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A Bandwidth Relocatable Lightwave Backbone Network

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Abstract

An all-optical point-to-point lightwave backbone network architecture based on wavelength cross connects is studied. We first consider the problem of finding the set of links and their capacities for setting up the proposed network for a given sets of switching nodes and traffic requirements at minimum cost. A general cost function covering the cost of fibre link installation, switching systems, transmitter and receiver modules are adopted. We call it the Network Dimensioning Problem (NDP). The NDP is formulated as a multi-commodity flows problem using integer programming.

We then consider how to allocate the wavelength channels to form wavelength paths for all source and destination node pairs of the backbone network such that the average blocking probabilities in the network is minimum for a given fibre link distribution matrix and a given traffic matrix. This is called the Capacity Apportionment Problem (CAP). Again, the CAP is formulated as a multi-commodity flows problem and as its solution is formidable, a heuristic algorithm is proposed.

Wavelength paths in the proposed network are formed by establishing a set of contiguous wavelength channels along the route linking the source and destination node pairs. What wavelength channels to use in establishing a path is called the Wavelength Channel Assignment Problem (WAP). Dynamic algorithms for establishing the wavelength paths are proposed and their performance are compared by simulation.

I. Introduction

With the emergence of single mode optical fibres and new photonic devices, optical fibres are becoming the dominant transmission medium for telecommunications. The single mode fibres with the low loss regions near 1300 and 1500 nm can provide transmission bandwidths in the order of GHz over hundreds of kilometers. By using dense Wavelength Division Multiplexing (WDM) technique, each optical fibre can accommodate hundreds of different wavelengths and hence can offer sufficient bandwidths for different broadband communication services like video conference and medical imaging etc. Two of the common architectural forms for building WDM-based lightwave networks are Broadcast-and-Select Networks and Wavelength Routing Networks [1].

In Broadcast-and-Select networks, all inputs are combined in a star coupler and broadcast to all outputs. Depending upon the tunability of optical transmitters and receivers, several designs like LAMBDANET, HYPASS and STAR-TRACK were proposed [2], [3], [4]. The advantage of this type of networks is its architectural simplicity and ease of control. However, these networks make inefficient use of wavelengths because each wavelength can only be used for one communication node pair. Moreover, it is difficult to expand the network other than by increasing the number of wavelengths.

Wavelength routing networks have better wavelength utilization in that the same wavelength can be used for multiple connections in spatially disjoint parts of the network. However, the design and control of such networks is more difficult as compared to Broadcast-and-Select type networks. The linear lightwave network [5,6] using linear wavelength divider and combiner (LCD) for routing is an example. The use of wavelength routing techniques for use in linking telephone central offices are discussed in [7] and a general interconnect structure using WDM is discussed in [8].

Despite the difficulty in design and control of wavelength routing networks, the use of WDM based wavelength routing techniques in constructing a multi-wavelength multi-hop lightwave networks is a good choice for implementation of large capacity, modular, and expandable communication infra-structure [9]. In this kind of networks, the large number of wavelength channels on various links of the network can be considered as a central pool of resources which can be combined and partitioned dynamically to provide the transmission capacity for different services. Our objective is to design a Bandwidth Relocatable Lightwave Backbone which can allow the number of wavelength paths between any nodes to be dynamically adjusted and allow wavelengths to be reused in spatially disjoint parts of the networks, or over different links on the same path. The network should also be easily expandable and survivable under network component failure. The backbone can be used for implementing packet-switched based, circuit-switched and multicast communication services.

In such a multi-wavelength multi-hop lightwave network, the blocking of wavelength paths can be caused by two factors: the unavailability of free wavelength channels and the lack of a common set of wavelength channels along a particular route. For the latter case, we refer it as wavelength conflicts. We will discuss wavelength conflicts in details in section III.

In designing multi-wavelength multi-hop lightwave networks, one of the major issues is how to make efficient use of the limited set of wavelengths to establish as many dynamic wavelength paths as possible. To achieve this, we have to resolve the wavelength conflicts in the network. An obvious solution is to use wavelength converters at the transit nodes so that the signal need not be carried by the same wavelength on the links along the route linking the source and destination nodes.

However, the realization of wavelength converters is difficult and costly. We therefore study how to minimize wavelength conflicts to achieve efficient use of resources in a wavelength routing lightwave network without using wavelength conversion facilities.

We propose an all-optical lightwave backbone network using only wavelength cross-connects, optical splitters and fixed wavelength optical receivers and transmitters. By using wavelength cross-connects and installing multiple fibre links between adjacent nodes, the signal carried on a particular wavelength from an input fibre link of a wavelength cross-connect in a node can be switched to any one of the outgoing fibre links and be carried on the same wavelength to the next node. With this multiple fibre links arrangement, the chance of wavelength conflicts is reduced. The idea is to use spatial means for resolving wavelength conflicts when setting up wavelength paths between nodes.

The rest of the thesis is organized as follows. In section II, the proposed lightwave network architecture and the components used in the lightwave network are described. In section III, the wavelength conflicts problem is discussed in details. Section IV presents a general network dimensioning model for the proposed architecture using integer programming. The problem of how to allocate wavelength channels to form wavelength paths between nodes such that the average blocking probabilities in a given network is minimized is described in section V. The problem is again formulated using integer programming and a heuristic algorithm is proposed. Section VI describes dynamic wavelength channel assignment algorithms for establishing wavelength paths in such backbone network and compares them by simulation on a 6-node network. Section VII is a conclusion of the study.

II. Architecture of The Proposed Lightwave Backbone Network

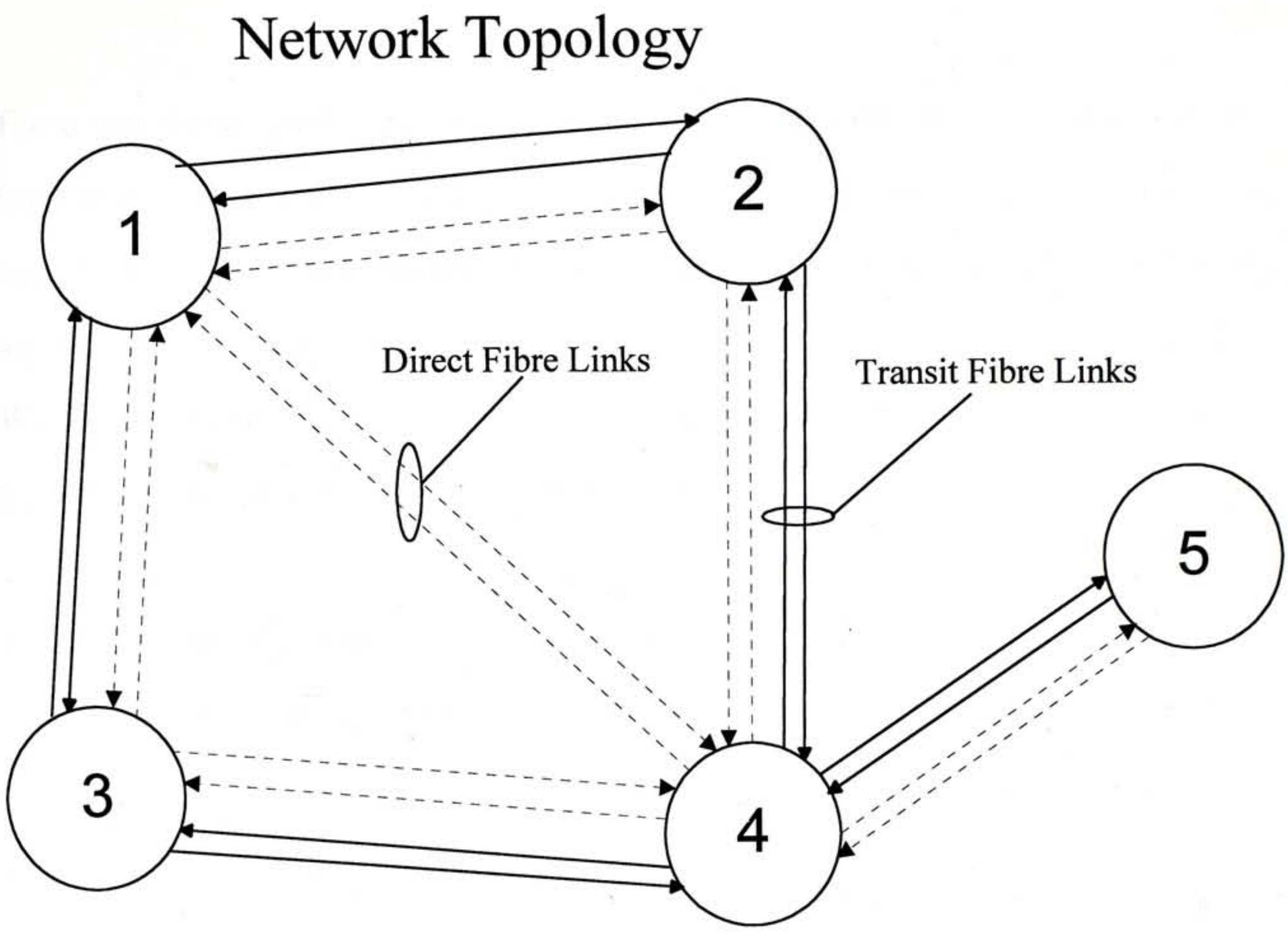

Figure 1 An example of a 5-node lightwave backbone network

The proposed lightwave backbone network is composed of a set of switching nodes interconnected by multiple fibre links. Figure 1 shows an example of a 5-node lightwave backbone network. There are two types of fibre links, *Transit Fibre Links* and *Direct Fibre Links*. Transit fibre links originate from the outgoing side of the Wavelength Cross Connect of a node and terminate at the incoming side of the Wavelength Cross Connect of the adjacent node. Direct fibre links originate from the outgoing side of the Wavelength Cross Connect of a node and terminate at the Receiver Modules of the adjacent node (See Figure 2)

By using WDM techniques, a set of *m* different wavelengths can be carried on a fibre link. A wavelength path is an interconnected set of common wavelength channels between the source and the destination nodes. For example, in Figure 1 a wavelength path of λ_k between node 1 and node 5 is established by occupying wavelength channel λ_k on transit fibre links (1,3) , (3,4) and direct fibre link (4,5).

For a wavelength path, the signal is carried by wavelength channels on transit fibre links from source node up to the last transit node and then onto the direct fibre links leading to the receiver module of the destination node. At the transit nodes, the signal on a particular wavelength of an incoming transit fibre link is switched by a Wavelength Cross Connect (WCC) to a particular outgoing fibre link determined by a path assignment algorithm to be discussed later.

Figure 2 shows the node architecture, which consists of Wavelength Cross Connect (WCC), Laser Transmitter Modules, Laser Receiver Modules and Optical Switches.

1) Wavelength Cross Connect:

The wavelength switching within a node is done by the Wavelength Cross Connect (WCC), which can switch a wavelength channel of an incoming fibre link to any one of the outgoing fibre links. WCC can be realized by Acousto-optic Tunable Filters [11], [12] or other technologies.

2) Transmitter Modules:

The Transmitter Modules consist of a set of *m* (total number of different wavelengths in a fibre link) laser transmitters each operating at a different wavelength. The outputs of each of these transmitters are coupled to a single fiber link connecting to the Wavelength Cross Connect.

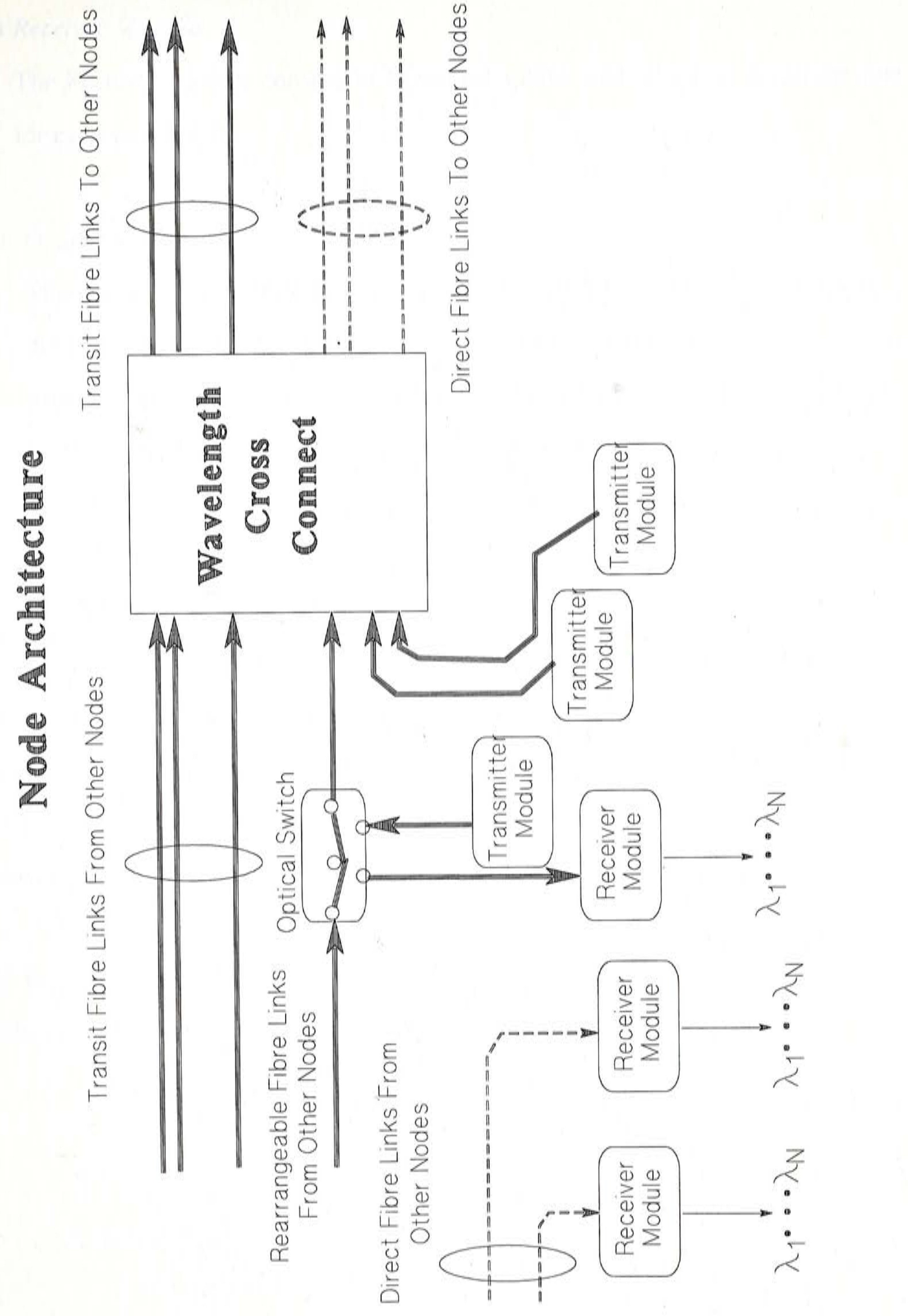

Figure 2 Node architecture for the proposed lightwave backbone network

3) Receiver Modules:

The Receiver Module consists of an optical splitter and m optical detectors, one for each wavelength.

4) Optical Switch:

The switch allows a fibre link to change from serving as a transit fibre link to a direct fibre link or vice versa. This arrangement extends the flexibility of the network by dynamically re-configuring the transit and direct fibre link arrangement to cope with the changing connection demand.

At each node, the transmitter modules serve as an access interface to the communication backbone and the laser receiver modules serve as termination interface from the backbone for wavelength paths. Each laser receiver module can receives up to m different wavelength Channels. To establish a wavelength path from a source node to destination node requires the finding of a free wavelength channel in the transmitter module of the source node and the same free wavelength channel on all fibre links along a route leading to the destination node.

In the following section, we will first discuss wavelength conflicts problem which affects the efficiency of wavelength utilization in the networks.

III. Wavelength Conflicts Problem

In a multi-wavelength lightwave network, wavelength conflicts occur when there is a lack of a common set of wavelength channels along a route from the source node to the destination node for establishing a wavelength path. Its presence causes an inefficient use of wavelength channels. To illustrate, Figure 3 shows the establishment of a wavelength path from node 1 to node 6.

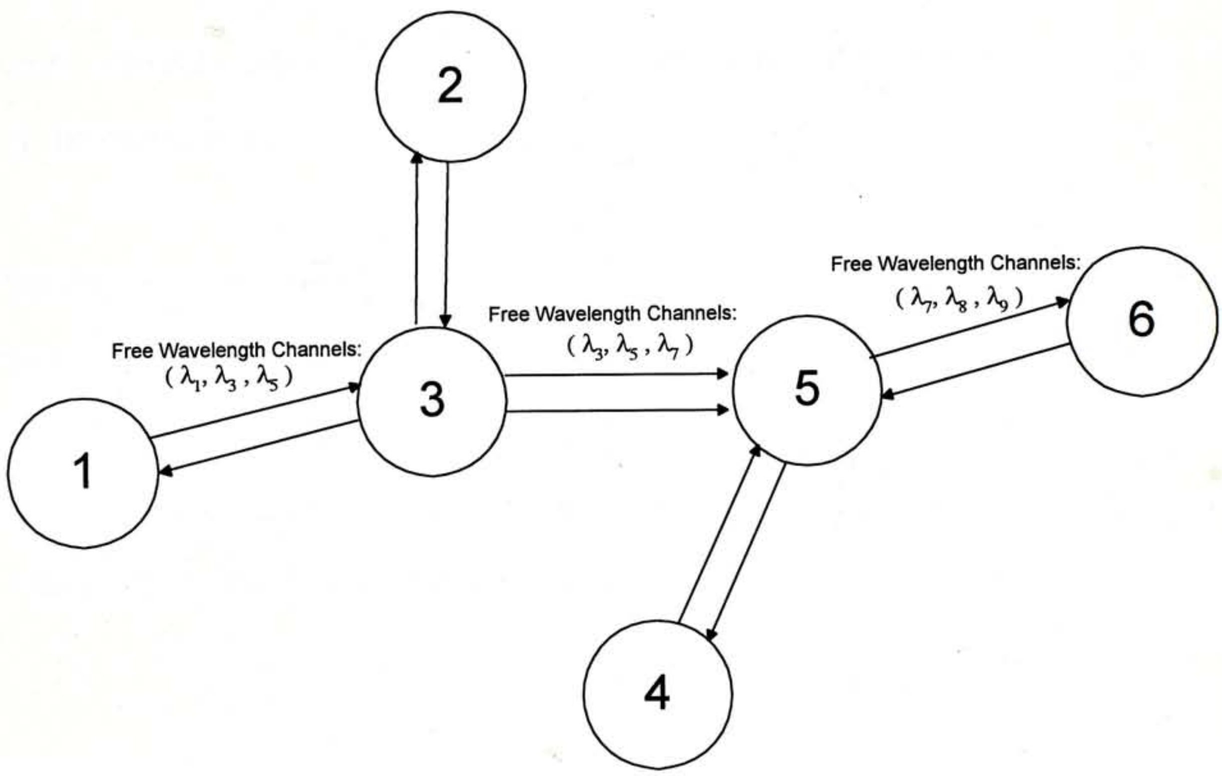

Figure 3 An illustrative example showing wavelength conflicts in a lightwave network

The sets of free wavelength channels on links (1,3), (3,5) and (5,6) are (λ_1, λ_3, λ_5), (λ_3, λ_5, λ_7) and (λ_7, λ_8, λ_9) respectively. Since there is no common free wavelength channel on the three links, a wavelength path cannot be established.

There are two types of wavelength conflicts, *resolvable and unresolvable*. Resolvable conflicts are those that can be resolved by re-arranging the wavelength channel assignments while unresolvable conflicts are those that cannot be resolved.

However, rearranging established wavelength assignment is not desirable because this causes interruption to the signals carried on the established wavelength paths. As a result, rather than rearranging the established wavelength paths, a good wavelength channel assignment algorithm is preferred to minimize the long-term blocking probability due to resolvable wavelength conflicts during path set up

Unresolvable wavelength conflicts can only be resolved by using wavelength converters at the transit nodes. The situation is then analogous to using electronic cross connects, where any channel of an input link can be mapped onto any channel of the output link.

Wavelength converters can give higher wavelength utilization. But its realization is both difficult and costly. In this study, we assume wavelength converters are not available and connection requests encountering unresovable wavelength conflicts are blocked. Instead, we focus on the problem of increasing wavelength channel utilization by avoiding resolvable wavelength conflicts as much as possible.

IV. Network Dimensioning Problem

The first problem to consider for the proposed network architecture is the network dimensioning problem. A general way of expressing the problem is that given the location of the switching nodes and the traffic matrix, assign capacities to a set of links such that the traffic requirements are satisfied at minimum cost. The cost includes not only the fibre cost, but also the cost of the switching system and the transmitter and receiver modules. The cost of each switching system depends on its size, which in turn depends on the number of links homed onto it.

The traffic requirements can be expressed in terms of number of wavelength paths required between any pair of nodes. The number of wavelength paths depends on the traffic model adopted and the routing scheme used. We assume a fixed set of wavelength paths are to be established between a source and destination pair to meet the traffic requirements. In the following, we present a general model of the network dimensioning problem using integer programming.

A. Integer Programming Formulation

Consider a lightwave backbone network. Let N be the set of switching nodes and n=|N| be the total number of nodes in the network. Let L_T be the set of transit fibre links and L_D be the set of direct fibre links. We denote the transit and direct fibre link distribution matrix as U and V respectively, which are defined as follows.

$$U = \left[u_{ij}\right], \quad \textit{where } u_{ij} = \textit{number of transit fibre links between node } i \textit{ and node } j$$

$$V = \left[v_{ij}\right], \quad \textit{where } v_{ij} = \textit{number of direct fibre links between node } i \textit{ and node } j$$

For example, the fibre link distribution matrices U and V for the network shown in Figure 1 are

$$U=\begin{bmatrix}0&2&4&0&0\\3&0&0&3&0\\2&0&0&3&0\\0&5&3&0&2\\0&0&0&3&0\end{bmatrix}\qquad V=\begin{bmatrix}0&3&3&4&0\\4&0&0&5&0\\3&0&0&4&0\\3&6&5&0&4\\0&0&0&4&0\end{bmatrix}$$

To facilitate the representation of the distribution of transit fibre links and direct fibre links on a single matrix, an augmented network $(N\cup N^*, L_T\cup L_D)$, is created by incorporating a set of conjugate nodes $N^*=\{n+1, n+2, \ldots\ldots\ldots 2n\}$, where the conjugate node of node i is denoted as node n+i. An example of the augmented network for the one in Figure 1 is shown in Figure 4.

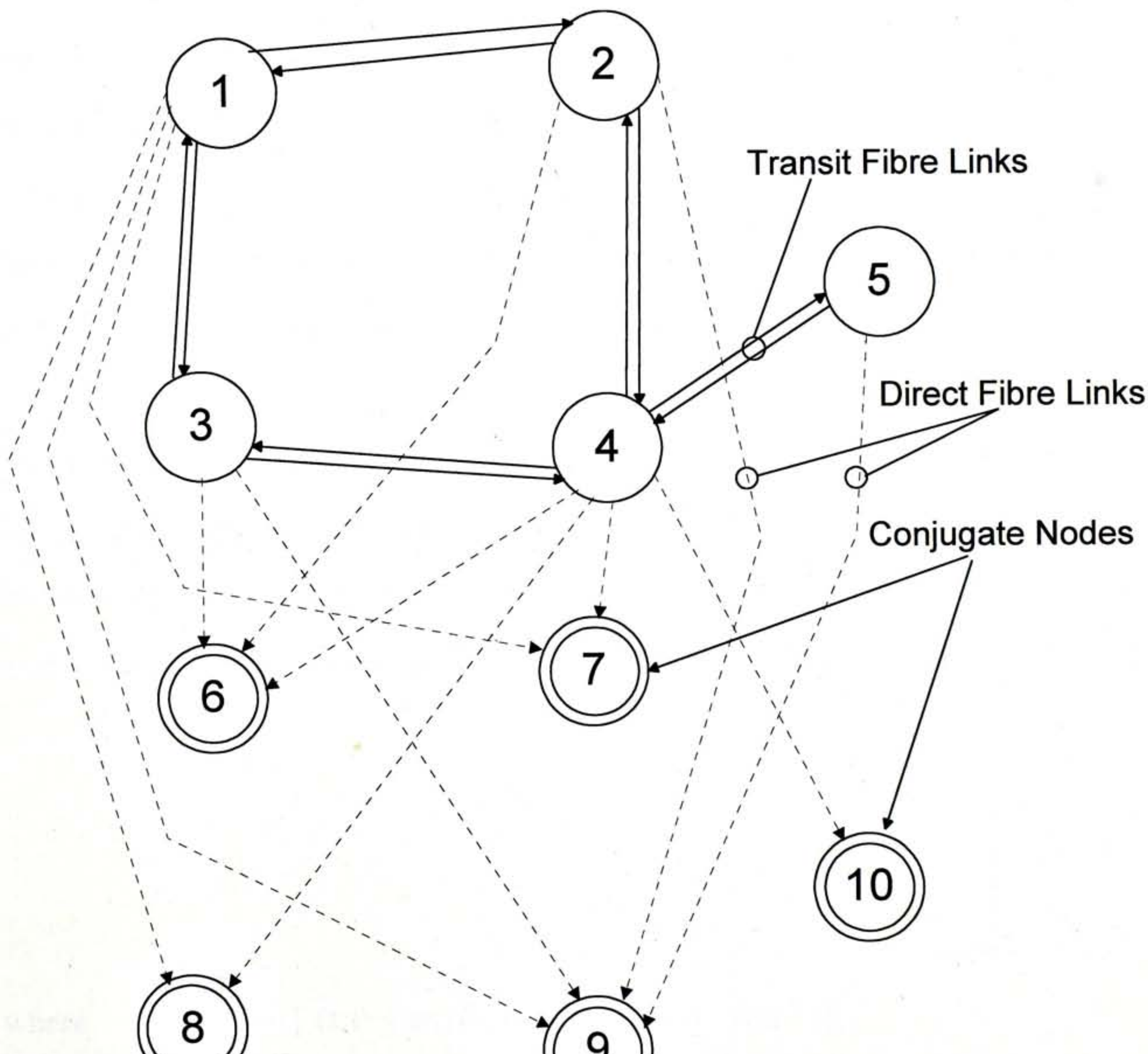

Figure 4 An example of an augmented network

The fibre link distribution matrix A of the augmented network is then given by $A=\left[a_{ij}\right]=\left(U \quad V\right)$. For the network shown in Figure 3,

$$A=\left[\begin{array}{ccccc:ccccc} 0 & 2 & 4 & 0 & 0 & 0 & 3 & 3 & 4 & 0 \\ 3 & 0 & 0 & 3 & 0 & 4 & 0 & 0 & 5 & 0 \\ 2 & 0 & 0 & 3 & 0 & 3 & 0 & 0 & 4 & 0 \\ 0 & 5 & 3 & 0 & 2 & 3 & 6 & 5 & 0 & 4 \\ 0 & 0 & 0 & 3 & 0 & 0 & 0 & 0 & 4 & 0 \end{array}\right]$$

With that, we can conveniently formulate the network dimensioning problem as a multi-commodity flows problem. To see this, we may think of the m different wavelength channels as m types of commodities. An establishment of a wavelength path from node s to node t using wavelength channel λ_k is equivalent to sending one unit of commodity-k from node s to node t. Establishing d_{st} wavelength paths between node s and node t is equivalent to sending d_{st} commodities from node s to node t, where these d_{st} commodities can be any combination of the m commodity types as long as the total is d_{st}. The objective function is the total implementation costs covering fibre link, switching and transceiver cost.

We first define $X_{ij,st}^{k}$ as the number of wavelength channel λ_k used for establishing wavelength paths between source node s and destination node t on a segment between adjacent nodes i and j. Given $\{X_{ij,st}^{k}\}$, the number of wavelength channel λ_k used for establishing wavelength paths between adjacent nodes i and j is given by

$$F_{ij}^{k} = \sum_{(s,t)\in\Omega_{ij}} X_{ij,st}^{k} \qquad 1 \le i \le n,\ 1 \le j \le 2n,$$
$$i \ne j,\ 1 \le k \le m$$

where $\Omega_{ij} = \{ (s,t) \mid s \in N,\ t \in N,\ s \ne j,\ t \ne i,\ t \ne n+s \}$

The number of fibre links L_{ij} needed between nodes i and j is thus

$$L_{ij} = \underset{k}{Max}\left\{F_{ij}^{k}\right\}$$

At each node, the input of the wavelength cross connect switch are the transit fibre links from other nodes and the fibre links from its local transmitter modules as shown Figure 5.

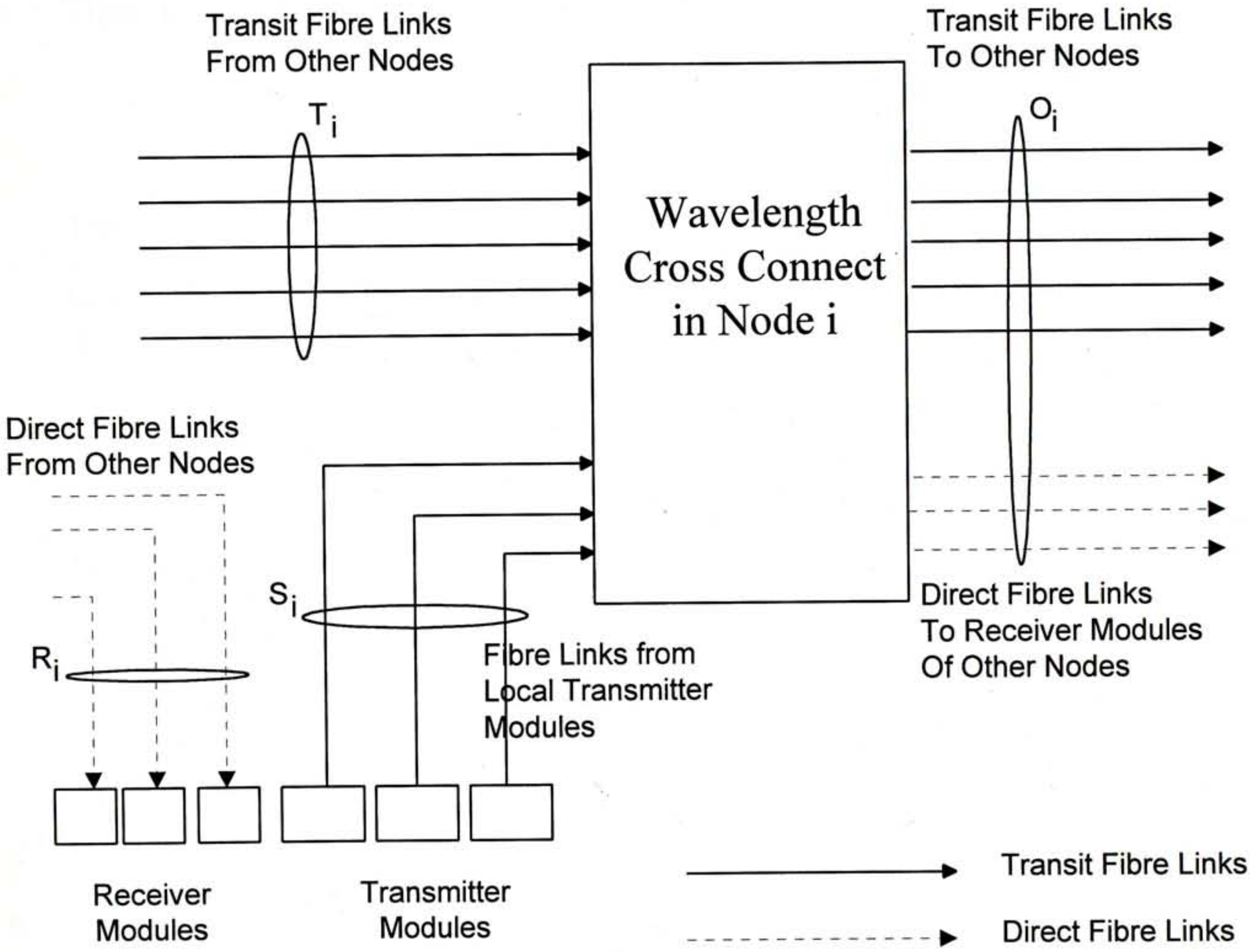

Figure 5 Fibre link connection of the wavelength cross connect of node i

The number of input fibre links from its transmitter modules S_i to the wavelength cross connect of node i, $i \in N$ is given by

$$S_i = \underset{k}{Max}\left\{\sum_{j=1}^{2n}\sum_{t=n+1}^{2n} X_{ij,it}^{k}\right\} \qquad 1 \le k \le m$$

The number of transit fibre links from other nodes connected to the input of the wavelength cross connect of node i, T_i is given by

$$T_i = \sum_{\substack{k=1 \\ k \neq i}}^{n} L_{ki} \qquad i \in N$$

The total number of outgoing transit and direct fibre links, O_i is given by

$$O_i = \sum_{\substack{k=1 \\ k \neq i, k \neq i+n}}^{2n} L_{ik} \qquad i \in N$$

Then, the dimension (M_i, N_i) of the wavelength cross connect at node i is

$$M_i = (S_i + T_i)m \qquad \text{and} \qquad N_i = O_i m$$

The number of receiver and transmitter modules required in node j, $j \in N^*$ is equal to $R_j = \sum_{\substack{i=1 \\ i \neq j}}^{n} L_{ij}$ and S_j respectively.

We now define the cost function Z_1. There are four cost components:

1. Fibre Link Installation Cost, $C_{ij}(n)$

   This includes the cost for fibre cables, laying conduits and pulling of fibres etc. for installing n links between node i and j. A typical cost function may look like the one shown in Figure 6.

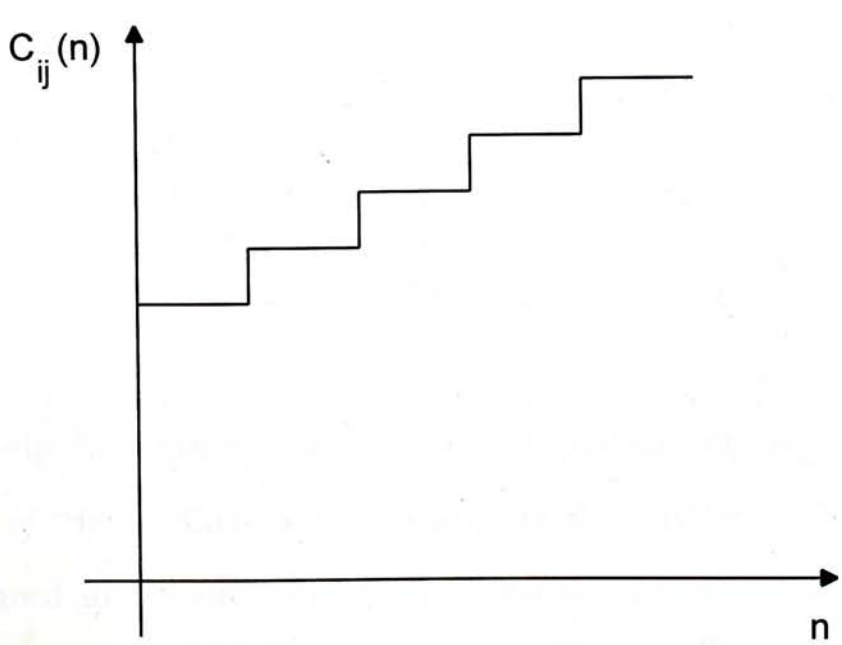

Figure 6 A typical cost function for installing n fibre links between node i and j

2. Cost of optical cross connect switch at node i, $f(M_i,N_i)$

3. Unit cost of a transmitter and receiver module, P_t and P_r

Let the traffic to the network be given in the form of a connection demand matrix $D=\{d_{ij}\}$, where d_{ij} is the number of wavelength paths required between node i and node j. The network dimensioning problem can be formulated as

$$Minimize \quad Z_1 = \sum_{i=1}^{n} \sum_{\substack{j=1 \\ j\neq i, j\neq i+n}}^{2n} C_{ij}(L_{ij}) + \sum_{i=1}^{n} f(M_i,N_i) + \sum_{i=1}^{n} T_i P_t + \sum_{i=n+1}^{2n} R_i P_r$$

subject to constraints

1. $$\sum_{s,t} X_{ij,st}^{k} = 0 \qquad \forall\ (i,j) \notin L_T \cup L_D, s \in N, t \in N^*, 1 \le k \le m$$

2. $$\sum_{k=1}^{m} \sum_{\substack{i=1 \\ i+n\neq t}}^{n} X_{it,st}^{k} = d_{st} \qquad \forall\ s \in N, t \in N^*$$

3. $$\sum_{k=1}^{m} \sum_{\substack{i=1 \\ i\neq s, i\neq s+n}}^{2n} X_{si,st}^{k} = d_{st} \qquad \forall\ s \in N, t \in N^*$$

4. $$\sum_{\substack{l=1 \\ l\neq s}}^{n} X_{il,st}^{k} = \sum_{\substack{l=1 \\ l\neq s}}^{n} X_{li,st}^{k} \qquad \forall\ i \in N, s \in N, t \in N^*, 1 \le k \le m$$

5. $X_{ij,st}^{k}$ is non-negative

Constraint 1 stipulates that wavelength channels should only be assigned on the candidate set of links. Constraint 2 states that the total number of wavelength channels assigned to a source and destination pair (s,t) on all direct fibre links terminating at the receiver modules of node t should be equal to d_{st}, the required number of wavelength paths between node s and node t. Constraint 3 states that the total number of wavelength channels assigned for a source and destination pair (s,t) on all output fibre links of node s should be equal to d_{st}, the required number of wavelength paths between node s and node t. Constraint 4 states that on a transit node, the number of type k wavelength channels assigned for a source destination pair (s,t) on all incoming fibre links should be the same as that on the outgoing fibre links.

The solution of the above optimization problem appears to be formidable. We resort to a non-linear programming approximation by treating all $X^k_{ij,st}$ as non-negative real variables and a sub-optimal solution can then be obtained by rounding off the non-integral solution to the nearest feasible one. As the number of fibre links is usually large, this approximation should give a decent solution.

V. Capacity Apportionment (CA) Problem

Traffic load in the network may vary due to factors like inaccurate forecasting, day to day variation, hour to hour variation, sudden surge in traffic due to special events (e.g. exhibition show, accidents) etc. On the other hand, the physical network may also change due to the failure or upgrading of network facilities. In either cases, network resources need to be reallocated to ensure the optimal rendering of networking services. Such reallocation of resources can be achieved by reassigning wavelength paths in the backbone network.

The variation in traffic load gives rise to a new traffic matrix, Γ and the change in physical network configuration due to facilities failure gives rise to a new fibre link distribution matrix, A. For a given Γ and A matrix, the capacity apportionment problem is to find the best assignment of wavelength paths such that the overall average blocking probabilities of the network is minimized.

A. Integer Programming Formulation

The CA problem can also be formulated as a multi-commodity flows problem as in the previous section. Instead of solving for a set of links and their capacities as in the previous problem, these are given quantities in the present problem.

The call blocking probability between a pair of source node s and destination node t depends on the number of allocated wavelength paths, the traffic load, traffic model used and the routing scheme. A general treatment for different traffic models and routing schemes is beyond the scope of this thesis. We assume Possion arrivals of connection requests with rate γ_{ij} between node i and node j and exponential connection time distribution with normalized mean of $1/\mu=1$. Let $Q=[q_{st}]$ be the wavelength path distribution matrix. In other words, q_{st} is the number of allocated wavelength paths between node s and node t. Since fixed wavelength paths are to be established between the nodes, we may think of them as being fully connected by the wavelength paths. We assume the use of direct path routing in this fully connected wavelength path network and the blocking probability between a node pair (s,t) is given by Erlang-B formula. Then, for a given traffic matrix Γ and the fibre link distribution matrix A, the CA problem can be stated as

$$\textit{Minimize} \quad Z_2(\Gamma, Q) = \sum_{s,t} \gamma_{st} \frac{\frac{\gamma_{st}^{q_{st}}}{q_{st}!}}{\sum_{i=0}^{q_{st}} \frac{\gamma_{st}^{i}}{i!}} \qquad \forall\, s \in N, t \in N^*$$

w.r.t. $\{q_{st}\}$ subject to constraints

1 $$\sum_{s=1}^{n} \sum_{t=n+1}^{2n} X_{ij,st}^{k} \le a_{ij} \qquad \forall \; i \in N, j \in N \cup N^*, 1 \le k \le m$$

2 $$\sum_{k=1}^{m} \sum_{\substack{i=1 \\ i+n \neq t}}^{n} X_{it,st}^{k} = q_{st} \qquad \forall \; s \in N, t \in N^*$$

3 $$\sum_{k=1}^{m} \sum_{\substack{i=1 \\ i \neq s, i \neq s+n}}^{2n} X_{si,st}^{k} = q_{st} \qquad \forall \; s \in N, t \in N^*$$

4 $$\sum_{\substack{l=1 \\ l \neq s}}^{2n} X_{il,st}^{k} = \sum_{\substack{l=1 \\ l \neq s}}^{n} X_{li,st}^{k} \qquad \forall \; i \in N, s \in N, t \in N^*, 1 \le k \le m$$

5 $X_{ij,st}^{k}$ is non-negative

The above problem is formidable even if we approximate the $\{ X_{ij,st}^{k}, \}$ as real variables. For a fast response to such a traffic variation and facilities failure events, a heuristics approach to the above solution seems to be the only realistic choice.

B. Heuristic Algorithm

The algorithm limits the length of the wavelength paths up to the second shortest routes. It assigns wavelength paths one at a time to source and destination node pairs until no further assignment is possible or a performance criterion is met. A new wavelength path is assigned to that node pair which gives the maximum reduction of Z_2. In the assignments, higher priority is given to node pairs linked by direct fibre links. The reason is that no alternate routes are available for these node pairs.

When selecting wavelength channels on a route, those that gives a more uniform wavelength channel utilization profile are chosen so that wavelength conflicts for future call can be reduced. The wavelength utilization profile is a set of numbers $\{f_1, f_2, \ldots\ldots f_m\}$ representing the assigned number of wavelength channels of a particular type on a link, where f_i denotes the number of type i wavelength channels assigned.

When a number of routes and wavelength channels are possible for the assignment, the one with the lowest sum of wavelength channel utilization profile variances along a route is selected. This is done to make the utilization of different wavelengths as uniform as possible so that the occurrence of wavelength conflicts can be minimized. The following is the pseudo code of the algorithm.

Pseudo code of the heuristic algorithm

1. Obtain the first and second shortest routes for all source and destination node pairs to form the set $\{P_{st}\}$, where P_{st} is the set of first and second shortest routes for the source and destination node pair (s,t).

2. Initialization.

   Create $U = \{(i,j) \mid i \in N, j \in N^*\}$ as a set of all source and destination node pairs of the network.

   Set $q_{ij} = 0$ for all i,j.

3. Do while U is not Null

   for all (i,j) in U,

   select (s,t) such that the reduction in Z_2 is the largest for all (i,j) and priority is given to those (s,t) connected by direct fibre links only.

   for each $p_k \in P_{st}$, where k = 1,2 . . . $|P_{st}|$

   Compute $f_{k,l} = \sum_{n \in p_k} c_n(\lambda_l)\,\mathrm{var}[B_n(\lambda_l)]$ for l = 1, . . ,.m

   where $B_n(\lambda_l)$: *wavelength channel profile of link n on path* p_k *when* λ_l *is selected.*

   $$c_n(\lambda_l) = \begin{cases} \infty & \text{if no free wavelength channel } \lambda_l \text{ on link } n \\ 1 & \text{otherwise} \end{cases}$$

   if $f_{k,l} = \infty$ for all k and l then

   remove (s,t) from U

   else

   Mark λ_{l^*} on all links of p_{k^*} for (s,t) such that f_{k^*,l^*} is minimum for all k and l.

   $q_{st} = q_{st} + 1$

   if blocking probability for (s,t) ≤ the required one then

   remove (s,t) from U

   endif

   end while

4. Terminate.

C. An Illustrative Example For The Heuristic Algorithm

In order to see how the algorithm works, we use the 6-node lightwave backbone network shown in Figure 7 to generate the result to illustrate the heuristic algorithm. For simplicity, a node and its conjugate node are drawn together.

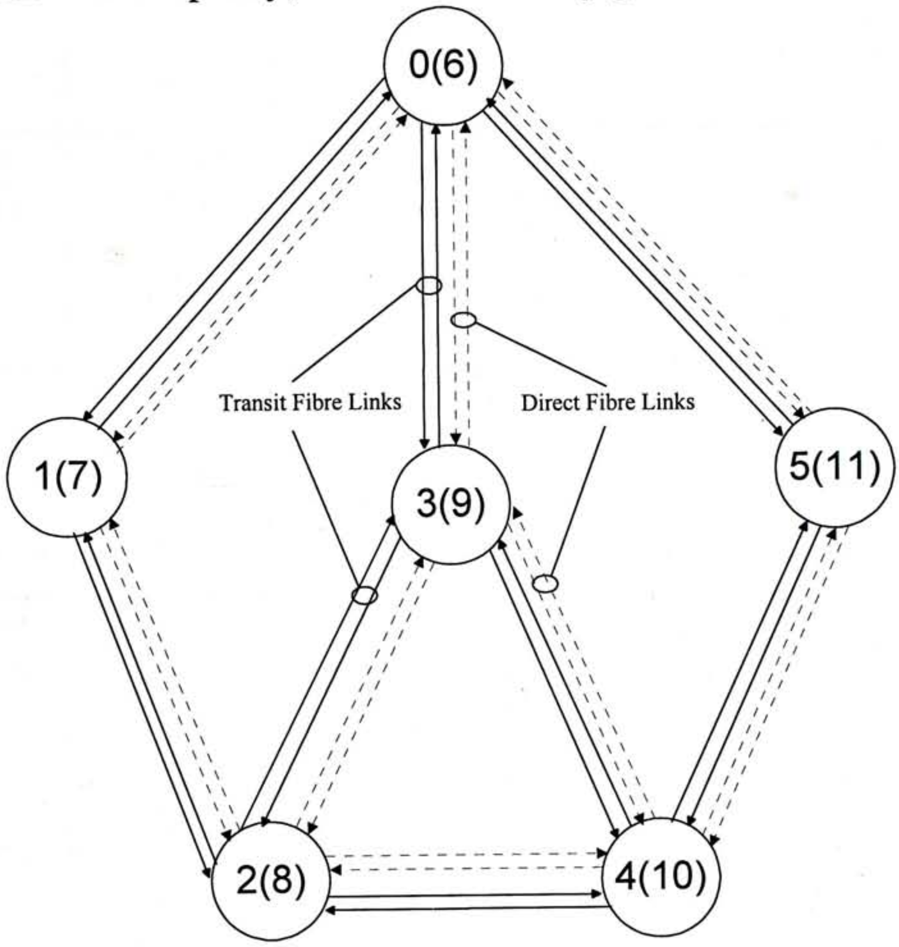

Figure 7 A 6-node backbone network for illustrative example of the heuristic algorithm

The fibre link distribution of the network is given as follows. It is assumed that in each fibre link, a total of 10 different types of wavelength channels are available.

From \ To	0	1	2	3	4	5	6	7	8	9	10	11
0	-	3	-	4	-	2	-	6	-	5	-	5
1	4	-	5	-	-	-	4	-	3	-	-	-
2	-	3	-	4	4	-	-	6	-	4	3	-
3	4	-	3	-	3	-	4	-	3	-	3	-
4	-	-	4	2	-	3	-	-	4	4	-	6
5	5	-	-	-	6	-	3	-	-	-	3	-

Table 1 Fibre link distribution of the network used for illustrating the heuristic algorithm for the CA problem

All possible routes up to the second shortest ones between all source and destination node pairs of the 6-node networks are listed in following table.

SD pair	(0,7)	(0,8)	(0,9)	(0,10)	(0,11)
Routes	0,7	0,1,8 0,3,8 0,3,4,8 0,5,4,8	0,9	0,3,10 0,5,10 0,1,2,10 0,3,2,10	0,11
SD pair	(1,6)	(1,8)	(1,9)	(1,10)	(1,11)
Routes	1,6	1,8	1,0,9 1,2,9 1,2,4,9	1,2,10 1,0,3,10 1,0,5,10 1,2,3,10	1,0,11 1,2,4,11
SD pair	(2,6)	(2,7)	(2,9)	(2,10)	(2,11)
Routes	2,1,6 2,3,6 2,4,3,6 2,4,5,6	2,7	2,9	2,10	2,4,11 2,1,0,11 2,3,0,11 2,3,4,11
SD pair	(3,6)	(3,7)	(3,8)	(3,10)	(3,11)
Routes	3,6	3,0,7 3,2,7 3,4,2,7	3,8	3,10	3,0,11 3,4,11 3,2,4,11
SD pair	(4,6)	(4,7)	(4,8)	(4,9)	(4,11)
Routes	4,3,6 4,5,6 4,2,1,6 4,2,3,6	4,2,7 4,3,0,7 4,3,2,7 4,5,0,7	4,8	4,9	4,11
SD pair	(5,6)	(5,7)	(5,8)	(5,9)	(5,10)
Routes	5,6	5,0,7 5,4,2,7	5,4,8 5,0,1,8 5,0,3,8	5,0,9 5,4,9	5,10

Table 2 The first and second shortest routes for all source and destination node pairs of the network used for illustrating the heuristic algorithm for the CA problem

We use the traffic load depicted in table 3 and the fibre link distribution of the network in table 1 as input to the algorithm to generate the result.

Destination Nodes

			6	7	8	9	10	11
	0		0	3.96	35.1	2.16	28.2	5.96
	1		3.96	0	4.61	43.9	7.38	7.38
Source	2		28.2	3.33	0	7.38	0.701	28.2
Nodes	3		0.105	24.0	4.61	0	7.38	24.0
	4		35.1	28.2	2.16	5.96	0	1.13
	5		2.73	14.2	12.6	24.0	7.38	0

Table 3 Traffic load for all source and destination node pairs of the network used for illustrating the heuristic algorithm of the CA problem

The result generated by the algorithm is presented in Appendix A, which shows the actual wavelength channel assignment arrangement on each fibre link. A bracket (i,j) on a wavelength channel of each link denotes the destination node pair to which it is assigned. The average blocking experienced by the network is 1.1% and we can see that the wavelength utilization profile on each link is quite even and most fibre links are highly occupied indicating a higher degree of resources utilization.

In the next section, we consider three dynamic wavelength channel assignment algorithms for establishing wavelength paths. We will compare the blocking performance at different traffic load of using these dynamic algorithms with that of using the above heuristic algorithm to obtain fixed wavelength paths between the node pairs with direct routing adopted.

VI. Wavelength Channel Assignment Problem

A. Wavelength Channel Assignment Strategies

The assignment of wavelength channels to form the wavelength paths can be done on either a static or a dynamic basis. In the previous section, we have considered the static approach, where the wavelength channels associated with a wavelength path are permanently reserved whether they are engaged or not. No sharing of resources among different wavelength paths is possible even they are idle.

The connection pattern of the wavelength paths remains unchanged until next connection plan is used to cater for change in traffic load or facility failure. The advantage of this type of static strategy is that as the assignment is done in a less time-critical manner as compared to that of dynamic assignment strategy for which the wavelength channels assignment in the network has to be derived every time a connection request for establishing a new wavelength path arrives. However, the static assignment strategy does not take the advantage of the statistical nature of the traffic in making full use of the free wavelength channels of the fibre links.

Instead of having fixed wavelength paths set up between the source and destination nodes, we may allow wavelength paths to be set up on a dynamic basis. What wavelength channels to use in establishing the wavelength paths is determined by the current network status. The objective is to make the best assignment so that the long-term blocking probability is minimized for the coming connection requests. We call this the Wavelength Channel Assignment Problem.

In the following section, we propose and study the performance of various dynamic wavelength channel assignment algorithms for the proposed network architecture.

B. Dynamic Wavelength Channel Assignment Algorithms

We will consider assignment algorithms that work in the following way:

1. A central control unit is responsible for keeping the resources information of the network and assigning the best routes for establishing the wavelength paths.

2. Upon an arrival of a connection request for a wavelength path between a node pair, the control unit will determine if there are resources available for establishing the wavelength path. If not, the request will be rejected. No re-arrangement of the established wavelength paths is allowed for setting up the new wavelength path.

3. Based on a specific wavelength channel assignment algorithm, the wavelength channels along the selected path will be marked for a successful connection request.

4. Upon release of a wavelength path, all the wavelength channels along the path will be released.

For such wavelength channel assignment arrangement, the rejection of a connection request will be due to the unavailability of wavelength channel λ_i on all links along a route from the source node to the destination node of the connection request for all i. The unavailability may be caused by either resource constraint or wavelength conflicts. By resource constraint, we mean that all wavelength channels on a link or links of a route are fully assigned while wavelength conflict means that there are free wavelength channels on all links along a route but we simply cannot find one common wavelength channel that is available on all links along a route from the source node to the destination node of a connection request.

Wavelength conflicts as mentioned in section III are either resolvable or unresolvable and unresolvable wavelength conflicts can only be resolved by having wavelength conversion facilities in the network, which is not considered in this study. In the following, we only deal with resolvable wavelength conflicts.

A situation of resolvable wavelength conflicts is illustrated in the Figure 8. Using the notation of augmented network described in section IV, a node i and its conjugate node i+n are drawn together with the conjugate node number put in bracket for simplicity. A directed solid arrow represents two transit fibre links and a directed dotted arrow represents two direct fibre links between adjacent nodes. Each fibre link can accommodate four wavelength channels (λ_1, λ_2, λ_3, λ_4). A total of 8 wavelength channels are therefore available on each fibre link (transit or direct) segment.

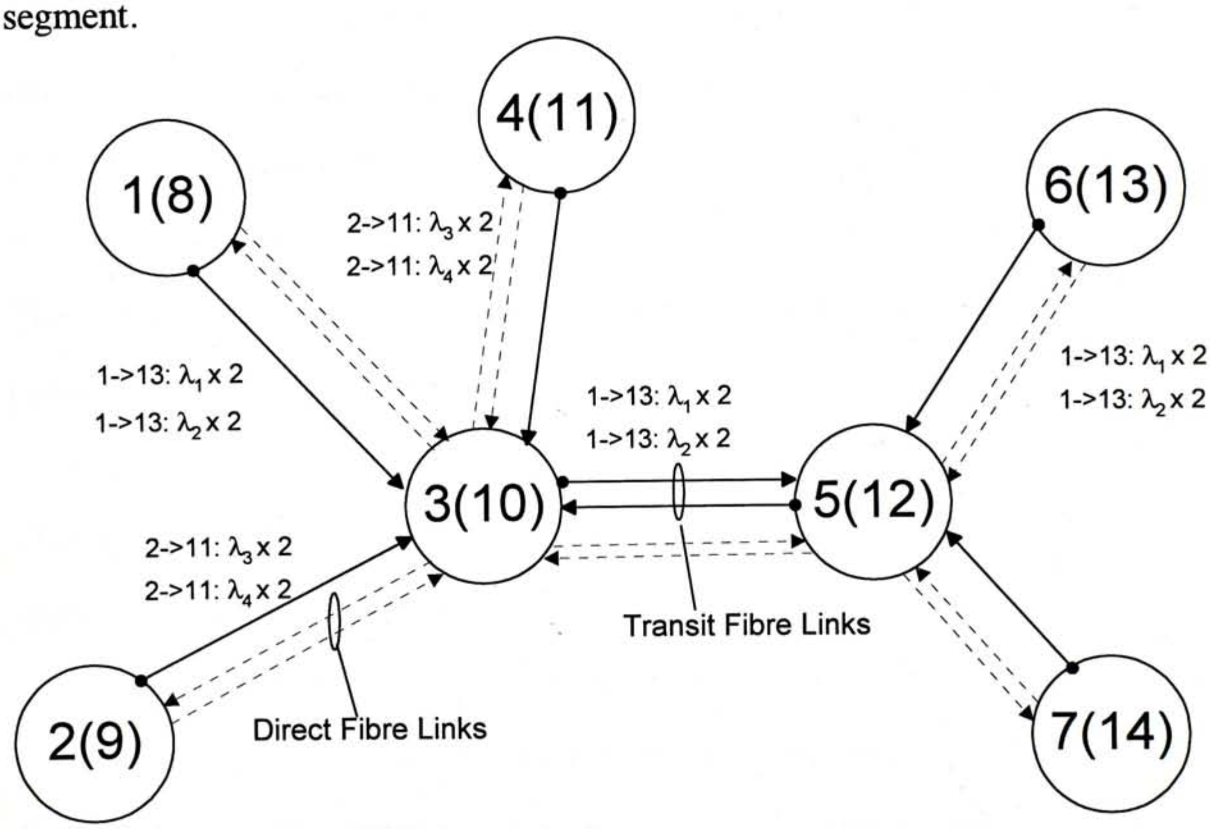

Figure 8 An illustrative example for showing how resolvable wavelength conflicts can be avoided by appropriate wavelength channel assignment

For the given situation, 8 wavelength paths were already established. The wavelength channels assignment on each link is as follows. For connection requests between node 1 and node 13, 4 wavelength paths were established along the route 1->3->5->13. On links (1,3), (3,5) and (5,13), two λ_1 wavelength channels and two λ_2 wavelength channels were occupied to form the four wavelength paths. Another 4 wavelength paths along the route 2->3->11 were established for the connection requests between node 2 and node 11. Two λ_3 wavelength channels and two λ_4 wavelength channels were allocated on links (2,3) and (3,11) for the wavelength paths.

A new connection between nodes 2 and 13 is requested. The only path linking the two nodes is 2->3->5->13. As we can see, on link (2,3) only wavelength channels λ_1 and λ_2 are available while on link (3,5) the free wavelength channels are λ_3 and λ_4. The connection request in this case is rejected as we cannot find an unassigned wavelength channel which is available on all links along the route 2->3->5->13. This situation could have been avoided if wavelength channels λ_1 and λ_2 were used for establishing the 4 wavelength paths between node 2 and node 11. Then, wavelength channels λ_3 and λ_4 can be used for the establishing wavelength paths between nodes 2 and 13.

This example shows that resolvable wavelength conflicts can be avoided with a appropriate wavelength channel assignment. In the following, we consider three dynamic wavelength channel assignment algorithms. The main objective of these assignment algorithms is to minimize the long-term average call blocking probability in the network due to resolvable wavelength conflicts without rearranging the established wavelength paths. We will study and compare the blocking performance for three different dynamic wavelength assignment algorithms by simulation.

The first one (Algorithm A) uses a minimum weighted sum of wavelength channel utilization profile variance of the fibre links of a route as selection criteria. The second one (Algorithm B) is a simple algorithm that use the first available free wavelength channel along the route from the source node to the destination node of a connection request. Both of them assume no wavelength conversion facilities are available in the network.

The third one (Algorithm C) assumes that wavelength converters are always available when needed. As a result, wavelength conflicts will not occur. The rejection of a connection request will only be due to the unavailability of free wavelength channels (channel of any wavelength will do) on a link or links along a route from the source node to the destination node. The performance results of Algorithm C can serve as a good upper bound for the results obtained from Algorithms A and B.

In order to prevent the dynamic algorithms from using up too many resources and restrict the computation complexity, the length of the shortest routes allowed for establishing the wavelength paths should be limited. Let us denote it by K. K=1 denotes the shortest routes, K=2 the second shortest routes and so on. To facilitate the development of the algorithms, we first define the following notations.

$B(\ell,\lambda_k)$: Wavelength channel utilization profile of link ℓ when λ_k is assigned for a new wavelength path. The wavelength utilization profile is a set of numbers $\{f_1, f_2, \ldots\ldots f_m\}$ representing the assigned number of wavelength channels of a particular type on a link, where f_i denotes the number of type i (i.e. λ_i) wavelength channels assigned and *m* is the total number of wavelengths used in a fibre link

w_ℓ: weight of link ℓ;

$$\delta(\ell,\lambda_k) = \begin{cases} \infty, & \text{if no free } \lambda_k \text{ wavelength channel is not available on link } \ell \\ 1, & \text{if a free } \lambda_k \text{ wavelength channel is available on link } \ell \end{cases}$$

A.1 *Algorithm A (No wavelength conversion facilities available in the network)*

Upon arrival of a wavelength path connection request for a source and destination node pair (s,t), the algorithm first obtains all the shortest routes not longer than a specified length for the node pair (s,t). Then, it searches through these routes one by one in ascending order of length for minimum-length feasible shortest routes. A feasible shortest route is one that a common set of free wavelength channels are available on all its links for establishing a new wavelength path. Among the set of the minimum-length feasible shortest routes, assign the wavelength channels on the one in the set such that the weighted sum of wavelength channel utilization profile variance of all links of the route is minimum to form the wavelength path. The request is rejected if no feasible shortest routes are available. The pseudo code of the algorithm is given on next page.

Pseudo code of Algorithm A

(1) Obtain all shortest routes up to the Kth shortest routes for the source and destination pair (s,t) to form

$$ {}_1P_{st}, {}_2P_{st}, \ldots, {}_iP_{st}, \ldots {}_KP_{st} $$

where ${}_iP_{st}$ is the set of the ith shortest routes from node s to node t

(2) *For i = 1 to K,*

For each $p_j \in {}_iP_{st}$, *where* $j = 1,2 \ldots |{}_iP_{st}|$

For each λ_k, *where* $k = 1,2 \ldots m$

Compute $f_{j,k} = \sum_{\ell \in p_j} w_\ell \cdot Var[B(\ell,\lambda_k)] \cdot \delta(\ell,\lambda_k)$

$f_{j^*,k^*} = MIN\{f_{j,k}\}$ *for all j and k*;

if $f_{j^*,k^*} \neq \infty$ then

Assign λ_{k^*} on all links of p_{j^*} for the node pair (s,t);

goto (3);

endif

next i;

Reject the connection request;

(3) Terminate.

This above process is repeated for every arrival of connection request.

A.2 *Algorithm B (No wavelength conversion facilities available in the network)*

The algorithm first obtains all the shortest routes of a specified length between the source and destination node pair of the connection request. It then searches through these shortest routes one by one until the first minimum-length feasible route is found and selected for establishing the wavelength path. The first found common set of wavelength channels on all links of the selected shortest route are assigned for setting up the new wavelength path. If no feasible route is found among all the shortest routes, the request is rejected. The pseudo code of the algorithm is given below.

<u>Pseudo code of Algorithm B</u>

(1) Obtain all shortest routes up to the Kth shortest routes for the source and destination pair (s,t) to form

$$ {}_1P_{st}, {}_2P_{st}, \ldots, {}_iP_{st}, \ldots {}_KP_{st} $$

where ${}_iP_{st}$ is the set of the ith shortest routes from node s to node t

(2) For i = 1 to K,

For j = 1 to $|{}_iP_{st}|$

For k = 1 to m

if λ_k wavelength channel on all links of $p_j \in {}_iP_{st}$, are available

Assign wavelength channel λ_k on all links of p_j for node pair (s,t);

goto (3);

endif;

next k;

next j;

next i;

Reject the connection request;

(3) Terminate.

A.3 *Algorithm C (Wavelength conversion facilities available in the network)*

The algorithm first obtains all the shortest routes up to certain length for the source and destination node pair of the connection request. Then, it searches through these routes one by one in ascending order of length for minimum-length feasible shortest routes. A feasible shortest route is one that free wavelength channels are available on all its links. Among the set of the minimum-length feasible shortest routes, assign the wavelength channels and perform wavelength conversion if necessary on the one in the set such that the weighted sum of wavelength channel utilization percentage of all links of the route is minimum to form the wavelength path. The wavelength channel utilization percentage of a fibre link is defined as the percentage ratio of the number of assigned wavelength channels to the total number of wavelength channels available in a fibre link. The request is rejected if no feasible shortest routes are available. As the pseudo code of algorithm C is similar to that of algorithm A, it is not given here.

C. Performance Results By Simulation

The 6-node network shown in Figure 7 of section V is again used for the simulation. The following traffic model is assumed for the simulation.

1. The arrival of the connection request from each node is a Poisson process with rate r.
2. The holding time of the wavelength path is exponentially distributed with mean $1/\mu$.
3. The connection request for a wavelength path from a source node to any other destination node is of equal probability.
4. Connection requests are rejected and lost if no free wavelengths are available.

Since it is the blocking introduced by the backbone that we are going to investigate, we assume that each node has sufficient large number of transmitters that it will never cause blocking to the setup of wavelength paths. The connection request will only be blocked by the unavailability of the wavelength channels on fibre links along a route.

We compare the performance of the three algorithms for different traffic intensity for different length of shortest routes and number of wavelengths used by simulation. Figures 9,10,11a-11c plot the blocking probability against arrival rate, r per node for the three algorithms. For algorithm A, we study the effect of using a smaller number of wavelengths on the blocking performance. In order to maintain the same channel capacity of the network, the number of fibre links of all segments are doubled to compensate for the reduction of the number of wavelength channels used in a fibre link to half of the original. The mean holding time of a wavelength path is $1/\mu=10$.

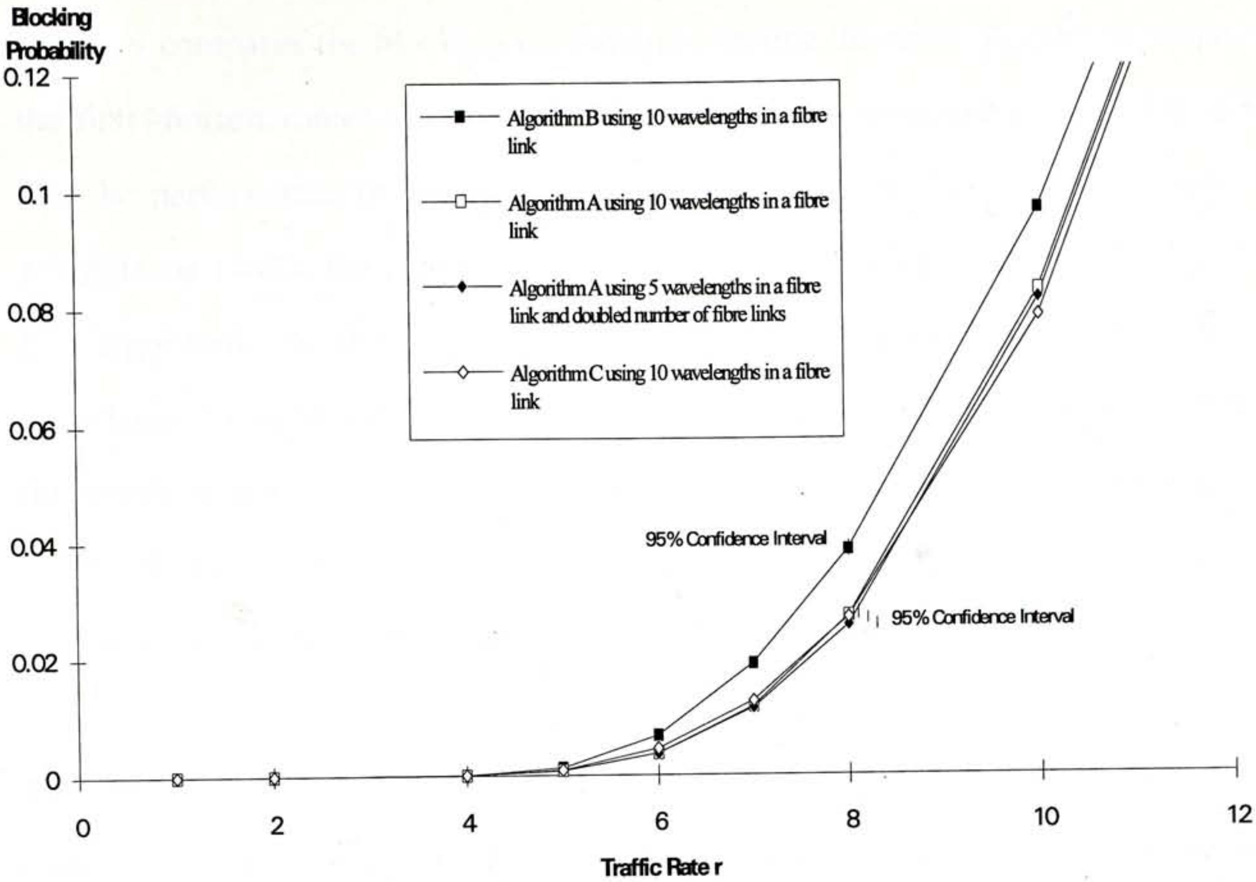

Figure 9 Comparison of blocking probabilities for different dynamic wavelength channel assignment algorithms using the first shortest routes only

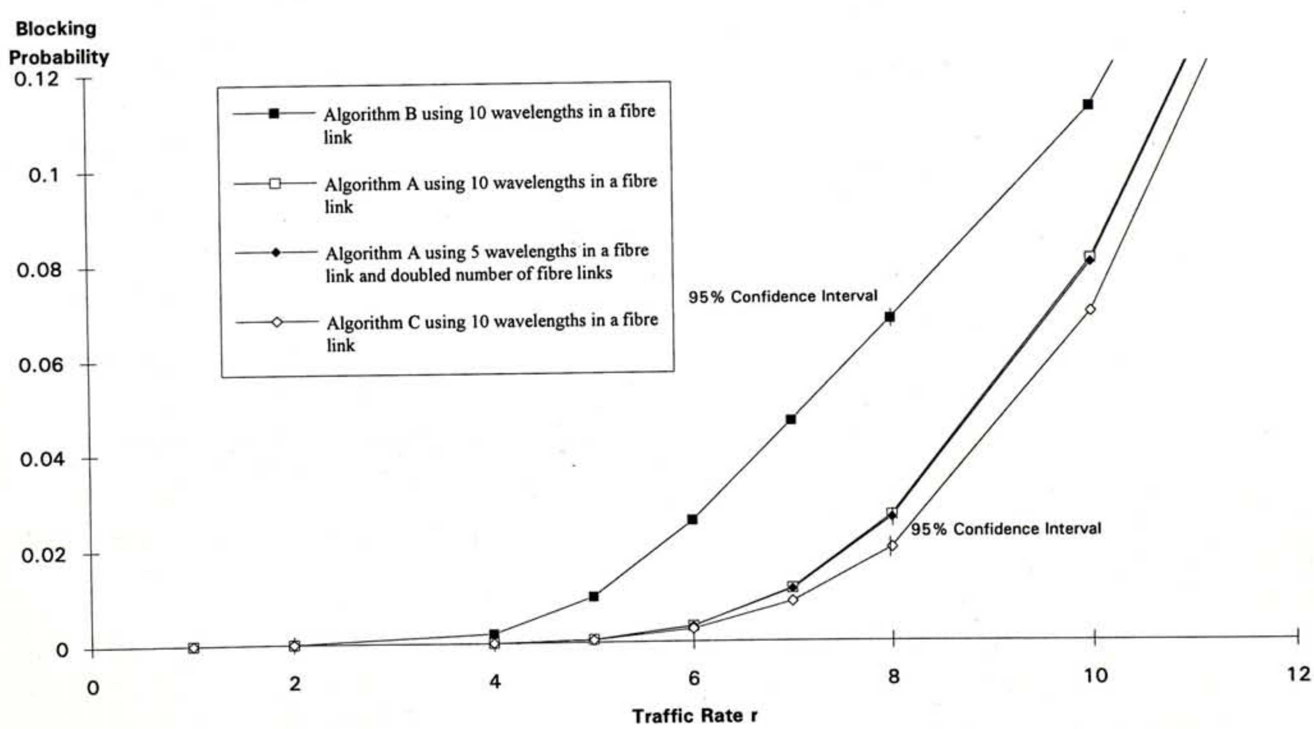

Figure 10 Comparison of blocking probabilities for different dynamic wavelength channel assignment algorithms using the first and second shortest routes only

Figure 9 compares the blocking performance among the three algorithms when only the first shortest routes are used for establishing the wavelength paths. We observe that the performance of algorithm B is the worst among the three algorithms. For example, at r=10, the difference in blocking as compared to algorithm C is 23%. For algorithms A and C, the difference in blocking performance is not very significant for light and heavy traffic rate. At medium traffic rate (e.g. r=10), the difference is just around 5%. On the other hand, it is seen the for algorithm A the effect of using smaller number of wavelengths with more fibre links used as compensation does not affect much of the blocking performance.

Figure 10 compares the blocking performance among the three algorithms when only the first and second shortest routes are allowed for establishing the wavelength paths. Again, the performance of algorithm B is the worst among other algorithms. For example, at r=8 and r=10, the difference in blocking as compared to algorithm C is 246% and 62% higher respectively. For algorithms A and C, the difference in blocking performance is again not very significant for light and heavy traffic rate. At medium traffic rate (6<r<10) the difference is noticeable as compared to that in Figure 11. For example, at r=10, the difference is around 16% (only 5% in Figure 11 for using first shortest routes only). However, again the effect of using smaller number of wavelengths with more fibre links used does not affect much of the blocking performance as exhibited by algorithm A.

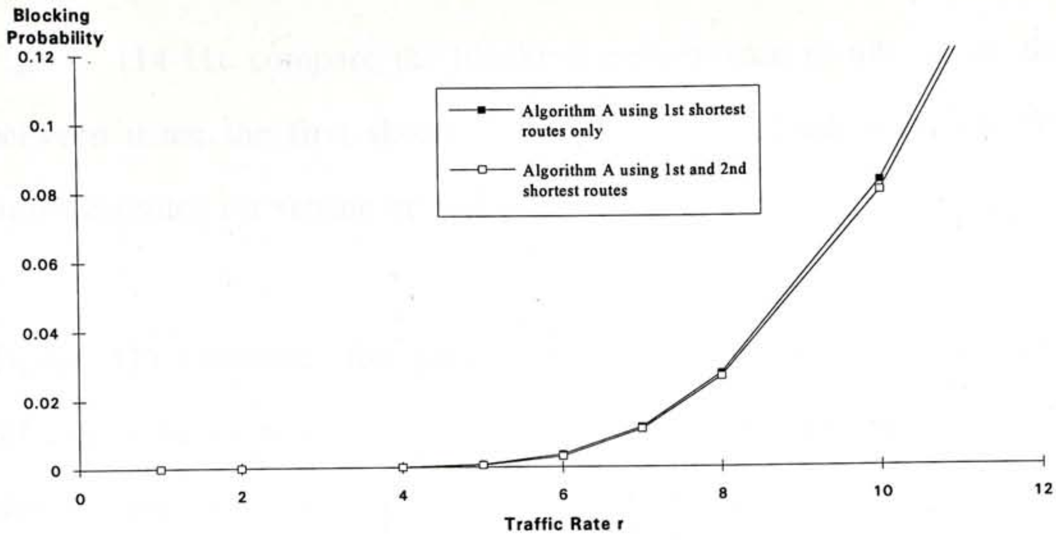

Figure 11a Comparison of blocking probabilities for algorithm A between using the 1st shortest routes and using the 1st and 2nd shortest routes only

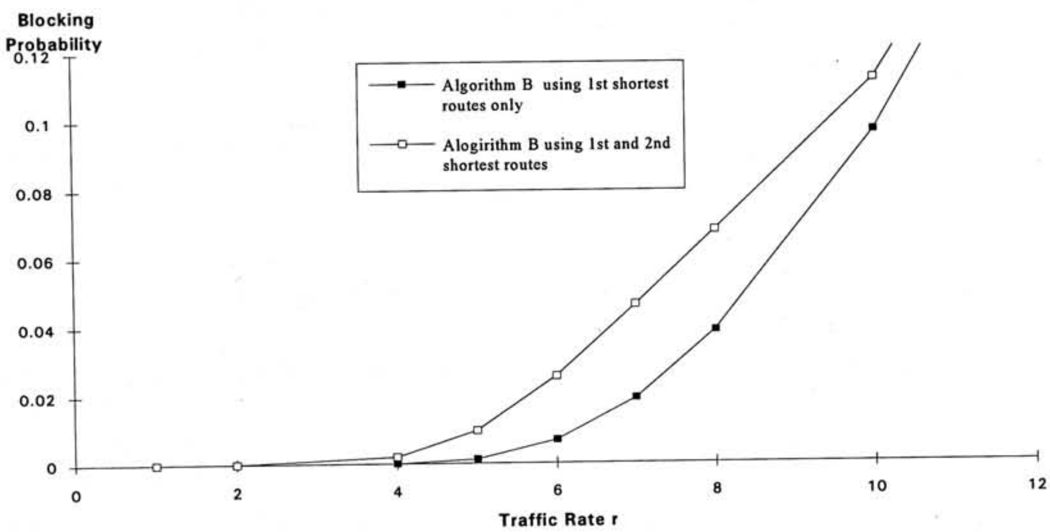

Figure 11b Comparison of blocking probabilities for algorithm B between using the 1st shortest routes and using the 1st and 2nd shortest routes only

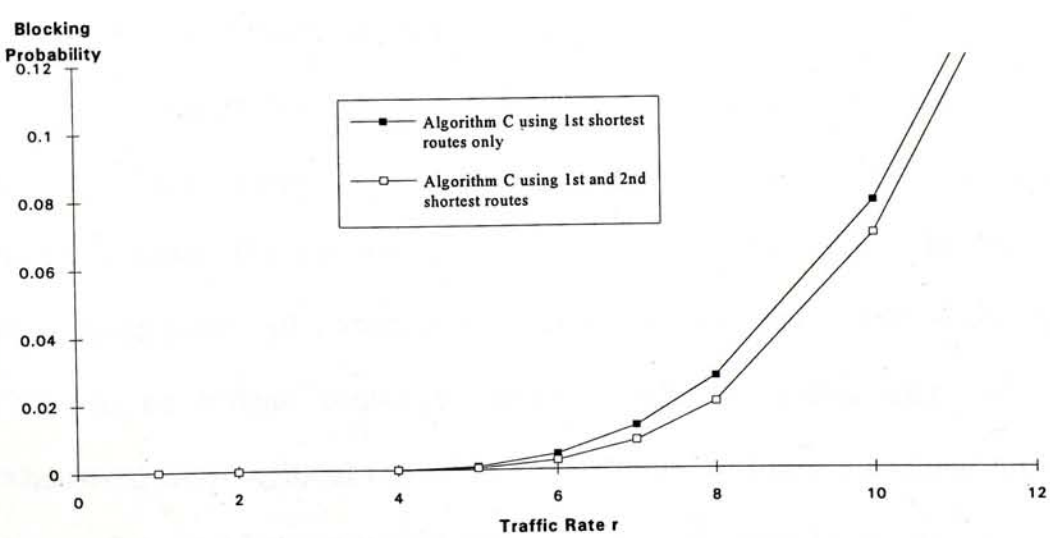

Figure 11c Comparison of blocking probabilities for algorithm C between using the 1st shortest routes and using the 1st and 2nd shortest routes only

Figures 11a-11c compare the blocking performance results of the three algorithms between using the first shortest routes only and those using the first and second shortest routes for setting up wavelength paths.

Figure 11a compares the performance for algorithm A. It is observed that the difference between using first shortest routes only and using both first and second shortest routes is not significant. For example, at r=10 the difference is only around 3%. As it becomes more difficult to find a common set of wavelength channels on all links of a route when the length of the route is increased, the inclusion of second shortest routes for establishing wavelength paths cannot of much help to the blocking performance. Therefore, we should only use first shortest routes for algorithm A to reduce computation complexity.

For algorithm B, the performance is compared in Figure 11b. We see that the performance of algorithm B is the worst among other algorithms under all conditions. Its blocking performance becomes worse when the length of shortest routes allowed for establishing wavelength paths is increased while other algorithms show no such behavior. For example, at r=8, the blocking probability of the one using first and second shortest routes is 75% higher than that using the first shortest routes only. This phenomenon is due to the fact that algorithm B does no planning on how to assign the wavelength channels evenly over different fibre links of the network. This causes assignment of wavelength channels to concentrate on some of the fibre links. If these fibre links happen to form part of the only routes linking other node pairs, all connection requests between such node pairs will be blocked. The use of longer routes to form wavelength paths increases the chance of exhausting more critical routes of the network as more wavelength channels may be chosen for establishing wavelength paths. The gain in accepting more wavelength paths by using more wavelength channels may not cover the loss caused by exhausting the wavelength channels on some fibre links that are critical to establishment of wavelength paths for many other source and destination node pairs. As a result, the overall blocking performance gets worse.

Figure 11c compares the results for Algorithm C. The algorithm using 1st and 2nd shortest routes performs better by 14% than the one using 1st shortest routes only at r=10. The difference in this case is more significant. Unlike algorithm A, we assume wavelength conversion facilities are available in the network, therefore as long as free wavelength channels are available on all links of a route linking a source and destination node pair, wavelength path can be set up. As a result, the inclusion of second shortest routes for establishing wavelength path for a source and destination node pair is easier.

Based on the above discussion, the results obtained from the 6-node network can be summarized as follows:

1. The difference in blocking performance of the three algorithms is not significant at light and high traffic rate. At medium traffic, algorithm A performs much better than algorithm B. This shows that for a network without wavelength conversion facilities, variance of the wavelength channel utilization profile of fibre links can serve as a good measure for how to even out the assignment of wavelength channels over different fibre links of the network.

2. The inclusion of a longer routes for establishing wavelengths may cause the blocking performance to get worse if no effort is made to even out the assignment of wavelength channels over different links of the network. However, with measure to even out the assignment of wavelength channels over all links of the network, the blocking performance can be improved and this is more significant if wavelength conversion are done in the network.

3. The blocking performance of a network with wavelength conversion facilities always available whenever needed as shown from the results of algorithm C is obviously the best. However, the blocking performance of Algorithm C using the first and second shortest routes is only 16% better than that of Algorithm A. This suggests that the performance is not dominated by unresolvable wavelength conflicts. Other factors like presence of bottleneck links, the sub-optimality of the algorithm etc. also affect the performance. This gives us the insight that full provision of wavelength converters all over the network seems to be not necessary. A limited number of shared wavelength conversion facilities and a good assignment algorithm may be sufficient to give decent performance.

D. Comparison Of Blocking Performance Between Static And Dynamic Wavelength Channel Assignment Scheme

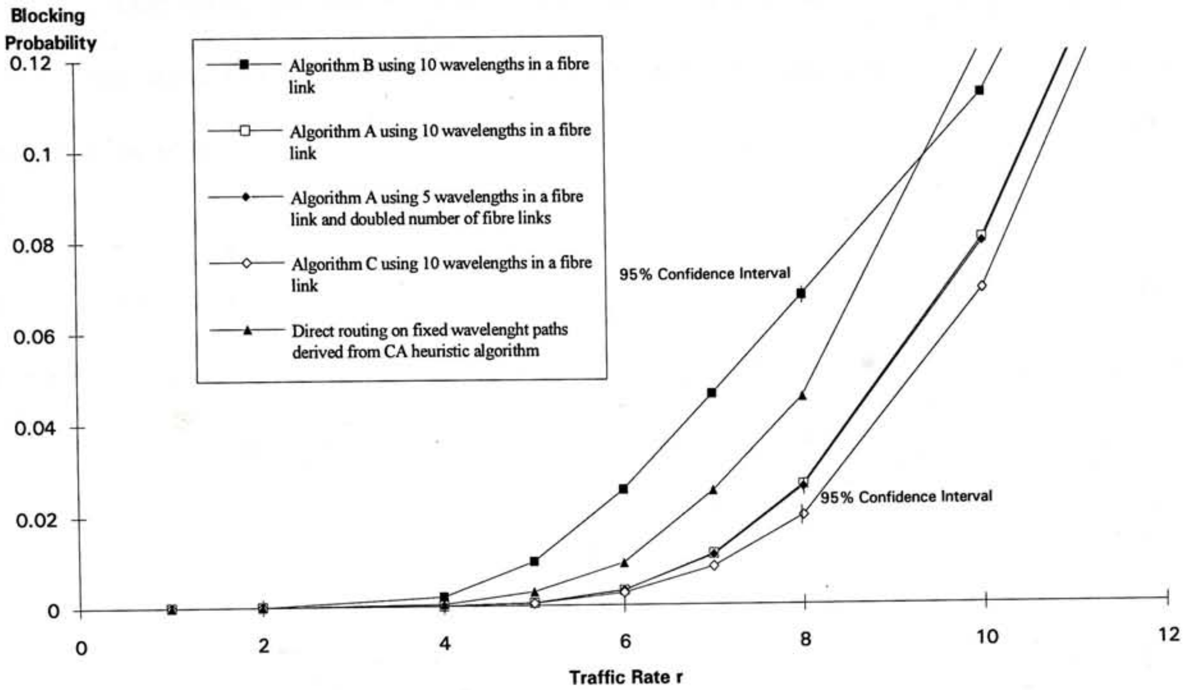

Figure 12 Comparison of the blocking performance between using dynamic and static wavelength channel assignment schemes for the 6-node network

In this section, we compare the blocking performance for the 6-node network between using dynamic and static wavelength channel assignment scheme at different traffic load. In figure 12, the dynamic algorithms use up to the second shortest routes for establishing the wavelength path. For the static assignment scheme, we use the heuristic algorithm for CA problem to obtain fixed wavelength paths for all the node pairs for a given traffic load. Then, the wavelength paths allocated for the wavelengths serving a node pair will permanently be reserved for the node pair. Direct routing scheme is adopted in this "fully-connected" wavelength paths network.

Figure 12 shows that using dynamic algorithms results in better performance than using direct routing on the fixed wavelength paths derived from the heuristic algorithm for CA problem except for algorithm B at medium and high traffic load. This is due to the fact that with dynamic algorithms, all free wavelength channels in the network are available for establishing new wavelength paths for all node pairs, while for static assignment scheme, once the wavelength paths are allocated to a specific node pair, all the wavelength channels are reserved for that node pair node even they are not occupied. Some free wavelength channels are thus wasted resulting in more blocking.

On the other hand, not all dynamic algorithms always perform better than the static assignment scheme as demonstrated by algorithm B because it does not even out the wavelength channel assignment over different links of the network and hence easily exhausts some of the critical links of the network. However, when the traffic gets higher ($r > 8$), the performance of static assignment scheme deteriorates sharply becoming the worse due to the wastage of sharable free wavelength channels.

From this results, we see that a heavier traffic can be handled by using a good dynamic algorithm like algorithm A as compared to using the static assignment scheme.

VII. Conclusion

An all-optical WDM-based lightwave backbone network is proposed and studied in this thesis. In the proposed network, we consider using only wavelength cross connects, optical transceivers and no wavelength conversion facilities are used. We have considered three problems for the proposed network.

The first one is the network dimensioning problem which considers finding the set of links and its capacities for establishing the network at minimum cost for a given location of switching nodes and traffic requirement. We have formulated the problem as a multi-commodity flows problem using integer programming. The original network was augmented to facilitate the formulation of the problem. A general cost function covering the cost of fibre links, switching systems and optical transceivers are adopted. As the solution to this optimization problem is formidable, we resort to a non-linear programming approximation by treating all the integer variables (fibre link quantities) as non-negative real variables and obtain a sub-optimal solution by rounding off the non-integral solution to the nearest feasible one. As the number of the fibre links are usually large, this approximation should give a decent solution.

We then consider the problems of how to set up or re-arrange wavelength paths in an established network to meet a changing traffic requirement or network facility reconfiguration due to failure or upgrade events. We first consider how to set up fixed wavelength paths for all node pairs such that the average blocking probabilities in the network is minimum for a given fibre link distribution matrix and traffic matrix when direct routing is adopted on these fixed wavelength paths for the node pairs. The is called the capacity apportionment problem. We have formulated the problem using integer programming. The solution to this optimization problem is still very complicated even we approximate those integer variables as real. For a fast response to such traffic variation and facilities failure events, a heuristic algorithm is therefore proposed. The algorithm tries to even out all the wavelength channel assignment over different links in the network.

The use of dynamic algorithms to set up the wavelength paths between node pairs are also studied. We propose three algorithms (algorithms A, B and C). For algorithm C, we assume wavelength conversion facilities are always available when needed. Its performance result is used for comparison to see the effect of the presence of wavelength converters when needed in the netwrok on resolving wavelength conflicts. Algorithm A selects the feasible wavelength channels on a shortest route that has minimum weighted sum of wavelength channel utilization profile variance on all links of the route to form the wavelength path. This is to make the wavelength utilization profile of the links as even as possible. Algorithm B selects the first available feasible wavelength channels on a shortest route linking the source and destination node pair to form the wavelength path. Algorithm C selects the feasible channels on a shortest route such that the sum of the wavelength channel utilization percentage of all its links is minimum. We compare the blocking performance for the three algorithms on a 6-node network by simulation. Simulation results show that Algorithm C gives the best performance among the three algorithms because the wavelength conversion facilities can resolve blocking caused by resolvable and unresolvable wavelength conflicts. Algorithm A performs much better than algorithm B showing that variance of wavelength channel utilization profile can serve as a good measure to even out the wavelength channel assignment over different links of the network. When algorithm A is compared to algorithm C, algorithm C performs only a bit better than algorithm A. This gives us a hint that full provision of wavelength conversion facilities in the network may not be necessary because unresolvable wavelength conflicts is not dominant. When we study the effect of length of route used for establishing different wavelength paths, we find that algorithm B get worse when we allow it to use up to second shortest routes for establishing wavelength paths while for algorithms A and C, they show improvement in the performance for including second shortest paths to establish wavelength paths. However, the improvement is more significant for algorithm C. This is because for algorithm A, as no wavelength conversion is done in the network, a longer route means a higher chance of having wavelength conflicts.

Finally, we compare the blocking performance between using dynamic and static wavelength channel assignment scheme for establishing wavelength paths for the 6-node network. For the static assignment scheme, the fixed wavelength paths established for the node pairs are derived from the heuristic algorithm for the CA problem. Direct routing is adopted in this "fully-connected" wavelength paths network for the node pairs. The blocking probabilities for using the static assignment scheme are thus obtained using Erlang-B formula given the number of fixed wavelength paths allocated by the algorithm and the traffic intensity between a node pair. The result shows that not all dynamic algorithms can perform better than the static assignment scheme as demonstrated by algorithm B. However, a good dynamic wavelength channel algorithms like algorithm A results in a lower blocking probabilities at medium and above traffic as compared to the case using static assignment scheme. This means that we can accept a heavier traffic by using a good dynamic algorithm like algorithm A as compared to using the static assignment scheme for a given blocking probability.

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Appendix A: Wavelength channel assignment plan generated by the heuristic algorithm for the illustrative example in section V

(i,j) denotes the source and the destination node to the wavelength channel is allocated. (--,--) means a free wavelength channel. Starting from the left, each bracket denotes a different wavelength channel from λ_1 up to λ_{10}.

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Assignment Plan for fibre link segment (0,1)
Link  3 ( 0,10)(--,--)( 0, 8)( 0, 8)(--,--)(--,--)( 0,10)( 0, 8)( 0, 8)( 0,10)
Link  2 ( 5, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0,10)
Link  1 ( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0,10)( 0, 8)( 5, 8)

Assignment Plan for fibre link segment (0,3)
Link  4 ( 0, 8)( 0, 8)( 0, 8)( 0,10)( 0, 8)( 0,10)( 0,10)( 0, 8)( 0, 8)( 0,10)
Link  3 ( 0, 8)( 0,10)( 0,10)( 0,10)( 0,10)( 0,10)( 0, 8)( 0,10)( 0,10)( 0, 8)
Link  2 ( 0,10)( 0, 8)( 0,10)( 0,10)( 0, 8)( 0, 8)( 0, 8)( 0,10)( 5, 8)( 0, 8)
Link  1 ( 0, 8)( 0,10)( 0, 8)( 0, 8)( 0,10)( 0, 8)( 0,10)( 0, 8)( 0, 8)( 0,10)

Assignment Plan for fibre link segment (0,5)
Link  2 ( 0,10)( 0, 8)( 0,10)( 0,10)( 0,10)( 0,10)( 0,10)( 0,10)( 0,10)( 0, 8)
Link  1 ( 0, 8)( 0,10)( 0,10)( 0,10)( 0,10)( 0, 8)( 0,10)( 0,10)( 0, 8)( 0,10)

Assignment Plan for fibre link segment (0,7)
Link  6 ( 3, 7)( 5, 7)( 5, 7)( 5, 7)( 5, 7)( 0, 7)( 0, 7)( 0, 7)( 0, 7)( 3, 7)
Link  5 ( 4, 7)( 0, 7)( 3, 7)( 5, 7)( 3, 7)( 3, 7)( 0, 7)( 5, 7)( 0, 7)( 4, 7)
Link  4 ( 3, 7)( 0, 7)( 5, 7)( 3, 7)( 0, 7)( 5, 7)( 3, 7)( 4, 7)( 4, 7)( 5, 7)
Link  3 ( 0, 7)( 5, 7)( 5, 7)( 0, 7)( 5, 7)( 3, 7)( 5, 7)( 3, 7)( 3, 7)( 0, 7)
Link  2 ( 3, 7)( 5, 7)( 0, 7)( 5, 7)( 3, 7)( 5, 7)( 5, 7)( 3, 7)( 5, 7)( 5, 7)
Link  1 ( 5, 7)( 5, 7)( 3, 7)( 4, 7)( 3, 7)( 5, 7)( 3, 7)( 3, 7)( 3, 7)( 4, 7)

Assignment Plan for fibre link segment (0,9)
Link  5 ( 1, 9)( 0, 9)( 0, 9)( 1, 9)( 1, 9)( 5, 9)( 5, 9)( 0, 9)( 5, 9)( 1, 9)
Link  4 ( 5, 9)( 1, 9)( 1, 9)( 0, 9)( 5, 9)( 1, 9)( 5, 9)( 5, 9)( 0, 9)( 1, 9)
Link  3 ( 1, 9)( 1, 9)( 5, 9)( 5, 9)( 5, 9)( 1, 9)( 1, 9)( 5, 9)( 5, 9)( 1, 9)
Link  2 ( 5, 9)( 5, 9)( 5, 9)( 1, 9)( 1, 9)( 1, 9)( 5, 9)( 1, 9)( 1, 9)( 1, 9)
Link  1 ( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 5, 9)( 5, 9)( 1, 9)( 5, 9)( 1, 9)( 5, 9)

Assignment Plan for fibre link segment (0,11)
Link  5 ( 1,11)( 0,11)( 2,11)( 3,11)( 0,11)( 0,11)( 1,11)( 3,11)( 0,11)( 0,11)
Link  4 ( 0,11)( 3,11)( 0,11)( 1,11)( 2,11)( 3,11)( 3,11)( 2,11)( 3,11)( 0,11)
Link  3 ( 0,11)( 1,11)( 1,11)( 3,11)( 0,11)( 1,11)( 3,11)( 0,11)( 1,11)( 3,11)
Link  2 ( 0,11)( 3,11)( 1,11)( 0,11)( 1,11)( 0,11)( 0,11)( 1,11)( 2,11)( 3,11)
Link  1 ( 2,11)( 3,11)( 3,11)( 3,11)( 1,11)( 3,11)( 1,11)( 1,11)( 3,11)( 0,11)

Assignment Plan for fibre link segment (1,0)
Link  4 ( 1,11)( 1, 9)( 1,11)( 1,11)( 1, 9)( 1,11)( 1,11)( 2,11)( 1,11)( 1, 9)
Link  3 ( 1, 9)( 1,11)( 1,11)( 1, 9)( 1,11)( 1, 9)( 1,11)( 1,11)( 2,11)( 1, 9)
Link  2 ( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1,11)( 1, 9)( 1, 9)( 1,11)( 1, 9)( 1, 9)
Link  1 ( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)

Assignment Plan for fibre link segment (1,2)
Link  5 ( 0,10)( 1,10)( 1, 9)( 1,10)( 1, 9)( 1,10)( 1, 9)( 1, 9)( 1, 9)( 0,10)
Link  4 ( 1,10)( 1,10)( 1,10)( 1, 9)( 1,10)( 1, 9)( 0,10)( 1, 9)( 1, 9)( 0,10)
Link  3 ( 1,10)( 1, 9)( 1, 9)( 1,10)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1,10)
Link  2 ( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1,10)( 1,10)( 0,10)( 1,10)( 1, 9)
Link  1 ( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)
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Assignment Plan for fibre link segment (1,6)
Link  4 ( 2, 6)( 2, 6)( 4, 6)( 2, 6)( 2, 6)( 1, 6)( 1, 6)( 2, 6)( 1, 6)( 1, 6)
Link  3 ( 2, 6)( 1, 6)( 2, 6)( 2, 6)( 1, 6)( 2, 6)( 2, 6)( 1, 6)( 1, 6)( 2, 6)
Link  2 ( 1, 6)( 2, 6)( 1, 6)( 2, 6)( 2, 6)( 2, 6)( 2, 6)( 1, 6)( 2, 6)( 2, 6)
Link  1 ( 4, 6)( 2, 6)( 2, 6)( 1, 6)( 2, 6)( 2, 6)( 1, 6)( 2, 6)( 2, 6)( 2, 6)

Assignment Plan for fibre link segment (1,8)
Link  3 ( 1, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 1, 8)( 0, 8)( 0, 8)( 1, 8)
Link  2 ( 5, 8)( 1, 8)( 0, 8)( 0, 8)( 1, 8)( 1, 8)( 0, 8)( 1, 8)( 0, 8)( 1, 8)
Link  1 ( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 5, 8)

Assignment Plan for fibre link segment (2,1)
Link  3 ( 2, 6)( 2, 6)( 4, 6)( 2, 6)( 2, 6)( 2, 6)(--,--)( 2, 6)( 2, 6)( 2, 6)
Link  2 ( 2, 6)( 2, 6)( 2, 6)( 2, 6)( 2, 6)( 2, 6)( 2, 6)( 2,11)( 2,11)( 2, 6)
Link  1 ( 4, 6)( 2, 6)( 2, 6)( 2, 6)( 2, 6)( 2, 6)( 2, 6)( 2, 6)( 2, 6)( 2, 6)

Assignment Plan for fibre link segment (2,3)
Link  4 (--,--)(--,--)(--,--)(--,--)(--,--)(--,--)(--,--)(--,--)(--,--)(--,--)
Link  3 ( 2, 6)(--,--)( 2,11)(--,--)( 2,11)(--,--)(--,--)( 2,11)( 2,11)( 4, 6)
Link  2 ( 2, 6)( 2, 6)( 2, 6)( 2, 6)( 4, 6)( 2, 6)( 2, 6)( 2, 6)( 2, 6)( 2, 6)
Link  1 ( 2,11)( 2, 6)( 2, 6)( 2, 6)( 2, 6)( 2, 6)( 2, 6)( 2, 6)( 4, 6)( 2, 6)

Assignment Plan for fibre link segment (2,4)
Link  4 (--,--)(--,--)( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)( 1, 9)( 1, 9)( 2, 6)
Link  3 ( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)
Link  2 ( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)
Link  1 ( 2,11)( 2,11)( 1, 9)( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)

Assignment Plan for fibre link segment (2,7)
Link  6 ( 2, 7)( 4, 7)( 3, 7)( 2, 7)( 2, 7)( 3, 7)( 3, 7)( 4, 7)( 5, 7)( 2, 7)
Link  5 ( 4, 7)( 3, 7)( 2, 7)( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 2, 7)( 3, 7)
Link  4 ( 3, 7)( 4, 7)( 4, 7)( 4, 7)( 2, 7)( 4, 7)( 4, 7)( 3, 7)( 2, 7)( 5, 7)
Link  3 ( 4, 7)( 4, 7)( 3, 7)( 3, 7)( 4, 7)( 3, 7)( 4, 7)( 4, 7)( 5, 7)( 3, 7)
Link  2 ( 4, 7)( 3, 7)( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 3, 7)( 3, 7)( 4, 7)
Link  1 ( 3, 7)( 4, 7)( 4, 7)( 4, 7)( 3, 7)( 4, 7)( 3, 7)( 4, 7)( 4, 7)( 3, 7)

Assignment Plan for fibre link segment (2,9)
Link  4 ( 2, 9)( 2, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 2, 9)( 2, 9)( 2, 9)
Link  3 ( 2, 9)( 1, 9)( 1, 9)( 2, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 2, 9)
Link  2 ( 1, 9)( 1, 9)( 2, 9)( 1, 9)( 1, 9)( 2, 9)( 2, 9)( 1, 9)( 1, 9)( 1, 9)
Link  1 ( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)( 1, 9)

Assignment Plan for fibre link segment (2,10)
Link  3 ( 0,10)( 2,10)( 2,10)( 2,10)( 2,10)( 2,10)( 2,10)( 2,10)( 2,10)( 0,10)
Link  2 ( 1,10)( 1,10)( 2,10)( 1,10)( 2,10)( 1,10)( 0,10)( 2,10)( 2,10)( 0,10)
Link  1 ( 1,10)( 1,10)( 1,10)( 1,10)( 1,10)( 1,10)( 1,10)( 0,10)( 1,10)( 1,10)

Assignment Plan for fibre link segment (3,0)
Link  4 ( 3, 7)(--,--)( 2,11)( 3,11)( 3, 7)( 3, 7)( 3,11)( 3,11)( 3,11)( 3, 7)
Link  3 ( 3, 7)( 3,11)( 3, 7)( 3, 7)( 2,11)( 3,11)( 3, 7)( 3, 7)( 3, 7)( 3,11)
Link  2 ( 3, 7)( 3,11)( 3,11)( 3,11)( 3, 7)( 3, 7)( 3,11)( 3, 7)( 3, 7)( 3,11)
Link  1 ( 2,11)( 3,11)( 3, 7)( 3,11)( 3, 7)( 3,11)( 3, 7)( 3, 7)( 3,11)( 4, 7)

Assignment Plan for fibre link segment (3,2)
Link  3 (--,--)(--,--)(--,--)(--,--)(--,--)(--,--)(--,--)(--,--)(--,--)(--,--)
Link  2 ( 3, 7)( 3, 7)( 3, 7)(--,--)(--,--)( 3, 7)( 3, 7)( 3, 7)(--,--)( 3, 7)
Link  1 ( 3, 7)( 3, 7)( 3, 7)( 3, 7)( 3, 7)( 3, 7)( 3, 7)( 3, 7)( 3, 7)( 3, 7)
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Assignment Plan for fibre link segment (3,4)
Link  3 ( 0, 8)(--,--)(--,--)(--,--)(--,--)(--,--)(--,--)( 3,11)( 2,11)( 3,11)
Link  2 ( 3,11)( 3,11)( 3,11)( 3,11)( 3,11)( 3,11)( 3,11)( 2,11)( 3,11)( 3, 7)
Link  1 ( 3,11)( 3,11)( 3,11)( 3,11)( 3,11)( 3,11)( 3,11)( 3,11)( 3,11)( 3,11)

Assignment Plan for fibre link segment (3,6)
Link  4 ( 2, 6)( 4, 6)( 2, 6)( 2, 6)( 4, 6)( 4, 6)( 2, 6)( 4, 6)( 2, 6)( 4, 6)
Link  3 ( 2, 6)( 2, 6)( 4, 6)( 4, 6)( 4, 6)( 2, 6)( 4, 6)( 2, 6)( 4, 6)( 2, 6)
Link  2 ( 4, 6)( 2, 6)( 4, 6)( 2, 6)( 4, 6)( 2, 6)( 2, 6)( 4, 6)( 4, 6)( 4, 6)
Link  1 ( 4, 6)( 4, 6)( 2, 6)( 4, 6)( 2, 6)( 4, 6)( 4, 6)( 2, 6)( 4, 6)( 2, 6)

Assignment Plan for fibre link segment (3,8)
Link  3 ( 3, 8)( 3, 8)( 3, 8)( 3, 8)( 3, 8)( 3, 8)( 3, 8)( 3, 8)( 0, 8)( 3, 8)
Link  2 ( 0, 8)( 0, 8)( 0, 8)( 3, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 5, 8)( 0, 8)
Link  1 ( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)( 0, 8)

Assignment Plan for fibre link segment (3,10)
Link  3 ( 3,10)( 3,10)( 3,10)( 0,10)( 3,10)( 0,10)( 3,10)( 3,10)( 3,10)( 3,10)
Link  2 ( 3,10)( 0,10)( 0,10)( 0,10)( 0,10)( 3,10)( 0,10)( 0,10)( 3,10)( 0,10)
Link  1 ( 0,10)( 0,10)( 0,10)( 0,10)( 0,10)( 0,10)( 0,10)( 0,10)( 0,10)( 0,10)

Assignment Plan for fibre link segment (4,2)
Link  4 ( 4, 7)( 4, 7)( 4, 6)( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 5, 7)( 3, 7)
Link  3 ( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 4, 6)( 4, 7)( 4, 7)( 4, 7)( 5, 7)( 5, 7)
Link  2 ( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 4, 6)( 4, 6)
Link  1 ( 4, 6)( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 4, 7)( 4, 7)

Assignment Plan for fibre link segment (4,3)
Link  2 ( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 7)
Link  1 ( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)

Assignment Plan for fibre link segment (4,5)
Link  3 ( 4, 7)( 4, 6)( 4, 6)( 4, 6)( 4, 6)(--,--)( 4, 6)( 4, 7)( 4, 7)( 4, 7)
Link  2 ( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 2, 6)
Link  1 ( 4, 6)( 4, 6)( 4, 6)( 4, 7)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)

Assignment Plan for fibre link segment (4,8)
Link  4 ( 5, 8)( 4, 8)( 5, 8)( 4, 8)( 5, 8)( 5, 8)( 5, 8)( 5, 8)( 4, 8)( 4, 8)
Link  3 ( 0, 8)( 4, 8)( 5, 8)( 5, 8)( 5, 8)( 4, 8)( 5, 8)( 5, 8)( 4, 8)( 0, 8)
Link  2 ( 5, 8)( 0, 8)( 5, 8)( 5, 8)( 4, 8)( 0, 8)( 5, 8)( 4, 8)( 5, 8)( 5, 8)
Link  1 ( 0, 8)( 5, 8)( 5, 8)( 5, 8)( 5, 8)( 5, 8)( 5, 8)( 5, 8)( 0, 8)( 4, 8)

Assignment Plan for fibre link segment (4,9)
Link  4 ( 5, 9)( 5, 9)( 4, 9)( 5, 9)( 5, 9)( 5, 9)( 4, 9)( 4, 9)( 5, 9)( 4, 9)
Link  3 ( 5, 9)( 5, 9)( 4, 9)( 4, 9)( 4, 9)( 5, 9)( 4, 9)( 1, 9)( 1, 9)( 5, 9)
Link  2 ( 4, 9)( 4, 9)( 5, 9)( 4, 9)( 5, 9)( 5, 9)( 4, 9)( 5, 9)( 4, 9)( 5, 9)
Link  1 ( 4, 9)( 5, 9)( 1, 9)( 5, 9)( 5, 9)( 4, 9)( 5, 9)( 5, 9)( 4, 9)( 5, 9)

Assignment Plan for fibre link segment (4,11)
Link  6 ( 2,11)( 4,11)( 4,11)( 2,11)( 2,11)( 2,11)( 2,11)( 3,11)( 2,11)( 4,11)
Link  5 ( 4,11)( 3,11)( 2,11)( 2,11)( 3,11)( 2,11)( 3,11)( 2,11)( 2,11)( 3,11)
Link  4 ( 3,11)( 2,11)( 2,11)( 3,11)( 2,11)( 3,11)( 2,11)( 2,11)( 3,11)( 2,11)
Link  3 ( 2,11)( 3,11)( 3,11)( 3,11)( 2,11)( 3,11)( 2,11)( 2,11)( 3,11)( 2,11)
Link  2 ( 3,11)( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)( 2,11)( 3,11)( 2,11)( 2,11)
Link  1 ( 2,11)( 2,11)( 3,11)( 2,11)( 3,11)( 2,11)( 3,11)( 2,11)( 2,11)( 3,11)
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Assignment Plan for fibre link segment (5,0)
Link  5 ( 4, 7)( 5, 7)( 5, 7)( 5, 7)( 5, 7)( 5, 9)( 5, 9)( 5, 7)( 5, 9)( 4, 7)
Link  4 ( 5, 9)( 5, 7)( 5, 7)( 5, 7)( 5, 7)( 5, 7)( 5, 9)( 4, 7)( 4, 7)( 5, 7)
Link  3 ( 5, 8)( 5, 7)( 5, 7)( 5, 9)( 5, 9)( 5, 7)( 5, 7)( 5, 9)( 5, 9)( 5, 7)
Link  2 ( 5, 7)( 5, 9)( 5, 9)( 5, 7)( 5, 9)( 5, 7)( 5, 7)( 5, 9)( 5, 7)( 5, 8)
Link  1 ( 5, 9)( 5, 7)( 5, 9)( 4, 7)( 5, 9)( 5, 9)( 5, 9)( 5, 9)( 5, 8)( 5, 9)

Assignment Plan for fibre link segment (5,4)
Link  6 (--,--)(--,--)(--,--)(--,--)( 5, 8)( 5, 8)(--,--)(--,--)(--,--)( 5, 9)
Link  5 ( 5, 8)( 5, 9)( 5, 8)( 5, 9)( 5, 9)( 5, 9)( 5, 8)( 5, 8)( 5, 9)( 0, 8)
Link  4 ( 5, 9)( 5, 9)( 5, 8)( 5, 8)( 5, 8)( 5, 9)( 5, 8)( 5, 8)( 5, 8)( 5, 9)
Link  3 ( 5, 9)( 0, 8)( 5, 8)( 5, 8)( 5, 9)( 0, 8)( 5, 8)( 5, 9)( 5, 7)( 5, 8)
Link  2 ( 5, 8)( 5, 8)( 5, 9)( 5, 8)( 5, 9)( 5, 9)( 5, 9)( 5, 8)( 0, 8)( 5, 9)
Link  1 ( 0, 8)( 5, 9)( 5, 8)( 5, 9)( 5, 8)( 5, 8)( 5, 8)( 5, 9)( 5, 7)( 5, 7)

Assignment Plan for fibre link segment (5,6)
Link  3 ( 5, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 5, 6)( 5, 6)( 2, 6)
Link  2 ( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 5, 6)( 4, 6)( 4, 6)( 4, 6)( 5, 6)
Link  1 ( 4, 6)( 4, 6)( 4, 6)( 5, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)( 4, 6)

Assignment Plan for fibre link segment (5,10)
Link  3 ( 0,10)( 5,10)( 5,10)( 5,10)( 0,10)( 0,10)( 5,10)( 0,10)( 5,10)( 5,10)
Link  2 ( 5,10)( 5,10)( 0,10)( 0,10)( 0,10)( 5,10)( 0,10)( 0,10)( 0,10)( 5,10)
Link  1 ( 5,10)( 0,10)( 0,10)( 0,10)( 5,10)( 5,10)( 0,10)( 5,10)( 5,10)( 0,10)
```

Source and Destination Node Pair	Blocking Probaility	Source and Destination Node Pair	Blocking Probability
0->7	0.000180	3->6	1.000000
0->8	0.017253	3->7	0.003222
0->9	0.046253	3->8	0.011984
0->10	0.010285	3->10	0.059569
0->11	0.000313	3->11	0.004984
1->6	0.000180	4->6	0.009611
1->8	0.052753	4->7	0.019649
1->9	0.009070	4->8	0.000070
1->10	0.019668	4->9	0.000313
1->11	0.019668	4->11	0.022080
2->6	0.001381	5->6	0.038330
2->7	0.013521	5->7	0.002825
2->9	0.059569	5->8	0.000159
2->10	0.000000	5->9	0.000438
2->11	0.004927	5->10	0.005023

The average blocking probability is equal to 0.011146.