Comparative Study on Restoration Schemes of Survivable ATM Networks

Kazutaka Murakami
Bell Laboratories
Lucent Technologies

Hyong S. Kim
Department of Electrical and Computer Engineering
Carnegie Mellon University

Abstract

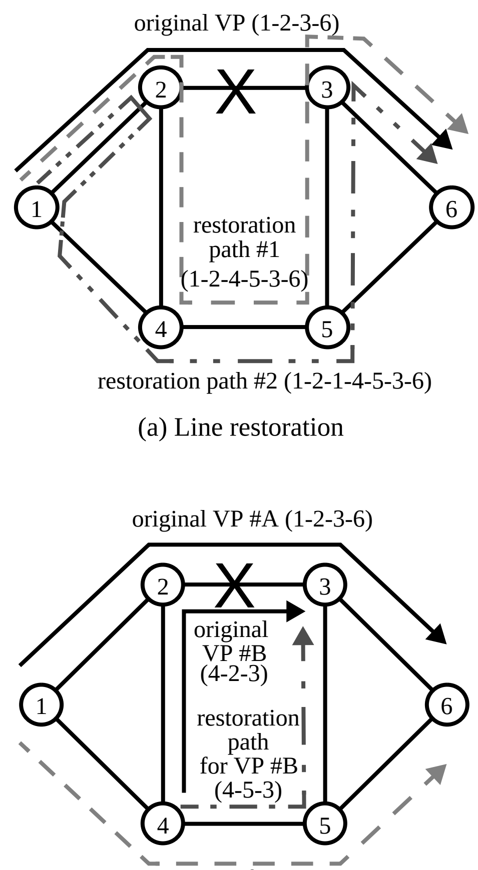
In self-healing networks, end-to-end restoration schemes have been considered more advantageous than line restoration schemes because of a possible cost reduction of the total capacity to construct a fully restorable network. This paper clarifies the benefit of end-to-end restoration schemes quantitatively through a comparative analysis of the minimum link capacity installation cost. A jointly optimal capacity and flow assignment algorithm is developed for the self-healing ATM networks based on end-to-end and line restoration. Several networks with diverse topological characteristics as well as multiple projected traffic demand patterns are employed in the experiments to see the effect of various network parameters. The results indicate that the network topology has a significant impact on the required resource installation cost for each restoration scheme. Contrary to a wide belief in the economic advantage of the end-to-end restoration scheme, this study reveals that the attainable gain could be marginal for a well-connected and/or unbalanced network.

Key words: *Survivable network design, Jointly optimal capacity and flow assignment, ATM self-healing networks*

1 Introduction

Network survivability has become a critical issue in telecommunication networks due to increasing societal dependence on communication systems and the growing importance of information. Fast restoration from a network failure has been recognized as a key ingredient in realizing survivable networks in emerging high-speed ATM environments. Self-healing techniques have been proposed to provide service continuity to end-users by autonomously switching affected virtual paths (VP's) to alternate routes [4] [5] [10] [12].

Depending on the location where traffic rerouting is performed, the proposed self-healing strategies can be categorized into two classes: line restoration and end-to-end restoration (Figure 1) [16]. When a link failure occurs, the line restoration scheme dispatches alternate routes between the two end-nodes of the failed link and reroutes all affected traffic around the link. On the other hand, the end-to-end restoration scheme switches failed VP's to alternate routes established between their respective source and destination nodes. When a failure is detected, recovery messages are sent to the source and destination nodes of all affected VP's to inform the failure. At this time, the bandwidth occupied by the affected VP's is released over their original routes. Then, each source node initiates virtual path switching over alternate routes. Note that all affected VP's are rerouted between the same end



(a) Line restoration

(b) End-to-end restoration

Figure 1. Line restoration and end-to-end restoration

0-8186-7780-5/97 $10.00 1997 IEEE

nodes with line restoration (between Nodes 2 and 3 in the example of Figure 1-a), while path rerouting takes place at different locations with end-to-end restoration (between Nodes 1 and 6 for the VP #A and between Nodes 4 and 3 for the VP #B in the example of Figure 1-b).

Despite the high complexity of its rerouting decision process, an end-to-end restoration scheme has been widely cited to be more advantageous than a line restoration scheme [5] [7] [8] [12] [15] [16]. The former scheme could effectively use the spare bandwidth, and thus less redundant capacity would be necessary to construct a fully restorable network. In addition, a VP may suffer backhauling [5] after restoration with line restoration. A VP relayed at a node adjacent to a failed link could be inefficiently rerouted back to the same link it traversed as in the restoration path #2 in Figure 1-a. However, no comprehensive work has been performed on the quantitative comparison of these two schemes to confirm this assertion for various network environments. The only available numerical results so far are based on computer simulation [5] or heuristics [12] using a single sample network. However, it is not clear how close the obtained solution is to the optimum. The comparison based on heuristics leaves us uncertain as to whether the benefit comes from the end-to-end restoration scheme or the optimization error.

In order to make a more meaningful comparison, an optimal spare capacity assignment should be sought for each restoration scheme. Previously, only a limited number of works have studied an optimal spare capacity placement problem for line restoration-based self-healing STM networks [11] [15]. Given the number of working transport paths per link, these studies calculate a spare link assignment with minimum installation cost, subject to the constraint that any single-link failure can be restored successfully. A flow is preassigned to each link, although there is no guarantee that this assignment gives the most cost-effective capacity placement. In [1], we have addressed the survivable capacity and flow assignment (SCFA) problem for line restoration based self-healing ATM networks. The goal is to find a capacity placement where full restorability is assured against any single-link failure. Joint optimization of capacity and flow assignment is carried out to find a truly optimal solution for a projected traffic demand. Since there is mutual dependency between the capacity placement and the survivable flow assignment, obtained solution cannot be claimed to be an optimum if these problems are treated separately [9]. As for end-to-end restoration-based networks, there is no published work on the optimal capacity assignment problem as far as we are aware of.

In this paper, a comparative analysis is extensively conducted to clarify the benefit of end-to-end restoration schemes quantitatively in terms of minimum resource installation cost. For this purpose, we first extend our previous approach reported in [1] to the SCFA problem for self-healing networks based on end-to-end restoration. This problem is referred to as the SCFA-ETE problem in this paper, while the one for the line restoration based networks is called as the SCFA-LINE problem. The problem formulation and the solution approach are described in the following two sections. Then, Section 4 reports the results of comprehensive numerical study. Several networks with diverse topological characteristics as well as several projected traffic demand patterns are employed in the experiments to see the effect of various network parameters. This is followed by the concluding remarks in Section 5.

2 Problem formulation

Figure 2 illustrates the survivable ATM network management architecture we have proposed [2] [3]. The survivability functions are embedded at the VP and higher layers, considering the fact that path level recovery enables rapid and efficient restoration and reduces the complexity of traffic management [16]. At the VP layer, the *VP manager* builds a VP sub-network over currently available physical network resources. Given a required VP-level bandwidth satisfying call level QOS, the VP manager configures virtual paths so that the survivability level is optimally enhanced. This issue is called the survivable VP assignment (SVPR) problem and is addressed in [2]. The VP manager also performs fast VP restoration when a network failure happens. If the VP manager cannot

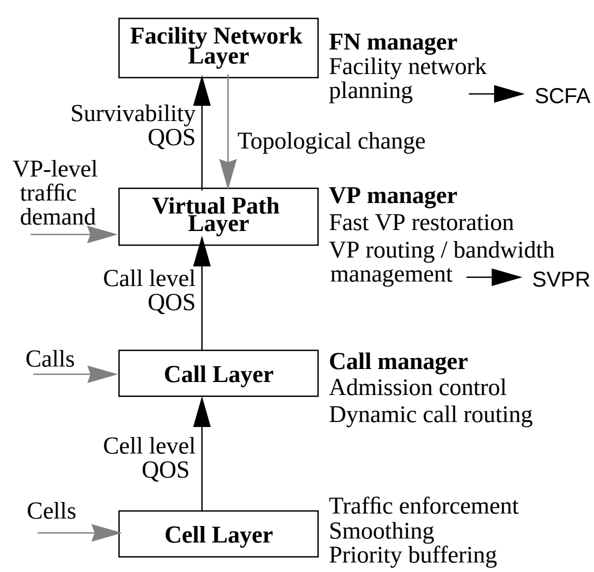


Figure 2. A survivable ATM network management architecture

maintain a survivability QOS[1] at a desired level due to a growth of traffic demand over months or years, the FN layer must trigger a facility network planning process. The *FN manager* designs a physical resource placement for a newly projected traffic demand so as to satisfy the survivability QOS objective. This leads to the SCFA problem discussed in this paper.

An ATM network is modeled as a directed graph $G = (V, A, \underset{\sim}{c})$ where V is a node set representing ATM switches, A is a set of directed arcs representing optical trunks, and $\underset{\sim}{c} = (c_a)$ is a vector of arc capacity ($a \in A$). Let E denote a set of undirected links. We assume that the network is bidirectional and that each link consists of two directed arcs with the same end-nodes but in opposite directions. A link represents a complete set of optical fibers installed between two nodes, and a network failure (e.g. a complete span cut) is expressed in terms of a link in the problem formulation. On the other hand, an arc embodies a set of transmission media going from one node to the other end of a link, and the capacity and flow assignments are calculated per arc.

Define a commodity as a traffic flow from an origin to a destination. One commodity is defined for each origin and destination pair. Let Π be a set of commodities in the network and $Q = \left(q^{\pi}\right)$ be a vector of the projected traffic demand for each commodity $\pi \in \Pi$. We assume that the required demand is expressed by a VP-level equivalent bandwidth discussed in [2] [3]. Multiple VP's could be established for each commodity to satisfy the traffic requirement. Let P^{π} be a set of all possible routes for commodity π, and $RP^{\pi, l}$ be a set of all possible end-to-end restoration routes for commodity π against a failure of link l. Define a path flow vector $\underset{\sim}{x} = \left(x_p^{\pi}\right)$, a commodity restoration path flow vector $\underset{\sim}{r} = \left(r_p^{\pi, l}\right)$, and an arc spare capacity vector, $\underset{\sim}{z} = (z_a)$. x_p^{π} takes the amount of a commodity flow over the route $p \in P^{\pi}$, $r_p^{\pi, l}$ holds the value of a restoration flow over the path $p \in RP^{\pi, l}$ upon a failure of link l, and z_a gives the spare capacity bandwidth of arc a.

Assuming that the network resource installation cost is a linear function of arc capacity, the problem is formulated as follows;

Minimize $\quad D(\underset{\sim}{x}, \underset{\sim}{r}, \underset{\sim}{z}) = \sum_{a \in A} d_a \cdot c_a$

over $\quad \underset{\sim}{x} \geq \mathbf{0},\ \underset{\sim}{r} \geq \mathbf{0}\ \ \underset{\sim}{z} \geq \mathbf{0}$

subject to

a) $\sum_{p \in P^{\pi}} x_p^{\pi} = q^{\pi} \qquad \forall \pi \in \Pi$

b) $z_a + r_a^l - z_a^l \geq 0 \qquad \forall a \in A, \forall l \in E_a$

c) $\sum_{p \in RP^{\pi, l}} r_p^{\pi, l} - \sum_{a \in l} \sum_{p \in P^{\pi}} \theta_{a, p} \cdot x_p^{\pi} = 0 \qquad \forall \pi \in \Pi, \forall l \in E$

$$c_a = f_a + z_a$$

$$f_a = \sum_{\pi \in \Pi} \sum_{p \in P^{\pi}} \theta_{a, p} \cdot x_p^{\pi}$$

$$z_a^l = \sum_{\pi \in \Pi} \sum_{p \in RP^{\pi, l}} \theta_{a, p} \cdot r_p^{\pi, l}$$

$$r_a^l = \sum_{\pi \in \Pi} \sum_{p \in P^{\pi}} \theta_{a, l, p} \cdot x_p^{\pi}$$

Constraints a), b) and c) correspond to the flow conservation law, the capacity constraints, and the full restorability constraints, respectively. d_a is a unit arc cost and E_a is a set of all links except for the one containing arc a. $\theta_{a,p}$ is the arc-path indicator variable which equals 1 if arc a is contained in path p and 0 otherwise. Similarly, $\theta_{a,l,p}$ takes a value 1 if both arc a and link l are contained in path p and 0 otherwise. f_a holds the total amount of flow over arc a, while z_l^a gives the amount of necessary spare bandwidth of arc a against a failure of link l. Finally, r_l^a expresses the amount of bandwidth of arc a which is released by affected VP's due to a failure of link l. In the above formulation, the most economic capacity placement is sought through a joint optimization, subject to the constraint that a network can survive any single link failure for a projected traffic demand.

3 Solution Approach

A similar approach to the SCFA-LINE problem [1] can be applied to the SCFA-ETE problem. The arc-chain flow representation [6] is employed on the commodity flow as well as restoration flow instead of the arc-node representation. The arc-chain flow representation significantly lowers the size of a constraint set, especially for a large network. For example, the size of flow conservation constraints is reduced from $|\Pi| \cdot |V|$ ($O(V^3)$) to $|\Pi|$ ($O(V^2)$). The column generation approach [13] is applied to accommodate infinitely many path variables in the arc-chain flow representation. The technique generates variables as needed during the course of the algorithm instead of listing all columns at once. Then, the solution procedure is decomposed into a master process and a sub-process. The sub-process adopts the simplex algorithm and calculates an optimal solution using generated columns. On the other hand, the master process checks whether the obtained solution is globally optimal or not. If not, it generates new columns which would help to decrease the total cost.

The computational burden of the simplex procedure in the sub-process can be greatly lowered by exploiting the special structure of the problem. The following theorem is

1. For example, an expected lost flow due to a failure event can be used as a survivability QOS [2].

used to develop our algorithm:

Theorem 1

Assume $q^{\pi} > 0$ for $\forall \pi \in \Pi$. Then the following statements are true at the end of any iteration.

- For each commodity $\pi \in \Pi$, at least one commodity path flow variable, x_p^{π} ($p \in P^{\pi}$), is in the basis.
- For each $\pi \in \Pi$ and $l \in E$, it is possible to maintain at least one restoration path flow variable, $r_p^{\pi, l}$ ($p \in RP^{\pi, l}$), in the basis.

(proof) Refer to [3].

We randomly choose one such basic column for each flow conservation law constraint as well as full restorability constraint, and call it a *key* flow column. Then, the basis matrix, B, can be arranged as shown below, and it can be readily factorized into an LU form:

$$B = \begin{bmatrix} I & & & & C \\ R & I & & & D \\ A_1 & H_1 & -I & K_1 & M_1 \\ A_2 & H_2 & & I & M_2 \\ A_3 & H_3 & & K_3 & M_3 \end{bmatrix}$$

$$= \begin{bmatrix} I & & & & \\ R & I & & & \\ A_1 & H_1 & I & & \\ A_2 & H_2 & & I & \\ A_3 & H_3 & & K_3 & \hat{L} \end{bmatrix} \cdot \begin{bmatrix} I & & & & C \\ & I & & & F \\ & & -I & K_1 & Y_1 \\ & & & I & Y_2 \\ & & & & \hat{U} \end{bmatrix} \qquad (1)$$

where $F = D - RC$, $Y_i = M_i - (H_i \cdot F) - (A_i \cdot C)$ (i = 1,2, 3), $Z \equiv \hat{L} \cdot \hat{U} = Y_3 - (K_3 \cdot Y_2)$ and I is an identity submatrix. The first set of columns corresponds to the key commodity path flow variables, and the second set is composed of the key restoration path flow variables. The remaining commodity and restoration path variables are collected into the last set. The third and fourth sets of columns contain the slack variables of the capacity constraints and the spare capacity variables, respectively. The first and second sets of rows represent the flow conservation law and the full restorability constraints, respectively. The capacity constraints are collected and arranged in the last three sets of rows so that the identity submatrices with proper sign can appear in the place as shown in Equation (1). All sub-matrices, R, A_i, H_i, K_i, and M_i (i=1,2,3) are sparse.

The major computational task here turns out to be the factorization of the submatrix Z since the matrix multiplications to obtain F, Y_i and Z can be easily performed by exploiting the problem structure. The dimension of Z is identical to the number of non-key flow variables which is significantly smaller than that of the original matrix. By taking advantage of the similarity between two successive submatrices, we can further economize the computation through a direct update of the $\hat{L}\hat{U}$ submatrices instead of new factorization at each iteration. This can be carried out in the same fashion as described in [1].

Additional mechanisms must be devised to tackle the new issues inherent to the SCFA-ETE problem. First of all, the number of full restorability constraints grows enormously, from $|A|$ ($O(A)$) in the SCFA-LINE problem to $|E| \cdot |\Pi|$ ($O(AV^2)$) in the SCFA-ETE problem (i.e. from 46 to 2,530 for an (11,46) network[2], and from 90 to 34,020 for a (28,90) network). Although the size of the submatrix Z and the computation of $\hat{L}\hat{U}$ factorization remain the same, the revised simplex procedure significantly slows down in the computation of an entering column vector and simplex multipliers at each iteration. The end-to-end restoration scheme requires that its full restorability constraints be expressed for all combinations of commodities and link failure scenarios. However, the full restorability constraint for commodity π and link l, which we call *(π, l) constraint* in this paper, is necessary only if at least one generated commodity flow for π, x_p^{π}, goes through link l. The (π, l) constraint is defined *active* if it satisfies the above condition and is called *inactive* otherwise. The inactive (π, l) constraints do not have any effect on the sub-process since the value of their related basic variables, $r_p^{\pi, l}$, stays zero in the entire operation of the sub-process. Since each commodity is expected to be transferred over only a fraction of a network, the number of the constraints can be largely reduced by generating only active (π, l) constraints.

The master process generates a (π, l) row when the row becomes active due to newly generated commodity flow variables of π. In addition, it deletes non-basic commodity and restoration flow variables which have not been referred to for some period. This decreases the number of non-basic variables involved in the pricing-out operation [14] in the subprocess. More importantly, the dimension of the basis matrix can be reduced. A (π, l) row can be removed if it turns inactive as a result of the deletion of a non-basic commodity flow variable. Note that this column deletion procedure can be performed only when the objective function value has improved in the previous sub-process. This condition is required to guarantee the termination of the algorithm in a finite number of iterations [3].

The major role of the master process is to test the dual feasibility conditions and to determine whether the solution obtained in the sub-process is globally optimal or not. The following dual feasibility conditions must be satisfied:

2. A network with n nodes and m arcs is referred to as an (n, m) network in this paper.

$$\sum_{a \in p} (d_a + w^{\pi}_{l \ni a}) - \sum_{l \in p} \sum_{a \in p} \mu^l_a \geq \sigma^{\pi} \qquad (2)$$

$$\forall p \in P^{\pi}, \forall \pi \in \Pi$$

$$\sum_{a \in p} \mu^l_a \geq w^{\pi}_l \qquad \forall p \in RP^{\pi, l}, \forall \pi \in \Pi, \forall l \in E \qquad (3)$$

where σ^{π}, w^{π}_l and μ^l_a are the simplex multipliers corresponding to the flow conservation, full restorability and capacity constraints, respectively. Note that $\mu^l_a = 0$ if $a \in l$. Although these conditions must hold for all non-generated commodity and restoration paths, it suffices to examine their shortest paths to verify the global optimality, as in the SCFA-LINE problem [1]. However, a well-known shortest path algorithm cannot be applied to the test on the dual feasibility condition (2). This condition is assured if the length of the shortest path of commodity π with the modified arc cost $\left(d_a + w^{\pi}_{l \ni a}\right)$ and the mutual arc cost $\left(-\mu^l_a\right)$ is not less than σ^{π}. The mutual arc cost is imposed if a path goes through both arc *a* and link *l*. A quadratic shortest path (QSP) algorithm, which we've developed in [3], can be used to obtain the shortest path of this type. As to the condition (3), a traditional shortest path algorithm can be adopted. This condition is satisfied if the length of the shortest path $p \in RP^{\pi, l}$ under modified arc length μ^l_a in the network $G \backslash \{l\}$ is not less than w^{π}_l. If the dual feasibility conditions are violated, then the master process generates all violated shortest paths and invokes the sub-process. Otherwise, the current solution is globally optimal.

4 Numerical Results

Extensive experiments have been carried out to analyze the effectiveness of the end-to-end restoration scheme in a wide variety of network environments. Eight sample networks with diverse topological characteristics have been explored in the experiment. Four of them are real networks which had appeared in the literatures [9] [10] [17] (Figure 3). The other four are artificial networks (Figure 4). In the experiments, two commodities are assumed to be defined between any node pair, one for each direction. The results based on the following two projected traffic demand patterns are reported in this paper: A uniform (UF) demand pattern with 1,000 BU[3] between any node pair, and a weighted (WT) demand pattern with 1,000 BU between any adjacent nodes and 500 BU for the others. We have further used several random demand patterns in the experiments, and the results are consistent to those reported in this paper [3].

The required spare capacity cost is investigated for the two restoration schemes: end-to-end restoration (ETE) and line restoration (LINE). It is expressed in terms of a normalized spare capacity cost (*NC*), which is defined as follows: Let *D** be the minimum link cost required to support the traffic demand. Obviously, the minimum is attained when all demands are sent over their shortest routes. Let D_T be the total link cost obtained using a fully restorable capacity placement scheme *T*. Now, define the required spare capacity cost of *T* as an additional cost necessary to realize full restorability with the scheme, which

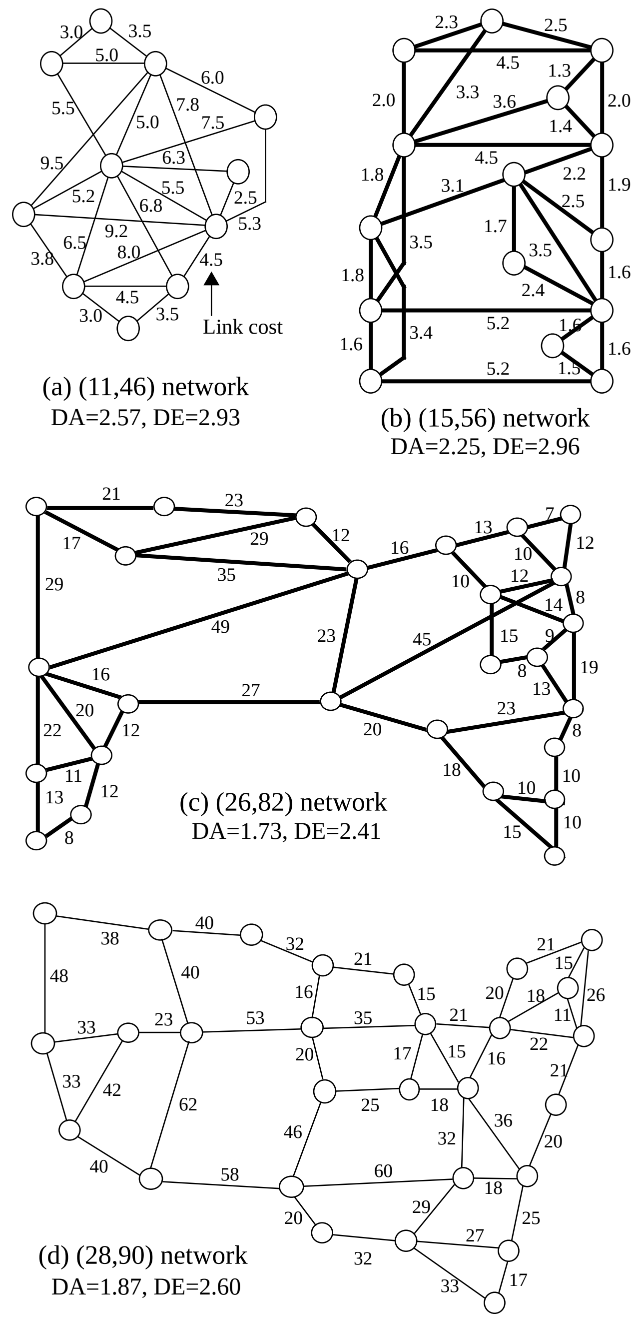


Figure 3. Sample networks 1. Real networks

3. BU (bandwidth unit) is an arbitrary unit of bandwidth, say Mbps

Network model	Unbalanced Networks				Balanced Networks			
	Well-connected <---> Sparse				Well-connected <----> Sparse			
	(11,46)	(15,56)	(28,90)	(26,82)	(12,50)	(16,56)	(13,40)	(24,60)
Cost (ETE) [NC]	52.86	43.93	51.86	78.69	25.31	30.76	39.86	37.80
Cost (LINE) [NC]	54.45	51.60	67.65	83.71	35.52	39.07	50.44	83.07
Savings rate[a]	2.93	14.87	23.35	6.00	28.74	21.27	20.98	54.50
Cost savings[b]	1.59	7.67	15.79	5.02	10.21	8.31	10.58	45.27

a. {LINE-ETE} / {LINE} (percent)
b. {LINE-ETE} (NC)

Table 1. Required spare capacity cost and cost savings (UF demand)

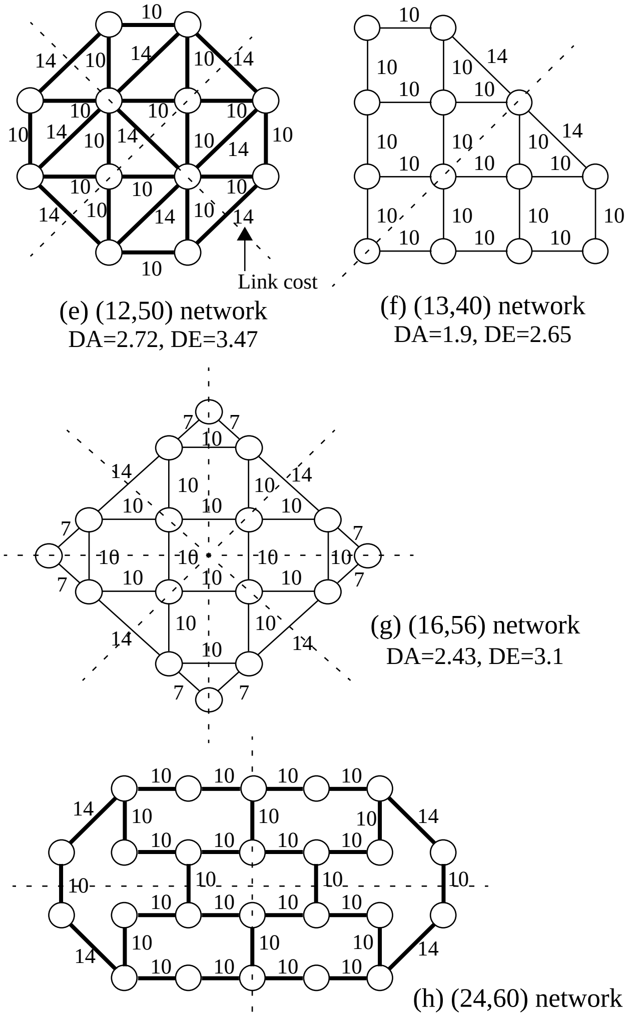


Figure 4. Sample networks 2. Artificial networks
The dotted lines represent the axes of symmetry.

is given by $(D_T - D^*)$. The normalized spare capacity cost (*NC*) is obtained through the normalization of the above cost with respect to D^*, which is given by $100 \cdot (D_T - D^*)/D^*$ %. Note that the additional cost is not necessarily equal to the cost of the actual spare bandwidth because a resulting flow assignment may be different from a shortest route flow.

Table 1 summarizes the results. The cost savings obtained by ETE restoration over LINE restoration are also listed in the table. The savings rate ranges widely from 3 to 55 percent, suggesting that network topology is a crucial factor for economic gain from end-to-end restoration. Then what kind of network topology obtains a more economic benefit by using an end-to-end restoration scheme? We find that the following two topological aspects have a large influence on the required spare capacity cost: *connectivity* and *connection regularity.*

Connectivity expresses how well nodes are connected in a network. It is expected that a well-connected network requires less spare capacity than a sparse network, since the former would have more candidate restoration paths than the latter. In the following discussion, the average number of disjoint arc restoration paths, *DA*, is employed as the measure of the connectivity for the networks based on the line restoration scheme. It is defined by:

$$DA = \sum_{a \in A} DA_a / |A|$$

where DA_a is the number of disjoint restoration paths for arc *a*. Our study shows that a network needs less spare capacity if more spare bandwidth is shared for restoration from different failure scenarios [3]. The *degree of sharing in spare capacity* (DSSC) among failure scenarios is expected to have something to do with the number of disjoint restoration paths; The more disjoint restoration paths, the more the effect of failure can be distributed over restoration paths. As for the network based on the end-to-end restoration scheme, the average number of disjoint end-to-

0-8186-7780-5/97 $10.00 1997 IEEE

end paths, *DE*, is employed as the measure of the connectivity. It is defined by:

$$DE = \sum_{\pi \in \Pi} DE_{\pi} / |\Pi|$$

where DE_{π} is the number of disjoint paths between the source and destination nodes of commodity π.

Connection regularity is another important topological measure. The measure should express how evenly the links are connected over a network and how symmetrically the connection is arranged in a network. If a connection is well-balanced, it is expected that the affected VP's can be distributed over the network more evenly, which could promote attainable DSSC among different failure scenarios and require less spare capacity in total. A major obstacle here is that the measure is very hard to quantify. In the following discussion, we classify eight sample networks into two categories: balanced networks and unbalanced networks. A good measure for the connection regularity needs to be considered further in future works. The eight sample networks can be categorized as follows:

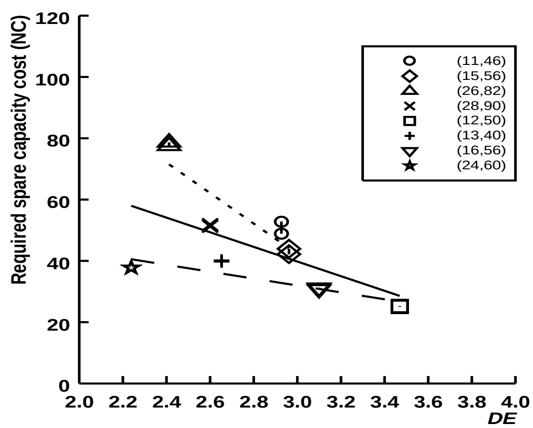
1. Balanced networks: (12,50), (16,56), (13,40) and (24,60) networks in decreasing order of network connectivity.
2. Unbalanced networks: (11,46), (15,56), (28,90), and (26,82) networks in decreasing order of network connectivity.

Figure 5 depicts the relationship between connectivity and the required spare capacity cost. Two demand patterns, UT and WT, are employed for each sample network. The solid line in the figure is the least-square line over all sample points, while the dashed line is the least-square line over all samples of the balanced networks, and the dotted line is that over all samples of the unbalanced networks.

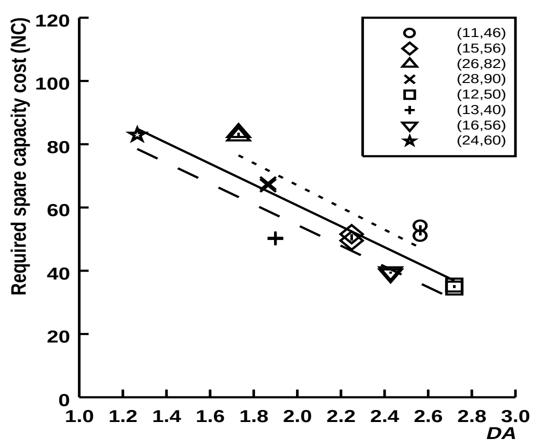
Figure 5-a shows that in case of end-to-end restoration all balanced sample networks necessitate less spare capacity than any unbalanced model networks. For example, the (24,60) network requires less spare bandwidth than the (15,56) network, although the former has a lower level of network connectivity (*DE*) than the latter. This indicates that connection regularity is a major factor in determining the required spare capacity; The DSSC is very high for balanced networks, since alternate paths could be dispersed in a geographically wider area in case of ETE restoration.

Among the balanced networks, well-connected networks can generally require less spare capacity cost. The only exception is the (13,40) network, which requires a slightly higher amount of redundant capacity than the (24,60) network in spite of its higher connectivity. This is because the (13,40) network is less symmetrical than the (24,60) network. The (13,40) network is symmetric along only one axis, while the (24,60) network is symmetric along two axes (see Figure 4). This suggests the regularity has a significantly larger impact on the required capacity. The same argument on the effect of connectivity can apply for the unbalanced networks, but it holds only weakly. A possible cause is the difference in the regularity level among those networks. In summary, connection regularity turns out to be an important factor in deciding the redundant capacity cost of fully restorable networks with end-to-end restoration, while connectivity plays a minor role in the determination of cost.

Next, consider the case of line restoration (Figure 5-b). The figure shows that balanced networks require less spare capacity than unbalanced networks if they have a similar level of connectivity. For example, although the connectivity level (*DA*) is almost the same for the (13,40) and (28,90) networks, the former requires less spare bandwidth due to its connection regularity. Unlike the end-to-end restoration, however, connection regularity is not a single key factor but connectivity also plays an important



(a) ETE restoration



(b) LINE restoration

Figure 5. Topological effect

role in determining the necessary spare capacity cost. For example, the (24,60) network requires a considerable amount of spare bandwidth due to its sparseness even though it is well-balanced. Since rerouting is executed between the two end-nodes of an affected link, all restoration flow must be sent over the unaffected arcs adjacent to the nodes. However, the number of such arcs is very small for a sparse network. Consequently, a larger amount of spare capacity must be installed over the arcs. In addition, backhauling happens with a higher possibility for a network with a low connectivity [3], and this further deteriorates the performance of line restoration. In summary, both connection regularity and connectivity are the key factors in determining the necessary spare bandwidth for fully restorable networks based on line restoration.

Now we address the following question posed before: What kind of network topology gets more economic benefit from the end-to-end restoration scheme? As shown in Table 1, large cost savings are generally expected for balanced sparse networks, as in the (24,60) network. This is because regularity gets a significant advantage from end-to-end restoration, and sparsity places a considerable penalty on line restoration. In a practical situation, however, network topology can not always be balanced due to a physical limitation or is not necessarily sparse.

On the other hand, such a disadvantage posed on line restoration may fade away for well-connected networks. Furthermore, end-to-end restoration may not be able to reap a large gain for an unbalanced network. Consequently, the cost savings could be small for unbalanced and/or well-connected networks. This accounts for the fact that only nominal savings can be obtained in the (11,46) (unbalanced and well connected) network, and small savings can be obtained for the (26,82) (unbalanced) network. In such networks, it may not be advisable to employ the end-to-end restoration scheme, considering its complicated decision making process on the alternate routes.

5 Summary

Extensive study on the required spare capacity cost for the end-to-end and line restoration schemes is presented. For this purpose, a joint capacity and flow optimization method is developed for the fully restorable networks based on the end-to-end restoration. In the study, we find that the regularity of a network is a critical factor for the required redundant capacity cost in the end-to-end restoration based systems, while both the connectivity and regularity are the decisive elements for the line restoration based networks. The result suggests that a balanced sparse network can gain a remarkable benefit from end-to-end restoration. Contrary to a wide belief in the economic advantage of the end-to-end restoration scheme, the analysis has revealed that the attainable gain could be marginal for a well-connected and/or unbalanced network. Considering its complicated decision making process on the alternate routes, it is not always advisable to employ the end-to-end restoration scheme in such networks.

References

[1] K.Murakami and H.S.Kim, “Joint optimization of capacity and flow assignment for self-healing ATM networks,” *IEEE ICC ‘95*, Jun. 1995.

[2] K.Murakami and H.S.Kim, “Virtual path routing for survivable ATM networks,” *IEEE/ACM Trans. on Networking*, vol.4, no.1, pp.22-39, Jan. 1996.

[3] K.Murakami, “Survivable network management for high-speed ATM networks,” Ph.D. dissertation, *Department of Electrical and Computer Engineering, Carnegie Mellon University*, Sep. 1995.

[4] Special issue on “Integrity of public telecommunication networks,” *IEEE JSAC*, vol.12, no.1, Jan. 1994.

[5] J.Anderson, B.T.Doshi, S.Dravida and P.Harshavardhana, “Fast restoration of ATM networks,” *IEEE JSAC*, vol.12, no.1, pp.128-138, Jan. 1994.

[6] A.A.Assad, “Multicommodity network flows - A survey”, *Networks*, vol.8, pp.31-91, 1978.

[7] J.E.Baker, “A distributed link restoration algorithm with robust preplanning,” *IEEE Globecom ‘91*, pp.306-311, Dec. 1991.

[8] R.Doverspike, “A multi-layered model for survivability in intra-LATA transport networks,” *IEEE Globecom ‘91*, pp.2025-2031, Dec. 1991.

[9] B.Gavish and I.Neuman, “A system for routing and capacity assignment in computer communication networks,” *IEEE Trans. on Comm.*, vol.37, no.4, pp.360-366, Apr. 1989.

[10] W.D.Grover, “The selfhealing network: A fast distributed restoration technique for networks using digital cross-connect machines,” *IEEE Globecom ‘87*, pp.1090-1095, Dec. 1987.

[11] W.D.Grover, T.D.Bilodeau and B.D.Venables, “Near optimal spare capacity planning in a mesh restorable network,” *IEEE Globecom ‘91*, pp.2007-2012, Dec. 1991.

[12] R.Kawamura, K.Sato, and I.Tokizawa, “Self-healing ATM networks based on virtual path concept,” *IEEE JSAC*, vol.12, no.1, pp.120-127, Jan. 1994.

[13] T.Leventhal, G.Nemhauser and L.Trotter, “A column generation algorithm for optimal traffic assignment,” *Transportation Science*, vol.7, no.2, pp.168-176, May 1973.

[14] D.G.Luenberger, “Linear and nonlinear programming,” 2nd ed., Addison-Wesley, Reading, M.A., 1984.

[15] H.Sakauchi, Y.Nishimura and S.Hasegawa, “A self-healing network with an economical spare-channel assignment,” *IEEE Globecom ‘90*, pp.438-443, Dec. 1990.

[16] T-H.Wu, “Fiber network service survivability,” Artech House, Norwood, M.A., 1992.

[17] T-H.Wu, H.Kobrinski, D.Ghosal, and T.V.Lakshman, “The impact of SONET digital cross-connect system architecture on distributed restoration,” *IEEE JSAC*, vol.12, no.1, pp.79-87, Jan. 1994.