LETTER

Effects of Optical Layer Protection Granularity in Survivable Hierarchical Optical Path Network

Yoshiyuki YAMADA[†a)], *Student Member*, **Hiroshi HASEGAWA**[†], *Senior Member*, *and* **Ken-ichi SATO**[†], *Fellow*

SUMMARY This study compares the performances of waveband protection and wavelength path protection in survivable hierarchical optical path networks. Network costs and the number of switching operations necessary are evaluated for different ratios of protected demand. Numerical results demonstrate that waveband protection can drastically decrease the number of switching operations in the case of failure, while both waveband and wavelength path protection effectively reduce the network resources needed compared to single layer optical path networks.
key words: *hierarchical optical path network, waveband, survivability, protection*

1. Introduction

The development of cost-effective and robust optical networks is urgently needed to support the continual rise in Internet traffic. New bandwidth intensive services such as high-/ultrahigh- definition TV and e-Science will trigger an explosion in traffic in the near future. The envisaged traffic growth will cause a significant increase in the number of wavelength paths needed, which requires large scale optical cross-connect switches and the complexity of network control operations will be substantial if optical paths are switched at the wavelength path level, that is, only a single layer optical path network is utilized [1]. One important and promising approach to mitigate this difficulty is the introduction of the higher-order optical path, the waveband path (a bundle of wavelength paths), and the hierarchical optical cross-connect (HOXC) [1]–[3]. It has been demonstrated that the hierarchical optical path network with waveband routing can greatly reduce the total number of optical switch ports needed, and thus, offset the expected OXC cost explosion [1]. An ultra-compact waveband cross-connect switch module has been developed recently and its transmission performance was verified [3]. The impact of introducing wavebands, however, strongly depends on the network design algorithm adopted. In order to make the best use of coarse granular routing, we must optimize routing and waveband/wavelength assignment for a given set of path connection requests. This is computationally more intensive than the corresponding problem in the single layer optical path network, which is known to be an NP complete task [4]. An efficient heuristic hierarchical network design algorithm has been developed recently [5]. It has been proven to significantly reduce network costs by efficiently aggregating traffic demands whose source/destination nodes are closely located.

Another important issue is network survivability. To provide the hierarchical optical path network with the resilience needed, two protection granularity levels in the optical layer are identified. One is waveband protection; it switches a working waveband path to its backup waveband path in the case of failure. The other is wavelength path protection in which the switching operation is done at the wavelength path layer. The former minimizes protection processing overhead while the latter can reduce the network resources needed for protection. Some studies have examined the design of survivable hierarchical optical path networks [6]–[8]. [6] considered the non-hierarchical node architecture, which results in limited grooming capability and thus reduced network flexibility. As seen from the present SDH/SONET or OTN networks, the hierarchical architecture is a natural approach for simple network operation. Another study [7] handled both waveband protection and wavelength path protection, however, clear distinctions are not given, despite the differences in each protection characteristic that stems from the granularity difference. In [8], the authors employed a three layer architecture including fiber cross-connect (FXC), which may be useful for implementing automated fiber distribution mechanism at a node. The usage and purpose is very different from those of optical path (wavelength path and waveband path) cross-connect. FXCs are rarely utilized since the requirement of dynamic fiber configuration rearrangement does not exist. This study hence assumes a two layer HOXC and utilizes two protection granularities with clear distinction. We have recently developed a heuristic design algorithm for each protection scheme. Both algorithms efficiently solve the routing and waveband/wavelength assignment problem. They offer about 5–40% cost reductions over the simple End-to-End waveband scheme, which establishes waveband paths that directly connect source and destination nodes of wavelength path demands. They also attain 40% cost reduction compared to the single layer optical path network with wavelength path protection for 7×7 regular mesh networks [9], [10].

In a practical situation, however, it will be necessary to optimize the survivability level in the optical layer to suit various services. For example, for some IP-oriented services, protection/restoration with label switched path (LSP)

Manuscript received February 9, 2012.
Manuscript revised May 20, 2012.
[†]The authors are with the Department of Electrical Engineering and Computer Science, Nagoya University, Nagoya-shi, 464-8603 Japan.
a) E-mail: yo_yamad@echo.nuee.nagoya-u.ac.jp
DOI: 10.1587/transcom.E95.B.2959

fast rerouting will provide sufficient survivability; optical layer protection will not be needed. Thus, it will be necessary to develop network design algorithms that can accommodate protected and non-protected optical paths irrespective of the wavelength path or waveband path protection scheme used. The network design algorithms need to support different ratios of protected demand in the optical layer. This paper, is the first to analyze the effectiveness of survivable hierarchical optical path networks employing waveband protection or wavelength path protection to satisfy various protection requirements. First, we present network design algorithms to support each protection granularity with arbitrary protection ratios. We then compare and discuss the performance of each protection scheme in terms of network costs and the number of switching operations needed through numerical evaluations. In this paper, the effect of two protection schemes is evaluated since they are quite different especially in terms of switching operation.

2. Design of Partially Protected Hierarchical Optical Path Networks with Different Protection Granularity

This paper assumes the hierarchical optical switch architecture, which consists of the wavelength cross-connect (WXC) and the waveband cross-connect (WBXC) as discussed in [1], [3]. Costly wavelength/waveband converters are not utilized since link utilization can be well improved by developing an efficient algorithm [5]. The characteristics of the two protection mechanisms in the hierarchical optical path network are summarized below.

(A) Waveband protection: This mechanism establishes pairs of primary and backup waveband paths that satisfy the node and link disjoint constraint. Switching is conducted in the waveband layer and processed at WBXC (see Fig. 1). This mechanism minimizes the number of required switching operations and signaling-related overheads because the recovery process involves coarse granularity switching. Another advantage is that the design problem is relatively simple. Please refer to [9] for more details.

(B) Wavelength path protection: Each pair of primary and backup wavelength paths satisfies the node and link disjoint constraint. Recovery switching is performed in the wavelength path layer, that is, wavelength granularity. This scheme reduces network resource requirements more than the waveband protection scheme since the finer switching granularity offers improved waveband utilization efficiency [10]. Figure 2 depicts the process of wavelength path protection at the destination node.

It should be noted that waveband protection automatically reserves backup resources in the optical layer for the wavelength paths accommodated within the protected waveband path. With the waveband protection scheme, therefore, in order to provide for the coexistence of protected and non-protected wavelength paths, two types of waveband paths need to be established; protected and non-protected wavebands. The wavelength path protection scheme, on the other hand, supports protected and non-protected services without distinction between protected and non-protected wavebands. In other words, both primary wavelength paths and

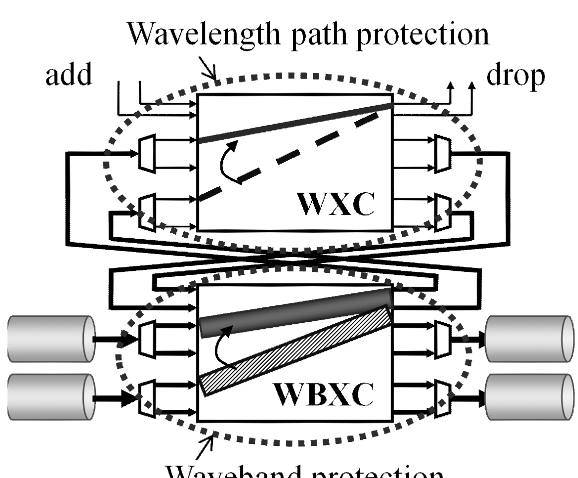

Fig. 1 Protection granularity in hierarchical optical path network.

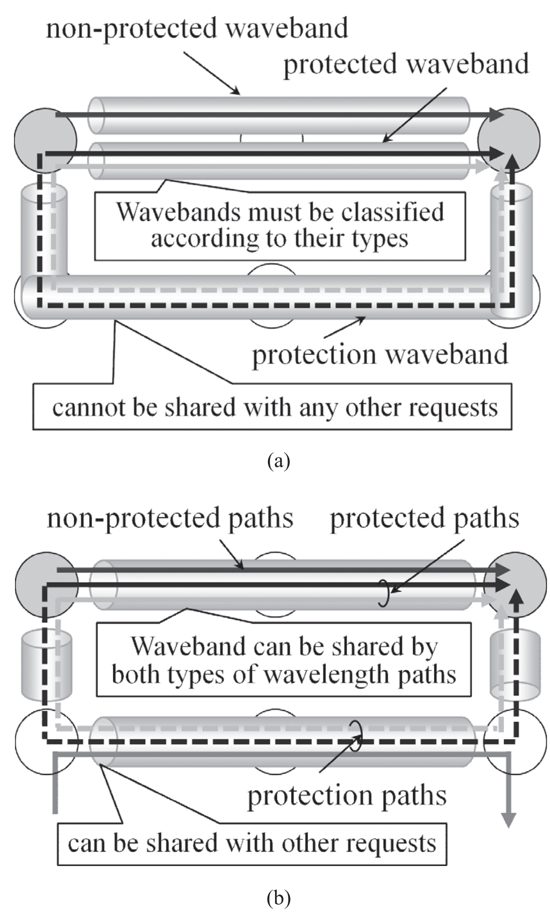

Fig. 2 Differences in the two protection schemes. (a) waveband protection, (b) wavelength path protection.

backup wavelength paths can be accommodated in the same waveband path as long as each primary wavelength path and its corresponding wavelength path do not violate the node and link disjoint constraint. This property enhances the utilization efficiencies of wavebands and fiber when the two types of optical path requests are intermingled.

No network design algorithm that supports partially protected demands has been developed so far. In order to design the partially protected hierarchical optical path network, we propose a new algorithm. The developed algorithm extends three existing efficient algorithms, which are the algorithm for waveband protection [9], the one for the wavelength path protection [10] and the one for non-protected networks [5]. These existing algorithms are known to construct cost effective hierarchical optical path networks. However, they support only the fully protected case or the entirely non-protected case. These algorithms apply the same basic idea of grooming wavelength path demands having closely located source/destination nodes into the same waveband set. The strategy of these algorithms is derived from the general objective of hierarchical optical path network design, which requires the simultaneous achievement of maximizing waveband routing and hence enhance cut-through WXC operation while improving the utilization of each waveband path. However, the network design algorithm that allows partially protected demand is not a straightforward extension since each design algorithm utilizes a different protection scheme or does not consider protection. Our newly developed algorithms, which can accommodate variable protection ratios, realize the desired network by provisioning the protected demands and the non-protected demands in that order.

The developed algorithms are composed of two stages. Only the key points are given here because of the space limitation. For a given set of wavelength path demands that need protection, the algorithm first constructs a protected sub-network for waveband protection or wavelength path protection, because the problem for designing protected network involves stronger constraints than the non-protected demand case. For waveband protection, the developed algorithm employs the concept of the waveband chain [9], which is the concatenation of loops made by a pair of working and backup waveband paths. The algorithm tries to connect two areas with large traffic demands by setting long waveband paths, which contributes to reducing network costs. The wavelength path protection algorithm uses the concept of the source-destination Cartesian product space to aggregate closely located wavelength path demands and to enhance the sharing rate of network resources among working wavelength paths and backup ones [10]. The second stage builds a non-protected network by applying the Cartesian product space based algorithm [5] over the protected sub-network just created. The second stage tries to utilize the spare capacity of both types of waveband paths generated by the first stage as much as possible, i.e. working waveband paths and backup ones, which leads to higher fiber utilization and network cost reduction.

In this paper, we consider static network design where a set of connection requests is given in advance. Hence, the fairness, including delay or the number of hops, among protected or non-protected demands is mostly retained, since necessary resources (fibers) are added to establish the paths demanded. However, for a small number of connection requests, there is a possibility of assigning a detoured route due to the property of the algorithm. In other words, not all paths are assigned to shortest routes. Please note that, since this situation will arise both in the first stage for protected demand and in the second stage for non-protected demand, fairness is balanced to a certain degree between the two classes of demands.

3. Simulation Results

The simulation parameters used in this paper are summarized as follows. An $N \times N$ (N=5, 7) regular mesh network without wavelength conversion is used. Traffic demands are uniformly and randomly distributed, and represented as the average number of wavelength paths between each node pair. Each fiber can accommodate 64 wavelengths, or 8 wavebands, i.e. each waveband accommodates 8 wavelengths. Further details will be specified in the following subsection.

3.1 Cost Evaluation under Variable Protection Ratio

The network cost variations are evaluated in terms of the ratio of traffic demands that require protection. Both waveband protection and wavelength path protection are tested. The network cost was calculated as the average of 20 trials with different random traffic distributions for each traffic volume; we applied a linear cost function of the number of cross-connect switch ports and that of fibers and so on (for detail, see [5], [9]). The obtained network costs are normalized by those of single layer optical path networks designed by an algorithm using Suurballe's algorithm to find the shortest disjoint pair of primary and backup paths and Dijkstra's algorithm to find the shortest path [11].

Figure 3 shows the obtained cost ratios for 5×5 regular mesh networks. The horizontal axis represents the ratios of traffic demands that require protection, and Demand represents the average number of wavelength path demands between each node pair. When the average demand is larger than 4, the hierarchical network is more cost effective than the single layer network for all protection values. When the demand equals 8, both schemes offer about 20–30% reduction in cost compared to the single layer network. The cost of waveband protection and that of wavelength path protection become almost the same as average traffic demand increases. Figure 4 also shows the results for 7×7 regular mesh networks. The hierarchical optical path network is superior to the single layer network for all protection values if the average wavelength path demand is larger than 2. Both protection schemes achieve 30–40% reduction in cost compared to the single layer network when the average demand

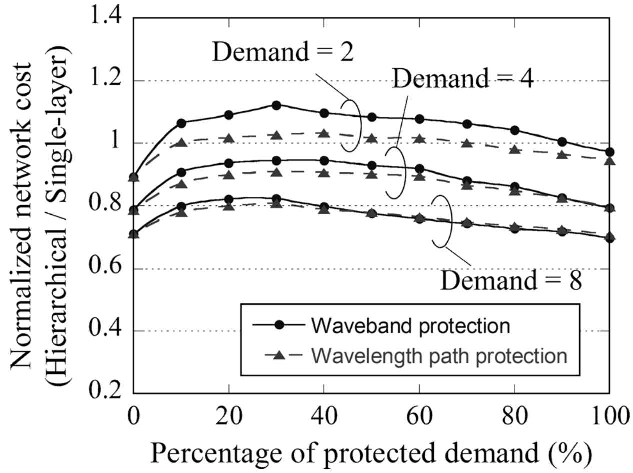

Fig. 3 Normalized network cost for 5 × 5 mesh network.

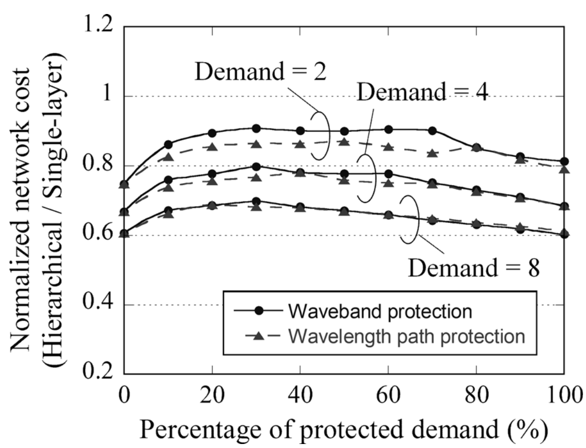

Fig. 4 Normalized network cost for 7×7 mesh network.

is 8. Similar to Fig. 3, both schemes offer almost the same cost at high traffic demand.

3.2 Evaluation of the Number of Switching Paths against Single Link Failure

Figures 5 and 6 compare the number of switching operations of primary paths (wavelength/waveband path) to the backup paths assuming single link failure protection for the 5 × 5 and 7 × 7 regular mesh networks, respectively. In this experiment, the percentage of protected demand is 100%, and we assumed a random single link failure in the network where all fibers on the failed link are cut. Consequently, all the paths accommodated are torn down between the nodes bordering the failure. In Figs. 5 and 6, the maximum and minimum number of rerouted paths (wavelength/ waveband path) obtained through 20 different failures are shown by the vertical bars. The average rerouted path number for each path demand is also indicated. The observed number of rerouted paths varies greatly since the failed link is randomly selected; the number of optical paths on a link near

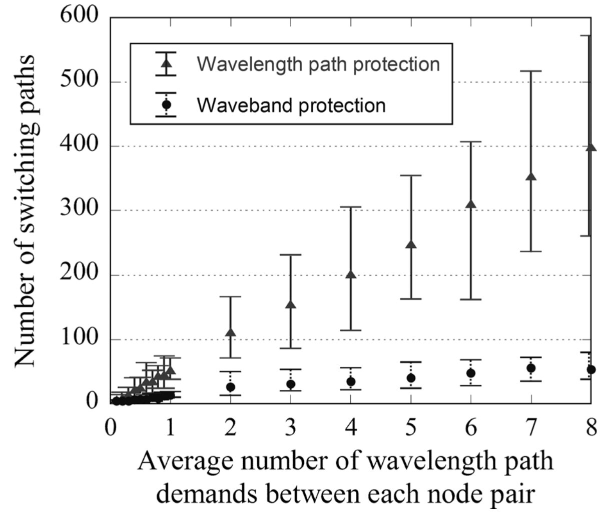

Fig. 5 Number of switching paths for 5 × 5 mesh network.

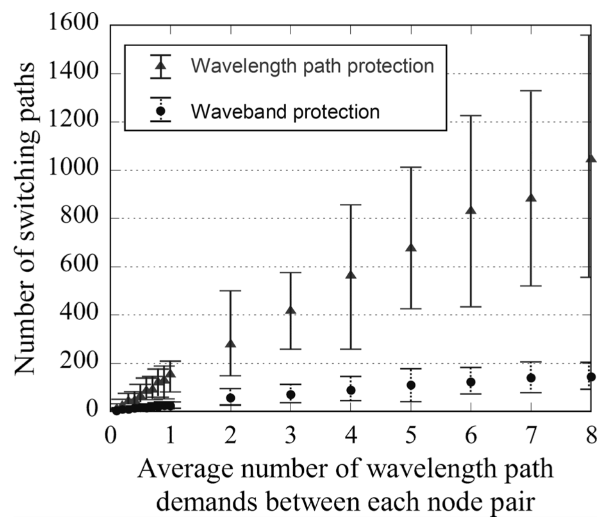

Fig. 6 Number of switching paths for 7 × 7 mesh network.

the central part of the network is much larger than those at the edges of the network. Regarding the relation between the results of Figs. 5, 6 and protected demand ratio, we can estimate the number of switching operations demanded by a failure for each demand ratio from the results of Figs. 5 and 6. For example, when the average traffic demand is 4 and the percentage of protected demand is 50%, the number of paths to be protected corresponds to that when demand is 2 and the protection ratio is 100%; this means that the number of switching operations against the single link failure is almost identical for the two situations.

It is proved that the waveband protection scheme drastically reduces the number of rerouted entities (wavelength path or waveband path), and so the switching operations needed for recovery are reduced accordingly. As shown in Figs. 5 and 6, the number of switching paths for waveband path protection in the case of failure can be reduced from that for wavelength path protection, roughly divided by the waveband capacity, if waveband protection is used; here, the waveband capacity stands for the number of wavelength paths in a waveband path. The ratio of the number of waveband paths to that of wavelength paths to be restored roughly equals the inverse of the waveband bandwidth. Considering these results, and the cost comparisons presented in Sect. 3.1, the waveband protection scheme is more attractive when traffic demands are more than about 4.

4. Conclusion

This paper demonstrated the effectiveness of hierarchical optical path networks with variable waveband protection and wavelength path protection ratios. We newly developed network design algorithms applicable to any protected demand ratio. It was shown that both protection schemes achieve 30–40% reduction in cost compared to the single optical path network regardless of the protection ratio. The major difference between these protection types was also elucidated by evaluating the number of rerouting operations needed for single link failure recovery. It was confirmed that waveband protection can greatly reduce the number of rerouting operations. These numerical results demonstrate, for the first time, that waveband protection is useful for all traffic volumes at which the hierarchical optical path network is more cost effective than the single layer optical path network.

Acknowledgments

This work was partly supported by NEDO Green IT project and JSPS KAKENHI (226957).

References

[1] K. Sato and H. Hasegawa, “Prospects and challenges of Multi-layer optical networks,” IEICE Trans. Commun., vol.E90-B, no.8, pp.1890–1902, Aug. 2007.

[2] X. Cao, V. Anand, and C. Qiao, “Framework for waveband switching in multigranular optical networks: Part I — Multigranular cross-connect architectures,” OSA J. Opt. Netw., vol.5, no.12, pp.1043–1055, Dec. 2006.

[3] K. Ishii, H. Hasegawa, K. Sato, M. Okuno, S. Kamei, and H. Takahashi, “An ultra-compact waveband cross-connect switch module to create cost-effective multi-degree reconfigurable optical node,” Proc. ECOC, 4.2.2, Sept. 2009.

[4] I. Chlamtac, A. Ganz, and G. Karmi, “Lightpath communications: An approach to high-bandwidth optical WAN’s,” IEEE Trans. Commun., vol.40, no.7, pp.1171–1182, July 1992.

[5] I. Yagyu, H. Hasegawa, and K. Sato, “An efficient hierarchical optical path network design algorithm based on a traffic demand expression in a Cartesian product space,” IEEE J. Sel. Areas Commun., vol.26, no.6, pp.22–31, Aug. 2008.

[6] S. Verma and J.P. Jue, “Protection in multigranular waveband networks,” OSA Journal of Optical Netw., vol.5, no.11, pp.790–806, Nov. 2006.

[7] M. Li and B. Ramamurthy, “Survivable waveband switching in WDM mesh networks under dedicated path-protection,” Proc. IEEE Globecom, vol.4, pp.1874–1878, Dec. 2005.

[8] Y. Wang and X. Cao, “Multi-Granular waveband assignment and protection in WDM networks,” J. Lightwave Technol., vol.28, no.13, pp.2004–2013, July 2010.

[9] Y. Yamada, H. Hasegawa, and K. Sato, “Hierarchical optical path network design algorithm considering waveband protection,” J. Lightwave Technol., vol.27, no.24, pp.5736–5748, Dec. 2009.

[10] Y. Yamada, H. Hasegawa, and K. Sato, “Survivable hierarchical optical path networks employing waveband and wavelength path protection,” Proc. OFC/NFOEC, Paper OWY3, March 2009.

[11] R. Bhandari, Survivable Networks, Kluwer, 1999, (ISBN 0-7923-8381-8).