# Design Methods of Multi–layer Survivability in IP over WDM Networks

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## ABSTRACT

IP (Internet Protocol) over WDM networks where IP packets are directly carried on the WDM network is expected to offer an infrastructure for the next generation Internet. For IP over WDM networks, a WDM protection mechanism is expected to provide a highly reliable network (i.e., robustness against the link/node failures). However, conventional IP also provides a reliability mechanism by its routing function. In this paper, we first formulate an optimization problem for designing IP over WDM networks with protection functionalities of WDM networks, by which we can obtain 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, nodes and/or wavelengths. We therefore propose two heuristic algorithms, *min-hop-first* and *largest-traffic-first* approaches in order to assign the wavelength for backup lightpath. Our results show that the min–hop–first approach takes fewer wavelengths to construct the reliable network, that is, all of lightpaths can be protected using the WDM protection mechanism. However, our largest-traffic-first approach is also a good choice in the sense 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 Problem, Protection Method, Survivability

## 1. INTRODUCTION

The popularity of the Internet and advancements of multimedia communication technologies have led to an exponential growth of the Internet traffic. WDM (Wavelength Division Multiplexing) is a new optical technology that provides multiple wavelengths with the order of 10 Gbps. By utilizing the WDM technology for transporting the IP traffic, we have a much low–cost solution to meet those traffic demands.

In building IP over WDM networks, we have several alternatives, 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 only uses the WDM technology 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. 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 multiplexed on the fiber. Of course, it is insufficient to resolve the network bottleneck against an 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 means an actual network consisting of the optical nodes and the optical–fiber links connecting nodes. Each node has optical switches directly connecting an input wavelength to an output wavelength, by which no electronic processing at packet level, namely electronic routing, is necessary at the node. Then, the wavelength path can be set up 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 a *lightpath*.

If lightpaths are placed between every two nodes, then no electronic routing is necessary within the network. However, too many wavelengths are necessary to establish such a network.[2] Multi–fiber networks may give a full-meshed network, but in a multi–fiber environment, we have a trade-off relationship between the number of wavelengths per fiber and the number of

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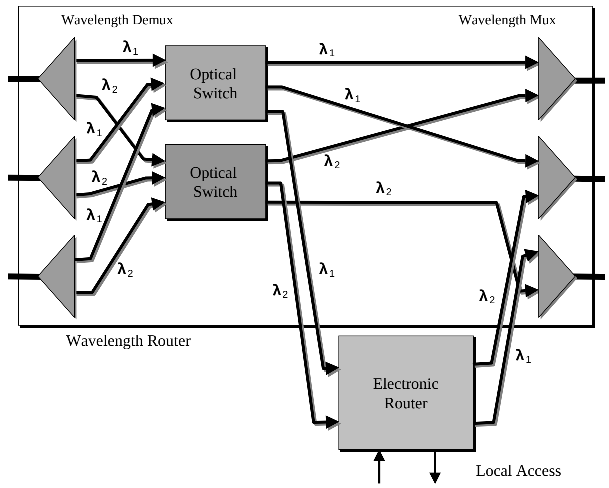


**Figure 1.** WDM node architecture

fibers per link[3]; The former is limited by the hardware and the latter is limited by cost (including the maintenance cost). In this paper, we therefore focus on the approach based on the logical topology (multi–hop approach) without explicitly modeling the multi-fiber link, by which we have both the lower number of wavelengths and lower number of fibers per link. The logical topology consisting of the lightpaths is first established 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.

For packet forwarding, we need the routing capability at nodes. One possible node architecture is shown in Figure 1. Packets on the lightpath terminating at the node are processed by the electronic IP router and then forwarded to other nodes using some lightpath. 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.

As mentioned above, the WDM network itself has a potential to offer several network functionalities such as the routing protocol, congestion control mechanism, and reliability mechanism. Perhaps, a most appropriate scenario for the 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. We believe that the first choice of the network control mechanism offered by WDM networks is its reliability mechanism. Of course, IP itself has such a functionality; the link and/or node failures 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, route alternation of WDM networks can be established within a few tens of milliseconds after the failure occurs. By combining those two mechanisms appropriately, we can expect more reliable networks than the current Internet.

There are two protection mechanisms in WDM protection.[4] The one is a dedicated protection method where a backup lightpath is dedicated to its corresponding primary lightpath, which is so called a “1+1” or “1:1” protection scheme. The other is a shared protection scheme where several primary lightpaths use the same wavelength as a backup lightpath. In the dedicated protection scheme, protection against simultaneous failures can be achieved, but the larger number of wavelengths is apparently necessary 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 must be sufficient that the WDM layer offers a protection mechanism against a single failure (i.e., the shared protection scheme), and the protection against the multiple failure is left to the IP layer. Furthermore, it may not be necessary to protect all the lightpaths by the WDM layer if it cannot lead to cost–saving even when we apply the shared protection scheme. As an extreme case, we may consider that all the wavelengths are used for establishing the primary lightpaths, and no protection is utilized by expecting that the failure seldom takes place. It certainly provides high performance networks (with less reliability). In this paper, we also discuss the interaction between IP layer’s reliability and WDM layer’s survivability, in the situation that a part of lightpaths are protected by the WDM protection mechanism and the rest are restored through IP layer’s routing function.

As mentioned before, we only consider the case of the single fiber on all links. From a viewpoint of fiber protection, it becomes a worst case scenario for a functional partitioning scheme. It is because in the case of multiple-fiber, we can utilize some wavelengths on the other fibers of the same link in the case of fiber–cut, while we cannot in our scenario. However, our main objective of this paper is functional partitioning the reliability mechanism between IP and WDM layers. By simply assuming the single–fiber link, we discuss on the best usage of wavelengths. Which is better to use the wavelengths on the link, WDM protection (by offering a sufficient number of backup lightpaths) or IP routing (by using wavelengths for primary lightpaths and by expecting the IP rerouting for reliability).

This paper is organized as follows. In Section 2, 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 3. Finally we present some concluding remarks in Section 4.

## 2. RELIABLE IP OVER WDM NETWORKS USING WDM PROTECTION MECHANISMS

### 2.1. Problem Formulation

In this paper, we consider the link protection mechanism, which gives a survivability against the fiber failure that is typically caused by a fiber cutoff. For this purpose, the shared link protection mechanism is considered for improving wavelength utilization under the assumption that the WDM network is highly reliable and the failure seldom occurs. Our objective is therefore to minimize the number of utilized wavelengths on the link. Our formulation in this subsection is based on.[4]

We will use the following notations.

$i, j$: 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 $mn$.

We first summarize notations characterizing the physical WDM network.

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

$W$: the number of wavelengths on a fiber

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

The followings are notations for representing the logical network.

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

$R^k_{ij}$: the route of the lightpath from node $i$ to node $j$ utilizing wavelength $k$. It consists of a set of physical links; $(i, m_1)$, $(m_1, m_2)$, . . ., $(m_p, j)$.

$A^k_{ij}$: the route of backup lightpath for the corresponding primary lightpath from node $i$ to node $j$ utilizing wavelength $k$. It consists of a set of physical links; $(i, n_1)$, $(n_1, n_2)$, . . ., $(n_q, j)$.

$c^k_{ij}$: if the primary lightpath utilizes wavelength $k$ on its way from originating node $i$ and terminating node $j$, then $c^k_{ij} = 1$, otherwise 0. $c^k_{ij}$ can be determined from $R^k_{ij}$.

$o^k_{mn}$: if the primary lightpath utilizes wavelength $k$ on the physical link $mn$, then $o^k_{mn} = 1$, otherwise 0. $o^k_{mn}$ is also determined from $R^k_{ij}$.

$\varphi_{mn}$: the maximum number of backup lightpaths going through physical link $mn$. It is determined from $A^k_{ij}$.

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 $mn$.

$m^w_{mn}$: if the backup lightpath utilizes wavelength $w$ on the physical link $mn$, then $m^w_{mn} = 1$, otherwise 0.

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

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.,

$$\min \sum_{m,n} (w_{mn} + b_{mn}) \tag{1}$$

**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.,

$$w_{mn} = \sum_{w \in W} o^w_{mn}. \tag{2}$$

(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.,

$$b_{mn} = \sum_{w \in W} m^w_{mn}. \tag{3}$$

(3) Either one primary lightpath or one backup lightpath utilizes wavelength $k$ on the physical link $mn$ if there exists a fiber.

$$o^k_{mn} + m^k_{mn} \leq P_{mn}. \tag{4}$$

(4) The lightpath utilizing wavelength $k$ between node $i$ and node $j$ must be protected by a backup lightpath when physical link $pq \in R^k_{ij}$ fails.

$$c^k_{ij} = \sum_{w \in W} \sum_{it \in A^k_{ij}} g^{it,w}_{ij,pq,k} \tag{5}$$

Note that it is unnecessarily to use different wavelength between primary lightpath and the corresponding backup lightpath.

(5) The lightpath utilizing wavelength $k$ between node $i$ and node $j$ must use the same wavelength $w$ on all the links of the backup lightpath (i.e., the wavelength–continuity constraint should hold).

$$g^{nt,w}_{ij,pq,k} = g^{tm,w}_{ij,pq,k}, \quad \forall pq \in R^k_{ij}, \forall nt, tm \in A^k_{ij} \tag{6}$$

(6) For each fiber failure scenario, a lightpath utilizing wavelength $k$ between node $i$ and node $j$ must use the same wavelength $w$ on physical link $mn \in A^k_{ij}$ for backup lightpath.

$$g^{mn,w}_{ij,p_1q_1,k} = g^{mn,w}_{ij,p_2q_2,k}, \quad \forall p_1q_1, p_2q_2 \in R^k_{ij}. \tag{7}$$

As the equation indicates, we assume that we allow to use the different wavelength for the backup path against the failure of the corresponding primary path.

(7) When the failure occurs at physical link $pq$, at most one backup lightpath should utilize wavelength $w$ on physical link $mn$, if the corresponding primary lightpath traverses the failure link $pq$.

$$\sum_{ij} \sum_{k \in W : c^k_{ij} > 0 \wedge pq \in R^k_{ij} \wedge mn \in A^k_{ij}} g^{mn,w}_{ij,pq,k} \leq 1 \tag{8}$$

(8) The number of backup lightpaths utilizing wavelength $k$ on the physical link $mn$ must be bounded.

$$\varphi_{mn}\, m^k_{mn} \geq \sum_{w \in W} \sum_{(i,j):(c^k_{ij} > 0, mn \in A^k_{ij})} \sum_{pq \in R^k_{ij}} g^{mn,k}_{ij,pq,w} \tag{9}$$

We note here that we do not distinguish two primary lightpaths having link disjoint routes in our formulation. However, in IP over WDM networks, the paths having different ways are viewed by the IP layer as having different delays. Hence, IP selects only the path providing the lowest delay, and it is not effective to consider link disjoint routes. This is the reason why we do not distinguish two primary lightpaths explicitly.

## 2.2. Proposed Heuristic Approaches

In the previous subsection, we have formulated wavelength assignment problems for backup lightpaths using the shared link protection mechanism. Our formulation results in a mixed integer linear problem (MILP), and a standard package such as CPLEX[5] 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 becomes 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 link 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 that the lightpath traverses. For the purpose of more sharing while avoiding conflicts among lightpaths with large hop–counts, we choose the backup lightpath in an ascending order of hop–counts, which will be referred to as a *min-hop-first* approach. It is expected that by assigning the wavelengths sequentially from the smallest hop–count lightpath, 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.

$h_{ij}^k$: the hop count of the primary lightpath that utilizes the wavelength $k$ for node pair $i$ and $j$.

$A_{ij}^k$: a set of physical links used for the backup lightpath for primary lightpath $ij$ utilizing wavelength $k$.

$B_{ij}^k$: a set of links that have not been checked whether lightpath can be placed between nodes $i$ and $j$ utilizing wavelength $k$ or not. 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 $h_{ij}^k$.

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 $j$ or not. More precisely, do the following steps.

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

Step 2.1.1: If wavelength $p$ on the physical link is not utilized by any of other lightpaths, then delete 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 $mn$ 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, which means that any of 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.

We also consider the *largest-traffic-first* approach, where the lightpath is selected in a descending order of the traffic load on the lightpaths, while its description is omitted due to space limitation. In the following numerical subsections, we also consider the *random* approach, in which the lightpath is selected randomly, for comparison purpose.

### 2.3. Numerical Examples

#### 2.3.1. Optimization Results

We first investigate the usefulness of the IP over WDM networks with high reliability. CPLEX 6.5 is used to solve the optimization problem described in Subsection 2.1. Since it is hard to solve the large–scaled network, we use a eight–node network shown in Figure 2.

We also applied our heuristic algorithms described in Subsection 2.2 to examine its optimality. For this purpose, we need a logical topology to apply our heuristic algorithms. We use the MLDA algorithm, which is a heuristic algorithm proposed in.[6,?] 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, lightpaths are placed as much as possible utilizing those wavelengths. 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.

The min-hop-first and random approaches do not require the traffic matrix since it is not considered in the algorithm, but the largest-traffic-first approach needs it. Traffic matrix given in[6] is used for the reference purpose. Furthermore, the number of wavelengths used for primary lightpath, that is, wavelength used by MLDA algorithm is set to five. The results of the optimization problem and our heuristic algorithms are compared in Table 1, where we consider the required number of wavelengths to protect all the lightpaths. From the table, we can observe that good results are obtained by our heuristic algorithms.

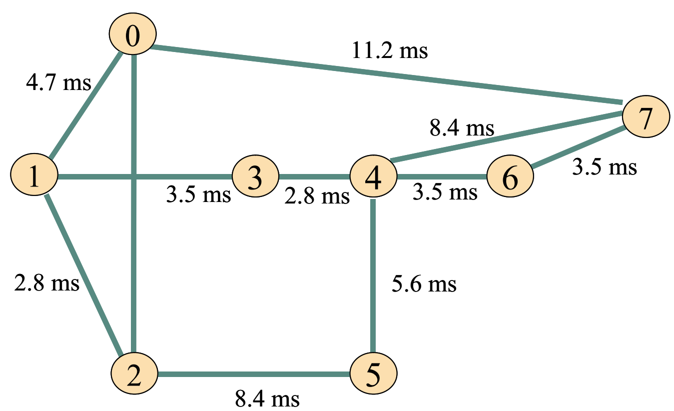


**Figure 2.** Physical topology of eight-node network

**Table 1.** The required number of wavelengths to protect all lightpaths

| MILP | min-hop-first | largest-traffic-first |
|---|---|---|
| 10 | 10 | 11 |

#### 2.3.2. Results by Heuristic Approach

We next consider 14–node NSFNET backbone network as a network model. Traffic matrix given in[6] is used for reference purpose. Since MLDA algorithm places lightpath on physical topology, we must identify where the IP packets go through. We modified the Dijkstra's shortest path algorithms to consider the nodal processing delays. We assume that the nodal delays are derived from a M/M/1 queuing model and the offered traffic rates are assumed to be $\sum_s \lambda^{sd}$.

Figure 4 compares three approaches in terms of the required number of wavelengths to protect all the lightpaths. The horizontal axis shows the number of wavelengths used for primary lightpaths. For example, if the primary lightpaths are

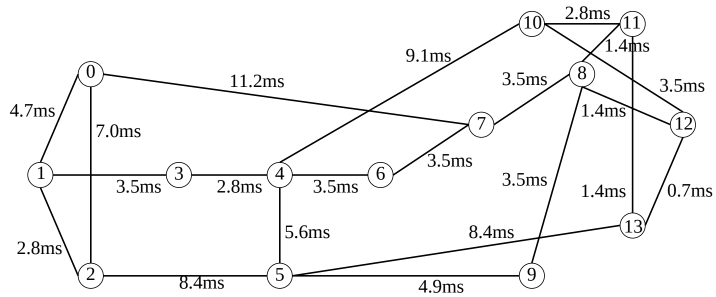


**Figure 3.** NSFNET network model

established by utilizing 10 wavelengths to establish the logical topology, the additional number of wavelengths to be able to protect all lightpaths is six when applying the min-hop-first approach. From Figure 4, we can observe that the min-hop-first approach requires a smallest number of wavelengths among three approaches.

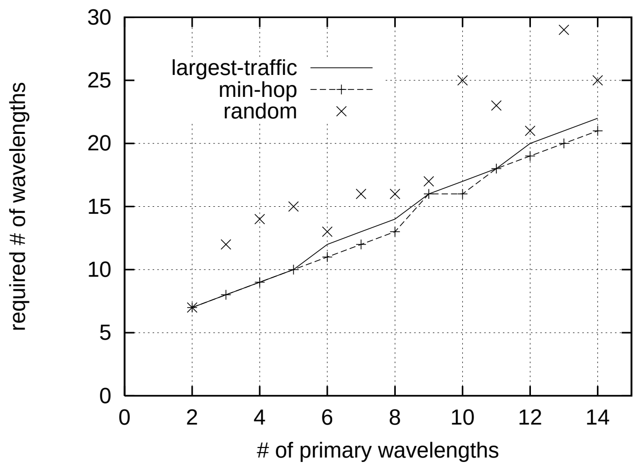


**Figure 4.** The number of required wavelengths to completely protect the primary lightpaths

## 3. MULTI-LAYER SURVIVABILITY FOR IP OVER WDM NETWORKS

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

### 3.1. Consideration on Multi–layer Survivability

It is ideal that the WDM network could protect all the lightpaths so that 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 a limitation on the number of wavelengths. Setting up more backup lightpaths 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. The smaller number of primary lightpaths results in that the traffic load at the IP router is increased, and that bottleneck caused by the IP router cannot be resolved. On the contrary, we can expect that more traffic can be carried by primary lightpaths if the wavelengths used for the primary lightpaths is increased, but in that case, the advantage of protection mechanisms of the WDM network cannot be enjoyed.

There is another problem. While a WDM protection mechanism switches to the backup lightpath in order of ten milliseconds, IP router may change the route to better one after IP routing table is updated. Suppose that after the failure occurs, the lightpath $ij$ utilizing wavelength $k$ is switched to the backup lightpath, which results in the increasing of propagation delay by its nature. After IP updates its routing table (typically in the order of 10 sec after), the IP router may find route (which may consist of two ore more concatenated lightpaths) shorter than the backup lightpath prepared by the WDM protection mechanism.

The main cause of the above–mentioned problem is that we did not consider the above case in the design method of the WDM protection mechanism described in the previous section. To utilize more wavelengths effectively, we change our heuristic algorithm as follows. A main idea is that we simply give up preparing backup lightpath if that backup lightpath is eventually not used by IP.

(1) In Step. 1, after selecting a lightpath $h^k_{ij}$, set $\{S\}$, elements of which are node pairs utilizing lightpath $h^k_{ij}$.

(2) Calculate the increased delay $\theta$ under the assumption that the backup lightpath is placed.

(3) For every node pair $sd$ in $\{S\}$, calculate the delay of primary lightpath $d_{sd}$ and that of the second shortest path $d^a_{sd}$. Then, check whether the sum of $d_{sd}$ and $\theta$ exceeds the delay of the second shortest path $d^a_{sd}$ or not. If it is true, check the next lightpath $h^{k'}_{i'j'}$ without protecting the current lightpath $h^k_{ij}$.

It is difficult to identify how many wavelengths should be assigned for primary and 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 therefore provide numerical examples in the following subsection to investigate a compromise between the above two objectives.

### 3.2. Numerical Examples and Discussions

In this subsection, we investigate the effect of IP/WDM interactions using the NSFNET backbone network model, which has 14 nodes and 20 links as having been shown in Figure 3 of Subsection 2.2

In Figure 5, we first show the number of protected lightpaths dependent on the total number of available wavelengths on the fiber. In obtaining the figure, we use the MLDA algorithm[6,7] to determine the logical topology. The number of wavelengths used for primary lightpaths is eight, and the wavelengths for the backup lightpaths are increased. In the figure, three cases of approaches (min-hop-first, largest-traffic-first, and random approaches) are compared. By the modified MLDA algorithm, 73 primary lightpaths are established. Then, those lightpaths are completely protected in all of three cases if we have additional seven wavelengths as shown in the figure. We note that even if the number of additional wavelengths for the backup lightpaths is set to be 0, the number of protected lightpaths 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 later use in protection. From the figure, we can observe that the min-hop-first approach can protect more lightpaths than largest-traffic-first and random approaches.

We next set the number of wavelengths to be fixed, and then change the number of wavelengths used for establishing primary lightpaths. Figure 6 shows such a case by setting the 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 numbers of the lightpaths protected by WDM protection mechanisms of three approaches. 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, too many wavelengths dedicated to 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 in terms of a required number of backup wavelength.

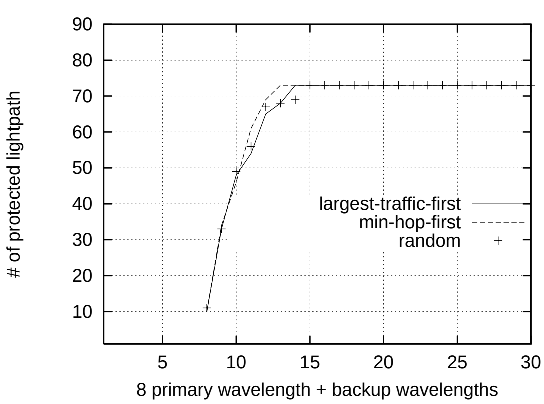


**Figure 5.** The number of protected lightpaths

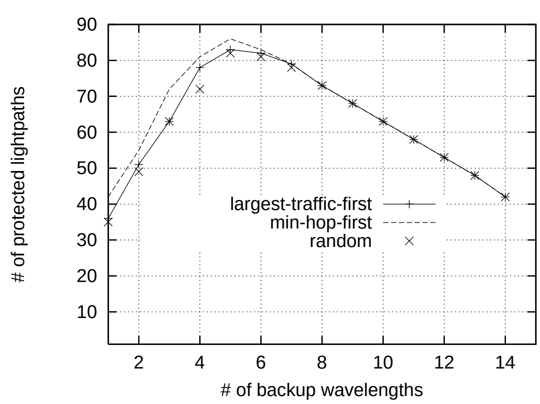


**Figure 6.** Number of protected lightpaths.

The traffic volume increased at the IP router when the failure occurred is another important measure to evaluate the protection mechanism of the WDM network. In obtaining the following set of figures, we fix the number of wavelengths to be 16, and then, change the number of wavelengths used for primary lightpaths. For each number of wavelengths for primary lightpaths, we measure the increased traffic load at the IP router after the single–failure of the fiber. By examining all cases of the single–failures of fibers, we choose the maximum value at nodes. The results are presented in Figures 7 through 9 by changing the number of wavelengths used for primary lightpaths as 10, 12 and 14. 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 [Mpps]. Here, packet length is assumed to be 1,000 bits, and the processing capability of IP router is set to 40 Mpps. From Figures 7 through 9, 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. In the min-hop-first approach, the traffic load becomes larger than that of the largest-traffic-first approach. That is, the largest-traffic-first approach becomes preferable in the IP over WDM network if the IP router is a primary cause of the bottleneck within the network.

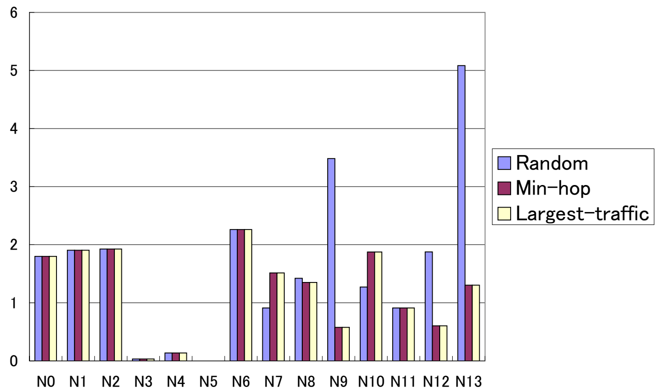


**Figure 7.** Maximum traffic load at the IP router after the failure in NSFNET backbone network: The number of wavelengths used for primary lightpaths is 10

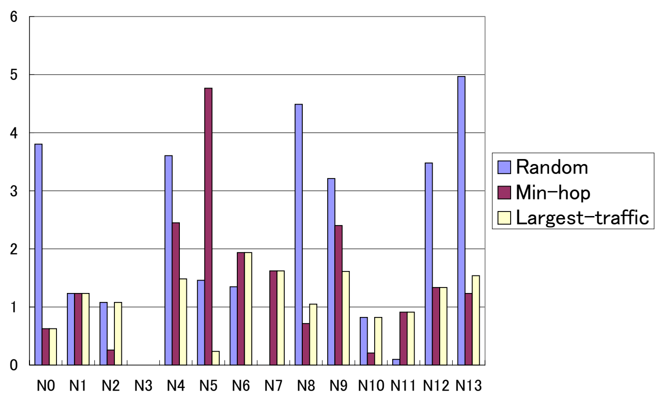


**Figure 8.** Maximum traffic load at the IP router after the failure in NSFNET backbone network: the number of wavelengths used for primary lightpaths is 12

To see the differences more clearly, we next examine the approaches in terms of traffic volume. Figure 10 compares the traffic rate protected by the backup lightpaths. As the number of wavelengths used for the primary lightpaths is increased, the traffic protected by the backup lightpaths gets large. Then, it is decreased since the wavelengths used for the backup lightpaths are limited. On the contrary, the traffic restored by the IP routing protocol is increased as the number of wavelengths used for the primary lightpaths gets large. The total volume of traffic that is not protected by the backup lightpaths is shown in Figure 11. When the number of wavelengths on the fiber is below nine, the traffic can be perfectly protected in this case. However, when it exceeds nine, the volume of the traffic not protected is increased suddenly. Of course, it can be restored by IP routing after the routing table is updated, which will be shown in the next set of figures. Before showing those figures, we compare three approaches. From Figures 10 and 11, it can be observed that the largest-traffic-first approach can protect more traffic than the min-hop-first approach since it prepare the backup lightpaths according to the traffic volume.

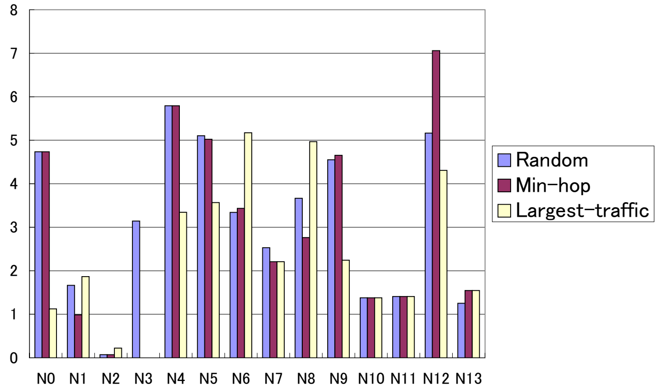


**Figure 9.** Maximum traffic load at the IP router after the failure in NSFNET backbone network: the number of wavelengths used for primary lightpaths is 14

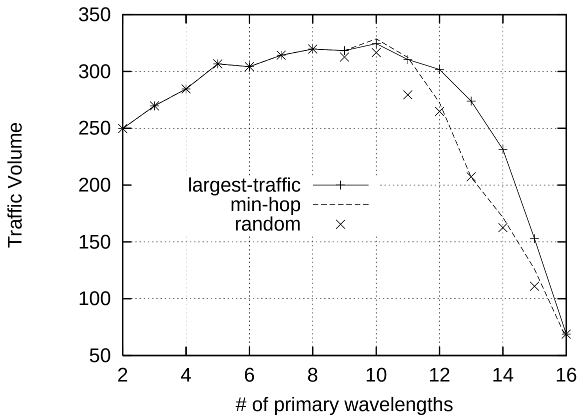


**Figure 10.** Total volume of the traffic protected by backup lightpaths before IP routing table update

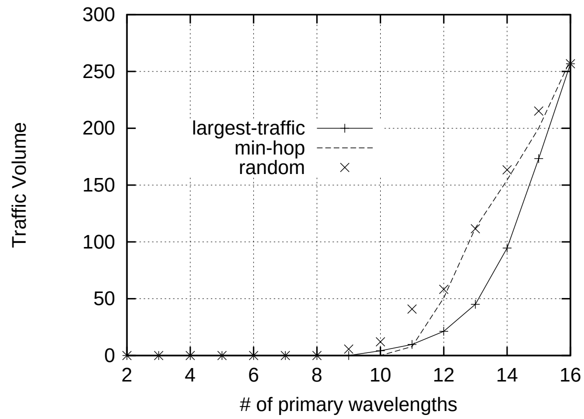


**Figure 11.** Total volume of the traffic not protected by backup lightpaths before IP routing table update

Next, we present the traffic volume protected by the WDM protection method after the IP routing table is updated in Figure 12. Here, we plot the figure in the situation that all of routing tables at every node are updated. The difference from Figure 10 is due to alternation of several IP routes. IP does not select several backup lightpaths as its routes. While we take into account this fact as described in Subsection 3.1, it is not perfect. It is our future research topic that we build the set of perfect backup lightpaths such that IP chooses those lightpaths as its own routes. Figure 13 shows the complement to Figure 12; i.e., it presents the traffic that is not supported by the WDM protection and is routed by IP.

From the above figures, it is clear that by our proposed method, the required number of the wavelengths assigned for primary/backup lightpaths can be estimated for good compromise between high performance by establishing WDM logical topology and high reliability by protecting a large part of primary lightpaths. Among three approaches that we have considered, the min-hop-first approach has better performance in order to make network reliable, but the largest-traffic-first approach is also a good choice when considering the traffic load at the IP router.

We also applied our heuristic algorithms to Japan backbone network of NTT, which consisting of 49 nodes and 200 links. For the traffic matrix, we use the publicly available traffic data provided by NTT.[8] It is a summary of the telephone traffic represented in Erlang between the nodes, and therefore, it does not represent the IP traffic. However, after we examine the data carefully, we convinced that it reflects the population distribution in Japan and the development level of the industries. At the same Web site, subscription numbers of the Internet accesses (actually 2B+D ISDN lines) are available. As in the previous NSFNET case, we apply the MLDA algorithm for generating the logical topology, and then use each of our heuristic algorithms to obtain the results. We fix the number of wavelengths to be 16, and then, change the number of wavelengths used for primary lightpaths. We measure the increased traffic load at the IP router after the single–failure of the fiber. By examining all cases of the single–failures of fibers, we choose the maximum value at nodes. The results are shown in Figures 14 through 16. Selected nodes are displayed. Those correspond to Figures 7 through 9 of NSFNET case. From the figures, we also observe that our largest-traffic-first approach can protect more traffic than the other algorithms. It is useful if our primary concern is traffic load at the IP router after the failure.

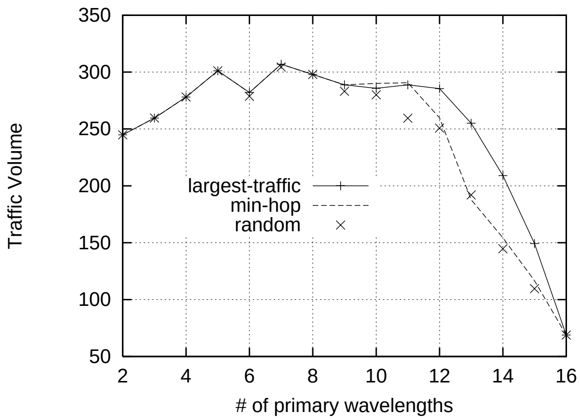


**Figure 12.** Total volume of the traffic protected by backup lightpaths after IP routing table update

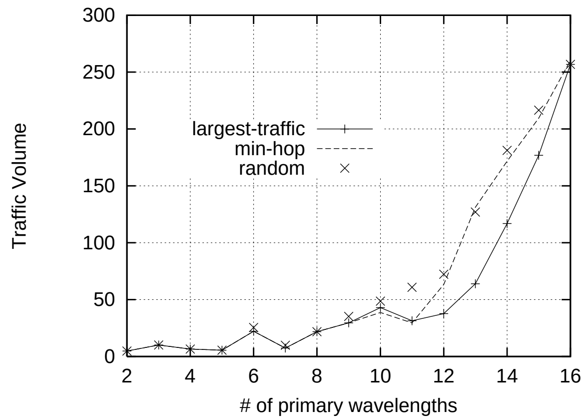


**Figure 13.** Total volume of the traffic not protected by backup lightpaths after IP routing table update

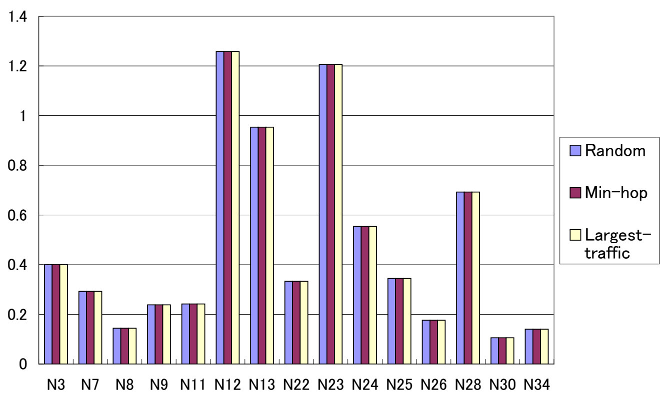


**Figure 14.** Maximum traffic load at the IP router after the failure in Japan backbone network: the number of wavelength used for primary lightpaths is 10

## 4. CONCLUDING REMARKS

In this paper, we have investigated the multi–layer survivability in IP over WDM networks. In Section 2, we have 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 network size grows. Accordingly, we have proposed the heuristic approaches and compared those with the solution obtained by MILP. Through numerical examples, we have compared the required number of wavelengths for the reliable network. We have next considered the functional partitioning of IP routing and WDM protection for reliable networks in Section 3. Based on our heuristic algorithm, we have also discussed the effect of interaction between IP and WDM layers. The results have shown that the largest-traffic-first approach is best if our primary concern is traffic load at the IP router after the failure.

Our heuristic approaches for the reliable networks do not explicitly formulate the minimization of the required number of wavelengths to construct the logical topology. While in the current paper, we have used the MLDA algorithm, more effective one is necessary. We have found that in multi–layer survivability, a few node pairs did not use the backup lightpath prepared by WDM protection of our algorithms after routing tables are updated. We may need another solution, but it is also left to be a future research topic.

## ACKNOWLEDGMENTS


This work was supported in part by Research for the Future Program of Japan Society for the Promotion of Science under the Project “Integrated Network Architecture for Advanced Multimedia Application Systems”（JSPS-RFTF97R16301 ). The

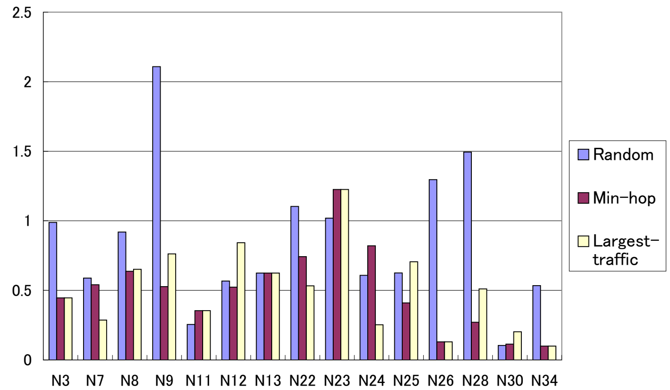


**Figure 15.** Maximum traffic load at the IP router after the failure in Japan backbone network: the number of wavelength used for primary lightpaths is 12

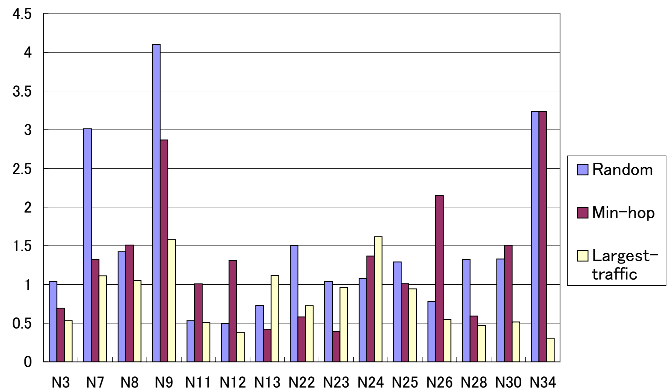


**Figure 16.** Maximum traffic load at the IP router after the failure in Japan backbone network: the number of wavelength used for primary lightpaths is 14

author wishes to thank all participants to these projects.

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