DESIGN, PROTOCOL AND ROUTING ALGORITHMS FOR SURVIVABLE ALL-OPTICAL NETWORKS

BY

HUI CHI CHUN RONALD

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Abstract

Thanks to the rapid development of fiber communication technology, a new type of optical communication network, called *All Optical Network (AON)*, has been developed. With numerous wavelength channels propagating in a fiber, the AON transmission capacity greatly exceeds that of other communication networks. The development of AON also brings new challenges in the area of network management protocol, design, routing and network planning algorithms.

This thesis has investigated two heuristic algorithms for solving network dimensioning problem in network planning. A heuristic based on the concept of minimum variance is developed and the results are evaluated. Its results are compared with a shortest path algorithm.

On the other hand, this work also has a thorough study of the problem of restoration. We have proposed a new network management scheme for supporting AON restoration. The scheme includes a surveillance network, a signaling network and a network management system. We also present different algorithms related to the restoration of an AON. Two of them are complete lightpath restoration algorithms, which restore all working lightpath under any single-link failure. One is the source-based restoration algorithm and the other one is the link-based restoration algorithm. The performance of the algorithms are studied and discussed. Based on these algorithms, two network planning algorithms are also developed.

摘要

由於光纖通訊科技的發展，一種新型的光纖通訊網絡，全光學網絡(AON)已發展出來。透過眾多在光纖內前進的波頻，傳送量幾乎沒有限制。可是， AON 的高速發展亦帶來不少可靠性、路由、網絡管理及設計方面的問題。

由於通訊頻寬的急速增加，資料大量放在同一條光纖內。如以受影響的通訊計算，光纖失效造成的影響大幅增加。因此我們將考慮網絡恢復功能的問題。三個功能恢復的方法將被提出。另外兩個方法，一個基於起點恢復，一個基於連接恢復，會重新建立所有已建立而受到影響的光道。

此外，功能恢復的問題又與網絡管理這個新的問題息息相關。我們會提出一個令管理訊息快速傳遞的網絡管理新架構。

我們亦將研究網絡設計的問題，並會介紹一個基於最少偏差概念的方法。它的結果會跟另一個最短路程的方法比較。

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Chapter 1. Introduction

The rapid development of the Internet and the World Wide Web (WWW) has enabled us to acquire information at our fingertips any time, anywhere, and in any format. However, the capacity of the existing broadband-access infrastructure is insufficient to keep up with the huge bandwidth demands.

A new type of optical communication network, the all-optical network (AON) [1-2], has become one of the most viable architectures to achieve a scalable, high-capacity network with multiple access capability. In AONs, the optical transmission window in the fiber is divided into a number of non-overlapping wavelength bands. Each band can accommodate a single communication channel operating at high data rate. As a result, over 100 wavelength channels can be multiplexed on a single fiber, achieving a total capacity in the order of 100 Gbit/s [3]. Several large-scale testbeds are concurrently undertaking in the U.S. [4-5] and Japan [6]. The development trend indicates that the AONs will be deployed as the nationwide and global backbone networks.

In general, AON can broadly be classified into two different architectures, namely, broadcast and select type and wavelength routing type. Broadcast and select network assumes an architecture similar to radio broadcast where data from each transmitting node is equally distributed throughout the entire network. Data receiving can either be achieved by tuning the transmitter wavelength or the receiver wavelength. Wavelength routing network is similar to the existing circuit-switched network where certain pathway can be setup between the transmitter node and the receiver node using a particular wavelength. Such pathway may have to go through several routing nodes as long as there is no overlap of same wavelength along the pathway. In this thesis, we focus our investigation on wavelength routing network, as broadcast-and-select type network is limited to the local-area and metropolitan-area size networks. A main feature of wavelength routing networks is the employment of optical switches, called *wavelength cross connects (WCC)* [7], which is designed to switch a wavelength channel from an incoming fiber to a wavelength channel in an outgoing fiber in a routing node. The setting can be more complicated if wavelength converters are used. Wavelength converters can change the incoming wavelength to another wavelength but carrying the identical data. We will only investigate wavelength routing networks without using wavelength converters since the additional cost introduced by wavelength converters can be avoided.

In the wavelength routing network, the node-to-node connection is set by the WCC in the intermediate nodes along its path, or lightpath, which is formed by a set of concatenated common wavelengths. Signals will be transmitted in optical form along this lightpath without any optical-to-electrical conversion. Lightpaths are thus used to set up a virtual topology on top of a physical topology. A virtual topology can be changed from time to time by lightpath reconfiguration to satisfy the changing traffic demands. Meanwhile, lightpath reconfiguration is also very important to restoration in case of network failures.

In this thesis, we will investigate a number of issues of wavelength routing networks, including:

1. AON planning without restoration consideration
2. Network management scheme for supporting AON restoration
3. Network restoration algorithms
4. Network planning algorithms for AON with complete restorability

We first investigate the problem of network planning without considering any restoration capability. Lightpaths should be set up in a way such that minimum network construction cost is achieved while satisfying all traffic demands. Our work is continuation from a heuristic algorithm based on minimum variance of wavelength channel utilization, Minimum Variance Algorithm (MVA) [8]. This algorithm minimizes the cost of all network components, including WCC, fibers, transmitters and receivers, etc. We investigate the algorithm in details. The results are compared with those derived from an algorithm based on finding the shortest path.

Another important research topic of AON is the restoration problem under failure conditions. Since the wavelength routing network often serves as the backbone network in which a large amount of data is carried by each fiber, any cable failure will cause significant loss to many users in terms of downtime and data loss. Therefore, it is necessary to have some kind of network management system to restore the traffic with a minimum delay. Moreover, we also have to design algorithms that efficiently allocate spare capacity for lightpath restoration.

The network management scheme for restoration has been intensely investigated by many researchers previously. Although none of these networks are all-optical WDM networks, there exists a lot of relevance and adaptations and can be applied to wavelength routing networks. Previously, restoration of the Asynchronous Transfer Mode (ATM) network can be achieved by constructing a pool of backup paths [10,11]. When a failure occurs, a backup path is selected for restoration from the pool. Another scheme [12] is to implement an efficient signaling mechanism for restoration and fast switching.

Many algorithms are designed for solving the problem of routing and network planning with spare capacities by using linear integer programming. Link-based restoration [13-16] of non-AONs is achieved by applying min-cut theory. The papers in [17,18] investigated different lightpath routing algorithms. Constrained by a given working capacity, the work in [19] solved the problem of spare capacity planning of AON with a minimum cost using a rather complex cost model.

In order to meet the stringent requirement of low restoration delay, we propose a network management scheme specially designed for supporting instant fault detection and pre-planned restoration. Among the five areas of network management [20] which include accounting, configuration, performance, fault and security management, we will focus on network restoration, in particular on fault and configuration management. A passive surveillance scheme [21] is deployed to monitor every network element. Meanwhile, the management protocol data units are sent on an electrical signaling network based on the common channel signaling 7 (CCS7) protocol [22,23]. Fault management messages are transmitted in the signaling network after fault detection. The network manager then retrieves the pre-computed restoration lightpaths and resets the WCCs to provide the backup lightpaths.

We present two lightpath restoration algorithms from two different operating principles. They both are based on integer linear programming. The first restoration scheme called link-based restoration (*LBR*) which is based on identifying the available bypass lightpaths around the failed link. The second scheme called source-based restoration (*SBR*) which is based on identifying all possible available lightpath not passing through the failed link. Both algorithms consider the assignments of working lightpaths and restoration lightpaths simultaneously to find the optimum solution. Moreover, the algorithms can be extended to multiple-link failure cases. Furthermore, we do not assume any wavelength conversion at the WCCs.

In addition to the restoration issue, we also consider the fairness issue. When all demands are satisfied, the problem of routing fairness is resolved. However, the fairness issue [24] has to be considered together with the restoration issue when the network does not have sufficient capacity to meet all demands. Allocating too many lightpaths for some node pairs can be avoided by setting an objective function which is designed to minimize the maximum bandwidth deficiency among all node pairs.

Case studies on an 11-node testbed network, the NSFNET backbone network, and the European optical network are presented to compare the performances of the two algorithms. Examples of working and restoration lightpaths are also shown for both algorithms. Moreover, the two restoration algorithms are adapted to two completely restorable network planning algorithms, source-based planning (*SBP*) and link-based planning (*LBP*) algorithms.

This thesis is divided into the following chapters. Chapter 2 introduces the wavelength routing architecture. Chapter 3 investigates the network dimensioning problem which is related to designing an algorithm to minimize network construction cost. Chapter 4 discusses the management scheme for wavelength routing network restoration. Chapter 5 presents four restoration algorithms and their performances will be discussed. Chapter 6 concludes this work and discusses some future works.

Chapter 2. AON Architecture

The AON architecture of interest is wavelength routing network where an example of a 9-node network is shown in Fig. 1. The network basically consists of a photonic switching fabric, comprising multiple WCCs interconnected by fiber links to form an arbitrary topology. To setup connection from one node to another, a particular physical pathway for a particular wavelength, called a lightpath, is established through proper switching of the intermediate nodes along the pathway between the starting and terminal nodes. As shown by an example illustrated in Fig. 1, a lightpath connecting node A to node G using a wavelength channel λ_1 has to be routed through node B and node C. The wavelength channel λ_1 on link 1 has to be spatially connected to link 2 through intermediate node B. Again, λ_1 on link 2 has to be spatially connected to link 6 via node C. This wavelength assignment suggests that any other lightpath sharing the same link as this lightpath cannot use λ_1 , owing to wavelength conflict which occurs when more than one lightpaths attempt to use the same wavelength channel on a fiber. Moreover, it is assumed in this thesis that AON nodes are capable of providing wavelength add-drop function when serving the source or destination node of a lightpath. In an AON, each node contains a WCC but some are also attached with an access node. Those nodes without attached access node, such as node F and node G in Fig. 1, can only serve as the intermediate nodes of lightpaths while those with access node can serve as intermediate nodes and end nodes.

One of the advantages of using lightpaths as communication channels is that AON can become more survivable. After a failure occurs, a restoration lightpath will be set up so that signals can be switched to the restoration lightpath by WCC reconfiguration. We shall discuss the restoration issue at the AON node level in the later section of this chapter while the other issues are postponed to later chapters.

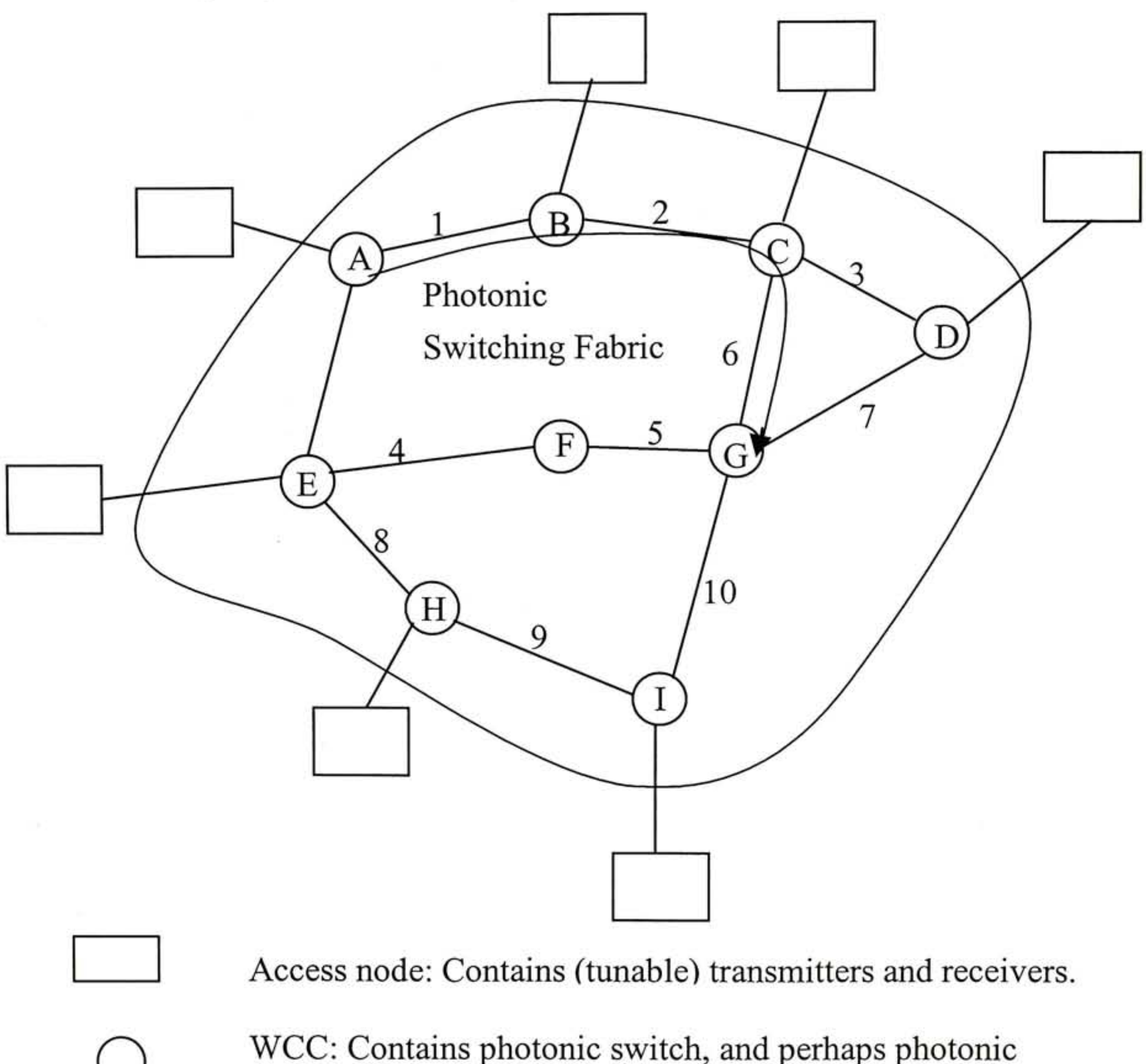

Fig. 1 A wavelength-routing (wide-area) optical network.

At a WCC, a certain wavelength from an input fiber is connected to a wavelength channel of a destined output fiber. Figure 2 shows the architecture of a WCC that can switch four wavelengths from each of the three input ports. As shown in the figure, the multiple wavelengths carried by an input fiber are first demultiplexed by an optical demultiplexer so that signals in wavelength channel λ_k is directed to the switch for λ_k. The switch can be formed by 2x2 optical switches arranged in Banyan based fabric. Signals are switched to the output ports corresponding to their output fibers. At the multiplexer stage, signals with different wavelengths from various switches are multiplexed on to each output fibers by an optical multiplexer.

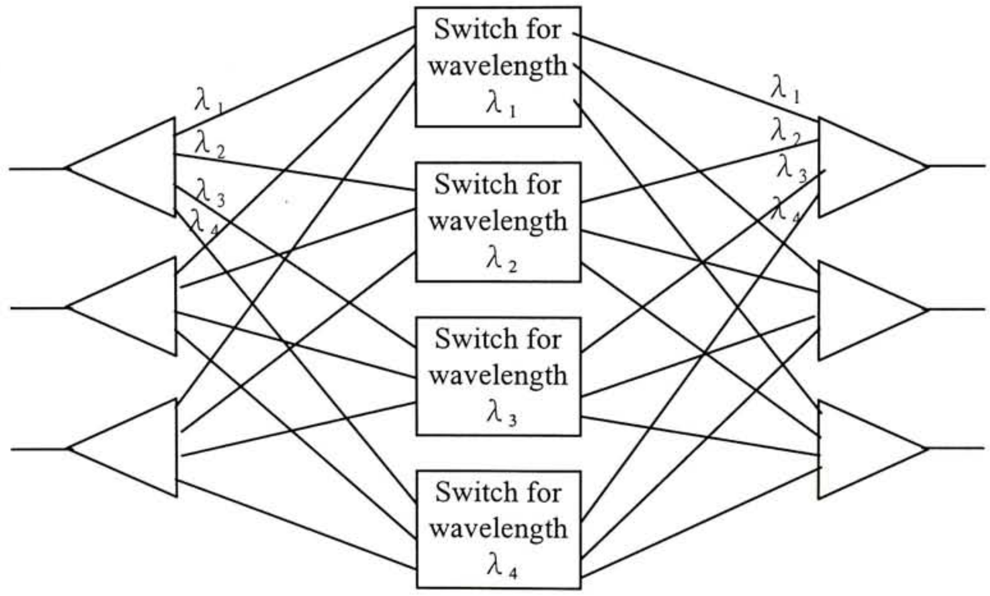

Fig. 2 A WCC architecture.

The lightpath can carry a time multiplexed signal and so can be shared by multiple end users attaching at the access node, which often equips with multiple-wavelength optical transmitters and multiple-wavelength optical receivers that are tuned to the wavelength on which the lightpath operates. There are different schemes for wavelength selection: a wavelength can be tunable at the transmitter but fixed tuned at the receiver, or wavelength fixed tuned at the transmitter but tunable at the receiver, or tunable in both transmitter and receiver. A summary of the technology can be found in recent issue of IEEE Communication Magazine [25].

2.1 WCC Dimension Reduction Node Architecture

In this section, a new node architecture is proposed. This architecture is used in Chapter 3 for reducing network construction cost during the network planning phase. But first we introduce the conventional architecture in Fig. 3. Signals coming from transmitters at the attached access node are directed to the input ports of a WCC for switching to outgoing fibers. Meanwhile, signals from other nodes are switched to the output ports connecting with the receivers at the attached access node. Optical amplifiers are appended at those output ports that link the fibers connecting to other nodes.

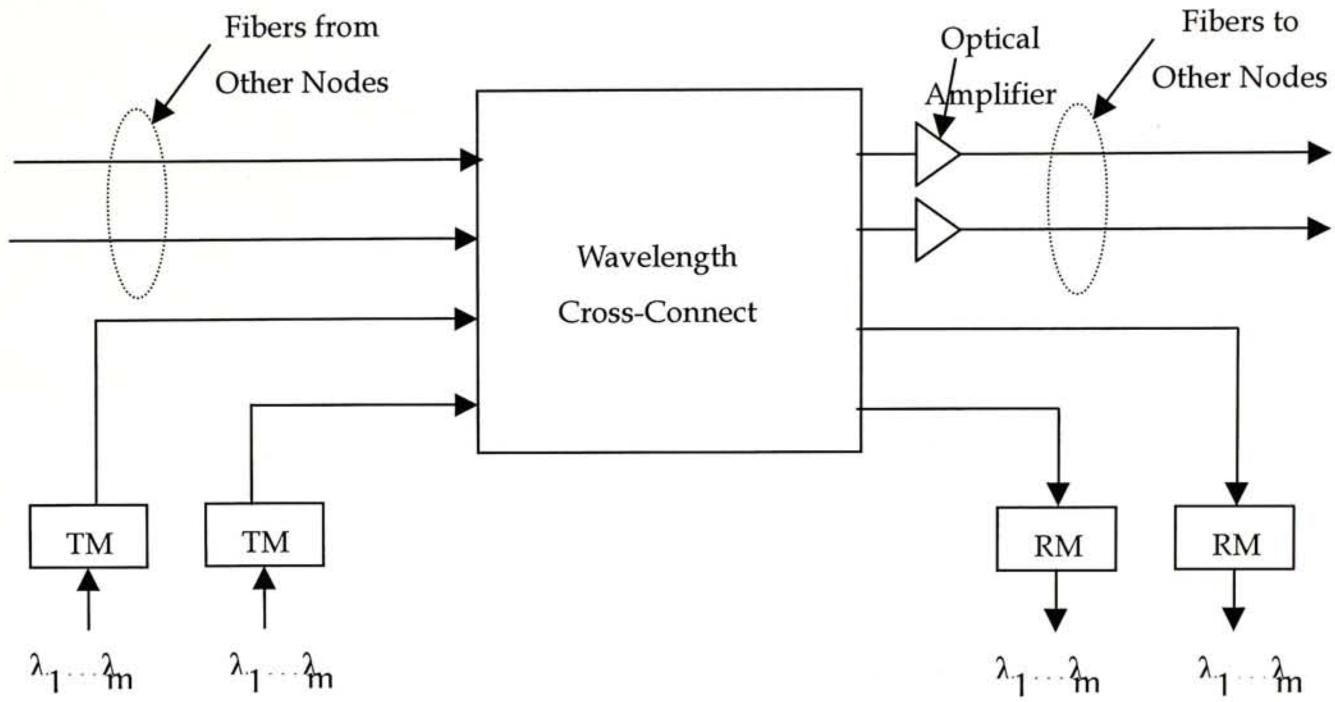

Figure 3. The conventional node architecture, where TM is transmitter module and RM is receiver module.

Our proposed architecture is a variation of the conventional architecture. This architecture, called WCC dimension reduction node architecture, allows some of the input fibers to terminate directly at the destination node without passing through the WCC. Therefore, there are two types of fibers linking the AON nodes, transit fibers and direct fibers. Transit-fiber links terminate at the WCC, while direct-fiber links terminate at the receiver module of the destination node. As shown in the Fig. 4, signals can be directly sent from the transmitter module from one node to the adjacent nodes through the direct fibers. Meanwhile, signals carried in transit fibers are routed by a

WCC to outgoing fiber links. Any switching between a transit fiber to a direct fiber can be assisted by an optical relay which serves as hybrid between direct and transit fibers.

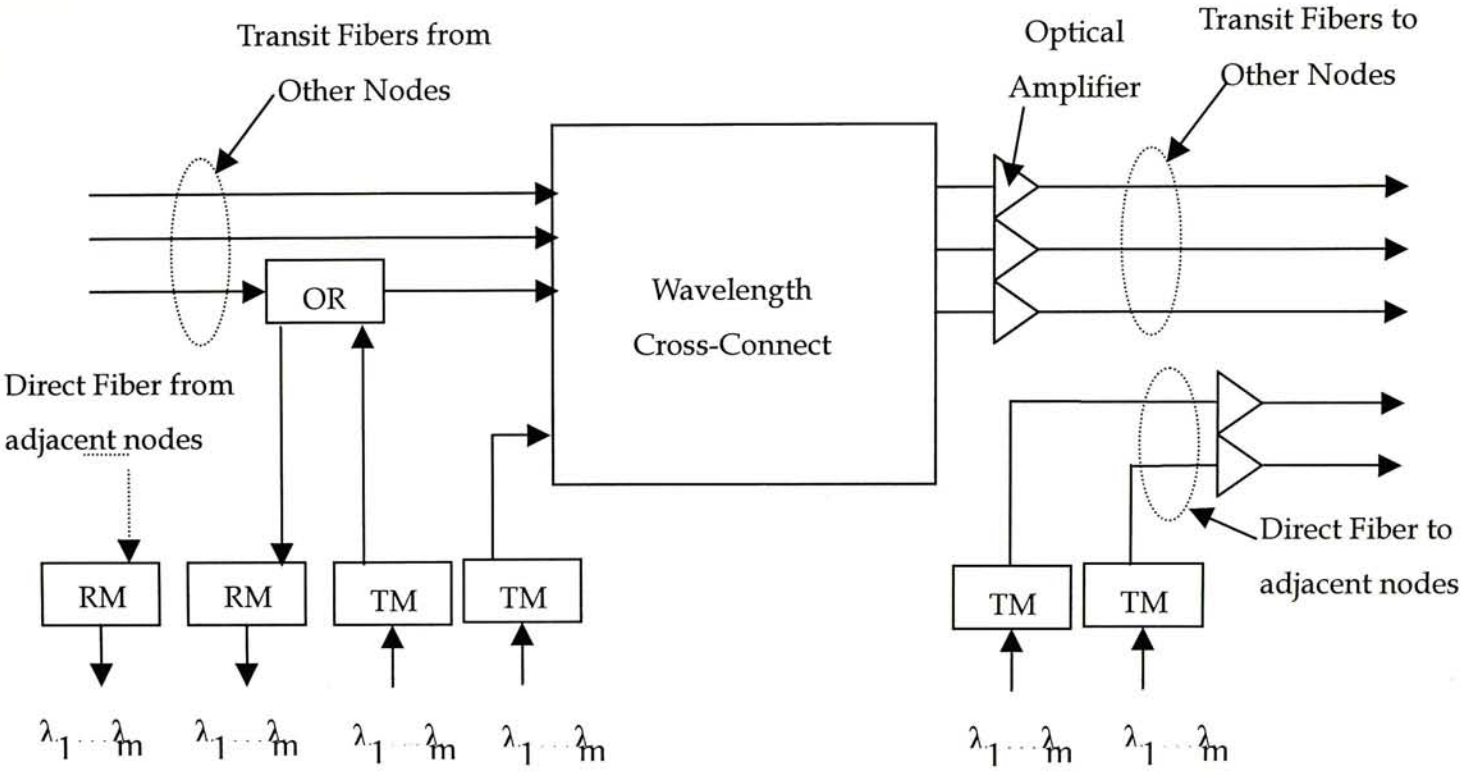

Figure 4. The proposed node architecture, where OR is the optical relay.

The main advantage of direct fiber links is the reduction in the dimension and thus the complexity of the WCC. For w incoming fibers consisting of w_1 transit and w_2 direct fibers, the dimension of the WCC in our proposed configuration is w_1^2, instead of $(w_1+w_2)^2$ of the conventional architecture. It is justified to use this configuration if there is little variation in the traffic pattern between two adjacent nodes.

The following example illustrates how lightpaths are established in a network using this node architecture. In Fig. 5, a lightpath between nodes 1 and 5 can be established by occupying wavelength λ_k on transit fiber links (1,3), (3,4) and direct fiber link (4,5), assuming the wavelength λ_k is available along all these links. Node 3 and 4 will serve as the switching nodes, and node 1 and 5 will be the corresponding source and terminal nodes.

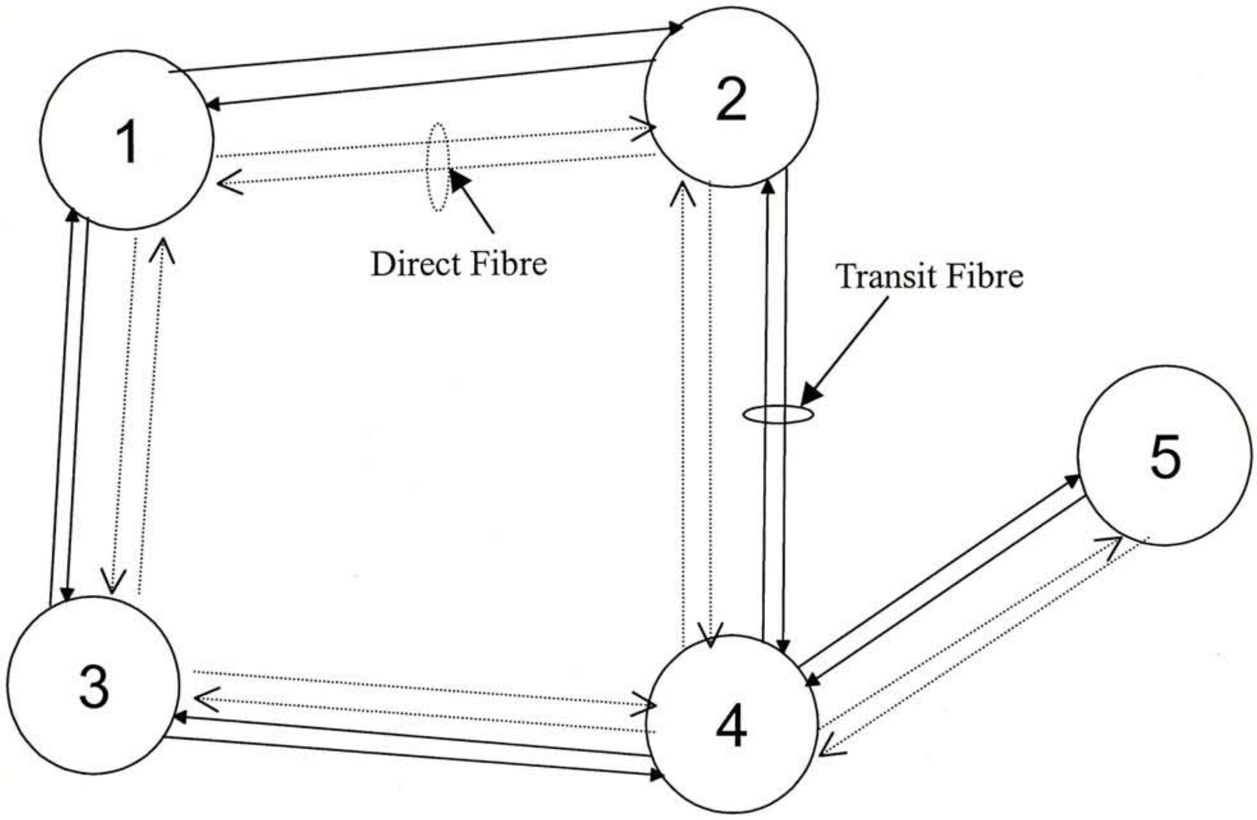

Figure 5. An example of a 5-node AON.

2.2 Restoration of a Survivable AON

Changing of the virtual topology requires the switch reconfiguration in the switch banks in each of the intermediate nodes. Reconfiguration will not occur very often in an AON. It is only needed when drastically different traffic demand is imposed on the network, or a bypass of faulty conditions in fiber links and intermediate nodes is required. Both node architectures shown in Fig. 3 or Fig. 4 can perform WCC reconfiguration. This section concentrates on the discussion of the reconfiguration process for AON restoration using the node architecture shown in Fig. 3.

A restoration lightpath may occupy a wavelength channel different from that of the working lightpath it restores. Therefore, lightpath restoration not only requires the reconfiguration of WCCs, but may also requires a change in wavelength channels. As a result, tunable transmitters and receivers are needed for changing wavelength channels. Lightpath restoration consists of the following processes. Firstly, the restoration lightpath is set up by the WCC along the new pathway. Moreover, at the source node of the lightpath, the wavelength of the transmitter may have to be changed if the wavelength of the working lightpath differs from that of the restoration lightpath. For the same reason, the receiver at the destination node may have to change wavelength it operates too. Indicated by the network management messages described in Chapter 4, a wavelength control module should be installed at each node to control the wavelengths on which the transmitters and the receivers operate.

Chapter 3. Network Dimensioning Problem

The traffic pattern in a network is usually periodic in nature. Within a certain period, we can divide the time into contiguous segments such that the traffic in each segment is approximately constant. A typical period could be a 24-hour day or a seven-day week. Assuming we are free from a given network topology (e.g. network planning), the network dimensioning problem can then be stated as follows: for a given set of traffic patterns (one for each time segment), determine the lightpath assignments for different time segments such that utilized resources are kept at the minimum. The network resources include wavelength channels, optical fibers, optical amplifiers, wavelength cross-connects, fixed tuned transmitters and fixed tuned receivers, optical relays, and other components necessary in the network, all of which can be translated to the system implementation cost. The complexity of this problem can be reduced by solving the two following inter-connecting problems:

- Lightpath assignment for different traffic patterns on different time segments;
- Number of optical fibers required to be installed between each node pair.

The lightpath assignment is further complicated by the presence of wavelength conflict, which occurs when there is no common wavelengths available along all paths connecting the source and destination nodes. This wavelength conflict problem can be resolved for networks with wavelength conversion, which is a simplified case of the network without the conversion capability.

3.1 Problem Setting

Let the traffic rate and the traffic matrix between the node pair *(i,j)* in time segment h be $t_{ij}(h)$ and $T(h)=[t_{ij}(h)]$, respectively. Let H be the number of time segments in a period and let $\{T(h)\}$ be the set of H traffic matrices. Given the location of the switching nodes and the set of traffic matrices $\{T(h)\}$, a general way of expressing the network dimensioning problem is to assign capacities to a set of candidate links of the network such that the blocking performance requirements are satisfied throughout the period at minimum resources.

An exact treatment of this problem is very complicated. To circumvent the complexity of the problem, we adopt the static approach which allows fixed lightpaths be established between the node pairs for the whole time segment. We assume the arrival of lightpath connection requests is a Poisson process and the connection holding time is exponentially distributed. Therefore, for a given blocking performance requirement, we can use the Erlang-B formula to transform the set of traffic matrices $\{T(h)\}$ to a set of lightpaths requirement or demand matrices $\{D(h)\}$ where $D(h)=[d_{st}(h)]$ and $d_{st}(h)$ is the number of lightpath required between node pair *(s,t)* in time segment h. Two solution approaches, one based on integer programming and the other on heuristic, are described in the following section.

3.2 Two Solution Approaches

Two solution approaches, one based on minimum variance and the other one based on shortest path is presented. We assume that WCC dimension reduction node architecture is applied in these algorithms.

3.2.1 Minimum Variance Algorithm (MVA)

The total number of routes R_o is an exponential function of the number of nodes n in the network. To start with, we choose $R_o \leq \alpha$ between any node pair. The total number of the candidate routes is then restricted to no more than $\alpha n(n-1)$ for an n-node network. Let us denote this set of candidate routes as R.

For a given source and destination node pair *(s,t)* with traffic matrices *D(h)*, we begin by putting an optical fiber between each connecting node pair for every possible route connecting *(s,t)*. The total fiber-link cost is calculated for each of these routes. For as long as $D(h)_{mn}>0$, we will keep on assigning lightpaths with unused wavelengths connecting the *(s,t)* by applying the Minimum Variance Subroutine (MVS) as described in 4.2.2. For each possible route, the average cost of setting up a lightpath is then evaluated by dividing the total cost of fiber links on that route with the number of lightpaths that can be established by the subroutine. We then choose the route that yields minimum average cost. This procedure is repeated until demands in all time segments *{D(h)}* are satisfied. The following is the pseudo code for MVA.

Initialization

- *Construct R, the set of all candidate routes linking the node pairs with* $d_{st}(h) > 0$ *of the network.*

- *Set* $L_{ij} = 0$ *for all i,j*
- *Set* $X^k_{ij,st}(h) = 0$ *for all i,j,s,t,k,h*
- *Set* $e_{st}(h) = d_{st}(h)$ *for all s,t,h, where* $e_{st}(h)$ *is the unsatisfied lightpath numbers between node pair (s,t) in time segment h.*

Repeat

{ 1. *For each* $r \in \Re$,

{

a) *Increase the number of fiber links along each segment of r by one,*

$$L^{\#}_{ij} = L_{ij} + 1 \qquad \text{if segment } (i,j) \in r$$

Calculate the incremental cost, ΔZ *, for adding the fiber links on route r as*

$$\Delta Z = Z\left(L^{\#}_{ij}\right) - Z\left(L_{ij}\right)$$

b) *Apply MVS with* $\{X^k_{ij,st}(h)\}$, $\{L^{\#}_{ij}\}$ *and* $\{e_{st}(h)\}$ *as input to obtain an updated lightpath assignment plan.*

c) *Add up the number of new lightpaths established in all time segments from the wavelength assignment plan and denote it by u.*

d) *Calculate the cost per lightpath,* $c = u^{-1}\Delta Z$

}

2. *Denote the route that gives minimum c as* r^*
3. *Update the link count on* r^*, $L_{ij} \leftarrow L_{ij} + 1$ *if* $(i,j) \in r^*$, *the cost* $Z = Z + \Delta Z|_{r^*}$ *and* $\{X^k_{ij,st}(h)\}$, $\{e_{st}(h)\}$ *based on the lightpath assignment plan for* r^*.
4. *Identify all source-destination node pairs that have their lightpath requirements satisfied, i.e. those (s,t) pairs with* $e_{st}(h) = 0$, $1 \le h \le H$ *and denote them by the set of Y.*
5. *Remove all routes belonging to Y from R.*

} *Until all* $e_{st}(h) = 0$.

3.2.2 Minimum Variance Subroutine (MVS)

The wavelength utilization profile of the fiber links between all adjacent node pair *(i,j)* in time segment *h* is given by $\{X_{ij}^k(h)\}$ where $X_{ij}^k(h)$ is the number of assigned lightpaths between *(i,j)* using λ_k in time segment *h*, and $1 \le k \le m$. $X_{ij}^k(h)$ equals to

$$X_{ij}^k(h) = \sum_{s=1}^{n} \sum_{t=n+1}^{2n} X_{ij,st}^k(h)$$

where $X_{ij,st}^k(h)$ equals to $X_{ij}^k(h)$ under the constraint that the source and terminal node pair must be *(s,t)*.

The variance of the wavelength utilization profile, $V(r_{st}, k, h)$, is then

$$V(r_{st}, k, h) = \sum_{(i,j) \in r_{st}} \left\{ \sum_{\substack{l=1 \\ l \neq k}}^{m} \left(X_{ij}^l(h) - \overline{X_{ij}(h)} \right)^2 + \left(X_{ij}^k(h) + 1 - \overline{X_{ij}(h)} \right)^2 \right\}$$

with respect to k *and* r_{st}. Here, $\overline{X_{ij}(h)} = m^{-1}\left(1 + \sum_{k=1}^{m} X_{ij}^k(h)\right)$ is the mean of wavelength utilization on link segment *(i,j)* in time segment *h* for every new lightpath assigned. This variance function is the measure for the uniformity of wavelength utilization in the network. It can be argued that the more uniform the profile, the fewer the chance the wavelength conflict occurs, thus requiring fewer number of fiber links established between nodes. Feasible route has a common set of free wavelengths on all its links of the route and can be expressed mathematically as:

$$x_{ij}^k(h) + 1 \le L_{ij}^{\#} \quad \textit{for all link segments } (i,j) \textit{ on } r_{st}, \textit{ where } r_{st} \in R_{st}$$

R_{st} is the set of all feasible routes for node pair *(s,t)*. We then extend the search for all possible *(s,t)* and λ_k, and determine the route with minimum variance denoted by $f_{st}(h)$. This process continues until no more lightpath can be set up in any time segments.

The idea behind this algorithm is that a good wavelength-path connection plan should make full use of all the wavelengths on all fiber links. The ideal case is that all wavelengths on the fiber links are used up for establishing lightpaths, which corresponds to zero variance in the wavelength utilization profiles. The following is the pseudo code for the *MV* subroutine:

Input: $\{L_{ij}^{\#}\}$ *Fiber links Count between node i and node j*

$\{X_{ij,st}^{k}(h)\}$ *Lightpath connection plans*

$\{e_{st}(h)\}$ *Unsatisfied lightpath numbers between nodes s and t*

for $1 \le h \le H$ *do {*

Construct U as the set of source-destination node pairs with $d_{st}(h) > 0$

Repeat{

for every node pair (s,t) in U do

{ Construct R_{st} *the set of all feasible routes for node pair (s,t).*

For a non-empty R_{st} *, obtain*

$$f_{st}(h) = \min_{\forall r_{st} \in R_{st}} \left\{ \min_{1 \le k \le m} \{ V(r_{st}, k, h) \} \right\}$$

and the corresponding k and r_{st} *values*

}

Select the node pair that has minimum $f_{st}(h)$ *for establishing a new lightpath using the* *corresponding* λ_k *and* r_{st}. *If the lightpath requirements for this node pair are satisfied, remove it from U.*

Update $\{X^k_{ij,st}(h)\}$ *and* $\{e_{st}(h)\}$.

} until no more feasible routes exist for all node pairs

}

A simple counting of the nested loops in the greedy algorithm and the MVS shows that the complexity equals to $H\alpha^2[n(n-1)]^3$, or $O(n^6)$. Typically for an optical backbone network of 5-20 nodes, the dimensioning problem can be solved within a reasonable time.

3.3 Shortest Path Algorithm (SPA)

In order to demonstrate how the MVA can maximize the wavelength utilization in an optical network, we compare it to another algorithm based on shortest path. Being itself also a greedy algorithm, the SPA pseudo codes are similar to that of the MVA. It establishes the lightpath based on the shortest distance between the source and destination. Using SPA, the cost of setting up a lightpath is proportional to the sum of the costs of fiber installation including all the links that the lightpath transverses. Since the cost of installing fibers is largely proportional to the distance between two nodes, the lightpath with the shortest distance also yields a local minimum cost.

3.4 An Illustrative Example

The minimum cost achieved by the SPA is only a local optimization and the resources may not be fully utilized for setting up all the lightpaths. The MVA can maximize the number of commonly available wavelengths in the network and thus the chances of wavelength conflicts are reduced. Consequently, MVA maximizes the wavelength utilization in the network and achieves an overall more efficient and better cost-saving configuration than that provided by SPA.

The main advantage of lightpath assignments by MVA is illustrated by the following example. As shown in Fig. 7a, there are altogether five nodes *(N1, N2, ... N5)* interconnected in our illustrated network. We deliberately set the node distances *N3-N2-N5* to be shorter than *N3-N4-N5*. We assume that each inter-connecting node pair is linked by one single fiber with a capacity of carrying up to m=4 wavelengths and only a single time segment, i.e., H=1, in the network. Table 1 shows the traffic pattern.

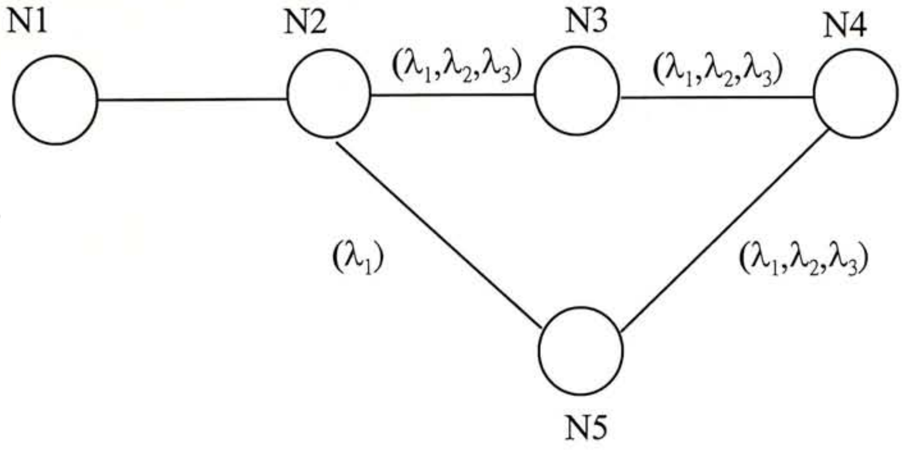

Figure 7a Initial wavelength assignments for our illustrative network.

Node pair	Traffic demand
N1-N5	3
N2-N3	3
N2-N5	1
N3-N4	3
N3-N5	1
N4-N5	3

Table 1: Traffic patterns for our 5-node illustrative example.

The wavelengths that fulfill existing traffic demands between node pairs *(N2,N3), (N3, N4), (N4,N5)* and *(N2,N5)* are represented by the number of occupied wavelength $(\lambda_1,\lambda_2,\lambda_3)$, $(\lambda_1,\lambda_2,\lambda_3)$, $(\lambda_1,\lambda_2,\lambda_3)$ and (λ_1) respectively, as shown in the figure. The demand request for *(N3,N5)* and *(N1,N5)* in Table 1 are yet to be satisfied.

To setup an additional lightpath between *N3* and *N5*, we can select λ_4 transversing either on route r_{325} (via nodes *N3-N2-N5*), or on route r_{345} (via nodes *N3-N4-N5*). Using SPA, the path with the shortest distance, i.e., r_{325}, will be chosen. Using MVA, the variances of the two lightpaths r_{325} and r_{345} are calculated, and the path with the smallest variance, i.e., r_{345}, will be selected. The computations of the variances are shown in Table 2.

$X_{2,3}^{1}=1$	$X_{2,3}^{2}=1$	$X_{2,3}^{3}=0$	$X_{2,3}^{4}=0$
$X_{2,5}^{1}=1$	$X_{2,5}^{2}=0$	$X_{2,5}^{3}=0$	$X_{2,5}^{4}=0$
$X_{3,4}^{1}=1$	$X_{3,4}^{2}=1$	$X_{3,4}^{3}=1$	$X_{3,4}^{4}=0$
$X_{4,5}^{1}=1$	$X_{4,5}^{2}=1$	$X_{4,5}^{3}=1$	$X_{4,5}^{4}=0$
$\overline{X_{2,3}}=0.75$	$\overline{X_{3,4}}=1$	$\overline{X_{2,5}}=0.75$	$\overline{X_{4,5}}=1$
$V(r_{325},4)=0.75$		$V(r_{345},4)=0$	

Table 2. The variances of the two lightpaths.

The path assignments by the MVA and the SPA are given respectively in Fig. 7b and Fig. 7c. Note that by selecting path r_{345}, the capacity limit in *(N3,N4)* and *(N4,N5)* is reached and no more wavelength can be inserted into these links. There is, however, extra wavelength capacity available between nodes *(N2,N3)* and *(N2,N5)*. For the SPA case, a new fiber has to be installed to setup three lightpaths between nodes *(N2,N5)* since there are only two commonly available wavelengths λ_2 and λ_3 on the path r_{125}. The assignment of the lightpath by using MVA may not necessarily be the shortest path, but the algorithm reserves more wavelengths on the links connecting *N2* and *N5*, thereby increasing the chance of finding common available wavelengths in future lightpath assignments.

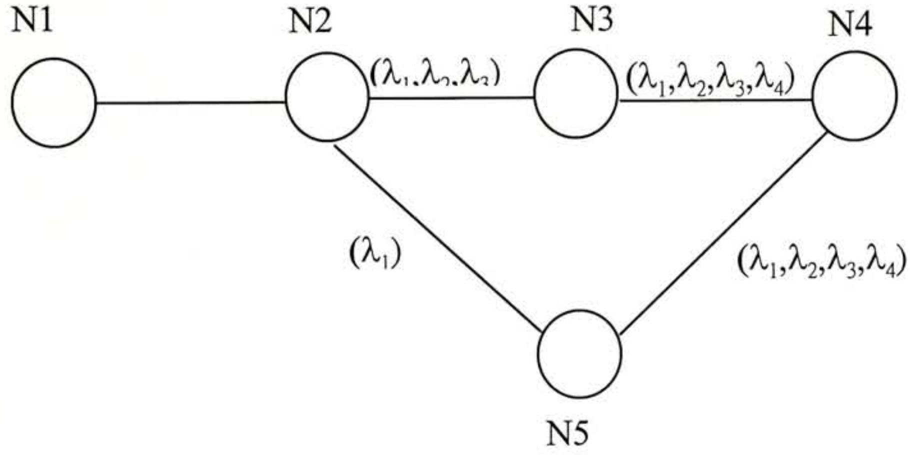

Figure 7b Wavelength-assignment after a lightpath is setup by using λ_4 on the path r_{345} when MVA is used.

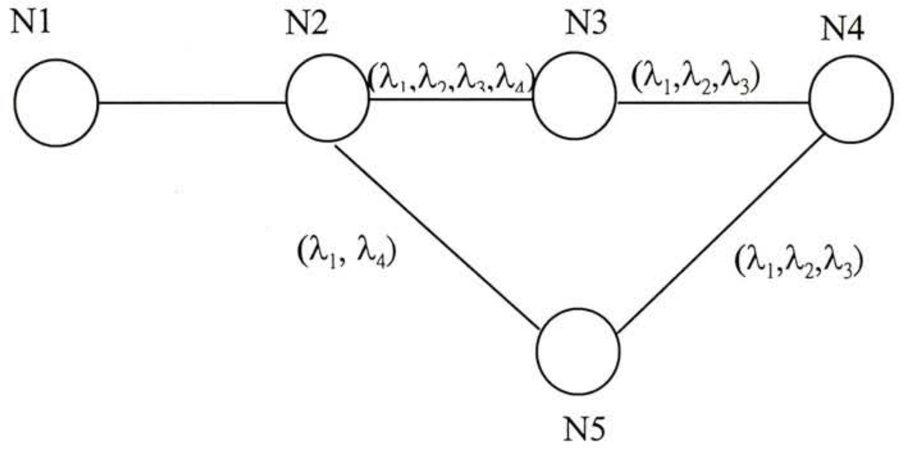

Figure 7c. Wavelength assignment after a lightpath is setup by using λ_4 on the path r_{325} when SPA is used.

3.5 Performance Comparisons

We assume 9 nodes are to be interconnected to form an optical backbone. Different combinations of randomly generated cost and demand matrices are inputted into MVA and SPA and the resulting networking costs are compared and analyzed. There are altogether three cost matrices *C1*, *C2* and *C3*. The traffic loads of the demand matrices vary from 200 to 3000, where the loads are defined as the total number of lightpaths required to be set up over the network. The number of wavelengths in the fibers, m, is taken to be 4, 8 and 16. The range of traffic demands (number of lightpath) and normalized fiber installation costs between any node pair is between 0 and 10. The costs of components other than optical fibers are absorbed by the normalized fiber installation cost and will not be treated as separate entities. The number of time segments H is taken to be 3. In our computation, the cost function of installing fibers is similar to the typical installation cost shown in Fig. 8.

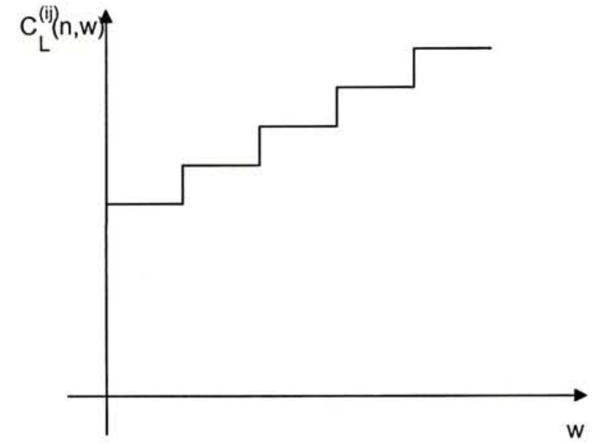

Figure 8. Typical fiber installation cost as a function of fiber number *w*.

Figure 9 shows the normalized cost as a function of the traffic load predicted by the MVA and SPA for $m = 4$, 8 and 16 and using cost matrix *C1*. In general, both MVA and SPA give a linear increase in cost as the traffic demand increases. Also, the cost decreases as m increases. Over the range of traffic load studied, the projected cost calculated by MVA is uniformly lower than that predicted by SPA. Similar results are obtained for different cost matrices *C2* and *C3*.

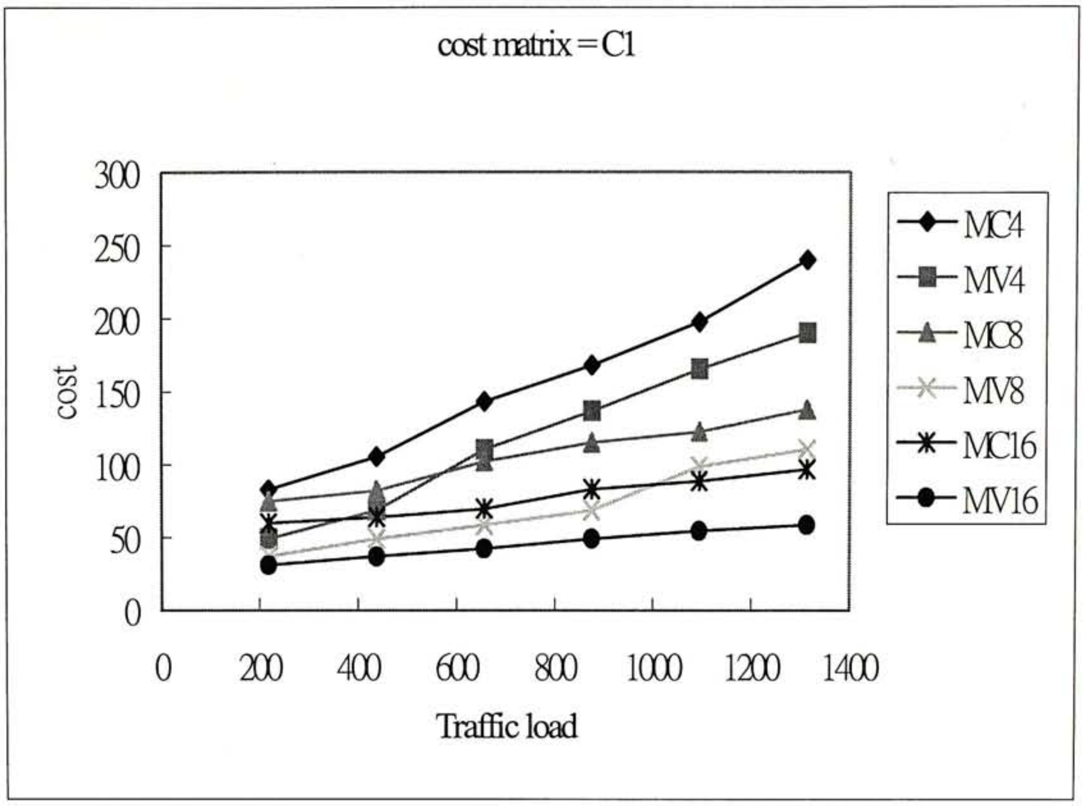

Figure 9. Network installation cost versus traffic load using cost matrix *C1*.

Table 3 further compares the two algorithms by evaluating the ratio of the average projected costs q, q = (average projected cost by MVA)/(average projected cost by SPA), for different cost matrices and number of wavelength. The average cost is generated over different traffic matrices. In general, q decreases as m increases. The results are similar to those obtained in Fig. 9.

Cost matrix Number of Wavelength	C1	C2	C3
4	0.743923	0.494199	0.821689
8	0.646571	0.454908	0.779649
16	0.587841	0.448158	0.756901

Table 3. The average cost ratio for different combinations of cost matrices and wavelength numbers.

For a given traffic matrix, the costs predicted by both MVA and SPA differ substantially. The much larger cost projection by SPA over MVA (20%-60% see Table 3) suggests that the total number of installed fibers is also larger in the SPA case. Consequently, the maximum network capacity scales accordingly, even though the number of request lightpath remains the same for both cases. This also implies that there are more unused wavelengths in the lightpath assignment generated by SPA. We can therefore argue that the wavelength conflict is more serious in the lightpath assignment generated by SPA than that from MVA.

We further investigate how the projected cost changes as wavelength increases for a given fixed number of installed optical fibers. Here, we only consider the case in which the cost is predicted by MVA, since we have already demonstrated MVA is superior than SPA. As the number of wavelength, or lightpath, doubles, the traffic capacity of the optical network will also double. Conversely, the fiber installation cost will be reduced by a maximum of 50% under the same traffic load. This effect is demonstrated in Table 4, showing that the projected cost by MVA (about 30-40% cost reduction) using the cost matrix *C1*. Similar results are obtained for cost matrices *C2* and *C3*.

Wavelength No. / Traffic loads	4	8	16
1200	110.6	66.5	44
1500	132.6	77.3	51.2
1800	155	89.3	56.2

Table 4: Assignment results for different combinations of wavelength numbers and traffic loads using cost matrix *C1*.

Chapter 4. Network Management for AON Restoration

In order to restore the lightpaths interrupted owing to network failures, faults have to be detected and fault reporting messages have to be sent from the source of failure to the network manager. The network manager decides how to set up restoration lightpaths and sends the restoration information back to the involved network elements. These functions are provided by three systems, namely, a surveillance network, a signaling network and a network management system.

4.1 Surveillance Network

For network surveillance, we assume the supervisory responsibility is carried out at the component level, and the monitoring information will be pushed to the network manager if any failure is detected. We adopt a passive, real-time fault detection scheme for optical fiber monitoring. In this scheme, a number of fiber Bragg gratings (FBG) having individual center wavelengths are installed at different locations of a link implemented with Erbium doped fiber amplifiers (EDFA) for loss compensation. The FBGs are used to slice and reflect the unused portion of EDFA spectrum, and the reflected signals will be monitored prior to each EDFA. Loss of the reflected signals indicates a cut in the fiber segment. When a failure is detected by the fault detection device, it triggers the transmission of fault management messages in the signaling network.

4.2 Signaling Network

The CCS7 protocol of ITU [26], is a well established protocol for existing telecommunication networks. Since AONs mainly serve as telecommunication networks, we assume that the transmission of the network management messages is supported by an independently operating CCS7 electrical signaling network. An independent signaling network is needed because any link or node failure in the AON should not affect the transmission of network management messages. The signaling network consists of signal points (SP) and signal transfer points (STP), providing correspondingly the sending and receiving, and the routing function of the protocol data units for network management. In order to enhance the reliability of the signaling network, each signaling point is connected to at least two signaling transfer points. If congestion on a certain pathway or failure of any link in the signaling network occurs, management messages can be sent on an alternate pathway via another signaling transfer point.

4.3 Network Management System

The fault information will first be sent to an assigned AON node serving as the node manager for that link. Fault reporting messages will then be generated by the node manager and forwarded to the network manager, the highest-level management elements in our network management scheme. The network manager is responsible for pre-computing the restoration lightpaths under each failure situation using the algorithms mentioned in Chapter 5. The restoration lightpaths are stored in a database in the network manager. When a failure occurs, the restoration information is retrieved and sent to the node managers which in turn control the operations of WCC and other network components to bring up the restoration lightpaths. A node is assigned as the backup network manager for the network manager. The backup network manager communicates with the network manager periodically to monitor the health of the network manager. Once abnormal behavior is detected, the backup network manager will take up the role of the network manager and another node is call upon to be the backup network manager.

Fig. 10 summarizes the relations among all the elements in the three systems. Each AON node contains a node manager, a WCC, fault detection devices and other AON elements. A node manager functions as the interface between the network manager and other components of the AON node.

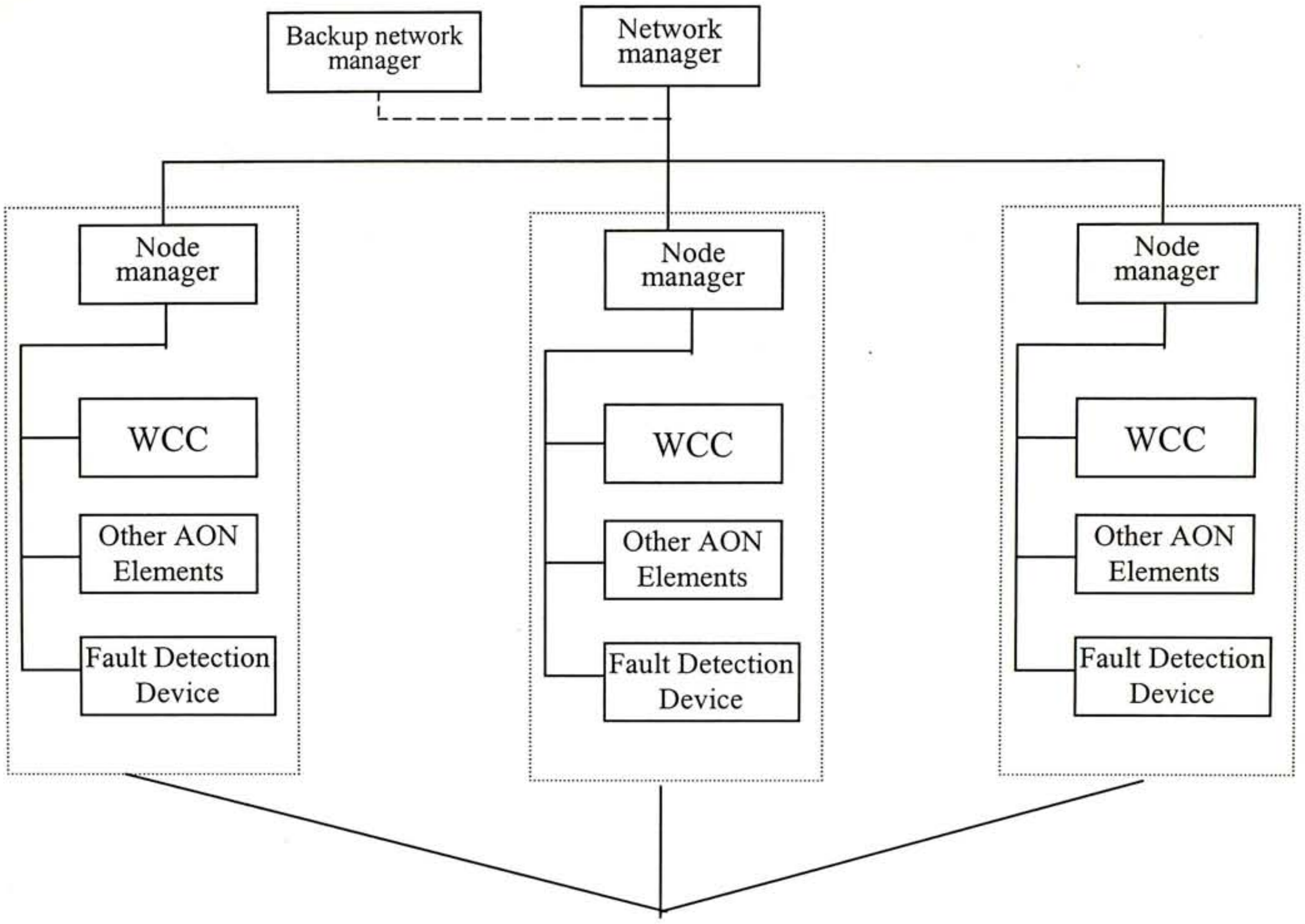

Figure 10. The relations between the different elements.

4.4 CCS7 Adaptation for Supporting AON Restoration

In this section, we propose some adaptation of the CCS7 protocol for delivering the network management messages required for AON restoration. Two management messages, the fault reporting message and the lightpath restoration message, are defined. The CCS7 protocol has four layers of protocol data units. The protocol data units in the layers below the forth layer provide functions like routing, error checking and congestion control, etc. Management messages are carried in the fourth layer protocol data units, called Message Signal Units (MSUs). An MSU is shown in the table below.

Fields in an MSU	*F*	*CK*	*SIF*	*SIO*		*LI*	*FIB*	*FSN*	*BIB*	*BSN*	*F*
Number of bits	*8*	*16*	*8n, n>2*	*8*	*2*	*6*	*1*	*7*	*1*	*7*	*8*

F: a marker defined as "01111110", identifying the start and end of an MSU.

BSN: backward sequence number.

BIB: backward indicator bit.

FSN: forward sequence number.

FIB: forward indicator bit.

BSN, BIB, FSN and FIB are used for error correction, message sequence control, confirmation and re-transmission.

LI: length indicator indicating the length of SIF.

CK: error checking code.

SIO: service indicator octet

SIF: signaling information field

Table 5. Message Signal Unit (MSU) of CCS7

SIO and SIF only appear in the MSUs and other fields appear in the protocol data units of different layers. Since we would like to add some new network management services for AON restoration, only the SIO and SIF fields have to be defined while other fields are kept unchanged. SIO carries the message identifiers assigned to different types of AON management messages discussed below. SIF carries the content of a network management messages. It has a maximum capacity of 272 octets. LI is 6 bit long. When used in an MSU, LI ranges from 3 to 63. If the length of SIF exceeds 63 octets, LI remains to be 63. However, this will not cause any trouble because the only purpose of this field is to distinguish MSUs from the protocol data units in the other layers, which have LI values always smaller than 3.

For the purpose of network management, different kinds of identifiers are assigned. Each AON element has a 32-bit identifier and the first 4 bits of the identifier indicate the type of the element, which may be a router, a fiber or a wavelength converter, etc.

The fault reporting message and the lightpath restoration message are defined as follows:

- *Fault reporting message*

Fault management is supported by the fault-reporting message, shown in Table 6.

Sub-fields in SIF	*FN*	FI_1	......	FI_f
Number of bits	*8*	*64*		*64*

FN: Number of failure elements detected.

FI: Information of one of the failure elements.

f is the value contained in FN.

Table 6. The sub-fields of SIF in a fault reporting message.

When a node manager receives failure reports, the identifiers and failure information of all fault elements are sent to the network manager. FI is 64-bit long. The first 32 bits represent the element identifier of one of the failure elements and the last 32 bits contain the corresponding failure information.

- *Lightpath restoration message*

Before lightpath restoration, the AON element failures are reported to the network manager by the fault reporting messages. After determining which working lightpaths have to be restored, the network manager retrieves the corresponding restoration information from its database. The restoration information contains the information about WCC reconfiguration and lightpath wavelength reassignments. WCC reconfiguration is necessary for releasing existing lightpaths and setting up new lightpaths on different pathways to bypass the faulty AON elements. Moreover, wavelength reassignments may also be required for the following reason. When a working lightpath is restored on a lightpath with a different wavelength, the source node and destination node of the lightpath have to be informed. They will then change the transmitter and receiver wavelength respectively. The network manager sends a number of restoration messages, with the format shown in Table 7, to all of the involved AON nodes.

Sub-fields in SIF	NI	WN	WI_1	……	WI_w	RN	RI_1	……	RI_r	MN	MI_1	……	MI_m
Number of bits	32	8	32		32	8	32		32	8	32		32

NI: The node identifier identifies one of the nodes where its WCC has to be reconfigured.

WN: The number of working lightpaths released at the WCC owing to network failures.

WI: The information about releasing a working lightpath.

RN: The number of restoration lightpaths passing through the WCC.

RI: The information about setting up a restoration lightpath.

MN: The number of wavelength reassignments at the WCC.

MI: The information about wavelength reassignments.

w, *r* and *m* are the values stored in the WN, RN and MN respectively.

Table 7. The sub-field definitions of SIF in a restoration message.

WI is 4-byte long and contains the information of how an affected working lightpath is released at the WCC. The first byte of the field represents the incoming port of the WCC that a lightpath passes through. The second byte denotes the outgoing port. The third byte indicates the wavelength of the lightpath before it enters the WCC. The fourth byte shows the wavelength after it leaves. The definitions of RI is same as that of WI, except the information is about a restoration lightpath to be set up at the WCC.

The definition of MI derived from the following observation. A node can be sources and destinations of many lightpaths. Therefore, a lightpath has to be identified by the incoming port and incoming wavelength at the its source. Similarly, it has to be identified by the outgoing port and outgoing wavelength at the its destination. MI is 32-bit long. The first byte indicates whether the node designated by NI is the source or destination of the lightpath. The second byte denotes the incoming or outgoing port. The third byte denotes the incoming or outgoing wavelength. The fourth byte shows the new wavelength.

The values of w, r and m may be zero. On the other hand, their values are limited by the maximum size of an MSU. If an MSU is not able to hold all the restoration information for a node, more than one MSUs are sent to it.

Chapter 5. Complete Restoration Algorithm for AON

Given the number of the working lightpaths and the working capacity (i.e., the number of fibers carrying the working lightpaths) as fixed quantities, paper [19] presents an algorithm for the optimum allocation of spare fibers for lightpath restoration. However, these algorithms may not find restorable working lightpaths if the number of fibers is fixed. In this thesis, a different approach is used. Since the assignments of working lightpaths and restoration lightpaths are inter-related, the number of working and restoration lightpaths should be jointly optimized as shown in the algorithms of this thesis.

Two restoration algorithms for restorable working lightpath routing, link-based restoration (*LBR*) algorithm and source-based restoration (*SBR*) algorithm are presented here. In these algorithms, two types of lightpaths, working lightpaths and restoration lightpaths, are determined. Working lightpaths are "working" under normal situations and restoration lightpaths are setup only when link failures occur. Both algorithms find working lightpaths as much as possible while guaranteeing the restoration of all working lightpaths under any single link failure. Since LBR restores a working lightpath by finding a bypass lightpath to avoid the failed link, the algorithmic search is minimal compared with that of SBR which searches all the lightpaths that do not pass through the failed link. Both algorithms can provide much better restoration results by allowing affected traffic to be split on different paths. Since the chance of multiple-link failures is very small, we only consider the complete restoration for single link failures in this thesis. However, this thesis can be extended to solving restoration problem of multiple-link failures.

Both restoration methods can be modeled by integer linear programming (ILP). The definitions of the parameters given in the algorithms are presented as follows:

K : the number of wavelength channels on each fiber;

N : the number of nodes in the network;

S : the number of source-destination pairs with traffic demands;

E : the number of edges in the network;

$d_{s,t}$: the number of demanded lightpaths between the node pair (s, t), where s and t $= 1, 2, \ldots\ldots N$;

f_e : the number of fibers on the edge e, where $e = 1, 2, \ldots\ldots E$;

All lightpaths are represented as linear variables in the ILP formulation. Here, $w_{p,k}$ denotes the number of lightpaths set up on the path p using the wavelength channel k in both SBR and LBR.

The objective function that maximizes the total number of working lightpaths is not used because this may set up many lightpaths between some node pairs but few between other node pairs. Therefore, the objective function is defined as minimizing the maximum insufficient allocation of lightpaths among all node pairs, z, which is an auxiliary variable. Mathematically, z is defined as:

$$z = \max_{(s,t)} \left[d_{s,t} - \sum_{\substack{\text{all } k, \\ p \text{ incident} \\ \text{on } s,t}} w_{p,k} \right]$$

To incorporate this definition into the linear programming model, the following demand constraint is required for all node pairs.

1. *Demand constraint* The total number of the working lightpaths originating from node s to node t must be between $d_{s,t} - z$ and $d_{s,t}$, or,

$$d_{s,t} - z \le \sum_{\substack{\text{all } k, \\ p \text{ incident} \\ \text{on } s,t}} w_{p,k} \le d_{s,t}$$

If the network have sufficient capacity, z must be zero and so the demand constraint reduces to

$$\sum_{\substack{\text{all } k, \\ p \text{ incident} \\ \text{on } s,t}} w_{p,k} = d_{s,t}$$

5.1 Link-Based Restoration Algorithm

For the *LBR* algorithm, we introduce the variable, $b_{e,p,k}$, which denotes the number of the bypass lightpaths set up on route p using wavelength channel λ_k when link e fails. Let a working lightpath be denoted by $(w_1, w_2, \ldots\ldots w_n)$, where w_i is the i^{th} link of the lightpath. Suppose a failure occurs on link e_f and the bypass lightpath for this link is $\{b_1, b_2, \ldots\ldots b_m\}$, then the restored working lightpath can be described as $\{w_1, w_2, \ldots w_{f-1}, b_1, b_2, \ldots\ldots b_m, w_{f+1}, \ldots w_n\}$. Loops, if existed in the restored lightpath, have to be removed. For the *LBR* algorithm, the following two additional constraints have to be satisfied:

2. <u>*LBR lightpath bypass constraint*</u> For each λ_k in a failed link e^*, the number of lightpaths that bypass e^* and are on path p^* must be no smaller than the number of working lightpaths that pass through e^* and are on the path p, i.e.

$$\sum_{p^* \text{ bypasses } e^*} b_{e^*,p^*,k} \geq \sum_{\substack{p \text{ passes} \\ \text{through } e^*}} w_{p,k}$$

3. <u>*Capacity constraint*</u>

   Under normal situation, the total number of working lightpaths passing through link e on wavelength channel λ_k must be no larger than f_e. Therefore, we have,

$$\sum_{\substack{p \text{ passes} \\ \text{through } e}} w_{p,k} \leq f_e$$

   Under a link failure situation, for each link e on the bypass lightpath of failed link e^*, the total number of working lightpaths plus the number of bypass lightpaths on e must be no larger than f_e.

$$\sum_{\substack{p^* \text{ bypasses} \\ e^* \text{ and passes} \\ \text{through } e}} b_{e^*,p^*,k} + \sum_{\substack{p \text{ passes} \\ \text{through } e}} w_{p,k} \leq f_e$$

5.2 Source-Based Restoration Algorithm

For the *SBR* algorithm, we introduce variable, $r_{e^*,p^*,k}$, denoting the number of the restoration lightpaths established on route p^* for wavelength channel λ_k when link e^* fails. The constraints for SBR are shown as following.

2a <u>*SBR restoration lightpath constraint*</u> For each wavelength channel λ_k in a failed link e^*, the number of restored lightpaths must be no smaller than the number of working lightpaths originally passing through e^*.

$$\sum_{\substack{p^* \text{ does not} \\ \text{pass through } e^* \\ \text{and incident on} \\ (s,t)}} r_{e^*,p^*,k} \geq \sum_{\substack{p \text{ pass} \\ \text{through } e^* \\ \text{and incident on} \\ (s,t)}} w_{e^*,p,k} .$$

3a <u>*Capacity constraint*</u>

Under normal situation, the capacity constraint is same as that of *LBR,* i.e.

$$\sum_{\substack{p \text{ passes} \\ \text{through } e}} w_{p,k} \leq f_e$$

Under a link failure situation, for each failed link e^* and for each λ_k, the sum of the number of the restoration lightpaths and the working lightpaths on any other healthy link e should not exceed f_e.

$$\sum_{\substack{p^* \text{ does not} \\ \text{pass through} \\ e^* \text{ but } e}} r_{e,p^*,k} + \sum_{\substack{p \text{ pass} \\ \text{through } e \\ \text{but not } e^*}} w_{p,k} \le f_e$$

5.3 Case Studies

Computer programs are developed for formulating the two restoration algorithms in MPS format, which is a file format used by the IBM OSL linear integer programming software[27]. The IBM OSL software is used to solve the problem. Our algorithms are tested under three case studies described below to compare the performance of the two restoration algorithms.

5.3.1 Case I and II

For the 11-node testbed network well known in restoration studies [13-16], we test the performances of the two algorithms for a randomly generated traffic demand matrix. The total demanded lightpaths is 38. The two algorithms are compared for $K = 2$ and $K = 4$. For $K = 2$, the numbers of lightpaths set up by the *LBR* and the *SBR* algorithms are 16 and 18 respectively. When $K = 4$, the numbers of lightpaths found by both algorithms are 32. Table 8 shows the assignment result for the *SBR* algorithm when $K = 4$. Fig.12 and Fig.13 show examples of restoration lightpaths set up by both algorithms. We shall defer the discussions on case I after presenting case II as the conclusions are similar.

Source	Destination	Traffic demand	Lightpaths assigned
0	7	2	2
1	3	1	1
6	8	3	2
1	2	1	1
0	8	2	2
1	7	5	5
7	9	2	2
5	8	4	2
4	10	4	4
0	3	4	3
1	6	2	2
6	7	4	2
7	10	1	1
2	8	2	2
3	8	1	1

Table 8. The assignment results for the *SBR* algorithm when $K = 4$.

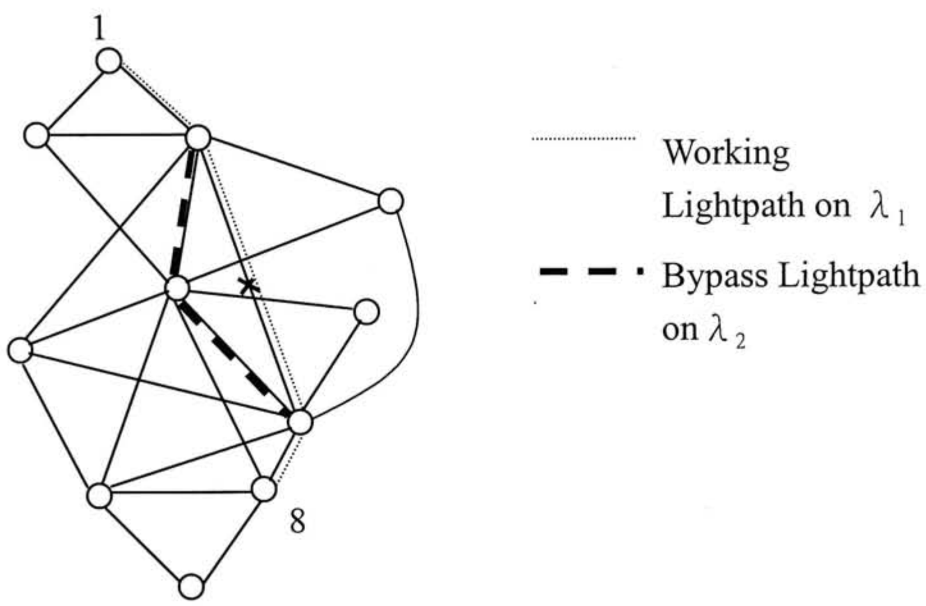

Figure 12. Link based restoration for the working lightpath between node 1 and node 8 by bypassing the cut edge.

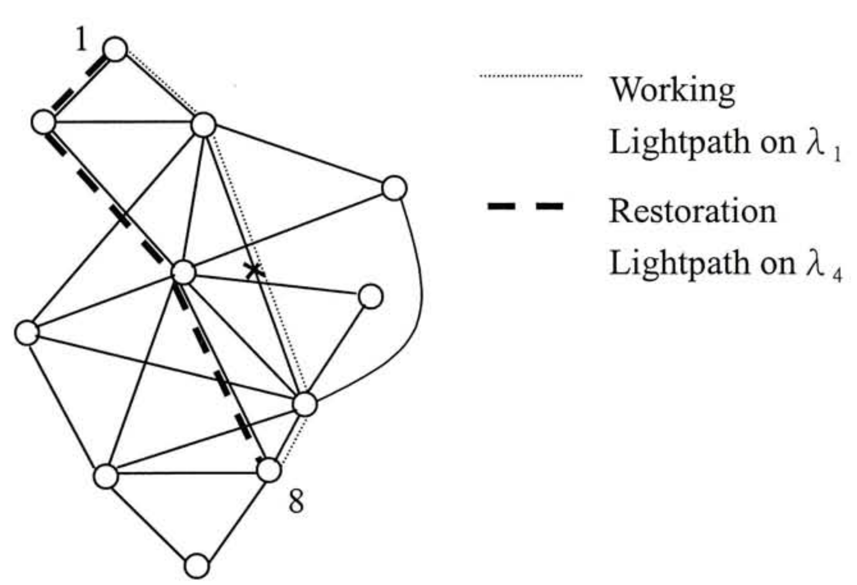

Figure 13. Source based restoration for the working lightpath between node 1 and node 8 by setting up a new lightpath not passing through the cut edge.

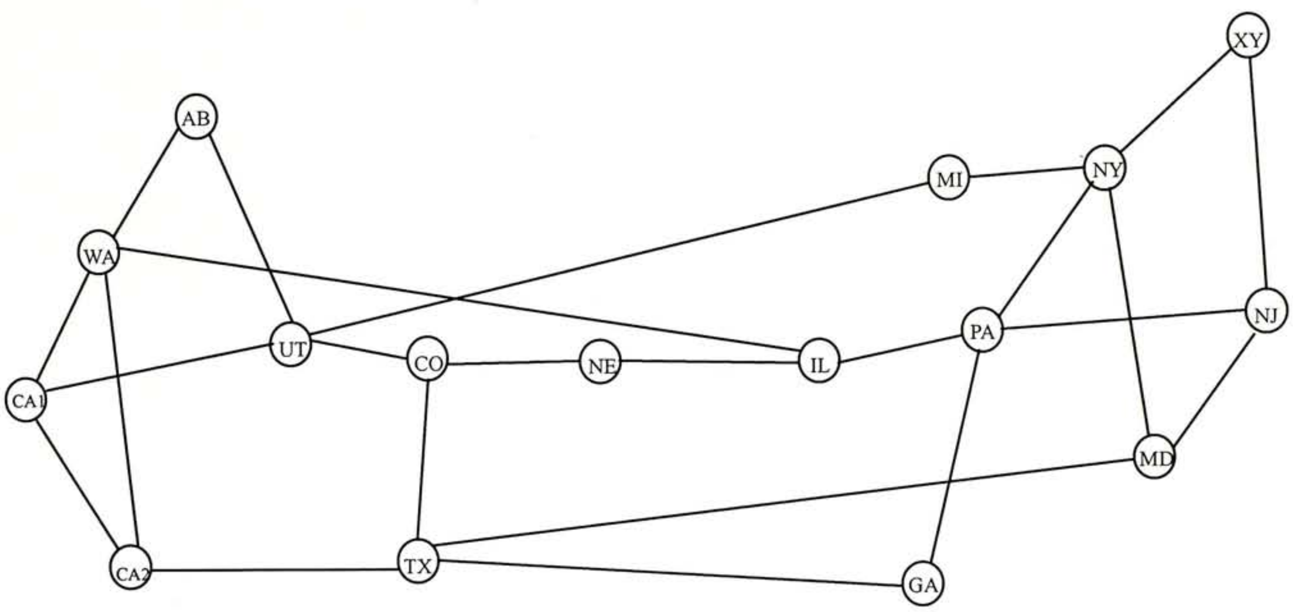

Fig.14. Physical topology of the NSFNET backbone network.

For case II, we study the NSFNET T1 backbone network [7]. The topology is shown in Fig. 14. The demand matrix, derived from Internet traffic statistics, is shown in Table 9. We assume that 10 fibers are installed on each edge. The total number of demanded lightpaths is 102. The two algorithms are compared for $K = 2$ and $K = 4$. When $K = 2$, the numbers of lightpaths set up by the *LBR* and the *SBR* algorithm are 42 and 48 respectively. When $K = 4$, the numbers of lightpaths set up by the *LBR* and the *SBR* algorithm are 82 and 83 respectively. Table 9 shows the assignment result for the *SBR* algorithm when $K = 4$.

Source	Destination	Traffic demand	Assigned Lightpaths
WA	NE	3	3
CA1	WA	2	2
CA1	GA	4	2
CA2	IL	21	20
UT	CA1	3	1
UT	PA	1	1
TX	NY	7	5
NE	CO	1	1
IL	MD	9	9
PA	WA	3	3
MI	CO	7	4
GA	CA1	2	2
NJ	NE	5	2
MD	WA	3	2
MD	NJ	7	7
GA	NE	6	3
PA	CA1	14	12
CO	NY	4	4

Table 9 Assignment result by SBR for NSFNET with $K=4$.

The execution time of *SBR* is much longer than *LBR* in cases I and II, confirming that a small increase in the number of variables and constraints leads to a substantial increase in computation time. As expected, the performance of *SBR* is better than or equal to that of *LBR* in general. In both case studies, when *K* increases from 2 to 4, the increase in the number of assigned lightpaths of *LBR* is around 100% while that of *SBR* is about 75%. This shows that *LBR* is more affected by wavelength conflicts because wavelength conflict decreases as *K* increases [18]. The number of possible paths on which restoration lightpaths can be set up is smaller in *LBR* than that in *SBR*. Therefore, the chance that no common wavelength can be found along a path to restore a working lightpath is larger in *LBR*, thus reducing the number of completely restorable working lightpaths. However, when *K* is sufficiently large, the two algorithms show similar performance.

When *K* is small, *SBR* gives better performance at acceptable computation time. On the other hand, when *K* is large, *LBR* should be used because *LBR* can give virtually the same performance at significantly shorter computation time. Moreover, for a large network, the *LBR* algorithm may be the only feasible algorithm to use since the number of paths grows exponentially with the network size.

5.3.2 Case III

The last network for simulation is the European Optical Network (EON) [22], shown in Fig. 15. A randomly generated demand matrix is used for this simulation. There are 70 node pairs having traffic demands. The total number of demanded lightpaths is 283. The simulations are performed for K = 4, 8 and 16.

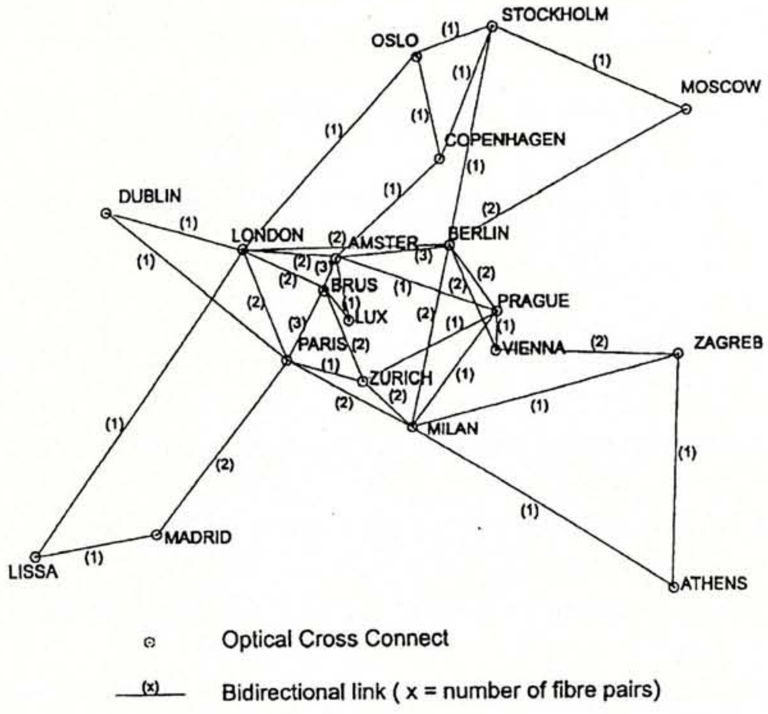

Fig. 15 The topology for EON

The results are shown in following table.

Wavelength channels in each fiber (K)	Assigned completely restorable lightpaths
4	65
8	142
16	283

Table 10. Simulation results for the EON.

When K = 4 and 8, the solution can be found within 10 hours. However, very long computation time (30 hours) is required when K = 16. Since the ILP problem is solved by exploring the Branch and Bound tree, a number of integer solutions are generated during the process. It is observed that there are significant improvements of the integer solutions found in the first 4 hours. Very little improvement is achieved in the next 21 hours of calculation. No improvement is obtained in the last five hours of calculation and so the calculation process was stopped. Meanwhile, there is very little difference between the final integer solution and the upper bound of the integer solution obtained by removing the integer constraints.

As the number of variables increases, the number of possible integer solutions increases exponentially. It is not practical to search all the possible solutions since the computation time for ILP is unbounded. However, as shown in our calculation results, little improvement is obtained in the solutions after a long search. Therefore, when solving a large problem, we can interrupt the searching process if no integer solution improvement is searched after a sufficiently long time.

5.4 Completely Restorable Network planning

There are two types of network planning for backbone networks. The first type assumes that no fiber has been installed and a network is to be built from scratch. This can be solved by the minimum variance algorithm introduced in Chapter 3. The second type assumes that the traffic demands can no longer be supported in an existing network and so the network capacity has to be expanded to satisfy future demands.

In many countries, a lot of spare fibers have already been installed in existing networks by telecommunication companies. Therefore, the future traffic demands can be met by bringing up these unused fibers by adding transmitters and receivers at both ends. In this section, we focus our discussion on the second type of network planning.

Based on the current traffic statistics, an estimate of the future traffic demands can be made so that the network can be expanded for completely satisfying the future demands. Besides, redundant capacity need also be allocated during the planning phase for the complete restoration of lightpaths upon link failures. The solution of the completely restorable network planning problem is

1. the number of fibers to be utilized on each edge and
2. the working lightpath and restoration lightpath assignments

Due to the similarities, the SBR and LBR algorithms can be easily transformed to the source-based planning (*SBP*) and link-based planning (*LBP*) algorithms. Here, the demands between every node pair are obtained by a forecast of the future demands. The network upgrading cost is the total utilization cost, which increases with the number of fibers between all node pairs. Let u_e be the utilization cost on edge e and f_e be a variable denoting the number of fibers to be utilized on e. The objective function of both algorithms is to minimize the upgrading cost C, where

$$C = \sum_{e} (u_e \cdot f_e) ,$$

subject to constraints 2, 3 and the following constraint for complete lightpath demand fulfillment:

4. *Network planning demand constraint* For any node pair *(s, t)*, the sum of all working lightpaths originating from s to t is no smaller than $d_{s,t}$, i.e.

$$\sum_{\substack{\text{all } k, \\ p \text{ incident} \\ \text{on } s,t}} w_{p,k} \geq d_{s,t}$$

5.5 A Summary on Problem Formulations

Tables 11 and 12 summarize the equations for formulating a restoration problem. If it is a restoration problem without the number of fibers fixed, then the equations in the first column of Table 11 should be used. If it is a restorable network planning problem, then the equations in the second column of Table 11 should be used. Moreover, additional constraints are needed for providing complete lightpath restorability. If link-based restoration is used, the constraints in first column of Table 12 are required. For source-based restoration, the constraints in the second column of Table 12 are needed.

	Restoration	Restorable network planning
Objective function	Min z, where $z = \max_{(s,t)} \left[d_{s,t} - \sum_{\substack{\text{all } k, \\ p \text{ incident} \\ \text{on } s,t}} w_{p,k} \right]$	$\min C = \sum_{e} (u_e \cdot f_e)$
Demand constraint	$d_{s,t} - z \leq \sum_{\substack{\text{all } k, \\ p \text{ incident} \\ \text{on } s,t}} w_{p,k} \leq d_{s,t}$	$\sum_{\substack{\text{all } k, \\ p \text{ incident} \\ \text{on } s,t}} w_{p,k} \geq d_{s,t}$

Table 11 Formulation table 1.

	Link-based restoration	Source-based restoration
Capacity constraint under normal situation	$\sum_{\substack{p \text{ passes} \\ \text{through } e}} w_{p,k} \le f_e$	
Capacity constraint under network failure	$\sum_{\substack{p^* \text{ bypasses} \\ e^* \text{ and passes} \\ \text{through } e}} b_{e^*,p^*,k} + \sum_{\substack{p \text{ passes} \\ \text{through } e}} w_{p,k} \le f_e$	$\sum_{\substack{p^* \text{ does not} \\ \text{pass through} \\ e^* \text{ but } e}} r_{e,p^*,k} + \sum_{\substack{p \text{ pass} \\ \text{through } e \\ \text{but not } e^*}} w_{p,k} \le f_e$
Complete Restoration constraint	$\sum_{p^* \text{ bypasses } e^*} b_{e^*,p^*,k} \ge \sum_{\substack{p \text{ passes} \\ \text{through } e^*}} w_{p,k}$	$\sum_{\substack{p^* \text{ does not} \\ \text{pass through } e^* \\ \text{and incident on} \\ \text{(s,t)}}} r_{e^*,p^*,k} \ge \sum_{\substack{p \text{ pass} \\ \text{through } e^* \\ \text{and incident on} \\ \text{(s,t)}}} w_{e^*,p,k}$

Table 12 Formulation table 2.

Chapter 6. Conclusion

This thesis has thoroughly studied three problems of AON:

1. Network dimensioning problem for AON planning without restoration;
2. Network management scheme required to support AON restoration;
3. Working lightpath assignments and restoration lightpath assignments under any single-link failure.

The works on different areas are concluded as follows.

Network dimensioning problem

The network dimensioning problem arises owing to the different traffic demands at multiple time segments. Two heuristic algorithms solve the problem and output the following information:

- Lightpath assignments for different traffic patterns on different time segments;
- Number of optical fibers required to be installed between each node pair.

One heuristic, MVA, is based on the minimum variance and the other one is based on the shortest path. In MVA, wavelength conflict in a network is reduced by assigning lightpaths with minimum variance of wavelength channel utilization. This can be confirmed by the performance comparison of the two algorithms, which shows that MVA performs considerably better than the shortest path algorithm.

Network management scheme

We have also introduced a network management scheme designed to support AON restoration. This scheme consists of a surveillance network, a signaling network and a network management system. The sequence of events that occur during failure detection and lightpath restoration can be summarized as follows:

1) Fault-detection device detects network element failures and informs the node manager.
2) The node manager generates fault-reporting messages and sends them to the network manager.
3) After receiving fault-reporting messages, the network manager retrieves the pre-computed restoration lightpaths from its database for generating the restoration messages. It then sends the messages to all involved AON elements.
4) Upon receiving the restoration messages, the AON elements perform restoration actions as indicated in the messages.

All messages are send in the signaling network using CCS7 protocol. In this thesis, CCS7 protocol is adapted to carry AON restoration messages by defining the *signal information field* (SIF) of the message signal units for different management messages.

Complete lightpath restoration algorithms

The major achievement of this thesis is a set of algorithms which solve the problem of complete lightpath restoration. The algorithms find the working lightpaths as well as their corresponding restoration lightpaths under different failure cases. However, the problem is complicated by the inter-dependency of the lightpath assignments. The assignments of working lightpaths

capacity and hence the chance of finding restoration lightpaths. Therefore, in order to obtain optimum assignment results, the algorithms have to consider the assignments of the two kinds of lightpaths simultaneously in the ILP formulation.

There are generally two types of restoration techniques: source-based restoration (*SBR*) and link-based restoration (*LBR*). In link-based restoration scheme, signal is re-routed to bypass the failure link while the other parts of the original path are kept unchanged. In the case of source-based restoration, the restoration path may be completely different from that of the original one. In addition to guaranteeing complete lightpath restoration, we also consider the fairness of lightpath assignments. Instead of setting the objective function to be maximizing the total number of working lightpaths, the algorithms aim at minimizing the maximum unsatisfied lightpath demand among all node pairs. The restoration algorithms are formulated by integer linear programming. Computer programs are also developed to convert the formulations into files of MPS format, which can be inputted into the IBM OSL software for solving the problem.

Three networks, an 11-node testbed network, the Internet backbone network and the European optical network are used to compare the performance of the algorithms. The results show that the performance of *SBR* is slightly better than *LBR* when *K* is small. For a large *K*, its performance is similar to that of *LBR*. Meanwhile, the computation time of *SBR* is longer than that of *LBR* in all cases since a lot more variables are used in *SBR*. As a result, the author suggests that *LBR* are suitable for large-scale problems since the computation time is reasonable and the solution is close to the optimal one. Furthermore, we found out that we can limit the calculation time with very small effect on the algorithm performance.

Based on these algorithms, another two algorithms are designed for planning the network expansion to satisfy the future demands as well as guaranteeing complete restorability. The formulations are similar to the previous ones, except the following differences. The objective function is to minimize the network upgrading cost and the number of fibers are defined as linear variables. Moreover, the demand constraint for SBR and LBR is replaced by the network planning demand constraint. The formulations for all the restoration algorithms are summarized in two tables.

Future works

For future works, we can extend this thesis to cover other research issues. We can explore the possibility of increasing the computation speed by obtaining some neo-optimal solutions so that the algorithms can be applied to very large-scale problems. In addition, in order to increase the network survivability, restoration under multiple-link failures should also be considered with some formulations similar to those mentioned in this thesis.

Moreover, we should also incorporate the wavelength converter cost into the cost function of network planning algorithms. In this way, we can consider the optimal implementation of wavelength conversion at some WCC so that more lightpaths can be assigned by resolving wavelength conflict.

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[1] Chun-Ming Lee, Chi-Chun R. Hui, Frank F.-K. Tong, Peter T.-S. Yum, "Network dimensioning in WDM-based All-Optical networks", IEEE GLOBECOM' 98, Sydney.

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