arcs with the appropriate residual capacities as well as update the residual capacity of the router-to-router arcs along the routed path.
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VIII. PERFORMANCE STUDIES

In this section, we will compare the performance of our routing algorithm, MOCA, with integrated min-hop routing (IMH). In the integrated min-hop routing, all the steps of the algorithm are the same as MOCA except that the weight of all the links are set to one before the shortest path is computed. Therefore, the experiments show how the weighting of the links using our method improves the performance of the algorithm. The main performance measure that we use is the number of demands rejected when a fixed number of demands are routed through the network. We tested the performance of the algorithms on two different graphs. The first graph is shown in Figure 9. The ingress-egress pairs are marked in the figure. The shaded nodes are routers and the nodes that are not shaded are OXCs with no wavelength conversion. In the first set of experiments the number of wavelengths per link is assumed to be two, and in the second set of experiments the number of wavelengths per link is assumed



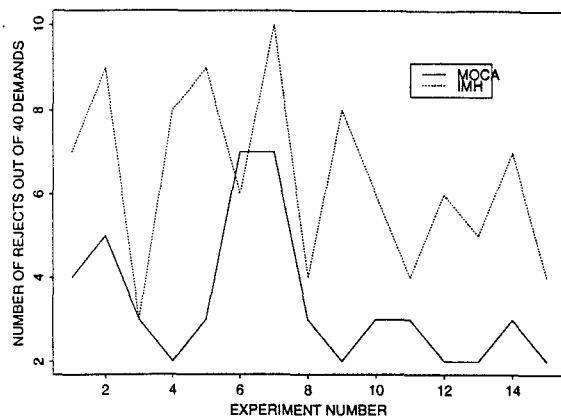


Fig. 13. Comparison of number of rejects for 2 wavelengths per link (large graph)

domain, and execute OSPF-like protocols (with MPLS traffic engineering and optical networking extensions) to distribute combined topology and resource usage information to all the network nodes. With such a combined view of the network, MPLS traffic engineering can be extended to the optical network. MPLS network's explicit path routing capability can be used to set-up bandwidth guaranteed label-switched paths, with wavelength paths in the optical network being also set-up using MPLS on an as-needed basis to accommodate the changing arriving patterns of LSP requests at the IP layer. Our algorithm, uses a combined view of the network to do the following: (1) It first determines whether a new demand can be routed over the existing IP level topology due to previously set-up wavelength paths and if so determines a "good" path (2) It determines whether it is better to open new wavelength paths to route the current request. We show that it is sometimes better to open new wavelength paths even when it is feasible to route the current request over the existing topology, (3) If a new wavelength path is to be set-up, determine which are the routers amongst which new paths are to be set-up, (4) Determine "good" paths for these new wavelength paths. The objective of the routing algorithm in determining all of the above is the accommodation of as many requests as possible without requiring any knowledge regarding future arrivals. The main idea used to achieve this is to pick the path for the current request such that after the current request is routed the residual available capacity between the ingress-egress pairs is maximized. We believe that an integrated dynamic routing scheme will be more robust to changing traffic patterns at the IP layer, than a scheme which uses dynamic routing at the IP layer only and uses a static wavelength topology determined by some a priori assumed traffic distribution. We showed by simulations that the proposed integrated routing algorithm has very good LSP acceptance performance in comparison to integrated min-hop routing. We expect the performance difference to be much higher if routing is separated at each layer. We also believe that most LSP routes can be computed using

only a shortest-path computation and that frequent determination of the "critical" links is not necessary to ensure good performance. An immediate extension to this work is the incorporation of priorities. Another topic for future study is aggregation for inter-domain routing.

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