A Novel Approach of Backup Path Reservation for Survivable High-Speed Networks

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ABSTRACT

For high-speed networks, a restoration mechanism based on backup path provides a means for assuring their survivability. In this article, we propose a two-phase BP reservation mechanism for high-speed networks. In the admission phase, a pair of working path and backup path is selected from the provisioned sets of WPs and BPs. In the adjustment phase, if backup capacity utilization exceeds the preset threshold, BP assignments are rearranged to optimize the usage of backup capacity. A mathematical model is formulated to verify the quality of the optimized solutions. Computational experiments indicate that the proposed mechanism significantly reduces the consumption of backup capacity while still maintaining a high degree of survivability. Moreover, experiments show that the optimized solutions obtained are on average within 3.6 percent of optimal.

INTRODUCTION

With the advent of the multimedia information age, high-speed networks have drawn much attention in recent years. As for high-speed networks, quality of service (QoS) is one key design requirement. How to maintain QoS in network failure is an important and difficult problem.

Restoration mechanisms redirect impacted paths of network traffic. R. Kawamura *et al.* proposed the backup path (BP) restoration scheme [1]. During call admission, this scheme preassigns one BP to each admitted working path (WP). Restoration using BP is the best way of ensuring the QoS of high-speed networks, since a BP not only provides a fast restoration mechanism but also guarantees 100 percent survivability when the network suffers a single link failure.

There are two ways of allocating backup capacity. One, which statically allocates spare capacity for known network traffic, is a network design problem. This is the so-called spare capacity allocation problem (SCAP) [2]. Spare capacity allocation is not suitable for dynamic network traffic. The other, which dynamically reserves backup capacity from available bandwidth, is a network operation problem. Mechanisms proposed by S. Chen [3] and L. Chen [4] belong to this category. However, neither algorithm can guarantee satisfactory results.

In this article we propose a two-phase mechanism of BP reservation for survivable high-speed networks. Note that in the following discussions, the *path* of concern could be a label switching path (LSP) of a multiprotocol label switching (MPLS) network, a virtual path (VP) of an asynchronous transfer mode (ATM) network, or paths defined in other types of high-speed networks. For each call request, the admission phase is followed by the adjustment phase. In the admission phase, the proposed mechanism selects a pair of WP and BP from the provisioned sets of WPs and BPs. Two BP selection methods, min-cost and combined min-cost, are presented. A backup dependency matrix (BDM) is introduced to record the most up-to-date information of backup capacity required on every link. The use of BDM allows BP selection that is adaptive to current traffic loads on the network and backup capacity on a link shared by all BPs passing this link. In the adjustment phase, if backup capacity utilization exceeds the preset threshold, BP assignments are rearranged to optimize the usage of backup capacity. A mathematical model of the BP reservation problem (BPRP) is formulated. The lower bound obtained by relaxing the BPRP is used to verify the quality of the optimized solution. Computational experiments indicate that the proposed mechanism significantly reduces the consumption of backup capacity while still maintaining 100 percent survivability through a single link failure and near 70 percent survivability in double link failures. Moreover, experiments show that the optimized solutions obtained in the adjustment phase are on average within 3.6 percent of optimal.

In the following section we briefly review related research articles. The formal mathematical model of BPRP is given. We detail the proposed BP reservation mechanism. We present computational experiments followed by a complete analysis of these experiments. We conclude this article with possible future research directions.

LITERATURE REVIEW

RESTORATION MECHANISM

Restoration mechanisms differ with respect to restoration methods:

- Path restoration
- Link restoration

Path restoration provides a new path between the source and destination nodes of the failed path. Link restoration establishes a new route only between the end nodes of the failed link while still using the rest of the links in the old path. A BP used in path restoration is assigned before network failures occur to provide fast restoration. On the contrary, link restoration dynamically restores failed links and provides transparent protection to the end nodes of the failed path.

In [5], A. Gersht *et al.* presented a path restoration architecture. This architecture consists of the VP level and the call level. The VP level is responsible for VP provisioning and VP restoration. For each pair of nodes, two sets of VPs are provisioned in advance:

- Working VP (WVP) set, to be used for regular call operation
- Backup VP (BVP) set, to be used for VP restoration in case of network failures

The call level performs WVP and BVP selections, survivability admission control, and working and spare capacity reservations. In this architecture the VP restoration scheme proposed by R. Kawamura *et al.* [1] is used. In order to guarantee full restorability in any single link failure, a BVP is assigned between terminator nodes, and the path is completely disjoint to its protected WVP. This restoration scheme is simple and fast.

BACKUP PATH RESERVATION

Dynamic Reservation — In the network operation phase, a survivability admission control algorithm (SACA) dynamically reserves backup capacity. The SACA determines whether the network can fulfill the survivability requirement of each call request and make call admission accordingly. When an incoming call is admitted, the SACA reserves both working and backup capacities for this call.

Two types of SACA are in use:

- The state-independent SACA
- The state-dependent SACA

An example of the state-independent SACA is S. Chen's algorithm [3]. This algorithm makes the call admission decision based on fixed criteria that are predetermined before the call establishment phase (i.e., it has no relationship to current network traffic). Although the state-independent SACA requires less network information and makes real-time decisions for survivability admission, this approach has two problems:

- It is difficult to decide the optimal values of critical parameters.
- It cannot guarantee full restoration in a single link failure.

As to the state-dependent SACA, call admission is made based on network status information such as the usage of working and spare capacities on each link. It dynamically evaluates whether there is enough spare capacity for ensuring the survivability of an incoming call. An example of the state-dependent SACA is L. Chen's algorithm [4]. This algorithm is employed only on a fully connected mesh network and usually causes excessive use of backup capacity.

Static Allocation — In the network design phase, a spare capacity allocation algorithm statically allocates spare capacities for known network flows to ensure their survivability. For these flows, solving the SCAP determines their BP and the amount of spare capacity required on this path. The SCAP can be formulated as a multicommodity flow problem [2], which is an integer programming (IP) problem. The objective here is to minimize the total spare capacity required. For a small size network, the branch-and-bound method can be used to search for optimal solutions. However, for a large size network, exact solutions are rarely obtained since an IP problem is *NP-complete*. In this case, heuristics are developed to solve the SCAP [6].

THE BACKUP PATH RESERVATION PROBLEM

The BPRP formulated in this section is a variant of the SCAP. The BPRP differs from the SCAP in the way that the former reserves backup capacity for existing network traffic during the network operation phase (in this case, only a fixed amount of backup capacity is preallocated), whereas the latter allocates spare capacity for known network flows during the network design phase (in this case, the required amount of spare capacity is preallocated). The BPRP is formulated by adding a capacity constraint (an upper bound) on every link of the SCAP. It is an *NP-complete* problem [7]. Optimal solutions are rarely obtained. In the following section, the lower bound obtained by relaxing the BPRP is used to verify the quality of the solution obtained by using the proposed mechanism.

We are given a network G with N nodes and L links. We assume all WPs and their corresponding sets of link-disjoint BPs are provisioned during the network design phase. The number of WPs is P. For WP p, the number of provisioned link-disjoint BPs is Q^p. The cost of selecting link i as a backup link is c_i, $1 \le i \le L$. The backup capacity reserved on link i is represented by x_i. The spare capacity available on link i, denoted s_i, is expressed as follows:

$$s_i = C_i - \sum_{p=1}^{P} \zeta_i^p \cdot f^p, 1 \le i \le L,$$

where C_i represents the total capacity of link i, f^p the working capacity of WP p, and ζ_i^p a 0/1 variable that is 1 if WP p passes through link i. For links i and j, δ_{ij}^{pq} is 1 if WP p passes through link j while its qth provisioned BP passes through link i; otherwise, 0. The 0/1 variable α^{pq} is equal to 1 if WP p is protected by the qth BP in the provisioned set of BPs.

> *In order to guarantee full restorability in any single link failure, a BVP is assigned between terminator nodes and the path is completely disjoint to its protected WVP. This restoration scheme is simple and fast.*

Backup capacity reservation is the key for the success of network restoration. When an affected WP due to network failures switches its traffic to its protecting BP, sufficient backup capacities on the BP are required.

The optimization problem of finding a minimum BP reservation cost network that satisfies the conditions described above is called the BPRP. The BPRP can be formulated as follows:

(P)

$$\min \sum_{i=1}^{L} c_i x_i$$

subject to

$$x_i - \sum_{p=1}^{P} \sum_{q=1}^{Q^p} \left(f^p \cdot \delta_{ij}^{pq} \cdot \alpha^{pq} \right) \ge 0, 1 \le i \le L, 1 \le j \le L; \tag{1}$$

$$\sum_{q=1}^{Q^p} \alpha^{pq} = 1, 1 \le p \le P; \tag{2}$$

$$x_i \le s_i,\ 1 \le p \le P; \tag{3}$$

$$x_i \text{ is an integer}; \tag{4}$$

$$\alpha^{pq} = 0 \text{ or } 1,\ 1 \le p \le P,\ 1 \le q \le Q^p. \tag{5}$$

Constraint 1 requires that the reserved backup capacity on a link be larger than the required backup capacity on the link. Constraint 2 ensures that for every WP, only one BP is selected from its provisioned set of BPs.

THE PROPOSED MECHANISM

In this section we give a detailed discussion of the proposed two-phase mechanism.

THE ADMISSION PHASE

In the admission phase, a survivability admission control procedure is developed to select a pair of WP and BP, and reserve both working and backup capacities for an incoming call request. This procedure is a state-dependent approach using the path restoration architecture presented by A. Gersht *et al.* [5] and the path restoration scheme suggested by R. Kawamura *et al.* [1]. Backup capacity reservation and BP selection form the basis of the survivability admission control procedure.

Backup Capacity Reservation — Backup capacity reservation is the key to success of network restoration. When an affected WP due to network failures switches its traffic to its protecting BP, sufficient backup capacity on the BP is required. In the proposed mechanism, backup capacity reservation is based on the backup dependency matrix (BDM) originated in this article. For each link, the BDM records the minimum backup capacity required on this link for path restoration upon failure of the other links. For a high-speed network of L links, the BDM is an $L \times L$ matrix, denoted by (e_{ij}), $1 \le i \le L$, $1 \le j \le L$, where e_{ij} represents the minimum backup capacity required on link i for restoration due to a failure on link j. We further require that backup capacity on a link is shared by all BPs passing this link. Let x_i be the shared backup capacity on link i. Note that x_i is the same as that defined in BPRP. Since x_i is shared by all BPs passing the same link, x_i is equal to the maximum of all e_{ij} ($j = 1, \ldots, i - 1, i + 1, \ldots, L$).

For every newly admitted call with its WP passing through link j and its BP passing through link i, the backup capacity reservation procedure adds the amount of working capacity of the WP to e_{ij}, and then recalculates x_i. The survivability admission control procedure ensures that there is enough backup capacity ($\ge x_i$) on link i.

Backup Path Selection — For every call request, BP selection selects a pair of WP and BP from the provisioned sets of WPs and BPs. BP selection is based on the information recorded in the BDM, which allows the selection to be adaptive to current network traffic; thus, it makes the sharing of backup capacity possible. Two BP selection methods, *min-cost* and *combined min-cost*, are proposed.

To back up a selected WP, a sufficient amount of backup capacity has to be reserved on every link of its protecting BP. For every link of the selected BP, if the backup capacity currently reserved on this link is not enough, an additional amount of backup capacity is required. A cost of selecting this BP, the backup capacity reservation cost (BCRC), is defined as the total additional amount of backup capacity required on this BP.

The aim of min-cost selection is to reserve backup capacity as little as possible. For a selected WP and its set of protecting BPs, the min-cost selection selects the BP with the minimum BCRC.

Combined min-cost selection is a variation of min-cost selection. It aims to optimize overall network capacity utilization by considering both working and backup capacities at the same time. During the selection of WP and BP, working capacity is also considered. For a pair of WP and BP, the combined cost is defined as the sum of the working capacity of WP and the BCRC of BP. All possible WP-BP pairs are checked. The pair with the minimum combined cost is selected.

The Survivability Admission Control Procedure — For every call request, the survivability admission control procedure either accepts it with a pair of WP and BP assigned and capacities reserved, or rejects it. This procedure consists of three steps: BP selection, call admission control, and capacity reservation. Figure 1 depicts the control flow of the survivability admission control procedure.

Note that in BP selection, the WP is randomly selected from the provisioned set of WPs. In fact, other routing algorithms [3] can be used to select the WP.

THE ADJUSTMENT PHASE

In the adjustment phase, a heuristic is suggested to optimize the usage of backup capacity. This phase is invoked only if backup capacity utilization has exceeded the preset threshold.

Backup Path Adjustment — For WP p and its protecting BP r, the aim of the proposed heuristic is to select a BP, BP q, from the provisioned set of BPs such that the replacement of BP r by BP q maximizes cost reduction. Here, cost reduction is defined as the difference between the decrement of BCRC due to the removal of BP r

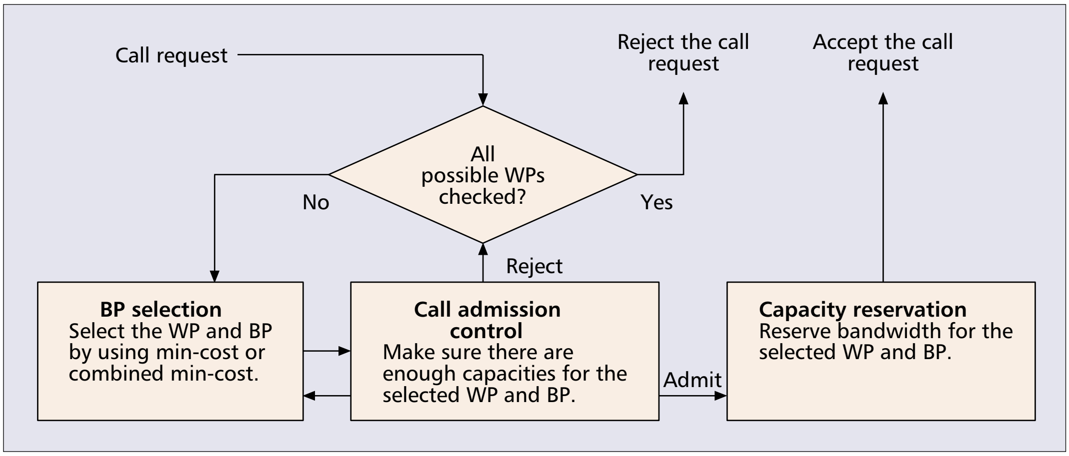

Figure 1. *Control flow of the survivability admission control procedure.*

There are cases in which more than one BP can maximize cost reduction. Under this situation, we will select the BP that allows backup capacity to be evenly distributed on every link so as to minimize the shared capacity required on every link.

and the increment of BCRC due to the addition of BP q ($q \neq r$) after the removal of BP r.

There are cases in which more than one BP can maximize cost reduction. Under this situation, we will select the BP that allows backup capacity to be evenly distributed on every link so as to minimize the shared capacity required on every link.

Let A_{pq} be the normalized difference between x_i and e_{ij} after removing BP r and adding BP q. A_{pq} is expressed as follows:

$$A_{pq} = \frac{\sum_{i\in \mathbf{BP}_q}\sum_{j\in \mathbf{WP}_p}(x_i^+ - e_{ij}^+)}{\left\|\mathbf{BP}_q\right\|\cdot\left\|\mathbf{WP}_p\right\|},$$

where ($e_{ij}{}^+$) represents the updated BDM by removing BP r and adding BP q;

$$x_i^+ = \max_j(e_i^+)$$

the shared backup capacity reserved on link i by removing BP r and adding BP q; $\|\mathbf{BP}_q\|$ the number of links in the link set $\mathbf{BP}_q$; and $\|\mathbf{WP}_p\|$ the number of links in the link set $\mathbf{WP}_p$.

Conceptually, a BP with high A_{pq} is routed along the path that has relatively low $e_{ij}{}^+$ compared to $x_i{}^+$. If the BP with the highest A_{pq} is chosen, backup capacity can be distributed more evenly to every link; thus, the chance of lowering x_i is increased.

For a given pair of WP p and BP r and all BP q ($q \neq r$) in the provisioned set of BPs, we present the following heuristic:

Step 1: BP q, which maximizes cost reduction, is selected to replace BP r.
Step 2: If there are more than one BP q that can maximize cost reduction, the one with the highest A_{pq} is selected to replace BP r.

The Backup Path Adjustment Procedure — The backup path adjustment procedure optimizes the usage of backup capacity whenever necessary. The control flow of the BP adjustment procedure is depicted in Fig. 2.

THE BACKUP PATH RESERVATION MECHANISM

The BP reservation mechanism includes the survivability call admission control procedure and the BP adjustment procedure. The control flow of the proposed mechanism is depicted in Fig. 3.

COMPUTATIONAL EXPERIMENTS AND ANALYSES

In order to test the proposed mechanism, we examine a set of network topologies. Four network topologies, as depicted in Fig. 4, are considered. The type A network is the New Jersey LATA network, type B is a 28-node network covering the continental United States, type C is fully connected [4], and type D is loosely connected.

PERFORMANCE METRICS

Two performance metrics are used to evaluate the effectiveness of the proposed mechanism.

- Average backup capacity consumption (ABCC): ABCC is equal to the total amount of reserved backup capacity divided by the number of admitted calls.
- Network survivability (NS): NS is defined as the ratio of the volume of restorable traffic loads to that of affected traffic loads due to link failures. In the following experiments, both single-link failure (NS1) and two-link failure (NS2) are considered

ASSUMPTIONS

In the experiments, the following assumptions are made:

- The provisioned set of WPs is generated as follows: for each pair of nodes of an experimental network, the shortest WP is first identified and included in the provisioned WP set; then all possible WPs whose hop number is greater than the number of hops of the shortest WP by 3 or less are included.
- The provisioned set of BPs is generated as follows: for a given WP, the shortest BP that is link-disjoint to the WP is first identified and included in the provisioned BP set; then all possible link-disjoint BPs whose hop number is greater than the number of hops of the shortest BP by 3 or less are included. Note that the link-disjoint property is required in [1]. The k-shortest path routing algorithm identifies link-disjoint paths.
- For each call request, the WP is randomly chosen from the provisioned set of WPs.

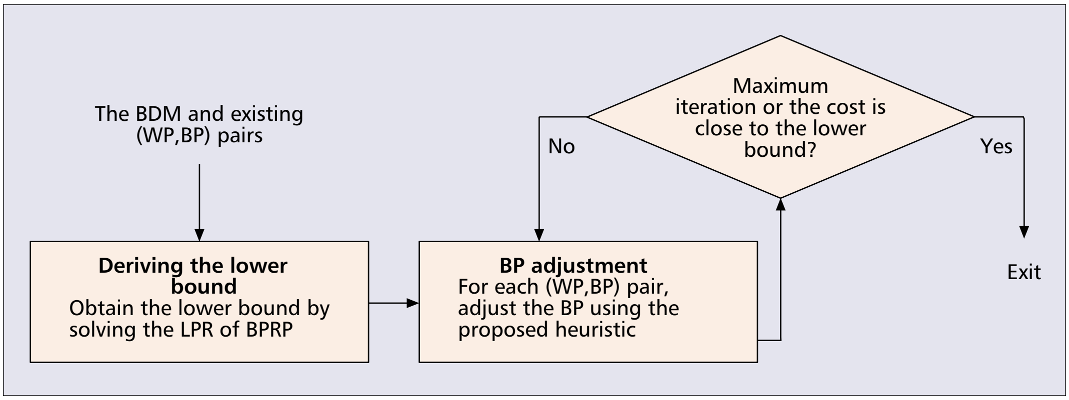

Figure 2. *Control flow of the backup path adjustment procedure.*

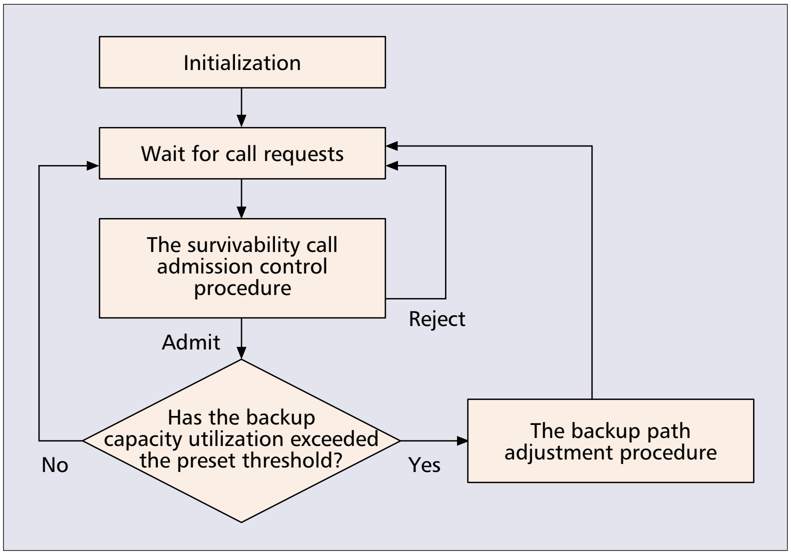

Figure 3. *Control flow of the proposed backup path reservation mechanism.*

- For all experimental networks, each link of the network is assigned 50 units of link capacity.
- For all experimental networks, the cost of backup capacity reservation on every link is set to 1.
- For each experiment we run 50 simulations, and then take the average. In each simulation we randomly generate 1000 call requests where each carries 1 unit of traffic load.
- The maximum number of iterations allowed in the adjustment phase is set to 30.
- In the adjustment phase, the threshold of the backup capacity utilization is set to 0 so that the effectiveness of the proposed heuristic can be verified.

RESULTS AND ANALYSES

The proposed mechanism is coded in C and runs on an IBM PC with an AMD Athlon processor and 256 Mbytes RAM. MATLAB v. 6.1 is used to solve the linear programming relaxation (LPR) of BPRP.

Effectiveness — Types A to D networks are considered. Both the ABCC and the NS are measured. For benchmarking, we have tested random selection and L. Chen's algorithm. Results are given in Table 1. In Table 2, saving represents the difference in percentage between the ABCC of the chosen selection and that of the random selection. The bigger the saving, the better the selection method.

By examining Tables 1 and 2, we make the following observations:

- The proposed mechanism with either min-cost or combined min-cost obtains better ABCCs than those obtained using the other two selection methods. Among all selection methods, combined min-cost obtains the best ABCC, since it is designed to optimize the total cost.
- For the two real networks, types A and B, the savings obtained by using min-cost and combined min-cost are substantial. Also, both min-cost and combined min-cost guarantee 100 percent survivability of a single link failure and provide nearly 70 percent survivability for double link failures.

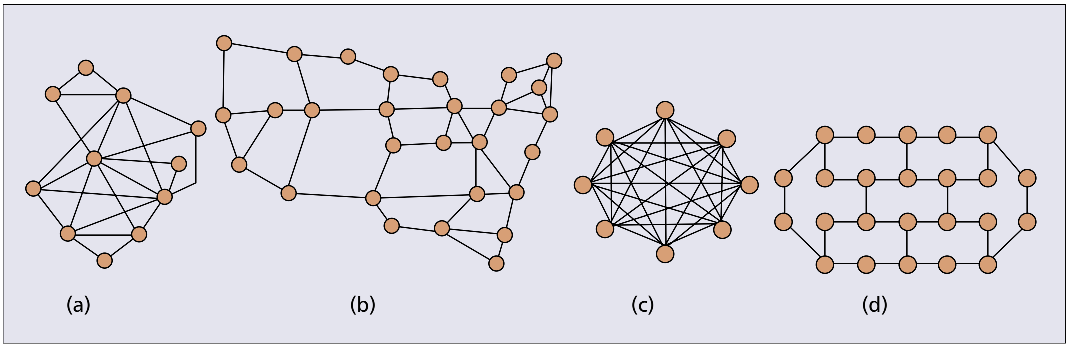

Figure 4. *Network topologies: a) type A; b) type B; c) type C; d) type D.*

Type	A			B			C			D		
	ABCC	NS		ABCC	NS		ABCC	NS		ABCC	NS	
Selection		NS1	NS2		NS1	NS2		NS1	NS2		NS1	NS2
(a)	1.03	100%	67%	1.37	100%	81%	0.52	100%	59%	1.61	100%	70%
(b)	NA	NA	NA	NA	NA	NA	0.38	100%	67%	NA	NA	NA
(c)	0.73	100%	66%	0.96	100%	79%	0.26	100%	64%	1.40	100%	69%
(d)	0.69	100%	64%	0.92	100%	77%	0.22	100%	63%	1.34	100%	64%

Legend (a) random selection; (b) L. Chen's algorithm; (c) min-cost selection; (d) combined min-cost selection; NA: not applicable

Table 1. *Comparison of different BP selections.*

Network type Selection	A	B	C	D
L. Chen's algorithm	NA	NA	26.9	NA
Min-cost selection	29.1	29.9	50	13
Combined min-cost selection	33	32.8	57.7	16.8

Legend NA: Not Applicable

Table 2. *Savings (%) in terms of backup capacity consumption.*

- Among all networks tested, the saving of a type C network is highest, since a type C network is fully connected. Also, for type C, the saving of L. Chen's algorithm is much lower than that of min-cost or combined min-cost. This phenomenon shows that L. Chen's algorithm results in excessive use of backup capacity.
- For a type D network, the saving is the lowest among all networks tested, since a type D network has the lowest connectivity.
- For types A, B, and D networks, the survivability for double link failures (NS2) of either min-cost or combined min-cost is slightly worse than that of the random method, since there is always a trade-off between backup capacity consumption and network survivability.
- For a type C network, L. Chen's algorithm has slightly better survivability in double link failures (NS2) than both min-cost and combined min-cost, since it is specifically designed for fully connected networks.

In summary, the higher the connectivity, the higher the saving. This suggests that the ABCC is related more to network connectivity than to network size.

Type	A		B		C		D	
Mechanism	**Cost**	**Gap (%)**	**Cost**	**Gap (%)**	**Cost**	**Gap (%)**	**Cost**	**Gap (%)**
LPR	170.88	–	222.25	–	50.56	–	290.5	–
RLPR	210	22.68	265	19.53	78	54.27	306	5.21
MI	201	17.63	290	30.48	102	101.74	324	11.53
1-phase	182	6.63	246	10.51	59	16.69	306	5.35
2-phase	179	4.87	233	4.84	55	8.78	293	0.72

Table 3. *Costs with respect to medium traffic load.*

Type	A		B		C		D	
Mechanism	**Cost**	**Gap (%)**	**Cost**	**Gap (%)**	**Cost**	**Gap (%)**	**Cost**	**Gap (%)**
LPR	313.53	–	524.08	–	232.8	–	408.6	–
RLPR	465	48.32	679	29.48	387	66.24	439	7.54
MI	354	12.91	629	20.02	373	60.22	446	9.15
1-phase	325	3.50	567	8.21	256	9.97	432	5.62
2-phase	316	0.91	541	3.30	241	3.52	414	1.27

Table 4. *Costs with respect to heavy traffic load.*

Quality — The quality of the proposed mechanism is measured in terms of the cost of backup capacity reservation. The lower the cost, the better the mechanism. The LPR of BPRP is solved to obtain the lower bound. Combined min-cost is used in the experiments. For the purpose of comparison, costs derived from the feasible solution obtained by rounding the LPR solution (RLPR), the proposed mechanism using only the admission phase (1-phase), and the proposed mechanism using both phases (2-phase) are considered. We have also tested the minimum interference (MI) heuristic proposed by Iraschko and Grover [7]. The MI dynamically selects a BP when network failures occur (i.e., the BP is not preallocated). Also, the objective of [7] is to maximize network survivability. Although the MI is not designed to solve the BPRP, it can be used to select a BP. Tables 3 and 4 present results for medium traffic load (200 WPs) and heavy traffic load (fully loaded network), respectively. In Tables 3 and 4, gap represents the difference in percentage between the cost derived from the chosen mechanism and the lower bound obtained by relaxing the BPRP. The smaller the gap, the better the mechanism.

By examining Tables 3 to 4, we notice:

- Comparing with the cost obtained by RLPR, we find that the cost obtained by 2-phase is much lower. The average cost, compared to the lower bound obtained by LPR, is within 3.6 percent of optimal.
- Comparing the cost obtained by 2-phase to that obtained by 1-phase, we notice that the

The proposed mechanism with either min-cost or combined min-cost obtains better ABCCs than those obtained using the other two selection methods. Among all selection methods, combined min-cost obtains the best ABCC, since it is designed to optimize the total cost.

adjustment phase significantly reduces the reservation cost. This observation indicates that the proposed heuristic is very effective.

- For 2-phase, gaps of the heavy traffic load are lower than those of the medium traffic load for types A, B, and C networks. The reason is that the proposed heuristic can distribute backup capacity more evenly for a heavy traffic load than for a medium traffic load.
- For all four networks, the cost incurred by using the MI is very high, since backup capacity is not always shared. In addition, the MI cannot guarantee 100 percent survivability in a single link failure.

In summary, a type C network has the highest gap. This suggests that for high-connectivity networks, an enhanced mechanism is needed to close the gap.

Complexity

Space Usage Analyses — For a network of V vertices and E links, the size of BDM is equal to E^2. For the provisioned set of WPs, its size is on the order of $O(V^2E)$. As for the provisioned set of BPs of a given WP, its size is also on the order of $O(V^2E)$.

Complexity Analyses — For a network of V vertices and E links, the initialization of BDM takes E^2 time units. A depth-first search algorithm of $\Theta(V + E)$ is used to construct both the provisioned WP and BP sets; therefore, the complexity of initializing both sets is $\Theta(V^3 + V^2E)$. For N call requests, the complexity of granting these request is $O(NE^2)$. In the adjustment phase, there are P ($P \leq N$) BP reassignments with $O(PE^2)$; thus, the complexity of admitting N call requests is $O(N^2E^2)$. In summary, we claim the complexity of the proposed mechanism is $O(N^2E^2) + \Theta(V^3 + V^2E) + E^2$, which is equal to $O(N^2E^2)$ if N is sufficiently large.

CONCLUSIONS

In this article, we propose a backup path reservation mechanism for survivable high-speed networks. This mechanism is the hybrid of the two well-known backup capacity reservation approaches: dynamic reservation and static allocation. The proposed mechanism has the following advantages:

- It significantly reduces the consumption of backup capacity while still maintaining a high degree of survivability.
- It is efficient since restoration using a BP is fast and robust.
- The optimized solution is verifiable using the lower bound obtained by relaxing the BPRP.

Here, we would like to mention the following areas of investigation that may merit further study:

- Refine the proposed mechanism for improving network survivability in multiple link failures.
- Make a comprehensive study on the problem of finding link-disjoint paths.

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