PAPER

Efficient Shared Protection Network Design Algorithm that Iterates Path Relocation with New Resource Utilization Metrics

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SUMMARY We propose an efficient network design algorithm that realizes shared protection. The algorithm iteratively improves the degree of wavelength resource usage and fiber utilization. To achieve this, we newly define two metrics to evaluate the degree of wavelength resource usage of a pair of working/backup paths and the fiber utilization efficiency. The proposed method iteratively redesigns groups of paths that are selected in the order determined by the metrics. A numerical analysis verifies that the proposed algorithm can substantially reduce the required wavelength resources and hence fiber cost. It is also verified that the computational complexity of the proposed algorithm is small enough to terminate within practicable time.

key words: optical path network, routing and wavelength assignment, shared protection, iterative re-optimization

1. Introduction

Due to the rapid deployment of broadband access technologies such as ADSL and FTTH, the amount of Internet traffic continues to increase [1]. Further continuous traffic expansion is expected due to the adoption of new broadband services that use Ultra-high definition video [2], 4-k cinema [2], Grid-computing, and e-science [3]. To cope with the explosive increase in traffic, photonic networks [4], [5] have been developed to replace costly electrical routing as much as possible. The networks are expected to be instrumental in preventing the envisaged electrical power demand explosion caused by layer 3 and layer 2 transport [6]. To maximally exploit the envisaged potential of photonic networking, development of efficient network design algorithms is a critical issue.

Network failures occur due to various reasons including accidental fiber cut by construction or human error [7]. Immediate recovery from failures is required for networks carrying mission critical services. Reliability of networks is achieved through path protection based on backup paths reserved in advance or dynamically establishing backup paths after calculating their routes after each failure. The former approach is called protection and the latter is called restoration. The former can be classified into two types: dedicated protection and shared protection [8]. In shared protection, multiple backup paths can share the same resources if their

working paths do not go through the same link, i.e., not in the same shared risk link group (SRLG). Therefore, shared protection requires fewer network resources than dedicated protection, which allocates independent backup paths to each working path. Shared protection, on the other hand, requires longer recovery time than dedicated protection since the recovery process includes signaling and switch reconfiguration processing at intermediate nodes. The recovery time can be shortened if backup routes candidates are computed in advance.

Shared protection schemes are grouped into several classes including Shared Link Protection (SLP), Shared Path Protection (SPP), Shared Segment Protection (SSP), and so on. SLP [9] defines a shared protection path for each link of a working path. When a link failure occurs, working paths going through the link are switched to their protection paths. Fast recovery operation is realized since switching operations are only necessary at the edge nodes of the failed link. SPP [10], [11] defines a shared protection path that directly connects the source and destination nodes of its working path. When a working path fails, its end nodes switch the working path to the protection path. Recovery takes longer than is needed by SLP, however, fewer resources are needed for the protection paths since the degree of restoration resource sharing is enhanced. SSP [12], [13] is a variant that considers sub-path protection. Each working path is divided into several segments and a protection path is defined for each segment. In the case of failure, the edge nodes of the failed segment switch the working segment to its protection segment. SPP has longer recovery time than SLP. The amount of resources assigned to protection paths tends to be smaller than that required with SPP [12]. The design problem becomes more complicated because we must split the working paths in an optimal or sub-optimal manner. Hereafter, we focus on the SPP approach given its high resource utilization efficiency and simplicity in terms of switching.

The routing and wavelength assignment (RWA) problem for optical path networks is known to be NP-complete [10] even for just working paths. Designing shared protection networks is an even more difficult task since we also need to perform RWA for protection paths, while maximizing capacity sharing among protection paths. Thus, the shared protection approach makes it computationally impossible to find the optimal solution. In response, several heuristic algorithms have been proposed [14]–[22]. They try to find suboptimal solutions by sequentially applying RWA to each working/protection path pair. An efficient such al-

gorithm is named the Iterative Two Step Approach (ITSA) [17]. It finds several route candidates for each path demand and then iteratively applies the Two Step Approach [22] to each route candidate to find its backup route. The best working/backup path pair is selected from among these path pairs. It has been shown that ITSA achieves high resource utilization efficiency [22]. Both the Potential Backup Cost (PBC) [19], [20] and Maximum Likelihood Relaxation (MLR) [21] approaches are also based on the strategy where paths are established one by one. PBC and MLR also iteratively establish a working path and then its backup path. At the establishment of each working path, the algorithms select a route whose backup path can maximally share fiber capacity with the other backup paths. The difference between the two algorithms lies in their cost functions for working-path establishment. PBC selects a route for each working path that minimizes the total capacity occupied by backup paths whose working paths are in the same SRLG with each corresponding working path. On the other hand, MLR assigns a route for each working path that maximizes the number of "Easy Links," i.e., the links whose capacity occupied by backup paths that are not in the same SRLG is not less than the capacity of the working path to be established. A common drawback of these algorithms is that paths established in the initial stages cannot be sufficiently optimized to maximize sharing of backup paths. In order to overcome this common drawback, several works studied re-assignment of route and wavelength for paths established in the initial stages [22]–[27]. A simple scheme, the Reoptimization algorithm of [22], is known to realize well-optimized RWA. The optimization process of this algorithm tries to find better RWA for each path while fixing the RWA for the other paths. If a better pair of route and wavelength is found, the current assignment for the path is changed to the new one. This simple optimization is repeatedly applied to all paths in random order and the algorithm terminates when no further improvement can be attained. A potential drawback of the algorithm is that the process can be trapped in a locally optimal solution since only one path is considered and updated at a time. For attaining a further improvement by the re-assignment of routes and wavelengths, we must consider global re-assignment among groups of paths. Another iterative algorithm named Optimization Cycle of [27] is also known to achieve well-optimized RWA. This algorithm aims to reduce the number of fibers needed in a network. In ascending order of the number of wavelength paths traversing each fiber, this algorithm tries to remove fibers one by one by relocating accommodating paths to other fibers. However, only one fiber is checked at a time and, so this algorithm can also become trapped in local minima. In addition, the path detouring created by relocation will potentially increase the total amount of wavelength resources occupied by the working/backup paths. This resource increment can limit further fiber reduction.

In this paper, we propose a novel SPP algorithm that more fully optimizes the network resource utilization. Fibers and the related necessary optical components

at nodes are expensive elements, so reducing the number of fibers is important. The direct minimization of the number of fibers is computationally impossible as noted above. However, the number of fibers is directly related to the amount of wavelength resources occupied by working paths and shared backup paths and the utilization efficiency of each fiber. Thus the amount of wavelength resources must be reduced as much as possible. To achieve these goals, we first propose two metrics that represent network resource utilization: efficiency of wavelength resource usage of working/shared backup paths and that of fiber utilization. The proposed algorithm iteratively redesigns working/shared backup path pairs by applying ITSA, where the redesigned paths are selected in ascending order of these metrics. Numerical experiments prove that the proposed algorithm can reduce the number of fibers necessary for working and backup paths simultaneously and is superior to ITSA, and Reoptimization and Optimization Cycle [27]. It is also demonstrated that the calculation time is practical. A preliminary document discussing this work [28] has been presented at an international conference.

2. Preliminaries

2.1 Assumptions

In this paper, we tackle the so-called "static design problem." We aim to minimize network resources including fibers and optical cross-connect switch ports by determining the most suitable routing and wavelength assignment for a given set of path demands. We assume optical path networks that do not implement wavelength conversion at any node [4]. For each working path, a node and link disjoint shared protection path is defined and the allocated capacity of fibers assigned to the backup path can be shared among other backup paths whose working paths do not belong to the same shared risk group (SRG) as the working path. The same wavelength is assigned to each working path and its backup path.

2.2 Iterative Two Step Approach [17]

ITSA was originally developed for dynamic routing and wavelength assignment in optical path networks that consider shared protection. For each path connection demand, ITSA computes a disjoint path pair by using the following process.

⟨*Two step approach vertex-disjoint pair algorithm*⟩
From a given source node to a given destination node, find a route on the graph for the working path using Dijkstra's algorithm [29]. For the route, define a modified graph where all intermediate nodes and connected edges are removed from the original graph, and compute the optimal route for the backup path on the modified graph; the optimality is defined by metrics such as hop count of the route or the sum of weight of links passed through where the weight of each

link is an assigned positive real number. Output the route pair whose total weight is minimum or whose total length is shortest.

ITSA generalizes the above scheme so that multiple route candidates for a working path are checked. In order to encourage sharing of fiber capacity among backup paths, link weight is defined using the information of the SRLG of each working path. ITSA first finds a route candidate set on the graph for the working path by using the k-shortest path algorithm [22]. Then, for each route candidate, it applies the above scheme to compute backup paths, and outputs the route pair with the minimum weight. We apply the above procedure to all wavelengths and select the pair of route and wavelength that minimizes the sum of link weights.

ITSA can easily be adapted to the static design of optical path networks without wavelength conversion. If we try to optimize all paths simultaneously, the computational complexity is known to be NP-complete due to the wavelength continuity constraint. A computationally efficient alternative to direct optimization is the sequential assignment of routes and wavelengths to a given path connection demand. For each assignment stage, we can straightforwardly apply ITSA and pursue the maximum capacity sharing among backup paths.

2.3 Reoptimization Algorithm [22]

Heuristic algorithms including ITSA establish paths one by one. In the establishment process of each path, only the relationship to paths already established is considered. Thus RWA done in the initial stage may not be well optimized. A simple technique named Reoptimization algorithm is proposed to solve this problem; it identifies a better RWA than the current assignment for each path. The algorithm is summarized below.

⟨*Reoptimization algorithm*⟩

Step 0 Find an initial RWA by a sequential heuristic such as ITSA.
Step 1 Set REPEAT = FALSE.
Step 2 For each demand d:
    (a) Set p_0 = current working path and q_0 = current backup path of demand d.
    (b) Remove p_0 and q_0 from network.
    (c) Compute new working and backup path pair $\{p^*, q^*\}$.
    (d) If combined weights of p^* and q^* are less than combined weights of p_0 and q_0, assign demand d to paths p^* and q^*, and set REPEAT = TRUE. Otherwise, reassign demand d to paths p_0 and q_0.
Step 3 If REPEAT = TRUE, repeat from Step 1. Otherwise, terminate.

Remark
If the metric assigned to each link is a positive integer, this is always satisfied when the metric is the hop count; the metric improvement for each cycle of Step 2 will be a positive in-

teger. Thus the number of iterations of Reoptimization will be bounded by the gap between the metrics of the initial solutions and optimal solutions.

2.4 Optimization Cycle [27]

Along with the Reoptimization algorithm, Optimization Cycle can improve the initial RWA by relocating paths repeatedly. This algorithm is specialized in that it reduces the number of fibers by trying to relocate paths that traverse sparsely-utilized fibers. Throughout this subsection, we call a fiber traversed by $m(< W)$ wavelength paths an *m*-fiber where W is the maximum number of fibers accommodated by a cable. The algorithm is summarized below.

⟨*Optimization cycle*⟩

Step 0 Find an initial RWA by a sequential heuristic such as ITSA and set counter m to 1.
Step 1 Search for *m*-fibers. If found, go to Step 2. Otherwise, let $m = m + 1$ and repeat Step 1 (if $m < W - 1$) or terminate (if $m = W - 1$).
Step 2 For one randomly selected *m*-fiber found in Step 1, temporarily remove the *m*-fiber and the paths traversing it.
Step 3 Try to accommodate the removed paths in Step 2 sequentially in the spare capacity of existing fibers. If all paths are successfully rerouted without adding any fibers, select the new RWA and remove the *m*-fiber; otherwise cancel the modification done in Step 2.
Step 4 If there is no *m*-fiber in the network or all *m*-fibers have already been examined, let $m = m + 1$ and go to Step 5. Otherwise, go back to Step 2.
Step 5 If $m = W - 1$, terminate. Otherwise, go back to Step 1.

Remark
In this paper, we focus on the so-called static network design issue where all working paths and backup paths are established simultaneously. The other design issues on shared protected networks include incremental network design at fixed intervals, say 3 or 6 months, or the dynamic relocation of paths [22]. It should be noted that our proposed design algorithm can also realize these functions with a slight extension.

3. Proposed Routing Algorithm

Although it is hard to define the exact accommodation efficiency of each working/backup path pair in a network, several metrics, such as the number of backup paths sharing the same fibers, can provide an appropriate answer.

The application of ITSA to the static wavelength path (WP) network design issue was briefly explained in Sect. 2. It is not straightforward to introduce these metrics of accommodation efficiency to the ITSA-based design method, since the metrics are computed after all routes and wavelengths have been determined.

Considering the above discussion, we propose two new metrics related to accommodation efficiency that involve working/backup path pairs and an iterative design algorithm for optical path networks with shared protection. The metrics are defined below.

3.1 Wavelength Utilization Efficiency

For given working and backup paths, this measure represents the estimated total hop count of the paths.

For fiber f on a route of the backup path of demand d, let s_f be the number of backup paths including the path itself that share the same fiber and wavelength with d at f. The sets of fibers that the working and backup paths for the demand d go through, respectively, are denoted by $RW(d)$ and $RB(d)$, respectively. We next define the wavelength utilization efficiency of d by

$$R_d := \frac{1}{shop}\left(\sum_{f \in RB(d)} \frac{1}{s_f} + whop\right),$$

where $shop$ represents the hop count of the shortest route for d, and $whop$ is the hop count of route selected for the working path of d. The wavelength resource for the working path will be $whop$. The wavelength resource used by the backup path on link f in $RB(d)$ is approximated by $1/s_f$ since the wavelength resource is shared by s_f backup paths. Therefore, this measure approximates the number of wavelength resources used to traverse one of the shortest routes. In our preliminary work [28], we evaluated the amount of wavelength resources occupied by shared backup paths. However, the modified measurement presented above includes the amount of wavelength resources occupied by working paths, which may use detouring routes, and will provide more accurate occupied resource estimation. Thus it provides better resource utilization evaluations and its impact on network design has been verified numerically.

3.2 Worst Fiber Utilization

For a given working/backup path pair, this measure represents the minimum number of reserved wavelengths in a fiber among the fibers traversed by the working/backup paths. In other word, it evaluates the number of relocation operations needed to remove the fiber. Its definition is given as follows;

$$F_d := \min_{f \in RW(d), RB(d)} (\#L_f),$$

where $\#L_f$ represents the number of reserved wavelengths in fiber f.

3.3 Proposed Iterative Design of Shared Protected Networks

A general objective can be the minimization of the sum of the first metric for all working and backup paths in order
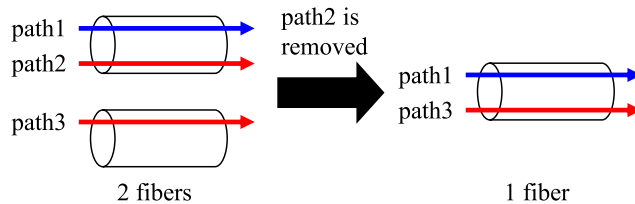
Fig. 1 An example of reducing fiber number.

to reduce the amount of network resources required. On the other hand, if some fiber is not sufficiently well utilized, we should relocate the accommodated paths to other fibers that have spare capacity so that we can minimize the total number of fibers. Since fiber is one of the most costly network resources, considering only the first measure is not sufficient. A desirable strategy is to improve the fiber utilization efficiency while removing fibers that are not well utilized by rerouting the accommodated paths. That is, we propose a design algorithm that repeatedly redesigns the network so that both metrics are improved. In the initial stage of redesign, we try to relocate many paths that are inefficient from the viewpoint of network resource utilization. The number of paths to be relocated is then gradually decreased by settling on sufficiently improved paths.

⟨*Iterative design of shared protected networks based on resource utilization estimation*⟩

Step 0   Apply ITSA as described in Sect. 2.2 in descending order of shortest hop count between source and destination nodes for the initial routes and assign wavelengths. Set thresholds P_1, P_2 (*in* [0, 1]) and the number of redesigns, N. Let $n = 1$.

Step 1   Calculate R_d for all demands.

Step 2   Remove $DP_1^{\frac{N-n}{N}}$ paths, where D is the number of given demands, from the network in decreasing order of R_d. For each adjacent node pair connected by parallel fibers, try to reduce fiber number by relocating some paths to the other fibers on the link. An example is shown in Fig. 1.

Step 3   Accommodate demands that are deleted in Step 2 by using the same assignment scheme in Step 0.

Step 4   Calculate F_d for all demands.

Step 5   Delete $DP_2^{\frac{N-n}{N}}$ demands from the network in increasing order of F_d. For each adjacent node pair connected by parallel fibers, try to reduce the fiber number.

Step 6   Accommodate demands that are deleted in Step 5 by using the same assignment process as in Step 0.

Step 7   If $n = N - 1$, output the results of the current assignment and terminate. Otherwise, let $n = n + 1$ and go to Step 1.

Reoptimization tries to relocate only one pair of working/backup paths at a time, and hence, trapping in local minima can occur if resource utilization demands that two or more pairs of paths be relocated simultaneously. On the other hand, Optimization Cycle tries to remove one fiber

at a time. However, Optimization Cycle aims at reducing only the number of fibers, not the number of wavelength resources. Although there is a close relationship between the number of wavelength resources and the number of fibers in a network, minimization only fibers or wavelength resources is not enough. For further improvement, we must develop an algorithm that considers fiber and wavelength resource optimization simultaneously. In this paper, we introduce the novel metrics of R_d and F_d to identify a group of path pairs that are not efficiently accommodated. The specified group of paths determined by the criteria are removed from the network and then accommodated again so that better efficiency is attained.

In the iterative redesign stage, the method always assigns node and link disjoint routes to each working/backup path pair. Thus robustness against single failure is guaranteed after the redesign.

3.4 Analysis on Computation Complexity

In this section, we evaluate the computational complexity of the proposed method. For route assignment for each pair of working and protection paths, ITSA employs the so-called k-shortest paths algorithm to derive a candidate route set for the working path. Dijkstra's algorithm is then applied to each route candidate. Let the number of nodes be v and that of links e. It is known that the computational complexity of the k-shortest paths algorithm is $O(kv^2)$ [30]. The computational complexity of Dijkstra's algorithm is $O(v^2)$ [31] and it is repeated k times. Therefore, the complexity of each ITSA iteration is $O(kv^2)$. The number of ITSA iterations is given by

$$D + DP_1 \sum_{n=0}^{N-1} \frac{N-n}{N} + DP_2 \sum_{n=0}^{N-1} \frac{N-n}{N}$$
$$= D\left\{1 + \frac{(N+1)(P_1+P_2)}{2}\right\} = O(DN).$$

Thus the complexity for path establishment is $O(kv^2) \cdot O(DN) = O(DNkv^2)$. For the fiber elimination operation in Step 2 and Step 5, we must check all links. Hence the complexity is $O(e)$. The resource utilization efficiency metrics R_d and F_d are computed DN times, path deletion is applied $D\left\{\frac{(N+1)(P_1+P_2)}{2}\right\}$ times, and fiber elimination is done $2N$ times. The total complexity of these operations is $O(DN) + O(DN) + O(Ne) = O(N(D+e))$. In summary, the computational complexity of the proposed method is $O(DNkv^2) + O(N(D+e)) = O(N(Dkv^2+e))$.

4. Numerical Analysis

In this section, we demonstrate the effectiveness of the proposed algorithm through numerical analysis. We first show the impact of R_d and find an appropriate range for threshold P_1 in Sect. 4.1. We then show the result derived by using both R_d and F_d in Sect. 4.2. In Sect. 4.3, the effects of changing the value of P_2 are presented. These evaluations
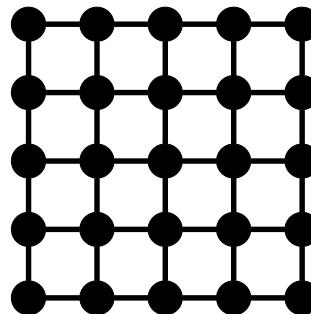

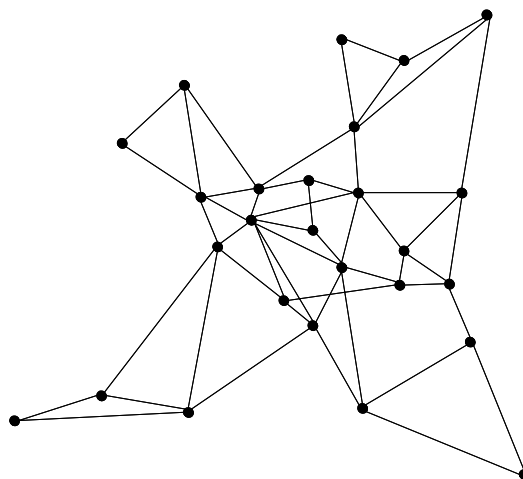**Fig. 2** 5×5 regular mesh.

Fig. 3 COST266 network.

involve a 5×5 regular mesh (Fig. 2) and the COST266 pan-European (Fig. 3) [32] network where the former is selected to demonstrate a general trend while the latter shows the application practicality of the proposed algorithm.

In Sect. 4.4, we demonstrate the effectiveness of the proposed algorithm on several topologies by comparing it against the conventional schemes described in Sect. 3. We then evaluate the effects of changing the ratios regarding the two metrics. Finally, computation times for regular mesh networks of different sizes are investigated in Sect. 4.6. Throughout the evaluations, we commonly employ the following conditions.

(a) Traffic is uniformly and randomly distributed.
(b) Each fiber can accommodate 80 wavelengths.
(c) Hop slug of the working path is set to 0 for the 5×5 regular mesh and 2 for other topologies. There is no hop slug limitation for backup paths. All routes that conform to the hop slug, the number of allowable hop increment from the shortest hop count, are regarded as candidate working paths.

Remark

1. For computing the optimal value pair of P_1 and P_2, it is a computationally intensive task to check all possible combinations of thresholds for P_1 and P_2. In this numer-

ical analysis process, we empirically confirmed that solutions derived from the sequential computation scheme in this section, i.e. changing only P_1 while fixing $P_2 = 0$ and then fix P_1 to the selected value and change only the value of P_2, is sufficiently close to the optimal value pair derived by exhaustive search. Therefore, we employ the latter method afterward for deciding the optimal value pair of P_1 and P_2.

2. The benchmark method, Re-optimization, improves the result by ITSA, which is known to provide well optimized solutions [17]; paths going through poorly utilized fibers are relocated until no further fiber reduction is achieved. Protection paths share wavelength resources and the total wavelength resource occupied by working paths is dominant. Therefore, it is hard in this experiment to reduce the wavelength resources for working and backup paths, especially the number of fibers.

4.1 Impact of Wavelength Utilization Efficiency

We show the effect of varying P_1 while keeping $P_2 = 0$. The number of iterations, N, is set to 100. The results are normalized by those derived by applying the Reoptimization algorithm [22]. Because the shortest route is always assigned to each working path in the 5×5 mesh network, the number of working resources is constant whichever algorithm we use. The ratio of backup resources in the 5×5 mesh network and that of working/backup resources in COST266 are, respectively, shown in Figs. 4(a) and (b). These figures show that, as P_1 increases, the ratios of wavelength resources are improved. On the other hand, no improvement is attained when P_1 is too small. The sum of all wavelength utilization efficiencies for all paths equals the total wavelength resource. The total working resource is generally fixed since lengthy detouring of working paths is generally prohibited. Therefore, the iterative optimization with large P_1 value directly contributes to the reduction of backup resources. This trend is also seen in the number of fibers, as shown in Figs. 4(c) and 4(d); note that these graphs are not so smooth due to the large granularity of fibers, i.e. 80 wavelengths. The optimal value of P_1 for wavelength resource reduction is around 0.7 for 5×5 and 1 for COST266.

4.2 Impact of Worst Fiber Utilization

We apply the two metrics, P_1 and P_2. N is set to 100. We fixed P_1 to the optimal value derived in the previous subsection; i.e. 0.7 for 5×5 and 1 for COST266. The obtained ratios of wavelength resources and numbers of fibers are shown in Figs. 5(a)–(d). Figures 5(a) and 5(b) show that deceasing P_2 reduces the wavelength resource requirements for both topologies. On the other hand, the number of fibers decreases over a wide range of parameter values except for small traffic areas for 5×5. By setting P_2 to an appropriate value, we can further reduce the number of fibers while allowing some increase in wavelength resource usage. This
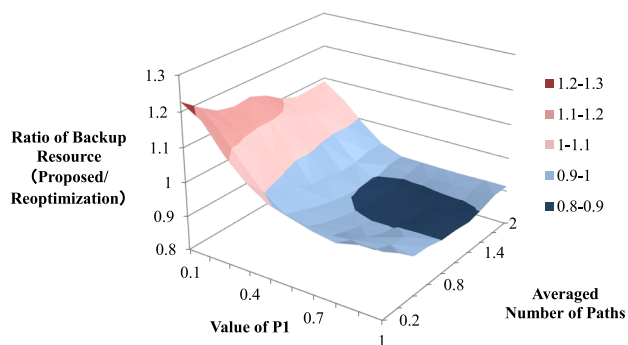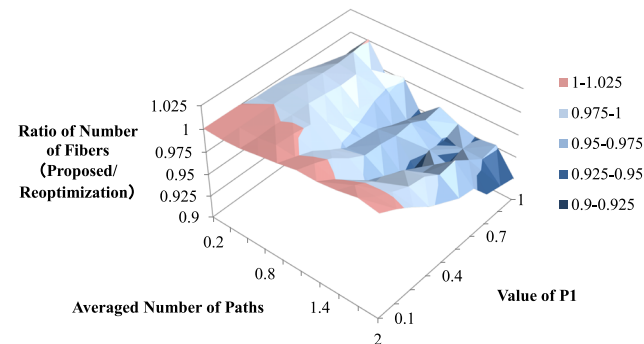

(a) Ratio of backup resources for 5x5.
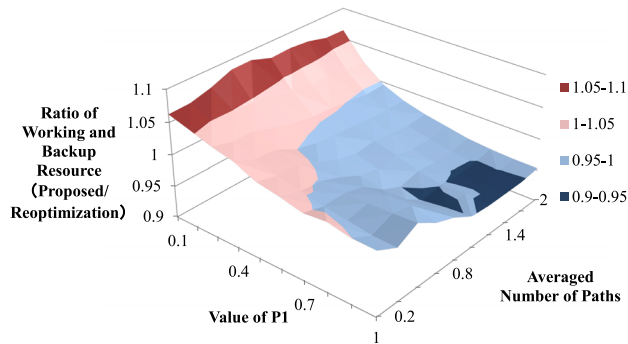
(b) Ratio of working and backup resources for COST266.
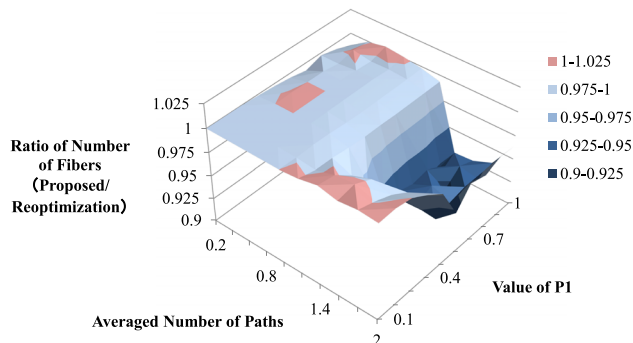
(c) Ratio of number of fibers for 5x5.

(d) Ratio of number of fibers in COST266.

Fig. 4 Iterative redesign that uses only wavelength utilization efficiency R_d.

(a) Ratio of backup resources in 5x5.

(b) Ratio of working and backup resources for COST266.

(c) Ratio of number of fibers for 5x5.

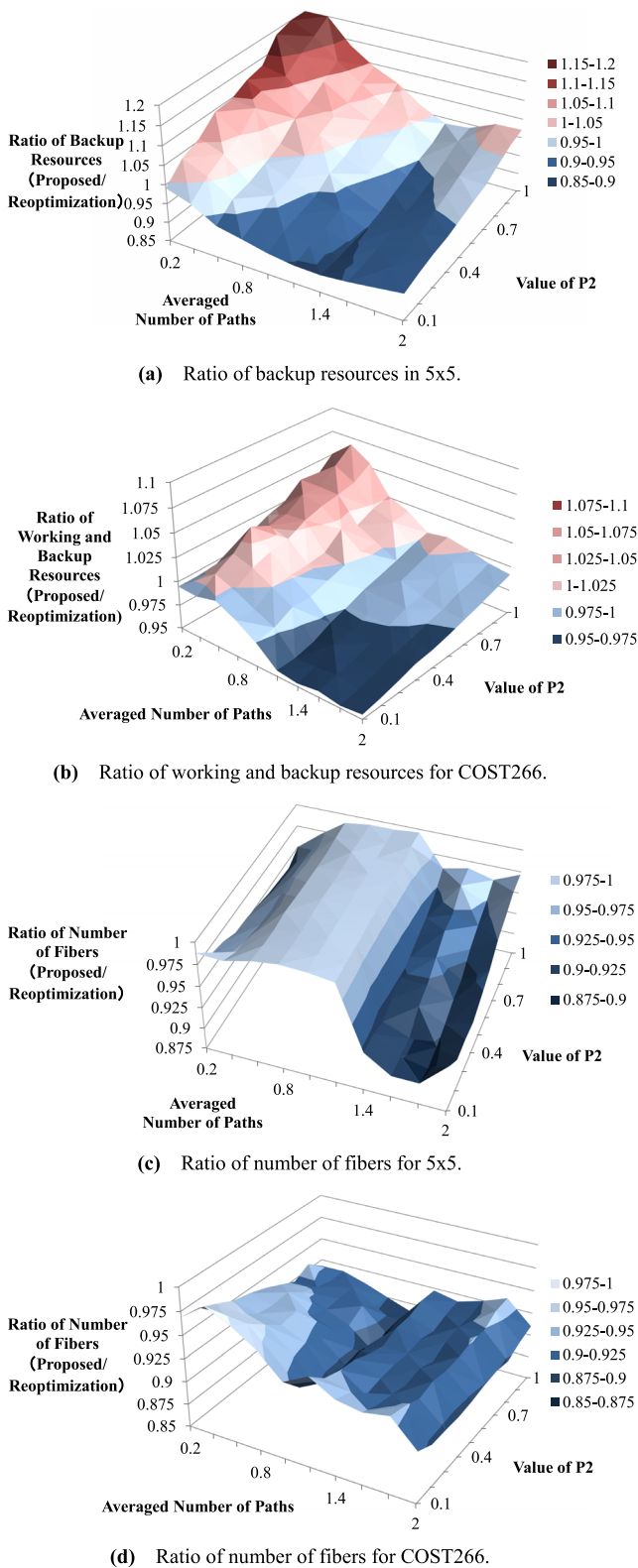**(d)** Ratio of number of fibers for COST266.

Fig. 5 Iterative redesign that uses two proposed metrics R_d and F_d.

is because some fibers can be removed by appropriate detouring of wavelength paths, which implies an increase in wavelength resources. When P_2 is 0.1 for 5×5 and 0.3 for COST266, both wavelength resource requirements and fiber resources are well reduced.

4.3 Impact of Iteration Number

We evaluate the impact of the number of iterations N. We fixed P_1 and P_2 to the optimal values derived in the previous subsection; $(P_1, P_2) = (0.7, 0.1)$ for 5×5 and $(1, 0.3)$ for COST266. The ratios of wavelength resources and numbers of fibers are shown in Figs. 6(a)–(d). Figures 6(a) and 6(b) demonstrate that, as the number of iterations increases, the wavelength resource requirements are reduced. It seems that at least ten iterations are necessary to achieve better reduction than Reoptimization. The trend is the same for the number of fibers. However, with only a single iteration, the proposed algorithm realizes a smaller number of fibers in most ranges. These results show that a sufficient number of iterations (∼100 times) can significantly reduce the number of fibers and the number of backup resources needed.

4.4 Reducing Network Resource Requirements

The proposed algorithm can reduce network resources required for the 5×5 regular mesh and COST266 networks. In this section, we demonstrate that the proposed algorithm can reduce network resources even if traffic demands are increased. It is also shown that network resources can be reduced in various topologies. Simulations examined the 5×5 regular mesh, COST266, Japan and France's networks (Figs. 7 [33] and 8 [34]) where the latter two new topologies are introduced to elucidate the effectiveness of the proposed algorithm on topologies with different key parameters; node degree and number of nodes. We fixed P_1 and P_2 to the optimal values; $(P_1, P_2) = (0.7, 0.1)$ for 5×5, $(1, 0.3)$ for COST266, $(0.7, 0.3)$ for Japan and $(0.9, 0.2)$ for France's network. These empirically-derived parameter values are the best from the viewpoint of network resource reduction. N is set to 100. The ratios of wavelength resources and number of fibers are shown in Figs. 9(a)–(c) and 10(a)–(c). Normalization is against the results obtained by the ITSA algorithm [17]. The average number of path demands between each node is changed. These figures show that the proposed algorithm can reduce network resource requirements in all ranges of traffic demands except for the point at which the average number of paths equals 1, see Fig. 9(c).

### 4.5 Effect of the Order of Applying Two Metrics

We evaluate the effect of the order of applying the two metrics, R_d and F_d (See Fig. 11 for the results). As shown in Sect. 3, the proposed algorithm executes R_d based redesign and F_d based redesign alternately. We define two variations of the proposed algorithm as described below.
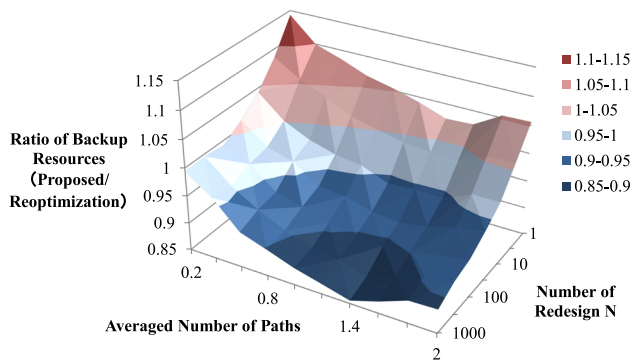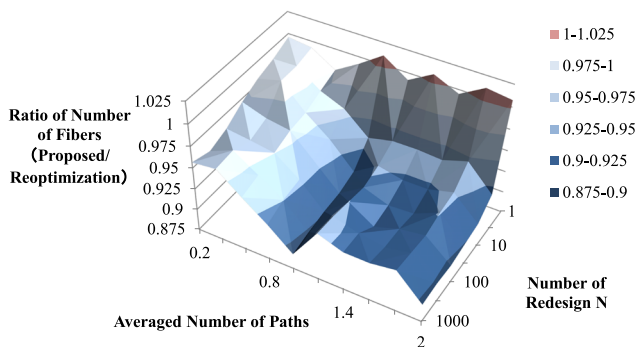
(a) Ratio of backup resources for 5x5.
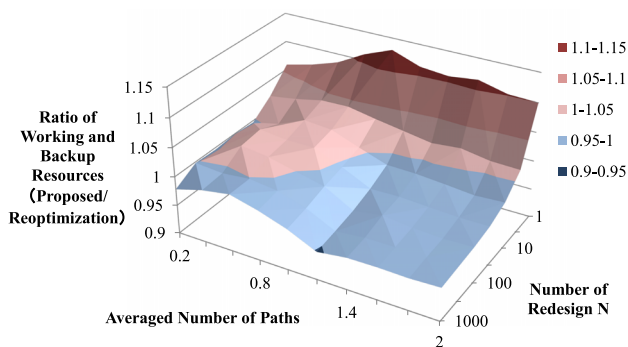
(b) Ratio of backup resources for COST266.
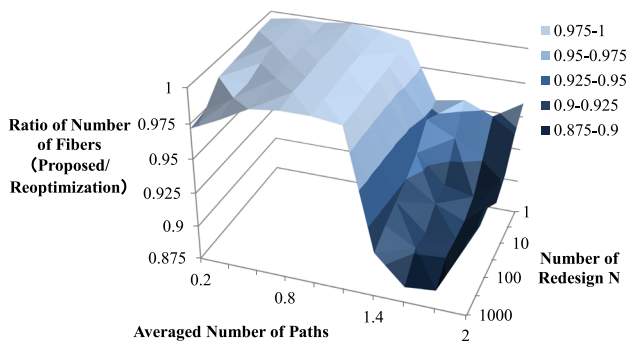
(c) Ratio of number of fibers for 5x5.

(d) Ratio of number of fibers for COST266.

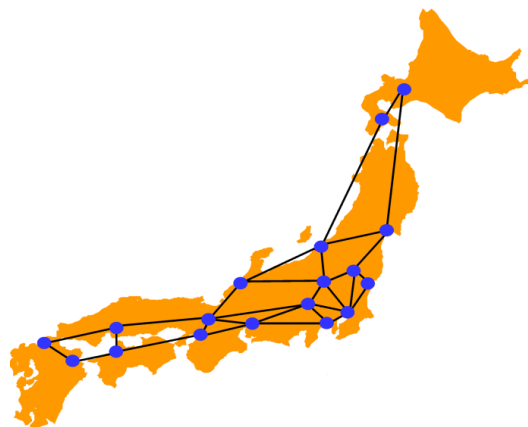**Fig. 6** Impact of iteration number on performance.
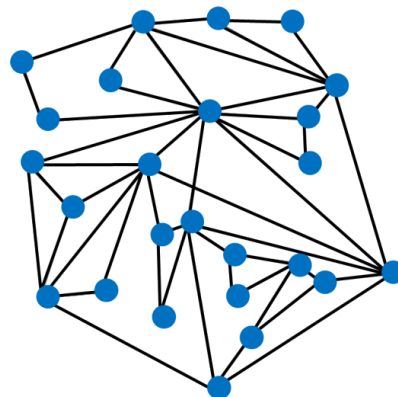

Fig. 7 Japan's network.

Fig. 8 France's network.

(a) Variation 1

Execute R_d based redesign 4 times in every 5 redesigns and then F_d based redesign once in every 5 redesigns until n reaches $\frac{N}{2} - 1$. After that, execute R_d based redesign once in every 5 redesigns and F_d based redesign 4 times in every 5 redesigns. n is incremented by one every 2 redesigns in the same way as in the proposed algorithm described in Sect. 3.

(b)Variation 2

Same procedure as variation 1 but R_d and F_d are switched.

N is set to 100. The parameters were set at, $(P_1, P_2) = (0.7, 0.3)$. Simulations were done for Japan's network. The obtained normalized number of fibers is shown in Fig. 5(a) and the normalized number of working and backup resources are shown in Fig. 5(b). These figures show that the three variations yield almost same the results. We can conclude that order of applying the two metrics, R_d and F_d, has little effect.
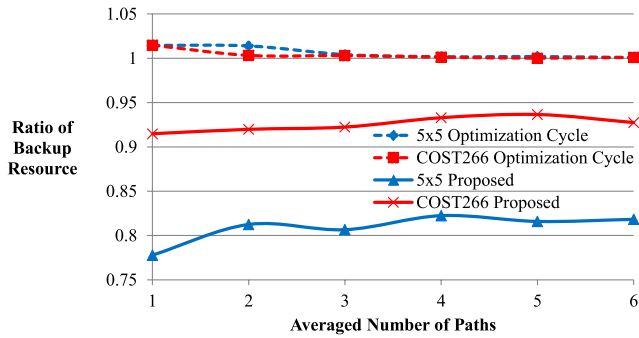
4.6 Computation Time

We evaluate the computation time of the proposed algorithm for regular mesh topologies of different size. The number of iterations, N, is fixed at 100. The thresholds for the mea-
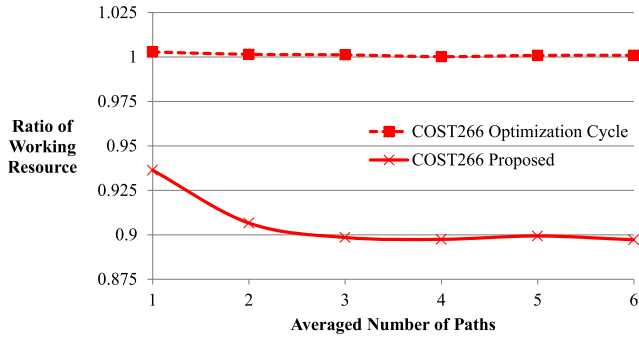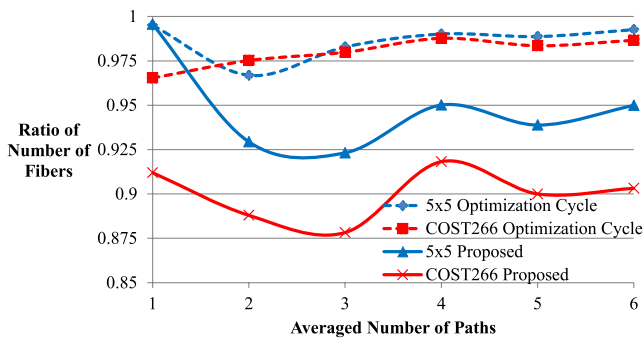
(a) Ratio of working resources for COST266.
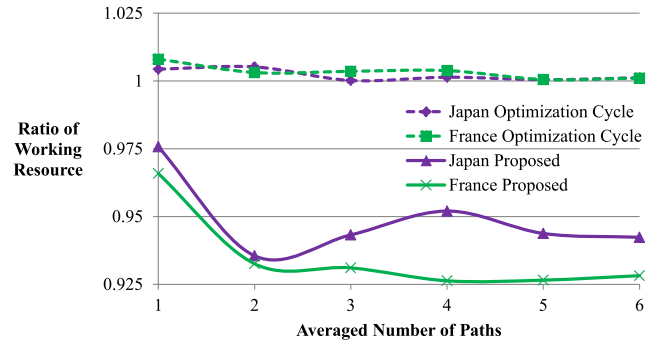

(b) Ratio of backup resources in 5x5 and COST266.
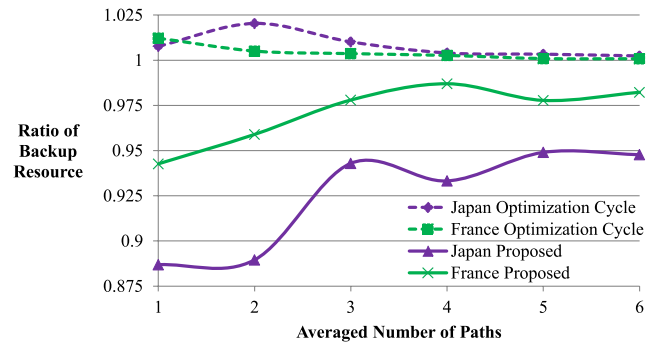

(c) Ratio of number of fibers in 5x5 and COST266.

Fig. 9 Results of proposed algorithm normalized against comparative approach for 5×5 and COST266.

(a) Ratio of working resources in Japan and France.

(b) Ratio of backup resource in Japan.

(c) Ratio of number of fibers for Japan.

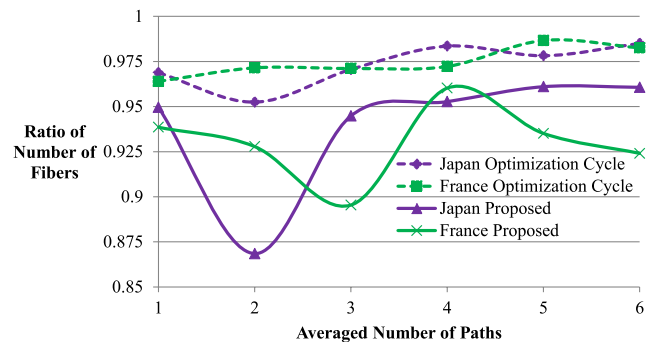**Fig. 10** Results of proposed algorithm normalized against comparative approach for Japan and France.

surements were set at $(P_1, P_2) = (0.7, 0.1)$. With this parameter setting, the total number of paths reassigned throughout the iterations of Step 2 will be 40 times the total number of paths. Thus the computation time of the proposed method is several tens of times more than that of ITSA, which provides the initial solution. The computation time of Reoptimization is also less than that of the proposed method in this experiment. However, the proposed method provides the best solutions in almost all cases, which is the most important requirement in static network design. Average number of paths between each node pair set is 2. The result on a PC with AMD Opteron 6180SE processor (2.5 GHz) is shown in Fig. 12. The number of paths in the network and the number of route candidates for each path increase

rapidly as the network is enlarged. Thus the computation time also increases with the topology size. Although the computation time also depends on the number of iterations and the thresholds for path relocation, reduction of computational load should be discussed elsewhere.

5. Conclusion

In this paper, we proposed a novel static network design algorithm for shared protected optical path networks. The algorithm iteratively optimizes path allocation by utilizing our newly defined metrics that well represent resource utilization. We verified the effectiveness of the proposed algo-
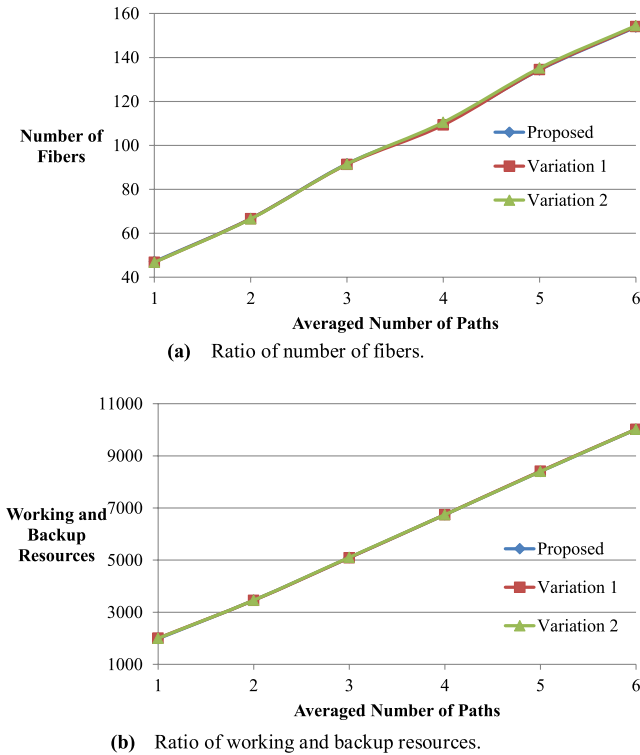
(a) Ratio of number of fibers.

(b) Ratio of working and backup resources.

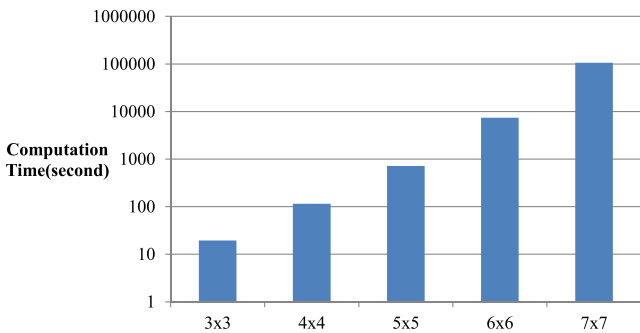**Fig. 11** Results of proposed algorithm and variations.

Fig. 12 Computation time for several regular mesh topologies.

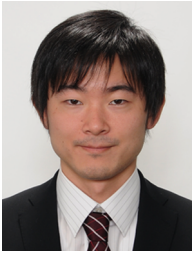rithm through numerical analyses in terms of reducing fiber and wavelength resource requirements.

Acknowledgments

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