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PAPER

Survivable Grouped Routing Optical Networks with Dedicated Path Protection

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SUMMARY A novel resilient coarse granularity optical routing network architecture that adopts finely granular protection and finely granular add/drop is presented. The routing scheme defines optical pipes such that multiple optical paths can be carried by each pipe and can be dropped or added at any node on the route of a pipe. The routing scheme also makes it possible to enhance frequency utilization within pipes, by denser path packing in the frequency domain, as we recently verified. We develop a static network design algorithm that simultaneously realizes the independence of working and backup paths and pipe location optimization to efficiently carry these paths. The design algorithm first sequentially accommodates optical paths into the network, then tries to eliminate sparsely utilized fibers and iteratively optimizes frequency slot/wavelength assignment in each coarse granular pipe so as to limit the impairment caused by dropping the optical paths adjacent in the frequency domain. Numerical experiments elucidate that the number of fibers in a network can be reduced by up to 20% for 400Gbps channels without any modification in hardware.
key words: *grouped routing optical networks, coarse granular routing, resiliency, dedicated path protection, impairment-aware*

1. Introduction

Deployment of photonic networks that utilize ROADMs has commenced to cope with the continuous Internet traffic increase (+30-40%/year). If the growth continues for fifteen years, the volume will become 100 times its current value. Such rapid growth motivates fiber capacity maximization and the wide deployment of photonic network technologies. To attain higher spectrum utilization, recently standardized flex-grid optical path networks [1] assign frequency bandwidth and center frequency to paths at much finer granularities than conventional fixed grid networks [2], [3]. Channel frequency bandwidths are multiples of 12.5 GHz and the center frequencies are aligned on a 6.25 GHz spaced grid while typical conventional fixed grid DWDM networks use coarser channel spacing and bandwidth, i.e., 50/100 GHz. This not only minimizes the frequency gap between paths, but also permits the efficient implementation of next generation 400 Gbps/1Tbps channel capacities [4]–[6], whose bandwidth requirements cannot be effectively realized by the channel spacing typical of conventional fixed grid networks.

The wide deployment of photonic network technologies results in transparent transmission in not only core networks but also metro networks. Benefits include longer distance transparent transmission over several networks yielding broader bandwidth and better energy efficiency. The number of nodes in metro networks connected to a core network will be generally much more than that in the core network. Therefore, for optical paths traversing several networks, the impairment caused by traversing nodes becomes a critical factor. In such a case, a key impairment stems from filter narrowing at the wavelength selective switches (WSSs) in the nodes. As the number of nodes traversed by a path increases, then the impact is accumulated and exceeds a limit. The mitigation of filter narrowing can be attained by broadening the frequency gap between paths, or setting guard bands. However, broader guard bands lower the fiber frequency utilization. Several studies have attempted to ease the impairment caused by filter narrowing [7]–[9].

The efficient optical path network architecture named Grouped routing network exploits coarse granular routing while add/drop operations are performed at the path granularity level [10], [11]. Routing is done at the level of bundles of optical paths named Grouped Routing Entities (GREs). A GRE can be used as a coarse granular optical pipe, or GRE pipe. A GRE pipe bridges nodes on its route to carry optical paths between those nodes. Wavelength paths can be added/dropped to/from a GRE pipe at any node traversed. Thus a GRE pipe can accommodate wavelength paths having different sources and destinations. Indeed, it was shown that a Grouped routing network can carry almost the same traffic volume as the corresponding conventional network with the same fiber set [10], [11]. Moreover, the introduction of grouped routing to fixed grid networks allows us to utilize compact routing devices named waveband multiplexer/de-multiplexers [12], [13] or waveband selective switches (WBSSs) [14], [15], which are realized as planar lightwave circuits on silica chips. Recently, another study on the application of grouped routing to elastic optical path networks has been presented [7]. It revealed that the spectrum utilization efficiency can be improved by mitigating the impairment caused by WSSs [7]. This mitigation is realized by concatenating the WSS passbands so as to exactly cover a GRE. This concatenation is possible with present LCOS (liquid crystal on silicon) based flexgrid WSSs, so no hardware development is necessary.

Network resiliency is the crucial requirement of the social infrastructure based on ICT technology. Typical frameworks for resiliency are dedicated/shared protection and restoration, and the efficient introduction of such frame-

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works has been extensively studied [15]–[22]. We were the first to achieve the resiliency of Grouped routing optical networks with our dedicated protection scheme that accommodates each working and backup optical path pair in a pair of working and backup GRE pipes that bridge the source and destination nodes of the optical path pair [23]. This architecture simplifies switching operation/signaling upon failure, since only the affected working GRE pipes need be switched to their backup GRE pipes. No path granularity switching to backups is required. Unfortunately, each GRE pipe pair can carry only optical paths whose source and destination nodes coincide with those of the pipe, which degrades the advantage of Grouped routing networks (optical paths can be added/dropped to/from a GRE pipe at any node on the route of the pipe). By allowing GRE pipe pairs to share their intermediate nodes, which allows the accommodation of more paths, the fiber utilization ratio was improved. However, the fiber number increase demanded by the routing restriction was still an issue.

In this paper, we discuss how resiliency in Grouped routing optical networks can be attained cost effectively, namely, with minimal fiber number. The objective is achieved by introducing path granular dedicated protection to Grouped routing optical networks; GRE pipes are efficiently filled by applying the proposed sequential path accommodation and pipe establishment algorithm. With this formulation, we can resolve the routing performance inefficiency caused by the coarse granular routing and the restriction that a pair of working/backup GRE pipes can only carry paths between nodes that are commonly traversed by these pipes. We propose a design algorithm based on sequential path pair accommodation that is aware of switching granularity, which is followed by frequency slot re-assignment sensitive to the impairment condition. Numerical experiments show that the necessary fiber number is reduced by 20% for networks that utilize next-generation 400 Gbps paths while resiliency is still guaranteed.

While a preliminary version of this paper has been presented at an international conference [24], this paper further clarifies the difference from GRE pipe granular protection and the dependency on key parameters including network size and GRE pipe capacity, i.e. the number of paths in a GRE.

2. Preliminaries

2.1 Grouped Routing Optical Networks

Grouped routing networks adopt coarse granular routing where the available frequency band (ex. C-band) is divided into several ranges and optical paths in each range are bundled and routed together (see Fig. 1). The division does not need to be uniform, however range uniformity is assumed throughout this paper for simplicity. Unlike the hierarchical optical path networks, optical path granular add/drop operations are applied on the GRE pipe (see Fig. 2). Pipe termination is not necessary for adding/dropping paths carried by the pipe. Indeed, a GRE pipe can form a loop. Thus a GRE pipe is not a path defined by ITU-T Rec. G.783. Since a GRE pipe can carry any wavelength paths within the GRE pipe connecting nodes on a route of the pipe. The flexibility in add/drop operations allows us to accommodate optical paths having different source and destination nodes, so GRE pipes with high accommodation ratios can be achieved if we can develop efficient network design/control algorithms.

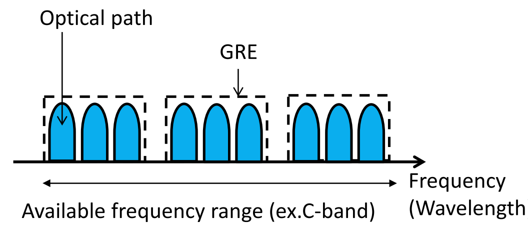


Fig. 1 Grouped Routing Entity (GRE).

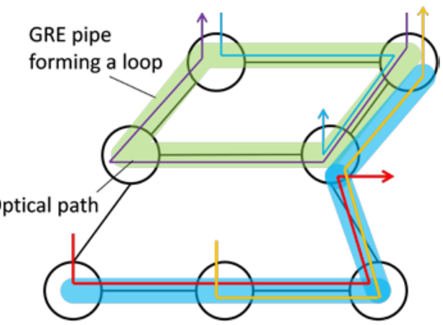


Fig. 2 Grouped Routing Entity pipe (GRE pipe).

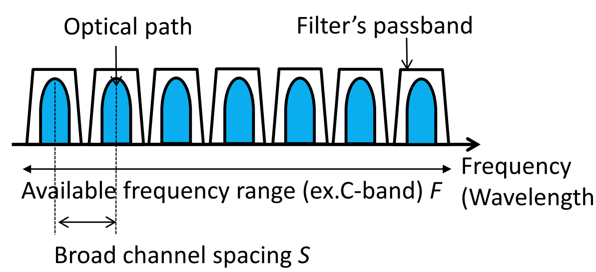


Fig. 3 Sparse path accommodation in conventional networks.

A GRE pipe is routed using bandpass filtering to pick up the pipe and then switching it to the desired output port. The filter shape should, ideally, be a rectangle that exactly covers the frequency range. However, such an ideal filter cannot be realized, and signal deterioration, especially at the edges of the passband, is inevitable. The problem is filter narrowing, which can be critical when multiple nodes are traversed. To avoid the impairment caused by filtering, conventional networks insert guard bands between adjacent paths, which results in ineffective utilization of frequency resources (Fig. 3). On the contrary, in grouped routing optical networks, guard bands are inserted between only each pair of adjacent frequency ranges while optical paths in a frequency range are densely packed with no broad guard bands (Fig. 4).

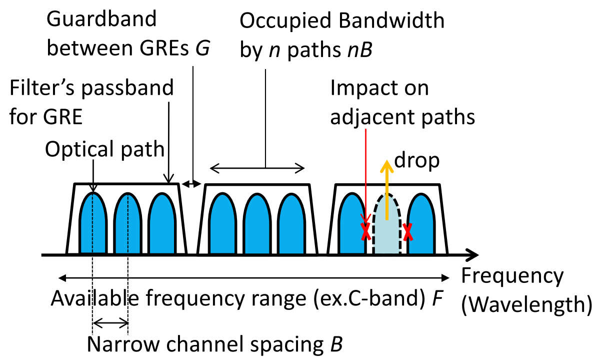


Fig. 4 Dense path accommodations in Grouped routing optical networks.

Suppose that conventional networks locate all optical paths on a uniformly spaced grid. The spacing, S, includes the bandwidth of an optical path and its guardbands. The maximum number of paths accommodated into the available frequency band (ex. C-band) F will be $\lfloor F/S \rfloor$ where $\lfloor \cdot \rfloor$ is a flooring operator yielding the nearest integer. On the other hand, for grouped routing networks which bundle n paths densely into a pipe, let the spacing of optical paths within a pipe be B, which includes the bandwidth occupied by an optical path and its narrow guardbands, and let the wide guard band between GREs be G. These three parameters will satisfy $S \leq B + G$. The maximum number of optical paths that can be accommodated in a fiber is $n\lfloor (F + G)/(nB + G) \rfloor$. The number of guardbands between pipes is almost proportional to $1/n$, and hence, the total guardband bandwidth is substantially reduced even for small n.

The possible values of S, B, G depend on the transmission characteristic. Smaller values are desirable; however they degrade the robustness against impairment. For example, in [7], fifty 400 Gbps (polarization-multiplexed 16QAM) paths, each of which occupies S = 87.5 GHz, can be accommodated within the C-band (F = 4400 GHz) in conventional networks. In a GR network, on the other hand, where each path occupies B = 87.5 GHz and letting n = 6, 66 paths (6 paths/GRE, 11 GREs/fiber) can be accommodated in the C-band. Ignoring the routing performance hit due to the coarse granular routing, the fiber capacity increases by 32%. Other examples of GRE configurations are: (# of paths/GRE, # of GREs/fiber) = (2, 29), (3, 20), (4, 16), (5, 13), and so on. We can verify that fiber capacity is enhanced in all cases.

Due to the dense packing in a GRE pipe, dropping an optical path from the pipe will affect the adjacent paths by filter narrowing (Fig. 4). However, if the number of drop operations of adjacent optical paths is bounded, the impact of filter narrowing will be limited. Indeed, we have already proven that the bounding limits the impairment to an acceptable level [7].

2.2 Survivability in Grouped Routing Networks

Survivability in Grouped routing networks was first investigated in our previous study [23], which also proposed two

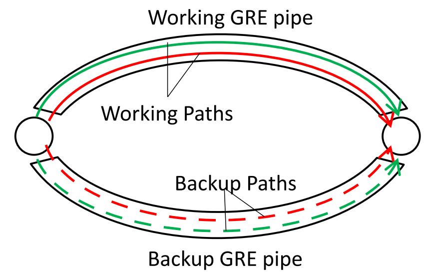


Fig. 5 An example of dedicated protection in GRE granularity.

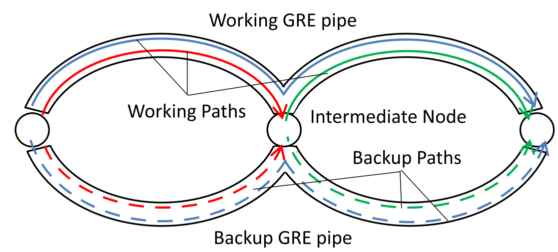


Fig. 6 A pair of working and backup GRE pipes sharing an intermediate node [23].

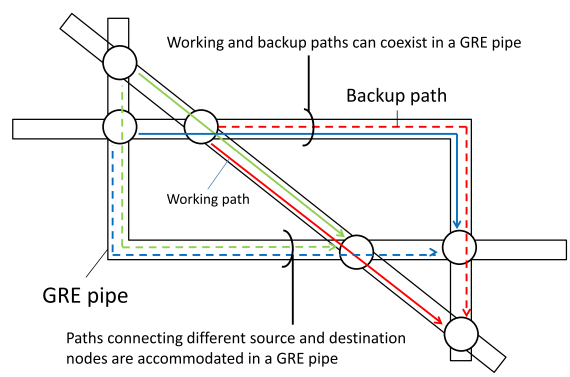


Fig. 7 Dedicated protection at the wavelength-path granularity level.

dedicated protection schemes. One scheme adopts GRE granular protection while the other adopts optical path level protection. The GRE level protection scheme utilizes pairs of GRE pipes; a working GRE pipe that carries only working paths and a backup GRE pipe that carries corresponding backup paths (Fig. 5). The optical path level protection scheme allows each GRE pipe to carry both working and backup optical paths (Fig. 7).

The difficulty of GRE level protection is that each pair of working/backup GRE pipes can carry only optical paths connecting nodes that are traversed by both pipes. This requirement destroys one advantage of grouped routing (optical paths can be added and dropped at any node on the route of a pipe), and it results in poor GRE pipe utilization. To improve the utilization, we propose to define pairs of pipes, each of which has three or more common nodes, are combine pairs to chains (see Fig. 6). This relaxation allows optical paths to be accommodated that connect two of these common nodes.

However, node disjointness is reduced. In addition, the fiber number increase caused by the poor utilization of GRE pipes should be minimized. GRE pipe granular shared protection, i.e. capacity sharing of backup pipes whose working pipes do not overlap, can be another way to improve GRE pipe utilization [25]. Moreover, pipe/path joint restoration could be another way to achieve survivability; however they are out of scope of this paper and could be discussed elsewhere.

Optical path level protection potentially improves GRE pipe utilization but path level switching to backups are necessary. Emphasizing the value of better GRE pipe utilization efficiency, this paper investigates the optical path level protection scheme. In Fig. 7, GRE pipes cross at some nodes in a network. Optical paths connecting two nodes such that a pair of link and node disjoint GRE pipes goes through them can be carried by the GRE pipe pair. The notable difference from GRE level protection is that a GRE pipe can be counted as a member of several GRE pipe pairs. Thus optical paths can be added/dropped to/from a GRE pipe at more nodes on the route, which is preferable for grouped routing. In the rest of this paper, we will show a design algorithm for grouped routing optical networks with optical path level protection and numerically evaluate its effectiveness.

3. Design of Grouped Routing Optical Networks with Fine Granular Dedicated Protection

We focus on the so-called static network design problem; i.e. minimizing the number of fibers in a network for given set of path demands. No wavelength conversion is assumed and each optical path is carried by a GRE pipe that goes through source and destination nodes of the path. Considering the high computation cost imposed by the fundamental intractability of routing and frequency slot assignment and the additional constraints placed on path accommodation into pipes and the independence between working and backup paths, we adopt a heuristic algorithm based on a sequential path accommodation strategy that is similar to the two-step approach [21]. The strategy allows us to easily handle the routing constraint such that all express paths in the same GRE pipe must be routed to the same output port.

Suppose that there is a request to establish a path from node s to node d on route r. Weighting function $w(s,d,r)$ approximates the amount of network resources necessary for establishing the path. The assignment of wavelengths in fixed grid networks or frequency slot sets in flexgrid networks is done so as to minimize that newly reserved network resource for the path, i.e. (s,d,r). There can be several metrics for resource evaluation, however, here we let $w(s,d,r)$ be a weighted sum of a number of hops h, that of newly established fibers f, and that of fibers on which GREs are newly reserved g; $w(s,d,r) = \alpha h + \beta f + \gamma g$. The weighting values α, β, γ will be determined so that they satisfy $\beta > \max\{\alpha, \gamma\}$, since fiber increment must be avoided as much as possible. The design algorithm is summarized below.

⟨Design Algorithm of Resilient Grouped Routing Optical Networks That Adopt Path Granular Dedicated Protection⟩

Step 0. Fix two thresholds; κ $(0 < \kappa < 1)$ and a positive integer μ where the former represents the acceptable utilization ratio of fibers and the latter an upper bound for adjacent drop operations for a path.

Step 1. For each node pair (s,d), find a set of route candidates $R(s,d)$ from s to d by the k-shortest route algorithm. For each route candidate $r_c \in R(s,d)$, remove all links and intermediate nodes of r_c from the given topology. Find the shortest route $\bar{r}_c$ on the residual topology by Dijkstra's algorithm. If found, let $(r_c, \bar{r}_c)$ be a route pair candidate. Let the set of all route pair candidates found for (s,d) be $P(s,d)$. Sort all route pair candidates in $P(s,d)$ in the ascending order of distance metric (total hop counts or length).

Step 2. In the descending order of distance metrics between source and destination node pairs, sequentially accommodates path establishment requests between a node pair. For each path accommodation, calculate $w(s,d,r_w) + w(s,d,r_b)$, where s and d are source and destination nodes and $(r_w, r_b) \in P(s,d)$ is a route candidate pair. Select a route pair minimizing $w(s,d,r_w) + w(s,d,r_b)$ and establish a pair of working and backup paths there. Install new fiber whenever necessary for path establishment.

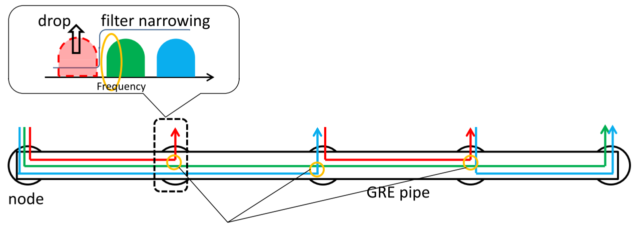
Step 3. Search for fibers whose utilization ratios are lower than κ. Remove these fibers and tear down paths going through them. Re-accommodate torn down paths according to the procedure in Step 2.

Step 4. Assign frequency slot index/wavelength index to each path in first-fit manner.

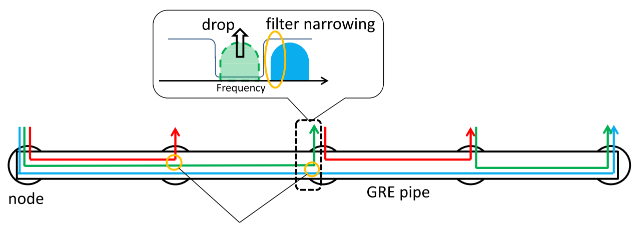
Step 5. Calculate the number of adjacent drop operations for all paths. If the number for a path exceeds bound, pick up the set of all paths, say $S(p)$, in the GRE pipe carrying the offending path p. For all pairs of slot index sets/wavelengths accommodating some paths in $S(p)$, calculate the maximum number of adjacent drop operations for these paths by assuming the selected slot index sets/wavelengths are adjacent. Interchange the slot indexes/wavelengths assigned to the offending path with the other, randomly selected, slot indexes/wavelengths whose calculated maximum number of adjacent drop operations satisfies the bound for the offending path (See Fig. 8 which shows the case where the maximum number of adjacent drops is reduced from 3 to 1 by interchanging blue and green wavelength assignment). Repeat this procedure until all paths violating the bound are processed or the number of operations reaches a given limit.

Remark

1. In Step 1, the shortest route $\bar{r}_c$ may not exist on the residual topology [26]. However, the aim of Step 1 is to find a sufficient number of route pair candidates between each node pair. Thus the number of route



(a) An assignment with up to three times adjacent drop operations.



(b) An assignment with up to once adjacent drop operation.

Fig. 8 Re-assignment of frequency slot sets/wavelengths to satisfy the limitation on adjacent drop operations.

candidates in $R(s, d)$ will be large enough and, as a result, the set of route pair candidates $P(s, d)$ cannot be empty in general. Another approach is to apply a technique to find a disjoint route pair, ex. Suurballe's algorithm, however it can only provide just one route pair candidate.

2. In Step 5, the slot index/wavelength interchange operation may fail to resolve the violation of the adjacent drop bound. Indeed, an exact evaluation of the number of adjacent drop operations for a path requires drop operations in the two adjacent frequency slot indexes/wavelengths (See Fig. 8). In other words, a triple of adjacent frequency slot index sets/wavelengths is necessary just to evaluate the center frequency slot index set/wavelength. However, the number of such triples is much larger than that of pairs, especially when the number of slot indexes/wavelengths in a GRE is large. Thus a reasonable way is to simply check the maximum adjacent drop operations for each pair of frequency slot index sets/wavelengths and apply interchange operations by using the result. However, this simplified scheme may fail to resolve the violation even if there is a feasible assignment. In the numerical experiments, we adopt this simplified scheme. Moreover, the sequential re-assignment in Step.5 is too simple as it checks only limited combinations, and hence, it will be another reason for failing to find an appropriate frequency slot index/wavelength assignment even though it exists. Another approach is to re-accommodate all paths into the GRE pipe considering the bound and add new GRE pipes as necessary which can easily resolve all violations. However, as we show in numerical experiments, the probability of the violation not being resolved is quite limited (~0.1%). Here, to keep the discussion simple, we assume the above interchange is successful and so avoid more complex re-accommodation operations.
3. All the route pair candidates are calculated in Step 1, and the result is memorized and referred to in Step 2. As a result, the processing time for Step 2 is dominant in the proposed algorithm. The processing time for Step 2 is proportional to the number of paths to be established and the number of route pair candidates, which will substantially increase with network size. Indeed, each simulation on a 5×5 regular mesh network finishes within several minutes while that on a 7×7 network takes several tens of minutes.

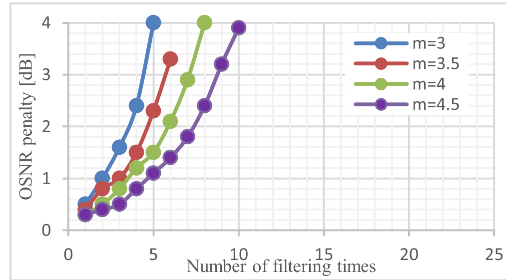
4. Numerical Experiments

In this section, the performance of the proposed resilient GRE network architecture is tested through experiments on several topologies. Throughout this section we adopt the following configurations. Available frequency range is C-band; i.e. 4400 GHz bandwidth. Random uniform traffic distribution is assumed. Traffic intensity in a network is denoted by the average number of optical paths to be established between each node pair. When assigning routes to paths, detours from the shortest hop routes, up to 2 hops, are allowed. The acceptable fiber utilization ratio is set at 0.1. Ten trials were performed for each parameter value setting and the averaged results are shown. For benchmarking, conventional flexgrid networks with dedicated protection were designed by utilizing the proposed design algorithm where each GRE pipe always carries just one optical path.

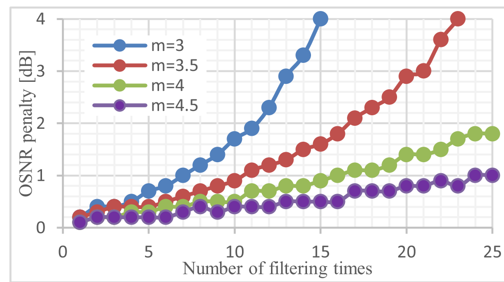
The benchmarking metric adopted is the number of fibers installed in the network. Note that the comparison of proposed grouped routing and conventional is done for the same path establishment demands, which needs exactly the same number of transponders. On the other hand, the number of costly wavelength selective switches is proportional to the fiber number and no specific hardware is necessary for the grouped routing scheme; only modification of the switching operation of WSSs is needed. In addition, if the link length is uniform, then requested fiber length and the number of amplifiers on a link will be almost proportional to the number of fibers.

When the frequency bandwidth assigned to a path is 62.5 GHz/75 GHz/87.5 GHz, the number of paths in a fiber will be 70/58/50, respectively, for conventional flexgrid networks that do not adopt grouped routing. If six paths are bundled as a GRE and 25 GHz guard band is used to isolate adjacent GREs, then the number of paths per fiber will be 66/54/48 [2].

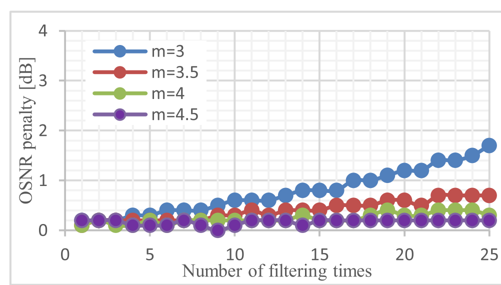
We assume the capacities and modulation formats of all paths are uniformly 400 Gbps, and polarization-multiplexed 16QAM, respectively. Figure 9 shows the relationship between OSNR penalty and the number of WSSs traversed for different bandwidth assignment cases; i.e. 62.5 GHz/75 GHz/87.5 GHz. The impact of filter narrowing in the figure is numerically evaluated through computer simulation. Here, the filter bandwidths are set to equal the -10 dB down channel spacing [2]. The number of paths in a fiber will be 70/58/50, respectively. The parameter is the Gaussian degree of the WSS filter pass band, which is denoted by m. We assume optical cross-connects that utilize the route and select configuration where one WSS is assigned to each input and output port, and two WSSs are traversed per node. For add/drop operations, optical couplers are attached to both sides of the optical cross-connect. Thus the number of WSSs traversed will be $2 \times (hop - 1)$ where hop is the number of links traversed. For 5×5 mesh networks, the maximum shortest hop between nodes is 8. Since up to 2 hop detours are allowed, the number of WSSs traversed will be $2 \times (8 + 2 - 1) = 18$. Considering the typical Gaussian degree of $m = 3.5$, 87.5 GHz spacing will be required for conventional flexgrid networks to keep the OSNR penalty to less than 1.0 dB or so. On the other hand, in Grouped routing networks, we assume that six paths are bundled as a GRE and 25 GHz guard bands are used to isolate adjacent GREs. Then the upper bound of the number of adjacent drop operations, μ, can be specified arbitrarily and the bound determines the necessary spacing. If we adopt $\mu = 2$, 62.5 GHz spacing can be utilized (see Fig. 9). In this case, 66 paths are accommodated in a fiber for Grouped routing networks while 50 paths are possible in conventional networks, as was explained in Sect. 2. Hereafter, all experiments adopt this configuration.



(a) 62.5GHz channel spacing



(b) 75GHz channel spacing.



(c) 87.5GHz channel spacing.

Fig. 9 OSNR penalty subject to number of WSSs traversed (m: Gaussian degree of filters in WSSs) [7].

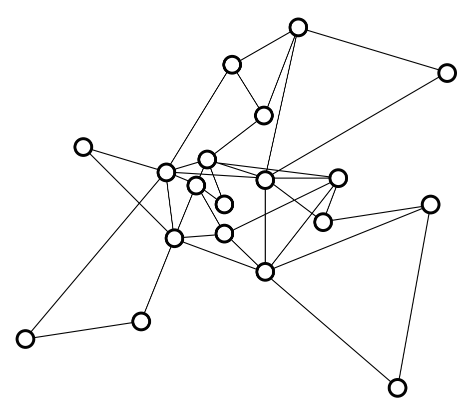


Fig. 10 Pan-European network.

4.1 Performance Evaluation on Several Topologies

The performance of proposed resilient GRE network architecture is tested on a 5×5 regular mesh network, the pan-European network [27] (Fig. 10) and the USNET topology [28] (Fig. 11). These networks consist, respectively, of 25 nodes and 40 (unidirectional) links, 19 nodes and 37 links, and 24 nodes and 43 links.

As we noted in the previous section, the simple frequency slot/wavelength index interchanging operation in Step 5 of the proposed algorithm may fail to resolve the adjacent drop bound constraint. To clarify the impact, Figure 12 shows the ratio of paths that violate the constraint. We call the ratio of paths, i.e. the ratio of violating paths relative to all paths, the violating ratio. The upper bound of violation ratio is 0.003 and the ratio will be around 0.001 as traffic volume grows for all topologies. In other words, 99.9% of requested paths were successfully established. Even if we succeeded in achieving 100% path accommodation ratio with some improved technique, the difference in resource utilization will be negligible, and therefore, there will be almost no effect on the total number of fibers in a network.

Figure 13 shows relative ratios of fiber numbers in a network. That is, the ratio of numbers of fibers, for proposed and alternative, required to accommodate the given paths to the network. The impact of Grouped routing becomes evident for large traffic volumes. The fiber number reduction reaches almost 20% for the highest traffic intensity case, an improvement close to the ideal value, $50/66 = 0.758\cdots$, regardless of the routing performance deterioration caused by the coarse granular routing and the need for establishing pairs of disjoint paths. On the other hand, the 20% reduction in fiber implies that 25% more traffic (0.2/0.8) can be ac-

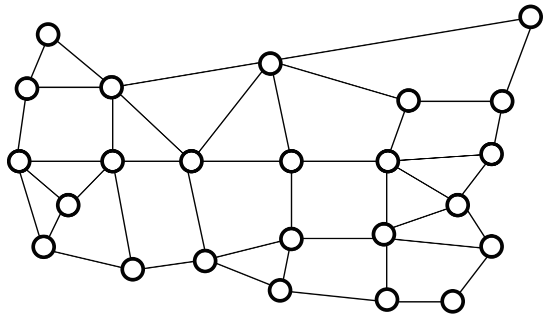


Fig. 11 USNET topology.

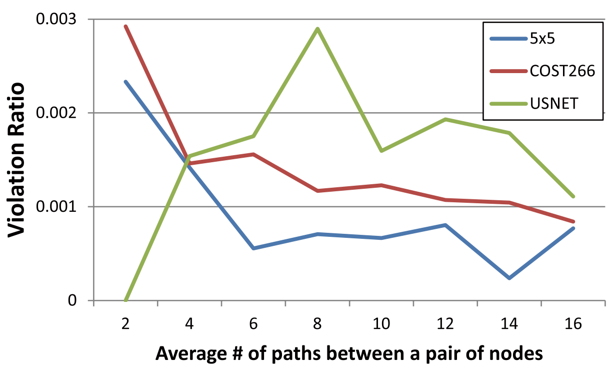


Fig. 12 Violation ratio for different traffic volumes.

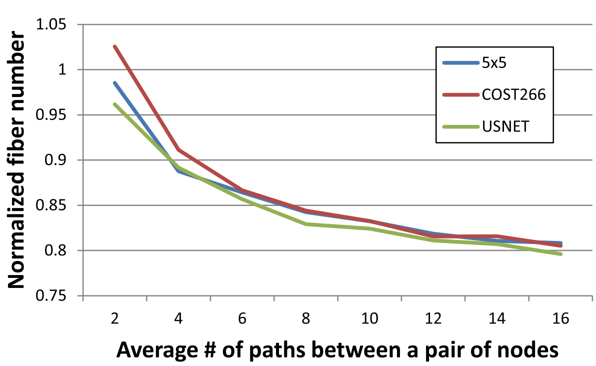


Fig. 13 Variation in fiber number relative to conventional flexgrid networks.

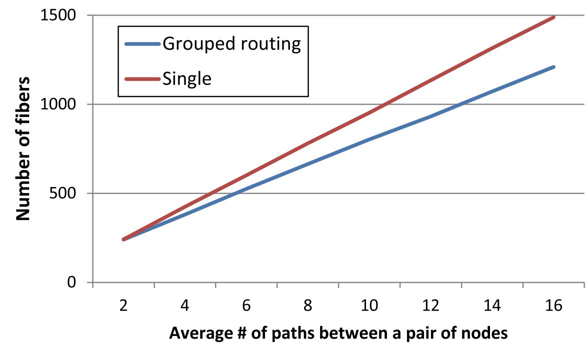


Fig. 14 Variation in absolute fiber number relative to conventional flexgrid networks: 5×5 topology.

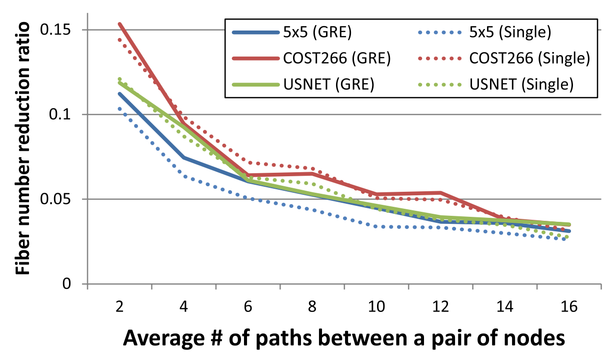


Fig. 15 Variation in fiber number reduction by re-accommodation.

commodated in the same network. Figure 14 also elucidates the absolute fiber number reduction in the 5×5 regular mesh network. The fiber numbers increase is almost linear and the inefficiency caused by the coarse granular routing will be negligible at high traffic intensity. The proposed resilient Grouped networks do not need any specific hardware, and the capacity improvement is simply achieved by controlling the operation of the flexgrid WSSs, and therefore, the fiber number reduction directly impacts the capital expense.

Finally, Fig. 15 plots the degree of the improvement attained by re-accommodation, Step 3 of the proposed algorithm, which tries to eliminate insufficiently utilized fibers. The metric for this evaluation is the ratio of number of removed fibers relative to that of installed fibers before the re-accommodation. Similar trends are observed for all cases. Up to 15% reduction is achieved for the small traffic range and the minimum reduction is 3%. The threshold was fixed to $\kappa = 0.1$, however the result was not substantially changed by adopting a different threshold. Moreover, repeated application of re-accommodation procedure has almost no impact on the result. Possible improvement by changing the metric or procedure is a future task.

4.2 Comparison to GRE Pipe Granular Protection

To achieve the requested resiliency, we adopt path granular dedicated protection in this paper while GRE pipe granular protection is also possible as we noted in Sect. 3. The former generally improves the utilization ratio of GRE pipes while the latter can simplify the signaling and switching operations. Here we provide a comparison of their relative performance to conventional single networks.

Figure 16 shows the variation in fiber number ratio as compared to conventional path granular routing optical networks. As adopted in Sect. 3 A, 400 Gbps DP-16QAM channels are commonly assumed, and 87.5 GHz spacing 50 and 62.5 GHz spacing 66 channels per fiber respectively for conventional networks and grouped routing networks with GRE pipe/optical path granular protection are used. The limitation on the number of adjacent drop operations is necessary for the 62.5 GHz channel spacing, and the GRE pipe granular protection can fulfill the requirement by limiting the number of loops (see Fig. 6) since an adjacent drop operation is only done at nodes connecting loops. Details of the dense

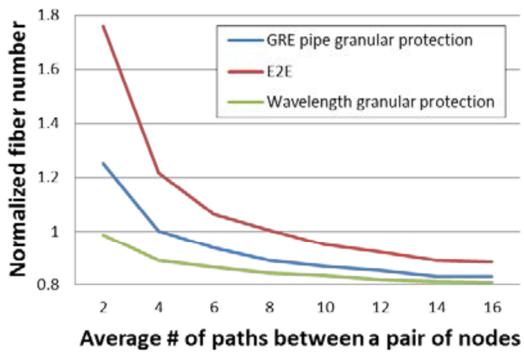


Fig. 16 Ratio of relative fiber number in a 5 × 5 mesh network.

path accommodation of GRE pipe granular protection are shown in [25].

Another advantage of GRE pipe granular protection, other than fewer switching/signaling operations in the case of failure, is the potential use of efficient routing devices such as a WBSS that is monolithically integrated on a PLC chip; its effectiveness can offset the fiber number increment caused by coarse granular routing [23].

For both protection types, the fiber number ratios decrease as the traffic increases, however the path granular protection proposed in this paper always outperforms the GRE pipe granular protection in terms of fiber number. Indeed, the fiber number ratio will be less than 1 for all traffic volumes if we adopt the proposed wavelength granular protection while the ratio exceeds 1 for the small traffic volume area for GRE pipe granular protection and GRE end-to-end.

4.3 Dependency on Network Size Variation

To evaluate the dependency of the performance of the proposed architecture on network size, we evaluate we compare it with conventional networks using $N \times N$ $(N = 4, 5, 6)$ mesh topologies. The number of paths in a GRE pipe is set to 6 and that of GREs in a fiber to 11, following the previous subsection. The average number of optical paths between nodes is commonly set to 2,4,6,8. As shown in the previous subsection, further traffic increment commonly enhances the impact of grouped routing.

The number of paths accommodated in each network is almost proportional to the product of the square of the number of nodes and the number of paths between each node pair. The number of GRE pipe routes also increases with network size. These facts yield performance improvements in larger networks. On the other hand, in larger networks we need more GRE pipes to cover all the nodes. Thus simulations on these topologies were conducted to evaluate the trade-offs. Figure 17 shows the variation in fiber number ratio relative to conventional networks that adopt dedicated path protection. The proposed protection scheme is superior for all cases.

The performance improvement seen with network size expansion is not substantial while the contribution of traffic intensity enhancement is significant. This indicates that grouped routing networks with the proposed dedicated path protection will be effective regardless of network size and its impact increases with the traffic volume.

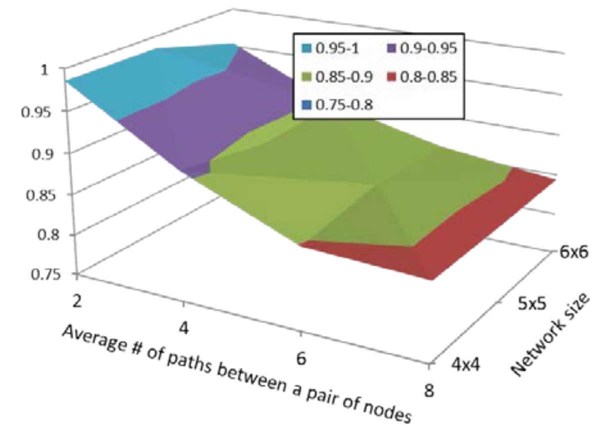


Fig. 17 Dependency of relative number of fibers to network size and traffic intensity.

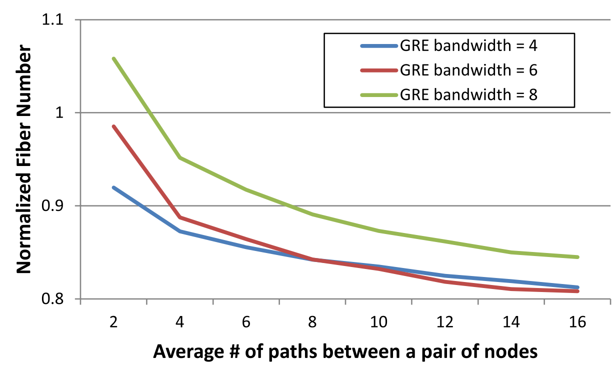


Fig. 18 Dependency of relative number of fibers to the number of paths bundled into a GRE on a 5 × 5 regular mesh network.

4.4 Dependency on GRE Bandwidth

As explained in Sect. 2.1, the number of paths accommodated in a fiber can differ with the GRE bandwidth. In protected grouped routing networks, working paths and corresponding backup paths must be accommodated in different GRE pipes which makes it necessary to optimize GRE pipe locations and path/pipe assignment to pipe/fiber. In order to verify this, we conducted simulations with (GRE capacity, # of GREs/fiber) = (4, 16), (6, 11), (8, 8), where GRE capacity stands for the number of paths that can be accommodated in a GRE.

Figure 18 shows the results. The narrower GRE pipe case is more cost effective for the small traffic demand area while the (6, 11) case is preferred for the large traffic demand area. All simulations assumed uniform bandwidth occupation by paths, however excessively narrow bandwidth GREs are not recommended if non-uniform bandwidth paths are accommodated. Therefore, considering these facts, (6, 11) would be the most appropriate setting for this experiment and so this value was adopted for all evaluations in the previous subsections.

5. Conclusion

We have proposed a resilient optical network architecture that achieves higher spectrum utilization than conventional optical path networks. The high spectrum utilization efficiency is achieved by dense path packing within GRE pipes and highly granular dedicated protection. Numerical experiments proved that the number of fibers in a network can be reduced by 20% without changing any hardware.

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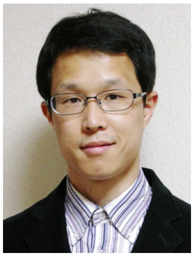

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