affect the individual sub-channels of a waveband is important for determining the ultimate reach, capacity, and channel spacing that can be achieved within a passband of existing networks and fiber infrastructure.

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FR2 **10:45 AM**

Cost-Effective WDM Backbone Network Design with OXCs of Different Bandwidth Granularities

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We propose a framework for designing a WDM backbone network with OXCs of different grooming granularities. Numerical examples are presented showing that granularity-heterogeneous networks are more cost-effective than granularity-homogeneous networks.

1. Introduction

As WDM technology advances, the capacity of a wavelength channel continues to increase (OC-48, OC-192, or OC-768). However, the bandwidth requirements of typical connection requests are versatile (e.g., STS-1, OC-3, OC-12, OC-48, and OC-192), and usually of small fractions of the bandwidth of a WDM channel. To efficiently use the bandwidth, grooming switches are introduced which can pack/unpack low-speed connections onto/from high-speed WDM channels and switch at sub-wavelength granularities. Different grooming switches may have different grooming granularities. For instance, some grooming switches can groom at STS-1 level, i.e., they are capable of unpacking a wavelength channel down to STS-1 timeslots, switching those STS-1 timeslots, and packing them back onto wavelength channels. Some other grooming switches may do grooming only at OC-48 level (assuming the capacity of a wavelength channel is greater than OC-48). Although this kind of grooming switches provides less flexibility in grooming, the port cost may be less than that of STS-1 grooming switches. These two kinds of grooming switches are both opto-electro-opto (OEO) switches, and need to be surrounded by transponders. Meanwhile, all-optical OXCs do not need transponders for OXC ports, which is a significant saving in optical transport networks, but at the price of no grooming capability and wasting channel capacities. Since the WDM backbone network topologies are usually irregular and traffic requests are of different bandwidth granularities, it is not necessary to deploy the same kind of OXC at all the nodes. If the granularities of all the OXCs in a network are the same, we call this network *granularity-homogeneous network*; otherwise, we call it *granularity-heterogeneous network*. When designing a WDM backbone network, it is desirable to take advantage of the benefit of all types of OXCs to accommodate the traffic while reducing the network capital expenditures.

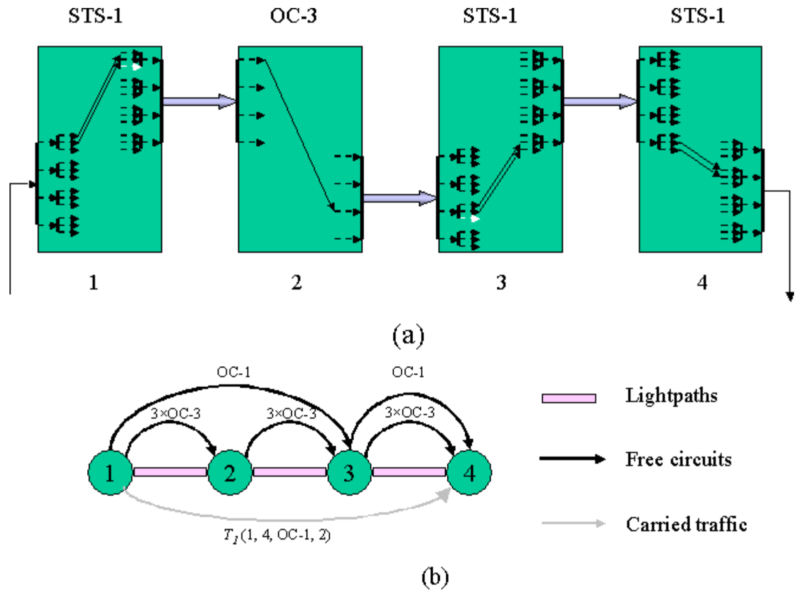

Figure 1. (a). State of the switches when routing T_1. (b) Network state after routing T_1.

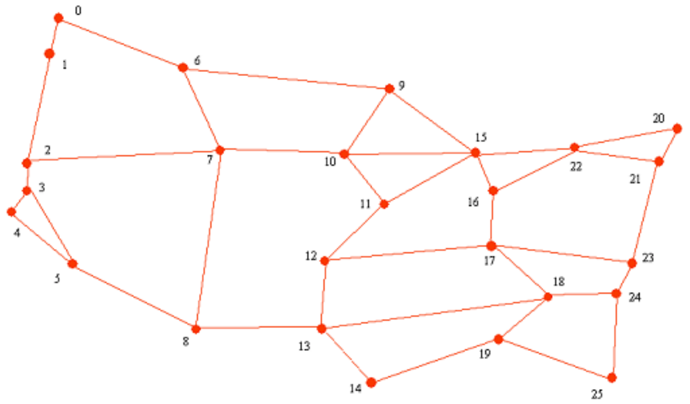

Figure 2. A 26-node nation-wide backbone network.

In [1], the authors compared the network cost when using different node architectures, but they assumed all the grooming nodes have the same STS-1 grooming capability. In this paper, we focus on designing a WDM backbone network with OXCs of different bandwidth granularities to minimize the network-wide OXC port cost. Specifically, we determine the type of OXC at each node, compute the route of each traffic request, and calculate the total OXC port cost.

2. Problem Statement

Given the physical topology of a network, a traffic matrix which contains various bandwidth requirement between different nodes, the types of OXCs which can be deployed in the network, and the port cost of each type of OXCs, we need to determine the type of OXC at each node, as well as the route of each traffic request, and the objective is to minimize the total OXC port cost of the network while accommodating all the traffic demands. A traffic demand is represented by *T(s, d, g, m)*, where *s* and *d* are the source and destination nodes, respectively; *g* is the granularity of the traffic demand, for instance, OC-48; and *m* is the amount of the traffic in units of *g*.

3. Side-Effect of Routing Traffic in Granularity-Heterogeneous Networks

In a granularity-heterogeneous network, routing a connection request and representing the network state will become significantly more complex than in a network where only OXCs with STS-1 grooming granularity exist.

In an STS-1 grooming granularity network, if there is a lightpath between two nodes, the free capacities on the lightpath can always be accessible by the end nodes of the lightpath.

In a multi-granularity network, OXCs switch traffic at different granularities. For a given traffic demand requiring certain bandwidth, certain amount of timeslots on the lightpaths along the route of the traffic are allocated to the connection. At a STS-1 grooming switch, only the timeslots occupied by the traffic are switched from the incoming OXC port to the outgoing OXC port. However, at an OXC with a switching granularity coarser than the bandwidth granularity of the traffic request, some free timeslots may also be switched together with those timeslots taken by the traffic, causing these free timeslots to bypass this node and become unavailable to this node. The fundamental observation is that the timeslots within the switching granularity of an OXC are transparent to the OXC and these timeslots can only be operated as a whole.

OXC	Switching technology	Have grooming capability?	Capacity of the OXC port	Grooming granularity	Need transponders for bypass traffic?
Type I	OOO	No	OC-192	N/A	No
Type II	OEO	Yes	OC-192	OC-48	Yes
Type III	OEO	Yes	OC-192	STS-1	Yes

Table 1. Comparison of the three types of OXCs.

Here we give a small example. To carry a traffic demand T_1(1, 4, OC-1, 2), we setup lightpaths L_1 (from node 1 to node 2), L_2 (from node 2 to node 3), and L_3 (from node 3 to node 4), and then route T_1 onto these lightpaths. The switching granularities of the nodes 1, 2, 3, and 4 are STS-1, OC-3, STS-1, and STS-1, respectively. The capacity of a wavelength channel is OC-12 for this illustration. Figure 1(a) shows the switching state of the OXCs. Since the switching granularity of node 2 (OC-3) is coarser than the bandwidth granularity of the traffic demand (OC-1), there is a free STS-1 timeslot (timeslot 3 in L_1) switched onto L_2 (timeslot 9 in L_2) by the OXC at node 2. Although this timeslot goes through node 2, it cannot be accessed by node 2. Any traffic carried by this timeslot will bypass node 2 and directly reach node 3, where it can be switched to any free outgoing grooming port. This is equivalent to having an STS-1 circuit directly connecting node 1 and node 3. Figure 1(b) shows the network state (virtual connectivity) after routing T_1. These circuits form another topology above the virtual topology, and traffic demands should be routed on this topology instead of on the virtual topology.

4. Network Design Framework

To accommodate characteristics of multi-granularity networks, we extend the graph model proposed in [2]. The graph model can route a traffic demand according to the current network state, and update the network state after carrying the traffic. The extended graph model can also intelligently choose the appropriate type of OXC to carry the current traffic demand, given there are several types of OXCs at a node. Due to space limitation, the extended graph model is not shown here.

Based on the extended graph model, we propose a design procedure as follows.

Step 1	Place one OXC of each type at each node.
Step 2	Compute a route for each traffic demand, and choose the most suitable OXC at each node along the route using the extended graph model, until all the traffic has been carried.
Step 3	For each type of OXC at each node, move the traffic going through the other types of OXC to this type of OXC, estimate the port cost of this type of OXCs, and choose the type of OXC with the least cost at each node.
Step 4	After determining the type of OXC at each node, reroute all the traffic demands and calculate the network cost.

5. Numerical Results

We conducted experiments on a typical nation-wide backbone network. The topology is shown in Fig. 2. It has 26 nodes and 40 bi-directional links. The capacity of a wavelength channel is OC-192. The bandwidth granularity of a traffic demand can be STS-1, OC-3, OC-12, OC-48, and OC-192, and the total traffic bandwidth requirement distribution of these 5 granularities is α_1: α_2: α_3: α_4: α_5, respectively. The traffic is uniformly distributed between all the nodes. There are 3 types of OXCs, shown in Table 1.

The per-port cost ratio of Type I, Type II, and Type III OXCs is β_1: β_2: β_3.

We compare the port cost in four scenarios. In Scenario 1, 2, and 3, there is only a Type I, II, and III OXC at each node, respectively; in Scenario 4, we use the above network design framework to determine the type of OXC at each node, and all three types of OXCs can coexist in the network. In the experiment reported here, the ratio of α_1: α_2: α_3: α_4: α_5, is 5:1:1:3:3, which is based on the projected traffic distribution of a typical nation-wide WDM backbone network, and the per-port cost ratio β_1: β_2: β_3 is 1:3:4. Note that these ratios are just inputs to our network design procedure, and more-accurate data, when available, can be plugged into our model.

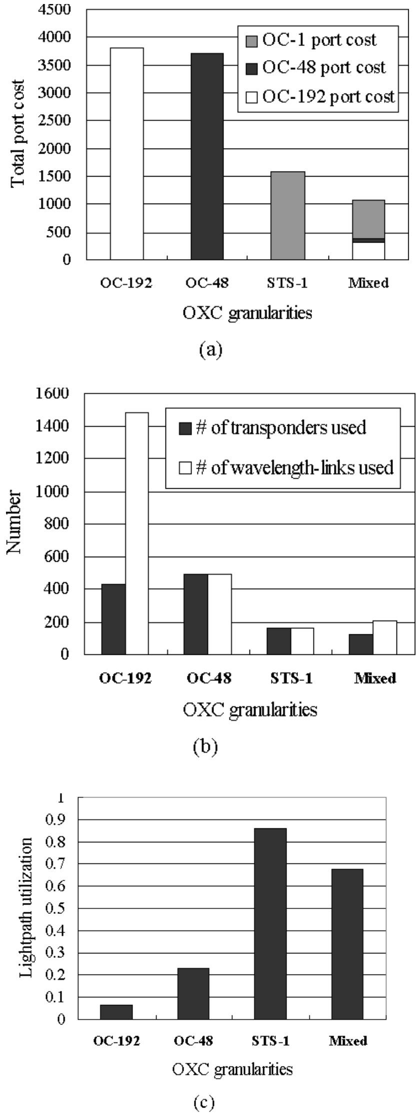

Figure 3. (a) Comparison of total port cost in the four scenarios. (b) Comparison of number of transponders and wavelength-links used in the four scenarios. (c) Comparison of the lightpath utilization in the four scenarios.

Figure 3(a) shows the total port cost, which is normalized by the per-port cost of all-optical OXCs, in the four scenarios, Fig. 3(b) shows the number of transponders used and wavelength-links used in the network, and Fig. 3(c) shows the lightpath utilization in the four scenarios. For the given traffic distribution and port cost ratio, the total port cost of the network in Scenario 1 is the highest, followed by the cost in Scenarios 2 and 3, and Scenario 4 achieves the lowest port cost. In Scenario 1, since the OXCs do not have grooming capability, the lightpath utilization is very low (6.5%) and 3822 OXC ports are used, resulting in highest total port cost despite the lowest per-port cost. In addition, this scenario uses the largest amount of wavelength-links to carry all the traffic. In Scenario 3, although the per-port cost of the type of OXCs used is the highest, the total port cost is less than that in Scenarios 1 and 2. This is because Type III OXCs can efficiently pack low-speed connections onto high-speed wavelength channels, making the lightpath utilization relatively high (86%). Hence, the total number of OXC ports (394), WDM transponders used (160), and wavelength-links used (160) are lower than those in Scenarios 1 and 2.

However, there is still room for improvement. For instance, not all of the nodes need such high flexibility in grooming fabric; some nodes may achieve similar performance with coarser grooming granularity or even no grooming capability, with the coordination of other nodes, thus further reducing the cost. This can be observed in Scenario 4. In this scenario, we choose an appropriate type of OXC for each node. Compared with Scenario 3, although more OXC ports may be used, the total port cost and the number of transponders used in the network are reduced about 33% and 23%, respectively, at the price of using more wavelength-links and lower lightpath utilization. This is because some Type III OXCs at some nodes are replaced with Type I and Type II OXCs, which have lower per-port cost than Type III, and Type I OXCs do not need transponders for bypassing traffic.

6. Conclusion

We proposed a framework for WDM backbone network design to better utilize the benefit of different type of OXCs, which have different bandwidth granularities. Our results demonstrate that using different type of OXCs will yield better network performance, and a design using our framework can reduce the network-wide OXC port cost.

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FR3 **11:00 AM**

Pre-Emptive Reprovisioning in Mesh Optical Networks

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Pre-emptive reprovisioning is a method to perform reprovisioning of a backup path in advance of a second failure, to reduce the time to recover service from seconds (reprovisioning) to milliseconds (restoration). We evaluate the tradeoff between benefits and operational complexity.

1. Introduction

In shared-mesh restoration [1,2,5], each working path has a diverse backup path. In one restoration architecture [1,2], backup routes are pre-computed, and shared protection channels on the backup path are pre-assigned at the time of path provisioning. Channels on the backup path may be shared between primary paths whose working paths are diverse. Upon a single failure event, the lightpaths whose primary paths are affected by the failure are restored on their backup paths. If restoration fails (because the shared-protection channels are either in a failed state or are already being used by another lightpath - which can happen in the case of a double failure), then re-provisioning of the backup path is attempted. If reprovisioning of the backup path is successful, then the newly reprovisioned backup path is used to carry traffic. If reprovisioning fails (due to lack of capacity), then the lightpath is not restorable. Reprovisioning is a time-consuming process since it is performed at a centralized management system, and lightpaths are sequentially reprovisioned to avoid contentions for capacity. Pre-emptive reprovisioning is a method to perform reprovisioning of a backup path in advance of a failure. The motivation for pre-emptive reprovisioning is to reduce the time it takes to restore service from several seconds or tens of seconds with reprovisioning to order of 10s to 100s of milliseconds with restoration. However, there is operational complexity in pre-emptive re-provisioning. In this paper, we evaluate the trade-off between the benefits of pre-emptive reprovisioning and the additional operational complexity.