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

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***Abstract*—We investigate the design of a WDM backbone network with optical cross-connects (OXCs) of different switching granularities to reduce the network-wide OXC port cost. We enhance our graph model proposed (Zhu *et al.*, 2003), and the extended graph model can represent different node architectures in which a node may have multiple OXCs with different switching granularities simultaneously. Based on this model, we propose a provisioning algorithm for a single connection and a framework for network design, which can intelligently determine the type of OXCs at each node according to the traffic so that the benefit of different types of OXCs can be utilized. Numerical examples are presented showing that granularity-heterogeneous networks are more cost-effective than granularity-homogeneous networks.**

***Index Terms*—Bandwidth granularity, cost-effective, graph model, mesh network, network design, optical cross-connect (OXC), optical network, wavelength-division multiplexing (WDM), traffic grooming.**

I. Introduction

As wavelength-division multiplexing (WDM) technology advances, the capacity of a wavelength channel continues to increase (from OC-48 to OC-192 to OC-768 and possibly beyond). However, the bandwidth requirement of a typical connection request (referred to as a traffic demand) is versatile (e.g., STS-1, OC-3, OC-12, OC-48, and OC-192), and usually a small fraction of the bandwidth of a WDM channel. To efficiently use the bandwidth, grooming switches have been developed which can pack/unpack low-speed connections onto/from high-speed WDM channels and switch at subwavelength 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 independently, 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, say OC-192). 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, which perform O/E and E/O conversion. Meanwhile, all-optical OXCs do not need transponders for OXC ports, which is a significant savings in optical transport networks, but at the price of no grooming capability and wasting channel capacities due to under-utilized wavelength channels. 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, especially if the OXCs are interoperable, which seems to be a major goal of current standards activities, e.g., those of the optical internetworking forum (OIF). 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 exploit the benefits of all types of OXCs to accommodate the traffic—which is typically nonuniform across all node pairs—while reducing the network capital expenditures.

The optical network design problem has been studied quite extensively [2]. In virtual-topology design, given the physical toplogy and node architecture, the task is to determine the routing and wavelength assignment (RWA) of lightpaths [3], as well as the route of subwavelength granularity traffic flows, to achieve some objectives, such as minimizing traffic delay [4], minimizing the network congestion [5], [6], and satisfying some survivable porperty [7]. On the other hand, the authors in [8] consider the design of physical topologies to support virtual ring topology in a survivable manner. Traffic grooming is an important and practical problem for designing WDM networks and it is receiving increasing research attention both in ring networks [9]–[11] and mesh networks [12]–[15]. Some research has focused on design of groomable network. In [16], the authors consider different node architectures and design synchronous optical network (SONET)/WDM ring networks, which can groom low-speed connections onto high-speed lightpaths to reduce the total system cost. In [17], the authors compare the network cost when using different node architectures, but they assume all the grooming nodes to have the same STS-1 grooming capability. In our present paper, we focus on the design of a WDM mesh 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. To the best of our knowledge, this is the first research report which considers the design of a network using OXCs with different switching granularities.

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The paper is organized as follows. Section II presents the problem formulation and the challenges faced when designing a granularity-heterogeneous network. In Section III, we construct the auxiliary graph for the network with different node architectures. Based on the auxiliary graph, a traffic-provisioning algorithm is proposed in Section IV, which is employed by the framework for network design. Section V demonstrates an example of a network design using the framework. Section VI concludes the paper.

II. Problem Statement and Challenges

A. Problem Formulation

The network design problem addressed here can be formulated as follows.

- 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;
  - —the port cost of each type of OXC.
- We need to determine:
  - —the type of OXC at each node;
  - —the route for each traffic request.
- Objective:
  - —minimize the total OXC port cost of the network while accommodating all the traffic demands.

A traffic demand is represented by the notation $T(s,d,g,m)$, 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. Without loss of generality, we assume the finest granularity of the bandwidth of a traffic demand is STS-1 for the rest of the paper.

Note that another version of the problem formulation can be specified, where each node in the network can have more than one type of OXC. Certainly, this is a more general case. However, only one OXC at each node is more practical today due to ease of maintenance and cost; hence, we proceed with this version in the rest of this study while noting that our approach can easily be adapted to the general node architecture with multiple types of OXCs.

B. Challenges in Designing a Granularity-Heterogeneous Network

When designing a network with OXCs of different bandwidth granularities, the first question we need to answer is: How to choose an OXC for each node? When determining which type of OXCs should be used at a node, there are several factors we need to consider: traffic originating from or terminating at this node, bypassing traffic, and the types of OXCs at other nodes. For instance, if most of the traffic from and to this node and bypassing traffic are of granularity of lightpaths, it is reasonable to put an OXC with no grooming capability at this node. Hence, the route of the traffic should be considered when determining the node architecture. On the other hand, the route of the traffic demand also depends on the type of OXCs at each node. If the type of OXC at a node is changed, some traffic in the network may need to or have to change the route to adapt to the change. Therefore, the type of OXCs at each node and the route of traffic interplay with each other, causing the network-design problem to be a difficult one.

We also need to ensure that the designed network can fully accommodate the traffic demands, and furthermore, we need to determine how to route the traffic in the network. However, even in a granularity-heterogeneous network, in which the type of OXCs at each node is already known, routing a connection request and representing the network state are still significantly complex problems, compared with those in a network where only OXCs with STS-1 grooming granularity or OXCs with no grooming capability exist.

Consider a network where some nodes have STS-1 grooming capability, while the others have no grooming capability. Although this network is granularity-heterogeneous, the complexity of computing a route for a connection and representing the network state is similar to that in a network where only OXCs with STS-1 grooming granularity or OXCs with no grooming capability exist. Note that, in this special case, an OXC either has finest grooming granularity or no grooming capability. In general, however, the routing and representation problem is more complicated when there are OXCs with other granularities. In this paper, we address the general case unless stated otherwise.

In a network consisting of only nongrooming OXCs, the free capacity of a lightpath can only be used by the connections which have the same source and destination node as the lightpath. In an STS-1 grooming granularity network, if there is a lightpath between two nodes, only the timeslots[1] carrying traffic are switched to outgoing lightpaths or dropped at the end node, and all the other free timeslots are not switched, which means the free capacities on the lightpath can always be accessible by the end nodes of the lightpath. However, in a multigranularity 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.

Here, we give a small example. To carry a traffic demand $T_1(1,4,\mathrm{STS}{-}1,2)$, 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. (Note that the terms STS-1 and OC-1 are used interchangeably in the literature.) 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. Fig. 1 shows the switching state of the OXCs.

[1]Without loss of generality, the time domain is assumed here for traffic multiplexing within a wavelength channel.

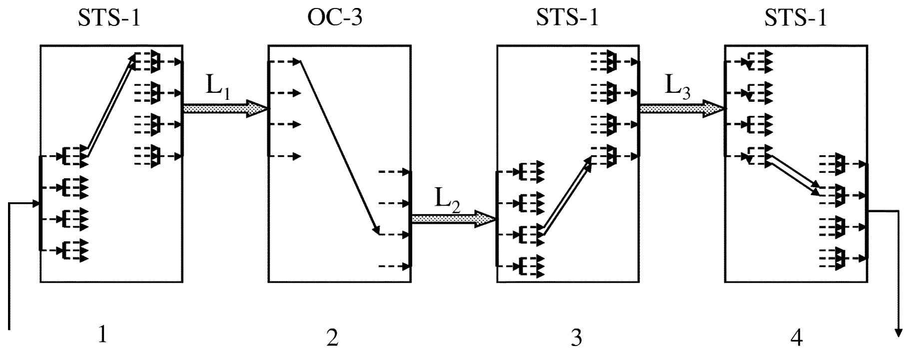

Fig. 1. State of the switches when routing traffic demand T_1 of bandwidth STS-1 from node 1 to node 4.

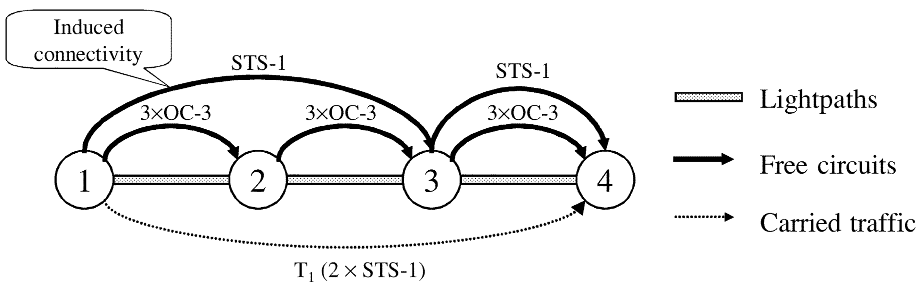

Fig. 2. Network state after routing T_1 traffic demand.

Since the capacity of a lightpath is OC-12, we can view a lightpath as a communication channel with 12 timeslots (TS_1 to TS_{12}). Node 1 puts traffic T_1 into the first two timeslots, TS_1 and TS_2, of lightpath L_1. Since the switching granularity of node 2 is OC-3, it can only unpack lightpath L_1 into four segments (each of capacity OC-3), with three timeslots in each segment, and node 2 can switch these segments as individual entities. In order to route traffic T_1 onto lightpath L_2, node 2 switches the first segment in lightpath L_1 to a segment, say the third segment, in lightpath L_2. Now the traffic, if any, in timeslots $\mathrm{TS}_1, \mathrm{TS}_2$, and TS_3 of lightpath L_1 will be in timeslots $\mathrm{TS}_7, \mathrm{TS}_8$, and TS_9 of lightpath L_2, respectively. Note that, although the order of the timeslots where the traffic is put may change when the traffic is switched at node 2, the order of the timeslots within a segment cannot be changed because a segment is treated as an integral entity. At node 3, lightpath L_2 is terminated and unpacked into timeslot level since the switching granularity of node 3 is STS-1, i.e., at the timeslot level. Here, only the timeslots used by traffic T_1, i.e., timeslots TS_7 and TS_8, are switched onto lightpath L_3; timeslot TS_9 will not be switched at this instant, and it can be switched to any free timeslot in any outgoing lightpath or dropped at this node later for future traffic. Finally, traffic T_1 reaches node 4 via lightpath L_3 and is dropped at node 4.

Because the switching granularity of node 2 (OC-3) is coarser than the bandwidth granularity of the traffic demand (2× STS-1), there is a free STS-1 timeslot (timeslot TS_3 in L_1) switched onto L_2 (timeslot TS_9 in L_2) by the OXC at node 2. Although this timeslot goes through node 2, it cannot be accessed by node 2 due to the switching configuration for traffic T_1. Any traffic carried by this timeslot will bypass node 2 and directly reach node 3, where it can be switched to any free outgoing lightpath or be dropped at that node. This is equivalent to having an STS-1 circuit directly connecting node 1 and node 3, and this circuit is called an *induced connectivity*. If there is an STS-1 traffic demand from node 1 to node 3 later, it can be directly put into timeslot TS_3 in lightpath L_1 at node 1 and dropped from timeslot TS_9 in lightpath L_2 at node 3, without any change in switching configuration at node 2. Fig. 2 shows the network state (virtual connectivity) after routing T_1. These circuits form another topology above the virtual topology, in which each edge is a lightpath and traffic demands should be routed on this topology instead of on the virtual topology.

C. Our Approach

To accommodate the diverse characteristics of multigranularity networks, we enhance the graph model proposed in [1]. The original graph model can route a traffic demand according to the current network state and update the network state after carrying the traffic, but only for the network in which all the grooming OXCs have the same (STS-1) grooming capability. The graph model has been extended by us now so that it can be applied to a network with OXCs of different grooming granularities. The extended graph model can also represent the situation where several types of OXCs coexist at the same node and intelligently choose the appropriate type of OXC to carry the traffic demand. Based on this enhanced and versatile model, we investigate a framework for designing a granularity-heterogeneous network.

III. Construction of an Auxiliary Graph

In the graph model, we construct an auxiliary graph according to the network state, compute a route in the auxiliary graph for a given traffic request, set up the connection according to the route, and then update the auxiliary graph to reflect the changes in the network state. We first demonstrate how to construct the

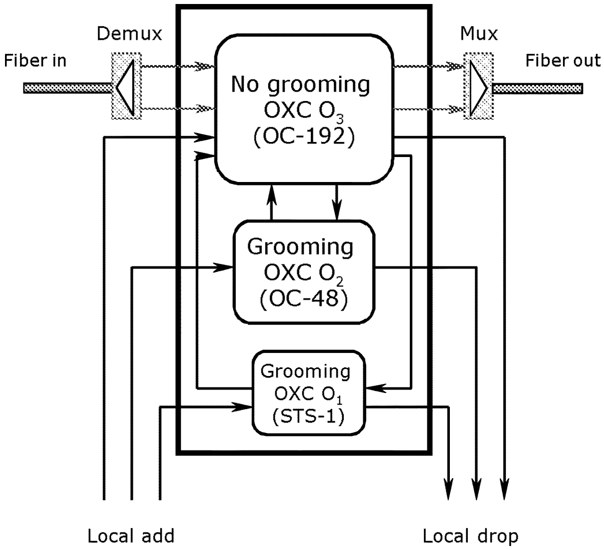

Fig. 3. Node with three different types of OXCs. (Each data path could be a multiline, i.e., there may be multiple fibers in and out of the OC-192 OXC, multiple add and drop ports for each OXC, etc.)

auxiliary model for a node according to the node architecture and then show how to build the auxiliary graph for the entire network.

A. Node Representation

The representation of a node in the graph model is determined by the node architecture. Different node architectures have different graph representations. With respect to node architecture, we focus on how OXCs with different switching granularity are interconnected, if there are multiple OXCs at the same node, and where the traffic requests can be originated and terminated.

Fig. 3 depicts an example of a generalized node architecture. In this node architecture, there are three OXCs: OXC O_1 with STS-1 grooming granularity, OXC O_2 with OC-48 grooming granularity, and OXC O_3 with no grooming capability, which can only switch at lightpath granularity, say OC-192 in this example. O_1 and O_2 are connected to O_3 which is directly connected to incoming and outgoing fibers. Local traffic can be added to or dropped from all three OXCs. Assume that there are two wavelengths in this network (λ_1 and λ_2). Also, for purpose of illustration, assume that this node can convert λ_1 to λ_2 without using grooming OXCs, but not *vice versa*. The corresponding auxiliary graph for this node architecture is constructed as in Fig. 4.

In general, the auxiliary graph for node i can be represented by $G_i(V_i, E_i)$, where V_i and E_i are its vertex set and edge set, respectively. In general, if there are W wavelengths on each link in the network, λ_1 through λ_W, and C possible grooming granularities at node i, F_1 through F_C, where F_1 is the finest grooming granularity and F_C is the coarsest grooming granularity, the auxiliary graph for node i is constructed as a layered graph with $(W + C + 3)$ layers. If the capacity of a lightpath is OC-192, the typical grooming granularities can be STS-1, OC-3, OC-12, and OC-48, as shown in Fig. 4.

- Layers 1 through W denote the W *wavelength layers*.
- Layer $(W + 1)$ is called the *transponder layer*.

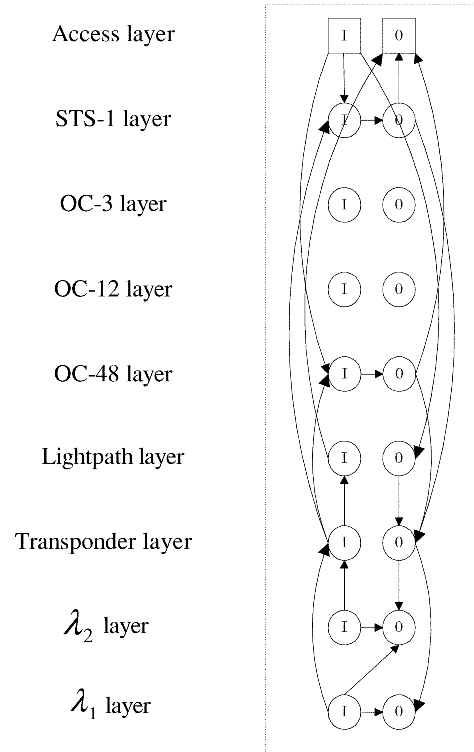

Fig. 4. Auxiliary graph for the node.

- Layer $(W + 2)$ is called the *lightpath layer*.
- Layers $(W + 3)$ through $(W + C + 2)$ denote the C *grooming layers*, i.e., from F_C grooming layer to F_1 grooming layer.
- Layer $(W + C + 3)$ is called the *access layer*, where a traffic flow starts and terminates.

There are two ports on each layer, an input port and an output port, shown as a vertex marked with "I" and a vertex marked with "O," respectively, in Fig. 4. (The numbers 0 and 1 will be used to refer to the input port and the output port in the discussion below.) Let $N_i^{l,p}$ denote port p on layer l at node i, then $V_i = \{N_i^{l,p} \,|\, p \in \{0,1\}, 1 \leq l \leq (W + C + 3)\}$, where $N_i^{l,0}$ and $N_i^{l,1}$ denote the input port and the output port on layer l at node i, respectively. According to the node architecture, the edges in the auxiliary graph for node i are inserted as follows.

1) **Wavelength Bypass Edges (WBE).**

There is an edge from the input port to the output port on each wavelength layer at node i if node i can bypass traffic without using grooming switches

$$\left\langle N_i^{l,0}, N_i^{l,1} \right\rangle \in E_i, \quad 1 \leq l \leq W. \tag{1}$$

We call the edge $\langle N_i^{l,0}, N_i^{l,1} \rangle$ a *wavelength bypass edge* on layer l at node i and it is denoted as $\mathrm{WBE}(i, l)$. If a path[2] contains $\mathrm{WBE}(i, l)$, that means a lightpath newly set up to carry the connection will bypass node i on λ_l.

2) **Wavelength Converter Edges (WCE).**

There is an edge from the input port on wavelength layer l_1 to the output port on wavelength layer l_2 at node

[2]For conciseness, a path means the path computed for a connection in the auxiliary graph.

i if wavelength λ_{l_1} can be converted to wavelength λ_{l_2} without using a grooming OXC at node i

$$\left\langle N_i^{l_1,0}, N_i^{l_2,1} \right\rangle \in E, \quad \text{wavelength } \lambda_{l_1} \text{ is convertible to } \lambda_{l_2} \text{ at node } i. \quad (2)$$

We call the edge $\langle N_i^{l_1,0}, N_i^{l_2,1} \rangle$ a *wavelength converter edge* from layer l_1 to layer l_2 at node i and it is denoted as $\mathrm{WCE}(i, l_1, l_2)$. For example, there is a wavelength converter edge $\mathrm{WCE}(i, 1, 2)$ in Fig. 4, which is from the input port on λ_1 layer to the output port on λ_2 layer, because this node can convert λ_1 to λ_2. There is no wavelength converter edge $\mathrm{WCE}(i, 2, 1)$ in Fig. 4 since λ_2 cannot be converted to λ_1 at this node. If a path contains $\mathrm{WCE}(i, l_1, l_2)$, that means a lightpath newly set up to carry the connection will be converted from λ_{l_1} to λ_{l_2} at node i without using a grooming OXC.

3) **Grooming Fabric Edges (GFE).**

There is an edge from the input port to the output port on F_j grooming layer at node i if node i has grooming capability at F_j granularity

$$\left\langle N_i^{W+2+j,0}, N_i^{W+2+j,1} \right\rangle \in E_i, \quad 1 \le j \le C. \quad (3)$$

We call the edge $\langle N_i^{W+2+j,0}, N_i^{W+2+j,1} \rangle$ a F_j *grooming fabric edge* at node i and it is denoted as $\mathrm{GFE}(i, F_j)$. If a path contains $\mathrm{GFE}(i, F_j)$, that means the connection will be switched by an OXC with F_j granularity to an outgoing lightpath or the access station at node i.

4) **Wavelength Add Edges (WAE).**

There is an edge from the output port on the transponder layer to the output port on wavelength layer l at node i

$$\left\langle N_i^{W+1,1}, N_i^{l,1} \right\rangle \in E_i, \quad 1 \le l \le W. \quad (4)$$

We call the edge $\langle N_i^{W+1,1}, N_i^{l,1} \rangle$ a *wavelength add edge* at node i and it is denoted as $\mathrm{WAE}(i, l)$. If a path contains $\mathrm{WAE}(i, l)$, that means we need to set up a new lightpath at node i using λ_l to carry the connection.

5) **Wavelength Drop Edges (WDE).**

There is an edge from the input port on wavelength layer l to the input port on the transponder layer at node i

$$\left\langle N_i^{l,0}, N_i^{W+1,0} \right\rangle \in E_i \quad 1 \le l \le W. \quad (5)$$

We call the edge $\langle N_i^{l,0}, N_i^{W+1,0} \rangle$ a *wavelength drop edge* at node i and it is denoted as $\mathrm{WDE}(i, l)$. If a path contains $\mathrm{WDE}(i, l)$, that means a lightpath newly set up to carry the connection will be terminated from λ_l at node i.

6) **Grooming-Transponder Edges (GTE).**

There is an edge from the output port on the F_j grooming layer to the output port on the transponder layer at node i if node i has an OXC with an available port which can perform grooming at F_j granularity and is connected to the transponders directly or via an OXC without grooming capability

$$\left\langle N_i^{W+2+j,1}, N_i^{W+1,1} \right\rangle \in E_i, \quad 1 \le j \le C. \quad (6)$$

We call the edge $\langle N_i^{W+2+j,1}, N_i^{W+1,1} \rangle$ a *grooming-transponder edge* at node i and it is denoted as $\mathrm{GTE}(i, F_j)$. If a path contains $\mathrm{GTE}(i, F_j)$, that means we need to set up a new lightpath originating from an OXC with F_j granularity at node i to carry the connection.

7) **Transponder-Grooming Edges (TGE).**

There is an edge from the input port on the transponder layer to the input port on the F_j grooming layer at node i if node i has an OXC with an available port which can perform grooming at F_j granularity and is connected to the transponders directly or via an OXC without grooming capability

$$\left\langle N_i^{W+1,0}, N_i^{W+2+j,0} \right\rangle \in E_i, \quad 1 \le j \le C. \quad (7)$$

We call the edge $\langle N_i^{W+1,0}, N_i^{W+2+j,0} \rangle$ a *transponder-grooming edge* at node i and it is denoted as $\mathrm{TGE}(i, F_j)$. If a path contains $\mathrm{TGE}(i, F_j)$, that means a lightpath newly set up to carry the connection will be terminated by an OXC with F_j granularity at node i.

8) **Lightpath-Transponder Edges (LTE).**

There is an edge from the output port on the lightpath layer to the output port on the transponder layer at node i

$$\left\langle N_i^{W+2,1}, N_i^{W+1,1} \right\rangle \in E_i. \quad (8)$$

We call the edge $\langle N_i^{W+2,1}, N_i^{W+1,1} \rangle$ a *lightpath-transponder edge* at node i and it is denoted as $\mathrm{LTE}(i)$. If a path contains $\mathrm{LTE}(i, F_j)$, that means we need to set up a new lightpath originating from a nongrooming OXC at node i to carry the connection. This lightpath can only be used to carry the traffic starting from node i.

9) **Transponder-Lightpath Edges (TLE).**

There is an edge from the input port on the transponder layer to the input port on the lightpath layer at node i

$$\left\langle N_i^{W+1,0}, N_i^{W+2,0} \right\rangle \in E_i. \quad (9)$$

We call the edge $\langle N_i^{W+1,0}, N_i^{W+2,0} \rangle$ a *transponder-lightpath edge* at node i and it is denoted as $\mathrm{TLE}(i)$. If a path contains $\mathrm{TLE}(i, F_j)$, that means a lightpath newly set up to carry the connection will be terminated by a nongrooming OXC at node i. This lightpath can only be used to carry the traffic terminating at node i.

10) **Grooming Add Edges (GAE).**

There is an edge from the input port on the access layer to the input port on the F_j grooming layer at node i if node i can add traffic into an OXC with F_j granularity grooming capability using an unused OXC port

$$\left\langle N_i^{W+C+3,0}, N_i^{W+2+j,0} \right\rangle \in E_i, \quad 1 \le j \le C. \quad (10)$$

We call the edge $\langle N_i^{W+C+3,0}, N_i^{W+2+j,0}\rangle$ a *grooming add edge* at node i and it is denoted as $\mathrm{GAE}(i, F_j)$. If a path contains $\mathrm{GAE}(i, F_j)$, that means the connection will be added to the network at its source node i using an unused port of an OXC with F_j granularity.

11) **Grooming Drop Edges (GDE).**

There is an edge from the output port on the F_j grooming layer to the output port on the access layer at node i if node i can drop traffic from an OXC with F_j granularity grooming capability using an unused OXC port

$$\left\langle N_i^{W+2+j,1}, N_i^{W+C+3,1}\right\rangle \in E_i, \quad 1 \le j \le C. \tag{11}$$

We call the edge $\langle N_i^{W+2+j,1}, N_i^{W+C+3,1}\rangle$ a *grooming drop edge* at node i and it is denoted as $\mathrm{GDE}(i, F_j)$. If a path contains $\mathrm{GDE}(i, F_j)$, that means the connection will be dropped from the network at its destination node i using an unused port of an OXC with F_j granularity.

12) **Lightpath Add Edges (LAE).**

There is an edge from the input port on the access layer to the output port on the lightpath layer at node i if node i can add traffic into an OXC with no grooming capability using an unused OXC port

$$\left\langle N_i^{W+C+3,0}, N_i^{W+2,1}\right\rangle \in E_i. \tag{12}$$

We call the edge $\langle N_i^{W+C+3,0}, N_i^{W+2,1}\rangle$ a *lightpath add edge* at node i and it is denoted as $\mathrm{LAE}(i)$. If a path contains $\mathrm{LAE}(i)$, that means the connection will be added to the network at its source node i using an unused port of a nongrooming OXC.

13) **Lightpath Drop Edges (LDE).**

There is an edge from the input port on the lightpath layer to the output port on the access layer at node i if node i can drop traffic from an OXC with no grooming capability using an unused OXC port

$$\left\langle N_i^{W+2,0}, N_i^{W+C+3,1}\right\rangle \in E_i. \tag{13}$$

We call the edge $\langle N_i^{W+2,0}, N_i^{W+C+3,1}\rangle$ a *lightpath drop edge* at node i and it is denoted as $\mathrm{LDE}(i)$. If a path contains $\mathrm{LDE}(i)$, that means the connection will be dropped from the network at its destination node i using an unused port of a nongrooming OXC.

14) **Grooming Cascade Edges (GCE).**

There is an edge from the output port on the F_j grooming layer to the input port on the F_k grooming layer at node i if traffic can flow from an unused OXC output port with F_j granularity grooming capability to an unused OXC input port with F_k granularity grooming capability at node i and granularities F_j and F_k are different

$$\left\langle N_i^{W+2+j,1}, N_i^{W+2+k,0}\right\rangle \in E_i, \quad 1 \le j,k \le C, j \ne k. \tag{14}$$

We call the edge $\langle N_i^{W+2+j,1}, N_i^{W+2+k,0}\rangle$ a *grooming cascade edge* at node i and it is denoted as $\mathrm{GCE}(i, F_j, F_k)$. If a path contains $\mathrm{GCE}(i, F_j, F_k)$, that means the connection will be groomed by an OXC with F_k granularity after having been groomed by an OXC with F_j granularity.

Each edge has a property tuple $\mathrm{PT}(c, w)$ associated with it, where c denotes the capacity of this edge and w denotes its weight. The capacity of each edge in the auxiliary graph G_i is assigned ∞. We will discuss weight assignment in Section IV-C.

B. Circuits and Induced Topology in Granularity-Heterogeneous Network

As we know, a lightpath may traverse one or more wavelength links, and a collection of lightpaths may form a virtual topology in a wavelength-routed network. Traffic requests are carried by these lightpaths. A traffic demand can traverse multiple lightpaths before it reaches its destination node. At intermediate nodes, grooming OXCs are used to switch the traffic from an incoming lightpath to an outgoing lightpath. If the grooming granularity of the OXC is coarser than the bandwidth granularity of the traffic request, some free timeslots in the incoming lightpath may also be switched together with those timeslots taken by the traffic to the outgoing lightpath, causing these free timeslots to bypass this node and become inaccessible to the node. Some or all of these free timeslots, possibly along with other free timeslots, may be further switched to the next lightpath by the next intermediate node, until they are not switched any longer or reach the destination. We refer to these switched free timeslots by the term *circuit*. In addition, the free timeslots not switched at the OXCs are also called circuits and these circuits traverse only one lightpath. Therefore, an unused lightpath can also be viewed as a circuit. One of the most important properties of a circuit is that traffic will come out at the end of a circuit *if and only if* it is put into the timeslots at the starting point of the circuit. A circuit can go through multiple lightpaths and a lightpath can be traversed by multiple circuits. Hence, circuits form another topology, which we call *induced topology*, above the virtual topology. The relationship between circuits and lightpaths is analogous to that between lightpaths and fiber links.

In granularity-heterogeneous network, a traffic demand cannot be routed according to the virtual topology since lightpath connectivity may not provide accurate information for routing the traffic. For instance, if there are some free timeslots in the lightpath from node 1 to node 2 and there is a traffic request from node 1 to node 2 asking for one timeslot, this lightpath may not be able to deliver the traffic from node 1 to node 2 since the situation may exist where all these free timeslots are switched further to another node 3 and traffic in these timeslots cannot be dropped at node 2. However, circuits provide exact information on whether or not traffic from one node can reach another node. Therefore, traffic demands should be routed on the induced topology instead of on the virtual topology. The relationship between induced topology and virtual topology is analogous to that between virtual topology and physical topology.

For a lightpath, both of its ends are OXCs, which may have different switching granularities. Since a circuit is a fraction of a lightpath or a concatenation of lightpaths in terms of bandwidth, it is also started from an OXC and terminated at another OXC, and the switching granularity of the starting OXC and the terminating OXC may be different. Meanwhile, a circuit itself has its own bandwidth granularity. Therefore, a circuit can be represented by the notation $\mathrm{CT}(s, g_s, t, g_t, g_c, m)$, where s and t are starting and terminating nodes of the circuit, respectively; g_s and g_t are the switching granularities of the starting OXC and terminating OXC, respectively; g_c is the bandwidth granularity of the circuit; and m is the amount of bandwidth of the circuit in unit of g_c. Moreover, we extend the concept of circuits by regarding also as circuits the connections between OXCs and their access stations, such as SONET add–drop multiplexer, ATM switches, and IP routers, and between different grooming OXCs inside a node. So, the end of a circuit can be either an OXC or an access station, and the granularity of the client can be various and is assumed as the finest granularity, STS-1, in the following development below. One key observation is that the switching granularity of the starting OXC g_s and that of the terminating OXC g_t are both no coarser than the bandwidth granularity of the circuit g_c and the switching granularities of all intermediate nodes traversed by the circuit are all coarser than g_c.

After carrying a traffic request, a circuit may be decomposed into one or more smaller circuits if the bandwidth requirement of the traffic is less than the bandwidth of the circuit. For example, a circuit $\mathrm{CT}(i, \mathrm{OC}{-}3, j, \mathrm{STS}{-}1, \mathrm{OC}{-}48, 3)$ will be decomposed into $\mathrm{CT}_1(i, \mathrm{OC}{-}3, j, \mathrm{STS}{-}1, \mathrm{OC}{-}48, 2)$, $\mathrm{CT}_2(i, \mathrm{OC}{-}3, j, \mathrm{STS}{-}1, \mathrm{OC}{-}12, 3)$, and $\mathrm{CT}_3(i, \mathrm{OC}{-}3, j, \mathrm{STS}{-}1, \mathrm{OC}{-}3, 1)$ after accommodating a traffic request $T(i, j, \mathrm{OC}{-}3, 3)$. This means that circuits are more dynamic than lightpaths, and they outnumber lightpaths in the network; hence, more intelligence is required to keep track of circuits than lightpaths.

C. Auxiliary Graph for the Network

Based on the auxiliary graph of each node, we can construct the auxiliary graph for the entire network.

In general, the physical topology of the network can be represented by a graph $G'(V', E')$, where V' and E' are its node set and link set, respectively. Assuming that each link has W wavelengths, λ_1 through λ_W, and there are C possible grooming granularities at nodes in the network, F_1 through F_C, where F_1 is the finest grooming granularity and F_C is the coarsest grooming granularity, we construct the corresponding auxiliary graph $G(V, E)$ for the network G' as follows, where V and E are the vertex set and edge set of graph G, respectively.

The auxiliary graph G is a layered graph with $(W + C + 3)$ layers. First, we construct an auxiliary graph $G_i(V_i, E_i)$ for each node i in the network G' according to the node representation method described above. These nodal auxiliary graphs are components of the network auxiliary graph $G(V, E)$. The vertex set V is the union of the vertex set of the auxiliary graph for each node i in the network G', i.e.,

$$V = \bigcup V_i, \quad \forall i \in V' = \left\{ N_i^{l,p} \,\middle|\, p \in \{0,1\}, 1 \le l \le W+C+3, \forall i \in V' \right\}. \quad (16)$$

All the edges in the auxiliary graph of each node i in the network G' are in the edge set E, so

$$E_i \subset E, \quad \forall i \in V'. \quad (17)$$

Then, we insert some additional edges according to the network state, as outlined below.

- **Wavelength-Link Edges (WLE).**
  There is an edge from the output port on wavelength layer l at node i to the input port on wavelength layer l at node j if there is a physical link from node i to node j and wavelength λ_l on this link is not used

$$\left\langle N_i^{l,1}, N_j^{l,0} \right\rangle \in E, \quad (i,j) \in E'; \ \text{wavelength } \lambda_l \text{ on link } (i,j) \text{ is not used.} \quad (18)$$

  We call the edge $\langle N_i^{l,1}, N_j^{l,0} \rangle$ a *wavelength-link edge* on layer l from node i to node j and it is denoted as $\mathrm{WLE}(i, j, l)$. The capacity of this edge is the capacity of the corresponding wavelength on the link from node i to node j. If a path contains $\mathrm{WLE}(i, j, l)$, that means a lightpath traversing link from node i to node j on wavelength λ_l needs to be set up to carry the connection.
- **Circuit Edges (CE).**
  Based on the positions of the ends of the corresponding circuits, circuit edges can be classified as internode circuit edges and intranode circuit edges.
  - **Internode Circuit Edges.**
    There is an edge from the output port on the F_{k_1} grooming layer or input port on the access layer at node i to the input port on the F_{k_2} grooming layer or output port on the access layer at node j if there is a circuit from an OXC with k_1 grooming granularity or a client at node i to an OXC with k_2 grooming granularity or a client at node j

$$\begin{aligned}&\left\langle N_i^{W+2+k_1,1}, N_j^{W+2+k_2,0} \right\rangle \in E\\&\left\langle N_i^{W+C+3,0}, N_j^{W+2+k_2,0} \right\rangle \in E\\&\left\langle N_i^{W+2+k_1,1}, N_j^{W+C+3,1} \right\rangle \in E\\&\left\langle N_i^{W+C+3,0}, N_j^{W+C+3,1} \right\rangle \in E, \quad 1 \le k_1, k_2 \le C\\&\exists \text{ a corresponding circuit from node } i \text{ to node } j\\&\text{in the network.}\end{aligned} \quad (19)$$

  - **Intranode Circuit Edges.**
    The intranode circuit edges can be parallel with any of the following edges: grooming add edges, grooming drop edges, and grooming cascade edges. We call those edges *grooming-port-associated edges*. The difference between these edges and intranode circuit edges is that these edges exist when there are unused OXC ports in the node, while intranode circuit edges denote the circuits inside a node, which are *induced* by using the OXC port to carry traffic requests.

  Circuit edges are denoted as $\mathrm{CE}(i, l_i, j, l_j, g_c, m)$, where i and j are nodes in the network, which can be the same; and l_i and l_j are the starting layer and ending layer of the circuit edge in the auxiliary graph, respectively, which can be from $(W+3)$ to $(W+C+3)$; g_c is the bandwidth granularity of the corresponding circuit; and m is the amount of bandwidth of the corresponding circuit in unit of g_c. The capacity of a circuit edge is the bandwidth of the corresponding circuit. If a path contains $\mathrm{CE}(i, l_i, j, l_j, g_c, m)$, that means the connection will be carried by using the corresponding circuit from node i to node j (if $i \neq j$), or will be added from or dropped to the access station or flow between different types of OXCs within a node (if $i = j$) by sharing a used OXC port with existing traffic.

Although we assume the numbers of wavelengths are the same on all fiber links in the network, it is straightforward to construct the auxiliary graph for the network, where different links may have different number of wavelengths.

Note that granularity-homogeneous network is a special case of granularity-heterogeneous network. The method for constructing the auxiliary graph described above can also be applied to granularity-homogeneous network.

From the construction of the auxiliary graph, it should be clear that the auxiliary graph reflects induced topology and the current state of the network.

IV. Framework for Network Design Based on the Auxiliary Graph

A. Algorithm for Routing a Connection Request

To carry a traffic request in a network, several questions need to be answered.

1) Should a new lightpath or lightpaths be set up to accommodate the traffic? Sometimes, it may be better to add a new lightpath or lightpaths even though the connection can be carried on the current virtual topology.
2) How to add the new lightpath(s)? In some cases, we can set up a lightpath directly from the source of the traffic to the destination. In other cases, it is not necessary or possible to set up this lightpath and we may need to set up one or more other lightpaths.
3) How to route the traffic on the virtual topology? As we mentioned before, the virtual topology is not able to provide sufficient information about the connectivity between nodes in granularity-heterogeneous network, and the induced topology should be used to route the traffic.

Based on the auxiliary graph, we propose the algorithm for routing a connection request (ARC) in a given network, which could be granularity-heterogeneous.

The ARC algorithm needs initialization before being used. The initialization takes as a parameter the network configuration, which includes the network topology, as well as the node and the link configurations; and according to the network configuration, it constructs the corresponding auxiliary graph G using the method discussed in Section III.

The ARC algorithm takes a traffic demand as the input and works as follows.

Algorithm ARC: Input: a traffic demand $T(s, d, g, m)$.

Step 1) Delete the edges whose capacity is less than the bandwidth granularity of T, since they cannot accommodate T.

Step 2) Find the shortest path p from the input port on the access layer of the source to the output port on the access layer of the destination of T on graph G. If not successful, restore the edges previously deleted in Step 1 and return -1.

Step 3) If p contains wavelength-link edges, one or more lightpaths going through the corresponding wavelength links needs to be set up. A lightpath starts whenever p travels through a wavelength add edge, follows the subsequent wavelength-link edges, and terminates at the first wavelength drop edge. Note that a lightpath is also a circuit. If p contains grooming-port-associated edges, the corresponding intranode circuits need to be set up.

Step 4) Route T along the preexisting circuits in p and/or circuits set up according to p. If the capacity of the path, which is defined as the minimum capacity of the circuits along the path, is less than the entire amount of T, route the maximum amount possible, say n units, of the traffic granularity g.

Step 5) Restore the edges previously deleted in Step 1.

Step 6) Update graph G as follows.

- For each circuit newly set up, a corresponding circuit edge is added.
- The wavelength-link edges denoting the wavelength-links used by the lightpath are removed from the corresponding wavelength layers.
- Starting from the origin of p, for each circuit used by T, remove the corresponding circuit edge. If the circuit is decomposed into one or more circuits, which have different bandwidth granularities, add the corresponding circuit edges into the auxiliary graph. Each of these circuits starts from the same OXC as the original circuits, possibly extends to the following circuits along p and terminates at the first OXC along p, that has a switching granularity not coarser than the bandwidth granularity of this circuit or at the destination of the traffic.
- For each node along p, check all the edges in the auxiliary graph of that node. Remove the edges whose existence conditions are not valid any longer. For instance, all the wavelength converter edges (WCE) in a node auxiliary graph should be removed if there is no wavelength converter available at this node; If there is no free port with a grooming granularity available at a node any more, all the grooming add/drop edge (GAE and GDE), grooming-transponder edge (GTE), transponder-grooming edge (TGE), and grooming cascade edge (GCE) connected to the layer representing that grooming granularity will be removed from the auxiliary graph of that node.

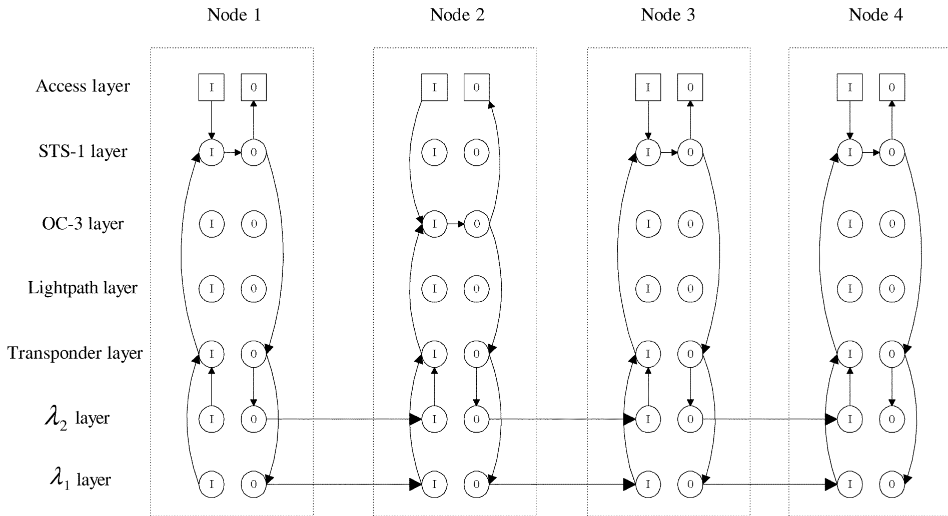

Fig. 5. Initial auxiliary graph.

Step 7) If the entire traffic is accommodated, return 0. Otherwise, return $m - n$, which is the amount of the uncarried traffic in units of g.

1) Complexity Analysis: The complexity of the ARC algorithm is determined by the running time of shortest-path computation in Step 2. Suppose there are N nodes in the network; each node has C OXCs with different grooming granularities; each OXC has P ports; and each link has W wavelengths. In the corresponding auxiliary graph, there are $2N(W+C+3)$ vertices. As there may be multiple parallel circuit edges between two vertices, we need to count the number of edges explicitly. Within the auxiliary graph of a node, the number of WCEs is $O(W^2)$; the number of GCEs is $O(C^2)$. Hence, the total number of edges in the auxiliary graph of a node except intranode circuit edges is $O(W^2+C^2)$. The number of WLEs in the auxiliary graph of the whole network is $O(WN^2)$. Since each node has $P \cdot C$ OXC ports, it can set up $O(PC)$ lightpaths. Each lightpath can be decomposed into C circuits, then the number of circuit edges in the auxiliary graph of the whole network is $O(NPC^2)$. Therefore, the total number of edges in the auxiliary graph of the whole network is $O(W^2+C^2+WN^2+NPC^2)$. Since the running time of shortest-path computation using Dijkstra algorithm is $O(V^2+E)$, where V and E are the number of the vertices and edges in the graph, respectively, the running time of the ARC algorithm is $O(N^2(W+C)^2+W^2+C^2+WN^2+NPC^2)$, i.e., $O(N^2(W+C)^2+NPC^2)$. Usually, the auxiliary graph is not dense, so the first part $O(N^2(W+C)^2)$ is dominant. If each node in the network has full wavelength-conversion capability, for instance only OEO switches are used, all the wavelength layers can be collapsed into one super wavelength layer since all the wavelengths are equivalent. In this special case, the running time of the ARC algorithm is $O(N^2C^2+NPC^2)$.

B. An Illustrative Example

To illustrate how the auxiliary graph and the ARC algorithm work, we use the same example mentioned in Section II. In the example network, there is one link between node 1 and node 2, node 2 and node 3, node 3 and node 4. Note that there may be other nodes and links in the network also, but for purpose of simplicity, we only focus on these four nodes in this example. Suppose the switching granularities of nodes 1, 2, 3, and 4 are STS-1, OC-3, STS-1, and STS-1, respectively. Each link has two wavelengths (λ_1 and λ_2), and the capacity of a wavelength channel is OC-12 for this illustration. Initially, there is no lightpath in the network and the auxiliary graph of this part of the network is shown in Fig. 5.

When a traffic demand $T_1(1,4,\mathrm{STS}{-}1,2)$ arrives, we need to find in the auxiliary graph a path from the input port on the access layer at node 1 to the output port on the access layer at node 4, shown as shaded ports in Fig. 6. It is easy to see that there exists a path p along the edges $\mathrm{GAE}(1,\mathrm{STS}{-}1)$, $\mathrm{GFE}(1,\mathrm{STS}{-}1), \mathrm{GTE}(1,\mathrm{STS}{-}1)$, $\mathrm{WAE}(1,1), \mathrm{WLE}(1,2,1)$, $\mathrm{WDE}(2,1)$, $\mathrm{TGE}(2,\mathrm{OC}{-}3)$, $\mathrm{GFE}(2,\mathrm{OC}{-}3)$, $\mathrm{GTE}(2,\mathrm{OC}{-}3)$, $\mathrm{WAE}(2,1)$, $\mathrm{WLE}(2,3,1)$, $\mathrm{WDE}(3,1)$, $\mathrm{TGE}(3,\mathrm{STS}{-}1)$, $\mathrm{GFE}(3,\mathrm{STS}{-}1)$, $\mathrm{GTE}(3,\mathrm{STS}{-}1)$, $\mathrm{WAE}(3,1)$, $\mathrm{WLE}(3,4,1)$, $\mathrm{WDE}(4,1)$, $\mathrm{TGE}(4,\mathrm{STS}{-}1)$, $\mathrm{GFE}(4,\mathrm{STS}{-}1)$, and $\mathrm{GDE}(4,\mathrm{STS}{-}1)$, shown as bold lines in Fig. 6. Since this path contains wavelength-link edge $\mathrm{WLE}(1,2,1), \mathrm{WLE}(2,3,1)$, and $\mathrm{WLE}(3,4,1)$, which denote wavelength-links, we need to set up three lightpaths (circuits) $L_1 = \mathrm{CT}(1,\mathrm{STS}{-}1,2,\mathrm{OC}{-}3,\mathrm{OC}{-}12,1), L_2 = \mathrm{CT}(2,\mathrm{OC}{-}3,3,\mathrm{STS}{-}1,\mathrm{OC}{-}12,1)$, and $L_3 = \mathrm{CT}(3,\mathrm{STS}{-}1,4,\mathrm{STS}{-}1,\mathrm{OC}{-}12,1)$ using λ_1 on the fiber link from node 1 to node 2, from node 2 to node 3, and from node 3 to node 4, respectively. Since this path also contains grooming-port-associated edges $\mathrm{GAE}(1,\mathrm{STS}{-}1)$ and $\mathrm{GDE}(4,\mathrm{STS}{-}1)$, two intranode circuits $\mathrm{CT}_1 = \mathrm{CT}(1',\mathrm{STS}{-}1,1,\mathrm{STS}{-}1,\mathrm{OC}{-}12,1)$ and $\mathrm{CT}_2 = \mathrm{CT}(4,\mathrm{STS}{-}1,4',\mathrm{STS}{-}1,\mathrm{OC}{-}12,1)$ are also set up. Here, i' denotes the client at node i. Then, traffic demand T_1 is routed along these newly set up circuits. The capacity of the path (OC-12) is greater than the bandwidth requirement of $T_1\,(2 \cdot \mathrm{STS}{-}1)$, and T_1 is successfully accommodated. After routing T_1, the auxiliary graph needs to be updated. Five circuit edges, i.e., $\mathrm{CE}_1 = \mathrm{CE}(1,7,1,6,\mathrm{OC}{-}12,1), \mathrm{CE}_2 = \mathrm{CE}(1,6,2,5,\mathrm{OC}{-}12,1), \mathrm{CE}_3 = \mathrm{CE}(2,5,3,6,\mathrm{OC}{-}12,1), \mathrm{CE}_4 = \mathrm{CE}(3,6,4,6,\mathrm{OC}{-}12,1)$, and

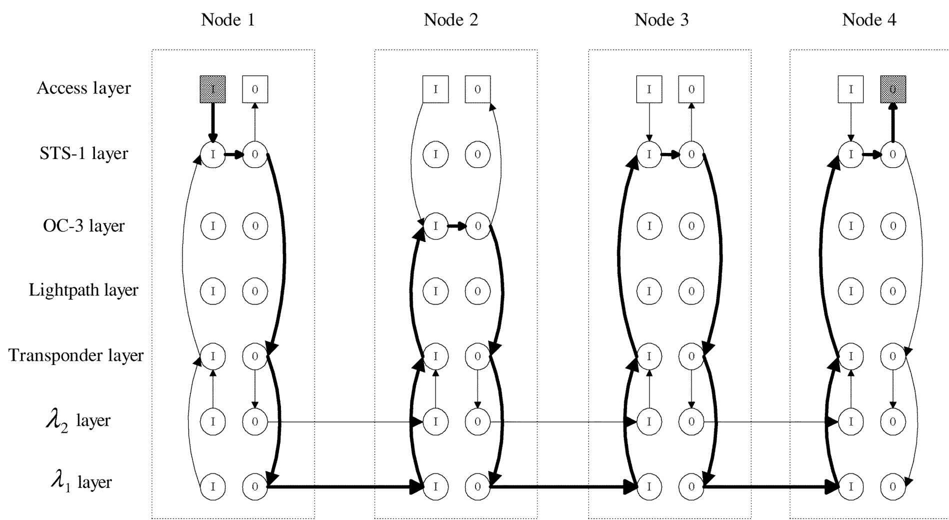

Fig. 6. Corresponding auxiliary graph before routing the first traffic request T_1.

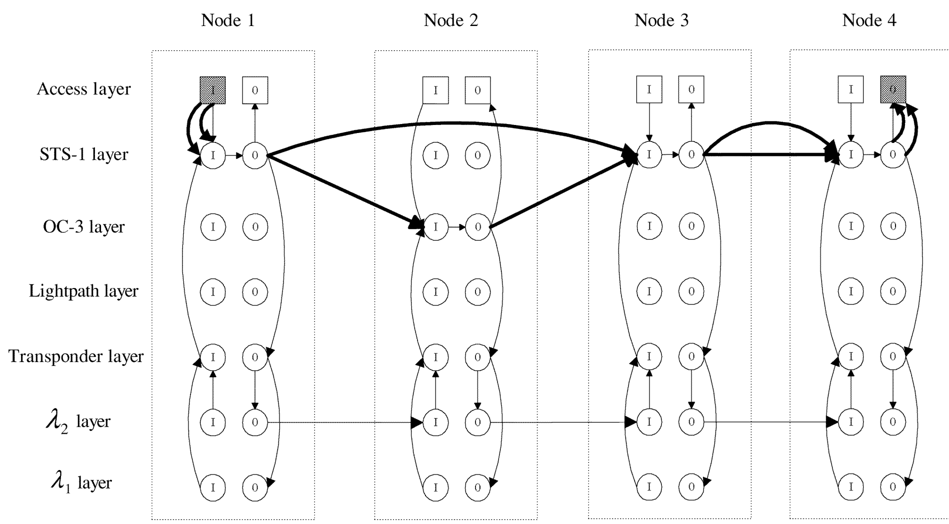

Fig. 7. Corresponding auxiliary graph after routing the first traffic request T_1.

$\mathrm{CE}_5 = \mathrm{CE}(4,6,4,7,\mathrm{OC}{-}12,1)$, are added into the auxiliary graph. Three wavelength-link edges, i.e., $\mathrm{WLE}(1,2,1)$, $\mathrm{WLE}(2,3,1)$, and $\mathrm{WLE}(3,4,1)$, are removed since they have been used and are not available no more. After routing T_1, circuit CT_1 is decomposed into two circuits: $\mathrm{CT}_3 = \mathrm{CT}(1',\mathrm{STS}{-}1,1,\mathrm{STS}{-}1,\mathrm{OC}{-}3,3)$ and $\mathrm{CT}_4 = \mathrm{CT}(1',\mathrm{STS}{-}1,1,\mathrm{STS}{-}1,\mathrm{STS}{-}1,1)$; circuit edge CE_1 is replaced by two circuit edges $\mathrm{CE}(1,7,1,6,\mathrm{OC}{-}3,3)$ and $\mathrm{CE}(1,7,1,6,\mathrm{STS}{-}1,1)$. After routing T_1, circuit L_1 is decomposed into two circuits: $\mathrm{CT}_5 = \mathrm{CT}(1,\mathrm{STS}{-}1,2,\mathrm{OC}{-}3,\mathrm{OC}{-}3,3)$ and $\mathrm{CT}_6 = \mathrm{CT}(1,\mathrm{STS}{-}1,2,\mathrm{OC}{-}3,\mathrm{STS}{-}1,1)$. As the granularity of the OXC at node 2 (OC-3) is coarser than that of $\mathrm{CT}_6, \mathrm{CT}_6$ traverses node 2 and extends further to circuit L_2 until it arrives at node 3, where the granularity of the OXC (STS-1) is not coarser than that of CT_6 (STS-1). Now, CT_6 becomes $\mathrm{CT}(1,\mathrm{STS}{-}1,3,\mathrm{STS}{-}1,\mathrm{STS}{-}1,1)$; and circuit edge CE_2 is replaced by two circuit edges $\mathrm{CE}(1,6,2,5,\mathrm{OC}{-}3,3)$ and $\mathrm{CE}(1,6,3,6,\mathrm{STS}{-}1,1)$. After routing T_1, circuit L_2 is decomposed into two circuits: $\mathrm{CT}_7 = \mathrm{CT}(2,\mathrm{OC}{-}3,3,\mathrm{STS}{-}1,\mathrm{OC}{-}3,3)$ and $\mathrm{CT}_8 = \mathrm{CT}(2,\mathrm{OC}{-}3,3,\mathrm{STS}{-}1,\mathrm{STS}{-}1,1)$. As CT_8 becomes a part of CT_6, circuit edge CE_3 is replaced by one circuit edge $\mathrm{CE}(2,5,3,6,\mathrm{OC}{-}3,3)$. Similarly, circuit edge CE_4 is replaced by two circuit edges $\mathrm{CE}(3,6,4,6,\mathrm{OC}{-}3,3)$ and $\mathrm{CE}(3,6,4,6,\mathrm{STS}{-}1,1)$; circuit edge CE_5 is replaced by two circuit edges $\mathrm{CE}(4,6,4,7,\mathrm{OC}{-}3,3)$ and $\mathrm{CE}(4,6,4,7,\mathrm{STS}{-}1,1)$. To carry traffic demand T_1, each of nodes 1, 2, 3, and 4 uses one unused input port and one unused output port. Fig. 7 shows the updated auxiliary graph after carrying traffic demand T_1, which represents the network state shown in Fig. 2.

Suppose another traffic demand $T_2(1,3,\mathrm{STS}{-}1,1)$ comes. There is a path in the auxiliary graph from the input port on the access layer at node 1 to the output port on the access layer at node 3, shown in Fig. 8: $\mathrm{CE}(1,7,1,6,\mathrm{STS}{-}1,1)$, $\mathrm{GFE}(1,\mathrm{STS}{-}1)$, $\mathrm{CE}(1,6,3,6,\mathrm{STS}{-}1,1), \mathrm{GFE}(1,\mathrm{STS}{-}1)$, and $\mathrm{GDE}(3,\mathrm{STS}{-}1)$. Since there is no wavelength-link edge in the path, we do not need to set up any new lightpath; an intranode circuit $\mathrm{CT}_9 = \mathrm{CT}(3,\mathrm{STS}{-}1,3',\mathrm{STS}{-}1,\mathrm{OC}{-}12,1)$ will be set up because the path contains a grooming-port-associated edge $\mathrm{GDE}(3,\mathrm{STS}{-}1)$. Hence, a new circuit edge $\mathrm{CE}_6 =$

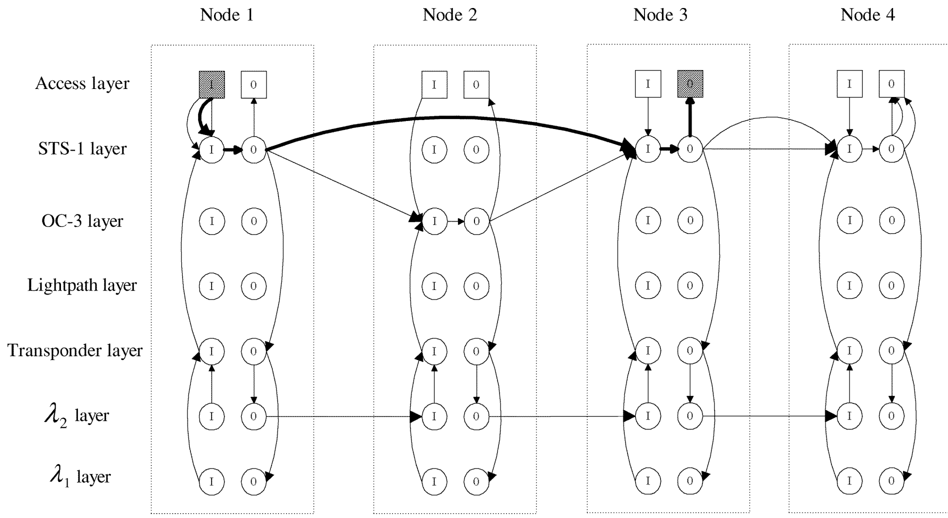

Fig. 8. Corresponding auxiliary graph before routing the second traffic request T_2.

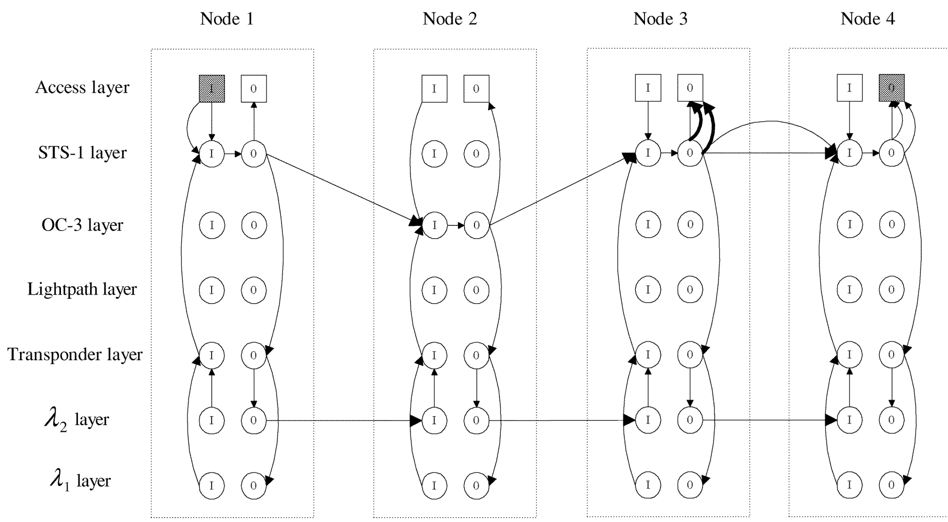

Fig. 9. Corresponding auxiliary graph after routing the second traffic request T_2.

$\mathrm{CE}(3,6,3,7,\mathrm{OC}{-}12,1)$ is added into the auxiliary graph. T_2 is carried by existing circuits $\mathrm{CT}_4 = \mathrm{CT}(1', \mathrm{STS}{-}1, 1, \mathrm{STS}{-}1, \mathrm{STS}{-}1, 1)$, $\mathrm{CT}_6 = \mathrm{CT}(1, \mathrm{STS}{-}1, 3, \mathrm{STS}{-}1, \mathrm{OC}{-}1, 1)$, and newly set up circuit $\mathrm{CT}_9 = \mathrm{CT}(3, \mathrm{STS}{-}1, 3', \mathrm{STS}{-}1, \mathrm{OC}{-}12, 1)$. After carrying T_2, CT_4 and CT_6 have no free bandwidth left and the corresponding circuit edges $\mathrm{CE}(1,7,1,6,\mathrm{STS}{-}1,1)$ and $\mathrm{CE}(1,6,3,6,\mathrm{STS}{-}1,1)$ are removed from the auxiliary graph; CT_9 is decomposed into two circuits: $\mathrm{CT}(3, \mathrm{STS}{-}1, 3', \mathrm{STS}{-}1, \mathrm{OC}{-}3, 3)$ and $\mathrm{CT}(3, \mathrm{STS}{-}1, 3', \mathrm{STS}{-}1, \mathrm{STS}{-}1, 2)$. Hence, circuit edge CE_6 is replaced by two circuit edges $\mathrm{CE}(3,6,3,7,\mathrm{OC}{-}3,3)$ and $\mathrm{CE}(3,6,3,7,\mathrm{STS}{-}1,2)$. To carry T_2, nodes 1 and 2 consume no new OXC port; T_2 shares OXC ports with existing traffic (T_1) at these two nodes. Node 3 uses one unused OXC output port to drop T_2 and does not consume new OXC input port. Fig. 9 shows the updated auxiliary graph after carrying the traffic demand T_1 and T_2.

C. Weight Assignment

Since the ARC algorithm applies the shortest-path algorithm to compute the route for a connection request, the route depends on the weight of each edge in the auxiliary graph. In order to choose a proper route for a connection, the weight function should be carefully designed. If we assign the weight to each edge according to the cost of the corresponding component, say the weights of GFE are proportional to the cost of the corresponding grooming fabric, the weight of a WCE is the cost of a converter, the weight of a WLE is proportional to the cost of the corresponding wavelength links, etc., the ARC algorithm will choose the most cost-effective operation to route a connection, under the current network state. After routing all the traffic using the graph model, we can determine the virtual topology and the induced topology, as well as the configuration of each node, such as the number of OXC ports needed at each node.

In this network design problem, for a given traffic request, how to choose the type of OXCs appropriately at each node along the route is a very important issue if there are multiple different types of OXCs at each node. A fixed weight function, which does not change the weights of the edges, cannot solve the problem. For example, if there is a connection request $T_1(i, j, \mathrm{OC}{-}48, 1)$ and there are three type of OXCs—OXCs with switching granularities STS-1, OC-48, and OC-192—available at an intermediate node along the path computed for the T_1, it may be more desirable to use the OXC with OC-48 grooming granularity. However, if the bandwidth requirement of T_1 is 2 × STS-1, the OXC with STS-1 grooming granularity may become the best choice. If the weights of the edges are fixed, the route for the connections will be the same. Therefore, in order to intelligently choose the type of OXCs, the weight of an edge may be different for different traffic requests, i.e., the weight function should be dynamic and traffic requests should be one of the parameter for determining the weight function.

If the port cost of each type of OXC is known, the cost of switching a single timeslot within each type of OXC can be calculated by dividing the port cost with port rate (in terms of the number of timeslots it can support.) To accommodate a connection, the number of timeslots required by the connection have to be switched at an OXC. The cost of switching these timeslots needs to be included in the total cost. Moreover, if the switching granularity of the OXC is coarser than that of the connection, some additional timeslots may also have to be switched. Although these timeslots are not taken by the connection and can be used to carry other connections, they lose some value because they can only carry the connections which go to the same output OXC port as the current connection since the switching fabric is already configured. To discourage this from happening, some penalty may apply in this situation.

Here is an illustrative example. Suppose the port costs of the OXCs with switching granularities STS-1, OC-48, and OC-192 are 5, 4, and 1, respectively, and the port rates are all OC-192. Then, the cost of switching a single timeslot is $5/192, 1/48$, and $1/192$. To carry a connection $T(i, j, \mathrm{OC}{-}48, 1)$, node i needs to determine to which OXC it should add the connection. By applying the method described above, we can get three cost values

$$\mathrm{Cost}_{\mathrm{STS-1}}(T) = 48 \times 5/192 = 1.25 \tag{20}$$

$$\mathrm{Cost}_{\mathrm{OC-48}}(T) = 48 \times 1/48 = 1 \tag{21}$$

$$\begin{aligned}\mathrm{Cost}_{\mathrm{OC-192}}(T) &= 48 \times 1/192 + \delta \cdot (192 - 48) \times 1/192 \\ &= 0.25 + 0.75\delta.\end{aligned} \tag{22}$$

When using STS-1 and OC-48 grooming OXCs, there is no penalty because no free timeslot is switched after carrying the connection. However, if an OXC with OC-192 switching granularity is used, 144 $(192-48)$ free timeslots are switched, causing some penalty. In (22), δ is the *penalty ratio*, which is defined as the ratio of penalty for wasting a timeslot to normal cost for a single timeslot. It is clear that OC-48 grooming OXC is the best choice for this connection. In order to make $\mathrm{Cost}_{\mathrm{OC-48}}$ the least, δ must be greater than 1. On the other hand, if penalty ratio δ is given, we can determine which OXC has the least cost for the connection.

In general, for a connection $T(s, d, g, m)$, the switching cost of T using an OXC O is

$$\mathrm{Cost}_O(T) = \frac{C_O \cdot g \cdot m}{R_O} + \frac{C_O \cdot \delta}{R_O}\left(\left\lceil \frac{g \cdot m}{g_O} \right\rceil \cdot g_O - g \cdot m\right) \tag{23}$$

where C_O is per-port cost of OXC O, R_O is the port rate of OXC O, and g_O is the switching granularity of OXC O. Note that the values of R_O, g_O, and g are in terms of the number of the smallest timeslots the network supports.

It is obvious that the switching cost not only depends on the port cost, but also depends on the bandwidth requirement of the connection, switching granularity of the OXC, and penalty ratio. If we assign the weights of wavelength bypass edges and grooming fabric edges using the corresponding switching cost mentioned above, the weights of these edges will dynamically change accordingly. If the penalty ratio is properly set, the ARC algorithm can intelligently choose a suitable OXC for connections.

When determining the weights of the edges in the auxiliary graph, we can also take into account load balancing. For example, if the load of a specific link is above some threshold, the weight for the wavelength-link edges representing the corresponding wavelength links can be increased to discourage connections from using them. Also, per-port cost can change for each individual OXC as the number of ports used varies. This reflects the facts that the per-port cost may be a function of the size of an OXC because different sizes of OXCs may employ different architectures.

D. Network Design Framework

The ARC algorithm computes a route for a give traffic demand, based on the auxiliary graph, which has the capability to represent the case where there are multiple different types of OXCs at a single node. By using the dynamic weight assignment for the edges in the auxiliary graph, the ARC algorithm can choose suitable OXCs along the route for a traffic demand. Based on the ARC algorithm, we propose the network design procedure as follows.

Step 1) Assume every node in the network has all types of OXCs.

Step 2) Compute a route for each traffic demand using the ARC algorithm, until all the traffic has been carried.

Step 3) Determine the type of OXC at each node.

- Count the number of used ports of each type of OXCs at each node. Let Q_i^j be the number of used ports of OXC with j switching granularity at node i.
- For each type of OXC at each node, calculate the number of OXC ports needed if all the traffic going through this node is carried only by this type of OXC. To calculate this number, we use *Port Conversion Ratio* $\mathrm{PCR}^{j\to k}$, which is defined as the number of ports of OXC with switching granularity k needed to replace one port of OXC with switching granularity j. For example, to replace one port of OXCs with OC-192 or OC-48 switching granularity, one port of STS-1 grooming OXC is enough as long as they operate at the same port rate. On the other hand, however, more than one OC-48 grooming port may be needed to replace one STS-1 grooming port since an OC-48 grooming port is not flexible

as an STS-1 grooming port and may not groom the traffic as an STS-1 grooming port does. We can estimate the value of Port Conversion Ratio $\mathrm{PCR}^{j\rightarrow k}$ as follows. Assuming there is only one type of OXCs (OXCs with switching granularity j or k) in the network, route all the traffic demands and count the number of the OXC ports needed in each case. The ratio of these numbers is a good estimation of Port Conversion Ratio. Port Conversion Ratio is a parameter to the design procedure and can be tuned to get better performance. Let $\bar{Q}_i^k$ be the calculated number of ports of OXC with swithing granularity k at node i, then

$$\bar{Q}_i^k = \sum_j Q_i^j \cdot \mathrm{PCR}^{j\rightarrow k} \tag{24}$$

- Suppose C_k is the per-port cost of OXC with swithing granularity k, then $\bar{Q}_i^k \cdot C_k$ is the port cost at node i using an OXC with swithing granularity k. We choose at node i the type of OXC with swithing granularity k such that $\bar{Q}_i^k \cdot C_k$ is the least among all the types of OXCs at node i.

Step 4) Reroute all the traffic demands in the determined network configuration and calculate the network-wide OXC port cost.

In Step 2, traffic demands are routed one by one. The order in which the requests are routed will affect the results. There are several traffic-request-selection schemes proposed in [1], which can be employed here. One of the schemes is maximum utilization first (MUF), which selects the connection with the highest utilization. Here, utilization is defined as the total amount of the request divided by the number of hops from the source to the destination on the physical topology. We choose MUF in Step 2 because it has been shown in [1] that MUF has good performance and scalability.

The running time of network design procedure is dominated by Step 2. Suppose there are D traffic demands, and the running time of the ARC algorithm is $O(A)$, then running time of design procedure is $O(D\log D + DA)$. Please see Section IV-A1 for the detailed information about the running time of the ARC algorithm.

Note that, in Step 2, for each traffic demand $T(s,d,g,m)$, we apply the ARC algorithm. Let x denote the value returned by the ARC algorithm. If $x > 0$, we need to compute another route for $T(s,d,g,x)$ to satisfy the bandwidth requirement. If $x = -1$, it means the traffic cannot be accommodated in the network. In this case, the operator may need to reconfigure the network to add more resources, and then restart the network design procedure.

V. Numerical Examples and Discussion

We conducted simulation experiments of the above design principles on a typical nation-wide backbone network. The topology is shown in Fig. 10. It has 26 nodes and 40 bidirectional links. Each link has 50 wavelengths and 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 five granularities is $\alpha_1 : \alpha_2 : \alpha_3 : \alpha_4 : \alpha_5$, respectively. The traffic is uniformly distributed between all the nodes. There are three types of OXCs, whose characteristics are shown in Table I; these OXC types are chosen for this study as representatives of the diverse characteristics in OXC technologies. The per-port cost ratio of Type I, Type II, and Type III OXCs is $\beta_1 : \beta_2 : \beta_3$.

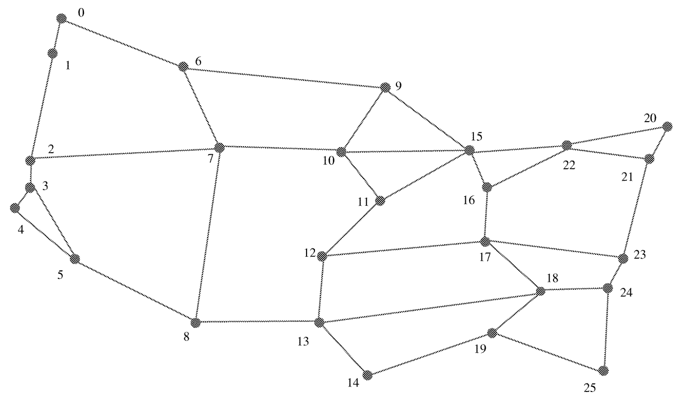

Fig. 10. The 26-node WDM backbone network.

We compare the port cost in four scenarios. In Scenario 1, there is only a Type I OXC at each node; in Scenario 2, only Type II OXCs are deployed in the network; and in Scenario 3, each node only has a Type III OXC. The networks in these three scenarios are granularity-homogeneous. In Scenario 4, each node can only employ one type of OXC, but different nodes may have different types of OXCs, and the network will be granularity-heterogeneous network. We use the network design framework described in Section IV-D to determine the type of OXC at each node, and all three types of OXCs can coexist in the network. In the experiments reported here, the ratio of $\alpha_1 : \alpha_2 : \alpha_3 : \alpha_4 : \alpha_5$ is $5 : 1 : 1 : 3 : 3$, which is based on the projected traffic distribution of a typical nationwide WDM backbone network, and the per-port cost ratio $\beta_1 : \beta_2 : \beta_3$ is $1 : 3 : 4$. Note that these ratios are sample inputs to our network design procedure, and more-accurate data, when available, can be plugged into our model. In addition, the weights of wavelength-link edges and circuit edges representing lightpaths are ten and one, respectively; the weight of the circuit edges representing the derived circuits is the summation of the weight of the circuits it derived from; the weight of grooming fabric edges and wavelength bypass edges dynamically change using the method described in Section IV-C; the penalty ratio (δ) is 10 and port conversion ratios $\mathrm{PCR}^{\mathrm{STS-1}\rightarrow\mathrm{OC-192}}$ and $\mathrm{PCR}^{\mathrm{STS-1}\rightarrow\mathrm{OC-48}}$ are 5.3 and 1.6,[3] respectively. Port conversion ratio $\mathrm{PCR}^{\mathrm{OC-48}\rightarrow\mathrm{OC-192}}$ can be derived as $5.3/1.6 = 3.3$. Note that port conversion ratios $\mathrm{PCR}^{\mathrm{OC-192}\rightarrow\mathrm{OC-48}}, \mathrm{PCR}^{\mathrm{OC-192}\rightarrow\mathrm{STS-1}}$, and $\mathrm{PCR}^{\mathrm{OC-48}\rightarrow\mathrm{STS-1}}$ are set to 1 because the port rates of different OXCs are the same and one OXC port with finer granularity can replace only one OXC port with coarser granularity.

[3]We experimented with other combinations of these parameters and found these choices of values to perform the best for this example.

TABLE I
COMPARISON OF THREE TYPES OF OXCs

OXC	Switching technology	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

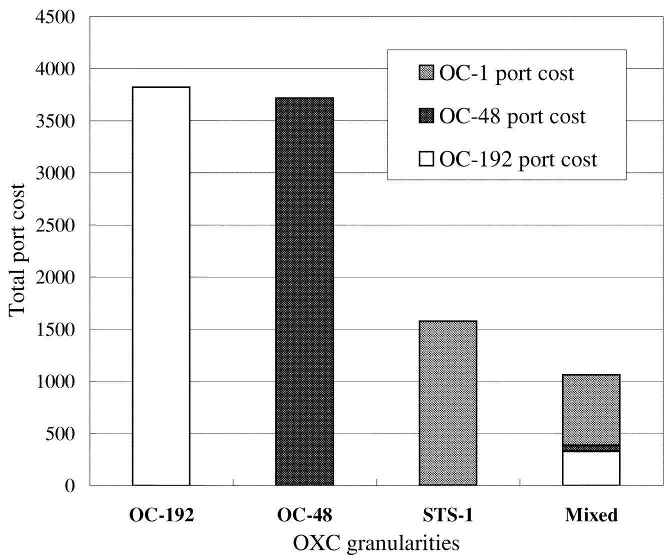

Fig. 11. Comparison of total port cost in the four scenarios.

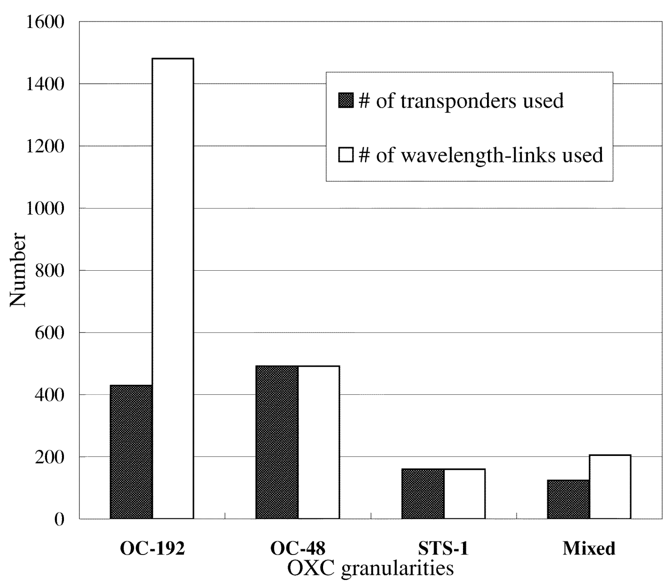

Fig. 12. Comparison of number of transponders and wavelength-links used in the four scenarios.

Fig. 11 shows the total port cost, which is normalized by the per-port cost of all-optical OXCs, in the four scenarios; Fig. 12 shows the number of transponders used and wavelength-links used in the network; and Fig. 13 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[4]), WDM transponders used (160), and wavelength-links used (160) are lower than those in Scenarios 1 and 2.

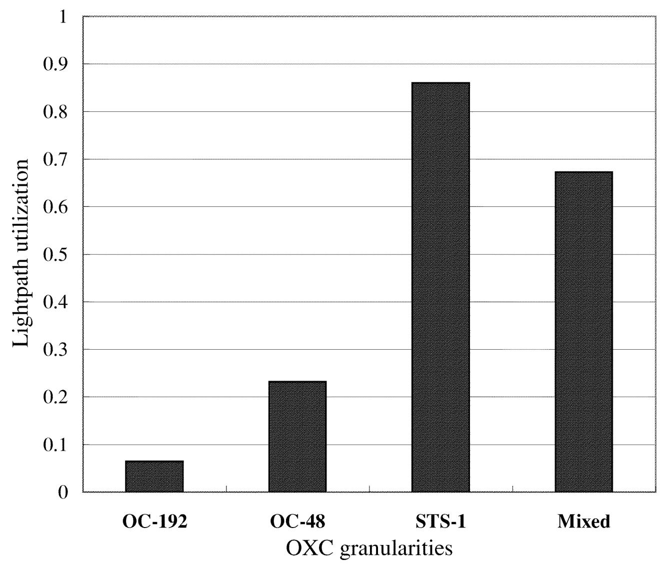

Fig. 13. Comparison of the lightpath utilization in the four scenarios.

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.

[4]Total port cost for Scenario 3 $(\mathrm{STS{-}1\ OXC}) = 1576$; per-port cost $(\beta_3) = 4$; so $\text{number of ports} = 1576/4 = 394$.

VI. Conclusion

We investigated the problem of designing a WDM backbone network which may consist of OXCs with different switching granularities. Our objective was to minimize the total network-wide OXC port cost. We found that, in a granularity-heterogeneous network, routing traffic on the virtual topology can result in additional connectivities between nodes, which form an induced topology above the virtual topology and which make traffic provisioning much more complex. To accommodate the characteristics of such a network, we enhanced our previous graph model to be able to represent different node architectures. Based on the extended graph model, we proposed a framework for WDM backbone network design to better utilize the benefits 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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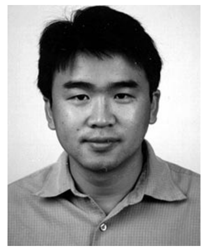

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