Reconfiguration of Survivable MPLS/WDM Networks

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***Abstract*— We present a novel group-based mechanism to reconfigure the virtual topology of survivable MPLS/WDM networks by using the existing shared protection backup resource. With this mechanism, lightpaths are divided into groups and those in the same group can be reconfigured simultaneously at one step. Ideally, this mechanism won't incur any service disruption during the reconfiguration process. The optimal reconfiguration policy is obtained through solving following two problems: the *Grouping problem* which minimizes the reconfiguration steps, and the *Sequencing problem* which minimizes the network resource used during the reconfiguration process. We prove these two problems to be NP-hard and present efficient heuristic algorithms. A general mathematical method of *rollout* is applied to the heuristics to improve the solution quality. Numerical results are presented to show the optimal tradeoff between the reconfiguration duration and the required redundant capacity.**

I. INTRODUCTION

The rapid evolution of optical technologies is moving toward a wavelength-routed network architecture allowing dynamic configuration of end-to-end all-optical wavelength paths (lightpaths). Generalized MultiProtocol Label Switching (GMPLS) is the proposed control plane solution to integrate the data and optical network to support the Label Switched Path (LSP) in multiple layers [6]. Within a typical MPLS/WDM architecture, the wavelength routed optical backbone provides interconnection to a number of IP/MPLS routers by forming a virtual topology consisting of $\lambda-$LSPs (lightpaths, logical hops), each of them may span a number of fiber links (physical hops) [7].

Due to traffic load and network condition changes, the virtual topology is subject to reconfiguration in order to maximize the total network throughput. The reconfiguration process involves existing lightpath teardown and new lightpath setup and is desirably conducted in a hitless way, *i.e.,* the existing service would not be disrupted due to existing lightpath teardown, and the reconfiguration process should be as short as possible.

In the deterministic case, a future traffic profile at a reconfiguration point is known so that the targeted virtual topology can be obtained [4]. Here the objective is usually minimizing the reconfiguration time and the traffic interruption during the reconfiguration process. If there is sufficient redundant capacity, the reconfiguration can be conducted in a concurrent way that all the lightpaths in the current virtual topology will only be torn down after the new virtual topology has been set up and the traffic has been rerouted on the new topology [1]. Otherwise, the reconfiguration can be conducted step-by-step, *e.g.,* by branch exchange (tear down and set up two lightpaths per step) [2], where service interruption is minimized. Apparently, the redundant network capacity required in the former case is very high, while the reconfiguration process is very long and some service interruptions is unavoidable in the latter case.

In this paper, we propose a group-based virtual topology reconfiguration mechanism by using the existing protection backup capacity. This scheme lies between the concurrent reconfiguration [1], which requires a large amount of redundant capacity, and the step-by-step reconfiguration [2] [8], which needs a long reconfiguration process. It aims to achieve an optimal tradeoff between the reconfiguration duration and the required redundant capacity.

Survivability is a common requirement for MPLS/WDM networks. Among several proposed survivability schemes, path-based shared protection is favored because of its more efficient utilization of backup capacity, compared to link-based protection and path-based dedicated protection [5].

In the dedicated protection case, the virtual topology reconfiguration problem is trivial as it is equivalent to the one-step concurrent reconfiguration. However, in the shared protection case, a piece of protection capacity is always shared by multiple primary lightpaths and we cannot tear down all the primary lightpaths and shift the traffic to the backup lightpaths simultaneously. Therefore a multiple-step reconfiguration policy is necessary such that the group of primary lightpaths released at a reconfiguration step do not share the same backup capacity.

We formally define the shared protection based virtual topology reconfiguration problem in Section II. In Section III we present the proposed solution approach and a number of heuristic algorithms to find the approximation solutions for the defined optimization problems. Section IV presents the numerical results and Section V concludes the paper.

II. PROBLEM DEFINITION

In this paper, we assume the single link failure scenario, *i.e.,* , any primary lightpaths can share the same backup capacity (wavelength) in a physical link as long as they do not traverse the same physical link. We also assume failure-free during the reconfiguration process, *i.e.,* , all backup wavelengths are available for the reconfiguration purpose.

For the sake of concise presentation, the primary network resource considered here is the wavelength. However, both wavelength and optical transceiver consumption during the reconfiguration will be considered when we present the solution approaches and the numerical results.

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With the proposed multiple-step reconfiguration mechanism, the existing primary lightpaths are divided into groups such that no primary lightpaths in the same group share the same backup wavelength in the same backup link. At the m^{th} step, the following sequential actions are made to the lightpaths in the m^{th} group: (a) Shift the traffic (T_m) carried by the existing (old) primary lightpaths in the m^{th} group to their backup lightpaths simultaneously as they don't share any backup resource; (b) Tear down the existing primary lightpaths in the m^{th} group; (c) Find and set up the new primary lightpaths in the m^{th} group so that the traffic on the existing lightpaths of m^{th} group can be supported (rerouted); (d) Shift traffic T_m to the new lightpaths; (e) Tear down the existing backup lightpaths in the m^{th} group; (f) Set up the shared protection paths for the new primary lightpaths. We first define following notations:

- $G(N,E)$: a bi-connected graph representing the physical topology of OXC nodes N and fiber links E.
- $V(N,L_{old},B_{old})$, $V(N,L_{new},B_{new})$: the old virtual topology and the new virtual topology. $V(N,L,B)$ defines a virtual topology of nodes N, primary virtual links L and shared backup links B.

Suppose there are k reconfiguration steps and all the primary lightpaths in $V(N,L_{old},B_{old})$, $V(N,L_{new},B_{new})$ are grouped into k groups accordingly, for $0 \leq m \leq k-1$, we have following:

- $O_{old} = \{O^0_{old},...,O^k_{old}\}$, $O_{new} = \{O^0_{new},...,O^k_{new}\}$: the lightpath groups in the old and new virtual topologies. Sets O^m_{old} and O^m_{new} represent the m^{th} group of old and new primary lightpaths respectively.
- $O^m_{old}(E)$, $O^m_{new}(E)$: link wavelength usage vectors for lightpath groups O^m_{old} and O^m_{new}, where $O^m_{old}(e)$ and $O^m_{new}(e)$ represents the total number of wavelengths used in fiber link e when the lightpaths in O^m_{old} and O^m_{new} are set up respectively, $e \in E$.
- $\pi = \{\pi_0,...,\pi_k\}$: a permutation of the k lightpath groups. Such a permutation is also called a reconfiguration sequence or a reconfiguration policy.

We formally define the optimal reconfiguration problem by using the proposed mechanism as follow:

Definition 1: *Given:* $G(N,E)$, $V(N,L_{old},B_{old})$, and $V(N,L_{new},B_{new})$. The routing and wavelength assignment (RWA) for the primary lightpaths L_{old} and backup lightpaths B_{old} of $V(N,L_{old},B_{old})$ is given. The routing of L_{new} and B_{new} is also obtained before the reconfiguration.
Objectives: An optimal lightpath grouping $O_{old} = \{O^0_{old},...,O^k_{old}\}$, $O_{new} = \{O^0_{new},...,O^k_{new}\}$, and an optimal reconfiguration sequence $\pi = \{\pi_0,...,\pi_k\}$ so that $V(N,L_{old},B_{old})$ will be reconfigured to $V(N,L_{new},B_{new})$ in minimum steps with minimum network resource consumption.

III. Solution approach

The optimal reconfiguration problem can be divided into following two subsequent optimization problems.

1) *Reconfiguration Grouping Problem:* Given the old and new virtual topologies, minimizing the number of reconfiguration steps which is equivalent to minimizing the number of lightpath groups. This is the primary optimization objective.
2) *Reconfiguration Sequencing Problem:* Given a set of lightpath groups, optimizing the reconfiguration process so that the required network capacity during the reconfiguration process is minimized.

Sequentially solving the two problems and making the optimal solution to the first problem as the input to the second problem give us an optimal solution.

Theorem 1: The *Optimal Reconfiguration Grouping Problem* is NP-hard.
Proof Sketch The number of reconfiguration steps is equal to the number of groups dividing the primary lightpaths. The decision version of this problem can be shown equivalent to the NP-complete vertex coloring problem. An induced graph G_C can be created with the nodes representing the backup lightpaths and a link between two nodes as long as the two lightpaths represented by the two nodes share a common wavelength in a common physical link. It follows that the primary lightpaths whose backup lightpaths are in the same coloring subset can be reconfigured simultaneously. ■

Theorem 2: Given a set of lightpath groups, the *Optimal Reconfiguration Sequencing Problem* is NP-hard.
Proof Sketch The objective is to determine an optimal reconfiguration sequence $\pi = \{\pi_m\}, m \in \{0,1,2,...k-1\}$ of $\{O^m_{old}\}$. Based on the definition, the link wavelength usage change because of reconfiguring O^m_{old} at m^{th} step can be represented by the following vector:

$$A_m(E) = O^m_{new}(E) - O^m_{old}(E). \tag{1}$$

Let $L_m(E)$ be the wavelength usage vector for all links, $|L_m(E)| = |E|$, *i.e.,* $L_m(e)$ represents the number of wavelengths occupied in link e after the m^{th} reconfiguration step. $\overline{A_m(E)}$ and $\overline{L_m(E)}$ denote the total number of wavelengths used at the m^{th} step and up to the m^{th} step respectively. We note that $L_0(E)$ represents the total wavelength usage of $V(N,L_{old},B_{old})$ and $L_k(E)$ represents the total wavelength usage of $V(N,L_{new})$. $L_m(E)$ can be represented by expression (2).

$$L_m(E) = L_0(E) + \sum_{i=1}^{m} A_{\pi_i}(E) \tag{2}$$

Therefore the objective can be represented by expression (3).

$$\min \quad \max_{m=0}^{k} \quad \overline{L_m(E)} \tag{3}$$

If we define the group O^m_{old} as a single lightpath and the new lightpaths are the same as the old lightpaths except the new lightpaths have different routes (on the physical topology), the decision version of the above defined optimal reconfiguration problem can be reduced to the NP-Complete LSP rerouting problem defined in [8]. Therefore it is NP-Hard. ■

We note that $O^m_{new}(E)$ depends on the previous reconfiguration groups and sequence and cannot be obtained *a priori*.

Shared path protection based virtual topology reconfiguration algorithm

Input: $G(N,E)$, $V(N,L_{old},B_{old})$ and $V(N,L_{new},B_{new})$.
Output: $O_{old} = \{O^0_{old},...,O^k_{old}\}$, $O_{new} = \{O^0_{new},...,O^k_{new}\}$, and $\pi = \{\pi_0,...,\pi_k\}$.

1. begin
2.   Construct the induced graph G_c for B_{old}
3.   Solve the vertex coloring problem for G_c and obtain the optimal lightpath grouping.
4.   According to step 3, group the lightpaths in L_{old} into groups $O_{old} = \{O^0_{old},...,O^k_{old}\}$.
5.   *Alg-Sort(O_{old})*. //find an initial sequence.
6.   While O_{old} is not empty.
7. m = current step.
8. O^m_{old} = *Current-Group()*.
9.   Tear down lightpaths in O^m_{old}.
10.   Route lightpaths in O^m_{old} on $V(N,L_{new})$ to find the lightpaths in O^m_{new}.
11.   Set up new lightpaths in O^m_{new}.
12.   Tear down backup lightpaths in O^m_{old}.
13. $m = m+1$.
14.   End while.
15.   Set up nonconfigured lightpaths in L_{new}.
16.   Set up backup lightpaths in B_{new}.
17. end of the algorithm.

Fig. 1. Virtual topology reconfiguration algorithm

The entire reconfiguration algorithm is depicted in Fig. 1. Function *Alg-Sort(O_{old})* provides an initial sequence of old lightpath groups and *Current-Group()* decides the actual reconfiguration group at current reconfiguration step. In Step 10, corresponding to a O^m_{old}, we first calculate the route between the two end nodes of every old lightpath $l^{ij}_{old,m} \in O^m_{old}$ in the virtual topology $V(N,L_{new},B_{new})$ (*e.g.,* using the shortest path routing). O^m_{new} consists of all new lightpaths that are on these routes and have not been configured in previous steps. In this way, the virtual topology in any intermediate reconfiguration step always maintains the connectivity of the old virtual topology. Lightpath groups in O_{old} are mutually exclusive, so are those in O_{new}. Step 15 in the algorithm is necessary because there may be new lightpaths that are not needed at all for rerouting of the traffic in the old lightpaths, in which case, they will not be assigned to any O^m_{new}.

We use an existing heuristic algorithm for vertex coloring problem [3] to obtain an approximate solution for the *Optimal Reconfiguration Grouping Problem*. Two objectives, minimizing the number of wavelengths and minimizing the number of transceivers, are considered for the *Optimal Reconfiguration Sequencing Problem*. In the following, we focus on the heuristic algorithms, which essentially define the functions *Current-Group()*.

A. Base Heuristic algorithms

A base heuristic for *Current-Group()* simply takes the sequence decided by a algorithms for *Alg-Sort(O_{old})*. We define following three sorting algorithms:

1) Random selection (*RS*): This algorithm is used as a reference algorithm. The lightpath groups in $\{O_{old}\}$ are randomly sorted and the reconfiguration is conducted on the randomly determined sequence.
2) Maximal number of hops (*Max-H*): The algorithm *Max-H* counts the sum of hop counts of the lightpaths in every group of $\{O^m_{old}\}$ and sorts the groups in the decreasing rank of the count. This algorithm prefers the group whose teardown will release the most wavelength resource.
3) Minimum number of hops of newly setup lightpaths (*Min-H*): The algorithm *Min-H* counts the number of hop counts of the lightpaths in every group of $\{O^{m'}_{new}\}$ and sorts the corresponding old lightpath groups in nondecreasing rank of the count. This algorithm intends to first use the group whose new lightpaths require the least wavelength resource.

B. Online heuristic Algorithm

As we have mentioned before, we can not decide the new lightpaths in O^m_{new} prior to the m^{th} step, so does the actual network capacity change $A_m(E) = O^m_{new}(E) - O^m_{old}(E)$. The online algorithm (*online*) starts with the first group decided by above base heuristics. At the m^{th} step, the algorithm calculates the value of network capacity usage for all remaining $k-m+1$ groups and picks up the one with the minimum as the m^{th} group.

C. Rollout Algorithm

Rollout is a general approximate policy iteration method to obtain an improved policy for Markov decision process and combinatorial optimization problems [9]. Starting from a base heuristic, it is guaranteed to obtain a solution that is better than that obtained with the base heuristic. Our *Optimal Reconfiguration Sequence Problem* is actually a discrete multistage deterministic optimization problem for which the rollout technique can be used to improve the solution quality.

The rollout method defines a one-step look-ahead policy, with the optimal cost-to-go approximated by the cost-to-go of the base heuristic policy. For our k-stage *Optimal Reconfiguration Sequence Problem*, a rollout algorithm works in the following way. Given a partial sequential solution $\pi(m) = (\pi_1,\pi_2,...,\pi_m), m < k$, the policy (reconfiguration sequence) defined by the base heuristic extends it to a complete solution $\pi(k) = (\pi_1,\pi_2,...,\pi_k)$. At step $(m-1)$, the rollout algorithm checks all admissible actions (reconfiguration groups) at the step m and chooses the one leading to the minimal solution according to the sequence decided by the base heuristic. We note that the rollout algorithm defines neither a greedy nor a open-loop policy as it permutes over all the admissible actions (the remaining $k-m+1$ groups) at the m^{th} stage and extends to a complete solution according to the sequence decided by the base heuristic.

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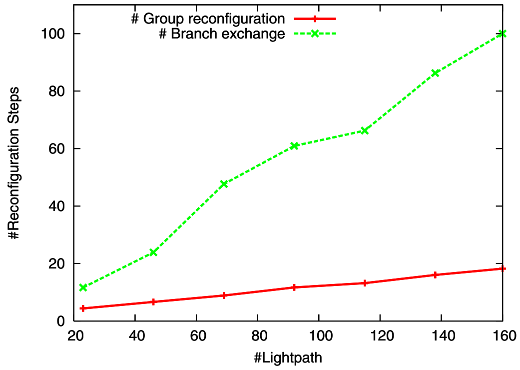

Fig. 2. Minimum number of reconfiguration steps vs. #Lightpaths L

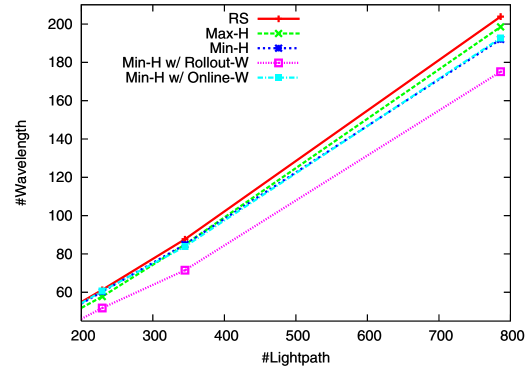

Fig. 3. Maximum number of wavelengths Vs. #Lightpaths L with different reconfiguration sequence algorithms

As we have identified three base heuristics, we get three online algorithms and three rollout algorithms accordingly for each of the two objectives. Therefore, we have six online algorithms and six rollout algorithms in total, which can be plugged into the base reconfiguration algorithm depicted in Fig. 1 to obtain the reconfiguration group at each reconfiguration step. In terms of the computation complexity, the rollout algorithms have the highest computation overhead, while the base heuristics have the lowest.

IV. Numerical analysis

In this section, we present numerical results to illustrate and compare the performance of the reconfiguration algorithms we discussed above. The simulation is conducted on an NSF network (14 nodes, 21 links) as the physical topology. Every point in the figures represents the average value over 100 independent runs with narrow statistical confidence range.

The virtual topology is constructed by a set of lightpaths and represented by a graph made up of nodes corresponding to the OXC nodes, *i.e.,* there is a virtual link between two OXC nodes if there is a lightpath between the two OXC nodes. Multiple lightpaths exists between a pair of OXCs and the virtual topologies we generated are all connected. We denote the number of lightpaths as L. As the routing and wavelength assignment problem itself is NP-Complete, existing heuristics are used to obtain the approximation solutions. Specifically, shortest path routing is used for both routing of lightpaths in the physical topology and the re-routing of old lightpaths in the new virtual topology. A constrained vertex coloring algorithm from [5] is used to obtain the approximate wavelength assignment for the old virtual topology and the shared protection backup lightpaths of the new virtual topology at the end of the reconfiguration process. The first-fit algorithm is used to assign the wavelength for the new primary lightpaths during the reconfiguration process. In all following figures, the X-axis represents the number of lightpaths needed to be reconfigured.

Fig. 2 shows the number of reconfiguration steps using our algorithm compared with the number of branch exchanges given in [2]. We note the topologies and virtual topology generation used in [2] are not the same as ours. However, as symmetric lightpath generation is assumed in both cases, statistically we believe the comparison is reasonable. It can be clearly observed that the number of branch exchanges increases much faster than the number of reconfiguration groups in our algorithm. For example, while 100 branch exchanges are required to reconfigure 160 lightpaths, our algorithm only needs about 19 reconfiguration steps. Actually, with larger number of lightpaths, the required branch exchange method may not work at all due to the large number of required reconfiguration steps. On the contrary, our algorithm increases the number of reconfiguration groups linearly with a very flat slope. For example, our algorithm only needs about 75 steps for reconfiguring 786 lightpaths in average.

Fig. 3 and Fig. 4 compare the performance of the different base reconfiguration sequencing algorithms and the corresponding online and rollout algorithms under the objective of minimizing the number of wavelengths. Fig. 3 shows the maximum number of wavelengths used during the reconfiguration process. When the number of lightpaths is small, the three base heuristics perform equally. When the number of lightpaths gets large, algorithms *Max-H* and *Min-H* start to perform better than the random algorithm *RS*. Specifically, *Min-H* always outperforms *Max-H*. However, the performance difference between these two algorithms is not very significant. For the three online algorithms, the one with *Min-H*, the best base heuristic, always performs the best. For the three rollout algorithms, the one with *Min-H*, the best base heuristic, always performs the best. We only depict the result from the best online algorithm (*Min-H w/ Online-W*) and the best rollout (*Min-H w/ Rollout-W*). The solution performance improvement with rollout is significant, which is more than 8% to reconfiguring 786 lightpaths. However, the online algorithm performs almost the same as the base heuristic.

Fig. 4 shows the maximum number of new lightpaths configured over all reconfiguration steps when applying different algorithms. It turns out that a LSR may only need one or two redundant transceivers for the reconfiguration purpose. For better illustration, we use the maximum number of newly setup lightpaths over all steps to approximate the total number

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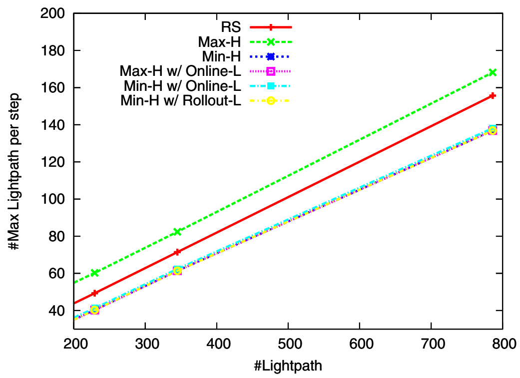

Fig. 4. Maximum number of newly setup lightpaths per step Vs. #Lightpaths L

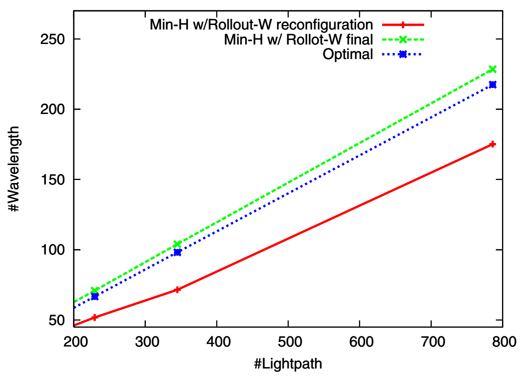

Fig. 5. Wavelength assignment Vs. #Lightpaths L

of redundant transceivers as the optimization objective. It clearly shows that *Min-H* performs much better than other two algorithms. The reason is that *Min-H* groups the lightpaths much more evenly such that only a moderate number of new lightpaths will be configured at every reconfiguration step. Again, the rollout algorithm (*Min-H w/ Rollout-L*) with the *Min-H* as the best base heuristic, always performs the best among the three rollouts. However, in this case, the rollout does not improve the performance of the base heuristic. The best of the three online algorithms (*Min-H w/ Online-L*) does not improve the performance of the heuristic too.

From the above analysis, we can see that the rollout algorithm with *Min-H* not only performs well in terms of the reconfiguration wavelength usage, but also achieves the best redundant optical transceiver performance among all the proposed reconfiguration group sorting algorithms. However, the solution to the reconfiguration sequence under the two different objectives are generally not the same.

Fig. 5 shows the wavelength assignment performance of the proposed reconfiguration mechanism when using the *Min-H w/ Rollout-W* algorithm. The approximate routing and wavelength assignment for the new virtual topology can be obtained before the reconfiguration for the comparison purpose and we call this solution as the *optimal solution*. Our algorithm will keep the same physical routes for the new lightpaths but the wavelength assignment for the new lightpaths would not be the same as the *optimal solution*. In Fig. 5, the curve *Optimal* represents the number of wavelengths required when running the approximate routing and wavelength assignment algorithm [5] for the new virtual topology independently on the physical topology, the curve *Min-H w/Rollout-W final* represents the final maximum number of wavelengths assigned at the end of our reconfiguration algorithm, and the curve *Min-H w/Rollout-W reconfiguration* represents the maximum number of wavelengths required during the reconfiguration process. It shows that the final wavelength assignment at the end of the reconfiguration is very close to the *optimal solution*. Another very desirable feature from Fig. 5 is that the maximum number of wavelengths used during the reconfiguration process is always less than that used to set up all the new lightpaths in the *optimal solution*.

V. Conclusion

In this paper, we present a novel multi-step mechanism to reconfigure the virtual topology in a survivable MPLS/WDM network by using the shared protection backup capacity. The existing primary lightpaths are grouped into subsets (groups) such that no primary lightpaths in the same group will share the same backup wavelength in the same link and therefore the lightpaths in a group can be reconfigured simultaneously at each step. Both single-hop and multi-hop traffic is taken care of. The optimal reconfiguration policy is obtained by solving the following two problems: (1) Minimizing the number of reconfiguration steps; (2) Minimizing the network resource (wavelengths and transceivers) required during the reconfiguration process. These two problems are proved to be NP-Hard and efficient heuristic algorithms are designed. A general policy iteration method, *rollout*, is applied to the heuristics to improve the solution quality. Through numerical analysis, the proposed reconfiguration mechanism demonstrates great scalability in terms of the number of reconfiguration steps and the amount of network capacity.

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