Design of Hierarchical Crossconnect WDM Networks Employing a Two-Stage Multiplexing Scheme of Waveband and Wavelength

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***Abstract*—The authors propose a design method for hierarchical crossconnect wavelength-division-multiplexed networks employing a two-stage multiplexing scheme of waveband and wavelength, in order to reduce the complexity and size of optical crossconnect at the nodes. The waveband is formed by grouping lightpaths with the same destination in a network. The authors present an integer linear programming formulation for the routing and grouping of lightpaths, and a heuristic design method is also proposed as a practical method to find a design solution for general large-scale networks. It is found that the proposed design method can largely reduce crossconnect requirements, although it slightly increases the wavelength requirements.**

***Index Terms*—Communication system planning, hierarchical systems, linear programming, networks, optical communications, wavelength-division multiplexing.**

I. Introduction

WAVELENGTH-DIVISION-MULTIPLEXED (WDM) networks using wavelength routing by optical crossconnects (OXCs) have emerged as the most feasible architectural solution for wide area backbone networks. In order to meet the very rapid increase in traffic demand due to the explosive growth of Internet and multimedia services, more numerous wavelengths are required in wavelength-routed optical networks. However, increases in the number of wavelength channels result in increased complexity of OXCs and increased difficulty in implementing and maintaining OXCs.

The concept of waveband has been recently introduced as a means to reduce OXC complexity. The waveband is formed by grouping several lightpaths and is routed as a single channel. Because the granularity of waveband is coarser than that of wavelength, its crossconnect requirements can be smaller than the case of using only wavelengths. Previously reported works are as follows: in [1], a two-stage optical crossconnect system was proposed and waveband crossconnection was demonstrated. The concept of waveband was introduced in WDM ring networks in [2] and [3]. Also the reduction of OXC complexity was investigated qualitatively in [4] and quantitatively in [5].

In this paper, we propose a design method for wavelength-routed networks employing a two-stage multiplexing scheme of waveband and wavelength. From now on, we refer to the networks using the two-stage multiplexing scheme as hierarchical crossconnect (HXC) networks and the networks using the single-stage multiplexing scheme as wavelength crossconnect (WXC) networks. Linear programming formulation for HXC network design is presented for waveband formation and routing. We also propose a heuristic design procedure as a practical method to design general large-scale networks. By applying the proposed design method to ARPA network, the benefits of the hierarchical multiplexing scheme are discussed with respect to the wavelength granularity.

II. Waveband Formation in HXC Networks

In WXC networks, an OXC consists of three major parts: demultiplexer, optical switch matrix, and multiplexer. OXC complexity can be characterized by the size of optical switch matrix. The lower bound on the maximum wavelength requirements to support all connection demands is $W_{\rm LB} = P\bar{D}\bar{H}/2LF = P\bar{D}\bar{H}/\bar{\Delta}NF$, where $P, \bar{D}, \bar{H}, L, F, N$, and $\bar{\Delta}$ are the number of logical connections, the average demand of a logical connection, the average number of hops, the number of links, the number of fibers, the number of nodes, and the average nodal degree ($\bar{\Delta} = 2L/N$), respectively [6]. Hence, the lower bound on the maximum size of the optical switch matrix is $S_{\rm LB} = W_{\rm LB}\bar{\Delta}F = P\bar{D}\bar{H}/N$. For the case of a fully connected logical topology, $S_{\rm LB}$ and the ratio R of incoming–outgoing traffic to add–drop traffic become $(N-1)\bar{D}\bar{H}$ and $\bar{H}$, respectively. Note that $S_{\rm LB}$ and R are proportional to the average number of hops. This implies that pass-through traffic dominates over add–drop traffic in large-scale networks. Since many lightpaths conveying path-through traffic might have the same route, the size of the optical switch matrix would be largely reduced if they were dealt with as a single channel.

Fig. 1 shows the node architecture for networks employing multistage multiplexing where the direct waveband drop ports in waveband crossconnect are added to the basic node architecture described in [1] and [3]. The switching units of FXC, WBXC, and WXC are fiber, waveband, and wavelength, respectively. Note that wavelength conversion is allowed only at the wavelength crossconnect because of the significant technical difficulty of waveband conversion.

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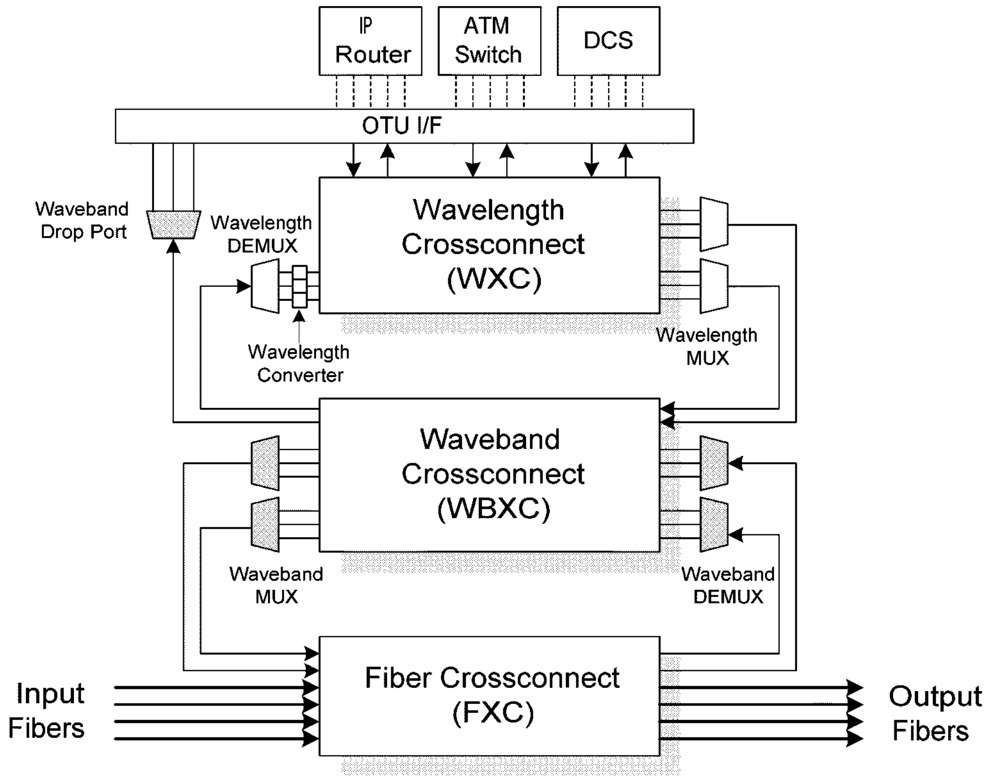

Fig. 1. Node architecture in optical networks employing multistage multiplexing.

Waveband formation scheme has an impact on overall crossconnect requirements. We consider the following three waveband formation schemes:

1) grouping lightpaths with the same source-destination pair;
2) grouping lightpaths with the same destination;
3) grouping lightpaths with common intermediate links.

The first scheme seems to be a natural choice but its efficiency can be reduced because the demand of each node is not always the same as the number of wavelength channels in a waveband. The third scheme can guarantee free routing of lightpaths. However, it causes an unexpected increase in the wavelength crossconnect size when we want to transfer the lightpaths in a waveband to another waveband. In the second scheme, once lightpaths with the same destination are grouped into a waveband, they do not need to be ungrouped until arrival at the destination node, expecting a substantial reduction in the wavelength crossconnect size. Consequently, we choose the second grouping scheme as the waveband formation scheme. In the following discussion, we refer to a waveband path consisting of only lightpaths with the same destination as a packed waveband path. The other waveband paths are referred to as unpacked waveband paths.

III. Problem Formulation of HXC Networks

In this section, we present the problem formulation for HXC networks in the form of integer linear programming, which is used to achieve an optimal design of HXC network. Fig. 2 defines the constants and variables at a node in HXC network.

Constants:

N number of nodes;
A number of arcs; one link consists of a pair of arcs with two opposite directions;
P number of logical connections;
F number of allowable fibers in a single link;
R_p set of candidate paths of logical connection p;
C_{limit} number of allowable channels in an arc;
D_p demand of logical connection p;
$\delta_{p,r,a}$ 1 if candidate path r of logical connection p passes through arc a; 0 otherwise;
W_B number of wavelength channels in a waveband, that is, wavelength granularity;
$\tau_{a,n}$ 1 if arc a terminates at node n, 0 otherwise;
$\sigma_{a,n}$ 1 if arc a starts at node n, 0 otherwise;
$\eta_{p,r,n,z}$ 1 if candidate path r of logical connection p passes through node n and terminates at node z; 0 otherwise;
A_n set of arcs terminating or starting at node n;
$\mu_{z,n}$ 1 if z equals to n; 0 otherwise;
E_n demand exiting node n;
I_n demand entering node n.

Variables:

S_n size of optical switch matrix at WXC of node n;
B_n size of optical switch matrix at WBXC of node n;
$C_{\max}$ maximum number of channels;
C_a number of channels in arc a;
F_a number of fibers in arc a.
$x_{p,r}$ capacity of candidate path r of logical connection p;

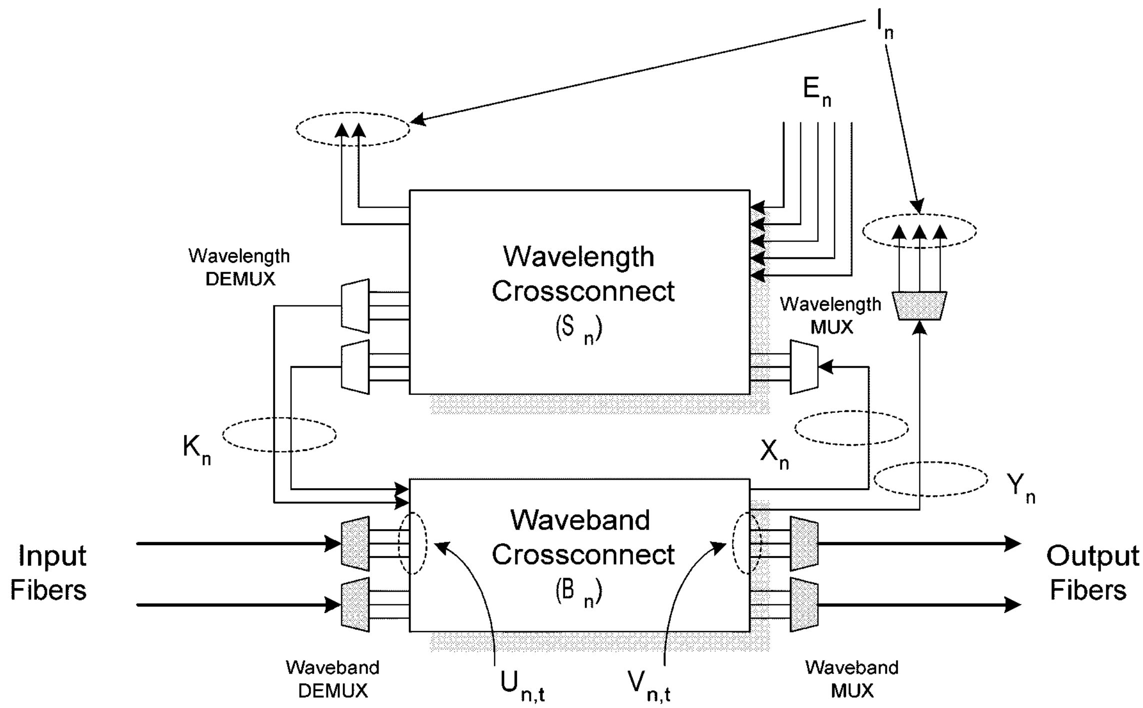

Fig. 2. Constants and variables at node n in HXC network.

- $U_{n,t}$ — number of waveband paths entering node n through arc t;
- $V_{n,t}$ — number of waveband paths exiting node n through arc t;
- $H_{n,t,z}$ — number of packed waveband paths passing through arc t of node n and terminating at node z;
- X_n — number of unpacked waveband paths entering WXC of node n;
- Y_n — number of packed waveband paths dropped at node n;
- K_n — Number of waveband paths exiting WXC of node n.

$$\text{Minimize} \sum_{n=1}^{N} S_n + \sum_{n=1}^{N} B_n + N \sum_{p=1}^{p} D_p \cdot C_{\max} \tag{1}$$

$$\text{Subject to} \sum_{r \in R_P} x_{p,r} = D_P \quad \forall p = 1, \dots, P \tag{2}$$

$$C_{\max} \geq C_a \quad \forall a = 1, \dots, A \tag{3}$$

$$C_a = \sum_{p=1}^{P} \sum_{r \in R_p} x_{p,r} \delta_{p,r,a} \quad \forall a = 1, \dots, A \tag{4}$$

$$C_{\text{limit}} F_a \geq C_a \quad \forall a = 1, \dots, A \tag{5}$$

$$F_a + F_{a+1} \leq F \quad \forall a = 1, 3, \dots, A-1 \tag{6}$$

$$W_B U_{n,t} \geq \sum_{a=1}^{A} \tau_{a,n} C_a \quad \forall n = 1, \dots, N, \quad \forall t \in A_n \tag{7}$$

$$W_B V_{n,t} \geq \sum_{a=1}^{A} \sigma_{a,n} C_a \quad \forall n = 1, \dots, N, \quad \forall t \in A_n \tag{8}$$

$$W_B H_{n,t,z} \leq \sum_{p=1}^{P} \sum_{r \in R_p} x_{p,r} \delta_{p,r,t} \eta_{p,r,n,z} \quad \forall n = 1, \dots, N, \quad \forall z = 1, \dots, N, \quad \forall t \in A_n \tag{9}$$

$$X_n = \sum_{t \in A_n} U_{n,t} - \sum_{z=1}^{N} \sum_{t \in A_n} H_{n,t,z} \quad \forall n = 1, \dots, N \tag{10}$$

$$Y_n = \sum_{z=1}^{N} \left(\mu_{z,n} \sum_{t \in A_n} H_{n,t,z} \right) \quad \forall n = 1, \dots, N \tag{11}$$

$$S_n = \sum_{a=1}^{A} \tau_{a,n} C_a - W_B \sum_{z=1}^{N} \sum_{t \in A_n} H_{n,t,z} + E_n \quad \forall n = 1, \dots, N \tag{12}$$

$$W_B K_n \geq S_n - I_n + W_B Y_n \quad \forall n = 1, \dots, N \tag{13}$$

$$B_n \geq \sum_{t \in A_n} U_{n,t} + K_n \quad \forall n = 1, \dots, N \tag{14}$$

$$B_n \geq \sum_{t \in A_n} V_{n,t} + X_n + Y_n \quad \forall n = 1, \dots, N. \tag{15}$$

The objective (1) is to minimize the size of optical switch matrixes at WXC and WBXC under the minimum link loading. Constraint (2) shows that the sum of the capacity of candidate paths for a logical connection should be equal to the demand of the logical connection. The number of channels on each arc and the maximum number of channels are acquired by constraints (3) and (4), respectively, in which the number of channels in an arc should be equal to the sum of the capacity of candidate paths on that arc. The number of fibers on each arc is acquired by constraint (5). Constraint (6) limits the number of allowable fibers in a link. Constraints (7)/(8) shows that the number of incoming/outgoing waveband paths to/from node should be greater than the number of incoming–outgoing channels divided by wavelength granularity. Constraint (9) determines the number of packed waveband paths entering each link attached to a node. Constraint (10) shows that the number of waveband paths from WBXC to WXC should be equal to the number of unpacked waveband paths entering that node. Constraint (11) determines the number of packed waveband paths dropped at that node. Constraint (12) determines the size of the optical switch matrix at WXC, which should be equal to the number of channels in unpacked waveband paths plus the number of channels added from that node. Constraint (13) shows the number of waveband paths exiting WXC should be greater than the number of channels exiting WXC divided by wavelength granularity. Constraints (14) and (15) show that the size of the optical switch matrix at WBXC should be greater than the number of waveband paths entering WBXC or the number of waveband paths leaving WBXC, respectively.

The number of variables and constraints in the formulation are $N_v = 1 + N(5 + 2\bar{\Delta}) + 4L + P\bar{R} + N^2\bar{\Delta}$ and $N_c = P + 7L + N(6 + 2\bar{\Delta}) + N^2\bar{\Delta}$, respectively, where $\bar{R}$ is the average number of candidate paths of a logical connection.

IV. Heuristic Design of HXC Networks

Due the complexity and huge size of the design problem presented in Section III, it is very difficult to obtain an exact design solution for large-scale networks. To cope with the difficulties, we exploit a heuristic design method, which is to maximize the reduction gain of crossconnect size with the minimum number of wavelengths. The heuristic design method explained below consists of three stages: routing, lightpath grouping, and wavelength assignment.

A. Routing

To maximize the number of packed waveband paths, it is clear that the lightpaths with the same destination should have the same route. Therefore, we make all lightpaths in the network satisfy the optimality principle. That is, if node x is on the optimal path from node y to node z, then the optimal path from node x to node z follows the same route on that part from y to z. As an optimal path, we use minimum hop path because the size of the optical switch matrix is proportional to the number of hops of a path as described in Section II. Based on the optimality principle, we can construct auxiliary graphs for each destination node. However, several auxiliary graphs may be found for one destination node because multiple minimum hop paths may exist. In order to choose an auxiliary graph leading to the small wavelength requirement, we use least loaded routing. This procedure is summarized as follows: find the minimum hop paths for each lightpath demand, list all lightpath demands in descending order of the minimum hop path length, and decide the route of each lightpath demand on the list. If a lightpath demand has several minimum hop paths, select a path with the least link loading on the route.

B. Lightpath Grouping

After selecting the route of each lightpath, we determine which waveband each lightpath would be grouped into. To achieve a large reduction gain of crossconnect size, it is clear that the lightpaths with many common links should be grouped into a waveband. We use the following simple lightpath grouping rules.

1) Classify each lightpath into classes according to the destination node, and list all lightpaths in each class in descending order of the number of hops.
2) Select a lightpath on the top of the list in a class and find $W_B - 1$ lightpaths which have the most common links to form a group. Then assign a waveband number to the lightpaths in the group and remove them from the list. Reapply this procedure to the remaining lightpaths in the class.
3) Repeat Step 2) for the other classes.

Once the wavebands and the routes for all the lightpaths are determined, we can straightforwardly calculate the size of optical switch matrixes in WXC and WBXC.

C. Wavelength Assignment

Each lightpath in packed waveband paths should have a wavelength for all links of its route because the wavelength conversion is not allowed in WBXC. It has been reported that, for the WXC networks with and without wavelength converters, the wavelength requirements are almost the same for static traffic demands [7]. However, that statement is valid only when a lightpath can be assigned any available wavelength, avoiding wavelength conflict problems. In the HXC networks concerned, the wavelength selection of lightpaths in packed wavebands is not free because the wavelengths should be contiguous, which results in more wavelength requirements in HXC networks. Wavelength assignment for lightpaths in an unpacked waveband path is trivial because the wavelength conversion is allowed in WXC. Therefore, we should first assign wavelengths to lightpaths in packed waveband paths and then to lightpaths in unpacked waveband paths. We use the following new wavelength assignment rule for the lightpaths in packed waveband paths.

1) Sum the number of hops of lightpaths in each packed waveband path, and list all packed waveband paths in descending order from the sum of the number of hops.
2) For each packed waveband path on the list, set w as the lowest wavelength given in the network. Lightpaths in this packed waveband path may have one of the wavelengths from w to $w + W_B - 1$. Then solve the following binary linear programming:

$$\text{Maximize} \sum_{p=1}^{W_B} \sum_{k=w}^{W_B+k} \alpha_{p,k}\beta_{p,k} \tag{16}$$

$$\text{Subject to} \sum_{k=w}^{W_B+w} \alpha_{p,k}\beta_{p,k} \le 1 \quad \forall p = 1, \ldots, W_B \tag{17}$$

$$\sum_{p=1}^{W_B} \alpha_{p,k}\beta_{p,k} \le 1 \quad \forall k = w, \ldots, W_B + w \tag{18}$$

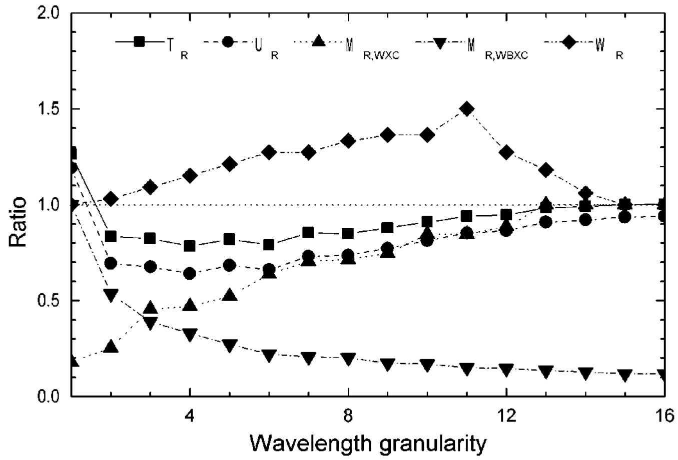

Fig. 3. Ratios with respect to wavelength granularity for uniform demand pattern of $D = 2$.

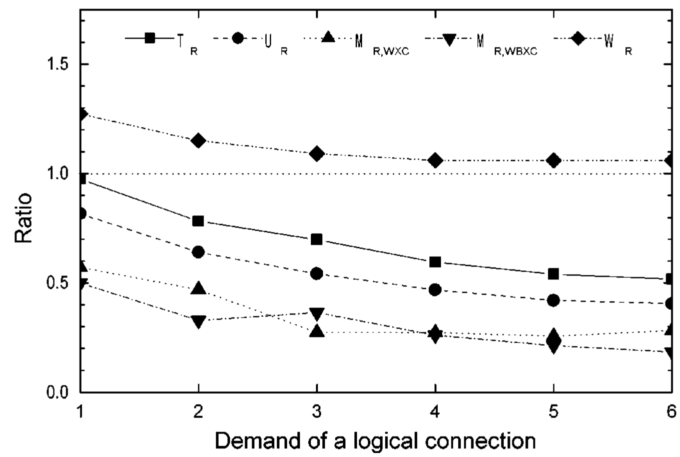

Fig. 4. Ratios acquired at optimal wavelength granularity values with respect to the demand of a logical connection under uniform demand pattern.

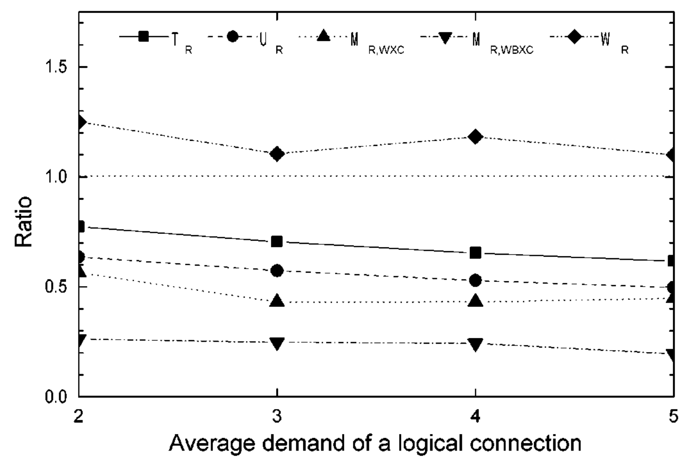

Fig. 5. Ratios acquired at optimal wavelength granularity values with respect to the average demand of a logical connection under random demand pattern.

where $\beta_{p,k}$ is a binary variable that becomes 1 when pth lightpath in a packed waveband path is assigned wavelength k, and $\alpha_{p,k}$ is a binary constant that becomes 1 when wavelength k is available for pth lightpath in a packed waveband path. The value of the objective function is equal to W_B if every lightpath in a packed waveband path is successfully assigned a wavelength. If not, increase w by W_B and solve again the above binary linear programming until the objective value is equal to W_B.

3) Repeat Step 2) until the lightpaths in all packed waveband paths are assigned wavelengths.

The above problem formulation is quite tractable because the numbers of constraints and the number of variables are $2W_B$ and W_B^2, respectively, and independent of network size.

V. Numerical Results

In order to compare HXC networks with WXC networks, the following four ratios of HXC networks to WXC networks are defined.

T_R Ratio of the sum of crossconnect sizes in all nodes. The crossconnect size corresponds to the number of ports of an optical switch matrix in a crossconnect.

U_R Ratio of the number of unit switches in all nodes provided that an optical switch matrix consists of 2×2 unit switches.

M_R Ratio of the maximum crossconnect size in the network.

W_R Ratio of the maximum number of wavelengths in the network.

The number of unit switches for an optical switch matrix of size S is $(S/2)\log_2 S$. It is noted that there are two M_Rs in HXC networks; $M_{R,\text{WBXC}}$ and $M_{R,\text{WXC}}$ are the ratios of the maximum WBXC size and the maximum WXC size in HXC network to the maximum WXC size in WXC network, respectively.

The ARPA network with $N = 20$ and $L = 30$ in [7] was chosen as a test network. Fig. 3 shows the previously defined ratios with respect to the various wavelength granularity values. For the uniform demand pattern of $D = 2$, we can achieve a maximum reduction gain of 22% for T_R and an even larger reduction gain of 36% for U_R at $W_B = 4$. Therefore, it can be concluded that an optimal wavelength granularity value leading to a maximum reduction gain may exist. Such an optimal wavelength granularity value, however, may depend on network topology, traffic demand, and traffic pattern. Nonetheless, the reduction of crossconnect requirements can still be expected with nonoptimal wavelength granularity values. Another advantage is that the maximum size of WXC and WBXC in an HXC network is less than half of the maximum size of WXC in a usual WXC network. On the contrary, the wavelength requirement is increased by 15% at the optimal wavelength granularity value.

Fig. 4 shows the predefined ratios with respect to the various uniform demands of logical connection. The curves in Fig. 4 were acquired at the optimal wavelength granularity values for each uniform demand. It is found that for the higher demand of logical connection, the larger reduction of the crossconnect requirement can be obtained. Also, the ratio of the wavelength requirement decreases as the demand of logical connection increases. The effects of random demand are also investigated in Fig. 5. It was assumed that the demand of a logical connection is one at its minimum and six at its maximum for convenience without loss of generality. Compared with Fig. 4, the reduction gain of crossconnect requirements is slightly reduced because the efficiency of packed waveband formation is decreased.

VI. Conclusion

This paper proposed an integer linear programming formulation for HXC networks which employs a two-stage multiplexing scheme of waveband and wavelength and a heuristic design method. It was demonstrated that the introduction of waveband leads to a very large reduction in crossconnect requirements for large-scale networks and high demand of logical connection. We found that an optimal wavelength granularity value leading to the minimum crossconnect requirements exists in the proposed method, but the exact value depends on network topology, traffic demand and traffic pattern. Nonetheless, a large reduction of crossconnect requirements can still be expected even at nonoptimal wavelength granularity values. Its wavelength requirement increases, whereas that increase tends to be insignificant as the demand of logical connection increases.

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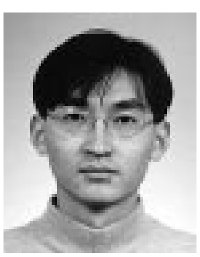

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