Spectral efficiency maximization of grouped routing optical networks with shared protection

Tomohiro Ishikawa, Yojiro Mori, Hiroshi Hasegawa, and Ken-ichi Sato

Abstract— **Reliable coarse granular routing optical network architectures that maximize fiber frequency utilization efficiency are presented. The architectures combine coarse granular routing and fine granular add/drop operation, where optical paths are carried by virtual optical pipes. Higher efficiency than conventional fine granular routing networks is achieved by dense path packing in the frequency domain. We propose two architectures that apply shared protection with different levels of granularity, and develop static network design algorithms for the two different shared protection schemes. The design algorithms neutralize the impairment caused by adjacent path dropping in the frequency domain. Numerical experiments verify that the necessary number of fibers in a network can be reduced by up to 20% due the improved spectral utilization efficiency.**

Index Terms—**Networks; assignment and routing algorithms; network survivability; shared protection.**

I. Introduction

The continuous increase in Internet traffic is spurring the introduction of photonic networks that employ Optical Cross-Connects/Rearrangeable Optical Add-Drop Multiplexers (OXCs/ROADMs). The recently standardized Flexgrid [1] substantially enhances optical fiber capacity by adopting fine frequency slot granularity [2, 3]. As a result, improved frequency utilization efficiency, transmission-distance-dependent modulation format adoption, and optimized broader capacity channel accommodation including 400Gbps have been introduced [4, 5]. To take advantage of enhanced fiber capacity with path elasticity and modulation format optimization, minimizing the transmission impairment caused by optical filtering at nodes is critical. Due to recent inter-datacenter traffic expansion and the growth of local traffic concentrations, such as that between clients and content cache servers, photonic network technologies are being applied to not only core networks but also metro networks. Thus the number of OXC/ROADM nodes that utilize Wavelength Selective Switches (WSSs) will increase.

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The traffic growth rate is so high that it exceeds the rate of fiber capacity enhancement. The number of fibers on each link must be increased while the degree of commercially available WSSs is limited to around 20+, which necessitates cascading WSSs to realize the very high port count WSSs needed. Due to the broadening of transparent transmission areas and the necessity of WSS cascading, the number of WSSs traversed will substantially increase. However, optical signals passing through many WSSs are degraded, called the spectrum narrowing effect, because of the non-ideal filter shape of WSSs. This limits the reach of transparent transmission. Thus mitigating this impairment will be critical in future optical networks. Spectrum narrowing can be mitigated by broadening the frequency gaps between optical channels or setting broad guard bands. However, such broad frequency spacing deteriorates the fiber frequency utilization efficiency. There is always a tradeoff between the achievable fiber capacity and the spatial scalability of networks. Several recent studies have tried to reduce the impairment caused by spectrum narrowing [6-8].

An efficient optical path network architecture that combines coarse granular routing and fine granular add/drop operations was first proposed in [9, 10]. The architecture, named the grouped routing network, routes optical paths at the optical path group level named the Grouped Routing Entity (GRE) pipe. A recent study has verified that grouped routing can achieve higher spectrum utilization efficiency as it suppresses the spectrum narrowing effect and allows frequency gaps between paths within a GRE pipe to be reduced [11]. This is made possible by concatenating the channel passbands to form a GRE, which is possible with conventional LCOS (liquid crystal on silicon)-based flexgrid WSSs.

Another key attribute to creating the network infrastructure demanded by the information society is survivability against failure including fiber cuts [12, 13]. The survivability of grouped optical-path routing networks was initially studied in [14, 15], where dedicated protection schemes at the GRE granularity level [14] and the path granularity level [15] are respectively proposed. Coarser granularity protection can simplify the switching operations against failure while finer granularity protection can improve the frequency utilization efficiency. Both studies find networks that satisfy some given impairment bound by restricting the number of add/drop operations of paths adjacent in the frequency domain, as such operations are the dominant cause of spectrum narrowing. However, considering the expected future traffic growth, we need to improve the spectral efficiency further. The introduction of shared protection can be an effective solution at the cost of more complicated impairment bounding, which necessitates evaluation of the worst impairment for all assumed failures.

In this paper, we propose a reliable grouped routing network architecture that maximizes fiber frequency utilization efficiency with two different types of shared protections; GRE pipe granularity shared protection and path granularity shared protection. As mentioned above, the introduction of shared backup path imposes new challenges on impairment management. To resolve the difficulty, the proposed pipewise granular shared protection scheme defines a chain-like structure of working and backup pipe pairs, where the number of joints in a chain limits the maximum number of drop operations. The chain-like structure also enables pipe granularity switching to backups. On the other hand, the other proposal, the pathwise granular shared protection scheme, offers a two-step design procedure to resolve the impairment bounding while efficiently sharing spectrum resources for backup paths. For each scheme, a network design algorithm that takes advantage of the scheme's characteristic is proposed. Numerical experiments show that a substantial spectral utilization efficiency improvement can be achieved with the introduction of the proposed architecture. Furthermore, we compare the performance given by different granular shared-protected grouped routing networks to clarify the advantages/disadvantages of each scheme relative to the other. Preliminary and restricted studies were shown at an international conference [16, 17], however, detailed investigations, including the dependency to the key parameter for grouped routing networks, GRE capacity, and the adaptability to different traffic distributions and topologies, were left to this paper. The following provides full details and a comparison clarifies the unique characteristics of each scheme.

II. Grouped Routing Networks That Enable Impairment Mitigation

Grouped Routing was initially proposed and investigated for conventional fixed grid optical networks in [9, 10]. In these studies, optical paths in a fiber are divided into several groups called Grouped Routing Entities (GREs, see Figs. 1 and 2). Routing at each node is done at the GRE granularity level while add/drop operations are done at the path granularity level. This routing scheme defines virtual pipes named GRE pipes that bridge nodes along the GRE. Unlike conventional hierarchical optical path networks [18-22], optical paths can be added/dropped at any intermediate node along the route of a GRE pipe (Fig. 3). A GRE pipe has no path functions such as termination as defined in ITU-T Rec. G.783 [23] for digital paths. Indeed, it may form a closed loop as seen in Fig. 3, which differentiates GRE pipes from waveband paths in conventional hierarchical optical path networks. The grouped routing is also different from the "super-channel", which is a bundle of sub-carriers, none of which can be independently terminated or routed at different nodes along the route.

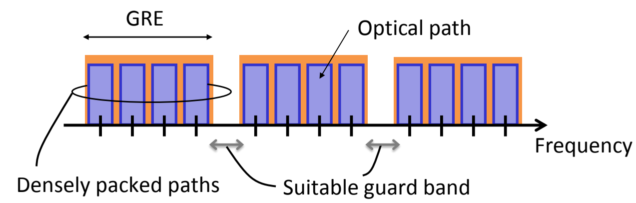


Fig. 1. Grouped routing entity (GRE).

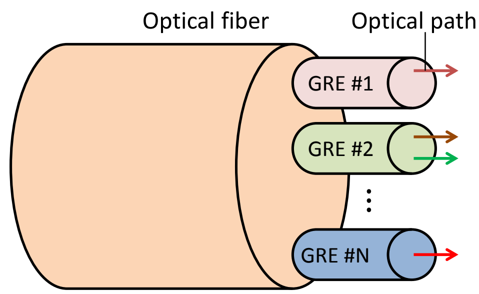


Fig. 2. Relationship among optical fibers, GRE and optical paths.

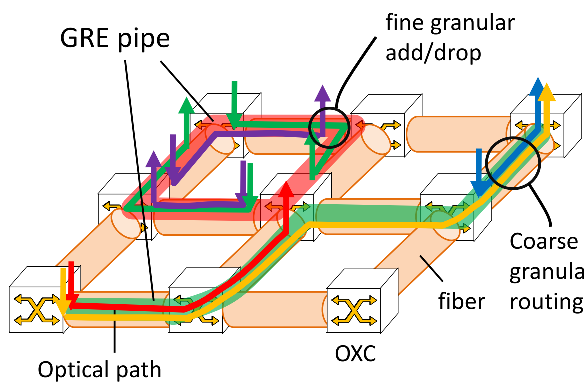


Fig. 3. Grouped routing networks.

For conventional flexgrid networks without grouped routing, using broad channel spacings, i.e. large guard bands, can mitigate the impairment. To guarantee the necessary pass-band bandwidth for a channel after traversing several nodes(WSSs), the total frequency band occupied by guard bands in a fiber will be broad, which degrades frequency utilization efficiency. For instance, if the guard band bandwidth is Δg and the number of optical channels is W, then all the guard-bands in a fiber occupy $\Delta g(W-1)$, which can be a substantial portion of fiber resources. Assuming we have 80 paths in a fiber and adjacent paths are separated by 12.5GHz guard-bands, the total guard band occupies $12.5\times(80-1)\cong 1$[THz]. In order to reduce the total fiber resources occupied by guard bands, it has been proposed to adopt grouped routing [11]. Here the filter shape at a WSS is set to cover each GRE and guard-bands are only inserted between adjacent GREs. This concatenated channel pass-band is possible with the conventional LCOS-based WSSs with frequency slot granularity (6.25GHz for ITU-T G.694.1). GRE bandwidth does not need to be uniform and can even be variable; however, we assume that the bandwidth is fixed and uniform throughout this paper just for simplicity. Spectrum narrowing can be also caused by the dropping of adjacent paths within the same GRE pipe (Fig. 4). However, if the number of adjacent drop operations for each path is carefully managed and bounded, the spectrum narrowing effect will be kept to an acceptable level. Throughout this paper, we assume that F_{max} represents the acceptable number of spectrum narrowing operations. A network design algorithm that considers this restriction has been developed and substantial fiber utilization efficiency improvements have been verified (≅30%) [11].

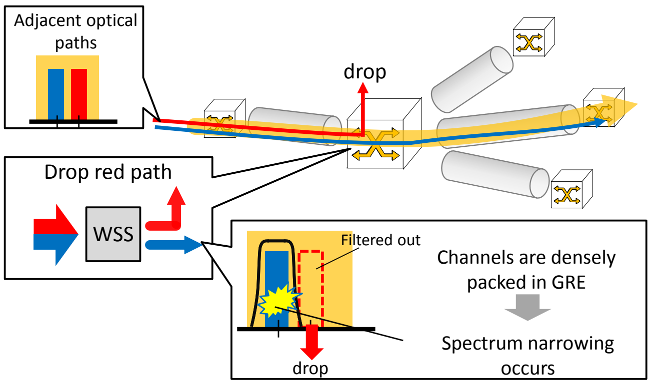


Fig. 4. Spectrum narrowing caused in Grouped Routing.

Several important attributes of grouped routing networks have been elucidated so far. The high frequency utilization efficiency is also kept in the periodic network expansion scenarios [24] and the dynamic path control cases [25,26]. GRE pipes are regarded as virtually defined fibers in a network, and therefore, signaling and optical switch control overheads can be reduced especially the dynamic path control cases. For example, assume that an optical path is established in an existing GRE pipe. No switch operation is necessary at all intermediate nodes.

III. Resiliency for Grouped Routing Optical Networks

In grouped routing optical networks, shared protection can be implemented at two granularities: pipe and path. The pros and cons of the corresponding schemes are summarized in Table I. GRE-pipe-level shared protection, i.e., Shared Risk Link Group (SRLG)-disjoint backup, a GRE pipe is provisioned for each working GRE pipe, as shown in Fig. 5. Backup GRE pipes can share their frequency resources as long as the corresponding working pipes do not traverse any common links. Each pair of working and backup paths is then accommodated into their respective GRE pipe. To enhance pipe utilization efficiency, a chain-like structure of working and backup pipe pairs (as shown in Fig. 6) was proposed, which contributes to not only enhancing GRE pipe utilization but also simplifying the impairment control needed to offset adjacent path dropping. The other is optical-path-level shared protection; each working path is routed by using its own GRE pipe while its corresponding backup path is routed by using a separate Shared Risk Grouped (SRG)-disjoint GRE pipe, as shown in Fig. 7. Optical-path-level protection attains more efficient use of GRE pipe capacity, because both working and backup optical paths can be carried by the same GRE pipe along the route of pipe. However, it is complex to resolve the tradeoff between the backup capacity sharing and the mitigation of spectrum narrowing by adjacent drops.

In the following, we show the characteristic of GRE-pipe granularity and optical-path granularity shared protected grouped routing networks with regard to the management of spectrum narrowing and backup path sharing.

TABLE I
Characteristic of Two Shared Protection Schemes in Grouped Routing Optical Networks

Routing architecture	**Conventional**	**Grouped Routing**	
Shared protection granularity	*Path*	*Pipe (with chain-like structure)*	*Path*
Pros/Cons	• No signaling/ switching cost reduction	• Reduced signaling/ switching cost • Lower GRE pipe capacity utilization • Dense channel accommodation into GRE pipe: Easy	• No signaling/ switching cost reduction • Higher GRE pipe capacity utilization • Dense channel accommodation into GRE pipe: Hard

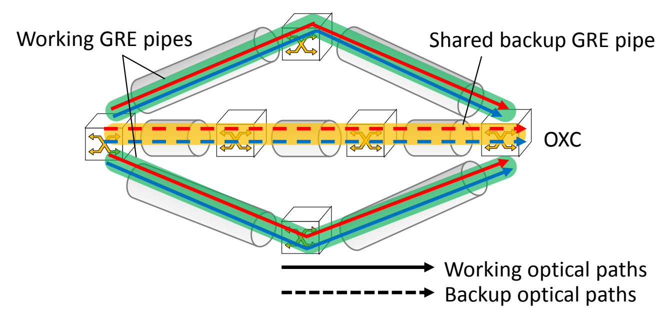


Fig. 5. An example of GRE-pipe-level shared protection.

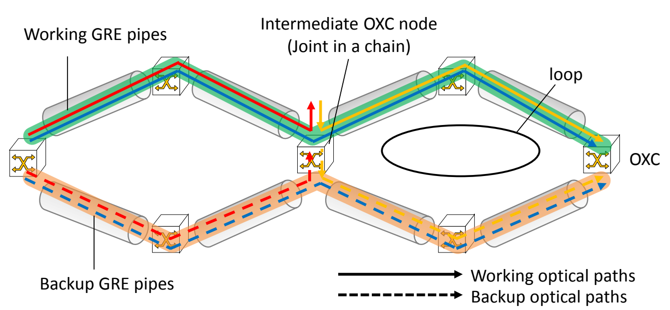


Fig. 6. A chain-like structure of working and backup GRE pipe pairs.

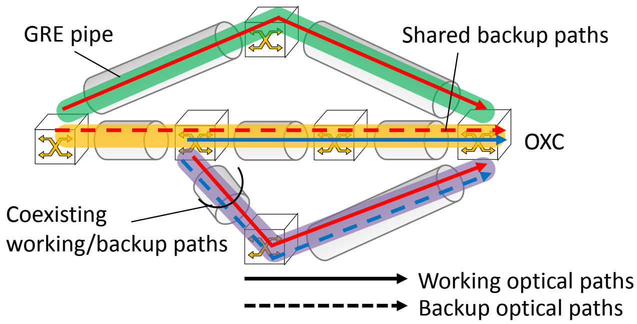


Fig. 7. An example of optical-path-level shared protection.

A. *GRE Pipe Granularity Shared Protected Grouped Routing Optical Networks*

Path drop operations are only done at intermediate nodes shared by the working and backup GRE pipe pair. Moreover, the same paths are added/dropped to/from both pipes. Therefore, the impairment levels with adjacent path dropping in both pipes are the same and they are represented by the number of loops in each chain as shown in Fig. 8. To bound the number of adjacent drop operations for all paths to F_{max}, a sufficient condition is that no pair of GRE pipes should have more loops than F_{max} + 1. This characteristic greatly simplifies the design of impairment-aware protected grouped routing optical path networks.

GRE pipe level shared protection also imposes another restriction as shown in Fig. 9. If we design backup pipe sharing for each section between a pair of adjacent edge/intermediate nodes, the necessary resiliency cannot be guaranteed for paths traversing several loops. Therefore, backup pipe sharing must be designed considering the entire GRE pipe configuration.

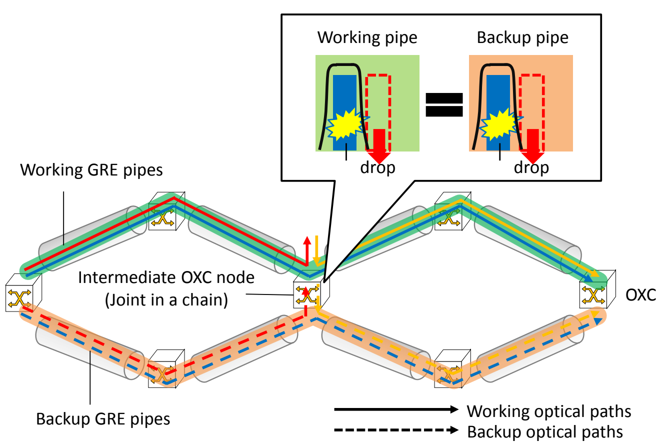


Fig. 8. Drop operations in chain-like structure of working and backup GRE pipe pairs.

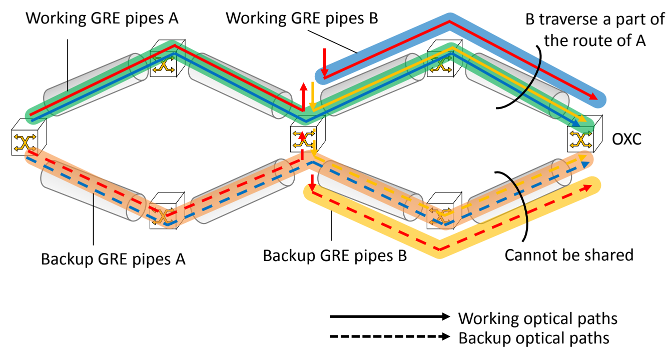


Fig. 9. Restriction imposed by GRE-pipe level shared protection.

B. *Optical Path Granularity Shared Protected Grouped Routing Optical Networks*

Figure 10 illustrates how working and backup paths are routed in grouped routing networks that adopt path-granularity shared protection. Paths can be carried by a GRE pipe pair only if both of these pipes traverse the source and destination nodes of these paths. Moreover, for backup paths that share frequency resources on certain links, the corresponding working paths must be SRLG independent. Therefore, we need to carefully design the GRE pipe set considering the distribution of source and destination nodes of all paths.

Another difficulty lies in managing the impairment caused by spectrum narrowing, especially for shared backup paths. In Fig. 11(a), there is no spectrum narrowing for the blue working path, since no adjacent path is dropped within the GRE pipe. Once the green backup path is activated which is adjacent to the blue working path in the frequency domain, as shown in Fig. 11(b), the blue working path suffers from spectrum narrowing at the destination node of the green backup path. As explained in Sec. II, densely packing paths into GREs requires bounding the number of filter narrowing events by F_{max}. Therefore, we must evaluate and bound the maximum possible number of spectrum narrowing events with consideration of failures.

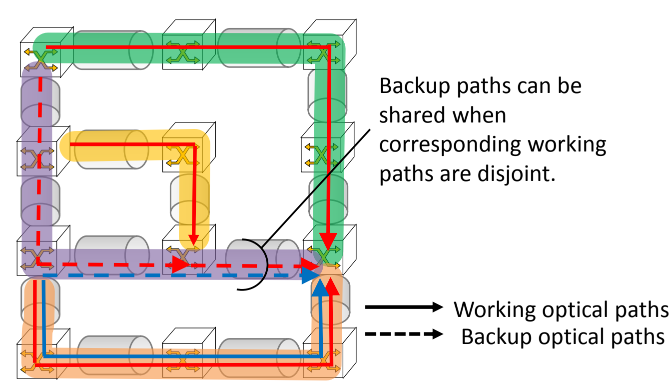


Fig. 10. Shared protection at optical path level in grouped routing networks.

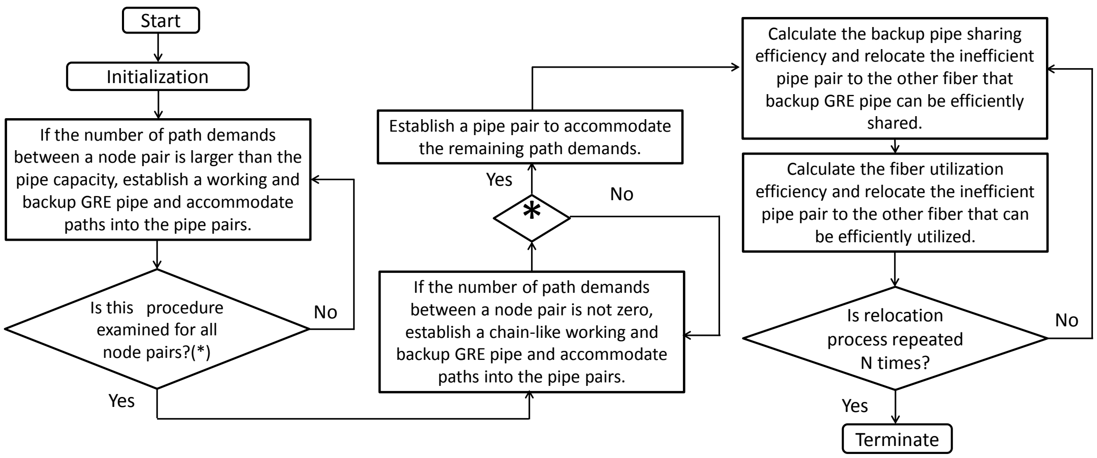
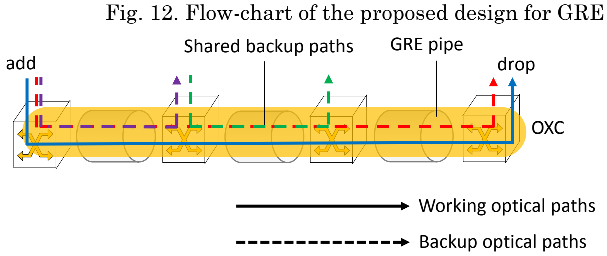
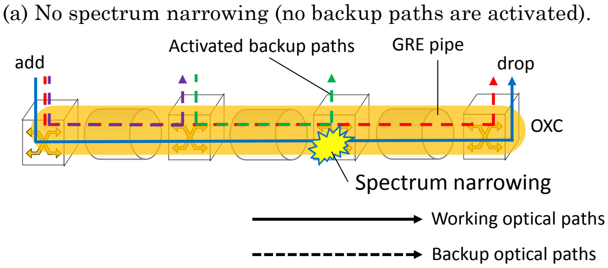


Fig. 12. Flow-chart of the proposed design for GRE pipewise granular shared protected grouped routing networks.



(a) No spectrum narrowing (no backup paths are activated).



(b) After green backup path is activated.

Fig. 11. Spectrum narrowing in shared-path-protected grouped routing optical networks.

IV. Design Algorithms for Grouped Routing Optical Networks That Employ Shared Protection

The design problem of shared protected grouped routing optical networks includes GRE pipe location optimization, optical path accommodation to pipes, wavelength/frequency assignment to paths/pipes, impairment management, and maximizing capacity sharing between backup GRE pipes. To resolve this computationally hard task, we introduce two simple sequential heuristic based network design algorithms for the different granular shared protection schemes. Summaries of the two algorithms are shown in this section and their details are given in the Appendix.

A. *Design Algorithm for GRE Pipewise Granular Shared Protected Grouped Routing Optical Networks*

The first algorithm is for the design of grouped routing networks with pipe granularity shared protection. This algorithm takes advantage of the chain-like structure for impairment bounding. Indeed, the capacity sharing among several backup paths does not affect the impairment bounding; only the number of joints passed by a path characterizes the impairment condition (Fig. 8). Thus it pursues better backup GRE pipe sharing by iterative pipe relocation. The relocation procedure has two optimization metrics, one is the capacity sharing of backup paths and the other is fiber utilization, to more efficiently use the capacity of each fiber. A summary of the algorithm is shown as a flow chart in Fig. 12. For details, see Appendix A.1.

B. *Design Algorithm for Pathwise Granular Shared Protected Grouped Routing Optical Networks*

Figure 10 illustrates an example of a pathwise granularity shared protected grouped routing network. The notable difference from the pipewise granularity shared protected case is that path impairment changes according to which backup paths are activated (Fig. 11). As described in Fig. 11, impairment management while maximizing capacity sharing between backup path demands is quite hard. However, the computation complexity must be so low so that large scale networks can be designed in practical times. Therefore, the original design problem is translated into several sub-problems as shown in the flow chart in Fig. 13. In the first stage, we adopt a simple sequential heuristic-based algorithm to design initial networks without considering filter narrowing. Then, in the second stage, paths violating the given bound of the adjacent drop number, F_{max}, are relocated so as to resolve the violation. For details, see Appendix A.2.

V. Performance Evaluation by Numerical Experiments

In this section, we evaluate the performances of the proposed resilient network architectures, that is, grouped routing optical networks with coarse/fine granularity shared protection.

Four network topologies sre considered; 5x5 grid (Fig. 14(a)) which consists of 25 nodes and 40 links, the British Telecom network topology [27] (Fig. 14(b)) which consists of 27 nodes and 40 links, the Japan photonic network model [28] (Fig. 14(c)) which consists of 25 nodes and 41 links, and the Spanish national optical network topology [29] (Fig. 14(d)) which consists of 21 nodes and 35 links. No signal regeneration/wavelength conversion at intermediate nodes was assumed.

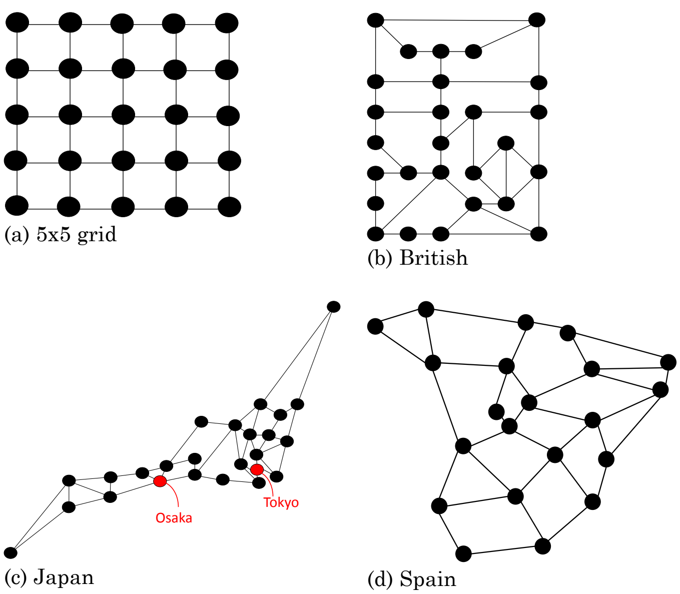


Fig. 14. Network topologies.

The available frequency range is the C-band, i.e., 4400 GHz bandwidth. We assumed a uniform capacity and all paths used the modulation format of 400 Gbps and 50 Gbaud polarization-multiplexed 16 QAM. One uniform and two non-uniform three traffic distribution patterns were considered. Each traffic demand was given by a set of path establishment requests with source and destination nodes. The first pattern, the uniform distribution, randomly assigns source and destination nodes of each path demand following a uniform distribution. The second pattern, called non-uniform distribution, makes the probability assigned to source and destination node pairs different. The probability for a node pair can be determined so that it is proportional

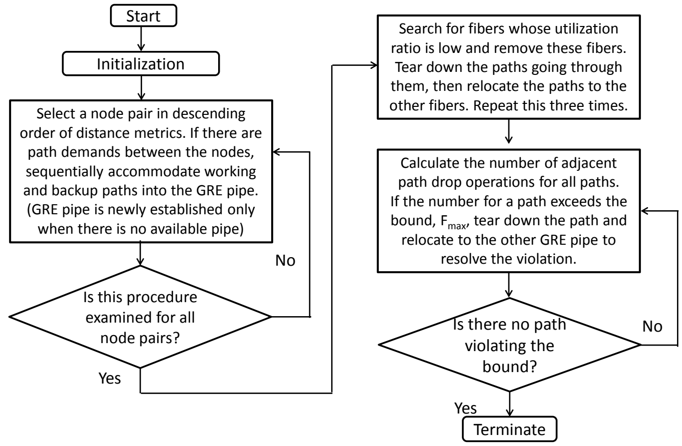


Fig. 13. Flow-chart of the proposed design of pathwise granular shared protected grouped routing networks.

to the product of populations assigned to the source and destination nodes. That is, the gravity model [30] is adopted here. We also introduce a more concentrated traffic pattern for Japan's network topology where all paths are from/to large cities, Tokyo and Osaka. This pattern also represents heavy upload/download traffic to/from datacenters. The traffic intensity was represented by the average number of paths between a node pair, which ranges from one to twenty optical paths. When assigning routes to paths, detours from the shortest hop routes, up to two hops, were allowed. Twenty trials were performed for each parameter value setting and the averaged results are shown. For benchmarking, conventional flexgrid networks with shared protection were tested by utilizing the proposed design algorithm, where each GRE pipe always carries just one optical path.

Figure 15 shows the distributions of filtering number when optical paths are individually routed, i.e., the conventional routing method, and when optical paths are routed in GREs. The comparison is done subject to the same total number of path demands. We assume that optical cross-connects adopt the route-and-select configuration [31], where one WSS is assigned to each incoming and outgoing fiber port; hence, two WSSs are traversed at each node. We also assume that add/drop is done at WSSs equipped outside the optical cross-connects. That is, no WSS filtering operation occurs at the source and destination nodes of a path. Thus, optical paths will traverse 2 x (hop – 1) WSSs (Fig. 16), where hops are the number of links traversed. For example, in the 5x5 grid, the maximum shortest hop between nodes is eight. Since up to two hop detours are allowed, the maximum number of WSSs traversed can be 2 x (8 + 2 – 1) = 18. Since the typical order of the approximated super-Gaussian optical filter of commercially available WSSs, m, is 4 [32], 87.5 GHz spacing is necessary for conventional flexgrid networks to keep the OSNR penalty to less than around 1.0 dB (see Fig. 17 [6]). On the other hand, in grouped routing networks, the number of adjacent path drop operations is bounded by F_{max} . It is shown that grouped routing can substantially reduce the number of filtering operations, and the maximum and average values. Moreover, the bound F_{max} can be specified arbitrarily to optimize the necessary spacing. If we adopt F_{max} = 3, 62.5 GHz spacing can be utilized (see Fig. 17). The number of paths in a fiber varies depending on the GRE capacity; i.e. the number of paths in a GRE. Table II shows the variation in the number of paths in a fiber subject to GRE capacity change when 62.5GHz path spacing and 25GHz guard-band between GREs are adopted. If six paths are bundled to form a GRE, 66 paths (6 paths/GRE and 11 GREs/fiber) are accommodated in a fiber for grouped routing networks, while 50 paths are possible in conventional networks; one path/GRE and 50GREs/fiber. In order to reduce the dependency of results to network design algorithms adopted, the algorithm for pathwise granular shared protected grouped routing networks in Sec. IV.B is utilized for conventional network design with the above GRE/fiber capacity configuration. Hereafter, considering the tradeoffs between the capacity enhancement yielded by coarse granular routing and the routing flexibility improvement by fine granular routing, we determine suitable configurations for each scheme in the following section. For pipewise granular shared protection, if the number of loops in a chain is no more than F_{max} + 1, then the filter narrowing can be sufficiently small for 62.5 GHz spacing. However, considering the risk of failure at the joint nodes, we limit the maximum number of loops to 2. In the following two sub-sections, we show performance evaluations for the two proposals in terms of key parameters; GRE capacity and topology/traffic distribution. The proposals are then compared in the last sub-section.

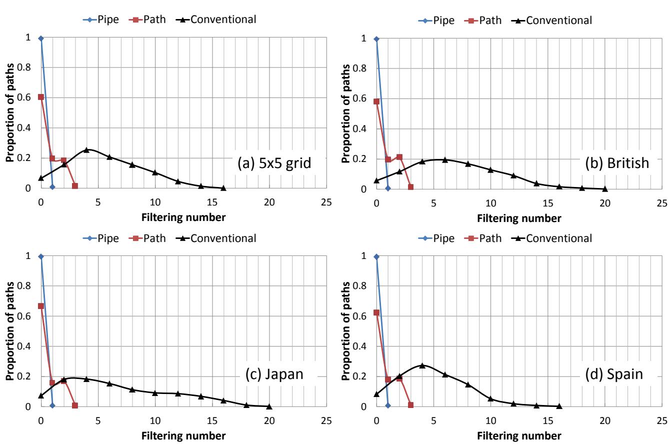


Fig. 15. Distribution of filtering number.

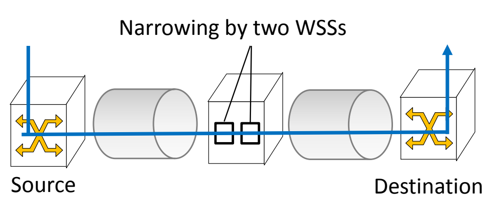


Fig. 16. Filtering operations when paths traverse cross-connects.

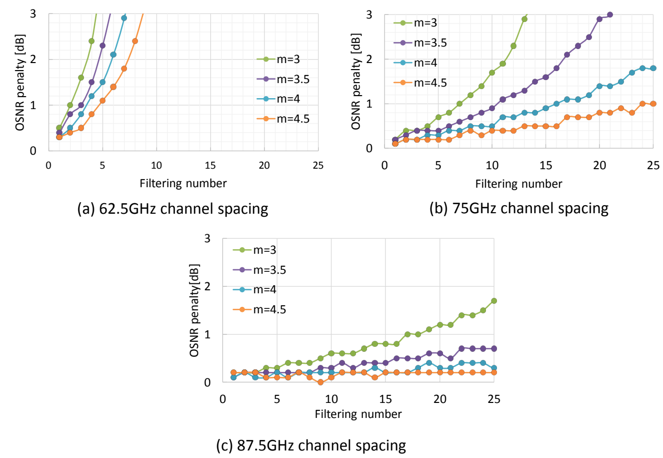


Fig. 17. Filtering penalty subject to number of filtering operations.

TABLE II
THE NUMBER OF PATHS THAT CAN BE ACCOMMODATED WHEN GRE CAPACITY IS VERIFIED

# of paths in a GRE	# of GREs in a fiber	# of paths in a fiber
1	50	50
2	29	58
3	20	60
4	16	64
5	13	65
6	11	66
17	4	68
35	2	70

A. *Evaluation of GRE Pipe-Level Shared Protection*

In this sub-section, we show the effectiveness of the proposed grouped routing optical networks with GRE pipe level shared protection relative to conventional alternative.

(1) Dependency on GRE pipe capacity

Figure 18 shows the averaged utilization ratio of GRE pipes in Japan's network topology for different GRE bandwidths. The solid line "B=1" corresponds to the conventional flexgrid networks. The coarse granular pipe gives greater fiber capacity as shown in Table II, however it suffers from lower pipe utilization. In this case, selecting broad GRE capacity (B=6) results in insufficient pipe utilization ratios, especially in small traffic areas. Accordingly, GRE pipe capacity, B, should set to a relatively small value, for example B=4, for pipe level shared protection.

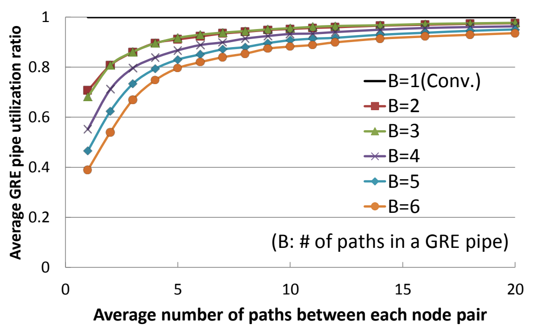


Fig. 18. Average GRE pipe utilization for each GRE capacity.

(2) Dependency on topology and traffic distribution

Figure 19 shows the variation in fiber number ratios necessary for the GRE pipe level shared protected grouped routing networks and conventional flexgrid networks for 5x5 regular mesh, Japan, Spanish, and British network topologies. As explained above, GRE pipe capacity was set to 4. Uniform and non-uniform traffic distributions were tested for all topologies; for non-uniform distributions, population dependent distributions, and Tokyo and Tokyo-Osaka centric traffic distributions were adopted for Japan's network topology. The special case of pipewise granular shared protection such that the number of loops in a chain is limited to one, i.e. no joint, is denoted as "E2E".

The relative number of fibers increases when the traffic intensity is low, due to the routing performance degradation triggered by the use of coarse granular routing. However, the proposed networks give better results if there is sufficient traffic. For all topologies, almost the same trends are observed with regard to fiber number ratio. On the other hand, there is some dependency of the performance on traffic distribution. The dependency stems from the variation in utilization efficiency of GRE pipes in concentrated/sparse traffic areas. However, the profit in areas with heavily traffic concentrations generally overwhelms the inefficiency; so the proposed networks outperform conventional alternatives over a wider traffic intensity range as the traffic becomes more concentrated. Without the chain-like structure as described in Sec III, the fiber increment is especially significant (Fig. 18(c)). This fact elucidates that the chain-like structure contributes to GRE pipe capacity utilization enhancement while limiting the impairment. The relative number of fibers needed gradually decreases as the traffic intensity rises, and finally reaches 80% of the alternatives.

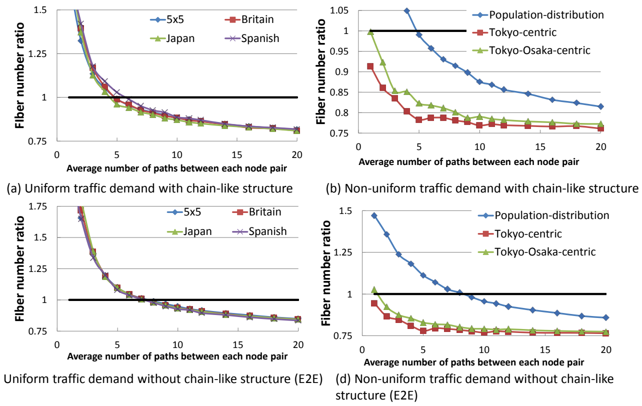


Fig. 19. Necessary fiber numbers of pipe level shared protected grouped routing network normalized by those of conventional network.

B. *Evaluation of Path-Level Shared Protection*

In this sub-section, we show the effectiveness of the proposed grouped routing optical networks employing path level shared protection. Similar to sub-section 5-1, dependencies on GRE pipe capacity, topology, and traffic distribution are verified.

(1) Dependency on GRE pipe capacity

The fiber frequency utilization of grouped routing networks is a product of the averaged utilization ratio of GRE pipes and that of fibers by GRE pipes. Thus higher pipe utilization implies better efficiency in grouped routing networks. Higher traffic intensity naturally improves the pipe utilization ratio, however we need to evaluate how much the requirement of route independence between each working and backup path pair does impact the extended improvement of pipe utilization. Figure 20 shows the averaged utilization ratio of GRE pipes in Japan's network topology for different GRE bandwidths. For path level shared protection, GRE pipe utilization can be improved since both working and backup optical paths can be carried by the same GRE pipe along the route of pipe. That is, the pipe capacity is easily assigned to paths. Moreover, broader GRE pipe capacity increases the fiber capacity (Table II). Therefore, it seems that six is suitable for GRE bandwidth.

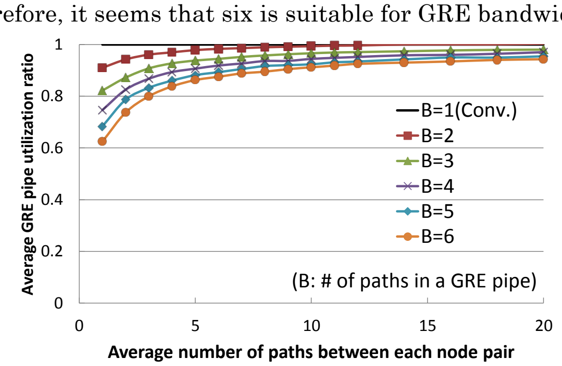


Fig. 20. Average GRE pipe utilization for each GRE capacity.

(2) Dependency on topology and traffic distribution

Figure 21 shows the variation in fiber number ratios necessary for the optical path level shared protected grouped routing networks and conventional alternatives for 5x5 regular mesh, Japan, Spanish, and British network topologies. The results are normalized with the values yielded by the conventional flexgrid networks. The relative number of fibers increases when the traffic intensity is low, similar to the case of pipe level shared protection. The necessary number of fibers gradually falls as the traffic intensity becomes large, which improves the accommodation efficiency of GRE pipes. The relative number finally reaches 80-90% of the alternatives. For path level shared protection, the network topology variation depends on the fiber number ratios. Since a GRE pipe does not branch or merge, the routing flexibility of each path is more limited than in conventional networks when physical node degrees are high. For example, in regular mesh networks, there are many route candidates between each node pair in conventional networks while the number of vacant GRE pipes connecting source and destination nodes of a path will be independent from the number of route candidates. Hence the performance gap is improved in real topologies where the number of route candidates is generally less. Similar to pipe level shared protection, concentrated traffic distributions contribute to better GRE pipe utilization and better performance.

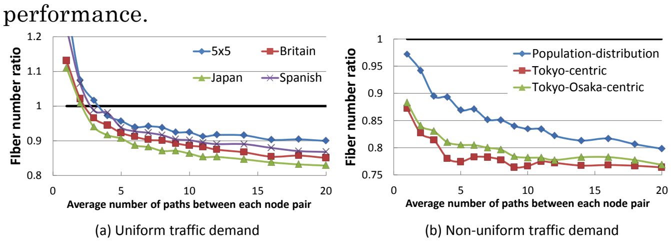


Fig. 21. Necessary fiber numbers of path level shared protected grouped routing network normalized by those of conventional network.

C. *Performance Comparison with Different Protection Granularities*

Figure 22 shows variations in normalized fiber number on the Japan's network topology given by shared protected grouped routing networks with pipewise granularity shared protection and pathwise granularity shared protection. To evaluate the difference in routing performance of each scheme, all GRE pipes had capacity of 6.

For the low traffic intensity case, both networks suffer from the routing performance degradation due to the use of coarse granular routing. However, pathwise granular protection achieves a better result. This is because it realizes more efficient GRE pipe capacity utilization. The gap between these results gradually falls as the traffic volume becomes large, which improves the accommodation efficiency of GRE pipes. Both proposed shared protected grouped routing networks outperform the conventional flexgrid networks when the traffic volume is sufficiently high. Moreover, in this area, pipe level shared protection slightly outperforms path level shared protection. It seems that relaxing the independence between working and backup pipes in the chain-like structure slightly improves the performance when traffic demand is large although the gap is not significant.

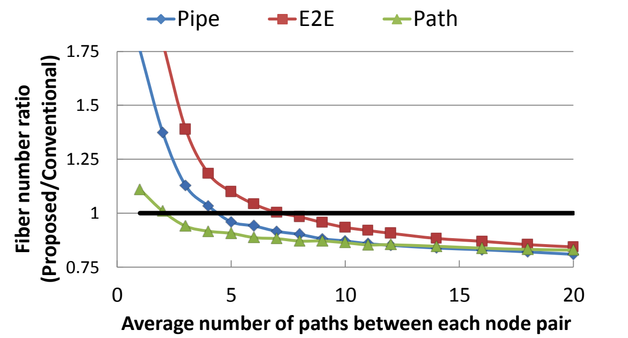


Fig. 22. Necessary fiber numbers for each proposed scheme in Japan's network topology with B=6.

In order to highlight the difference between the proposed networks, we observed two metrics; averaged fiber utilization ratio and backup path sharing efficiency where the former is the averaged proportion of paths to fiber capacity and the latter is how many backup pipes/paths share the same backup resource. The measures' variations subject to traffic intensity in Japan's network topology are shown in Figs. 23 and 24, respectively. In the case of small traffic demand, the path level shared protection scheme achieves higher fiber utilization ratios since GRE pipes can efficiently accommodate paths regardless of path status (i.e. working or backup). For the pipe level shared protection scheme, on the other hand, paths can be added/dropped to/from GRE pipes at limited nodes. This leads to low fiber utilization efficiency. As the traffic demand increases, GRE pipe and fiber utilization ratio and backup path sharing efficiency improve for both schemes. Finally, the pipe level shared protection scheme offers better backup path sharing efficiency than the path level shared protection scheme since the relaxed independence between working and backup pipes enhances backup sharing. In conclusion, both shared protection schemes for grouped routing networks are effective compared with schemes for conventional flexgrid networks when the traffic volume is sufficient.

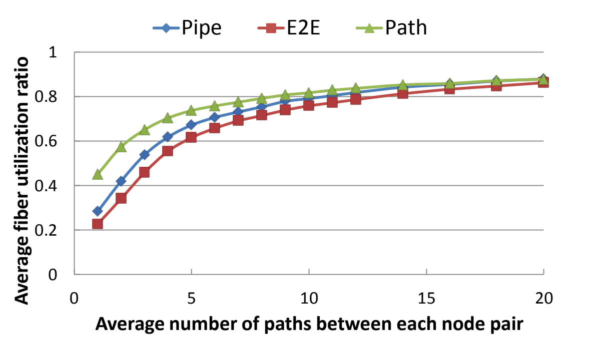


Fig. 23. Average fiber utilization ratio on Japan's network topology with B=6.

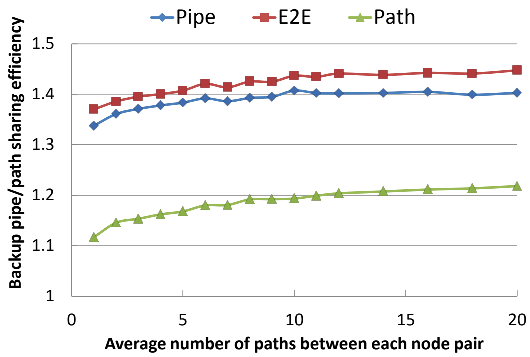


Fig. 24. Backup resource sharing efficiency on Japan's network topology with B=6 .

VI. Conclusion

We proposed a coarse granular routing optical network architecture and design algorithms that adopt two different types of shared protection schemes. The developed algorithms make it possible to manage the impairment caused by path granularity filtering operations. The result, improved spectrum resource utilization, is realized not only by dense path accommodation in the frequency domain but also by backup pipe/path capacity sharing. Numerical experiments elucidated that the necessary number of fibers can be reduced by up to 20% compared with conventional shared protected flexgrid networks.

Appendix

A-1. Design Algorithm of GRE Pipewise Granular Shared Protected Grouped Routing Optical Networks

The first algorithm is for the design of grouped routing networks with pipewise granularity shared protection. This algorithm takes advantage of the chain-like structure for impairment bounding. Thus it optimizes backup GRE pipe sharing by iterative pipe relocation. The relocation procedure has two optimization metrics, the capacity sharing of backup paths and fiber utilization, to more efficiently use the capacity of each fiber. The algorithm is as follows.

Step 1. In the descending order of given distance metrics between node pairs (ex. The minimum number of hops or total link length of routes between each node pair), select a node pair (s, d). If the number of optical path demands to be established between the node pair (s, d), say $dem(s, d)$, is larger than the GRE pipe capacity B, establish $\left\lfloor \frac{dem(s,d)}{B} \right\rfloor$ pairs of working and backup GRE pipes between corresponding node pair where $\lfloor x \rfloor$ is the maximum integer that does not exceed x. Establish $B\left\lfloor \frac{dem(s,d)}{B} \right\rfloor$ paths and accommodate into the pipes. Move to the next node pair. Repeat this procedure until the number of optical path demands that have yet to be accommodated is smaller than the pipe capacity B at any node pair.

Step 2. In the descending order of given distance metrics between node pairs, select a node pair (s, d). If the number of remaining path demands between the node pair (s, d) is not zero, establish a chain-like working and backup pipe pair between the nodes. The intermediate nodes are selected so as to maximize the averaged utilization ratio of the working and backup pipe pair. The number of intermediate nodes that are shared between working and backup pipes must be less than F_{max}. Finally, establish a pipe pair to accommodate the remaining path demands. Repeat until all node pairs are processed. So far, all path demands are accommodated using GRE pipe pairs.

Step 3. We move to the GRE pipe relocation process to improve the fiber utilization and backup pipe sharing efficiency. Fix two thresholds; acceptable pipe utilization efficiency and acceptable fiber utilization efficiency. For all working and backup pipe pairs, calculate the backup pipe sharing efficiency. A part of pipe pairs whose pipe sharing efficiencies are lower than the threshold are torn down and relocated to other fibers such that backup pipes can be more efficiently shared. For all pipe pairs, then, calculate the fiber utilization. A part of pipe pairs whose fiber utilization efficiencies are lower than the threshold are torn down and relocated to other fibers in like manner. This relocation process is repeated N times.

A-2. Design Algorithm of Pathwise Granular Shared Protected Grouped Routing Optical Networks

The second algorithm is for the design of grouped routing networks of pathwise granularity shared protection. As described in Section III, impairment management while maximizing capacity sharing between backup path demands especially difficult with path level shared protection. Another requirement is that the algorithm must be so simple as to permit verification of the impact of the proposed shared protection schemes. Therefore, the design issue is translated into several sub-problems. In the first stage, we adopt a simple sequential heuristic-based algorithm to design initial networks without considering filter narrowing. Then, in the second stage, paths violating the given bound of the adjacent drop number, F_{max}, are relocated so as to resolve the violation. The algorithm is as follows.

Step 1. Sort node pairs in the descending order of distance metrics. Select a node pair. If there are path demands between the selected node pair that are not established yet, try to accommodate the pairs of working and backup paths sequentially into existing GRE pipes. A GRE pipe is newly established only when there is no available pipe to accommodate paths, and the route of the pipe is selected so that the number of newly installed fibers to accommodate the pipe is minimized. Repeat this accommodation procedure until all node pairs are processed.

Step 2. Fix a threshold; acceptable fiber utilization efficiency. Search for fibers whose utilization ratio is lower than the threshold and remove these fibers. Tear down paths going through them, then relocate the paths in the same manner. Repeat this process three times.

Step 3. Calculate the number of adjacent drop operations for all paths. If the number for a path exceeds the bound, F_{max}, tear down the path and relocate it to another pipe to resolve the violation.

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