Design of Self-Healing Algorithm for ATM Networks *

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Abstract

Automatic and rapid network service restoration (self-healing) when failures occur is of increasing importance for network operations and management as network speed and bandwidth increase. In this paper, we study the self-healing problem of an ATM network at the virtual path (VP) configuration level. We analyze the design issues of self-healing algorithms, and develop a state transition and bandwidth division model of individual VPs and links. On top of the model, we design a restoration algorithm that searches and activates alternate VPs for the failed VPs by combining a preplan method and a double search method. The preplan method activates preassigned backup VPs dynamically, while the double search method searches for alternate VPs from both the source and destination nodes of failed VPs. The double search method is also applied to reconstruction of the backup VP plan. Simulations demonstrate that our new algorithms outperform existing preplanned and dynamic self-healing algorithms in both restoration time and restoration ratio.

I Introduction

An ATM (asynchronous transfer mode) network [1] is a high-capacity optical fiber network, which transports signals of various services such as voice, data, image, and video. As an ATM-based network offers a high transimission capacity of integrated services, the failure of a network element (NE) such as a link or a node can cause a significant loss of services to users and a loss of revenue to the network operating companies. It is estimated that if the network is disabled for one hour, up to $6,000,000 loss of revenue may occur in the trading and investment banking industries [2]. Therefore, automatic and rapid network service restoration (self-healing) when failures occur is of increasing importance for network operations and management.

In the literature, there have been a few approaches for self-healing. In [3][4], a class of three-phase (route-search/acknowledgement/confirmation), distributed, flooding schemes are designed for self-healing in STM networks. The restoration is performed by the end nodes of the failed link. One of the nodes is called the sender node and the other is called the chooser node. When a failure occurs, the search message is initiated at the sender, flooded throughout the network, and finally terminated at the chooser. This algorithm is very simple and easy to implement, but its large number of restoration messages may waste the network resource or worsen the congestion situation when failures occur. Yoshikai and Wu [5] proposed a reliable protocol by extending the flooding algorithm to ATM networks with the consideration of self-healing control messages loss. To speed up the route search, a double search method [6] is proposed that search messages are initiated by both end nodes of a failed link.

In addition to the flooding algorithm-based self-healing schemes, many recent developements [7][8][9][10] exploit the concept of the VP (virtual path) in ATM networks, and develop the class of preassignment or preplan methods. In a preplan method, each VP is assigned a backup VP in advance. When a failure occurs, some backup VPs are activated to replace the failed VPs. This technique simplifies the message transmission processes and reduces the number of restoration messages. Self-reconstruction techniques of backup VPs are also proposed.

To provide a prioritized restoration based on the quality of service (QoS) requirements of users, Chang and Huang [11] designed a scheme of prioritized backup VP assignment, where a high priority VP is assigned a backup VP and a reserved bandwidth while a low priority VP is only assigned a backup VP with zero bandwidth.

This paper focuses on designing a distributed algorithm for self-healing at VP configuration level under signle ATM network failure. It combines both the preplan and double search methods into a superior self-healing algorithm. The remainder of the paper is organized as follows. Section II defines the self-healing problem. A VP state transition model is then developed in Section III. Based on the model, a failed VP restoration algorithm and a backup VP reconstruction algorithm are proposed in Section IV. A simulation study in Section V demonstrates the superior time efficiency and restoration ratio of our self-healing algorithm. Finally, Section VI concludes the paper.

II Self-Healing Problem of ATM Networks

A virtual path (VP) in an ATM network is a pre-established path between two ATM network nodes, which may go through a few links and nodes with the same bandwidth provision. The topology and band-

*This work was supported in part by the National Science Council of Republic of China, Taiwan, under Grants NSC85-2213-E-002-045 and NSC86-2221-E002-016.

0-8186-7225-0/98 $10.00 © 1998 IEEE

width allocation of VPs in an ATM network is called a VP configuration. In a VP configuration, a source-destination (S-D) pair may be sequentially connected via several VP links, [12].

There are two types of VPs : regular VPs, and backup VPs [7]. A regular VP is a normal VP which has both a VP identifier (VPI) and a non-zero bandwidth allocation, whereas a backup VP has also a VPI but is allocated zero bandwidth. The objective of backup VPs is to provide alternate paths when regular VPs fail. Although a backup VP has the same terminal nodes with its corresponding regular VP, it goes through a completely different set of links from the regular VP to avoid a simultaneous failure of both. When a backup VP is activated, it can only use the residual bandwidth of individual physical links through which it passes. The bandwidth is called a captured bandwidth.

Since an ATM network supports high speed transport of multimedia services, its regular VPs and backup VPs are determined by the network management system based on QoS requirements of individual services and traffic demand distribution of the network. It is recalculated periodically in order to gain an up-to-date optimality of resource allocation. After each computation of VP configuration, the network management system downloads the VP configuration data to each node (or switch).

When a link failure occurs, it must first be identified which VPs are on the failed link and all nodes on failed VPs should be notified about the failure. In order to recover the interrupted services on failed VPs, an alternate VP should be established to replace each failed VP. As an alternate VP may be prone to failure itself, a backup VP should be constructed for it as soon as the alternate VP is activated. Hence, there are three basic sub-problems for ATM network self-healing: failure detection and diagnosis, alternate VP search and activation, and backup VP plan reconfiguration.

Failure Detection and Diagnosis

In an ATM network, the availability of a VP is monitored and tested as part of the fault management functions of operation, administration, and maintenance (OAM)[13][14]. ATM cells which transmit various types of OAM information are called OAM cells. Among them, we concentrate on the type F4 OAM cells for VP failure notification, which can be generated due to a physical link failure or a node (switch) failure. Such an OAM cell should indicate the occurrence of NE failure, the location of failure, and the VPs that are affected. We consider the alarm surveillance method for failure detection because it is the most time efficient among the three methods proposed by the ATM Forum [15].

A VP failure is reported in the ATM Layer with two types of cells: VP-AIS(Alarm Indication Signal) and VP-FERF(Far End Report Failure). Upon receiving a persistent failure indication from the Physical Layer, a detecting node will periodically issue VP-AIS cells to notify downstream nodes of the VP about connection unavailability until the fault is corrected. After receiving a certain number of VP-AIS cells, the VP endpoint will begin to send VP-FERF cells upstream to notify the source VP endpoint of the downstream failure.

Alternate VP Search and Activation

Once a failure is detected, the self-healing function should then find an alternate path for each failed VP to recover the interrupted services. There are several issues of consideration:

1. physical connectivity: A self-healing system must search for an alternate VP that has the same terminal nodes with the failed VP but goes through a completely different set of physical links.
2. time constraint: There is a time limit for recovering the interrupted services, for example, 2 seconds for a metropolitan LATA mesh network [16], which in turn poses a constraint on the number of VP links to search.
3. bandwidth capturing: An alternate VP should be allocated the same bandwidth as the bandwidth of the failed VP if possible to maintain a desirable QoS [17]. Routing tables in ATM switches should be modified accordingly.

Backup VP Plan Reconfiguration

After alternate VPs are found and activated, the interrupted services are recovered. A question then arises : "what should be the backup VP to an alternate VP itself?". So the backup VP plan needs to be reconfigured based on the current VP configuration and physical link availability.

III Self-Healing Algorithm Design Model

To describe the dynamic system behavior of a VP configuration, we first define a state set X of seven states for a VP as follows. In the definition, both classes regular VPs and activated (non-zero bandwidth) backup VPs are called active VPs. A VP that replaces a failed VP is called an alternate VP of the failed VP.

State Set $X \equiv \{x_1, x_2, ..., x_7\}$

x_1 (active_static state): an active VP with a backup VP;

x_2 (active_dynamic state): an active VP with no backup VP;

x_3 (r-invalid state): a VP in failure but with an alternate VP;

x_4 (invalid state): a VP in failure with no alternate VP (including the backup VP in failure);

x_5 (backup_inactive state): a backup VP with zero bandwidth;

x_6 (backup_semiactive state): an activated backup VP onto which no new calls can be added;

x_7 (inactive state): a repaired backup VP which is of zero bandwidth and backing up no other VP after repair.

There are nine events that may cause state transitions:

Event Set $E \equiv \{e_1, e_2, ..., e_9\}$

e_1 : the VP under discussion fails;

e_2 : the VP under discussion is repaired;

e_3 : the backup VP of the VP under discussion fails;

e_4 : the backup VP of the VP under discussion is repaired;

e_5 : an alternate VP is found for the VP under discussion;

e_6 : the backup VP is activated and captures a bandwidth after the regular VP under discussion fails;

e_7 : the corresponding regular VP of the backup VP under discussion is repaired;

e_8 : the VP under discussion is selected as a backup VP;

e_9 : the last call terminates on the backup VP under discussion.

State transitions are shown in Fig.3.1. For example, consider a regular VP in an active_static state and its backup VP in a backup_inactive state. If now the regular VP fails, it transits to the invalid state, and its backup VP becomes active_dynamic; If the failure occurs on the backup VP, it then transits to the invalid state, and its regular VP transmits to be active_dynamic. Since regular VPs and their bandwidth allocations are determined via optimization in the configuration phase, traffic provisioning should be through regular VPs whenever possible. So when a failed regular VP is repaired, no new calls can be placed to its backup VP but the regular VP itself.

Link Bandwidth Division

In our model, the bandwidth of each link in the network is divided into three parts: normal bandwidth, reserved bandwidth and available bandwidth. A reserved bandwidth is allocated to backup VPs when activated in order to guarantee a given minimun restoration ratio. The normal bandwidth is the total allocated bandwidth of all VPs on a link. The available bandwidth equals to the bandwidth of a link bandwidth minus both reserved bandwidth and normal bandwidth.

In the self-healing procedure, the alternate VP of a failed VP may capture its bandwidth from different categories of link bandwidth based on the state of the failed VP. If a failed VP is active_static, when activating its backup VP, the bandwidth is to be captured from the available or the reserved bandwidth. In activating an alternate VP of an active_dynamic VP, the bandwidth is captured from the available bandwidth only.

IV Algorithm Design

On top of the model described in Section III, we combine ideas of the preplan method and the dynamic double search method into a new self-healing algorithm in order to achieve a short restoration time and a high restoration ratio at the same time. When VP failures due to a single link failure occurs, if a failed VP is at an active_static, active_dynamic, or backup_semiactive state, a restoration algorithm is designed to find an alternate VP for it. If the state is backup_inactive, we design a reconstruction algorithm to construct a new backup VP. If the state is inactive, r-invalid, or invalid, there needs no actions because these failed VPs do not affect the transmission traffic in the network and do not incur a revenue loss.

A regular VP can be either active_static or active_dynamic before failure. The restoration algorithm adopts two methods of restoration based on the state of a regular VP when failure accurs: preplan method for an active_static VP and double search method for an active_dynamic VP.

IV.1 Preplan Method for Restoration

The preplan method preassigns a backup VP in advance for each regular VP and thus requires a short restoration time of searching for an alternate VP at occurrence of a failure. Since the active_static VPs have their individual backup VPs, when an active_static VP fails, the preplan method first finds and activates its backup VP from the destination node to the source node. The required bandwidth should be captured by each node along the backup VP when activated. If any link en-route does not have enough available bandwidth to support the backup VP, the preplan method then fails, and the interrupted service on this failed VP is not recovered.

An algorithmic summary of the preplan method is described as follows.

Preplan Method Algorithm

Step P1: Activate the backup VP at the destination node.

P1.1 Find the backup VP of the failed VP from the node's VPI mapping table;

P1.2 Change the failed VPI in the routing table to its backup VPI;

P1.3 Send a restoration message to the node one link upstream along the backup VP;

Step P2: Capture the required bandwidth and activate backup VP at an intermediate node.

P2.1 When a node, say n_1, receives a restoration message from node n_2, if the node is the source node for the VP to be restored, then go to step 3;

P2.2 If (available + reserved) bandwidth > required bandwidth on the link from node n_1 to n_2 that is traversed by the backup VP,
then capture the required bandwidth from the available bandwidth first and then from the reserved bandwidth;

P2.3 Elseif the preplan method fails,
a release message is sent to node n_2 to release all the bandwidths that have been captured from n_2 to the destination node of the backup VP, and restoration of the failed VP stops;
endif.

P2.4 Activate one VP link upstream (towards the source node) following the same procedure of Step P1 but at the intermediate node.

Step P3: Complete restoration at the source node.

P3.1 When the source node receives a restoration message, it follows Steps P2.2 and P2.3;

P3.2 If it goes through 2.2, then go to the reconstruction algorithm steps since a backup VP is successfully activated for restoring the failed VP and a new backup VP is needed for the activated backup VP itself.

Note that both restoration and release messages used in the method belong to the class of self-healing control (SHC) messages.

IV.2 Double Search Method for Restoration

An active_dynamic VP cannot be restored by the preplan method because it has no backup VP. Ideas of the distributed double search method by [6] are adopted to search for and activate an alternate VP when an active_dynamic VP fails. Both the source and destination nodes of a failed active_dynamic VP broadcast a SHC search message for a VP link with the required bandwidth to all of their neighborhood nodes. Neighborhood nodes that can locally provide the required bandwidth will then relay the search to their respective neighborhood nodes, so on and so forth. When any node in the network receives two search messages originated from the source and destination nodes respectively, the node is defined to have a collision. The node combines the contents of the two colliding search messages to construct a new SHC message called a response message and returns the response message along the coming paths of the two search messages to source and destination nodes respectively. An alternate VP between the source and destination nodes is then established.

In searching for an alternate path by the double search method, there may be more than one collisions in the network because the searching messages are broadcasted, i.e., more than one alternate VPs may be identified. Information of these VPs are sent to the destination node by individual response messages. In this paper, the destination node takes the first response message arrival (and ignores the later ones) to construct the alternate VP. It then sends a completion message to complete the construction. If the source node of the failed VP does not receive a completion message in a limited amount of time, the restoration fails and stops.

Double Search Algorithm (Sketch)

For the source node:

Step S1: Broadcast a search message when failure of the actvie_dynamic VP is detected and start a timer;

Step S2: If the timer value > a limit, then time is out, discard the restoration process, reset the timer and stop.

Step S3: Elseif a completion message is received, change the failed VPI in the routing table to its alternate VPI.

For the destination node:

Step D1: The same as Step S1;

Step D2: The same as Step S2;

Step D3: Elseif a response message is recevied, change the failed VPI in the routing table to its alternate VPI.

Step D4: Send a completion message along the alternate VP.
Endif.

For any other node,say node V_1:

Step n1: The same as Step S2.

When a search message is received

Step n2: Assume that the search message is from node V_2. If (available + reserved) bandwidth on the link between nodes V_1 and V_2 is larger than the required bandwidth, then reserve the required bandwidth over the link, add the link and node to the path information of the search message, and ignore other search messages from the same origin (source or destination) node regarding the failed VP. Start a timer;
else ignore the search message.
endif.

Step n3: Check if recevied search message from the source node collides with one from the destination node in their corresponding failure VP information.

Step n4: If not, generate and broadcast a search message to neighboring nodes.

Step n5: Else, synthesize a response message by combining the two colliding search messages and send the response messages to nodes traverse by the two colliding search messages;
endif.

When a response message is received

Step n6: Update the routing table, capture appropriate bandwidth, and relay the response message to the next node en-route.

When a completion message is received

Step n7: Relay the completion message originated from the destination node to next node upstream along the alternate VP, check the routing table according to the completion message, and reset the timer.

Both preplan and double search methods do not allow partial restoration. Namely, a backup or alternate path must capture at least the same bandwidth as the failed VP. This of course may reduce the restoration ratio of our self-healing algorithm. However, consideration of partial restoration is expected to increase the problem complexity and the decision time for self-healing.

IV.3 Reconstruction Algorithm

Reconstruction of backup VPs is needed on the following three occasions: that backup VPs fail, that new VPs are established without backup VPs, and that network bandwidth allocations are changed due to failure restoration. Although the time requirement for finding a backup VP is not so stringent as finding an alternate VP, it is still highly desirable to be fast so that each active VP has a backup VP to cope with the next failure. To reduce the search space, a limitation is set on the number of VP links that a backup VP may go through. If no backup VP can be found under the constraint, then the reconstruction of a backup VP for the source-destination pair fails.

Our reconstruction algorithm design is also based on the double search method in order to keep the advantage of high restoration ratio and low restoration time. Once a need is identified for a backup VP between a pair of source and destination nodes, a double search algorithm as described in Section *IV* is used to establish a backup VP except that SHC-help and confirmation messages are used for broadcasting and routing table setting instead, and that no bandwidth is assigned to the backup VP.

V Simulation Results

In this section, we make up an examplary ATM network based on Taiwan's ATM testbed network. The examplary network consists of 7 nodes and 15 bidirectional links, which has more links than reality in order to increase the options of alternate paths. Two VP configurations are designed for the network, one with 20 VPs and the other with 30 VPs. Regular and backup VPs are generated in random, and route of a regular VP is disjoint from the route of its backup VP.

In both VP configurations, the reserved bandwidth per links is 10% of link capacity. In order to prevent all backup VPs from going through the few links, we control the bandwidth that can be used by backup VPs per link via a backup bandwidth parameter. This parameter affects the probability of finding a backup VP and the distribution of VPs over the VP configuration. It is set to 5 times of the reserved bandwidth in our simulation study.

Two types of failure situations are simulated: single link failure and a second link failure on the backup VP before the regular VP failure is repaired. A link failure is randomly generated in each simulation run and Monte-Carlo simulation runs are conducted for each type of failure situation. We evaluate the restoration time and ratio performance of our self-healing algorithm and compare with self-healing methods of purely preplan method and purely double search (dynamic) method.

Figures 6.1-6.4 summarize the simulation results, where Figures 6.1 and 6.2 are for VP configuration 1 and Figures 6.3 and 6.4 are for configuration 2. Each figure indicates the average restoration ratio as a function of the restoration time. From all these figures, we observe that given a restoration time less than 0.43 second, the preplan method is the best in restoration ratio because the backup VPs in the preplan method are preplanned via optimization. Our proposed algorithm stays quite close in average restoration ratio performance to the preplan method. The dyanmic (double search) method searches for the alternate VPs in real time and is thus the worst in restoration ratio. When given a restoration time longer than 0.45 second, our proposed algorithm outperforms both preplan and dynamic methods. The asymptotic performance between our proposed algorithm and the dynamic algorithm is close for both VP configurations. The restoration ratio of preplan method levels off quickly after 0.38 second. These results indicate that our proposed algorithm may perform well under a high VP density configuration and when sequential link failures occur within a short duration.

VI Conclusion

In this paper, based on the features of ATM network VP configuration, we developed a seven-state and bandwidth division model for self-healing algorithm design. A restoration algorithm which combines the preplanned method and double search method is designed to deal with alternate VP search and activation for VPs at different states. A reconstruction algorithm was also developed based on the concept of double search method for backup VP reconstruction. Simulation results demonstrated that our proposed self-healing algorithm indeed capture the features of both the preplan and the double search algorithms and thus achieved superior performance in restoration ratio and restoration time. Futher evaluation and extension of the algorithm to node and multiple failures are now underway.

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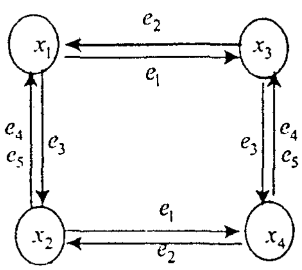
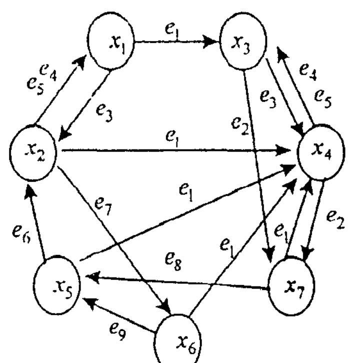


(a) state transition model for regular VPs



(b) state transition model for backup VPs

Figure 3.1: State Transition Model

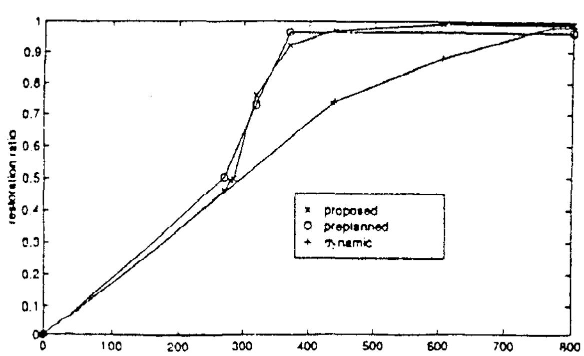


Figure 6.1: Self-Healing of First Failure for VP Configuration 1

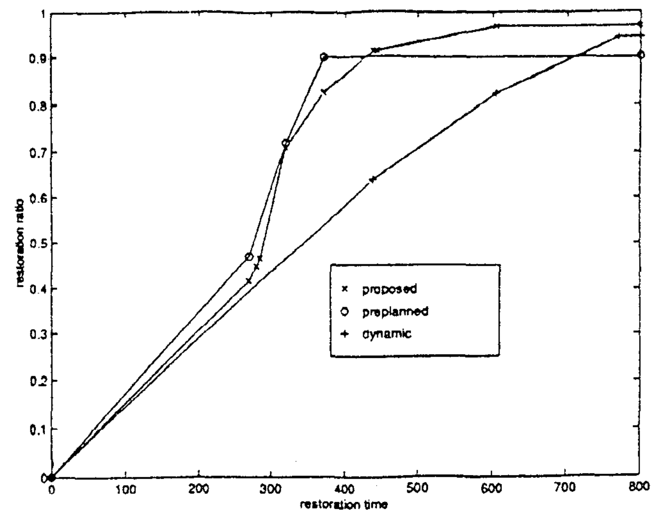


Figure 6.2: Self-Healing of Second Failure for VP Configuration 1

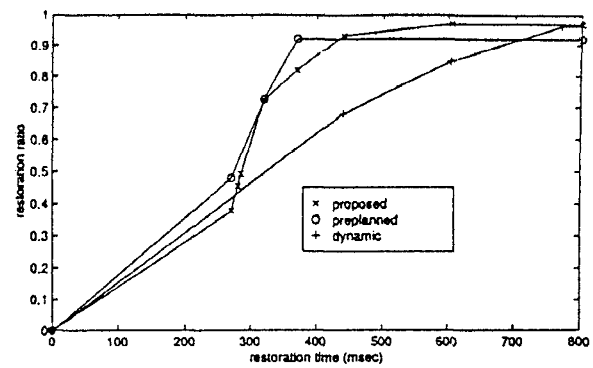


Figure 6.3: Self-Healing of First Failure for VP Configuration 2

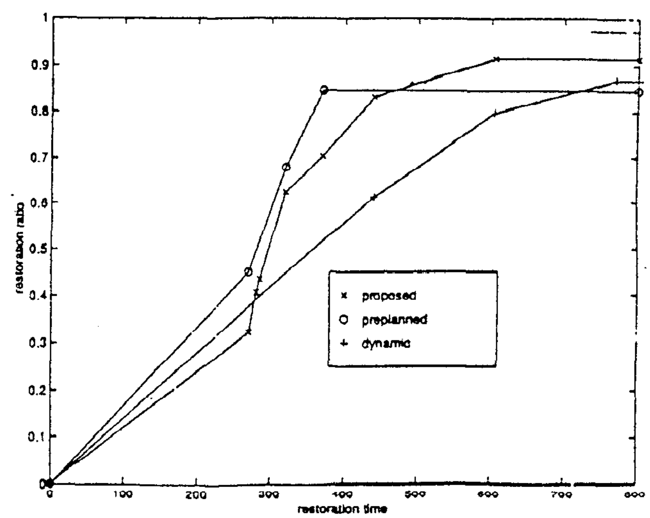


Figure 6.4: Self-Healing of Second Failure for VP Configuration 2