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ภาคผนวก

เนื่องจาก ส่วนหนึ่งของงานวิจัยในวิทยานิพนธ์นี้ ได้รับการตีพิมพ์และเผยแพร่ในงานการประชุมทางวิชาการ Networking 2000 ที่กรุงปารีส ประเทศฝรั่งเศส ในวันที่ 14-19 พฤษภาคม พ.ศ. 2543 ในชื่อบทความทางวิชาการเรื่อง A Comparative Study of Mesh and Multi-ring Design of Survivable WDM Networks ดังนั้น จึงขอนำบทความที่ได้รับการตีพิมพ์มาเสนออีกครั้งหนึ่ง ในภาคผนวก

A Comparative Study of Mesh and Multi-ring Designs for Survivable WDM Networks

T. Iamvasant, C. Bawomtummarat, L. Wuttisittikulkij

Department of Electrical Engineering
Faculty of Engineering
Chulalongkorn University
Bangkok, Thailand 10330
Tel. +662 2186512 Fax. +662 2518991
lunch@ee.eng.chula.ac.th

Abstract. In this paper, two distinct optical network design approaches, namely mesh and multi-ring, for survivable WDM networks are investigated. The main objective is to compare these two design approaches in terms of network costs so that their merits in practical environments can be identified. In the mesh network design, a new mathematical model based on integer liner programming (ILP) and a heuristic algorithm are presented for achieving a minimal cost network design. In the multi-ring network design, a heuristic algorithm that can be applied to large network problems is proposed. The influence of wavelength conversion and the number of wavelengths multiplexed in a fiber on system designs are also discussed. Based on the simulation results, the redundancy quantities required for full protection in multi-ring approach are significantly larger in comparison to the minimal cost mesh counterpart.

1 Introduction

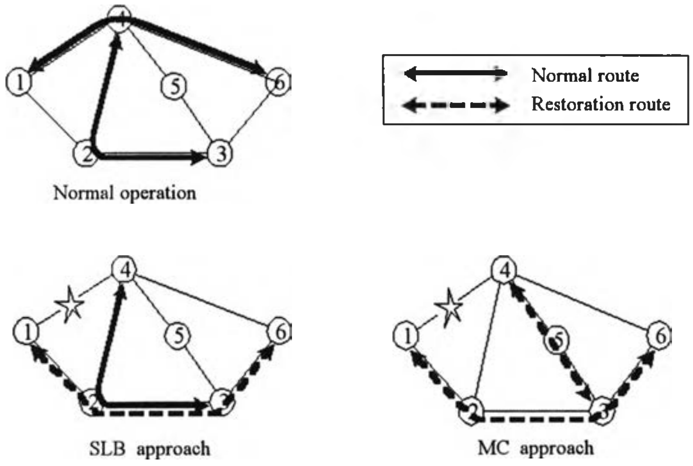
Recently, wavelength division multiplexing (WDM) has been seen as a promising technology for realizing future broadband networks to support the increasing bandwidth demands of various emerging applications, such as multimedia and web-browsing. In such networks, a few number of wavelength channels can be multiplexed into a single fiber, each operating at a few Gbit/s. Therefore, these types of networks are expected to offer an aggregate capacity in the order of Tbit/s, serving as a viable technology to overlay the existing transport networks.

One of the key issues associated with WDM network designs is the problem of wavelength allocation. Over the past few years, many research activities have made considerable efforts to solve this problem [1,2,3,4]. Moreover, some of these studies also include the network protection issue into their design considerations. This is because there is an increasing concern on the impacts of network failures in modem communication systems. It is important that certain network protection measures must be provided at the network design and dimensioning stage.

This paper studies the problem of network resource allocation in WDM networks employing wavelength routing technique. The key objective is to determine how fiber and wavelength resources can be simultaneously assigned to satisfy traffic demands while providing full protection against all single link failures. The solution techniques for this problem are based on two design approaches: mesh and multi-ring.

In the mesh design, two path restoration schemes, namely a minimal cost protection and a single link basis protection, are examined. For the minimal cost protection approach [5], in the events of failures all optical connections are subject to be rearranged even when they may not be directly interrupted by the failures. Accordingly, this particular approach can allow, in principle, the design to be very efficient and result in the minimal network cost. This protection technique is therefore called the minimal cost approach (MC). For the restoration on a single link basis (SLB), only interrupted traffic connections are rerouted and other connections remain unchanged. Failures on different links along an active path can have different restoration paths depending on the place of link failure. Consequently, this approach is called the single link basis approach (SLB).

In order to illustrate the difference between the MC and SLB approaches, an example of a network scenario is given in Figure 1. In this example, the connections (1,6) and (3,4) are set up along the physical routes of 1-4-6 and 3-2-4 respectively under normal operation. Now, consider a situation when a failure occurs on the link between nodes 1 and 4. In SLB approach, only the connection (1,6) is subject to reroute as it is directly affected by the failure and in this example the new route chosen is through nodes 1-2-3-6 resulting in an extra wavelength channel being needed on link 2-3. In contrast, the MC approach requires no additional wavelength as both connections are re-arranged.



Normal operation

SLB approach

MC approach

Fig. 1. An example illustrating the difference between the MC and SLB approaches

Although the minimal cost protection technique is very cost-efficient, it may not be suitable for practical use, due to unnecessary reconfigurations of the entire optical nodes in the networks. However, the design outcomes of this protection technique are useful for comparisons in terms of network costs with the other path restoration schemes such as SLB approach.

In the ring design, realizing a large-scale network using a single ring may not be practical due to the low efficiency of network bandwidth utilization. A new design technique using multiple rings described in [6] has been proposed. Instead of using a large single ring to cover the entire network, the network is divided into a number of rings. These rings are used to support all traffic of the network. The criterion used in the design is that the traffic demands between each node pair must be accommodated over a single ring. No traffic is allowed to get across between rings in order to avoid complicated control and management. Consequently, the main problem of this design is how to select the rings from the number of possible rings in network in order to minimize the number of required fibers.

The multi-ring design may not be as efficient as the mesh design in terms of network utilization but it is an interesting alternative and currently attracts much attention. Firstly, since its structure is much simpler than that of the mesh, only add-drop multiplexers are needed whereas optical cross-connects would be required for mesh. Secondly, each unit of rings in the network can operate independently, thus the control and management can be fully distributed. Thirdly, the multi-ring design provides a full network protection against certain types of failures: all single-link and all single-node failures. This restoration feature is particularly important in future optical network which requires high level of network protection. Because of the multi-ring's simple structure, the entire restoration process in the ring network can be achieved through automatic hardware reconfiguration without rerouting the entire path, hence it is very fast and reliable. However a disadvantage of the multi-ring approach is that protection cost is 100% of unprotected rings.

The key issue that is addressed in this paper is determining and comparing the network costs between the two different design schemes in a quantitative manner. In addition, this paper also considers two different systems, namely wavelength path (WP) and virtual wavelength path (VWP). The VWP system differs from the WP system in that its node configurations include an additional wavelength conversion capability. Therefore, when setting up an optical path for a connection, the VWP can assign wavelengths on a link-by-link basis, whereas the WP must choose a single wavelength for all links along the entire physical route.

2 Minimal Cost Protection Technique

2.1 Integer Linear Programming (ILP)

Given a set of traffic demands and a physical network topology, the network topology is modeled as an undirected graph $G(v,\varepsilon)$ where v is a set of nodes with size N and ε is a set of edges with size L. Let M be the number of wavelengths multiplexed into a fiber. Let X_i be the number of fibers (or capacity) on i^{th} edge and the characteristics of each fiber is assumed to be bi-directional and can only contain one wavelength (M=1), the objective function of this model is

$$\text{Min} : \sum X_i \qquad \text{where } i\in\varepsilon \tag{1}$$

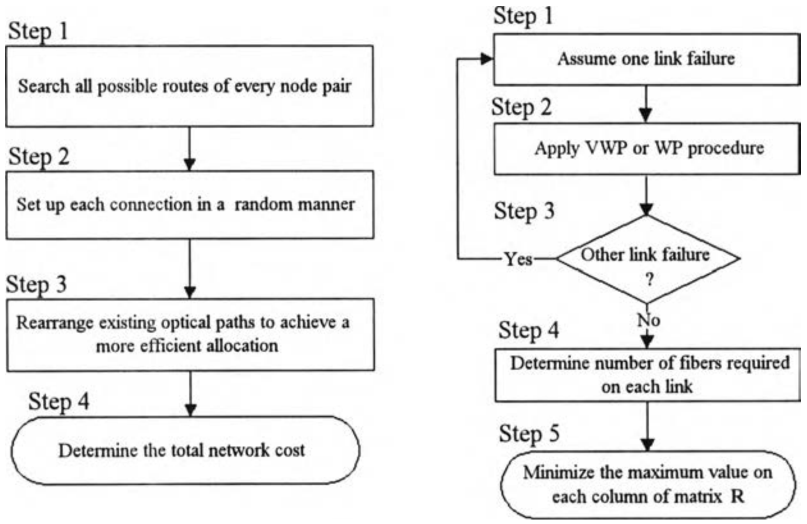
The constraint to formulate the equation is derived from the minimum flow on a cut set which is defined as follows. The network graph is partitioned into two parts, G_1 and G_2 with cut set ε_c which corresponds to a set of edges that has one endpoint in G_1 and the other in G_2. The possible minimum traffic of a cut set, $d_{min}(c)$, is the summation of each traffic demand which has a source and a destination lying on different parts. As a result, the capacity of any cut set must be larger than or equal to the possible minimum traffic:

$$\sum X_i \quad d_{min}(c) \qquad \text{where } i\in\varepsilon_c \tag{2}$$

Now, we can determine the network capacity from the linear formulations related to every possible cut set of the network graph. This capacity only provides for the traffic demands in normal operation. In order to extend the model to cover the protection requirements against all single link failures, additional constraints are included as follows. An edge is removed from the network graph in turn, simulating each link failure event. Given a network graph with an edge removed, the same formulation of the minimum flow on a cut set is applied, producing a new set of required constraints. By applying this procedure to all edges, a total of L additional new sets of constraints would result, covering all link failure scenarios. All these constraints are sufficient to determine the minimal network cost with full protection. However, this model does not provide an exact solution, instead it can only be used as a lower bound on the network cost required.

2.2 Heuristic Algorithm

Due to the complexity of the problem, the design process is divided into three procedures: path accommodation, wavelength assignment, and restoration. The wavelength assignment procedure used in this paper is adopted from [7]. Since the wavelength assignment in VWP system is considered on a link-by-link basis, only the path accommodation procedure is required. Firstly, we will explain the path accommodation procedure. The flow chart of path accommodation is shown in Figure 2 (a).



(a) (b)

Fig. 2. Procedure of (a) the path accommodation and (b) MC restoration

The outline is described as follows:

Step 1: All possible routes between each node pair are searched

Step 2: Randomly select an appropriate physical route for each traffic connection

Step 3: After all connections have been established, the next step is an attempt to rearrange the existing allocation, so that the overall network cost is reduced. To accomplish this, each connection is reconsidered in turn to see whether they can be redirected on another route that leads to more efficient wavelength resource utilization

Step 4: As the VWP system assigns wavelengths on a link-by-link basis, the number of wavelength channels required on each link is equal to the number of optical connections passing through the corresponding link. The number of fibers required on each link can be obtained from $\lceil P/M \rceil$ where P is the number of optical paths going through the link and M is the number of wavelengths multiplexed in one fiber. Note that $\lceil X \rceil$ is the smallest integer greater than or equal to X. Consequently, the network cost can be obtained from the summation of the number of required fibers of every link times the number of wavelengths. In WP system, the wavelength assignment procedure is applied before determining the protection cost

The following restoration algorithm guarantees 100% protection against any single link failure in the network and it can be applied to both VWP and WP systems. The outline of this algorithm is shown in Figure 2 (b).

Step 1: A fiber link i is removed from the original structure for simulating a link failure event i. The resulting network is referred here as an incomplete network i. Note that there exists a total of L different incomplete networks

Step 2: Apply algorithms of VWP or WP to the incomplete network i and determine the number of fibers required for each fiber link, a total of L-1 results. These numbers are then memorized in row i of an L×L matrix **R**. Each row i in the matrix **R** contains results from each failure event i. Each column j contains the number of fibers required on link j for each failure event

Step 3: Repeat step 1 until all link failure events have been considered

Step 4: The maximum value of column j in the matrix **R** is taken as the number of fibers required to place on link j. Therefore, the total number of fibers required for full protection is the summation of the largest value in each column

Step 5: The matrix **R** obtained from the above steps is used as an initial result for further improvement. Since the network cost depends on the largest value in each column, it is useful to reduce the largest value of a certain column while keeping the largest values in all other columns unchanged. This technique can be repeated iteratively, until no further cost reduction is observed

3 Multi-ring Protection Technique

The design approach uses a heuristic algorithm which can be divided into two main steps. In the first step, ring selection and wavelength allocation are performed. The second step improves the design in order to minimize cost of the network and increase wavelength utilization in selected ring while getting rid of those rings that have low wavelength utilization. This step is iteratively performed until a satisfied solution is obtained, or no further improvement is observed. The details of each step are given as follows:

Step 1: Figure 3 (a) depicts the flowchart of step 1 process. Ring selection is a process in which an appropriate small set of rings is selected from all possible rings for handling all traffic demands. For each connection, a criterion used in the algorithm is that only one ring is selected to support all traffic of connection. The ring must include the shortest route between that node pair and should also be of the smallest size possible since a smaller ring is found to be more efficient in terms of bandwidth usage. Note that a ring provides two disjoint paths between each connection. Selecting the shortest ring that contains the shortest route ensures that traffic demands are transported over the shortest distance. This is similar to the mesh design, in which high resource utilization could be achieved. If there is more than one appropriate ring, a ring which accommodates the highest number of shortest routes of all connections is selected in order to minimize the number of selected rings. This process is performed on each connection until there is no further unassigned connection. Next, the wavelength allocation is accomplished ring-by-ring by algorithms H3 and H4 proposed in [8]. The number of fibers required on each ring can then be obtained from $\lceil N_\lambda / M \rceil$ where N_λ is the number of maximum wavelengths required in all links and M is as defined previously. The network cost can be obtained from the summation of each selected ring cost which is the number of required fibers times the number of nodes in that ring

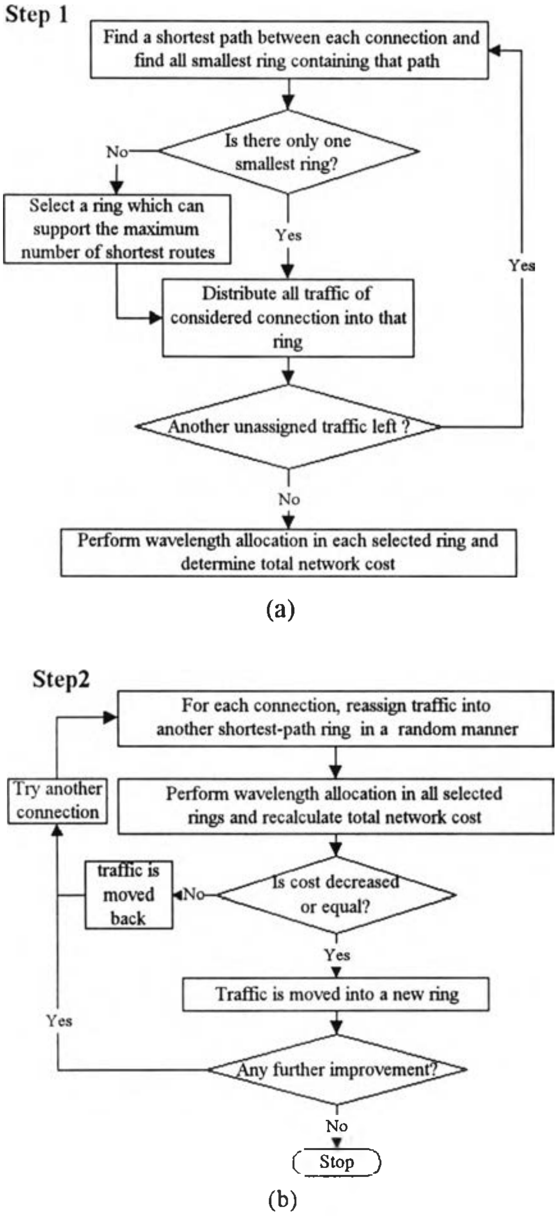


Fig. 3. (a) Procedure of the ring selection and wavelength allocation

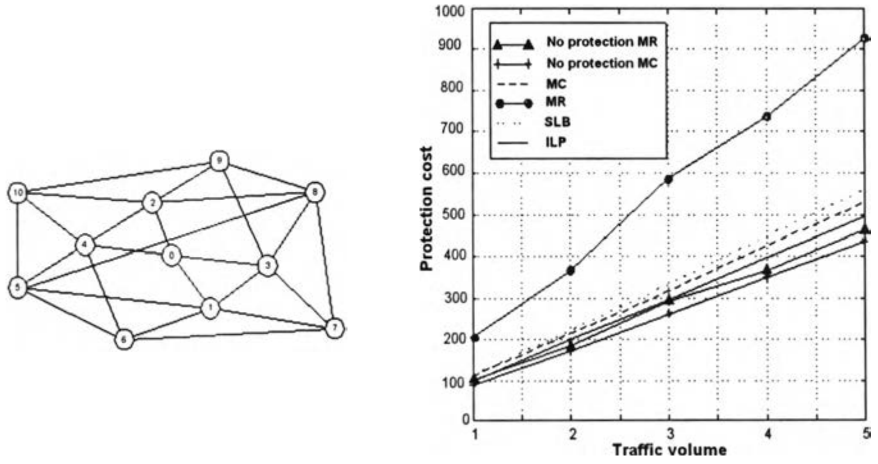
(b) Procedure of the design improvement

Step 2: In general, the first solution may not always be satisfactory because the number of selected rings could be very large. In an extreme case, the total number of rings in the network can be equal to the number of connections because the traffic of each connection is exclusively supported by an individual ring. Under this condition, the total network cost will be very expensive. Therefore, it is used as an initial result which needs further improvement using the following process. The traffic demand between each connection is considered again in turn to see whether other alternative rings would result in a more effective allocation. In each round of improvements, the traffic between only one connection is considered. We attempt to move this traffic from pre-selected ring into a random alternative ring. For each connection, a candidate ring is selected randomly and must be a member of previously selected ring set. If an alternative ring produces similar or better results, the new design outcome is accepted as the current solution before performing the next iteration. Otherwise, the traffic will be moved back to the old ring. This procedure is repeated until all traffic demands are considered and no further improvement is observed. The process described above is shown in Figure 3 (b).

4 Simulation Results and Discussion

4.1 Protection Cost

A network topology from [9] is used to illustrate the protection costs of mesh and multi-ring approaches with varying values of M (1,2,4,8), see Figure 4 (a). This network which is referred to here as Euro-Core is deliberately selected for discussion purposes in this paper, because it has relatively small number of nodes (N = 11 nodes) such that the ILP can still obtain the bound on the protection cost within a reasonable period of time. In addition, the network has very high level of connectivity, allowing a clear distinction between the costs of both design approaches. The traffic demands are assumed uniform with five levels of traffic volumes, *i.e.* 1 to 5. Therefore, the traffic volume of level i is defined as i times the total number of active paths among all node pairs, *i.e.* i x N(N-1)/2 active paths.



(a) (b)

Fig. 4. (a) Experimental network: Euro-Core (N=11, L=25) (b) the protection cost with M=1

Figure 4 (b) shows the protection cost of every approach with M=1. Note that when M=1 there is no difference between the WP and VWP systems. Let first look at the bound on the total network cost obtained from the ILP formulation and the cost of the MC design scheme achieved by the heuristic algorithm. It appears that the network costs with full protection from the MC design are slightly higher than the lower bound for all traffic volumes. This implies that the heuristic algorithm is quite effective for this network sample. When comparing the network costs of the MC and SLB designs (the SLB network cost is obtained from the heuristic algorithm in [7]), it is found that the differences between them are marginal, meaning that the SLB scheme can be made as cost-effective as the MC.

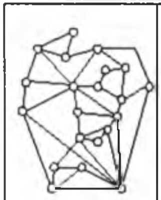
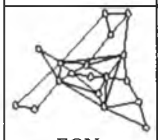
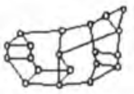
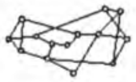
For the multi-ring protection technique, it is interesting to see that when no protection is provided the network cost (No protection MR) is just a little higher than that of the MC mesh approach (No protection MC). Note that the network cost of the MC approach is easily obtained from the summation of the number of lowest hop count of all node pairs; this is truly a minimal cost. The heuristic algorithm used for the MR design is therefore considered effective, because it is able to optimize the path allocation, such that both costs are comparable. The additional cost of the MR in respect to that of the MC is caused by the constraint that connections between a node pair must be confined only on one selected ring. For a given set of selected rings a pattern of traffic distribution, the multi-ring algorithm will attempt to balance the traffic load on every link of each individual ring, so that the number of fibers in the rings are minimized. To achieve this, some traffic loads will have to be assigned on a longer route.

We now turn to consider the differences between the MR and MC design approaches when protection is provided. For the multi-ring, it is a well-known fact that 100 % extra capacity is always needed for full protection. For the MC mesh the amount of extra capacity depends on the network topology and its connectivity in relation to traffic patterns. Usually the higher the connectivity is the lower the extra capacity will result. As mentioned earlier that this network sample has rather high connectivity, *i.e.* each node has on average 4.54 links adjacent to it, it is expected that the amount of extra capacity should be rather small. The heuristic algorithm used for finding the protection cost for the MC scheme described in this paper was able to achieve very good results, as the protection cost is only approximately 22.93% over the unprotected network cost. This particular example is certainly in favor of the MC mesh design, as it is much more expensive (up to 78.09%) to employ the multi-ring protection scheme in comparison to the MC mesh design. However, in a practical system which does not require 100% protection, the level of protection can easily be scaled to the desired level by removing some protection rings without changing or rerouting the existing design; this is an advantage of the multi-ring design over the mesh design.

In order to demonstrate further the differences between the protection costs of the multi-ring design and the MC mesh design, the results of several different network scenarios are given in Table 1. The traffic demands assumed in these networks are uniform with a volume of one and only one wavelength is multiplexed in each fiber. In the NSFNet, the multi-ring design requires 55.31% more capacity over the MC mesh counterpart, whereas in the ARPANet the difference is even smaller, *i.e.* only 40.74%. These two network configurations show a closer gap between the costs of the multi-ring and the mesh design when full protection against single link failures is provided. It is interesting to point out that both network structures have almost the same average number of links adjacent to a node *i.e.* 3, meaning that they both should theoretically require spare capacity of about 50%. This figure is obtained from a simple calculation. If a failure occurs at a certain link of a node, the traffic carried over that link would have to be redirected through the remaining 2 links connected to the node. If these disrupted traffic loads are split equally over the two links, each of the two links will have to provide an extra capacity of 50% of the normal traffic. It turns out that the ARPANet demands more than 50% spare capacity (54.14%) whereas the reverse is true for the

NSFNet (40.00%). As the costs of the multi-ring and MC mesh are not very different when no protection is included, it means that the total cost differences between the multi-ring and the MC mesh will depend on that how much each individual topology can take advantage on the alternative routes under a network failure.

Table 1. The network costs with and without protection achieved from the MC and MR heuristic algorithms. The value of C is the average number of links adjacent to a node. The percentage of difference between the cost with and without protection of MC is given in parenthesis

Network	*N*	*L*	*C*	*MC*		*MR*		$\frac{(MR-MC)}{MC}*100$ *(with protection)*
				without protection	*with protection*	*without protection*	*with protection*	
 UKNet	21	39	3.71	526	732 (39.16%)	597	1194	63.11%
 EON	18	35	3.89	336	505 (50.29%)	394	788	56.04%
 ARPANet	20	31	3.10	543	837 (54.14%)	589	1178	40.74%
 NSFNet	14	21	3.00	195	273 (40.00%)	212	424	55.31%

Let now turn back to our EURO-core example. Figure 5 illustrates the protection cost of the VWP system as a function of M and in this case the traffic volume is set to four. The network cost increases as the value of M increases. This means that, for each link of the network, the fibers have many channels that are unassigned wavelength for communications (in order words, the efficiency of fiber utilization of that link is low). As the value of M gets large, the number of unassigned channels becomes greater. Moreover, in multi-ring scheme, all links in a selected ring occupied the same number of fibers, which is the maximum fiber requirement of all links. Thus, the utilization of fibers in multi-ring scheme is certainly less efficient than the mesh design.

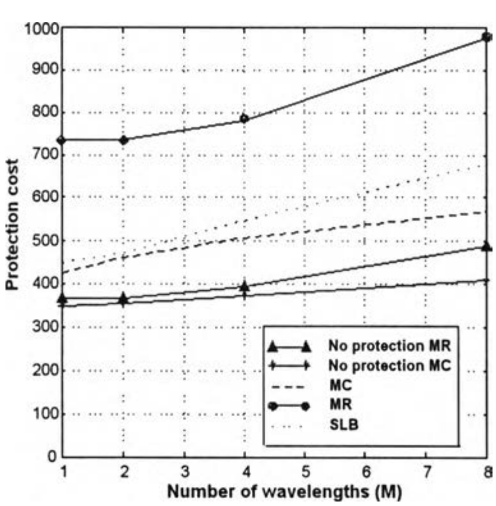
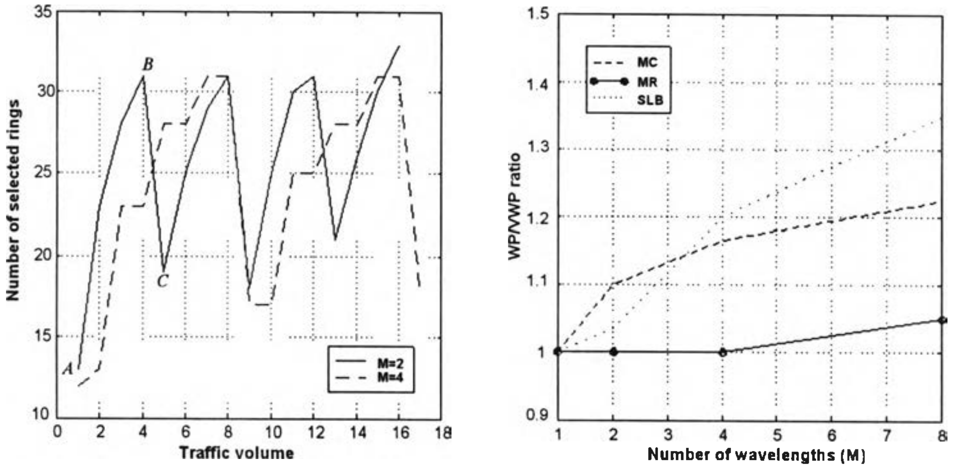


Fig. 5. The VWP protection cost with various values of M

Let us focus on the effect of M and the traffic demands on the ring utilization. To illustrate this, the number of selected rings is chosen to indicate the ring utilization as shown in Figure 6 (a). When the traffic demand is set at low level with a value of M greater than 1 (such as at point *A*), if the traffic loads are distributed among many separated rings, each ring will have a very low link utilization. Therefore, it is useful and more effective to aggregate these traffic loads into a smaller number of rings in order to increase the utilization of these chosen rings. When traffic is higher, each fiber of ring is more filled up and has a high utilization even if the traffic loads are distributed on many separated rings. Therefore, the higher traffic demand at this point results in a higher number of selected rings (such as at point *B*). This is true until the traffic is high enough that there are some remaining traffic loads which may need to be assigned on a new fiber. The ring utilization will be at a low level as in the case of a low traffic if the traffic loads are distributed among many rings. To maximize the ring utilization, a small number of rings are selected and this results in a decreased value of selected rings again (such as at point *C*). As seen from Figure 6 (a), the number of rings is repeated in this manner periodically. Moreover, the longer period at a higher value of M implies that the value of ring utilization changes more slowly when we multiplex more wavelengths into the fiber.

Here we investigate the effects of wavelength conversion. In the mesh designs, the ratio of the total network costs between the WP and VWP systems tend to increase with the number of wavelengths multiplexed in each fiber (M); this is depicted in Figure 6 (b). This highlights the importance of wavelength conversion when using a higher number of wavelengths in a fiber. This is particularly obvious in the SLB mesh technique. A reduction of 20-35% in the network cost is observed with the values of M between 4 to 8. On the other hand, in the multi-ring technique, wavelength conversion has so little influence. Since conversion is not useful for wavelength allocation in a single ring network as described in [8], no cost savings will be accomplished.



(a) (b)

Fig. 6. (a) Relationship between number of selected rings and traffic volume

(b) Difference between WP and VWP systems

4.2 Execution Time Requirement of the ILP Technique

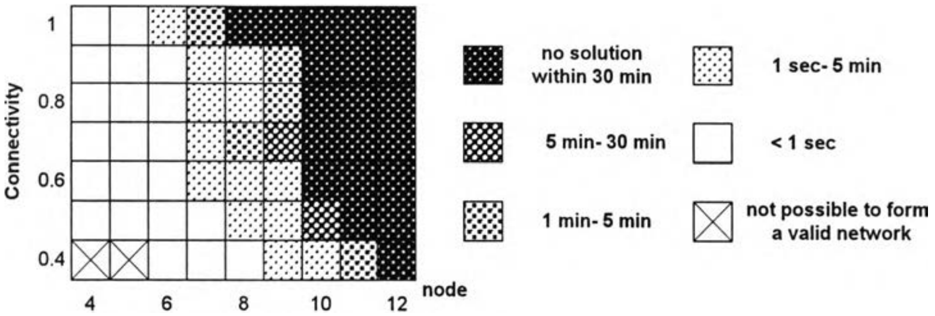


Fig. 7. The computational time for the ILP technique

A chart of the computational time requirement of the ILP technique of the MC approach is summarized in Figure 7. The execution results here are selected from test samples and the traffic patterns are uniform. Experimental network topologies are presented in term of the number of nodes and the physical network connectivity. The network connectivity is defined as the ratio of the number of links of testing networks to a full-connected network of the same number of nodes [9]. Based on these results, the execution time is longer as the connectivity or the number of nodes increases (corresponding to the large problem formulation). Therefore, the ILP technique is not practical when the network is greater. For example, the solution cannot be found within 30 minutes when the number of nodes is more than 10.

5 Conclusions

Strategies for designing WDM transport network against the single link failure based on the multi-ring and mesh designs have been discussed. In the mesh network, from the concept of MC scheme, integer linear programming (ILP) and heuristic algorithms are used to evaluate the protection cost. The complexity of ILP, however, depends on the network size, and the result is used as a lower bound of protection cost. The comparison between MC and SLB costs shows that the improvement due to the former is marginal. It is clear that the SLB scheme is sufficient for finding the minimal cost. In the multi-ring design, a heuristic algorithm is proposed. It was found that the protection cost of the multi-ring design is higher than that of the mesh design. However, in the case when full protection cost of multi-ring is not required, there are substantial benefits.

Based on our simulation, it is found that the number of wavelengths multiplexing into a fiber (M) plays a major role on the network protection cost in both mesh and ring design. Wavelength conversion affects the protection cost in the mesh design especially with a high value of M. In multi-ring design, It does not significantly reduce the protection cost.

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ประวัติผู้เขียนวิทยานิพนธ์

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