On Incremental Capacity Dimensioning 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). However, many conventional 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 build the logical topology. Our incremental approach consists of three steps for designing 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 backup lightpaths are reconfigured when the new primary path is set up since the backup lightpaths do not affect the carried traffic on the 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. Then, the backup lightpaths are actually reconfigured. For this purpose, we also formulate an optimality problem for reconfiguring the backup lightpaths. Our results show the total traffic volume which the IP over WDM network can accommodate is improved by using our MRB algorithm.

Keywords: IP over WDM, Reconfiguring, Optimization Problem, Wavelength Division Multiplexing, Protection, Network Management

1. INTRODUCTION

According to a rapid growth of a user population and multimedia applications on the Internet, traffic volume on backbone networks has been dramatically increasing, and a very high-speed network is necessary. WDM (Wavelength Division Multiplexing) technology that provides multiple wavelengths on a fiber has a capability of offering an infrastructure for the next generation Internet. Currently an IP (Internet Protocol) over WDM network [1, 2] is one promising candidate, in which the logical network consisting of the channels (lightpaths) is built on the physical WDM network. Then, IP traffic are carried on the logical topology.

Another 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, reliability mechanisms 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.

To construct 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 prepares a dedicated backup path for every primary path. In the shared protection, 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, by which optimal structure of the logical topology is obtained.

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However, such an assumption is apparently inappropriate especially when the WDM technology is applied to the Internet. In the traditional telephone network, network provisioning (or capacity dimensioning) method has already been established: the target call blocking probability is first set. Then the traffic is measured, and if necessary, the number of telephone lines (or the 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 probability. The reasons are as follows: (1) the call blocking probability is directly related to the user's perceived QoS in the telephone network, (2) capacity provisioning is easy based on stably growing traffic demands and the 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.

However, a network provisioning method for the Internet has not been established yet. 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 explosional traffic growth of 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 in a priori is not adequate. 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 it is found theory the above–mentioned feedback loop by utilizing wavelength routing. If it is found through the traffic measurement the user's perceived QoS is not satisfactory, then wavelength paths are newly set up to increase the path bandwidth (i.e., to increase the number of lightpaths). A heuristic algorithm for setting up primary and backup lightpaths on demand basis is already proposed in [5]. For each lightpath setup request, routing and wavelength assignment are performed. 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.

On the contrary, we consider the centralized approach for establishing the logical topology. In general, the centerized approach has a scalability problem especially when the number of wavelengths and/or the network size become large. However, we need to establish the multiple number of wavelengths due to traffic fluctuation. In that case, the distributed approach taken in [5] is inappropriate. Furthermore, only the dedicated protection is considered in [5], but as described above, it would be sufficient that the WDM layer offers the shared protection scheme, which we will consider in this paper. However, we should note here that 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 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 lightpath and backup lightpaths. In this phase, we do not know the traffic demand, but we need to establish the network anyway. It is important that the incorrect projection on traffic demands 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 of the traffic demand, or the mis-projection on the traffic demand as mentioned above. We formulate the lightpath setting process 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 pursuing the optimality. However, an incremental setup of the primary lightpaths may not lead to the optimal logical topology, and our logical topology might be less utilized than the one designed by the static approach. Therefore, we finally consider the readjustment phase where *both* primary and backup lightpaths are reconfigured. However, an one-by-one readjustment of the established lightpaths is considered so that we can achieve service continuity of the IP over WDM networks.

Another issue that we treat in this paper is related to QoS in the IP over WDM networks. The granurality is wavelength in IP over WDM networks. In the past, a lot of researches have been devoted to QoS (Quality of Service) guarantee or differentiation mechanisms in the Internet; e.g., an int-serv architecture for per-flow QoS guarantee, and a diff-serv architecture for per-class QoS differentiation. However, in IP over WDM networks, such a fine granularity is not adequate. Instead, we introduce QoP (Quality of Protection); the QoS differentiation on 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.

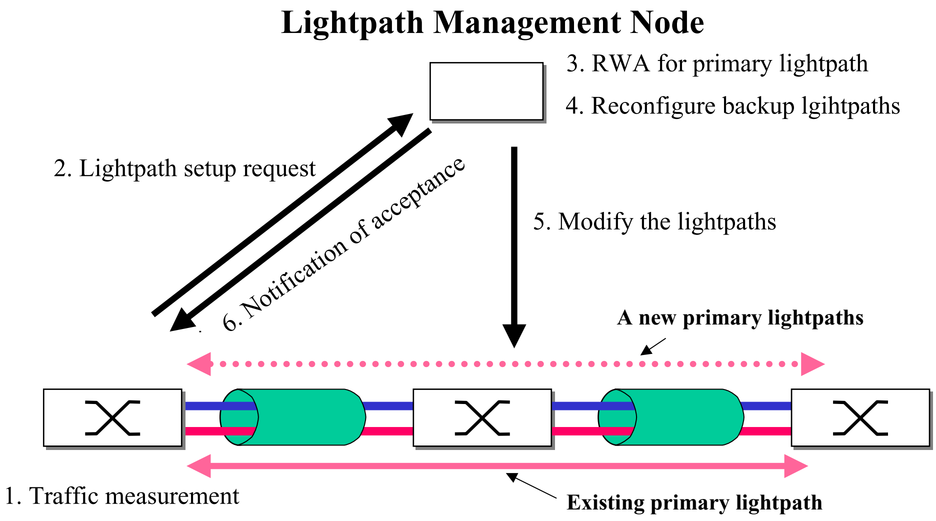

Figure 1. Logical topology management model in the incremental phase

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

2. MANAGING LOGICAL TOPOLOGY FOR RELIABLE IP OVER WDM NETWORK

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. Those will be described in the following subsections in turn. Note that in each phase, if lightpaths cannot be set up due to the 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 in the previous section, our approach allows that the projected traffic demands are 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 of 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.

2.2. Incremental Phase

After a logical topology is established in the initial phase, we need to change the logical topology according to the traffic change. 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 is insufficient in the data network, and we need an active measurement approach to meet the user-oriented QoS requirement.

In our model, 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 WDM network.

As lightpath setup requests are generated, the number of available wavelengths would decrease, which eventually results in blocking. To minimize such a possibility, we reconfigure the backup lightpaths for an effective use of wavelengths. It is because the backup lightpaths do not carry the traffic unless the failure occurs. On the other hand, we do not change the primary lightpaths in this phase so that the active traffic flows are not affected by lightpath rearrangement. At 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 aims at resolving an inefficient usage of wavelengths, which is caused by the dynamic and incremental wavelength assignments at 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. Differently from the initial phase, however, primary lightpaths are already serving to transport the active traffic. Thus, an influence of a reconfiguration operation should be minimized even if the resulting logical topology would be a semi–optimal solution. It is because a global optimal solution tends to require the rearrangement of most 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].

Note that this phase should be performed, e.g., once per month, since the readjustment phase reconfigures the primary lightpaths.

3. INCREMENTAL CAPACITY DIMENSIONING APPROACH

As we have described in Subsection 2.2, LMN solves a routing and wavelength assignment for the new primary lightpath and an optimization problem for reconfiguring the set of backup lightpaths. Those will be described in detail in the following subsections.

3.1. Routing and Wavelength Assignment for Primary Lightpath

For each of new lightpath setup request, 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 and wavelengths being used for the backup lightpaths.

If there is the lightpath having the same source–destination pair as the newly requesting lightpath, 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. Hence, IP selects only the path with the lower delay, and there is no effect by having multiple lightpaths among source-destination pair. In some cases the route fluctuation may occur between multiple routes. If none of existing lightpaths has the same source-destination pair, the new lightpath is set up on the shortest route.

For assigning 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. Our heuristic is that, by minimizing the number of backup lightpaths to be reconfigured, the optimal logical topology obtained at the initial phase or readjustment phase is 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 the 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, do 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 (P_{old}), then set $\phi_k = \phi \cup P_{old}$. After all of the wavelength is checked, go back to Step 2 and examine the next wavelength. Otherwise, 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 the 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 an explicit routing in MPLS [8], and the traffic between the source–destination pair would be adequately divided onto the multiple primary lightpaths by explicitly determining the lightpath via labels [9]. In such a case, our algorithm should be extended in such a way 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 possibility of blocking of 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^k_{ij}: If a backup lightpath for a primary lightpath between node i and node j utilizing wavelength k must be reconfigured, then $P^k_{ij} = 1$, otherwise $P^k_{ij} = 0$. P^k_{ij} is determined from our MRB algorithm.

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), $\ldots$, (m_p, j).

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

A^k_{ij}: 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), $\ldots$, (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 $P^k_{ij} = 1$,
$$g^{pq,w,r}_{ij,p_1q_1,k} = g^{pq,w,r}_{ij,p_2q_2,k}, \qquad \forall p_1q_1, p_2q_2 \in R^k_{ij}. \tag{6}$$
As the above equation indicates, we allow to use the different wavelength for the backup path against the failure of the corresponding primary path.

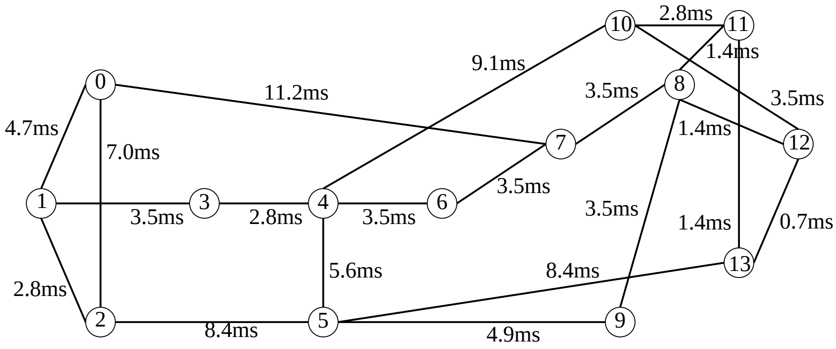

Figure 2. Network model:NSFNET

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.

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

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

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

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 same as the case of the multiple primary lightpaths as mentioned before. Eq. (9) gives this constraint. As described earlier, the option of explicit routing in MPLS can be again used. In such a case, the above constraint can be eliminated.

4. SIMULATION RESULTS

In this section, we simulate the incremental phase to evaluate our proposed algorithm. We use the network consisting of 14 node and 21 link 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 [10] is used for reference purpose. 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 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, 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 [11] for solving the problem. In simulation, we generate 10000 lightpath

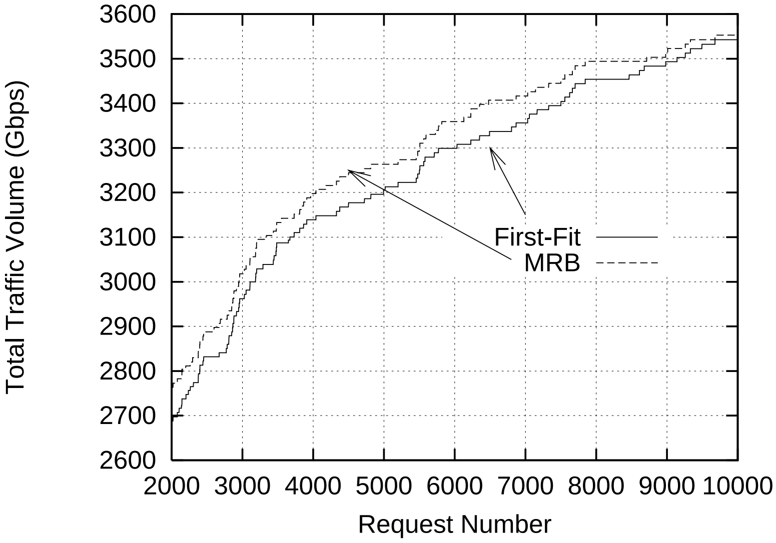

Figure 3. Carried traffic volume in first–fit and MRB algorithms

setup requests. For each request, the node checks whether the utilization of primary lightpath exceeds 80% of the lightpath capacity or not. 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 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 next shown. In Figure 4, we plot the number of rejected lightpath setup requests due to the reason that backup lightpaths cannot be reconfigured. 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). 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.

1. Always provide both the primary and backup lightpaths at the incremental phase if the wavelength is available.
2. Provide a backup path, but it may be stolen by the primary lightpath of QoP class 1 when the wavelength is not available.
3. Only provide 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 notation.

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

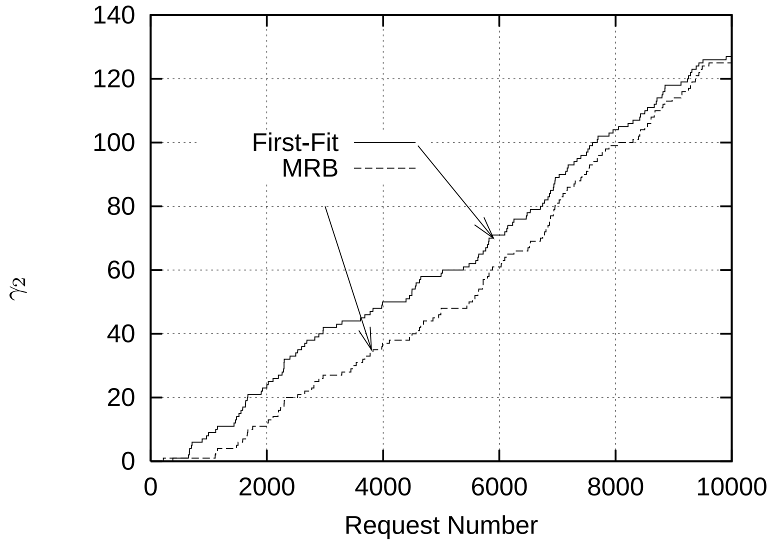

Figure 4. Comparison of γ_2, the number of rejected lightpath setup requests due to the reason that backup lightpaths cannot be reconfigured.

In the incremental phase, QoP classes 2 and 3 are treated in a 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.

$$QoP_{ij} = \sum_{w \in W} \sum_{r \in A_{ij}^k} \sum_{it \in r} g_{ij,pq,k}^{it,w,r}. \tag{10}$$

If $QoP_{ij} = 0$, then $g_{ij,pq,k}^{it,w,r}$ 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 the 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, and it is 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).

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