A Study on Differentiated RWA Algorithm for QoS Services in the Next Generation Internet based on DWDM Network

DWDM 망 기반의 차세대 인터넷에서 QoS 서비스를 위한 차등화된 RWA 알고리즘에 관한 연구

by

Jung-Hyun Bae

A thesis submitted in partial fulfillment of the requirements

for the degree of Master of Engineering

in the Department of Telematics, Graduate School,

Pukyong National University

February 2004

배정현의 공학석사 학위논문을 인준함

2003년 12월 26일

주 심 공학박사 하 덕 호 (인)

위 원 공학박사 정 연 호 (인)

위 원 공학박사 김 성 운 (인)

A Study on Differentiated RWA Algorithm for QoS Services in the Next Generation Internet based on DWDM Network

A Dissertation

by

Jung-Hyun Bae

Approved as to style and content by :

(Chairman) Deock-Ho Ha

(Member) Yeon-Ho Chung

(Member) Sung-Un Kim

December 26, 2003

CONTENTS

LIST OF FIGURES

LIST OF TABLES

DWDM 망 기반의 차세대 인터넷에서 QoS 서비스를 위한 차등적인 RWA 알고리즘 연구

배 정 현

부경대학교 대학원 정보통신공학과

요 약

차세대 인터넷 백본망에서 인터넷 사용자의 증가와 그에 따른 요구 대역폭을 수용하기 위한 방안으로 DWDM 전송 기술이 각광 받고 있으며, 이러한 DWDM 망에서는 연결 요구에 대해 최적의 경로를 선택하고 선택된 경로에 효율적으로 파장을 할당하는 RWA 문제가 자원 효율성 측면에서 매우 중요하게 다루어지고 있다. 또한 DWDM 망 기반의 차세대 인터넷에서는 데이터 위주의 인터넷 서비스에서 데이터, 음성 및 영상 등 다양한 멀티미디어 서비스로 발전해감에 따라 RWA 문제도 QoS 를 고려한 방식으로의 접근이 한층 더 요구되어진다.

그러나 기존의 RWA 알고리즘들은 잠재적인 망의 혼잡 상황을 고려하지 않으므로 성능이 매우 제한적이며, 이는 차세대 인터넷에서 높은 QoS(Quality of Service)를 요구하는 다양한 실시간 멀티미디어 서비스들을 만족하게 제공할 수 없는 문제도 야기시킨다.

본 논문에서는 이러한 문제를 해결하기 위한 방안으로 미래의 잠재적인 연결 요구들에 대해 간섭을 최소화하면서 경로를 설정하는 MW-MIPR(MultiWavelength-Minimum Interference Path Routing) 알고리즘을 제안하고, 제안된 알고리즘은 현재의 경로설정이 미래의 연결 요구에 영향을

미치는 정도를 정량적으로 평가하여 가장 영향을 덜 미치는 경로를 선택함으로써 파장 사용의 효율성을 향상시킨다. 또한 본 논문은 차세대 인터넷의 차등화된 QoS(Quality of Service)서비스 모델에 기반하여 MW-MIPR 알고리즘을 적용함으로써 각 서비스 타입별로 차등적인 RWA 기법을 제안한다.

시뮬레이션 결과에서 제안된 MW-MIPR 알고리즘과 차등적인 RWA 알고리즘 기법은 연결 요구에 대한 블록률 및 생존성 측면에서 향상된 성능을 보일 뿐 아니라 각 서비스 클래스에 대해서도 신뢰적인 QoS 보장을 제공한다.

A Study on Differentiated RWA Algorithm for QoS Services in the Next Generation Internet based on DWDM Network

Jung-Hyun Bae

Department of Telematics Engineering, Graduate School

Pukyong National University

Abstract

Over the past decade, the improvement of communications technologies and the rapid spread of WWW (World Wide Web) have brought on the exponential growth of users using Internet and real time multimedia services like voice telephony, video conferencing, tele-immersive virtual reality, and Internet games. The dense-wavelength division multiplexing (DWDM) networks have been widely accepted as a promising approach to meet the ever-increasing bandwidth demands of Internet users, especially in next generation Internet (NGI) backbone networks for nation wide or global coverage. A major challenge in the NGI backbone networks based on DWDM is the provision of guaranteed quality-of-service (QoS) for a wide variety of multimedia applications.

This paper proposes a new routing algorithm called MultiWavelength-Minimum Interference Path Routing (MW-MIPR) to provide more reliable QoS guarantees by consideration of the potential future network's congestion status, which improves wavelength utilization by choosing route that does not interfere too much with potential future connection requests.

This paper also proposes a differentiated RWA mechanism combined with recovery capability and the proposed MW-MIPR algorithm based on differentiated QoS service model to provide guaranteed QoS for various multimedia services in the NGI.

In simulation results, the proposed MW-MIPR algorithm achieves more enhanced blocking probability than dynamic routing (DR) that yields the best performance among previous RWA algorithms. And simulation result shows that the proposed differentiated RWA provides satisfied QoS assurance for each service class in terms of survivability ratio.

Ⅰ. Introduction

Over the past decade, the improvement of communications technologies and the rapid spread of WWW (World Wide Web) have brought on the exponential growth of users using Internet and real-time multimedia services like voice telephony, video conferencing, tele-immersive virtual reality, and Internet games. But current Internet based on electronic transmission rates with time division multiplexing (TDM) cannot supply sufficient transmission capacity for these services. Therefore, dense-wavelength division multiplexing (DWDM) networks have been widely accepted as a promising approach to meet the ever-increasing bandwidth demands of Internet users, especially in the next generation Internet (NGI) backbone networks for nation wide or global coverage [1-3].

In a wavelength-routed DWDM network, the network edge systems communicate with one another via all-optical WDM channels, which are referred to as lightpaths [4]. Given a set of connection requests, the problem of setting up lightpath by routing and assigning wavelength for each connection so that no two lightpaths on a given link share the same wavelength is called the routing and wavelength assignment (RWA) problem. The RWA problem is embossed as very important and plays a key role in improving the global efficiency for capacity utilization in DWDM networks providing multi-gigabit rates per wavelength. However, it is a combinational problem known to be NP-complete because routing and wavelength assignment problems are tightly linked together [5]. Since it was more difficult to work out RWA as a coupled problem, this problem has been approximately divided into two sub-problems: routing and wavelength assignment, and several RWA algorithms have been proposed as shown in Figure 1. In previous studies, the routing scheme is recognized as a more significant factor on the performance of the solution of the RWA problem than the wavelength-assignment scheme [6,7]. Among approaches for the routing problem, dynamic routing (DR) yields the best performance because DR approaches determine a route by considering the network status at the time of connection request [8]. On the other hand, static routing approaches such as fixed routing (FR) and fixed alternate routing (FAR) set up a connection request on fixed paths without acquiring the information of the current network status [9].

Thus, in order to increase the request connection probability it is necessary that the network status is continually taken into consideration for the RWA problem [8-10]. Additionally, if this problem is considered for potential connection requests that may be demanded in the future, then network performance in terms of blocking probability will be enhanced more and more. Henceforth, existing routing schemes that not considering potential traffic demands can lead to serious network congestions by not efficiently utilizing wavelengths in terms of traffic-engineering [10]. They cannot also provide services with satisfied quality-of-service (QoS) guarantee to users in the NGI based on DWDM [11,12].

To overcome this problem, this paper proposes a new dynamic routing method choosing a route that does not interfere too much with potential future connection requests and call it MW-MIPR (Multi Wavelength-Minimum Interference Path Routing). This work is inspired by the previously proposed MIR (Minimum Interference Routing) algorithm with traffic engineering in a MPLS (Multi-Protocol Label Switching) network [13-16]. To determine a minimum interference path in the context of a DWDM network, this paper remodels the previous "critical link" notion [13] in terms of maximum available wavelengths for potential future demands and introduce two different MW-MIPR formulations according to the case without or with the wavelength-continuity constraint requiring that the same wavelength must be assigned to all links of the route [8]. The proposed MW-MIPR algorithm provides a more advanced routing scheme than existing routing algorithms from viewpoint of providing an appropriate traffic-engineering scheme based on particular attributes of DWDM networks as well as more reliable QoS guarantees through efficiently utilizing wavelengths by taking into consideration the potential future network congestion status. In the simulated results, the proposed MW-MIPR algorithm achieves more improvement in blocking probability than previous routing algorithms used in DWDM networks regardless whether a wavelength converter at a node is present or not.

This paper also proposes a differentiated RWA mechanism in combination with recovery capability and the proposed MW-MIPR algorithm based on the differentiated QoS service model to provide guaranteed QoS for various multimedia services in the NGI based on DWDM networks. This mechanism accomplish quality assurance of services by choosing the route and assigning a wavelength band that satisfy the optical signal-to-noise ratio (OSNR) constraint of each service class, including differentiated recovery schemes that are in accordance with QoS level for each service. Simulation result shows that the proposed differentiated RWA mechanism based on MW-MIPR provide more reliable and stable QoS guarantees in terms of survivability ratio.

The remainder of the paper is organized as follows. Section 2 describes existing RWA schemes and analyzes problems of previous RWA problem researches. Section 3 proposes a new dynamic routing algorithm to solve the RWA problem in case that a wavelength converter is at a node or not. Differentiated RWA mechanisms with recovery capability are taken into account for the differentiated service model in Section 4. Simulation results and conclusions are presented in Sections 5 and 6, respectively.

Ⅱ. The State of RWA Problem Research

1. The Analysis of Previous RWA Schemes

Generally, the trend of RWA research approached to various viewpoints with respects to traffic assumptions and the possibility of wavelength conversion. Almost all existing algorithms for the RWA problem have been decoupled into two separate sub-problems, i.e., the routing sub-problem and the wavelength assignment sub-problem because finding an optimal solution by solving the RWA at the same time known as NP-complete problem [6]. Each sub-problem is independently solved as shown in Figure 1. Next two sub-sections focus on various approaches to routing connection requests and assigning a wavelength to them.

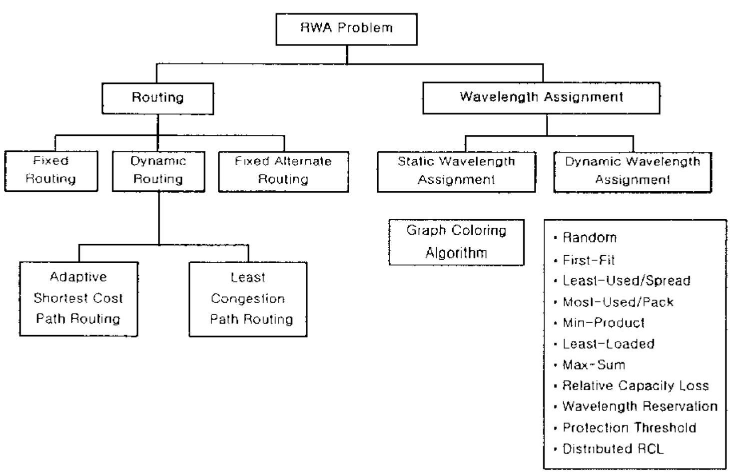


Figure 1. The previous RWA schemes

1.1 Routing Schemes

There are three fundamental approaches to solve routing sub-problem: fixed routing (FR), fixed-alternate routing (FAR) and dynamic routing (DR).

1) Fixed Routing (FR)

The simplest method for routing a connection always chooses the same fixed route for a given source-destination pair i.e., (S, D). Generally, the fixed shortest-path routing approach is used. The shortest-path for each source-destination pair is computed off-line in advance using standard shortest-path algorithms, e.g. Dijkstra's algorithm or Bellman-Ford algorithm. When the request comes, the light path is set up using the pre-determined route just like the fixed shortest-path from Node 0 to Node 2 as shown in Figure 2. Obviously, the disadvantage of this approach is that the routing decision is not made based on the current state of network. It might lead to the situation where some links on the network are over-utilized while other links are underutilized. This might potentially result in high blocking probability.

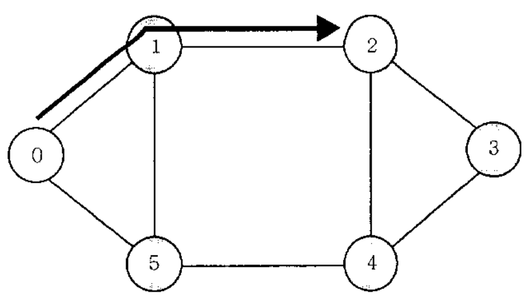


Figure 2. Fixed routing

Also, FR may be unable to handle fault situations in which one or more links in the network fail. To handle link faults, the routing scheme must either consider alternate paths to the destination, or must be able to find the route dynamically. Note that, in Figure 2, a connection request from Node 0 to Node 2 will be blocked if a common wavelength is not available on both links in the fixed route, or if either of the links in the fixed route is cut.

2) Fixed Alternate Routing (FAR)

As an improvement over FR, FAR is an approach that sequentially considers an available path among pre-determined fixed routes and selects one. Each node in the network is required to maintain a routing table that contains an ordered list of a number of fixed routes to each destination node. For example, these routes may include the shortest-path, the second shortest-path, the third shortest-path, etc. A primary route between a (S, D) pair is defined as the first route in the list routes to the destination node in the routing table at the source node. An alternate route between a (S, D) pair is any route that dose not share any links with the first route in the routing table at the source node. Figure 3 illustrates multiple alternate routes from Node 0 to Node 2. When a connection request arrives, the source node will decide the best route form a list of candidate routes by some metric, e.g. the minimal hop count and then set up the lightpath over that route. This approach could reduce the blocking probability compared to FR, and provide some degree of fault tolerance upon link failures.

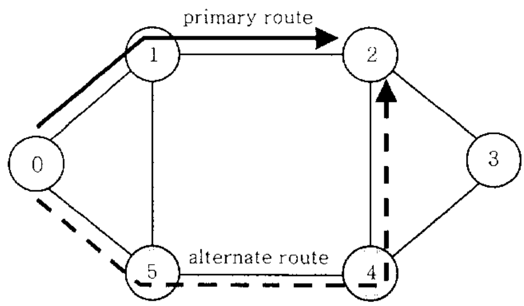


Figure 3. Fixed alternate routing

3) Dynamic Routing (DR)

In dynamic routing (DR), the route from a source to destination is determined depending on the network state that is determined by all the connections that are currently in progress. A typical form of dynamic routing (DR) is adaptive shortest-cost-path routing. When a connection request arrives, a source node computes the shortest-cost-path to a destination node based on the network state as shown in Figure 4. If no path is available, the request will be blocked.

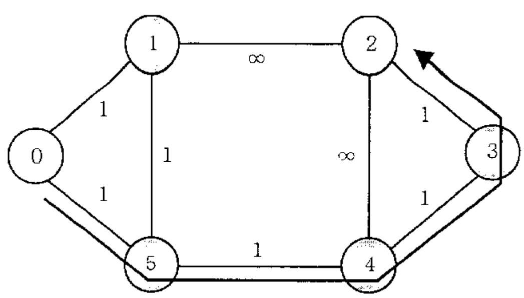


Figure 4. Dynamic routing

For example, if each unused and used link has a cost of 1 and ∞ respectively in the network in Figure 4 and the links between (1, 2) and (4, 2) are busy, then this approach can still establish a connection between Node 0 and 2, while both the FR and FAR as shown in Figure 2 and 3 would block the connection.

Another form of DR is least congested path (LCP) routing. This approach is similar to FAR that pre-selects multiple routes for each (S, D) pair. Upon the arrival of a connection request, least congested path among the pre-determined routes is chosen. The congestion on a path is measured by the number of wavelengths available on the most congested link in the path.

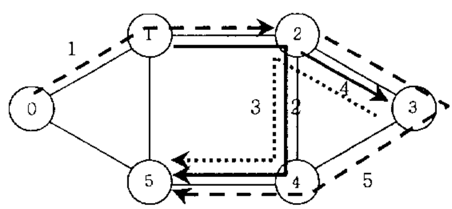
The advantage of DR is that it results in lower connection blocking probability than FR and FAR because it is too hard to find an optimal route using static routing approaches such as FR and FAR that determine the route without considering network's status [9]. Compared to static routing methods, DR approach is the most efficient because a route is dynamically chosen by considering network's status at the time of connection request, which improves network performance in terms of blocking probability [8-10]. Also, DR approach can provide the protection scheme for a connection by setting up backup path against link or node failures in the network.

1.2 Wavelength Assignment Schemes

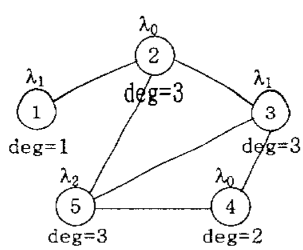
For the wavelength assignment sub-problem, it is the goal to efficiently assign a wavelength to each lightpath without sharing the same wavelength with other lightpaths on a given link, which has been respectively studied in terms of static and dynamic traffic.

1) Static Wavelength Assignment

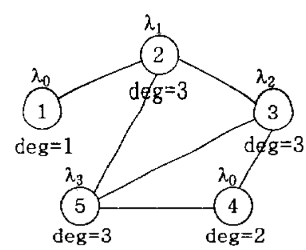
Generally, graph-coloring algorithms [6] were employed to assign wavelengths for static traffic where the set of connections are known in advance. This algorithm operates to minimize the number of wavelength used as follows. First, construct an auxiliary graph G(V,E), such that each lightpath in the system is represented by a vertex(V) in graph G. There is an undirected edge(E) between two vertexs in graph G if the corresponding lightpaths pass through a common physical fiber link as shown in Figure 5. Second, coloring the vertexes of the graph G such that no two adjacent nodes have the same color. If the number of edges at a node denotes degree, then coloring vertexes from the maximum degree (Figure 5(b)) can have the minimum number of wavelengths required for the set of lightpaths in Figure 5(a).



(a) A network with five routed lightpaths



(b) Coloring vertexes sequentially from the maximum degree



(c) Coloring vertexes sequentially from the minimum degree

Figure 5. Graph coloring algorithm

2) Dynamic Wavelength Assignment

Under dynamic traffic where connection requests arrive randomly, a number of heuristics have been proposed as follows; Random Wavelength Assignment (R), First-Fit (FF), Least-Used/Spread (LU), Most-Used/Pack (MU), Min-Product (MP), Least-Loaded (LL), MAX-SUM (MΣ), Relative Capacity Loss (RCL), DRCL (Distributed RCL), Wavelength Reservation (Rsv) and Protection Threshold (Thr) [5-6].

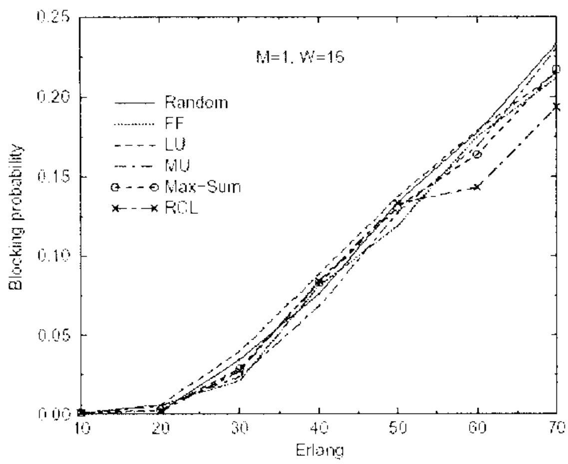
R scheme randomly chooses one among available wavelengths for request route. FF selects the first wavelength among all the available wavelengths numbered. This scheme is preferred in practice because of no requiring global knowledge and simple computation. LU chooses the wavelength that is least used in network. This scheme causes communication overhead that collects global information to compute the least-used wavelength. MU chooses the most-used wavelength in the network contrary to LU method. This scheme is expected to have better performance than LU due to conservation the spare capacity of less-used wavelengths. But MU also has the communication overhead same as LU scheme. MP scheme computes the number of occupied fibers for each wavelength on a link and choose the wavelength with the minimal value in multiple fiber networks. LL chooses the wavelength that has most residual capacity on the most loaded link along the path selected in multiple fiber networks. M∑ considers all possible paths in the network and attempts to select the wavelength that minimizes the capacity loss on all lightpaths. RCL tries to minimize the relative capacity loss based on MS. Currently, RCL offers the best performance; however this scheme requires global information and complex computation. DRCL scheme based on RCL is more efficient in a distributed-controlled network. In Rsv, a wavelength on a specified link is reserved for a traffic stream. Thr assigns a wavelength only if the number of idle wavelengths on the link is at or above a given threshold.

2. The Performance and Problem of Previous RWA Schemes

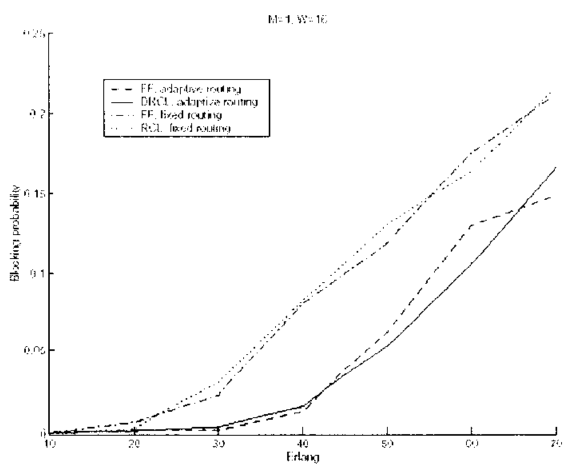
Until now, researches for the RWA problem have been divided into routing sub-problem and wavelength assignment sub-problem.

As an analysis previous researches for RWA problem, Figure 6 shows performance of existing RWA schemes for connection blocking probability in case of DWDM network that the number of fibers per link is one (M = 1), and that the number of wavelengths per fiber is sixteen (W = 16); Figure 6(a) is comparison of various wavelength assignment algorithms when using FR scheme and Figure 6(b) is to compare performance of FR and DR for two wavelength assignment schemes such as FF and RCL.

In an overall result of previous RWA researches as shown in Figure 6, the routing scheme has much more of an impact on the performance of the system than the wavelength-assignment scheme [6][7]. That is to say, "routing scheme is more significant factor for RWA problem" conclusion is consistent with the findings in previous studies. Among approaches for the routing problem, dynamic routing (DR) yields the best performance (Figure 6(b)) [8]. On the other hand, for wavelength assignment approaches, MU is found to achieve the best performance under low load while M$\sum$ and RCL work well when the load is high ($\geq$ 50 Erlangs), with the other approaches not that far behind; however, the differences in performance among the existing various wavelength assignment schemes is not too significant (Figure 6(a)).



(a) Comparison of the existing various wavelength assignment schemes



(b) Comparison of the existing routing schemes

Figure 6. Comparison of the previous RWA schemes

Until now, the objective in researches for the RWA problem is to set up lightpaths and assign wavelengths in a manner that minimizes the number of wavelength needed, or that maximizes the number of connection established for a given physical topology.

However existing RWA schemes, without considering potential traffic demands and attributes of each traffic related to QoS service class, can lead to henceforth serious congestion state of network by not efficiently utilizing wavelength in terms of traffic-engineering [10], which cannot also provide services with satisfied QoS guarantee to users in the NGI based on DWDM transmitting various multimedia services such as voice telephony, video conferencing, tele-immersive virtual reality, and Internet games [11][12].

To achieve successive construction of the NGI using DWDM technology, studies for RWA problem must be accomplished in consideration of QoS. This paper accesses to a solution for RWA problem in terms of potential connection requests and differentiated QoS service model in the NGI.

Ⅲ. The MW-MIPR Algorithm

1. MW-MIPR Definition and Notations

Generally, the routing scheme has a much higher an impact on the performance of the connection blocking probability in networks than the wavelength-assignment scheme [6,7]. Especially, routing under consideration of the network status is more and more important to improve wavelength utilization [9,10]. However, existing routing algorithms referring only to current network conditions can still cause about high blocking probability at a later time.

This paper proposes MW-MIPR algorithm as a new dynamic routing algorithm considering potential blocking possibilities of future traffic demands. This algorithm chooses a route that does minimize interference for many potential future connection requests by avoiding congested links. This work is inspired by MIR algorithm proposed in a MPLS network [13-16].

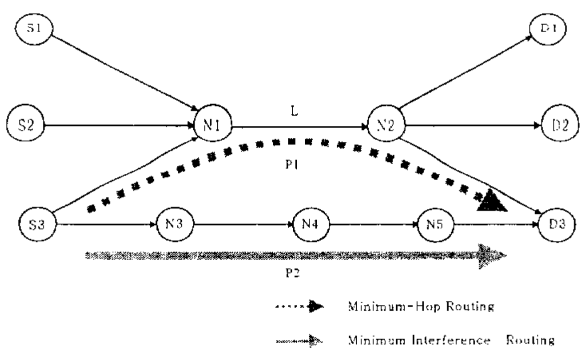


Figure 7. Multiwavelength-minimum interference path routing

For a simple example as shown in Figure 7, if there are three potential source-destination pairs such as (S1, D1), (S2, D2), (S3, D3) and the connection between the (S3, D3) pair is set along path P1 selected by min-hop routing as demanded, then this route may block the paths between (S1, D1) as well as (S2, D2) when the capacity of link L is not large enough. Thus it is better to pick route P2 that has a minimum effect for other connection requests even though the path is longer than P1.

Proposed MW-MIPR is to pick a path that does not interfere too much with potential future setup requests between some (S, D) pairs under the assumption that the (S, D) pairs for which a connection can potentially be requested or terminated are generally known, even though future demands are completely unknown and demands between (S, D) pairs arrive one at a time.

To achieve that, this paper fit the previously mentioned "critical link" concept [13] into the context of DWDM networks. These are links with the property that the available wavelengths on the minimum hop routes of one or more node-pairs decreases whenever a lightpath is routed over those links. Based on the new notion, the formulation of the proposed algorithm is presented differently for the following two cases: networks with full wavelength conversion (WC) capability and networks without WC capability based on single-fiber. Before formulating the MW-MIPR algorithm, some notations commonly used in this algorithm are defined as follows.

• $G(N, L, W)$: The given network, where N is the set of nodes, L is the set of links and W is the set of wavelengths per link. In this graph, W is the same for each link l belongings to L, i.e., $\forall l \in L$.

• M : Set of potential source-destination node pairs that can request connections in future. Let (s, d) denote a generic element of this set.

• p_{sd} : The minimum hop lightpath between a (*s, d*)-pair, where $\forall (s, d) \in \mathrm{M}$.

• π_{sd} : Set of links over the minimum hop path p_{sd}.

• $R(l)$: The number of currently available wavelengths on a link l, where $\forall l \in L$.

• Λ_{sd} : The union set of available wavelengths on each link l, where $\forall l \in \pi_{sd}$.

• F_{sd} : The set of available wavelengths on the bottleneck link that has the smallest residual wavelengths among all links within π_{sd} i.e., $\forall l \in \pi_{sd}$ (if all nodes in the network have the wavelength-continuity constraint, then F_{sd} is equal to Λ_{sd}).

• Ω_{sd} : Set of wavelengths assigned to the minimum hop path p_{sd}.

• C_{sd} : Set of critical links for a (*s, d*)-pair, where $\forall (s, d) \in \mathrm{M}$.

• α_{sd} : The weight for a (*s, d*)-pair, where $\forall (s, d) \in \mathrm{M}$.

Among above notations, C_{sd} and α_{sd} are key parameters in the MW-MIPR algorithm. C_{sd} indicates critical links belonging to π_{sd} of a (*s, d*)-

pair and are shared on the minimum hop paths of other node pairs at the same time. These links have higher congestion possibility for potential future requests than other links within π_{sd}. Thus, this notation is necessarily considered for determining a critical link regardless of the case that a wavelength converter at a node is present or not. α_{sd} is the weight for each node pair, which is chosen in order to reflect the "importance" of (*s*, *d*)-pair where $\forall(s,d) \in \mathrm{M}$. For example, it may reflect the relative QoS of the traffic carried between each node pair. Based on these notations, the ultimate object of MW-MIPR is represented below in Equation (1). It is a maximum available wavelengths problem for each source-destination pair in M except the current demands. Then, it is assumed that demands arrive one at a time and the current connection request is between a and b nodes, where $(a,b) \in \mathrm{M}$.

$$\max \sum_{(s,d)\in M\setminus(a,b)} \alpha_{sd} \cdot F_{sd} \qquad \textbf{(1)}$$

To achieve Equation (1), the proposed MW-MIPR algorithm routes the current demand along a path that does not interfere too much with potential future requests. The proposed algorithm defines a route between a (*a*, *b*)-pair selected by MW-MIPR as p_{ab}^{m} and similar to the above-mentioned notations, the MW-MIPR algorithm uses π_{ab}^{m}, Λ_{ab}^{m}, F_{ab}^{m} and Ω_{ab}^{m}. And for the wavelength assignment problem on the route p_{ab}^{m} selected by MW-MIPR, the FF scheme is used due to its small computational overhead and low complexity [6]. The next two sub-sections will describe the concrete routing operation for each case i.e., networks with full WC capability or networks without WC capability.

2. Network with Full Wavelength Conversion Capability

2.1 MW-MIPR Formulation

In DWDM networks, the wavelength-continuity constraint can be eliminated if a wavelength converter exists at each node [18]. Especially, in the network consisting of nodes with full WC capability from any wavelength to any other one, a wavelength can be easily assigned if a residual free wavelength is on links along the selected route [12][19]. For such a network, the number of available wavelengths on a link is regarded as an important factor to improve network performance in terms of blocking probability. In this sub-section, a new notation Δ is added as a threshold value of available wavelengths on a link to choose the minimum interference path for potential future connection requests with consideration of critical links as well as non-critical links with few wavelengths. Based on notations such as C_{sd} and Δ, MW-MIPR algorithm determines links with congestion possibility for a potential future demand between a (*s, d*)-pair in a network with full WC capability according to Equation (2), where $\forall(s,d) \in \mathrm{M} \setminus (a,b)$ and $\forall l \in L$, and call them CL_WC_{sd}.

$$CL\_WC_{sd} : (l \in C_{sd}) \cap (R(l) < \Delta), \quad \forall(s,d) \in \mathrm{M} \setminus (a,b), \forall l \in L \qquad \textbf{(2)}$$

If a link l belongs to the set of critical links, i.e., $l \in C_{sd}$ and the number of residual wavelengths on that link is lower than the threshold value, i.e., $R(l) < \Delta$, then link l is the critical link. In this equation, the appropriate choice for thresholds value Δ is very important for efficient wavelength utilization. If Δ is chosen to be large, then pre-reserving many wavelengths for future connection requests can cause wavelength waste. On the other hand, if Δ is set too small, then the potential blocking probability for upcoming traffic may be high. In this paper, the threshold value Δ is set within 20 % or 30 % of the total wavelength number on a link, this ratio is assumed by accomplished simulation results regardless the number of wavelength per link. The proposed MW-MIPR algorithm gives appropriate weights to each link based on the amount of available wavelengths on a link l where $\forall l \in L$, so that the current request does not interfere too much with potential future demands. The link weights are estimated by the following procedures. First, let $\partial F_{sd} / \partial R(l)$ indicates the change of available wavelengths on the bottleneck link l for the potential connection request between a (*s*, *d*)-pair when the residual wavelengths of link l are changed incrementally. With respect to the residual wavelength of the link, the weight $w(l)$ of a link l is set to

$$w(l) = \sum_{(s,d) \in M \setminus (a,b)} \alpha_{sd} (\partial F_{sd} / \partial R(l)), \quad \forall l \in L \tag{3}$$

Equation (3) determines the weight of each link for all (*s*, *d*)-pairs in the set M except the current request when setting up a connection between the (*a*, *b*)-pair, i.e., $(s,d) \in \mathrm{M} \setminus (a,b)$, but computing weights for all links is very hard, where $\forall l \in L$. To solve this problem, MW-MIPR considers more restricted links than other links for routing with Equation (4) if a link belongs to the set of congestion links for a certain (*s*, *d*)-pair, i.e., $l \in CL\_WC_{sd}$.

$$\begin{cases} \partial F_{sd} / \partial R(l) = 1 & [if\ (s,d): l \in CL\_WC_{sd}] \\ \partial F_{sd} / \partial R(l) = 0 & [otherwise] \end{cases} \quad \textbf{(4)}$$

$$w(l) = \sum_{(s,d):l \in CL\_WC_{sd}} \alpha_{sd} \quad \textbf{(5)}$$

Therefore, computing the link weights is simplified as shown in Equation (5). And then if the value of $\alpha_{sd} = 1$ for all (*s, d*)-pairs, $w(l)$ will represent the number of source-destination pairs for which link l is critical. Based on above formulations, the formal description of the MW-MIPR algorithm in the network with full WC capability is given as Figure 8.

MW-MIPR $(L, M, w(l), \alpha_{sd}, R(l), C_{sd}, CL\_WC_{sd})$

(1) If connection is requested between a node pair (a,b) then {

(2) For each link l, where $\forall l \in L$ {

(3) link weight $w(l) = 0$

(4) If $R(l) < \Delta$ then {

(5) For each node pair (s,d), where $\forall (s,d) \in M \setminus (a,b)$ {

(6) node pair weight α_{sd}

(7) If $l \in C_{sd}$ then{

(8) $CL\_WC_{sd} := CL\_WC_{sd} \cup l$

(9) $w(l) := w(l) + \alpha_{sd}$ } } } }

(10) Remove a link l from L with $R(l) = 0$ }

(11) Choose the minimum hop path with the smallest $w(l)$ using the Dijkstra's algorithm

Figure 8. MW-MIPR algorithm in networks with full WC capability

Once the weight of each link l where $\forall l \in L$ is determined, MW-MIPR routes the current traffic between the (*a, b*)-pair along the path with the smallest $w(l)$ to achieve Equation (1). If there is a tie, then min-hop path routing will be used to break the tie. This paper accomplishes the RWA problem in networks with full WC capability through the following procedures.

2.2 The RWA Procedure

INPUT : Request a connection from node a to node b in a given network $G(N, L, W)$.

OUTPUT : A route for (a,b) having minimum interference links for potential future requests $\forall(s,d)\backslash(a,b) \in \mathrm{M}$.

PROCEDURE

Step 1. Compute p_{sd} for $\forall(s,d) \in \mathrm{M}$.

Step 2. Compute C_{sd} for $\forall(s,d) \in \mathrm{M}$.

Step 3. Wait for a lightpath request between a (*a, b*)-pair as the current demand.

(a) If it is a lightpath connection request, go to *Step 4*.

(b) If it is a lightpath release request, go to *Step 7*.

Step 4. Route the request between the (*a, b*)-pair along a path p_{ab}^{m} selected by MW-MIPR.

Step 5. Assign a wavelength with the lowest number among the available wavelengths set Λ_{ab}^{m} over a path p_{ab}^{m} to the request for the (*a, b*)-pair using the FF scheme.

Step 6. Decrease $R(l)$ on each link, where $\forall l \in \pi_{ab}^{m}$, i.e., $R(l) := R(l) - 1$. Go to *Step 8*.

Step 7. Release the assigned wavelength Ω^{m}_{ab} to path p^{m}_{ab} and increase $R(l)$ on each link, where $\forall l \in \pi^{m}_{ab}$, i.e., $R(l) := R(l) + 1$.

Step 8. Update an assigned or a released wavelength, and go to *Step 3*.

3. Network without Wavelength Conversion Capability

3.1 MW-MIPR Formulation

In the absence of wavelength converter, a lightpath cannot be established unless there is at least one common wavelength available in common on each link of the requested route, even if all links on that route have free wavelengths [12,17,18]. Thus, the weight of a link variably changes according to an assigned wavelength compared with one in the wavelength-convertible network. This causes tremendous computation complexity when searching a route under the previous MW-MIPR formulation. In this section, the MW-MIPR algorithm pre-selects three minimum hop paths and wavelengths for each (s, d)-pair, where $\forall(s,d) \in M$, to reduce computation complexity. Then, for the wavelength assignment problem, one wavelength satisfying the wavelength-continuity constraint among the available wavelengths is chosen by the FF scheme [6]. To apply these notions to a feasible MW-MIPR formulation under the wavelength-continuity constraint, let p^{i}_{ab} denote a pre-selected i th minimum hop path between a (a, b)-pair for the current connection request and the remaining notations modify as π^{i}_{ab}, Λ^{i}_{ab}, F^{i}_{ab}, Ω^{i}_{ab}, and C^{i}_{ab}. With these notations and Equation (6), MW-MIPR algorithm searches congestion paths for a (s, d)-pair as a potential future request, where $\forall(s,d) \in M \setminus (a,b)$, among three paths pre-selected between the (*a*, *b*)-pair and calls them CP_NWC_{sd}.

$$CP\_NWC_{sd} : (l \in C_{sd}) \cap (l : \Omega^{i}_{ab} \subset F_{sd})$$
$$\forall(s,d) \in \mathrm{M} \setminus (a,b), \qquad \forall l \in \pi^{i}_{ab}, \qquad (i = 1, 2, 3) \tag{6}$$

Equation (6) reflects whether each minimum hop path pre-selected between the (*a*, *b*)-pair, i.e., p^{i}_{ab} ($i = 1, 2, 3$) interferes with potential future demands or not. If a link l among links over the i th minimum hop p^{i}_{ab} is critical link for a certain (*s*, *d*)-pair (i.e., $l \in C_{sd}$) and the pre-assigned wavelength Ω^{i}_{ab} on that link l belongs to the set of available wavelengths F_{sd} of that node pair, then the link l is the congestion link for the a (*s*, *d*)-pair. Then, even though one link l among links over a certain p^{i}_{ab} is a congestion link, that path p^{i}_{ab} will belong to CP_NWC_{sd} for potential future requests because the wavelength assigned on one link l is equal to the other links over path p^{i}_{ab} in the network with the wavelength continuity constraint, where $\forall l \in \pi^{i}_{ab}$. The MW-MIPR algorithm computes the weight of each path p^{i}_{ab} ($i = 1, 2, 3$) based on CP_NWC_{sd}, where $\forall(s,d) \in \mathrm{M} \setminus (a,b)$, as Equation (7) so that the current request does not interfere too much with potential future demands. And then, let v_i denotes the i th minimum hop p^{i}_{ab} with an assigned wavelength Ω^{i}_{ab} by the FF scheme.

$$w(i) = \sum_{(s,d) \in P \setminus (a,b)} \alpha_{sd} (\partial F_{sd} / \partial v_i), \qquad (i = 1,2,3) \tag{7}$$

In this equation, $(\partial F_{sd} / \partial v_i)$ as the interference weight denoted to reflect the change rate of available wavelengths on the bottleneck link $l \in \pi_{sd}$ for the potential connection request between a (*s*, *d*)-pair, where

$\forall(s,d) \in M \setminus (a,b)$, when the current connection demand between the *(a, b)*-pair route along path the i th minimum hop p^i_{ab}, which indicates how many potential connection requests for all node pairs i.e., $\forall(s,d) \in M \setminus (a,b)$ are blocked by each path p^i_{ab} pre-selected between (a,b) pair.

$$\begin{cases} (\partial F_{sd} / \partial v_i) = 1, & [\,if (s,d): p^i_{ab} \in CP\_NWC_{sd} \cap \{(F_{sd} - \Omega^i_{ab}) = \phi\}\,] \\ (\partial F_{sd} / \partial v_i) = 1/2, & [\,if (s,d): p^i_{ab} \in CP\_NWC_{sd} \cap \{(F_{sd} - \Omega^i_{ab}) \neq \phi\}\,] \\ (\partial F_{sd} / \partial v_i) = 0, & [\,otherwise\,] \end{cases} \quad \textbf{(8)}$$

As shown in Equation (8), the value of $(\partial F_{sd} / \partial v_i)$ is appropriately given according to an assigned wavelength Ω^i_{ab} over each path p^i_{ab} pre-selected between the *(a, b)*-pair as follows: when the minimum hop path p_{sd} between a potential request node pair $\forall(s,d) \in M \setminus (a,b)$ shares any link l with the pre-selected i th minimum hop path p^i_{ab}, and if the same wavelength is assigned on the all links over p_{sd} (i.e., $\forall l \in \pi_{sd}$) regardless of allocated wavelength Ω^i_{ab} over p^i_{ab}, then $(\partial F_{sd} / \partial v_i)$ is equal to 1/2, else $(\partial F_{sd} / \partial v_i)$ is equal to 1. In all other cases, $(\partial F_{sd} / \partial v_i)$ is equal to 0. And then, the MW-MIPR algorithm chooses the optimal route with the smallest weight $w(i)$ among the three pre-selected paths between the *(a, b)*-pair under the wavelength-continuity constraint i.e., a route with the minimum interference for connection demands in future. Figure 9 represents the MW-MIPR algorithm in networks without WC capability.

Once the weight of each path p^i_{ab} ($i = 1, 2, 3$) has been computed, the MW-MIPR algorithm would like to route the request between the *(a, b)*-pair along the i th minimum hop path p^i_{ab} with the smallest $w(i)$. If there is a tie, then the minimum hop path among them will be chosen.

MW-MIPR $(w(i), \alpha_{sd}, p^{i}_{ab}, \pi^{i}_{ab}, C_{sd}, F_{sd}, \Omega^{i}_{ab}, \partial F_{sd} / \partial v_{i}, CP\_NWC_{sd})$

(1) If connection is requested between a node pair (a, b) then {

(2) For pre-selected each path p^{i}_{ab}, $i = 1,2,3$ {

(3) path weight $w(i) = 0$

(4) For each node pair (s, d), where $\forall(s,d) \in \mathrm{M} \setminus (a,b)$ {

(5) node pair weight α_{sd}

(6) For each link l, where $\forall l \in \pi^{i}_{ab}$ {

(7) If $(l \in C_{sd}) \cap (l : \Omega^{i}_{ab} \subset F_{sd})$ then {

(8) $CP\_NWC_{sd} := CP\_NWC_{sd} \cup p^{i}_{ab}$

(9) If $(F_{sd} - \Omega^{i}_{ab}) = \phi$ then $(\partial F_{sd} / \partial v_{i}) = 1$ and Goto (11)

(10) Else $(F_{sd} - \Omega^{i}_{ab}) \neq \phi$ then $(\partial F_{sd} / \partial v_{i}) = 0.5$ and Goto (11) } }

(11) $w(i) := w(i) + \alpha_{sd} (\partial F_{sd} / \partial v_{i})$ } } }

(12) Choose the minimum hop path p^{i}_{ab} with the smallest $w(i)$ using the Dijkstra's algorithm

Figure 9. MW-MIPR algorithm in networks without WC capability

The process of RWA in the network without WC capability is as follows.

3.2 The RWA Procedure

INPUT : Request a connection from node a to node b in a given network $G(N, L, W)$.

OUTPUT : A route for (a, b) having minimum interference links for potential future requests $\forall(s,d) \setminus (a,b) \in \mathrm{M}$.

PROCEDURE

Step 1 and *Step 2* are equal to those in a network with full WC capability.

Step 3. Wait for a lightpath request between a (a, b)-pair as the current demand.

(a) If it is a lightpath connection request, go to *Step 4*.

(b) If it is a lightpath release request, go to *Step 9*.

Step 4. Compute three minimum hop paths between the (a, b)-pair and pre-select them.

Step 5. Pre-assign a wavelength Ω_{ab}^{i} on each minimum hop path p_{ab}^{i} ($i = 1, 2, 3$) with the FF scheme.

Step 6. Establish the connection between the (a, b)-pair along a path p_{ab}^{m} selected by MW-MIPR.

Step 7. Remove the assigned wavelength Ω_{ab}^{m} to path p_{ab}^{m} from available wavelengths F_{sd} for each the (s, d)-pair with status as $\forall l \in (\pi_{sd} \cap \pi_{ab}^{m})$, where $\forall (s,d) \in \mathrm{M} \setminus (a,b)$.

Step 8. Decrease $R(l)$ on each link, where $\forall l \in \pi_{ab}^{m}$ i.e., $R(l) := R(l) - 1$. Go to *Step 10*.

Step 9. Release the assigned wavelength Ω_{ab}^{m} to path p_{ab}^{m} and increase $R(l)$ on each link, where $\forall l \in \pi_{ab}^{m}$, i.e., $R(l) := R(l) + 1$.

Step 10. Update an assigned or a released wavelength, and go to *Step 3*.

Ⅳ. Differentiated RWA Mechanisms for QoS Services

The explosive increase of traffic volumes and real-time multimedia applications with the rapid development in Internet technologies calls for the NGI based on DWDM as high-speed transport network [12]. One of the important issues of future generation high-speed networks is the provision of proper QoS guarantees for a wide variety of multimedia services such as voice telephony, video conferencing, tele-immersive virtual reality, and Internet games [20]. This section introduces QoS parameters to guarantee a satisfying QoS for each multimedia service and propose differentiated RWA mechanisms with recovery capability based on the differentiated QoS services model in the NGI.

1. QoS Parameters

A generic classification by application types as supported by the NGI may be divided into differentiated service classes (premium service, assured service and best-effort service) based on the level of their QoS [21]. Let us have a look at the features of each service. Premium service requiring absolute guarantees on QoS is constant bit rate application flow service such as virtual leased lines or switched service for voice and video circuits. It provides guaranteed peak bandwidth with the lowest end-to-end delay, jitter, and loss. Assured service demands for certain minimal statistical guarantees on QoS and offers an expected level of bandwidth with a statistical delay bound as service that exhibits a greater degree of time-sensitivity, for instance distributed simulation and real-time streaming. Best-effort service corresponds to current Internet services such as file transfer, web browsing, and e-mail. They do not require explicit QoS guarantees at all. This service tries to make the best use of the remaining bandwidth and allows injecting traffic at an arbitrary rate into the network. If QoS requirements and constraints of each service mentioned above are differentially applied to the NGI based on DWDM, the result can be summarized as Table 1.

Table 1. Differentiated services model in the NGI

Classification criteria	Premium service	Assured service	Best Effort service
BER (Q)	10^{-16} (8)	10^{-16} (8) ~ 10^{-14} (7.5)	10^{-10} (6)
el. SNR	18.06 dB	18.06 dB ~ 17.5 dB	15.56 dB
OSNR (f_0=10 Gbit/s)	20.67 dB	20.67 dB ~ 20.1 dB	18.17 dB
Resource allocation	Pre-specified percentage (10%) for this service (C band: 1530 nm ~ 1565 nm)	Pre-specified percentage (30%) for this service (L band: 1565 nm ~ 1625 nm)	Best use of the remaining bandwidth (L band: 1565 nm ~ 1625 nm)
Recovery scheme	Protection (1:1) /backup lightpath	Protection (1:N) /backup lightpath	Restoration at IP level
Recovery time	< 50 msec (Detection time: < 100 msec)	< 50 msec (Detection time: < 100 msec)	1 – 100 sec (Detection time: 100 msec ~ 180 sec)

This paper introduces two main approaches to QoS evaluation in order to provide services with differentiated QoS in the NGI.

First, one is related to the transmission quality of a lightpath. In DWDM networks, an optical signal passing through network components such as

OXC (Optical Cross-Connect), fiber, wavelength converter, and EDFA (Erbium-Doped Fiber Amplifier) undergoes many transmission impairments throughout its route. Then, the quality of optical signal on each link is affected by several impairments ranging from simple attenuation to complex nonlinear effects [22,23], which is determined by calculating bit error rate (BER) in the receiving node. BER is the most important one among several parameters proposed for monitoring signal quality [24] and is complemented by other parameters to diagnose the system problems like optical signal-to-noise ratio (OSNR) or electrical signal-to-noise ratio (el. SNR) [23]. But it is difficult to measure directly BER from a signal at system and OSNR may vary significantly for a specific BER value because of nonlinear effect unrelated to noise accumulation. BER in an optical network can be estimated by the Q-factor as a new parameter evaluating signal quality [25]. It measures SNR based on assuming Gaussian noise statistics in the eye-diagram.

$$BER(Q) \cong (1/\sqrt{2\pi}) \cdot (\exp(-Q^2/2)/Q) \quad \textbf{(9)}$$

$$el.SNR = 10\log Q^2 \quad \textbf{(10)}$$

$$OSNR_{0.1nm} = \frac{(1+r)(1+\sqrt{r})^2}{(1-r)^2} \cdot \frac{Be}{Bd} \cdot Q^2 \quad \textbf{(11)}$$

$r = 0.15$ (*extinction ratio of the transmitted optical signal*)
$Be = 0.75 \times fo$ (*effective electrical noise bandwidth due to bit rate fo*)
$Bd = 12.6$ *GHz or* 0.1 *nm* (*optical bandwidth for OSNR measurement*)

Thus, the QoS parameter related to the transmission quality of the lightpath is determined by the following Equations (9) to (11) [26]. The measured SNR must strictly comply with BER, el.SNR and OSNR constraints for each service presented in Table 1 on all links of the selected route.

The other one is considered for survivability of the lightpath. As mentioned above, an optical signal carrying high-speed data will experience loss or degradation of signal by various impairments. The survivability in DWDM networks is an important problem because a single failure can cause loss of vast traffic volumes [27]. That is essentially needed to the foundation and success of the NGI expected to transmit real-time multimedia services and many other Internet applications entail high reliability and QoS guarantees. It would be desirable 100% resilience guarantees to all various traffic with differentiated QoS level and constraints over the Internet. However, it is not very inefficient in terms of wavelength utilization and QoS guarantees. Thus, the differentiated survivability capability based on the service type is needed in the NGI based on DWDM. For premium service, assured service, and best-effort service, this paper introduces recovery schemes such as 1:1 protection where a link-disjoint backup path and wavelength is reserved at the time of connection setup for each working path, and 1:N protection where one protection path shared among several working paths.

2. The Differentiated RWA Mechanism with QoS Guarantees

To provide services with satisfied QoS in the NGI based on DWDM, RWA must be accomplished in consideration of several attributes affecting optical signal quality related to network performance. This paper proposes the differentiated RWA mechanism with QoS recovery capability for each service classified in above section under the following scenario: (a) the loss of optical signal is in proportional to the hop length of the selected route, (b) wavelengths passing through the same type of physical components have different QoS attributes according to its own wavelength band, and (c) the recovery schemes for each service depend on the service priority and recovery time.

For case (a), the more an optical signal passes through nodes consisting of OXCs, OADMs (Optical Add/Drop Multiplexers), and wavelength converters, the more the quality of the optical signal falls. Thus, premium service and assured service that require high quality would be routed along the shortest-path selected by OSNR of the wavelength regardless of the amount of residual wavelengths on a link. To provide optimal routes for these services, $(OSNR)_l$ as OSNR of each link must satisfy $(OSNR)_{th}$. This means the OSNR constraints of each service class expressed in Table 1 must be fulfilled throughout all links over the selected path as shown in Equation (12). And then, the MW-MIPR algorithm proposed in Section 3 is applied for best-effort service to protect routes with the best OSNR for services with high QoS level.

$$(OSNR)_l \geq (OSNR)_{th} \qquad \forall l \in p_{sd} \qquad \textbf{(12)}$$

For case (b), both attenuation and dispersion result in more serious damage for signal quality and can change by wavelength range. Considering the attributes of these impairments, premium services with the highest QoS assurance should be assigned to wavelengths that correspond to the C-band (1530-1565 nm) with zero-dispersion and low attenuation coefficient of 0.28 dB/km [28] among the feasible wavelength ranges for the current signal transmission. Wavelengths within the L-band (1565-1625 nm) [29] with a little lower quality than the C-band can be used for assured services and best-effort services. To provide more sufficient QoS with this wavelength assignment strategy, this paper also proposes the service-differentiation by assigning service-specific wavelength ratio on each link in the network. The amount of the total available wavelengths on each link is allocated to each service class like 10 % for premium service, 30 % for assured service, and 60 % for best-effort service. Generally, thereby gaining the load balancing effect by avoiding heavy loaded links and failing lightpath settings. The proposed wavelength assignment strategies are presented in Table 1.

For case (c), this paper applies differentiated recovery schemes for each service to protect a lightpath against a link or node failure in the network according to Table 1. For premium services that command the highest priority and fast recovery time less than 50 msec, 1:1 protection is performed because it can guarantee 100 % survivability by quickly switching traffic to the dedicated back-up path as soon as service degradation is detected. For sustaining QoS of assured service with a lower QoS level than premium services, this paper applies 1:N protection providing high wavelength utilization by sharing one back-up path with N working paths. But, unlike 1:1 protection, the traffic switched protection path must be switched back to the working path after it is repaired so that the protection path is available for any future working path failures. This paper adopts 1:3 protection with respect for these characters. In generally, the protection paths for premium services and assured services should be chosen in such manner so as to support the necessary transmission quality guaranteed along selected link-disjointed QoS path within the assigned wavelength ratio. And best-effort service is protected by restoration at IP level. If a failure occurs, then disrupted traffic can be compensated by TCP retransmissions within from 100 ms to a few seconds.

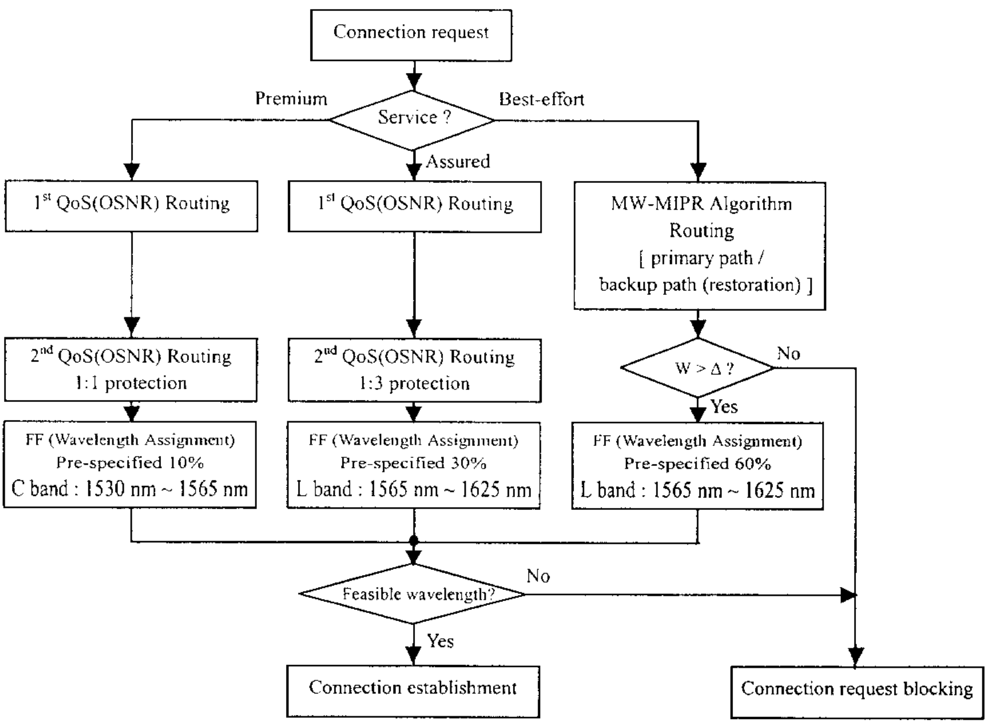


Figure 10. The differentiated RWA mechanism with QoS guarantees

Based on articles proposed in the case (a), (b) and (c), the differentiated RWA mechanism for each service class are implemented as illustrated in Figure 10.

If the residual wavelengths on a bottleneck link of the chosen route for best-effort service are less than threshold value Δ on a link, then MW-MIPR algorithm will block traffic for best-effort service. It can reduce the blocking probability of traffic of the higher priority services.

V. Simulation Results

1. Network Model

In this section, simulations are carried out to evaluate the performance of MW-MIPR and differentiated RWA algorithm with QoS recovery. To prove the efficiency of the MW-MIPR algorithm proposed in Section 3, this paper analyzes the blocking performance of MW-MIPR in case of network with or without wavelength converters and compare with that of the existing FR and DR algorithm via simulations. Similarly, to perform an efficiency test for differentiated RWA with QoS recovery capability described in Section 4, the same conditions with the test for MW-MIPR are applied. And this paper also examines the survivability ratio for each differentiated QoS service class.

Topology used in simulations is NSFnet currently used for WDM network model in USA and adopted in most of papers relation to WDM networks.

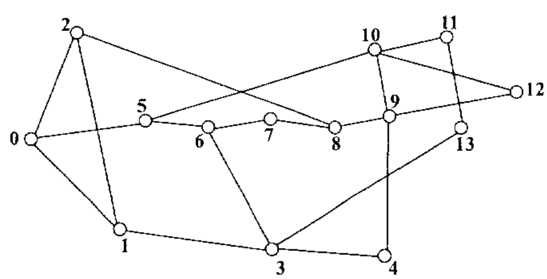


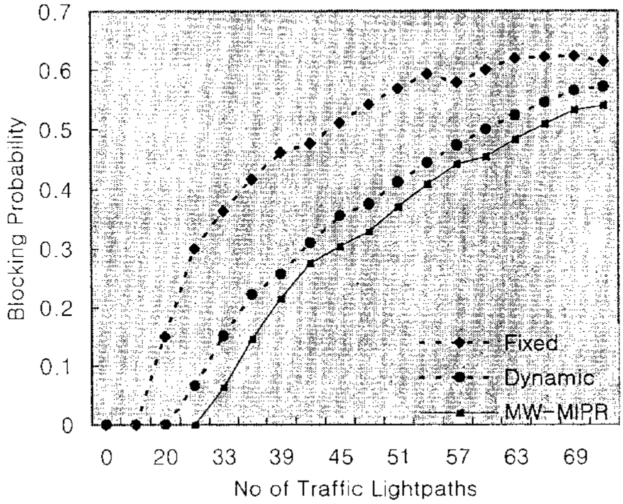
Figure 11. 14-node NSFnet

The assumptions are as follows: (i) The physical topology consists of 14 nodes and 20 links as shown in Figure 11. (ii) The number of fibers per a link is one, and the number of wavelengths per a fiber is eight. (iii) The topology is static and is not reconfigured during the simulation. (iv) A set of node pairs which can originate the lightpath connection setup is arbitrarily selected from the set of total node pairs and this paper chooses 7 pairs for simulations. (v) Connection requests arrive in sequence. (vi) Blocking probability is the ratio of the number of working or backup lightpath requests rejected to the number of lightpath connections requested. If a connection request for the working path is blocked, the procedure for backup path setup is not done.

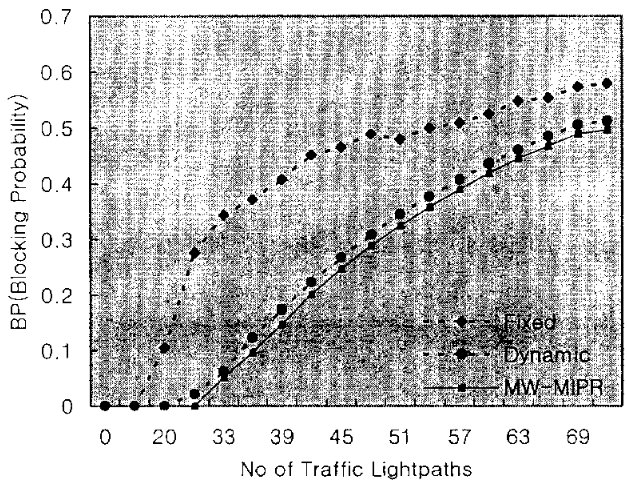
2. The Analysis of Simulation Results

First, this paper compares proposed MW-MIPR to the existing routing (FR and DR) algorithms in case of a network without WC capability. The result is illustrated in Figure 12(a).

The blocking probability is almost the same for nearly 10 lightpath requests (about 15 % of total network capacity) but it makes a difference in blocking probability performance according to each algorithm for lightpaths set above 10. The result indicates that FR has the lowest performance. It is because this approach to set up lightpath connections is very simple. If, however, wavelengths along the path are tied up, it can potentially lead to high blocking probabilities. And then the proposed MW-MIPR algorithm has the lower blocking probability than DR (improved by about 10 ~ 15 %.) because of selecting the minimum interference path with potential future setup requests.



(a) Network without WC capability

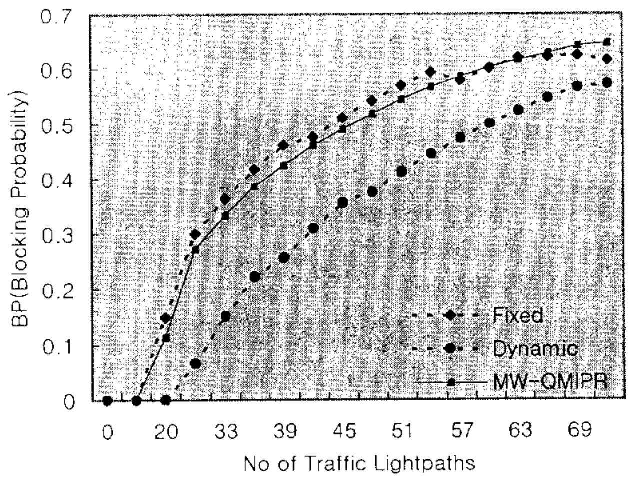


(b) Network with full WC capability

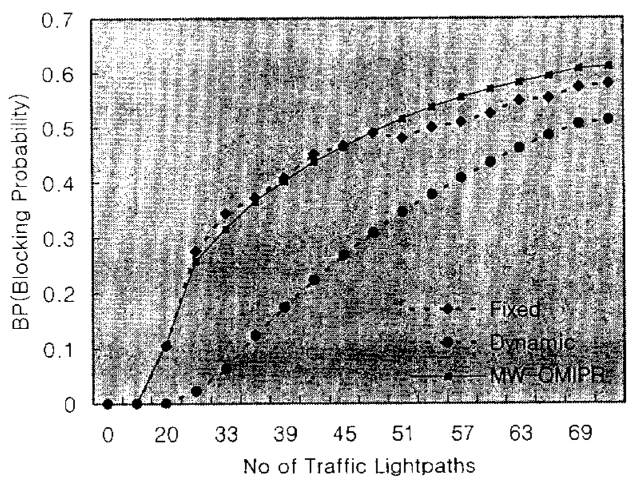
Figure 12. Comparison of FR, DR and MW-MIPR

Generally, the restriction imposed by the wavelength continuity constraint can be removed by the use of wavelength converters. They play an important role in enhancing the resource utilization and in reducing the overall call blocking probability of the network. Figure 12(b) shows the comparison of FR, DR and MW-MIPR with full WC capability. Compared with the results in Figure 12(a) without wavelength converters, all approaches exhibit lower values outperform them in Figure 12(a). Moreover, the proposed MW-MIPR algorithm performs better than the others too. Actually, the blocking probability of MW-MIPR is improved by 10 % to DR.

The importance of QoS guarantees is described in Section 4. Accordingly, we define MW-MIPR applied to differentiated QoS routing as MW-QMIPR, and analyze the blocking probability and performance of MW-QMIPR for a network with and without WC capability, in Figures 13 (a) and (b), respectively. In Figure 13, the blocking probability of MW-QMIPR is higher than previous results in Figure 12. The primary reason for this inefficiency is because QoS routing algorithm reserves the backup path for QoS guarantees of premium and assured service in advance. Therefore, the efficiency of blocking probability, as such, is not good, but through QoS guarantees, it provides continuous confidential service in the presence of failures. When the connections are established with wavelength converters as shown in Figure 13 (b), the blocking probability is lower than that of network without wavelength converters. The reason was explained before.



(a) Network without WC capability



(b) Network with full WC capability

Figure 13. Comparison of FR, DR and MW-QMIPR

Finally, another significant observation in differentiated RWA mechanisms with recovery capability is a survivability ratio. For its measurement, this paper has generated multiple faults on arbitrary links in the network.

Table 2. Survivability ratio

Service class	Premium (1:1 Protection)	Assured (1:3 Protection)	Best-effort (Dynamic Restoration)
Survivability ratio	Fixed		Not fixed
	100%	33%	

Table 2 shows the survivability ratios for differentiated service classes. As this paper described in Section 4, dedicated path-disjoint protection (1:1 protection) for premium service is applied. On this account, survivability can be guaranteed by 100 percent from not only single-link failures, but also some multi-link failures. Assured service using shared protection mechanism (1:3 protection) has lower survivability ratio than premium service, but it is possible to utilize the capacity more efficiently, while still achieving over the minimum 33 % for single-link failures.

Moreover, protection mechanisms for both services can guarantee absolute survivability under any circumstances: Fixed. However, dynamic path restoration for best-effort can guarantees only relative survivability, according to residual bandwidth: Not fixed. This phenomenon occurs due to discovering backup path after the primary lightpath fails, not to reserve backup bandwidth in advance.

VI. Conclusion

This paper suggested a new dynamic routing method choosing a route that does not interfere too much with many potential future connection requests for two cases: networks with full wavelength conversion capability and networks with no conversion capability, and presented the differentiated RWA mechanisms with recovery capability based on proposed MW-MIPR algorithm. With respect to the future potential network congestion, proposed work can achieve advanced global efficiency in wavelength utilization as well as guarantee satisfied QoS for widely various multimedia applications in the DWDM network as the NGI backbone network. Simulation results show that the proposed MW-MIPR algorithm significantly improves network performance in blocking probability comparing with previous routing algorithms used in DWDM networks regardless whether a wavelength converter at node is present or not, and that differentiated RWA mechanisms by applying MW-MIPR algorithm provide more reliable and stable QoS guarantees for each service by considering signal quality and survivability. Therefore the proposed approach can be also applied to generalized multi-protocol label switching (GMPLS) as control protocol in the DWDM network.

As future research, this paper will study the MW-MIPR algorithm based on sparse wavelength conversion with regard to the impact of the location or the number of wavelength converters on signal quality and cost efficiency in the network. And, this paper will expand the RWA problem for various multimedia applications in the NGI by subdividing more detailed QoS levels in the diverse service classes.

References

[1] B. Mukherjee, Optical communication networks, McGraw-Hill Publishers, 1997.

[2] R. Ramaswami, Optical networks – A practical perspective, Morgan Kaufmann Publishers, 1998.

[3] T. E. Stern and K. Bala, Multiwavelength optical networks: A layered approach, Addison Wesley Publishers, 1999.

[4] I. Chlamtac et al., "Lightpath Communications - An Approach to High-Bandwidth Optical WANs," IEEE Transactions on Communications, vol. 40, no. 7, pp. 1171-1182, July 1992.

[5] J. S. Choi and N. Golmie et al., "Classification of Routing and Wavelength Assignment Schemes in DWDM Networks," Proceedings of OPNET 2000 (Paris, France), pp. 1109-1115, January 2000.

[6] H. Zang et al., "A Review of Routing and Wavelength Assignment Approaches for Wavelength Routed Optical WDM Networks," Optical Networks Magazine, vol. 1, no. 1, pp. 47-60, January 2000.

[7] S. Ramamurthy and B. Mukherjee, "Fixed-Alternate Routing and Wavelength Conversion in Wavelength-Routed Optical Networks," Proceedings of IEEE GLOBECOM 1998 (Sydney, Australia), vol. 4, pp. 2295-2302, November 1998.

[8] J. S. Kim and D. C. Lee, "Dynamic Routing and Wavelength

Assignment Algorithms for Multifiber WDM Networks with Many Wavelengths," Proceeding of ECUMN 2002 (Colmar, France), pp. 180 -186, April 2002.

[9] L. Li and A. K. Somani, "Dynamic Wavelength Routing Using Congestion and Neighborhood Information," IEEE/ACM Transactions on Networking, vol. 7, no 5, pp. 779-786, October 1999.

[10] S. Xu et al., "Dynamic Routing and Assignment of Wavelength Algorithms in Multifiber Wavelength Division Multiplexing Networks," IEEE Journal on Selected Areas in Communications, vol. 18, no. 10, pp. 2130-2137, October 2000.

[11] S. Chen and K. Nahrstedt, "An Overview of Quality of Service Routing for Next-Generation High-Speed Networks: Problems and Solutions," IEEE Network, vol. 12, no. 6, pp. 64-79, November/ December 1998.

[12] C. B. Ahmed et al., "QoS Routing with Wavelength Conversion and Call Admission Connection in DWDM Networks," Proceedings of IEEE ICCNMC 2001 (Beijing, China), pp. 61-66, October 2001.

[13] K. Kar et al., "Minimum interference routing of bandwidth guaranteed tunnels with MPLS traffic engineering applications," IEEE Journal on Selected Areas in Communications, vol. 18, no. 12, pp. 2566-2579, December 2000.

[14] K. Kar et al., "MPLS traffic engineering using enhanced minimum interference routing: an approach based on lexicographic max-flow," Proceedings of IEEE IWQOS 2000 (Karlsruhe, Germany), pp. 105-

114, June 2000.

[15] D. Bauer, "Minimum-interference routing based on flow maximization," Electronics Letters, vol. 38, no. 8, pp. 364-365, April 2002.

[16] S. Suri et al., "Profile-Based Routing: A New Framework for MPLS Traffic Engineering," Washington University Computer Science Technical Report WUCS-00-21, July 2000.

[17] R. K. Ahuja et al., Network Flows: Theory, Algorithms, and Applications, Englewood Cliffs, NJ: Prentice-Hall, 1993.

[18] M. Frey and T. Ndousse, "Wavelength Conversion and Call Connection Probability in WDM networks," IEEE Transactions on Communications, vol. 49, no. 10, pp. 1780-1787, October 2001.

[19] Jing Fang et al., "Performance Analysis of WDM Optical Networks with Wavelength Usage Constraint," Photonic Network Communications, vol. 5, no. 2, pp. 137-146, March 2003.

[20] M. Ma and M. Hamdi, "Providing Deterministic Quality-of-Service Guarantees on WDM Optical Networks," IEEE Journal on Selected Areas in Communications, vol. 18, no. 10, pp. 2072-2083, December 2000.

[21] S. Blake et al., "An Architecture for Differentiated Services," RFC 2475, IETF, December 1998.

[22] J. Strand et al., "Issues for Routing in the Optical Layer," IEEE Communications Magazine, vol. 39, no. 2, pp. 81-87, February 2001.

[23] P. S. André et al., "Optical-signal-quality monitor for bit-error-ratio assessment in transparent DWDM networks based on asynchronously sampled amplitude histogram," Journal of Optical Networking, vol. 1, no. 3, pp. 118-127, March 2002.

[24] C. P. Larsen and P. O. Andersson, "Signal Quality Monitoring in Optical Networks," Optical Networks Magazine, vol. 1, no. 4, pp. 17-23, October 2000.

[25] WorldCom's White Contribution COM-D.126, "Proposed Optical Performance Monitoring Parameters for OTN," ITU-T SG 15 Contribution, October 2001.

[26] Alcatel's White Contribution COM 15-33-E, "Electrical (BER, Q-factor, el. SNR) and Optical (OSNR, OCR) System Performance Parameters for G.DSN," ITU-T SG 15 Contribution, December 2000.

[27] D. Zhou and S. Subramaniam, "Survivability in Optical Networks," IEEE Network, vol. 14, no. 6, pp. 16-23, November/December 2000.

[28] Lucent's White Contribution COM-15-39-E, "L- and C-band Attenuation in Installed Fibre Links," ITU-T SG 15 Contribution, August 2001.

[29] KDDI's White Contribution D.97 (WP4/15), "Recent technical information on C- and L-band in optical transmission systems," ITU-T SG15 Contribution, February 2001.

Acknowledgments

I appreciate a steady attention and precious advice of Prof. Kim, Sung-Un for the completion of this dissertation with all my heart. In particular, his diligent and patient guidance and his unselfish sharing of ideas made this dissertation possible. Moreover, I am very thankful to Prof. Ha, Deock-Ho and Prof. Chung, Yeon-Ho for examining this dissertation along with much good advice. Of course, I acknowledge several professors in Dept. of Telematics Engineering, Pu-Kyong National University for considerable instructions and encouragement till now.

Meanwhile, I thank all members in the protocol-engineering laboratory. I would like to acknowledge many seniors: Jae-Yun, Young-Suk, Sung-Su, Jae-Ho, Heung-Sik, Eui-Sub, Seong-Kil, Seon-Kyu, Ik-Seob, Mi-Kyoung and Du-Jin who already graduated. And especially, Hyun-Soo, Ju-Dong and Mi-Ra who gave much advice and helped me during mater's degree course. I thank Chang-Hyun, Kwang-Hyun, Mi-Seon, Jin-Ho, Suk-Jin, Kyung-Dong, Jung-Mi and Kamil, too.

Finally, I would like to heartily acknowledge my parents who have devoted themselves to support me even despite of many difficulties, my lovely younger brother Min-Sung and Sang-Pyo who is always as a stout pillar close to me. I am also thankful to my friends Eun-Kyung and U-Jung as well as the other acquaintances who know me.