Lightpath Establishment in Wavelength-Routed WDM Optical Networks

Jason P. Jue
Center for Advanced Telecommunications Systems and Services
University of Texas at Dallas, Richardson, TX 75083
E-mail: jjue@utdallas.edu

1 Introduction

Wavelength-division multiplexing (WDM) technology has been improving steadily in recent years, with existing systems capable of providing huge amounts of bandwidth on a single fiber link. WDM systems are currently being deployed in long-distance telecommunication networks on a point-to-point basis, with the optical signals being converted back to electronics at each node. The electronic switching and processing costs at the nodes can potentially be very high, leading to severe performance bottlenecks and limiting the delivery of optical link bandwidth to the end users.

Emerging wavelength-routed WDM systems, which utilize photonic crossconnects (PXCs), are capable of switching data entirely in the optical domain. Configuring these optical devices across a network enables one to establish all-optical connections, or lightpaths [1], between source nodes and destination nodes (Fig. 1). Data carried on these lightpaths avoid electronic conversion and processing at intermediate nodes, thereby alleviating the electronic bottleneck.

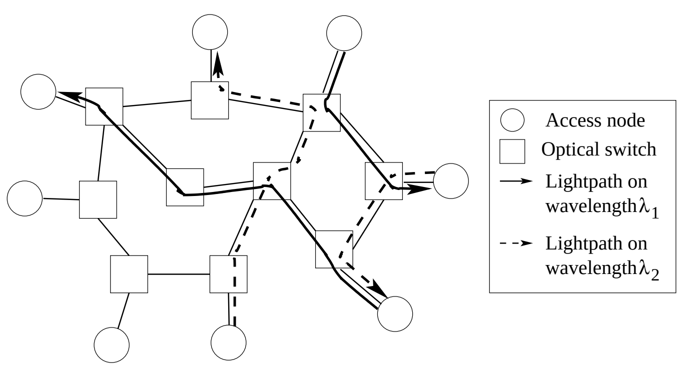

Figure 1: Wavelength-routed WDM network with lightpaths established between nodes.

One of the challenges involved in designing wavelength-routed networks is to develop efficient algorithms and protocols for establishing lightpaths in the optical network. The algorithms must be able to select routes and assign wavelengths to connections in a manner which efficiently utilize network resources and which maximizes the number of lightpaths that can be established. Signaling protocols for setting up lightpaths must effectively manage the distribution of control messages and network state information in order to establish a connection in a timely manner.

In this article, we discuss the various issues related to the control and management of lightpaths in a wavelength-routed optical network, and we review various approaches for handling these issues. Section 2 covers routing and wavelength assignment algorithms for WDM networks. Section 3 reviews various signaling protocols for reserving resources and setting up lightpaths in a wavelength-routed network. Section 4 presents various control and management models, as well as some standard protocols for lightpath establishment in an IP over WDM environment.

2 Routing and Wavelength Assignment

The problem of finding a route for a lightpath and assigning a wavelength to the lightpath is often referred to as the routing and wavelength assignment problem (RWA). The objective of the problem is to route lightpaths and assign wavelengths in a manner which minimizes the amount of network resources that are consumed, while at the same time ensuring that no two lightpaths share the same wavelength on the same fiber link. Furthermore, in the absence of wavelength conversion devices, the RWA problem operates under the constraint that a lightpath must occupy the same wavelength on each link in its route. This restriction is known as the wavelength-continuity constraint. The optimal formulation of the RWA problem is known to be NP-complete; therefore, heuristic solutions are often employed.

The RWA problem can be considered under two different traffic assumptions. The static RWA problem applies to the case in which the set of connections is known in advance, and a lightpath must be established for each connection. In the dynamic RWA problem, connections arrive to the network dynamically and remain for some amount of time before departing; thus, lightpaths must not only be established dynamically, but must also be taken down. In both the static and dynamic RWA problems, the routing component and the wavelength assignment component of the problem are often decoupled into two separate subproblems in order to make the problem more tractable. In the following sections, we discuss routing and wavelength assignment approaches for static and dynamic lightpath establishment. We assume that no wavelength conversion is available.

2.1 RWA for Static Lightpath Establishment

A number of studies have investigated the RWA problem for setting up a static set of lightpaths [1] [2] [3]. These studies formulate the problem using integer linear program (ILP) formulations, or rely on heuristic approaches in an attempt to minimize the number of wavelengths required to establish a given set of lightpaths. The ILP formulations are NP-complete and therefore may only be solved for very small systems. For larger systems, heuristic methods must be used.

In [3], the routing problem is formulated as an ILP in which the objective is to minimize the number of wavelengths required to establish a fixed set of lightpaths. The search space of the problem is reduced by restricting the set of links through which a lightpath for a given source-destination pair may traverse. The resulting ILP is then solved by relaxing the integer constraint, solving the resulting non-integer linear program, and then utilizing a randomized rounding approach on the result to obtain an integer solution.

Other heuristics consider only alternate shortest-hop paths between a source-destination pair, and choose one of the paths according to a predefined policy [4, 5]. In [4], a shortest-hop path is randomly chosen for each source-destination pair. Each source-destination pair is then considered individually, and the route for the pair of nodes is switched to an alternate shortest-hop path if doing so results in a reduction of load on the most heavily loaded link in the original shortest-path route. In [5], an approach similar to that in [4] is considered; however, the objective is to minimize the number of fibers in a multifiber network, and the set of alternate paths includes routes which may be longer than the shortest-hop routes.

The wavelength-assignment sub-problem of the RWA problem can itself be formulated as a graph coloring problem, which is also NP-complete. Greedy heuristics for the wavelength-assignment problem for a static set of lightpaths typically involve ordering the wavelengths, and assigning the same wavelength to as many lightpaths as possible before moving on to the next wavelength [1]. Also, the set of lightpaths may be ordered by length, such that wavelengths are assigned to longer lightpaths before wavelengths are assigned to shorter lightpaths.

2.2 RWA for Dynamic Lightpath Establishment

When lightpaths are established and taken down dynamically, routing and wavelength assignment decisions must be made as connection requests arrive to the network. It is possible that, for a given connection request, there may be insufficient network resources to set up a lightpath, in which case the connection request will be blocked. The connection may also be blocked if there is no common wavelength available on all of the links along the chosen route. Thus, the objective in the dynamic situation is to choose a route and a wavelength which maximizes the probability of setting up a given connection, while at the same time attempting to minimize the blocking for future connections. Similar to the case of static lightpaths, the dynamic RWA problem can also be decomposed into a routing subproblem and a corresponding wavelength assignment subproblem. Approaches to solving the routing subproblem can be categorized as being either fixed or adaptive, and as utilizing either global or local network state information.

2.2.1 Fixed Routing

In fixed routing, a single fixed route is predetermined for each source-destination pair. When a connection request arrives, the network will attempt to establish a lightpath along the fixed route. If no common wavelength is available on every link in the route, then the connection will be blocked. A fixed routing approach is simple to implement; however, it is very limited in terms of routing options and may lead to a high level of blocking. In order to minimize the blocking in fixed routing networks, the predetermined routes need to be selected in a manner which balances the load evenly across the network links. Fixed routing schemes do not require the maintenance of global network state information.

2.2.2 Adaptive Routing Based on Global Information

Adaptive routing approaches increase the likelihood of establishing a connection by taking into account network state information. For the case in which global information is available, routing decisions may be made with full information as to which wavelengths are available on each link in the network.

Centralized Versus Distributed Routing Adaptive routing based on global information may be implemented in either a centralized or distributed manner. In a centralized algorithm, a single entity, such as a network manager, maintains complete network state information, and is responsible for finding routes and setting up lightpaths for connection requests. Since a centralized entity manages the entire network, there does not need to be a high degree of coordination among nodes; however, a centralized entity becomes a possible single point of failure. Furthermore, a centralized approach does not scale well, as the centralized entity would need to maintain a large database to manage all nodes, links, and connections in the network.

Alternate-Path Routing One approach to adaptive routing with global information is alternate-path routing. Alternate-path routing relies on a set of predetermined fixed routes between a source node and a destination node [6, 7, 8, 9]. When a connection request arrives, a single route is chosen from the set of predetermined routes, and a lightpath is established on this route. The criteria for route selection is typically based on either path length or path congestion. An example of a routing algorithm based on path length is the K-shortest paths algorithm [6], in which the first K shortest paths are maintained for each source-destination pair, and the paths are selected in order of length, from shortest to longest. A connection is first attempted on the shortest path. If resources are not available on this path, the next shortest path is attempted. A path selection policy based on path congestion examines the available resources on each of the alternate paths, and chooses the path on which the highest amount of resources are available. Choosing the shortest-path route consumes less network resources, but may lead to high loads on some of the links in the network, while choosing the path with the least congestion leads to longer paths, but distributes the load more evenly over the network.

Unconstrained Routing Another adaptive routing approach utilizing global information is unconstrained routing which considers all possible paths between a source node and a destination node. In order to choose an optimal route, a cost is assigned to each link in the network based on current network state information, such as wavelength availability on links. A least-cost routing algorithm is then executed to find the least-cost route [10, 11, 12]. Whenever a connection is established or taken down, the network state information is updated. Two examples of unconstrained routing approaches are link-state routing and distance-vector routing.

In a distributed link-state routing approach, each node in the network must maintain complete network state information [11]. Each node may then find a route for a connection request in a distributed manner. Whenever the state of the network changes, all of the nodes must be informed. Therefore, the establishment or removal of a lightpath in the network may result in the broadcast of update messages to all nodes in the network. The need to broadcast update messages may result in significant control overhead. Furthermore, it is possible for a node to have outdated information, and for the node to make an incorrect routing decision based on this information.

A distance-vector approach to routing with global information is also possible [12]. This approach doesn't require that each node maintains complete link-state information at each node as in [11], but instead has each node maintain a routing table which indicates for each destination and on each wavelength, the next hop to the destination and the distance to the destination. The approach relies on a distributed Bellman-Ford algorithm to maintain the routing tables. Similar to [11], the scheme also requires nodes to update their routing table information whenever a connection is established or taken down. This update is accomplished by having each node send routing updates to their neighbors periodically or whenever the status of the node's outgoing links changes. Although each node maintains less information than in [11] and the updates are not broadcast to all nodes, the scheme may still suffer from a high degree of control overhead.

Although routing schemes based on global knowledge must deal with the task of maintaining a potentially large amount of state information which is changing constantly, these schemes often make the most optimal routing decisions if the state information is up to date. Thus, global-knowledge based schemes may be well suited for networks in which lightpaths are fairly static and do not change much with time.

2.2.3 Adaptive Routing Based on Local Information

While near-term emerging systems will be fairly static, with lightpaths being established for long periods of time, it is expected that, as network traffic continues to scale up and become more bursty in nature, a higher degree of multiplexing and flexibility will be required at the optical layer. Thus, lightpath establishment will become more dynamic in nature, with connection requests arriving at higher rates, and lightpaths being established for shorter time durations. In such situations, maintaining distributed global information may become infeasible. The alternative is to implement routing schemes which rely only on local information.

A number of adaptive routing schemes exist which rely on local information rather than global information. The advantage of using local information is that the nodes do not have to maintain a large amount of state information; however, routing decisions tend to be less optimal than in the case of global information. Two examples of local-information-based adaptive routing schemes are alternate routing with local information, and deflection routing.

Alternate-Path Routing with Local Information While alternate-path routing schemes typically rely on global information, variations exist which utilize only local information. A least-congested alternate path routing scheme is investigated in [13]. In this scheme, the choice of a route is determined by the wavelength availability along the alternate paths. Two variations of the scheme are considered: the case in which wavelength availability information is known along the entire path, and the case in which only local information is available.

In the first approach, the decision making entity is aware of the wavelength availability information for all of the links in each of the alternate paths. In this case, the chosen route is that which has the greatest number of wavelengths which are available along all of the links in its path. For example, in Fig. 2, if we consider two alternate routes from source node A to destination node D, with available wavelengths as shown on each link, then two wavelengths (λ_1 and λ_3) are available along the entire length of route 1, while only one wavelength (λ_2) is available along the entire length of route 2; thus, route 1 will be chosen.

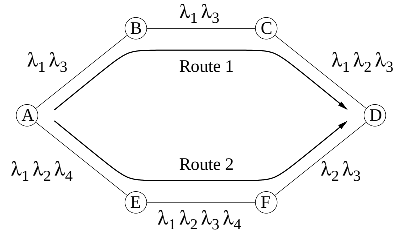

Figure 2: Alternate routing. Available wavelengths are shown on each link.

The limitation of basing the route selection decision on full path information is that the information may be difficult to maintain or difficult to obtain in a timely manner. Each node would be required to either maintain complete state information, or the information would need to be gathered in real time, as the lightpath is being established. The alternative, based on local information, is to gather wavelength availability information only along the first k hops of each path. The route is then chosen based on which path is the least congested along its first k hops. In Fig. 2, if $k = 2$, then route 2 would be chosen, since it has three wavelengths available on the first two links (λ_1, λ_2, and λ_4), while route 1 only has two wavelengths available on the first two links (λ_1 and λ_3). Although local information may provide a good estimate of the congestion along a path, it does not guarantee that any particular wavelength will be available along the entire path; thus, it is possible that after choosing a route, the connection will still be blocked due to lack of available wavelengths.

Deflection Routing Another approach to adaptive routing with limited information is deflection routing, or alternate-link routing [14]. This routing scheme choses from alterate links on a hop-by-hop basis rather than choosing from alternate routes on an end-to-end basis. The routing is implemented by having each node maintain a routing table which indicates, for each destination, one or more alternate outgoing links to reach that destination. These alternate outgoing links may be ordered such that a connection request will preferentially choose certain links over other links as long as wavelength resources are available on those links. Other than a static routing table, each node will only maintain information regarding the status of wavelength usage on its own outgoing links. When choosing an outgoing link for routing, the decision can be determined on either a shortest-path or least-congested basis.

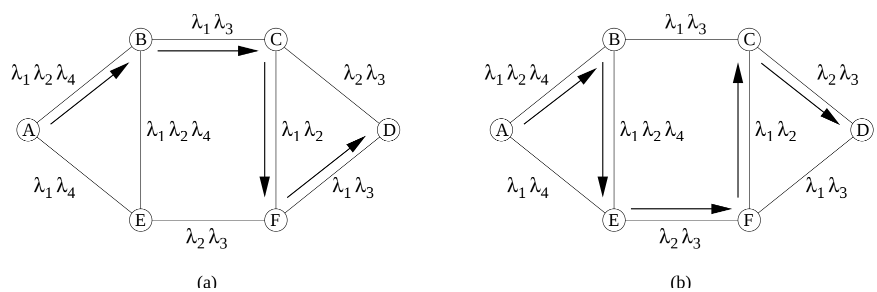

Figure 3: Deflection routing. Available wavelengths are shown on each link.

Under the shortest path criteria, the routing scheme will first attempt to choose the outgoing link which results in the shortest path to the destination. If there is no feasible wavelength available on the link, then the routing scheme will attempt to choose an alternate outgoing link which leads to the next shortest path to the destination. The routing scheme proceeds in this manner until the destination is reached or the connection is blocked. Figure 3(a) illustrates the deflection routing scheme for a connection request from node A to node D. The default shortest path in this example is along the path A→B→C→D. When the request reaches node C, it cannot continue over link CD, since no common wavelength is available on links AB, BC, and CD. The request is therefore deflected to node F, where it can continue to the destination along link FD. The wavelength selected for the lightpath will be λ_1. Note that, in the absence of any deflections, the default routing for any connection will be shortest-path routing. Also, once the routing for a lightpath is deflected at a node, the default routing from the point of deflection onward will again be shortest-path routing if no further deflections take place.

In a least-congested deflection routing approach, the routing scheme chooses, from among the alternate outgoing links, the link which has the largest number of feasible wavelengths. The set of feasible wavelengths consists of the set of wavelengths which are available on all of the previous hops as well as the next outgoing link. Least-congested deflection routing is illustrated in Fig. 3(b) for a connection from node A to node D. On the first hop, link AB is selected, since it has three available wavelengths, while link AE has only two available wavelengths. When the connection request arrives to node B, it will be routed to node E, since there are three feasible wavelengths (λ_1, λ_2, and λ_4) available on link BE, and there is only one feasible wavelength (λ_1) available on link BC. The least-congested deflection routing approach will generally result in longer paths than the shortest-path deflection routing approach; however, least-congested deflection will allow a lightpath to be routed around congested areas in the network, balancing the load more evenly across the network. The results in [14] show that a shortest-first policy results in lower blocking at low loads, while a least-congested policy results in lower blocking at higher loads.

A number of issues arise when implementing a deflection routing scheme. One such issue is the problem of looping, in which a connection request message returns to a node which has already been visited. Loop detection may be addressed by having each connection request message maintain a path vector containing a list of visited nodes. If a node receives a connection request message which indicates that the message has already visited this node, then the connection attempt will be blocked. An alternative to maintaining a path vector is to utilize a time-to-live field, which would prevent the connection request message from looping in the network indefinitely.

Another problem which may arise is that a connection request may be deflected a large number of times, leading to an unreasonably long route for the lightpath. Possible solutions to this problem include limiting the maximum length or number of hops in a lightpath, or limiting the number of deflections that a route can take. When a connection request message reaches its limit on the maximum number of hops or deflections, the connection attempt will be blocked. Further restrictions may also be placed on the selection of possible outgoing ports in order to prevent routes from heading back towards the source node.

2.3 Wavelength Assignment

In general, if there are multiple feasible wavelengths between a source node and a destination node, then a wavelength assignment algorithm is required to select a wavelength for a given lightpath. The wavelength selection may be performed either after a route has been determined, or in parallel with finding a route. Since the same wavelength must be used on all links in a lightpath, it is important that wavelengths are chosen in a way which attempts to reduce blocking for subsequent connections. A review of wavelength-assignment approaches can be found in [15].

One example of a simple, but effective, wavelength-assignment heuristic is first-fit. In first-fit, the wavelengths are indexed, and a lightpath will attempt to select the wavelength with the lowest index before attempting to select a wavelength with a higher index. By selecting wavelengths in this manner, existing connections will be packed into a smaller number of total wavelengths, leaving a larger number of wavelengths available for longer lightpaths.

Another approach for choosing between different wavelengths is to simply select one of the wavelengths at random. In general, first-fit will outperform random wavelength assignment when full knowledge of the network state is available [7]. However, if the wavelength selection is done in a distributed manner, with only limited or outdated information, then random wavelength assignment may outperform first-fit assignment. The reason for this behavior is that, in a first-fit approach, if multiple connections are attempting to set up a lightpath simultaneously, then it may be more likely that they will choose the same wavelength, leading to one or more connections being blocked.

Other simple wavelength assignment heuristics include the most-used-wavelength heuristic and the least-used-wavelength heuristic. In most-used wavelength assignment, the wavelength which is the most used in the rest of the network is selected. This approach attempts to provide maximum wavelength reuse in the network. The least-used approach attempts to spread the load evenly across all wavelengths by selecting the wavelength which is the least-used throughout the network. Both most-used and least-used approaches require global knowledge.

A number of more advanced wavelength assignment heuristics which rely on complete network state information have been proposed [16, 17]. It is assumed in these heuristics that the set of possible future lightpath connections is known in advance. For a given connection, the heuristics attempt to choose a wavelength which minimizes the number of lightpaths in the set of future lightpaths that will be blocked by this connection. It is shown that these heuristics offer better performance than first-fit and random wavelength assignment.

3 Signaling and Resource Reservation

In order to set up a lightpath, a signaling protocol is required to exchange control information among nodes and to reserve resources along the path. In many cases, the signaling protocol is closely integrated with the routing and wavelength assignment protocols. Signaling and reservation protocols may be categorized based on whether the resources are reserved on each link in parallel, reserved on a hop-by-hop basis along the forward path, or reserved on a hop-by-hop basis along the reverse path. Protocols will also differ depending on whether global information is available or not.

3.1 Parallel Reservation

In [11], the control scheme reserves wavelengths on multiple links in parallel. The scheme, which is based on link-state routing, assumes that each node maintains global information on the network topology and on the current state of the network, including information regarding which wavelengths are being used on each link. Based on this global information, the node can calculate an optimal route to a destination on a given wavelength. The source node then attempts to reserve the desired wavelength on each link in the route by sending a separate control message to each node in the route. Each node that receives a reservation request message will attempt to reserve the specified wavelength, and will send either a positive or negative acknowledgement back to the source. If the source node receives positive acknowledgements from all of the nodes, it can establish the lightpath and begin communicating with the destination. The advantage of a parallel reservation scheme is that it shortens the lightpath establishment time by having nodes process reservation requests in parallel. The disadvantage is that it requires global knowledge, since both the path and the wavelength must be known ahead of time.

3.2 Hop-by-Hop Reservation

An alternative to parallel reservation is hop-by-hop reservation in which a control message is sent along the selected route one hop at a time. At each intermediate node, the control message is processed before being forwarded to the next node. When the control message reaches the destination, it is processed and sent back towards the source node. The actual reservation of link resources may be performed either while the control message is traveling in the forward direction towards the destination, or while the control message is traveling in the reverse direction back towards the source.

3.2.1 Forward Reservation

In forward reservation schemes, wavelength resources are reserved along the forward path to the destination on a hop-by-hop basis. The method of reserving wavelengths depends on whether or not global information is available to the source node. If the source node is maintaining complete state information, then it will be aware of which wavelengths are available on each link. Assuming that the state information is current, the source node may then send a connection setup message along the forward path, reserving the same available wavelength on each link in the path.

For the case in which a node only knows the status of its immediate links, the wavelength selection becomes more complicated, as the source node doesn't know which wavelength will be available along the entire path. The source node may utilize a conservative reservation approach, choosing a single wavelength and sending out a control message to the next node attempting to reserve this wavelength along the entire path; however, there is no guarantee that the selected wavelength will be available along every link in the path. If the wavelength is blocked, the source node may select a different wavelength and reattempt the connection. The limitation of this approach is that it may result in high setup times, since it may take several attempts before a node can establish a lightpath.

An alternate approach to maximizing the likelihood of establishing a lightpath in a forward reservation scheme is to use an aggressive reservation scheme which over-reserves resources [18]. Multiple wavelengths may be reserved on each link in the path, with the expectation that at least one wavelength will be available on all links in the path. In a greedy approach, all feasible wavelengths will be reserved at every link in the path. The source node will first reserve all available wavelengths on the desired outgoing link. A connection request message containing the wavelength reservation information is then sent to the next node along the

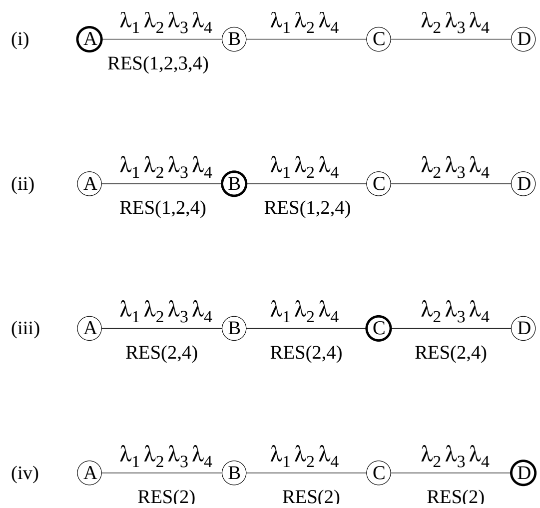

Figure 4: Forward reservation. As the control message propagates from A to D, each node reserves the set of wavelengths which have been available on all links traversed by the control message.

path. At each intermediate node, the subset of wavelengths consisting of the intersection of the wavelengths reserved on the previous link and the wavelengths available on the next link will be reserved. For example, if S_n is the set of wavelengths available on the nth link, then the set of wavelengths reserved on the first link in the path will be S_1, the set of wavelengths reserved on the second link will be $S_1 \bigcap S_2$, the set of wavelengths reserved on the third link would be $S_1 \bigcap S_2 \bigcap S_3$, etc. When the connection request reaches the destination, one wavelength of the remaining set of wavelengths will be chosen, and all of the other wavelengths will be released. Figure 4 illustrates the forward reservation of wavelengths when establishing a lightpath from node A to node D.

One disadvantage of over-reserving resources is that, during the time that the resources are reserved, the reserved resources cannot be utilized by other users, even if these resources will never be used by the connection. In order to reduce the amount of time that an unused wavelength is reserved on a link, the wavelength may be released as soon as it is apparent that the wavelength is not viable for a given connection. For example, if wavelengths λ_1, λ_2, λ_3, and λ_4 are available on the first link, then all four of the wavelengths will be reserved on this link. However, if it is subsequently discovered that only λ_1, λ_2, and λ_4 are available on the second link, then not only will λ_1, λ_2, and λ_4 be reserved on the second link, but λ_3 will immediately be released on the first link.

Another approach to limiting the number of wavelengths that are reserved is to divide the wavelengths into groups. When reserving wavelengths on a link, a node will reserve only those wavelengths which belong to a specific group [19]. The choice of the group is made at the source node and is based on the number of available wavelengths in each group. The source node will find the group with the largest number of available wavelengths, and the node will reserve all of the available wavelengths in that group before sending the request on to the next node. The size of the group is a critical parameter. If the group is too large, then too many resources will be reserved, but if the group is too small, then the likelihood of establishing a lightpath will be smaller.

3.2.2 Backward Reservation

To prevent the over-reservation of resources altogether, reservations may be made after the control message has reached the destination and is headed back to the source. Such reservation schemes are referred to as backward reservation schemes [18]. By reserving wavelengths in the reverse direction, the reserved wavelengths are idle for less time than if the wavelengths are reserved in the forward direction. Another advantage is that the connection request message can gather wavelength usage information along the path in the forward direction. This information can then be used by the destination node to select an appropriate wavelength to reserve. Figure 5 illustrates the backward reservation scheme. It is shown in [18] that, in general, backward reservation schemes outperform forward reservation schemes for the case in which there is no wavelength conversion. One possible drawback of a backward reservation scheme is that if multiple connection are being set up simultaneously, it is possible that a wavelength that was available on a link in the forward direction will be taken by another connection request and will no longer be available when the reservation message traverses the link in the reverse direction.

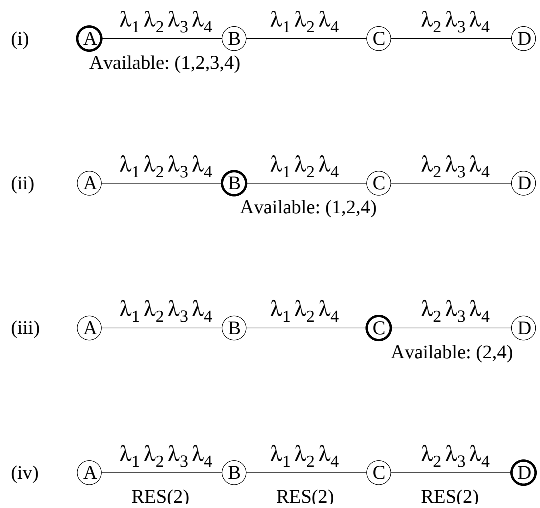

Figure 5: Backward reservation. As the control message propagates from A to D, it records the set of available wavelengths. Node D then chooses a wavelength and reserves the wavelength on each link by sending a reservation message back towards the source.

3.3 Holding Policies

To improve the connection setup probability at the cost of higher setup times, it is possible to hold or buffer connection requests at intermediate nodes if wavelength resources are not immediately available [20, 21]. If an appropriate wavelength becomes available, the connection request will continue towards the destination. If, after waiting for some time, the appropriate resources do not become available, then the connection is blocked.

In [21], it is shown that a holding policy decreases the blocking probability without significantly increasing setup time. However, it is also shown in [20] that a holding policy reduces the network throughput compared to a policy in which calls are blocked immediately if resources are not available.

4 IP over WDM Control and Management

With the rapid growth of the Internet, it is becoming apparent that IP traffic will soon become the dominant type of traffic in emerging networks; thus, there is much interest in optimizing the underlying optical network to handle IP traffic. When IP networks are implemented over optical WDM network, it is possible to modify existing IP protocols to handle the control and management associated with establishing and taking down lightpaths at the optical layer. The advantage of such an approach is that it reduces the need to develop new protocols for the optical layer, and it enables the control of both IP and optical layers through a single integrated control plane.

The relationship between the IP layer and the optical layer is defined by the control model. In an overlay model, the IP layer is a client to the optical layer, with the optical layer providing point-to-point lightpath services between IP routers. The control protocols for the IP layer are independent of the optical layer control protocols; however, it is possible for the optical layer protocols to be based on modified versions of IP protocols. The IP and optical layers interact through a user-to-network interface (UNI). The UNI defines specific services that the IP layer may request from the optical layer, such as lightpath establishment, lightpath removal, and lightpath modification.

Another control model is the peer model in which IP routers and optical crossconnects are peers with regard to control and management. Each optical node is treated as an IP addressable entity and runs the same control protocols as other IP routers. In this situation, the same protocol which is used to establish a virtual circuit connection between IP routers can also be used to establish a lightpath between two routers. One of the limitations of this approach is that the entire optical network must be made visible to all of the IP routers in the same domain; thus the approach is not very scalable.

A third control model is the integrated model in which the IP and optical layers are running separate instances of the same control protocols. In this case, optical crossconnects are still IP addressable; however, the optical network is viewed as a separate IP domain by the rest of the network. The integrated model is more scalable than the peer model, while at the same time, the IP nodes may still interact with the optical layer through existing IP protocols.

In each of the control models, the establishment of lightpaths in the optical network may be performed through a multi-protocol lambda switching (MPλS) control framework [22, 23], which is a variation of the multi-protocol label switching (MPLS) framework.

4.1 MPLS and MPλS

MPLS is a control framework which is currently being developed as a standard to enable fast switching in IP networks [24]. MPLS control mechanisms can be used to establish a label-switched path (LSP) between two non-neighboring IP routers. In an LSP, packets do not need to be processed at the IP layer at any of the intermediate IP routers; thus, the packets experience much lower delays. To route a packet over a LSP, labels are applied to packets, and these labels are used to switch the packets within the network. When a labeled packet arrives at an input port of a label-switched router, the label is used to index a table which specifies the outgoing port for the packet and the packet's new label. The old label is replaced by the new label, and the packet is sent to the appropriate output port.

The concept of MPLS can be extended to wavelength-routed optical networks as MPλS. In MPλS, rather than applying labels to packets, the wavelengths themselves act as labels and are used to route the packets through the optical network. A signal coming in on a given input port is directed to an appropriate output port based on the wavelength of the signal. Since a wavelength in MPλS is analogous to a label in MPLS, the process of swapping labels would correspond to the process of converting an optical signal from one wavelength to another. Thus, in the absence of wavelength conversion devices, it is not possible to swap "labels" in MPλS.

The MPλS control mechanism can be used to establish a lightpath in a similar way that MPLS establishes a label-switched path. The establishment of a lightpath in the MPλS framework requires a routing protocol and a signaling protocol. Neither of these protocols is specified by MPλS; however, it is possible to use standard IP-based protocols to provide routing and signaling functionality.

4.2 Routing

Routing in most IP networks is currently handled by the open shortest path first (OSPF) protocol [26]. OSPF is a link-state protocol in which the state of each link in the network is periodically broadcast to all nodes in the form of link-state advertisements (LSAs). The LSA will provide link information such as whether the link is up or down, and the amount of bandwidth on the link. In the context of wavelength-routed optical networks, the link-state information may indicate whether a wavelength is in use or not. Given the link-state information, each node will have full knowledge of the network state, and will use this information to construct the network topology and to route packets through the network. The routing itself is based on Dijkstra's shortest path algorithm. The limitations of OSPF are similar to the limitations of any other routing algorithm which utilizes global state information. The signaling overhead may potentially be very high when lightpaths and other connections are being established and taken down at a high rate. Also, incorrect routing decisions may result from outdated state information.

4.3 Signaling Protocols and Label Distribution

In MPLS and MPλS, signaling protocols are required to exchange control messages for setting up LSPs and lightpaths, to reserve network resources, and to distribute labels. Possible signaling protocols include RSVP (resource reservation protocol) [27] and CR-LDP (constraint-based label distribution protocol) [28]. Both protocols perform signaling on a hop-by-hop basis, with RSVP reserving resources in the backward direction (destination-initiated reservation), and CR-LDP reserving resources in the forward direction (source-initiated reservation). Routing can either be done based on OSPF, or an explicit route can be specified by the source node.

4.3.1 RSVP

In RSVP, signaling takes place between the source router and destination router. At the source router, a PATH message is created and sent to the destination node. The PATH message may be routed according to standard routing protocols, such as OSPF. Alternatively, an explicit route through the network may be specified if the source router is aware of the network topology. The PATH message may also contain information such as QoS requirements for the carried traffic and label requests for assigning labels at intermediate nodes. At an intermediate node, the request is recorded, and the PATH message is forwarded to the next node. If the message cannot be forwarded or if resources are not available, the path setup fails, and a message is sent back to the source router. At the destination node, an RESV message is generated to distribute labels, and is sent back to the previous node. The intermediate nodes reserve the appropriate resources, allocate new labels for the path, and send the RESV message back towards the source router.

4.3.2 CR-LDP

The CR-LDP protocol may also be used to provide signaling and to distribute labels. CR-LDP utilizes TCP sessions between nodes in order to provide a reliable distribution of control messages. At the ingress node, a LABEL_REQUEST message is created. The message indicates the route and the required traffic parameters for the route. Resources are reserved at the ingress node, and the LABEL_REQUEST is forwarded to the next node. At the intermediate node, resources are reserved, and the LABEL_REQUEST is forwarded. At the destination, resources are reserved and a label is assigned to the request. The destination node creates a LABEL_MAPPING message which contains the new label, and passes the message back towards the source node. Each intermediate node allocates a label and sets up its forwarding table before passing the LABEL_MAPPING to the previous node.

Both RSVP and CR-LDP may be used to reserve a single wavelength for a lightpath if the wavelength is known in advance. These protocols may also be modified to incorporate wavelength selection functionality into the reservation process.

5 Conclusion

As optical networks continue to develop and emerge, WDM systems will evolve from static point-to-point links to optically switched wavelength-routed networks. The establishment of lightpaths in such networks requires the implementation of control and management protocols to perform routing and wavelength assignment functions, as well as to exchange signaling information and to reserve resources. In this article, we have presented some of the routing, wavelength assignment, and signaling protocols for establishing lightpaths in a wavelength-routed network.

In routing and wavelength assignment algorithms for dynamic lightpaths, the goal is to minimize the number of blocked connections. The performance of these algorithms depends heavily on the amount of state information available to each node. If global information is known, then the routing and wavelength assignment decisions can be nearly optimal; however it is difficult to maintain complete up-to-date information in a very dynamic environment. When only limited information is known, routing and wavelength assignment decisions may be based on either shortest path or least congested criteria. By choosing routes or links which result in a shorter path, network resources are conserved, possibly leading to lower blocking for future connections. On the other hand, a least-congested approach to routing and wavelength assignment may result in the load being more evenly distributed across the network.

The effectiveness of a wavelength assignment policy depends on the amount of information available, as well as on the connection arrival rate. With global information, a first-fit policy will perform well. However, with only local information, a random policy may perform better, since lower indexed wavelengths are more likely to be used on other links throughout the network. Also, when connection requests are arriving at a high rate, using first-fit may result in higher blocking for simultaneous connection requests.

The performance of signaling protocols for reserving wavelengths along a lightpath will depend on whether or not global information is available, and whether or not multiple connection requests may be attempted simultaneously. For the case in which global information is available, reservations may be made either in parallel or on a hop-by-hop basis, with parallel reservations leading to lower connection establishment times. When only local information is available, wavelength selection may be combined with the reservation scheme. In both forward and backward reservation schemes, additional information is gathered along the path before deciding on a wavelength. The two schemes differ in how they are affected by simultaneous connection requests. In forward reservation, the over-reservation of wavelength resources leads to higher blocking for other connections, while in backward reservation, there is the possibility that a previously available link in the route will be taken by another connection request.

In emerging IP over WDM systems, the routing and signaling protocols for establishing lightpaths are likely to exist within an MPλS framework and are expected to be based on existing IP protocols such as OSPF, CR-LDP, and RSVP. However, it is important to note that the MPλS framework is not limited to any particular routing or signaling protocol, and that in certain situations, such as the case of rapidly arriving and departing lightpaths, alternative protocols may offer better performance.

References

[1] I. Chlamtac, A. Ganz, and G. Karmi, "Lightpath Communications: A Novel Approach to High Bandwidth Optical WANs", *IEEE Transactions on Communications* Vol.40 No.7 (1992) pp. 1171-1182.

[2] R. Ramaswami and K. Sivarajan, "Routing and Wavelength Assignment in All-Optical Networks," *IEEE/ACM Transactions on Networking* Vol.3 No.5 (1995) pp. 489-500.

[3] D. Banerjee and B. Mukherjee, "A Practical Approach for Routing and Wavelength Assignment in Large Wavelength-Routed Optical Networks," *IEEE Journal on Selected Areas in Communications* vol. 14 No.5 (1996) pp. 903-908.

[4] S. Baroni and P. Bayvel, "Wavelength Requirements in Arbitrary Connected Wavelength-Routed Optical Networks," *IEEE/OSA Journal of Lightwave Technology* Vol.15 No.2 (1997) pp. 242-251.

[5] M. Alanyali and E. Ayanoglu, "Provisioning Algorithms for WDM Optical Networks," *IEEE/ACM Transactions on Networking* Vol.7 No.5 (1999) pp. 767-778.

[6] K. Bala, T.E. Stern, and K. Bala, "Algorithms for Routing in a Linear Lightwave Network," *Proceedings, IEEE Infocom '91*, Miami, FL, Apr. 1991.

[7] A. Birman and A. Kershenbaum, "Routing and Wavelength Assignment Methods in Single-Hop All-Optical Networks with Blocking," *Proceedings, IEEE Infocom '95*, Boston, MA, Vol. 2, Apr. 1995, pp. 431-438.

[8] H. Harai, M. Murata, and H. Miyahara, "Performance of Alternate Routing Methods in All-Optical Switching Networks," *Proceedings, IEEE Infocom '97*, Kobe, Japan, Apr. 1997, pp. 516-524.

[9] S. Ramamurthy and B. Mukherjee, "Fixed-Alternate Routing and Wavelength Conversion in Wavelength-Routed Optical Networks," *Proceedings, IEEE Globecom '98*, Sydney, Australia, Nov. 1998, pp. 2295-2302.

[10] A. Mokhtar and M. Azizoglu, "Adaptive Wavelength Routing in All-Optical Networks," *IEEE/ACM Transactions on Networking* vol. 6 No.2 (1998) pp. 197-206.

[11] R. Ramaswami and A. Segall, "Distributed Network Control for Wavelength Routed Optical Networks," *Proceedings, IEEE Infocom '96*, San Francisco, CA, Mar. 1996, pp. 138-147.

[12] H. Zang, L. Sahasrabuddhe, J. P. Jue, S. Ramamurthy, and B. Mukherjee, "Connection Management for Wavelength-Routed WDM Networks," *Proceedings, IEEE Globecom '99*, Rio de Janeiro, Brazil, Dec. 1999, pp. 1428-1432.

[13] L. Li and A. K. Somani, "Dynamic Wavelength Routing Using Congestion and Neighborhood Information," *IEEE/ACM Transactions on Networking* Vol.7 No.5 (1999) pp. 779-786.

[14] J. P. Jue and G. Xiao, "An Adaptive Routing Algorithm with a Distributed Control Scheme for Wavelength-Routed Optical Networks," *Proceedings, Ninth International Conference on Computer Communications and Networks*, Las Vegas, NV, Oct. 2000.

[15] H. Zang, J. P. Jue, and B. Mukherjee, "Review of Routing and Wavelength Assignment Approaches for Wavelength-Routed Optical WDM Networks," *Optical Networks Magazine* Vol.1 No.1 (2000) pp. 47-60.

[16] S. Subramaniam and R. A. Barry, "Wavelength Assignment in Fixed Routing WDM Networks," *Proceedings, IEEE ICC '97*, Montreal, Canada, Vol.1, June 1997, pp. 406-410.

[17] X. Zhang and C. Qiao, "Wavelength Assignment for Dynamic Traffic in Multi-fiber WDM Networks," *Proceedings, 7th International Conference on Computer Communications and Networks*, Lafayette, LA, Oct. 1998, pp. 479-485.

[18] X. Yuan, R. Melhem, R. Gupta, Y. Mei, and C. Qiao, "Distributed Control Protocols for Wavelength Reservation and Their Performance Evaluation," *Photonic Network Communications*, vol. 1, No.3, 1999, pp. 207-218.

[19] A. G. Sotica, A. Sengupta, "On a Dynamic Wavelength Assignment Algorithm for Wavelength-Routed All-Optical Networks," *Proceedings, SPIE/IEEE/ACM OptiComm 2000*, Dallas, TX, Oct. 2000, pp. 211-222.

[20] Y. Mei and C. Qiao, "Efficient Distributed Control Protocols for WDM All-Optical Networks," *Proceedings, International Conference on Computer Communication and Networks*, Las Vegas, NV, Sept. 1997, pp. 150-153.

[21] A. Sengupta, S. Bandyopadhyay, A. R. Balla, and A. Jaekel, "Algorithms for Dynamic Routing in All-Optical Networks," *Photonic Network Communications* Vol.2 No.2 (2000) pp. 163-184.

[22] N. Ghani, "Lambda Labeling: A Framework for IP-Over-WDM," *Optical Networks Magazine* Vol.1 No.2 (2000) pp. 45-58.

[23] D. O. Awduche, "Multi-Protocol Lambda Switching: Combining MPLS Traffic Engineering Control with Optical Crossconnects," *IETF Draft*, draft-awduche-mpls-te-optical-01.txt, Nov. 1999.

[24] R. Callon, P. Doolan, N. Feldman, A. Fredette, G. Swallow, and V. Srinivasan, "A Framework for Multiprotocol Label Switching," *IETF Draft*, draft-ietf-mpls-framework-05.txt, Sept. 1999.

[25] D. Awduche, J. Malcolm, J. Agogbua, M. O'Dell, and J. McManus, "Requirements for Traffic Engineering Over MPLS," RFC 2702, Sept. 1999.

[26] W. R. Stevens, *TCP/IP Illustrated, Volume 1*, Addison-Wesley, 1994.

[27] R. Braden, L. Zhang, S. Berson, S. Herzog, and S. Jamin, "Resource ReSerVation Protocol (RSVP) – Version 1 Functional Specification," IETF RFC 2205, September 1997.

[28] B. Jamoussi et al., "Constraint-Based LSP Setup Using LDP," *IETF Draft*, draft-ietf-mpls-cr-ldp-04.txt, July 2000.