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Logical Topology Design and Multi-layered Survivability for IP over WDM Networks

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Abstract

A WDM (Wavelength Division Multiplexing) techonology is a new optical technology, which provides multiple wavelengths at the rate of 10 Gbps on the fiber. IP (Internet Protocol) over WDM networks where IP packets are directly carried on the WDM technology is expected to offer an infrastructure for the next generation Internet and researched intensively. However, current IP over WDM technology only utilize WDM as link. Hence, the network bottleneck against the explosion of the traffic demands since it only results in that the bottleneck is shifted to an electronic router. One possible solution to overcome IP router’s bottleneck through assignment of *Lightpath*, where each optical node has optical switches directly connecting an input wavelength to an output wavelength, by which no electronic packet processing is necessary.

WDM protection mechanism switches backup lightpath when failure is occured in somewhere in the network. However, Conventional IP also provides a reliability (i.e.,robustness against the link/node failures) by a routing function. If we can utilize protection methods of WDM networks, we can expect much more reliable networks. However, for IP over WDM networks, we need to build the WDM path networks by carefully taking account of the properties of IP routing mechanisms. In this paper, we formulate an optimality problem for designing IP over WDM networks with protection functionalities, by which we can offer IP over WDM networks with high reliability.

Our formulation results in a mixed integer linear problem (MILP). However, it is known that MILP can be solved only for a small number of variables, in our case, node and/or wavelength. In this paper, we also propose two heuristic algorithms, *min-hop-first* approach and *traffic-large first* approach to assign the wavelength for backup lightpath.

Our results show that min–hop–first approach takes fewer wavelength to construct the reliable network, that is, all of lightpaths is protected using WDM protection mechanism. However, our traffic-largest-first approach is also a good choice in a sence that the approach can be saved the traffic volume increased at the IP router by the link failure.

Keywords

Photonic Network

IP over WDM

Optimization

Topology Design

Protection Method

Survivability

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1 Introduction

The Internet popularity and an advancement of multimedia communication technologies have led to an exponential growth of the Internet traffic. To meet the rapidly growing traffic demands, an optical networking technology such as SONET/SDH (Synchronous Optical NETwork/Synchronous Digital Hierarcy) is currently deployed in many ISPs (Internet Service Providors). However, switching systems based on the current electronic technology cannnot provide enough capacity to accommodate the growing traffic.

A WDM (Wavelength Division Multiplexing) technology is a new optical technology, which provides multiple wavelengths with the order of 10 Gbps on each wavelength. By utilizing the WDM technology, we have a much low-cost solution to meet traffic demands. However, it is still controversial how to utilize the WDM technology for transporting the IP traffic. One aspect is related to the protocol stack. It is possible to use the ATM (Asynchronous Transfer Mode) technology on SONET where SONET is built on the WDM technology, which is so called an *IP over ATM over SONET over WDM network*. An *IP over SONET over WDM network* is another solution since the ATM technology only introduces the protocol overhead (i.e., five byte cell header within 53 byte cell). Another and more promising solution is IP over WDM networks where WDM is directly used by IP (more exactly, we need a data link layer protocol such as PPP or HDLC between IP and WDM protocol stack).

We have several alternatives even for IP over WDM networks, depending on whether we utilize the capabilities of WDM networks or not. Those include capabilities of routing, congestion control, and reliability. A currently available IP over WDM technology only uses WDM on the fiber link. That is, each wavelength on the fiber is treated as a physical link between the conventional IP routers, and therefore multiple links of wavelengths are offered between IP routers by the WDM technology. See Figure 1. We will refer to it as *WDM link network* in the below. The conventional multiple–link handling technique of IP can be utilized in this case. This approach does not use the above–mentioned capabilities of the WDM network, but by introducing the WDM technology, the link capacity is certainly increased by the number of wavelengths

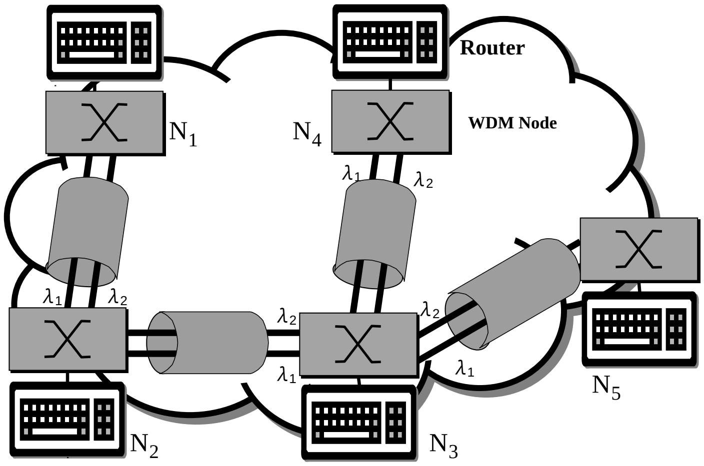

Figure 1: WDM link network

multiplexed on the fiber. Of course, it is insufficient to resolve the network bottleneck against the explosion of traffic demands since it only results in that the bottleneck is shifted to an electronic router.

To alleviate the bottleneck at the router, an introduction of optical switches has actively been discussed. One possible realization is that a logical topology is constituted by wavelengths on the physical WDM network (see [1] and references therein). Here, the physical network is an actual network consisting of the optical nodes and the optical–fiber links connecting nodes. Each optical node has optical switches directly connecting an input wavelength to an output wavelength, by which no electronic packet processing is necessary at that node. Then, the wavelength path can be setup directly between two nodes via one or more optical switches (i.e., cross–connect switches). Hereafter, we will call the wavelength path directly connecting two nodes as *lightpath* or *logical path*.

If lightpaths are placed between every two nodes, then no electronic processing is necessary within the network. We can see such an example in MPLS (Multi Protocol Lable Switching) network [2]. Actually, the applicability of MPLS to the IP over WDM network is now discussed in the IETF [3] where the wavelength is viewed as a label. However, too much wavelengths are necessary to establish such a network [4]. We thus need to take a compromise; we establish the logical topology consisting of the lightpaths by using the available wavelengths as much as possible. If the direct lightpath cannot be set up between two nodes, two or more lightpaths are used for packets to reach the destination. See Figure 2 as an example of the logical topology, which we will call it as a *WDM path network*. In the figure, packets from node N_1 to N_3 are forwarded on the direct logical path using the wavelength λ_2. However, the packets from node N_1 to N_4 takes two hops since it has no direct logical path. That is, the packets are first forwarded to node N_3 and then passed to node N_4 by node N_3.

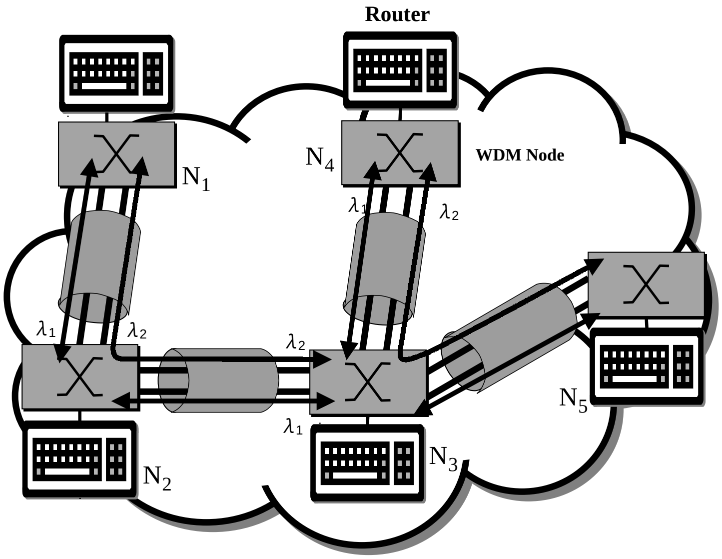

Figure 2: WDM path network

For packet forwarding, we need the routing capability. One possible node architecture is shown in Figure 3, where IP packets on the lightpath terminated at the node is processed by the IP router and then forwarded to other nodes using some lightpath. Figure 4 shows a logical view of the underlying network (i.e., the logical topology established by the WDM network) to the IP routers. We should note here that the other structure of optical nodes can also be considered, but the above–mentioned node architecture is preferable since there is no need to modify the IP routing mechanism.

A logical topology design problem for the WDM network has already been studied in the past literature. Several papers formulated it as an optimization problem [5, 6]. In [5], it is formulated to minimize the maximum of traffic load on the lightpath, which was referred to as *traffic congestion* in [5]. Namely, the

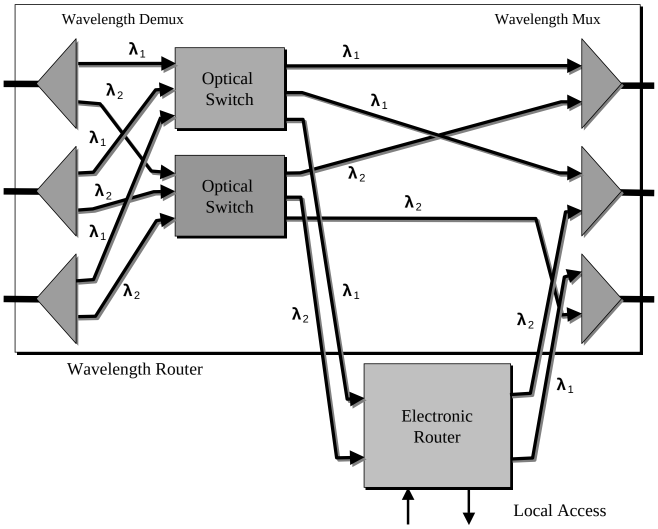

Figure 3: WDM node architecture

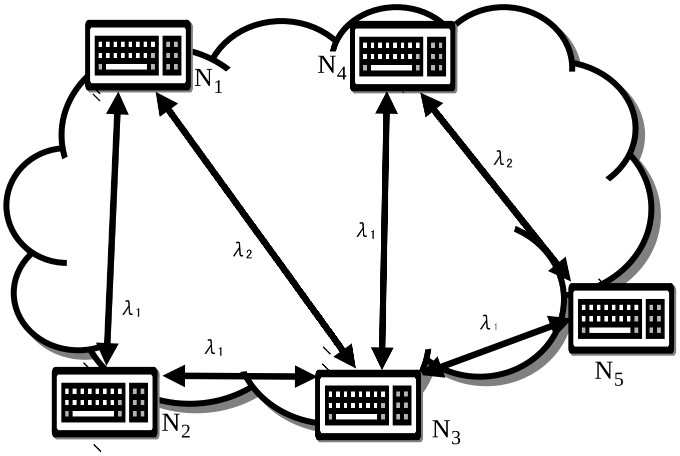

Figure 4: Logical Topology viewed by the IP layer

constraint on the number of wavelengths is not taken into account. In [6], the authors divide the optimization problem into several subproblems to resolve it efficiently, and an application of meta–heuristic algorithms such as a simulated annealing approach is suggested. However, most of them including the above papers do not consider the IP network as a upper–layer protocol. Thus, those solution approaches may or may not suitable to the logical topology design problem for IP over WDM networks. For example, the shortest path derived by the conventional design problem and the actual path used by IP may be different. Or, the IP route may be fluctuated on the logical topology when RTTs of two logical paths between source–destination pair are not different. The main problem is an inadequate setting of the objective function and constraints. On the contrary, we formulate the optimal design problem of the logical topology by carefully taking account of the IP routing, which is our first subject in this paper.

As mentioned above, the WDM network itself has a potential to offer several network functionalies such as the routing protocol, congestion control mechanism, and reliability mechanism. However, a protocol suite of TCP/IP also has those capabilities. Building the same functionality in multiple layers often gives an ill effect for the objective. One such an example can be found in TCP over ATM ABR service class where each of TCP and the ABR service class has its own congestion control mechanism. If the parameters of two layers are appropriately chosen, the congestion control works very well. However, if parameters are inadequate, the performance is degraded unexpectedly and becomes even worse than the case where no congestion control mechanism is introduced. Perhaps, a most appropriate scenario for next–generation IP over WDM networks is that we limitedly use network control functionalities of WDM networks for IP over WDM networks to be successfully deployed.

The first choice of the network control mechanism offered by WDM networks is certainly its reliability mechanism. Of course, IP itself has such a functionality; the link and/or node with failure can be avoided in determining the route. However, an exchange interval of the routing metrics is slow (e.g., every 30 sec). On the other hand, the route alternation of WDM networks can be established within a few tens of miliseconds if the failure occurs. By combining those two mechanisms appropriately, we can expect much more reliable networks than the current Internet.

There are two protection schemes in the WDM protection [7]. The one is a ‘1+1’ protection scheme where the backup lightpath is dedicated to the corresponding primary lightpath. The other is a shared protection scheme where several primary lightpaths uses the same wavelength as a backup lightpath. In the 1+1 protection scheme, protection against simultaneous failures can be achieved, but apparently the larger number of wavelengths is apparently needed than that of the shared protection scheme. Furthermore, in the IP over WDM network, IP routing protocol also has its own reliability and survivability mechanism. Therefore, it is sufficient that the WDM layer offers a protection mechanism against a single failure (i.e., the shared protection scheme), and multiple failures could be left to the IP layer.

Our second subject in this paper is to build the logical topology by considering the shared protection scheme, and we will formulate the optimal problem for determining the logical topology with high reliability. For this purpose, we consider two cases of failures; a lightpath failure due to the malfunction of the optical port, and a fiber failure where all lightpaths on the fiber is protected. In Subsections 3.1.1 and 3.1.2, we will treat these two cases, respectively.

We last note that the optical burst switching is another important approach to fully exploit control capabilities of the WDM networks. In the burst switching networks, the lightpath is setup on demand basis. In [8–11], we treat the optical burst switching network, and investigate its performance by taking account of the relation between the burst length and propagation delays since the successful deployment of the optical burst switching is largely dependent on the effect of propagation delays. The optical burst switching seems to be a good choice for the future WDM networks, but is out of scope in the current paper.

This paper is organized as follows. In Section 2, we formulate the logical topology design problem suitable to IP over WDM network as a optimization problem. In Section 3, we apply protection mechanisms of the WDM network in order to build IP over WDM networks with high reliability. Based on our results, we will also discuss the multi-layer survivability for IP over WDM networks in Section 4. Finally we present some concluding remarks in Section 5.

2 Logical Topology Design Problem for IP over WDM Networks

In designing the logical topology on the physical WDM network, lightpaths should be placed to optimally meet its objective function. Most of past researches have treated a minimization problem for the traffic congestion (the maximum traffic load on the logical path) or the mean delay averaged over all end-to-end paths. In IP over WDM path networks, however, IP packets are routed based on IP metrics. Henceforth, without consideration on the overlayed IP network, routing instability may occur between the appropriate route determined by the logical topology of the WDM network and the route determined by IP itself. We thus need to build the WDM path networks by carefully taking account of properties of IP routing. Since in a recent IP routing mechanism, a shortest path is determined not based on hop-count, but based on end-to-end delay, we should incorporate it in formulating the WDM path network topology design algorithm. Unless otherwise, routing instability cannot be avoided even when we minimize end-to-end delays for all source-destination pairs.

We will use the following conventions in notations throughout this paper. See also Figure 5.

s, d: source and destination nodes of IP traffic

i, j: originating and terminating nodes for a logical link. We will simply call the logical link between nodes i and j as lightpath ij.

m, n: end nodes of a physical link. We will call the physical link connecting nodes m and n as physical link mn.

2.1 Formulation for Logical Topology Design Problem

In this subsection, we formulate a logical topology design problem as an optimization problem. We first summarize notations characterizing the physical WDM network.

N: the number of nodes within a physical (and logical) network

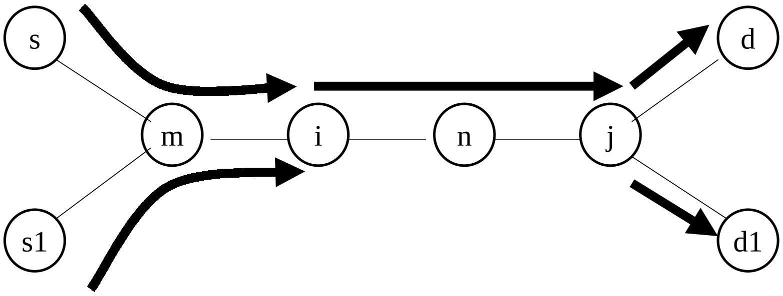

Figure 5: A summary of notations

W: the number of wavelengths on a fiber

C: the capacity of the wavelength

λ_{sd}: traffic generation rate from source node s to destination node d

P_{mn}: a physical topology defined by a set of $\{P_{mn}\}$. If there exists a physical fiber between nodes m and n, then $P_{mn} = 1$, otherwise $P_{mn} = 0$.

d_{nm}: a propagation delay between nodes m and n.

The followings are notations for the logical network.

V_{ij}: the number of lightpaths placed between nodes i and j

$p_{mn}^{ij,k}$: if kth wavelength of the physical link mn is used for lightpath ij, then $p_{mn}^{ij,k} = 1$. Otherwise, 0.

λ_{ij}^{sd}: the traffic rate on lightpath ij for the traffic between nodes s and d

We now formulate our logical topology design problem as an optimization problem.

Objective Function

As we mentioned above, we want to minimize the end-to-end delay for each source-destination pair. Here, the end-to-end delay is defined as a sum of propagation delays on the fiber and the queueing delay at the logical node, i.e., the processing delay at the router. We assume that the queueing delay at the router can be obtained by applying an M/M/1 queueing model. To assure the minimum end-to-end delay for all source-destination pairs, we take a sum of the delays for each source-destination pair, i.e., our objective function is given as

$$\min \sum_{i,j} \Big[\textstyle\sum_{mn} (\max_{k \in W} p_{mn}^{ij,k}) d_{ij} + \dfrac{1}{V_{ij} \cdot C - \sum_{sd} \lambda_{ij}^{sd}} \Big] \tag{1}$$

Constraints

In obtaining an optimal solution, the following constraints should be incorporated.

(1) For the wavelength assignment on the logical topology, the number of lightpaths originating at node i should equal to the number of lightpaths between nodes i and j, i.e.,

$$\sum_{k} \sum_{n} p_{in}^{ij,k} = V_{ij}. \tag{2}$$

The relation should also hold for termination node j as

$$\sum_{k} \sum_{m} p_{mj}^{ij,k} = V_{ij}. \tag{3}$$

(2) A wavelength continuity condition should be assured, that is, the same wavelength should be assigned on the way of the lightpath from originating node i to terminating node j.

$$\sum_{m} p_{mx}^{ij,k} = \sum_{n} p_{xn}^{ij,k}, \qquad \text{if} \quad x \neq i, j. \tag{4}$$

(3) The traffic rate between nodes s and d, λ_{sd}, should equal to the sum of traffic rates on lightpaths

originating at node s. It should also be applied to terminating node d. That is,

$$\sum_{j} \lambda_{sj}^{sd} = \lambda_{sd}, \tag{5}$$

and

$$\sum_{i} \lambda_{id}^{sd} = \lambda_{sd}. \tag{6}$$

(4) All traffic should traverse the same lightpath. It is important for stability of IP routing.

$$\sum_{i} \lambda_{ik}^{sd} = \sum_{j} \lambda_{kj}^{sd} \qquad \text{if } k \neq s, d. \tag{7}$$

(5) The total capacity of the lightpath, which may consist of the multiple number of wavelengths, should accommodate the traffic from node i to node j.

$$\sum_{s,d} \lambda_{ij}^{sd} \leq C\, V_{ij}. \tag{8}$$

(6) For wavelength k between adjacent nodes m and n, the number of lightpaths should be restricted by the existence of the fiber.

$$\sum_{ij} p_{mn}^{ij,k} \leq P_{mn}. \tag{9}$$

2.2 Derivation of Optimal Solution by Simulated Annealing Method

We adopted a SA (Simulated Annealing) method to obtain the solution for our optimization problem. If the intermediate solution can decrease the objective function, it is naturally accepted in the SA method. It also realizes a random search. Namely, it accepts some changes that increase the objective function with some probability in order to avoid trapped at local minima. See Figures 6 and 7. It is an advantage of the SA method over other ones. In the SA method, if a feasible space defined by the constraints is suspect to be disjoint, it cannot move to all feasible solutions without passing through an infeasible space. Therefore, our objective function is transformed into an unconstrained one by constructing an augmented objective function incorporating any violated constraints as penalty functions [12].

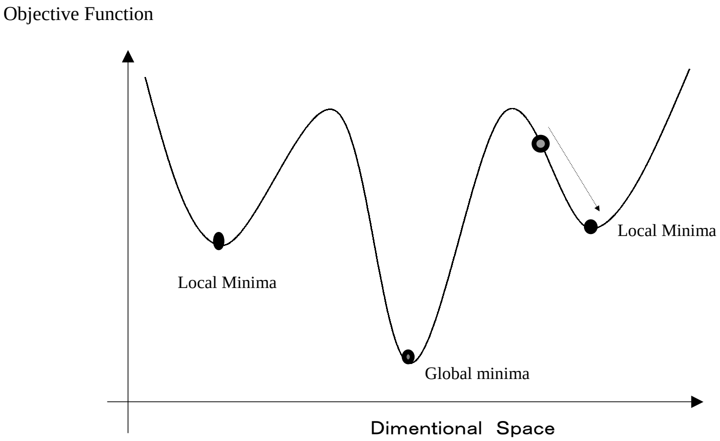

Figure 6: Local Search Method

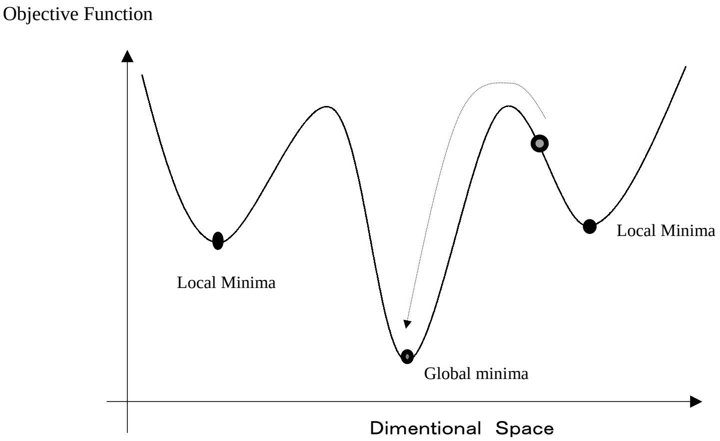

Figure 7: Simulated Annealing Method

Table 1: Optimal values for WDM link and path networks

WDM Architecture	Optimal Value
WDM Link Network	6.10
WDM Path Network	5.64

2.3 Numerical Examples

In this subsection, we show the results of our optimization problem. We use four–node network as a network model (Figure 8) to investigate basic characteristics of our problem. The wavelength capacity is assumed to be 1.0. We assume the number of wavelengths on the fiber, W, to be two. For each physical link, the propagation delays are also assumed to be 0.1.

Using these parameters, we derive the solution through the SA method. The optimal value is shown in Table 1. In the table, we also show the result of applying the WDM link network. As shown in Table 1, the average delays can be reduced. The resultant wavelength allocation is shown in Figure 10. By comparing it with Figure 9, node N_3 is free from processing the traffic between nodes N_0 and in the WDM path network. Because no queuing delay occur at N_3Node 3, we can obtain the smaller value of the objective function in the WDM path network.

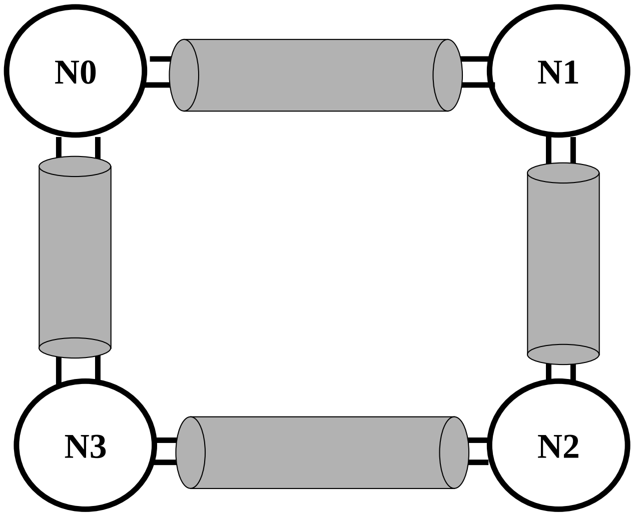

Figure 8: Network model for logical topology design

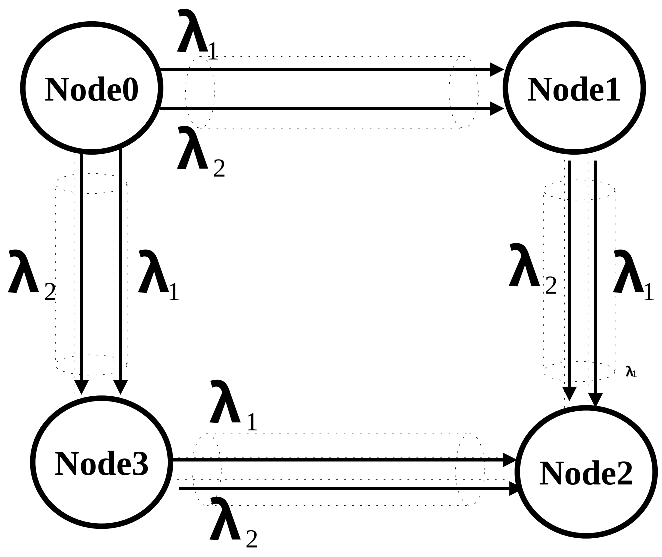

Figure 9: Wavelength allocation in WDM link network

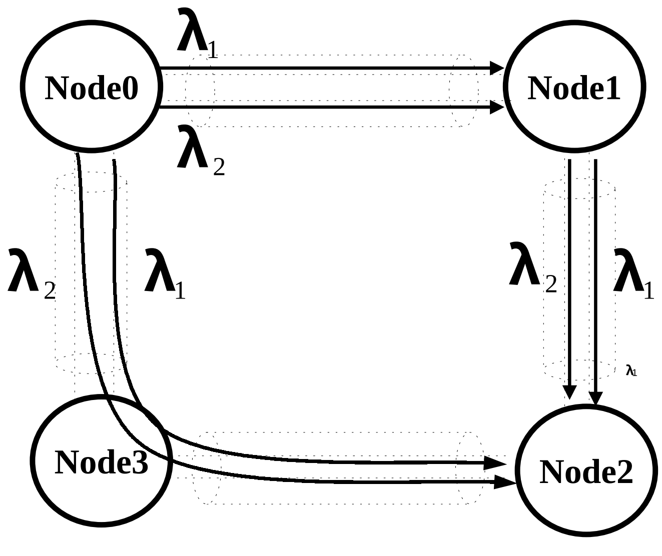

Figure 10: Wavelength allocation in WDM path network

3 Reliable IP over WDM Networks using Protection Mechanisms

3.1 Problem Formulation

By using the protection mechanism described in Section 1, the WDM layer can switch an alternate lightpath in the order of ten milliseconds. We consider two kinds of protection mechanisms. The lightpath protection mechanism offers the survivability against the lightpath failure scenario, which is mainly caused by a port failure. Another one is the link protection, which gives not only the survivability against lightpath failure, but also the fiber failure that is typically caused by a fiber cutoff. In this paper, we concentrate on the shared protection scheme for improving the wavelength utilization under the assumption that the WDM network is highly reliable and the failure seldom occurs. Different from the previous section, we minimize the number of utilized wavelengths on the link.

In addition to the notations introduced in the previous section, we will also use the following notations.

R_{ij}^k: The route of lightpath from nodes i to j (i.e., lightpath ij) utilizing wavelength k. It consists of a set of physical links; (i, m_1), (m_1, m_2), $\ldots$, (m_p, j).

A_{ij}: An backup lightpath for the primary lightpath. Its originating and terminating nodes are i and j, respectively. It consists of a set of physical links; (i, n_1), (n_1, n_2), $\ldots$, (n_q, j).

We also introduce the following variables in order to formulate our optimization problem.

w_{mn}: The number of primary lightpaths placed on the physical link between directly connected two nodes m and n.

b_{mn}: The number of backup lightpaths placed on the physical link mn.

o_{mn}^k: If the primary lightpath utilizes wavelength k on the physical link mn, then $o_{mn}^w = 1$, otherwise 0.

m_{mn}^w: If the backup lightpath utilizes wavelength k on the physical link mn, then $m_{mn}^w = 1$, otherwise 0.

$g_{ij,k}^{mn,w}$: If the lightpath originating at node i and terminating at node j utilizes wavelength k for the primary lightpath, and also utilizes wavelength w between nodes m and n as a backup lightpath, then it is equal to 1, otherwise 0.

3.1.1 The Case of Lightpath Protection

Using notations above, we now formulate the wavelength assignment problem for backup lightpaths as an optimization problem.

Objective function

Minimize the number of used wavelengths, i.e.,

$$\min \sum_{m,n} (w_{mn} + b_{mn}) \tag{10}$$

Constraints

(1) The number of primary lightpaths placed on physical link mn equals to the sum of the number of primary lightpaths utilizing wavelength w on that physical link, i.e.,

$$w_{mn} = \sum_{w \in W} o_{mn}^{w}. \tag{11}$$

(2) Similarly, the number of backup lightpaths placed on the physical link mn equals to the sum of wavelengths used on that link for the backup lightpaths, i.e.,

$$b_{mn} = \sum_{w \in W} m_{mn}^{w}. \tag{12}$$

(3) Either one primary lightpath or one backup lightpath utilizes wavelength k on the physical link mn

if there exists a fiber.

$$o_{mn}^{k} + m_{mn}^{k} \leq P_{mn}. \tag{13}$$

(4) The number of backup lightpaths equals to the number of corresponding primary lightpaths ij.

$$V_{ij} = \sum_{k \in W} \sum_{it \in A_{ij}} g_{it}^{ij,k}, \tag{14}$$

$$V_{ij} = \sum_{k \in W} \sum_{tj \in A_{ij}} g_{tj}^{ij,k}. \tag{15}$$

(5) The lightpath must use the same wavelength on all the backup links of the backup path (i.e., the wavelength–continuity constraint).

$$g_{nt}^{ij,k} = g_{tm}^{ij,k}. \tag{16}$$

(6) The backup lightpath can be shared by several primary lightpaths if the corresponding primary lightpaths are port–disjoint.

$$g_{ij}^{mn,k} \leq m_{mn}^{k}. \tag{17}$$

3.1.2 The Case of Link Protection

In the case of link protection, the backup link can be shared by two or more primary links. This case can be formulated in a natural way by extending the previous case of lightpath protection. The optimization problem can be formulated as follows.

Objective function

Minimize the number of utilized wavelength,

$$\min \sum_{m,n} (w_{mn} + b_{mn}) \tag{18}$$

Constraints

For the constraints, only the differences from the previous case are shown below.

(1) The backup lightpath can be shared by several primary lightpaths if the corresponding primary lightpaths are fiber–disjoint.

$$m_{mn}^{k} \geq \sum_{x \in W} \sum_{(i,j):((m,n) \in A_{ij}^{k} \wedge o_{mn}^{x} > 0)} g_{ij,x}^{mn,k} \tag{19}$$

3.2 Proposed Heuristic Approach

In the previous subsections, we have formulated wavelength assignment problems for backup lightpaths. Our formulation results in a mixed integer linear problem (MILP), and a standard package such as CPLEX [13] can provide the solution. However, it is known that MILP can be solved only for a small number of variables. In our case, the number of variables increases exponentially as the number of nodes and/or the number of wavelengths become large. We therefore need to introduce a heuristic approach to be applicable to the large scaled network.

Our basic idea is as follows. In the case of the shared path protection, several primary lightpaths are allowed to share the single wavelength as the backup lightpath. However, sharing of the backup lightpath is possible only when the corresponding primary lightpaths are fiber–disjoint. If the hop count of the primary lightpath is small, the possibility of conflicting with another lightpath is decreased. Here, we note that the hop-count of the lightpath refers to the number of physical links the lightpath traverses. For the purpose of more sharing while avoiding conflicts among lightpaths large hop–counts, we choose the backup lightpath in an ascending order of hop-counts which will be refer-ed to as a *min-hop-first* approach. It is expected that by assigning the wavelengths sequentially between short hop–count lightpaths, the number of wavelengths not assigned tends to be increased. After the lightpaths with short hop–counts are assigned as the backup lightpaths, the lightpaths with large hop–counts can utilize wavelengths not yet assigned, since many wavelengths tend to still remain unused for those paths.

We introduce some notations for explaining our min-hop-first algorithm.

c_{ij}^k: the number of lightpaths utilizing wavelength k for node pair i and j.

A_{ij}^k: A set of physical links used for the backup lightpath for primary lightpath ij.

B_{ij}^k: A set of links that have not been checked whether lightpath ij can use wavelength k. Initially, it is set to A_{ij}^k

Using those notations, we now describe our min-hop-first approach.

Step 1: Choose the lightpath with the smallest value of c_{ij}^k.

Step 2: For each wavelength p ($p = 1, 2, \cdots, W$), check whether the backup lightpaths utilize wavelength p on its way from originating node i to the terminating node j. More precisely, do the followings steps.

Step 2.1: For each physical link connecting two nodes m and n (i.e., $\in B_{ij}^p$), do the followings.

Step 2.1.1: If wavelength p on the physical link is not utilized by any of other lightpaths, then delete the link mn from B_{ij}^p and go to Step 3. If wavelength p is already used by another lightpath, go to Step 2.1.2.

Step 2.1.2: If wavelength p on the physical link connecting mn is already used by primary lightpath, then the backup lightpath cannot be placed using wavelength p. Thus, go back to Step 2 to examine the next wavelength. If wavelength p is already used by another backup lightpath, then check whether these lightpaths can be shared or not. Sharing is accepted if corresponding primary lightpaths are fiber–disjoint. Fiber–disjoint means that any two corresponding primary lightpaths has no common link. If the lightpath can share with each other, then delete the link mn from B_{ij}^p and go to Step 3. Otherwise, the backup lightpath cannot be placed using wavelength p, and therefore go back to Step 2.

Step 3 If $B_{ij}^{p} = \phi$, then assign wavelength p to the link $mn \in A_{ij}^{p}$, and go back to Step 1. Otherwise, go back to Step 2.1 to examine the next link.

3.3 Numerical Examples

3.3.1 Optimization Results

We investigate the usefulness of the IP over WDM networks with high reliability. For this purpose, we use CPLEX 6.5 to solve the optimization problem described in Subsection 3.1. Since it is hard to solve the large–scaled network, we use a five-node network, which is shown in Figure 11. The number of wavelengths on the fiber is set to 2. The traffic matrix is shown in second column of Table 2. As we can see from the table, wavelength λ_1 on link E24 can be shared by two lightpaths, N1→N4 and N3→N2. In the '1+1' protection scheme, wavelength λ_1 on E24 cannot be shared. Hence, both of lightpaths can use wavelength λ_2. In such a way, shared protection can reuse more wavelength than the '1+1' protection scheme.

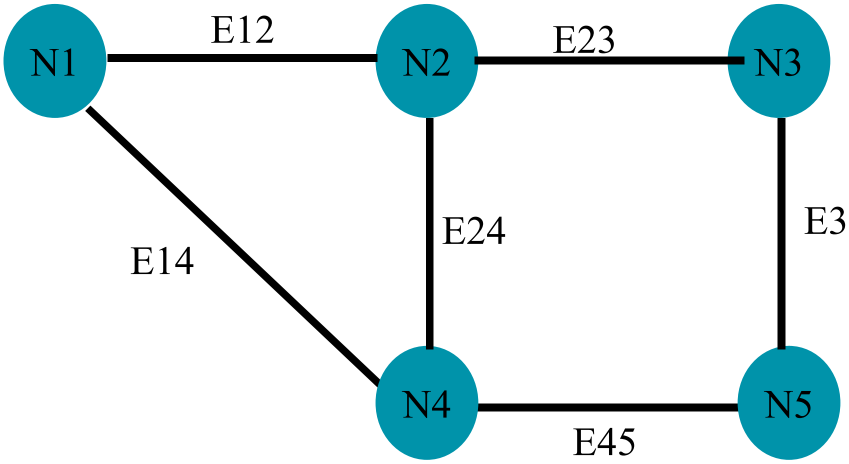

Figure 11: Physical topology of five-node network

Table 2: Lightpath placed on the logical topology

primary path	traffic rate	set of routes	backup lightpath
N1 → N4	0.1 (E25, λ_1)	(E23, λ_1)	E14, E24
N3 → N2	0.1	(E12, λ_1)	E35, E45, E24

Table 3: Results of link protection

primary path	alternate route
N1 → N4	(E12, λ_1) (E24, λ_1)
N3 → N2	(E35, λ_1) (E45, λ_1) (E24, λ_1)

3.3.2 Results by Heuristic Approach

We next consider the NSFNET topology as an example network. For comparison purpose, we also evaluate a *traffic-large-first* approach and a *random* approach. In the former, the lightpath is selected in an descending order of the traffic load of the lightpath. The lightpath is selected randomly in the random approach.

In Subsection 2.2, we have shown the logical topology design problem and solved it by a simulated annealing method. However, it takes unacceptable time for middle and large sizes of networks, and we cannot use the approach described in Subsection 2.2. Instead, we use the MLDA algorithm which is a heuristic algorithm for building the logical topology [14]. The MLDA algorithm works as follows. First, it places the lightpath between nodes if there exists a fiber. Then, attempts to place lightpaths between nodes in the order of descending traffic rate are made. Finally, if there still exist non-utilized wavelengths, those lightpaths are placed as much as possible. However, the direct application of the MLDA algorithm is not appropriate since the MLDA algorithm does not consider the protection. We modify the MLDA algorithm in the following points.

(1) While the MLDA algorithm places lightpaths even if the lightpath has already been placed, we do not set up multiple wavelengths between two nodes so that remaining wavelength are left as a possible

use for the backup lightpaths.

(2) While the MLDA algorithm places lightpaths randomly if there exist unused wavelengths at the final step of the algorithm, we do not assign non-utilized wavelengths due to the same reason above.

We use 14–node NSFNET backbone network as a network model. Traffic matrix given in [14] is used for the reference purpose. Alternate path for a node pair is obtained from dijkstra's shortest-path algorithm by eliminating physical links that is already used by primary wavelength. Figure 13 compares three approaches in terms of the required number of wavelengths to protect all the lightpaths dependent on the number of protection wavelengths. For example, if the MLDA algorithm utilizes ten wavelengths to establish the logical topology, the additional number of wavelengths to be able to protect all lightpaths is 16 when applying the min-hop-first approach. From Figure 13, we can observe that the min-hop-first apporach requires a smallest number of wavelengths among three approaches. In other words, the min-hop-first approach can protect all lightpaths with the lowest cost.

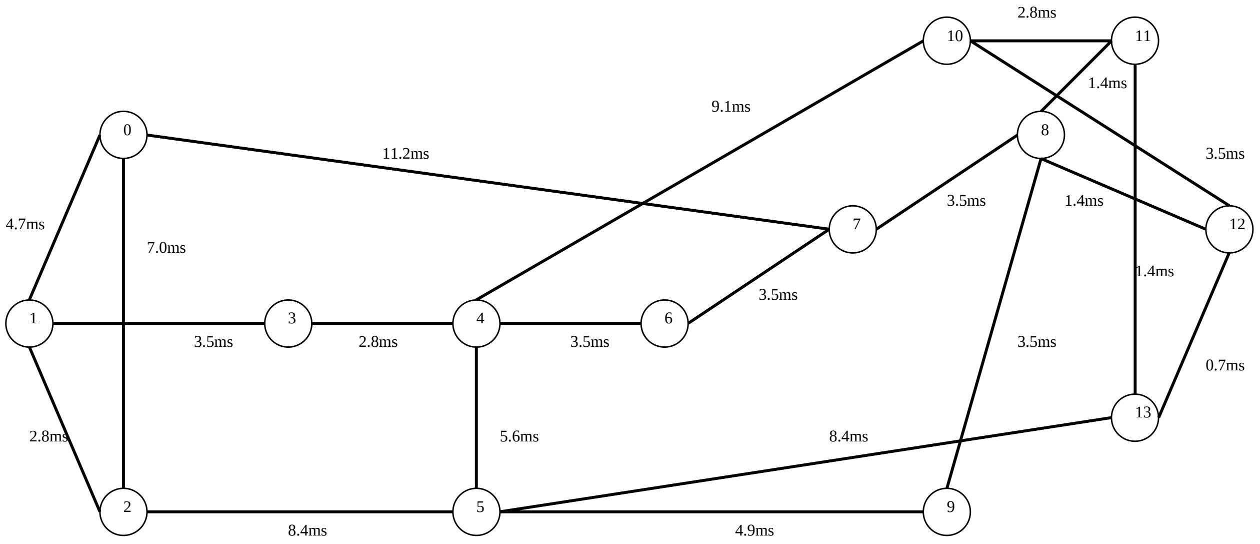

Figure 12: NSFNET network model

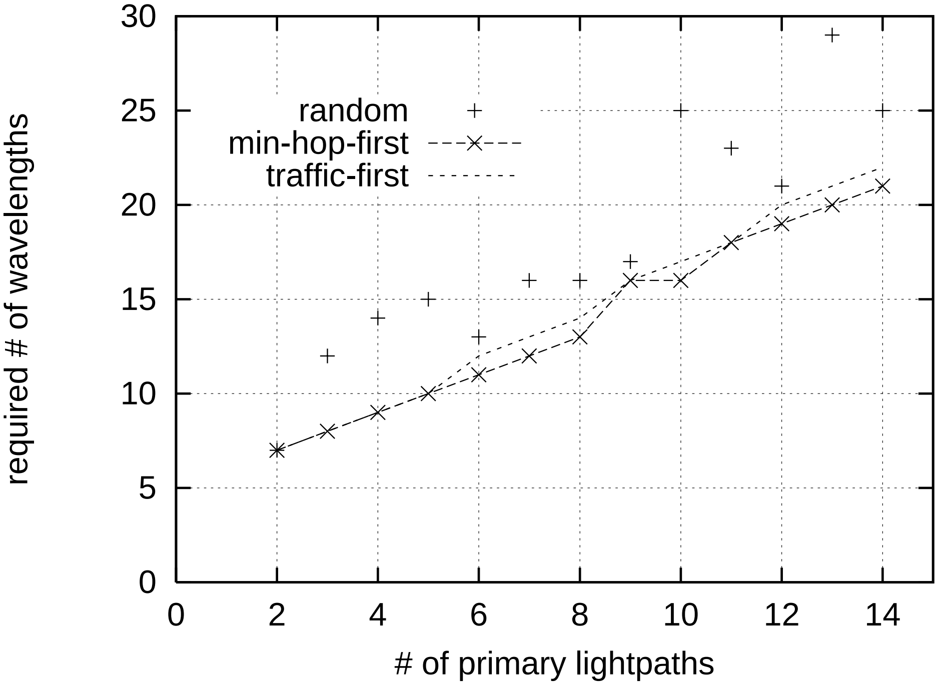

Figure 13: The number of required wavelengths to construct the reliable network in NSFNET

4 Multi-Layered Survivability for IP over WDM Networks

In the previous section, we show the required number of wavelengths to protect all of the primary lightpaths. We now discuss on the interaction between IP layer's reliability and WDM layer's survivability. In IP over WDM networks, the IP layer has its own reliability mechanism. Thus, it is not necessary to protect all the lightpaths by the WDM layer if it can lead to much cost-saving.

4.1 Multi-Layered Survivability for IP over WDM Networks

It is ideal that the WDM network could protect all the lightpaths, by which all of lightpaths can be protected against the single–failure and the traffic on the primary lightpath can be switched to the backup lightpath in the order of ten milliseconds. However, we need to consider the tradeoff relationship between the processing capability of IP routers and the limitation of wavelengths. By setting up more backup lightpaths, we can protect more lightpaths. However, because of the limitation on the number of wavelengths, the number of primary lightpaths should be limited in order to increase the number of backup lightpaths. It results in that bottleneck caused by the IP router cannot be resolved at all. On the contrary, we can expect that more traffic can be carried by increasing primary lightpaths, but in that case, the advantage of protection mechanisms of the WDM network cannot be enjoyed.

It is difficult to identify how many wavelengths should be assigned for primary/backup lightpaths, since it depends on the requirement of the network capacity provided by the primary lightpaths and the network survivability by the protection mechanism of the WDM network. We will provide the numerical examples in the next subsection to investigate the compromise between the above two objectives.

4.2 Multi-Layered Survivability for NSFNET

In this subsection, we investigate the effect of IP/WDM interactions using the NSFNET backbone network. As having been shown in Figure 12 of Subsection 3.3.2, it has 14 nodes and 20 links.

In Figure 14, we show the number of protected lightpaths dependent of the total number of available wavelengths on the link. In obtaining the figure, we use the MLDA algorithm to obtain the logical topology. The number of wavelengths used for primary lightpaths is eight. Three cases of approaches (min-hop-first, large-traffic-first, and random approaches) are compared in the figure. By the MLDA algorithm, the number 73 of primary lightpaths are established. Then, those lightpaths are completely protected in all of three cases if we have additional seven wavelengths. We note that even if the number of backup wavelengths is set to be 0, the number of protected lightpath is not 0 but 10. It is because we modify the MLDA algorithm such that wavelengths not assigned by the algorithm remains unused for the latter use in protection. From the figure, we can observe that the min-hop-first approach can protect more lightpaths than traffic-large-first and random approaches.

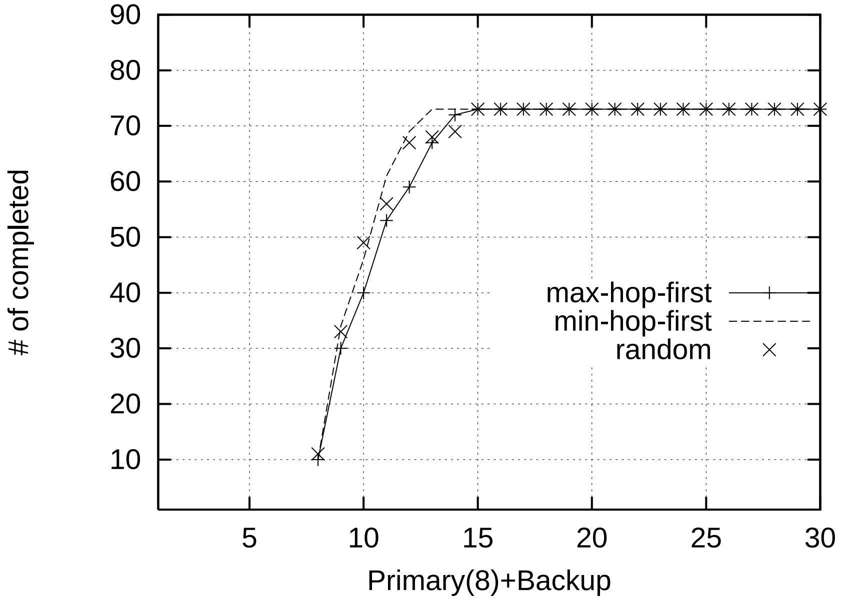

Figure 14: The number of protected lightpaths

We next set the number of wavelength to be fixed, and then change the number of wavelengths used for establishing the backup lightpaths. Figure 15 shows such a case by setting the total number of wavelengths on the fiber to be 16. The horizontal axis shows the number of wavelengths used for backup lightpaths, and the vertical axis does the number of the lightpaths protected by the WDM protection mechanisms of three approaches. For another view, we also plot the ratio of the number of protected lightpaths to the one of primary lightpaths in Figure 16.

From the figures, we can observe that the number of protected lightpaths is first increased as the number of backup wavelengths is increased, and then decreased. The reason is that when the number of wavelengths reserved for the backup lightpaths is small, more lightpaths can be protected by the increasing number of wavelengths for the backup lightpaths. However, a too many number of wavelengths dedicated for the backup lightpaths inhibits generation of the primary lightpaths. Then, the number of wavelengths unused is increased. Among three, the min-hop-first approach can attain the best result. That is, we can obtain a good compromise between the primary and backup lightpaths by our protection method.

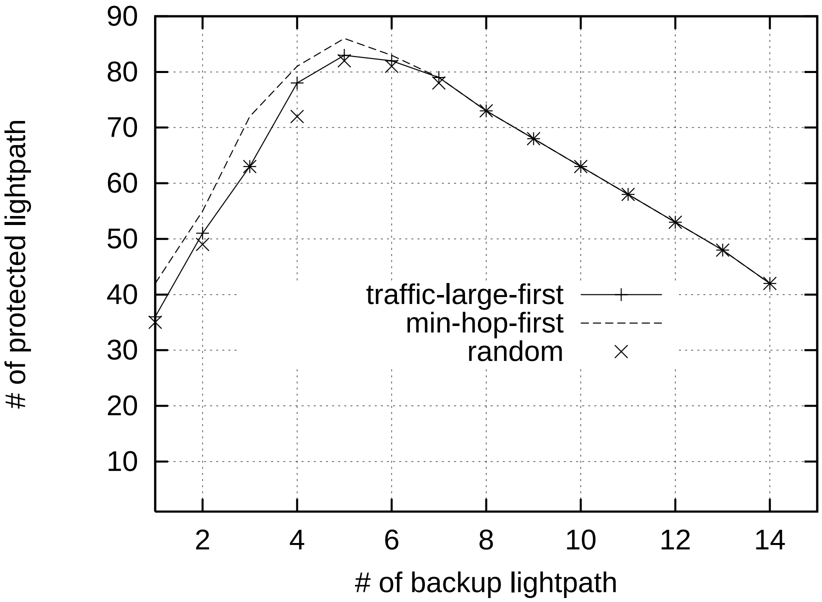

Figure 15: Number of Protected wavelength.

The traffic volume increased at the IP router by the link failure is another important measure to evaluate the protection mechanism of the WDM network. In obtaining the following set of figures, we set the number of wavelengths to be 20, and then, change the number of wavelengths used for setting up the primary

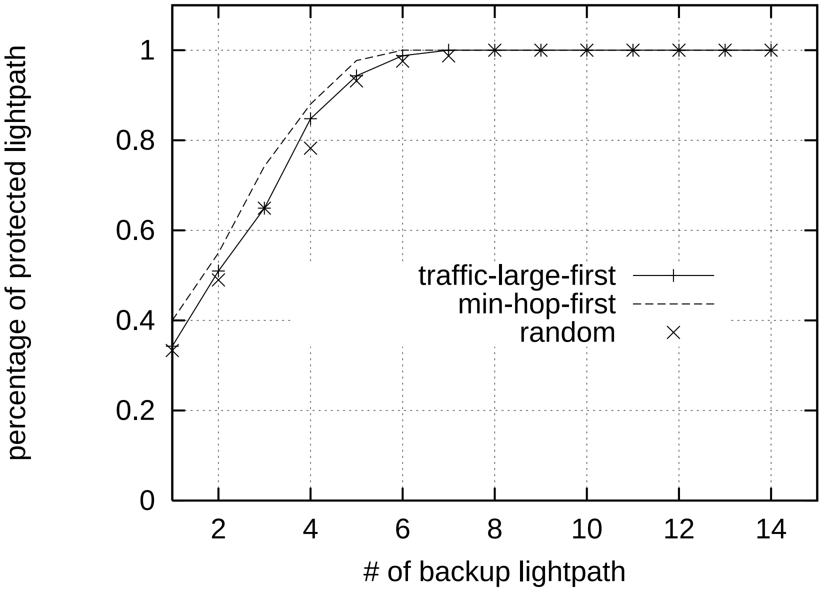

Figure 16: Number of Protected wavelength relative to the total number of primary lightpath.

lightpaths from 11 to 19. For each number of the primary lightpaths, we measure the increased traffic load at the IP router after the single fiber failure. By examining all cases of the single fiber failures, we choose the maximum value at each node, which is plotted in each figure. The results are presented in Figures 17 through 25 by changing the number of wavelengths used for primary lightpaths from 11 to 19. In each of the figures, the horizontal axis shows the node number, and the vertical axis does the increased traffic rate in terms of the packet rate [pps]. Here, packet length is assumed to be 1,000 bits.

¿From Figures 17 through 25, we can see that the maximum traffic rate at the IP router is gradually increased as expected. That is, the traffic rate at the IP router is increased as the number of backup lightpaths becomes small. Unfortunately, in the min-hop-first approach, the traffic load becomes larger than that of the large-traffc-first approach, and most figures (except Figure 25) indicate that the traffic-large-first approach has lowest traffic rate. Thus, the traffic-large-first approach is preferable in the IP over WDM network when the IP router is a primary cause of the bottleneck within the network.

In summary, the min-hop-first approach has better performance in order to make network reliable, but the traffic-largest-first approach is also a good choice when considering the traffic load at the IP router.

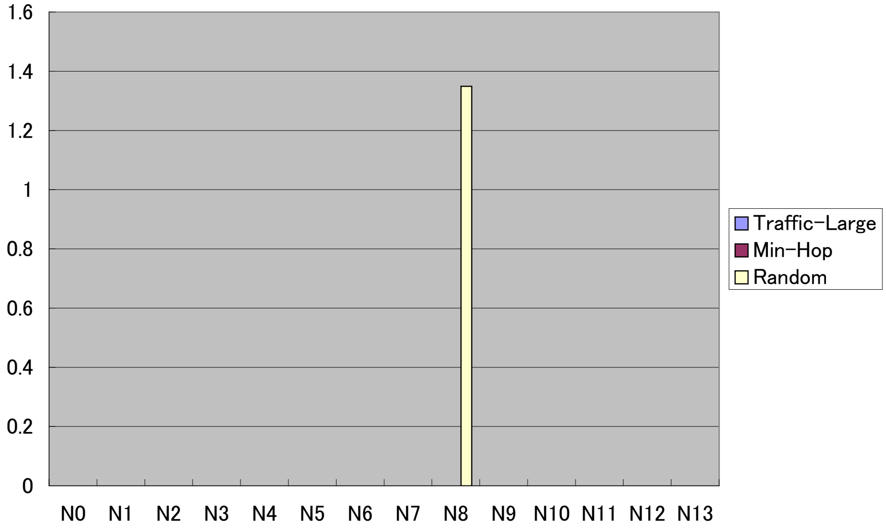

Figure 17: Maximum traffic load at the IP router after the failure: The number of wavelength used for primary lightpaths is 11

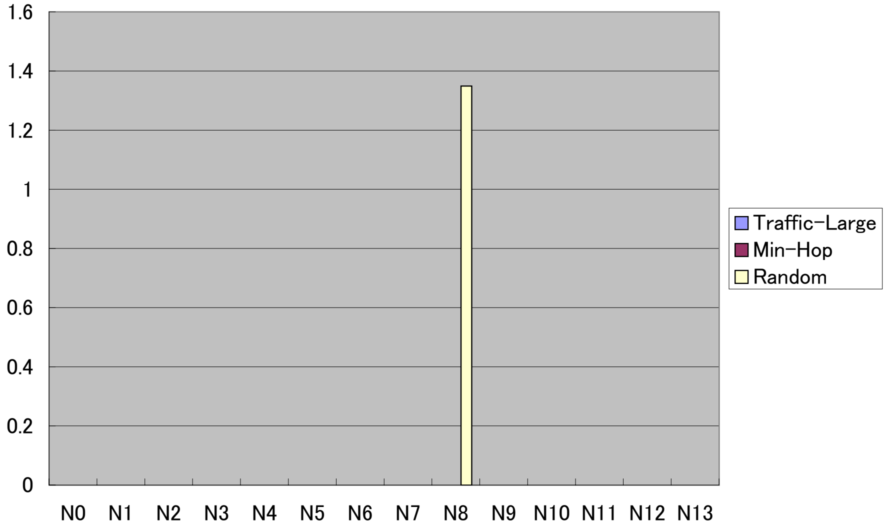

Figure 18: Maximum traffic load at the IP router after the failure: The number of wavelength used for primary lightpaths is 12

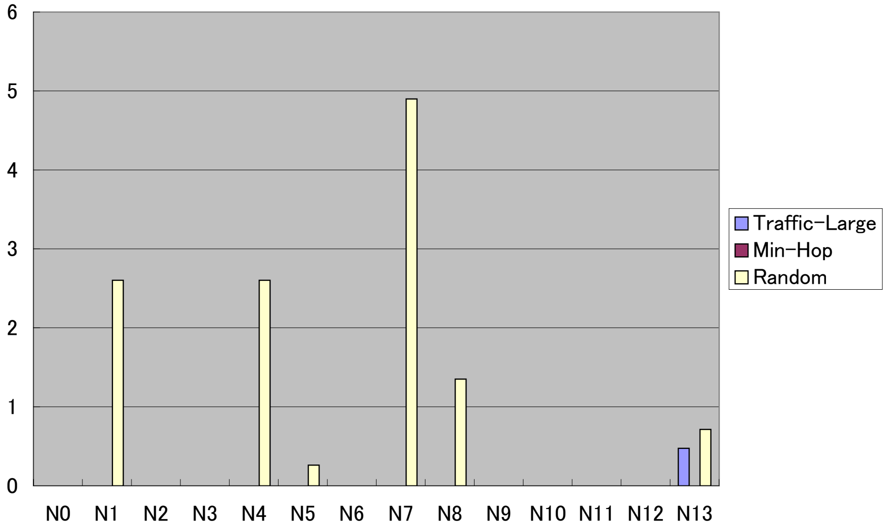

Figure 19: Maximum traffic load at the IP router after the failure: The number of wavelength used for primary lightpaths is 13

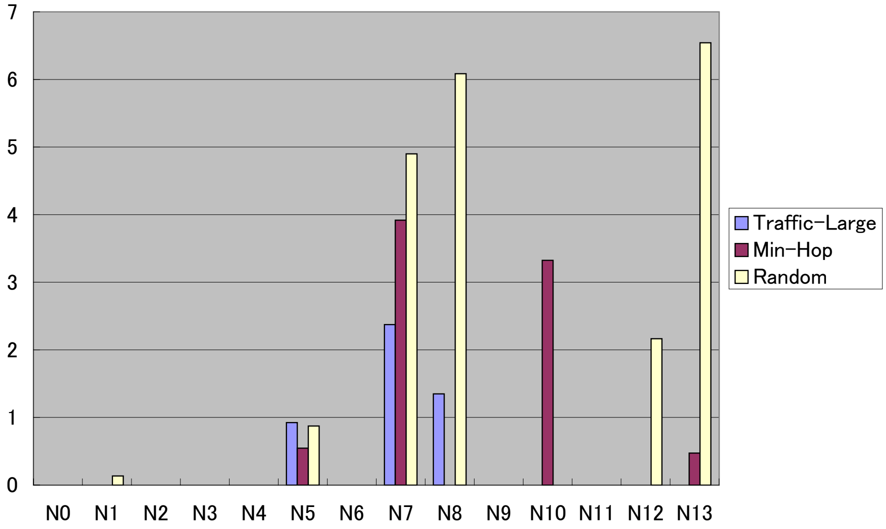

Figure 20: Maximum traffic load at the IP router after the failure: The number of wavelength used for primary lightpaths is 14

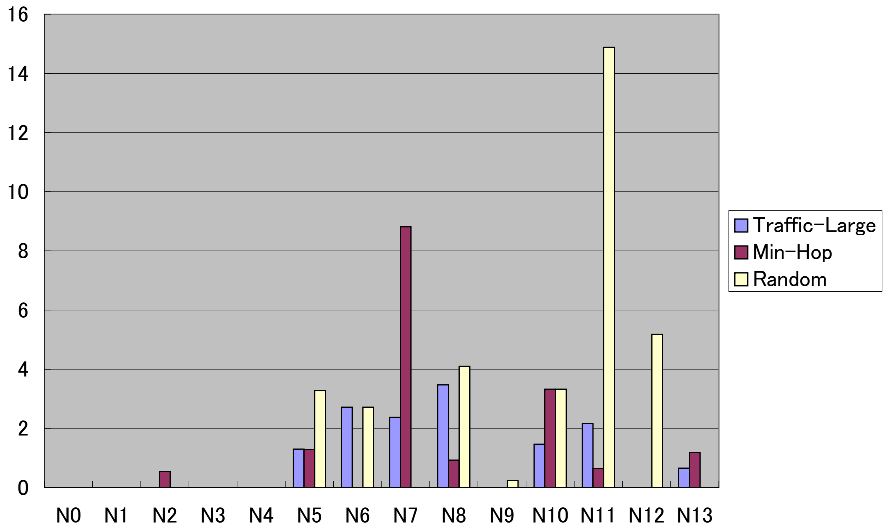

Figure 21: Maximum traffic load at the IP router after the failure: The number of wavelength used for primary lightpaths is 15

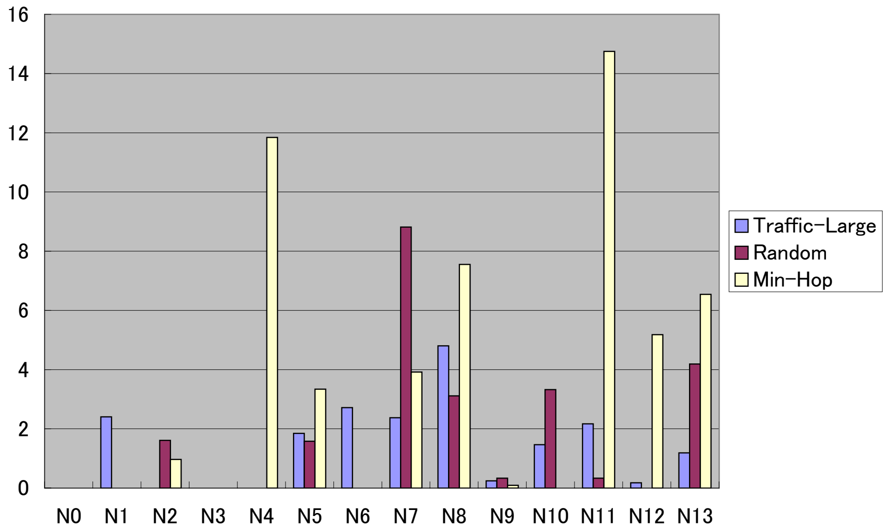

Figure 22: Maximum traffic load at the IP router after the failure: The number of wavelength used for primary lightpaths is 16

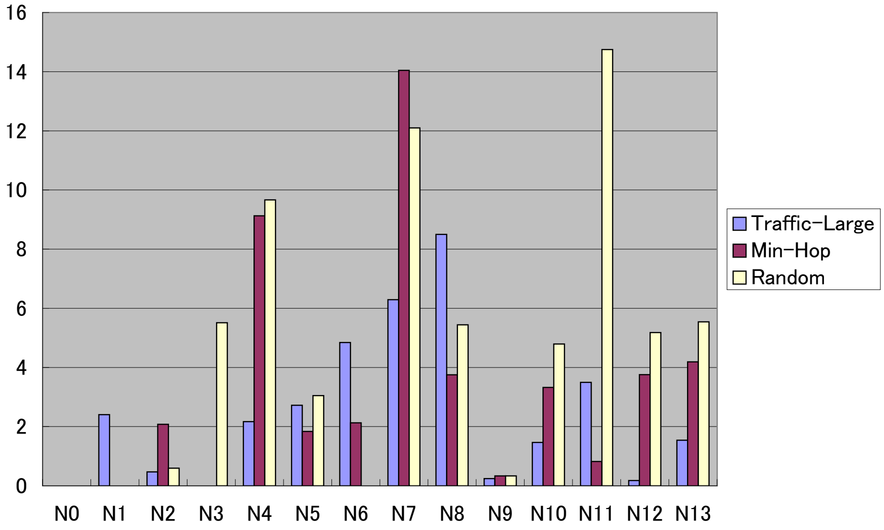

Figure 23: Maximum traffic load at the IP router after the failure: The number of wavelength used for primary lightpaths is 17

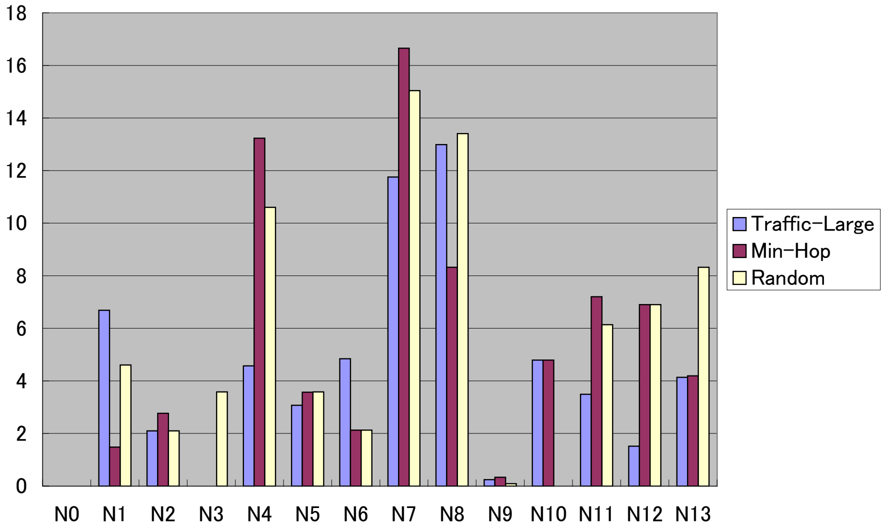

Figure 24: Maximum traffic load at the IP router after the failure: The number of wavelength used for primary lightpaths is 18

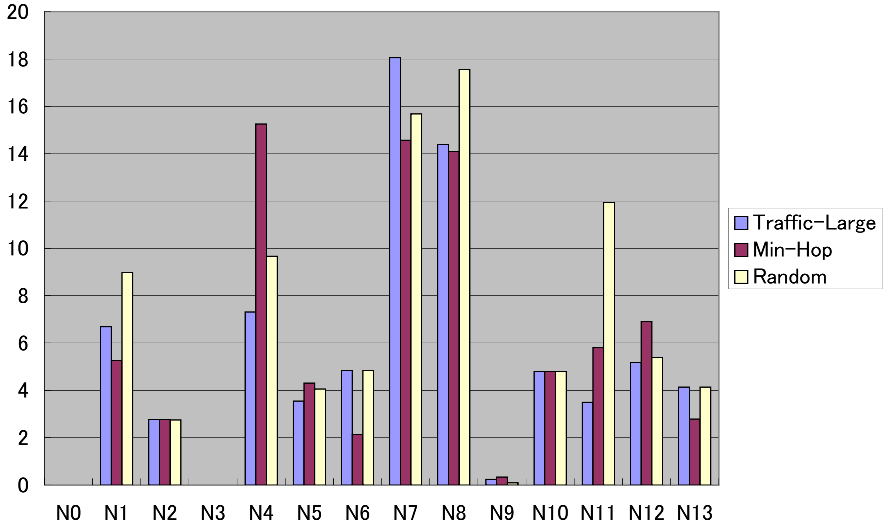

Figure 25: Maximum traffic load at the IP router after the failure: The number of wavelength used for primary lightpaths is 19

5 Conclusion and Future Works

In this paper, we have investigated the multilayered–survivability functionalities offered by IP over WDM networks.

In Section 2, we have first treated the routing instability problem in IP over WDM network. Since it has not been considered in the existing logical topology design problems, we have newly formulated an optimal design problem of the logical topology by taking account of the IP routing.

In Section 3, we have next considered the reliability mechanism in the IP over WDM network. By assuming the single–failure within the network, we have formulated the shared link protection mechanism as an optimization problem. It is formulated as MILP, and computationally intensive as the size of the network grows. Accordingly, we have proposed the heuristic approach and compared it with other approaches. Through numerical examples, we have shown that our proposed approach can offer the reliable network with perfect protection by the least number of wavelengths among three. However, the required number of wavelengths is rather large even when the shared protection is considered.

Therefore, we have next considered the the multiple reliability control mechanism in the IP over WDM network in Section 4. Based on our heuristic algorithm, we have also discussed the effect of interaction between IP and WDM layers. The results have shown that traffic-large-first approach is best.

In this paper, the logical topology design problem that we have proposed was computationally intensive, and it cannot be applied to the middle/large sizes of the network. A heuristic method for time-saving is necessary. Our optimization problem for the reliable networks does not explicitly formulate the minimization of the required number of wavelengths, which is another future research topic.

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