Lightpath Management of Logical Topology with Incremental Traffic Changes for Reliable IP over WDM Networks

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Abstract

In order to construct a reliable IP over WDM network, backup paths as well as primary paths should be embedded within a wavelength-routed topology (or logical topology). There are many researches treating a design problem of such logical topologoies. However, most of existing approaches assume that the traffic demand is known a priori. In this paper, we propose a new approach, called an incremental capacity dimensioning approach, to design the logical topology. Our incremental approach consists of three steps for building the logical topology: an initial phase, an incremental phase, and a readjustment phase. By our approach, the logical topology can be adjusted according to the incrementally changing traffic demand. During the incremental phase, the primary path is added according to the traffic increase. At that time, the backup lightpaths are reconfigured since those do not affect the carried traffic on the operating primary paths. Our proposed algorithm, called MRB (Minimum Reconfiguring for Backup lightpath), assigns the wavelength route in such a way that the number of backup lightpaths to be reconfigured is minimized. Our results show that the total traffic volume which the IP over WDM network can accommodate is improved by using our MRB algorithm. Then, under the condition that the traffic load within the operating network is appropriately measured, the existing approach for designing the logical toplogy can be applied in the reconfiguration phase. In this paper, we also introduce a notion of "Quality of Protection (QoP)." It descriminates the wavelength routes according to the quality level of those routes, which is a realization of "QoS (Quality of Service)" suitable to IP over WDM networks. For this purpose, we extend our proposal and formulate the design problem in order to treat QoP.

Key Words: IP over WDM, Logical Topology, Optimization Problem, Wavelength Division Multiplexing, Quality of Protection, Network Management

1 Introduction

A WDM (Wavelength Division Multiplexing) technology that provides multiple wavelengths on a fiber has a capability of offering an infrastructure for the next generation Internet. A promising approach for building an IP (Internet Protocol) over WDM network [1,2] is that a logical network consisting of the wavelength channels (lightpaths) is built on the physical WDM network. Then, IP traffic are carried on the logical topology, by utilizing the MPλS (Multiple Protocol Lambda Switching) or GMPLS (Generalized MPLS) technologies for packet routing. An important feature that the WDM network can provide to the IP layer is a reliability function. IP has its own routing protocol, which can find a detour and then restore the IP traffic upon a failure of the network component, but it takes a long time (typically 30 sec for routing table update). On the contrary, a reliability mechanism provided by the WDM network layer can offer much faster failure recovery [3]. It is important in very high-speed network just like IP over WDM networks since a large amount of IP traffic is lost upon a failure occurrence in such a network.

When constructing the IP over WDM network with protection, backup paths as well as primary paths are embedded within the logical topology. In [3], two protection mechanisms are proposed: dedicated and shared protection methods. The dedicated protection method prepares a dedicated backup path for every primary path. In the shared protection method, on the other hand, several primary paths can share a backup lightpath if and only if the corresponding primary lightpaths are fiber–disjoint. Since IP routing protocol also has its own reliability mechanism, it would 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 [4]. In [4], the logical topology design method is proposed to set up backup paths as well as primary paths to be embedded within the logical topology. However, a lot of past researches including [3] and [4] assume that traffic demand is known a priori. Then, an optimal structure of the logical topology is obtained.

Such an assumption is, however, apparently inappropriate especially when the WDM technology is applied to the Internet. In the traditional telephone network, a network provisioning (or capacity dimensioning) method has already been well established. The target call blocking probability is first set, and the number of telephone lines (or the capacity) is determined to meet the requirement on the call blocking. After installing the network, the traffic load is continuously measured, and if necessary, the link capacity is increased to accommodate the increased traffic. By this feedback loop, the telephone network is well engineered to provide QoS (Quality of Service) in terms of call blocking probabilities. Rationales behind this successful positive feedback loop include: (1) the call blocking probability is directly related to the user's perceived QoS in the telephone network, (2) capacity provisioning is easily based on stably growing traffic demands and the rich experiences on past statistics, (3) we have well-established fundamental theory, i.e., Erlang loss formula, and (4) the network provider can directly measure a QoS parameter (i.e., blocking probability) by monitoring the numbers of generated and blocked calls.

On the other hand, a network provisioning method suitable to the Internet has not yet been established. By contrast with the telephone network, there are several obstacles. (1) The statistics obtained by traffic measurement is packet level and henceforth the network provider cannot monitor or even predict the user's QoS, (2) an explosion of the traffic growth in the Internet makes it difficult to predict a future traffic demand, (3) there is no fundamental theory in the Internet like the Erlang loss formula in the telephone network. A queueing theory has a long history and has been used as a fundamental theory in the data network (i.e., the Internet). However, the queueing theory only reveals the packet queueing delay and loss probability at the router. The router performance is only a component of the user's perceived QoS in the Internet. Furthermore, the packet behavior at the router is reflected by the dynamic behavior of TCP, which is essentially the window-based feedback congestion control [1].

According to the above discussions, the "static" design that the traffic load is assumed to be given a priori is completely inadequate. Instead, a more flexible network provisioning approach is necessary in the era of the Internet. Fortunately, the IP over WDM network has a capability of establishing the above–mentioned feedback loop by utilizing wavelength routing. If it is found through the traffic measurement that the user's perceived QoS is not satisfactory, then new wavelength paths are set up to increase the path bandwidth (i.e., the number of lightpaths).

A heuristic algorithm for setting up primary and backup lightpaths on demand basis is already proposed in [5], in which routing and wavelength assignment are performed for each lightpath setup request. The authors in [5] allow backup lightpaths to be reconfigured in order to meet future lightpaths setup requests for an effective use of wavelengths. Their method is intended to be performed in a distributed fashion. However, only a dedicated protection is considered in [5]. As described above, the shared protection scheme is more appropriate in IP over WDM networks since IP also has a capability of the protection against the failure.

In this paper, we consider the centralized approach for establishing the logical topology. In general, the centralized approach has a scalability problem especially when the number of wavelengths and/or the network size become large. However, we need to establish multiple number of wavelengths due to traffic fluctuation. In such a case, the distributed approach taken in [5] is inappropriate. However, our main purpose of this paper is to propose the framework for an incremental use of the wavelengths in IP over WDM networks, and therefore, the approach taken in [5] can be incorporated in our framework by replacing our centralized approach by their distributed approach.

In this paper, we first propose an incremental logical topology management scheme, consisting of three phases for setting up primary and backup lightpaths; an *initial phase*, an *incremental phase*, and a *rearranging phase*. In the initial phase, a reliable IP over WDM network is built by setting up both primary and backup lightpaths. In this phase, we do not know the traffic demand, but we have to establish the network anyway by using some statistics on the traffic demands. It is important that an estimated traffic demands than the exact demand must be allowed. For that purpose, a flexible network structure is necessary. In our method, an easy reconfiguration of the logical topology is allowed, which is performed in the incremental phase. In the incremental phase, the logical topology is reconfigured according to the newly set up request of the lightpath(s) due to changes in the traffic demand, or the mis-projection on the traffic demand as mentioned above. We formulate the process of setting of lightpaths as an optimization problem. We also propose a heuristic algorithm, called a MRB (Minimum

Reconfiguring for Backup lightpaths) algorithm, for selecting an appropriate wavelength. During the incremental phase, the backup lightpaths are reconfigured for achieving the optimality. However, an incremental setup of the primary lightpaths may not lead to the optimal logical topology, and our logical topology might be under utilized compared to the one designed by the static approach. Therefore, we also consider the readjustment phase where *both* primary and backup lightpaths are reconfigured. In our readjustment phase, a one-by-one readjustment of the established lightpaths is considered so that we can achieve service continuity of the IP over WDM networks. In this paper, we will mainly discuss the incremental phase and the issues realizing the rearrangement phase remain future topics of research.

Another issue that we treat in this paper is related to QoS in the IP over WDM networks. The granularity is at the wavelength level. In the past, a lot of work has been devoted to QoS (Quality of Service) guarantee or differentiation mechanisms in the Internet; e.g., an Intserv architecture for per-flow QoS guarantee, a Diffserv architecture for per-class QoS differentiation. However, in IP over WDM networks, treating such a fine granularity is impossible. Instead, we introduce QoP (Quality of Protection): the QoS differentiation in the lightpath protection. We will explain how to realize a QoS mechanism suitable to IP over WDM networks with a little modification to our logical topology design framework.

This paper is organized as follows. In Section 2, we introduce three phases for managing a logical topology design. In Section 3, we show a formulation for reconfiguring backup lightpaths, and propose heuristic algorithms for assigning wavelengths for the primary lightpath request. We then evaluate the proposed algorithms in Section 4. In Section 5, we present the modification to our optimization formulation that support QoP. We finally conclude our paper in Section 6.

2 Managing Logical Topology for Reliable IP over WDM Networks

In this section, we explain our incremental approach for the capacity dimensioning of the reliable IP over WDM networks. It consists of initial, incremental, and readjustment phases. These will be described in the following subsections. Note that in each phase, if lightpaths cannot be set up due to lack of wavelengths, alert signals are generated and the network provider should increase fibers against increasing traffic demand.

2.1 Initial Phase

In the initial phase, primary and backup lightpaths are set up for given traffic demands. As described before, our approach allows that the projection on traffic demands is incorrect. It will be adjusted in the incremental phase, which will be presented in the next subsection.

The existing design methods for the logical topology can be applied in this phase. For example, a design method for the logical topology for primary lightpath is shown in [6], and a heuristic algorithm for setting up backup lightpaths for the IP over WDM network is shown in [4]. In this phase, the number of wavelengths used for setting up the lightpaths should be minimized so that remaining wavelengths can be utilized for the increasing traffic in the incremental phase.

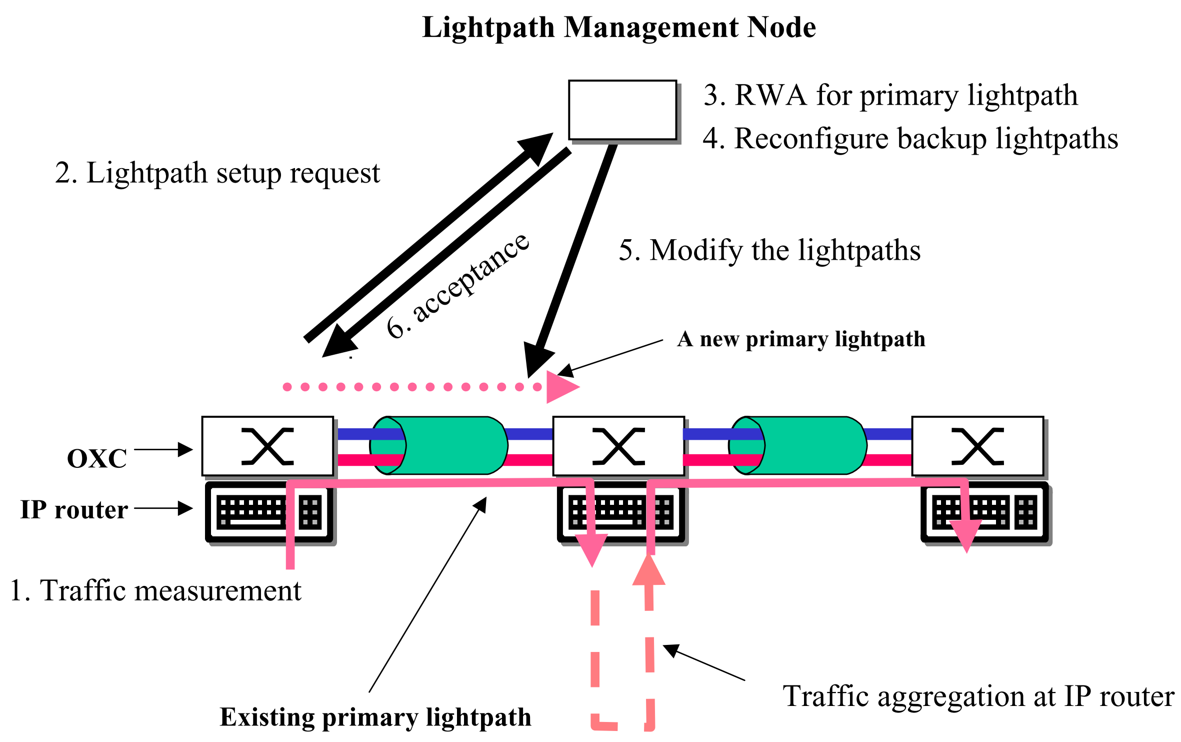

Figure 1: Logical topology management model in the incremental phase

Thus, some modification is necessary in our case. For example, MLDA (minimum delay logical topology design algorithm) proposed in [6] is intended to maximize wavelength utilization and works as follows.

1. First, it places a lightpath connection between two nodes if there is a fiber directly connecting those respective nodes.
2. Then, MLDA attempts to place lightpaths between nodes in the order of descending traffic demands on the shortest-path.
3. Finally, if any free wavelengths still remain, lightpaths are placed randomly utilizing those wavelengths as much as possible.

The last step in the above procedure is omitted in our initial phase, but used in the later phase.

2.2 Incremental Phase

After the logical topology is established in the initial phase, we need to change the logical topology according to the traffic changes. It is performed in the incremental phase. In Figure 1, our logical topology management model is illustrated. In our model, traffic measurement is mandatory. One method would be to monitor the lightpath utilization at its originating node. Then, if utilization of the lightpath exceeds some threshold α $(0 < \alpha < 1)$, the node requests a LMN (Lightpath Management Node), which is a special node of managing a logical topology of the WDM network, to set up a new lightpath.

This is a simplest form of a measurement-based approach. As described in the previous section, it would be insufficient in the data network. To know the user-oriented QoS level achieved by the current network configuration, an active measurement approach is necessary.

We assume that LMN eventually knows the actual traffic demand by the traffic measurement to establish a new lightpath. Then, LMN solves a routing and wavelength assignment problem for both primary and backup lightpaths after receiving the message. The new lightpath setup message is returned to the corresponding nodes, and the result is reflected to the logical topology of the WDM network.

As lightpath setup requests are generated, the number of available wavelengths would decrease, which eventually results in blocking of the lightpath setup request. To minimize such possibility, we reconfigure the backup lightpaths for an effective use of wavelengths at the same time. It is because the backup lightpaths do not carry the traffic unless the failure occurs. Note that we do not change the existing primary lightpaths in this phase so that the active traffic flows are not affected by the lightpath rearrangement. In the incremental phase, we need (1) a routing and wavelength assignment for the new primary lightpath, and (2) a reconfiguration algorithm for the backup lightpaths, which will be described in Section 3 in detail.

2.3 Readjustment Phase

Readjustment phase is aimed at minimizing the inefficient usage of wavelengths, which is likely to be caused by the dynamic and incremental wavelength assignments in the incremental phase. For an effective use of wavelengths, all the lightpaths including primary lightpaths are reconfigured in this phase. The static design method may be applied for this purpose under the condition that the traffic measurement to know the link usage is appropriately performed. Different from the initial phase, however, primary lightpaths are already in use to transport the active traffic. Thus, an influence of a reconfiguration operation should be minimized even if the resulting logical topology would be a sub–optimal solution. It is because a global optimal solution tends to require the rearrangement of many lightpaths within the network. Thus, we should configure a new logical topology from the old one step by step. One promising method is a branch–exchange method proposed in [7].

Another important issue in this readjustment phase is *when to reconfigure* the logical topology. One straightforward approach might be that the lightpath readjustment is performed when the alert signal is generated due to the lack of wavelengths. Then, we reconfigure the logical topology so as to minimize the number of wavelengths used for the logical topology, and consequently the lightpath would be accommodated. References [8, 9] give a reconfiguration policy for this issue, but they only address the primary lightpaths, and a further study is necessary to include the rearrangement of the backup lightpaths.

Another simple method is that the readjustment phase is performed periodically (say, once per month).

3 Incremental Capacity Dimensioning

As we have described in Subsection 2.2, LMN should solve a routing and wavelength assignment (RWA) problem for the new primary lightpath and reconfigure the set of backup lightpaths. These are described in detail in the following subsections.

3.1 Routing and Wavelength Assignment for Primary Lightpath

For each of new lightpath setup requests, LMN first solves the routing and wavelength assignment problem for the primary lightpath. In setting up the primary lightpath, we choose it from the free wavelengths or wavelengths used for the backup lightpaths.

If there is a lightpath having the same source–destination pair as the newly arrived request, the new lightpath is set up on the same route with the existing lightpath. It is because in IP over WDM networks, the IP layer recognizes that the paths on different routes are viewed as having different delays. Henceforth, IP selects a single path with the lowest delay, and there is no effect on the delay if there are multiple lightpaths behaving same the source-destination pair. Otherwise, the route fluctuation may occur between multiple routes in some cases. If none of existing lightpaths has the same source-destination pair, the new lightpath is set up on the shortest route.

In order to assign the wavelength, we propose a MRB (Minimum Reconfiguring for Backup lightpath) algorithm. It selects the wavelength such that the number of backup lightpaths to be reconfigured is minimized. Recall that the backup lightpaths do not carry the traffic when the new primary lightpath is being set up. However, by minimizing the number of backup lightpaths to be reconfigured, the optimal logical topology obtained at the initial phase or readjustment phase is expected to remain unchanged as much as possible. Note that the actual wavelength assignment is performed only after the backup lightpaths can be successfully reconfigured (see the next subsection). If there is no available wavelength, then an alert signal is generated. More specifically, our algorithm is performed as follows.

MRB algorithm

Step 1 For each wavelength k, set $\phi_k = \{\ \}$.

Step 2 Check the number of backup lightpaths that have to be reconfigured on the route of requesting primary lightpath P_{new}. For each wavelength k, execute Step 3.

Step 3 For each link pq along the route of P_{new}, check whether wavelength k is currently being used or not. If wavelength k is already used by another primary lightpath, then set $\phi_k \leftarrow \infty$ and go back to Step 2. If wavelength k is used by other backup lightpath (denoted by P_{old}), then set $\phi_k = \phi \cup P_{old}$. Then, go back to Step 2 and examine the next wavelength. If all the wavelengths are examined, go to Step 4.

Step 4 Select wavelength k' such that the number of elements of $\phi_{k'}$ is minimal.

When multiple lightpaths are necessary between a source-destination pair, we do not allow to set up those lightpaths on different routes. Our intention is that multiple lightpaths with different routes should be avoided since the IP routing may not choose those paths adequately. That is, IP routing puts all the packets on the primary lightpath with shorter delays. It can be avoided by using the explicit routing in MPLS [10], and the traffic between the source–destination pair would be adequately divided onto the multiple primary lightpaths by explicitly determining the lightpath via labels [11]. It can be included in our method, by modifying our algorithm such that if there is no available wavelength along the shortest path, the next shortest route is checked for assigning a wavelength.

3.2 Optimization Formulation for Reconfiguring the Backup Lightpaths

If the wavelength that is currently assigned to the backup lightpath is selected for the new primary wavelength, we need to reconfigure the backup lightpaths within the logical topology. In this subsection, we show the optimization formulation that minimizes the number of wavelengths used for backup lightpaths. By this, we can expect that the possibility of blocking the next arriving lightpath setup requests is minimized. We consider the shared protection scheme for an effective use of wavelengths [3]. For formulating the optimization problem, we first summarize notations characterizing the physical WDM network.

N: the number of nodes in the physical WDM network.

W: the number of wavelengths on a fiber.

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

C_{mn}: a cost between node m and n. In this paper, we use the propagation delay.

We next introduce the parameters for representing a logical topology after route and wavelength of a primary lightpath is determined by our MRB algorithm.

P_{ij}^k: If a backup lightpath for a primary lightpath between node i and node j utilizing wavelength k must be reconfigured, then $P_{ij}^k = 1$, otherwise $P_{ij}^k = 0$. P_{ij}^k is determined from our MRB algorithm.

R_{ij}^k: 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).

o_{nm}^w: if the primary lightpath utilizes wavelength k on the physical link mn, then $o_{mn}^k = 1$, otherwise 0. o_{mn}^k is determined from R_{ij}^k.

A_{ij}^k: a set of routes of backup lightpaths 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).

φ_{nm}: the maximum number of backup lightpaths on the physical link mn. It is determined from A^k_{ij}.

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

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

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

$g^{mn,w,r}_{ij,pq,k}$: 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 on $r-$th alternate route, then it is equal to 1, otherwise 0.

We now formulate our optimization problem.

Objective function

Minimize the number of wavelengths used for the backup lightpaths, i.e.,

$$\min \sum_{mn} b_{mn} \tag{1}$$

Constraints

1. 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.,
$$b_{mn} = \sum_{w \in W} m^w_{mn} \tag{2}$$
2. Either a primary lightpath or a backup lightpath utilizes wavelength k on the physical link mn if there exists a fiber.
$$o^k_{mn} + m^k_{mn} \leq P_{mn} \tag{3}$$
3. 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. That is, if $P^k_{ij} = 1$,
$$\sum_{w \in W} \sum_{r \in A^k_{ij}} \sum_{it \in r} g^{it,w,r}_{ij,pq,k} = 1. \tag{4}$$
Note that it is unnecessary to use the same wavelength by primary and the corresponding backup lightpaths.
4. Wavelength Continuity Constraints; the lightpath utilizing wavelength k between nodes i and j must use the same wavelength w on all links of the backup lightpath ($r \in A^k_{ij}$) when a link between node p and node q fails. Namely, if $P^k_{ij} = 1$,
$$g^{nt,w,r}_{ij,pq,k} = g^{tm,w,r}_{ij,pq,k}, \qquad \forall pq \in R^k_{ij}, \forall nt, tm \in r, \forall r \in A^k_{ij}. \tag{5}$$

5. The lightpath utilizing wavelength k between node i and node j must use wavelength w for the backup lightpath. This means, for each fiber failure scenario of the physical link along the lightpath utilizing wavelength k between node i and node j, the same wavelength w is utilized. That is, if $P_{ij}^{k} = 1$,

$$g_{ij,p_1q_1,k}^{pq,w,r} = g_{ij,p_2q_2,k}^{pq,w,r}, \qquad \forall p_1q_1, p_2q_2 \in R_{ij}^{k}. \tag{6}$$

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

6. When the physical link pq fails, at most one backup lightpath should utilize wavelength w on physical link mn, if the corresponding primary lightpath traverses the failed link pq.

$$\sum_{ij} \sum_{k \in W: pq \in R_{ij}^{k}} \sum_{r \in A_{ij}^{k}: mn \in r} \sum_{mn \in r} g_{ij,pq,k}^{mn,w,r} \leq 1 \tag{7}$$

7. The number of backup lightpaths utilizing wavelength k on the physical link mn must be bounded.

$$\varphi_{mn} \times m_{mn}^{w} \geq \sum_{k \in W} \sum_{ij} \sum_{r \in A_{ij}^{k}: mn \in r} \sum_{pq \in R_{ij}^{k}} g_{ij,pq,w}^{mn,k,r} \tag{8}$$

8. For two primary lightpaths between node i and j utilizing wavelength k and k', the cost of corresponding backup lightpath must be same along routes $r(\in A_{ij}^{k})$ and $r'(\in A_{ij}^{k'})$. That is, if $P_{ij}^{k} = 1 \wedge P_{ij}^{k'} = 1 \wedge r \equiv r'$,

$$\sum_{w} \sum_{mn \in r} C_{mn} \times g_{ij,pq,k}^{mn,w,r} = \sum_{w'} \sum_{m'n' \in r'} C_{m'n'} \times g_{ij,pq,k'}^{m'n',w',r'} \tag{9}$$

Note that in Eqs. (7) and (8), we do not impose a condition $P_{ij}^{k} = 1$. It is because wavelength sharing is allowed only if the corresponding primary lightpaths are link-disjoint.

When we set up multiple backup lightpaths between originating node i and terminating node j, we want to set up those backup lightpaths on the same route. The reason is just the same as in the case of multiple primary lightpaths as mentioned earlier. Eq. (9) gives this constraint. As described earlier, however, the constraint can be eliminated if explicit routing is utilized.

4 Simulation Results

In this section, we simulate the incremental phase to evaluate our proposed algorithm. We use a network consisting of 14 nodes and 21 links as the physical topology. See Figure 2. The number of wavelengths on each fiber, W, is set to 50. As an initial condition, we place one primary lightpath for each node–pair, which emulates the initial phase of our approach. The traffic rate given in [12] is used for an initial traffic matrix. The primary lightpaths are set up on the shortest route. Here, the shortest path is the path along which the propagation delay is smallest. The wavelength of the primary lightpaths are

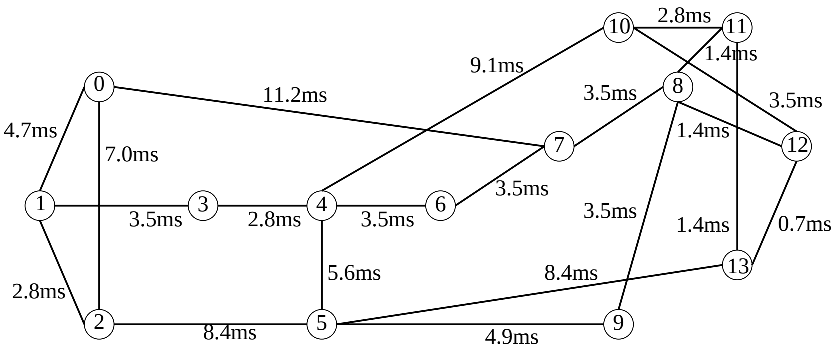

Figure 2: Network model:NSFNET

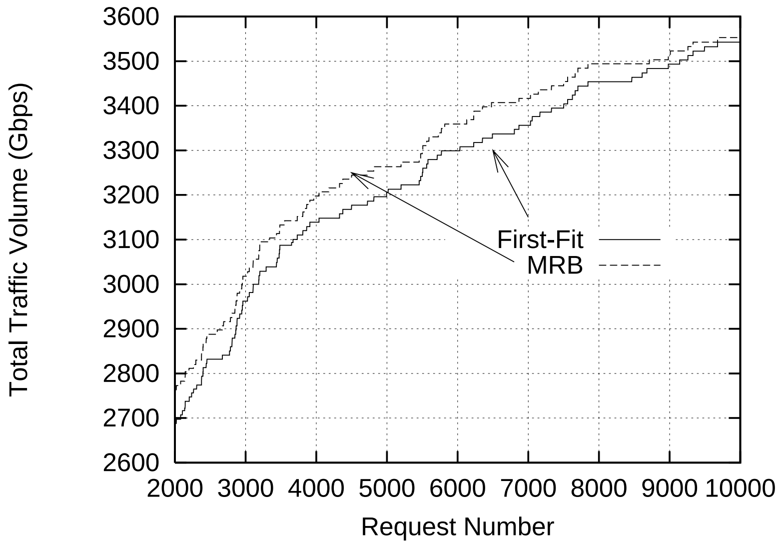

Figure 3: Carried traffic volume in first–fit and MRB algorithms

determined based on the first–fit policy [5]. The backup lightpaths are determined by a min-hop-first algorithm in [4], which assigns the wavelengths in a descending order of hop–counts of primary lightpaths.

In our framework, we assume that the traffic measurement is performed, and if the utilization of the primary lightpath exceeds the threshold value, the lightpath setup request is generated. However, in evaluation, we do not consider such a scenario. Instead, we simply consider that during the incremental phase, a new traffic demand (lightpath setup request) arrives randomly at node pairs. The volume of the traffic demand is randomly chosen between 0 and C (Gbps), where C represents the wavelength capacity. In our simulation, C is set to 10 Gbps. For each lightpath setup request, we apply the MRB algorithm and solve the optimization problem as presented in Section 4. We used the standard package CPLEX [13] for solving the problem. In simulation, we generate $10,000$ lightpath setup requests. For each request, the node checks whether the utilization of the primary lightpath exceeds 80% of the lightpath capacity or not (i.e., $\alpha = 0.8$). If the utilization exceeds the threshold, the node generates a lightpath setup request. According to the request, the wavelength of the primary lightpath is determined by our MRB algorithm, and the optimization problem is solved for reconfiguring the backup lightpaths if

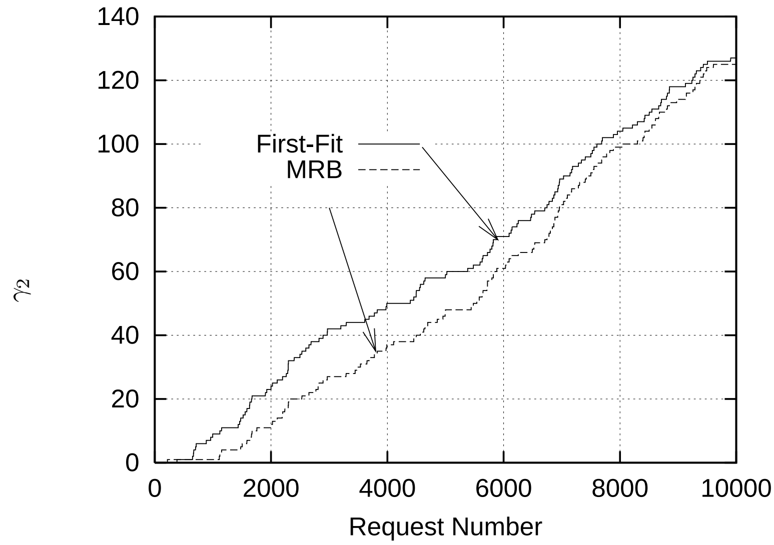

Figure 4: Comparison of γ_2, the number of rejected lightpath setup requests due to the failure of reconfiguring backup lightpaths.

necessary. We count the number of blocked requests as a performance measure. For comparison purpose, we also considered the first–fit approach for establishing the new lightpath. In the first–fit approach, the wavelength of the new primary lightpath is always checked from λ_1 to λ_W. If the available wavelength is found (say, λ_m), then the new primary lightpath is set up using λ_m.

In Figure 3, we compare the first–fit and our MRB algorithms against the request number. The vertical axis shows the total carried traffic. The carried traffic is not increased when the new lightpath setup request is blocked due to the lack of the available wavelengths. In the figure, we can observe that the MRB algorithm is slightly superior to the first–fit approach. More important result is shown next. In Figure 4, we plot the number of rejected lightpath setup requests due to the failure of reconfiguring backup lightpaths. We denote it by γ_2. Recall that the primary lightpath setup request is rejected (1) if the primary lightpath cannot be setup due to the lack of the wavelength (γ_1), or (2) if the backup lightpath cannot be reconfigured (i.e., γ_2). Thus, a lower value of γ_2 means more primary lightpaths can be accepted by reconfiguring backup lightpaths. We observe that by using our MRB algorithm, we have the lower value of γ_2 and an effective usage of wavelength can be achieved.

5 Introducing QoP: QoS differentiation on the lightpath protection

In the previous sections, we prepared the backup lightpath based on the shared link protection method. In this section, we consider QoS support suitable to IP over WDM networks. We introduce QoS classes with respect to the reliability, and call it as *QoP* (Quality of Protection). QoP is classified into the following three classes.

QoP Class 1 always provides both the primary and backup lightpaths at the incremental phase if the wavelength is available.

QoP Class 2 provides a backup path, but it may be stolen by the primary lightpath of QoP class 1 when the wavelength is not available.

QoP Class 3 only provides the primary lightpath, and no protection mechanism is offered.

It is easy to incorporate the above–mentioned QoP by modifying on logical topology design algorithm. We introduce the following notations.

QoP_{ij}: If backup lightpaths must be provided between node i and j at the incremental phase, then $QoP_{ij} = 1$. Otherwise 0.

In the incremental phase, QoP classes 2 and 3 are treated in the same way. We simply set QoP_{ij} to be 0 in those two classes. For providing both the primary and backup lightpaths in the incremental phase, we change Eq. (4) to the following equation.

$$QoP_{ij} = \sum_{w \in W} \sum_{r \in A^k_{ij}} \sum_{it \in r} g^{it,w,r}_{ij,pq,k}. \tag{10}$$

If $QoP_{ij} = 0$, then $g^{it,w,r}_{ij,pq,k}$ is also set to be 0. Then, we can provide the backup lightpath for QoP classes 1 and 2.

6 Concluding Remarks

In this paper, we have proposed a framework for an incremental use of the wavelengths in IP over WDM networks with protection. Our framework provides a flexible network structure against the traffic change. Three phases (initial, incremental, and readjustment phases) have been introduced for this purpose. In the incremental phase, only the backup lightpaths are reconfigured for an effective use of wavelengths. In the readjustment phase, on the other hand, both primary and backup lightpaths are reconfigured, since an incremental setup of the primary lightpaths tends to utilize the wavelengths ineffectively. In the readjustment phase, a one-by-one readjustment of the established lightpaths toward a new logical topology is performed so that we can achieve a service continuity of the IP over WDM networks. The branch–exchange method can be used for that purpose. However, improving the algorithm for minimizing the number of the one-by-one readjustment operations is necessary, this issue is left for future research.

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