

Optimization and Performance of Network Restoration Schemes for Wide-Area Teletraffic Networks

D. Medhi¹ and R. Khurana²

(October 1994, revised May 1995)

In the event of a major network outage such as a fiber cable cut, a network can experience significant deterioration of network performance. To address such a situation, a network can be equipped with restoration capacity. We present here a mathematical model and design algorithm for determination of transmission network restoration capacity. We then present models for two restoration options – connection based restoration and load directed restoration (for restoration of bundle of circuits) – and consider their impact on a wide-area dynamic call routing teletraffic network when the restoration capacity is limited (tight). Our network simulation of failure and restoration of a dynamic call routing teletraffic network shows that the load directed approach generally performs better than the connection based approach.

KEY WORDS: Wide-area networks, dynamic call routing teletraffic networks, restoration capacity design, restoration rerouting, multi-commodity flow models, network restoration performance.

1. INTRODUCTION

A major network outage such as a fiber cable cut can significantly deteriorate the performance of a network [1]. In a recent paper [2], we have noted that to improve the performance of the network in such an event, various network planning and management implementation options such as the following can be sought: dynamic call routing between switching nodes, pre-planned circuit diversity through cross-connect nodes, pre-planned augmented trunk capacity design to address failure, real-time restoration in the transmission facility network (and associated pre-planned capacity required), or a combination of these options. (We refer to the traffic network as the network where the services such as voice, video and data are offered, and the transmission network is where the circuit required to provide the above services are routed; see section 2 for more detail). In this paper, we address the issue of network restoration for a dynamic call routing teletraffic network. By network restoration, we do not mean physical restoration of the actual failed circuits (on the failed link); rather, we mean reconnection of failed circuits around the failure using any available (restoration) capacity. Thus, we will use the terms restoration and reconnection interchangeably. Specifically, we address the problem of restoration capacity design in the transmission network for failure of a link; secondly, network reconnection algorithms in the transmission network, and thirdly, the traffic network performance as reconnection in the

¹ Computer Science Telecommunications, University of Missouri–Kansas City, 5100 Rockhill Road, Kansas City, Missouri 64110. (E-mail: dmedhi@cstp.umkc.edu)

² Was with the University of Missouri–Kansas City. Now with Sprint Corporation, Burlingame, California.

transmission network is done after the failure using the restoration capacity, especially when the reconnection capacity is limited. We address these issues in the context of a wide-area dynamic call routing network (see, for example, [3], [4], [5], [6]).

Network survivability and restoration have been gaining attention in recent years. Designing for survivability has been addressed by several researchers for various networks (for example, see, [7], [8], [9], [10], [11], [12], [13], [14], [15]). Results on network performance under a failure for wide area circuit-switched networks have been presented in ([2], [12], [16], [17], [18]), and for wide area packet networks in [19]. Network restoration has also been addressed by several researchers; e.g., Coan *et al* [20] have presented a discussion on network configuration for trunk network survivability; Kawamura *et al* [21] discuss network restoration for ATM networks; Dunn *et al* [22] have compared k -shorted path to maximum flow routing for network facility restoration; Doverspike and Wilson [23] have addressed the issue of capacity efficiency in Digital Cross-connect System (DCS) network restoration. Balakrishnan *et al* [24] have addressed the issue of timing of virtual circuit restoration in a wide-area packet network. Our present work is significantly different from these works. We briefly discuss our work below before we go into each aspect in detail in subsequent sections.

For reconnection capacity design, we present a model for design for failure of a single transmission link (at a time). In this model, we introduce a parameter, connection restoration factor, which can be specified to design for restoration of a specified percentage of failed trunk capacity. If cost of full recovery is larger than the budget permits, then this factor can, for example, be specified at the appropriate level. Our work considers the case when full restoration capacity can not be provided in the transmission network, e.g., due to budget; we will refer to this situation as the network being under ‘tight’ capacity. This leads to the second problem we address: given tight availability of restoration capacity, how can the network make best use of the available capacity to bring the network back to (near) normalcy. Towards this end, we present two network restoration approaches: connection based restoration (CBR) and load directed restoration (LDR). These approaches are for reconnection rerouting in the transmission network of failed trunks (circuits) using the restoration capacity in the transmission network. These two approaches can be used to generate pre-planned restoration configuration for specific failure scenarios that can be stored in a database, and can be triggered in the event of a failure. It is well known that offered traffic varies depending on the time of the day [3]. While connection based restoration is generated and is indifferent to the load variation during the day, the load directed restoration is to generate different restoration rerouting depending on the time of the day (at major time epochs when load changes) taking into account variation of load during the day and the dynamic call routing in effect for the traffic network. The third related issue we consider here is the interplay of the reconnection rerouting of circuits in the transmission network and dynamic call routing in the traffic network towards integrated network restoration: we address this problem by doing network simulation of specific failure scenarios where we also consider staggered restoration of restorable trunks. For our computational works, we have used a network testbed extracted from an actual network. Finally, we discuss relevance of our approach in asynchronous transfer mode (ATM) based broadband networks.

It is instructive to discuss two recent work ([25], [26]) which have some similarities to our work. Both these papers, like us, have considered an integrated view of the traffic and transmission network towards the issue of network survivability and restoration. However, we differ from both of them in various ways. We discuss each one separately below.

Ash *et al* [25] have presented design and analysis of a fully-shared network where dynamism in the transmission network through cross-connect systems is addressed along with dynamic call routing in the circuit-switched traffic network. While they address transmission network reconfigurability and its implication on network performance under various network conditions in a substantial manner, we do not consider reconfigurability in the transmission network (under normal network operating conditions); on the other hand, we provide the restoration capacity design

for the transmission network to support the traffic network while no discussion is presented in this regard in [25]; further, while we have attempted to provide trade-off of doing transmission network restoration (including staggering) under tight capacity compared to additional trunking capacity in the traffic network performance, this is not addressed in [25]; finally, an approach such as load directed restoration that we present here is not addressed in [25], or perhaps, not even explicitly required in a fully-shared network environment.

In the other work, Krishnan *et al* [26] have presented a unified network design approach to consider network survivability and restoration by looking at a layered view of the network, and have considered trade-off of doing restoration either in the traffic network or in the transmission network or in both (it may be noted that this is done beyond what we have addressed in a previous work towards network survivability [15]). They present their analysis for a symmetric network. The authors indeed have made an important contribution towards understanding the trade-off of restoration at various level. However, our focus is more on understanding the difference between connection based restoration and load directed restoration given a tight restoration capacity, as well as staggering of actual restoration towards understanding the implication of timing towards what actually may be appropriate as the circuit layout/diversity in the transmission network.

The rest of the paper is organized as follows. In section 2, we discuss preliminaries and assumptions. In section 3, we describe the network restoration capacity design model. In section 4, we present connection based and load directed restoration models. In section 5, we present computational results for restoration design and the impact of network restoration schemes on the performance of dynamic call routing circuit-switched networks. Finally, in section 6, we summarize our work and discuss possible future work including extension to ATM-based broadband networks.

2. PRELIMINARIES AND ASSUMPTIONS

We briefly describe the difference between the traffic network and the transmission network as considered in this paper. The reader may want to refer to, for example, [2], [12], [15], [27] for additional detail which have also used this two-layer approach. The traffic network refers to the logical network where different services [e.g. voice, data, video] are offered, and the transmission network refers to the network through which the circuit connectivity for the traffic network is provided. Based on a given traffic demand (in erlangs) and a specified grade-of-service (GoS), the traffic network is designed to determine the (logical) trunks required [5] for a specified call routing procedure. Usually, the traffic network is engineered for 1 % blocking GoS (to be referred as n-GoS hereafter) under normal network operating conditions. Thus, for the traffic network, we are usually given a set of traffic switching nodes, the traffic matrix between the switching nodes [possibly for different load periods (hours) during the day]. For the transmission network, we assume that we are given a set of cross-connect nodes and a set of transmission links. The trunks required between switching nodes are connected using cross-connect nodes and transmission links.

It may be noted that the T1 committee report on survivability [28] presents a four-layer approach towards network survivability: service, logical, system and physical. We, however, take here a two-layer approach for simplicity and manageability. Comparatively, the service layer in [28] corresponds to the traffic layer here and the aggregation of the other three layers as in [28] to the transmission layer here. Due to this aggregation, for our purpose here, transmission link is synonymous with physical link. Due to this aggregation and also since our primary interest is on the impact in the traffic network, we do not take into consideration the role of automatic protection switching or self-healing ring [13], [28].

For the trunks required for the traffic network, a circuit layout procedure [29] is used to determine the transmission path on which various trunk demands (and how much) should be routed between cross-connect nodes. This routing is called circuit routing, not to be confused with

call routing. For clarity, we will refer to the demand to be routed between cross-connect nodes as ‘connections’. Note that a traffic link commonly known as a trunk group is different from a transmission link and it connects two switching nodes as a logical link while a transmission link as considered here connects two cross-connect nodes at the transmission level. For clarity, we refer to a traffic link (trunkgroup) as a t-link and a transmission link as an f-link. A traffic path (route) for call routing consists of at most two t-links connecting a demand pair (switching node pair) either directly or via another switch (this is a standard assumption for dynamic call routing networks, see [5]). A transmission path is the path between two cross-connect nodes consisting of f-links connected by a chain. Typically, a switching node is associated with a cross-connect node in the same city for routing circuits through the transmission network to another switching node. Here, we will consider a switching node to be co-located with an associated cross-connect node, at the same time there may be some independent cross-connect nodes; if a node marked n has co-located switching node and cross-connect node, then we refer to the switching node as SW_n and the cross-connect node as CC_n . For example, consider the switching pair SW_1 – SW_6 in Figure 1. The logical t-link is simply SW_1 – SW_6 connecting the switching nodes SW_1 and SW_6 , while two transmission paths between SW_1 and SW_6 are, for example, SW_1 – CC_1 – CC_8 – CC_6 – SW_6 and SW_1 – CC_1 – CC_{11} – CC_6 – SW_6 ; note that the trunks for the trunkgroup/t-link SW_1 – SW_6 that is circuit routed on transmission path CC_1 – CC_8 – CC_6 goes through the cross-connect node at 8, but does not enter the switching node at 8. As mentioned before, the demand between the cross-connect nodes will be referred to as connections, to distinguish from trunk demand between the same associated switching nodes. Thus, the loss of a trunk in the traffic network due to an outage corresponds to the loss of an associated connection in the transmission network. For example, the loss of trunks between SW_1 and SW_6 in the traffic network means loss of corresponding connections between CW_1 and CW_6 in the transmission network. Thus, at times, the terms, connections and trunks, will be used interchangeably. It may be noted that, in this work, we address only link failure in the transmission network such as the failure of f-link CC_1 – CC_8 which is usually referred to as link 1–8; we do not address any failure of interface transmission units between SW_n and CC_n , e.g., between SW_1 and CC_1 . Also, typically, the demand between cross-connect nodes also have private line demand; this is not considered here. Further, the demand between cross-connect nodes is typically given in multiples of DS1 rate; however, here, we will assume the connections to be in multiples of DS0 as is the case with trunks. If the traffic network is fully inter-connected, the number of switching-node (traffic demand) pairs is the same as the number of t-links (trunk groups). Here, we keep the distinction assuming that the traffic network may not be fully interconnected.

We state below the main assumptions in our work followed by explanation of the assumptions:

- (A1) The traffic network is non-hierarchical in the sense that all switches are at the same level. A call between the origin and the destination switch is connected either on the direct traffic link (if it exists) or on at most two traffic link alternate routes.
- (A2) A two-layered view consisting of the traffic and the transmission network is considered here.
- (A3) The transmission network is two-arc connected [30, p. 445].
- (A4) The circuit layout for provisioned trunks remains static during the course of a day (possibly for a longer period).
- (A5) When restoration is done after a failure, the switch ports can not be re-arranged in real-time. That is, switch ports assigned to a particular switching node pair, can not be reassigned to another switching pair.
- (A6) Transmission restoration capacity on f-links is stand-by capacity which can be used only for reconnecting failed trunks.

- (A7) The time to fix the actual physical link failure from the time of failure is less than the time between successive failures. This says only one transmission link can fail at a time.
- (A8) When a transmission link fails due a fiber cable cut, it affects all the trunks provisioned on it as well as the restoration stand-by transmission capacity on that link.

Assumption (A1) states that the network is a dynamic call routing, non-hierarchical network – the main premise of our work. Discussion on assumption (A2) is already covered. Due to assumption (A3), at least a physical path exists between switching nodes to reconnect circuits in case of failure of a transmission link; otherwise some switching nodes can be isolated. Assumption (A4) is typical in present day networks; however, we note that recently dynamism in the transmission network has been considered by Ash *et al* [25]. Assumption (A5) is a realistic assumption about not being able to rearrange port in real-time due to a failure. Assumption (A6) is to ensure that the restoration transmission capacity is not provisioned in for some other services on demand, and is available for the sole purpose of restoration for the traffic network it services. Regarding assumption (A7), although multiple transmission link failures can conceivably occur, the probability of such an event is negligible; thus, assumption (A7) is reasonable which is used in the model for restoration capacity design and also in analysis. Assumption (A8) states that between two cross-connect nodes we assume that we have a physical link that has both provisioned circuits as well as standby restoration capacity — this is assumed in our modeling framework for restoration capacity design model as well as reconnection rerouting and network simulation since in a major fiber cable cut this situation can/does occur; thus, no parallel links are assumed here.

3. RESTORATION CAPACITY DESIGN

The reconnection capacity problem is to place the minimum amount of spare capacity needed in the transmission network to restore a part of lost connections (corresponding to trunks in the switched network) from a single f-link failure at a time, provided that the trunk requirements between switching nodes and the corresponding transmission network topology and layout (under normal network operating conditions) are given. This is used in pre-planned capacity design. We consider here end-to-end restoration; i.e., when an f-link failure occurs, the trunks affected for each origin-destination switching node pair which was using this f-link may be rerouted around the failure on different transmission paths on each origin-destination switching node pair basis (as opposed to link or “patch” restoration where all the circuits on the failed f-link are rerouted around the immediate two transmission end points without regard to which o-d switching pairs they are for; see [23] for a study on computational efficiency of end-to-end restoration over patch restoration in the transmission network). We use a factor called *Connection Restoration Factor* (CRF) which is to specify the percentage of lost connections to be designed for in the restoration capacity design phase.

To discuss the capacity design problem, we first present an optimization model where the failure of a single f-link, say, m , is considered. The input to the reconnection capacity problem is assumed to be a set of switched demand pairs which are affected by a failure, the demand (connections) that is lost for the affected trunk groups in the cross-connect network, and any initial reconnection capacity that is already available in the transmission network. We list the notation used here.

Notations

- \mathcal{L} Set of transmission links (f-links) in the network.
- \mathcal{K}_m Set of affected t-links (groups) due to failure of f-link m
- c_ℓ Unit cost of transmission capacity on f-link $\ell \in \mathcal{L}$
- r_ℓ Existing reconnection capacity available (if any) on f-link $\ell \in \mathcal{L}$

- f_ℓ Reconnection capacity to be added on f-link $\ell \in \mathcal{L}$ (variable)
- $d_{k(m)}$ Connections affected (lost) for cross-connect node pairs associated with t-link (trunkgroup) $k \in \mathcal{K}_m$ for failure of f-link m
- $\mathcal{J}_{k(m)}$ Set of valid transmission paths (surviving paths) for t-link $k \in \mathcal{K}_m$ for failure of f-link m
- δ_{kj}^ℓ f-link/path indicator: 1 if path $j \in \mathcal{J}_{k(m)}$ for t-link $k \in \mathcal{K}_m$ uses f-link $\ell \in \mathcal{L}$, 0 otherwise
- x_{kj} Amount of flow (circuits routed) on path j for t-link (group) k (variable)
- α Connection Restoration Factor ($0 \leq \alpha \leq 1$)

The mathematical optimization model (Model (1)) for f-link failure m to determine the reconnection capacity can be given as follows:

$$\min_{\{x_{kj}, f_\ell\}} \sum_{\ell \in \mathcal{L}} c_\ell f_\ell \quad (1a)$$

subject to

$$\sum_{j \in \mathcal{J}_{k(m)}} x_{kj} = \alpha d_{k(m)}, \quad k \in \mathcal{K}_m \quad (1b)$$

$$\sum_{k \in \mathcal{K}_m} \sum_{j \in \mathcal{J}_{k(m)}} \delta_{kj}^\ell x_{kj} \leq r_\ell + f_\ell, \quad \ell \in \mathcal{L} \quad (1c)$$

$$x_{kj} \geq 0, \quad j \in \mathcal{J}_{k(m)}; \quad k \in \mathcal{K}_m \quad (1d)$$

$$f_\ell \geq 0, \quad \ell \in \mathcal{L} \quad (1e)$$

The expression (1a) represents the minimization of the total cost for reconnection capacity augmentation on f-links in the transmission network. The expression (1b) says that all the surviving transmission paths (valid paths) together are required to carry the connections lost for each affected demand pair at the prescribed CRF level. The expression (1c) refers to the total flow (connections) carried on each f-link for various demand pairs being satisfied by any new reconnection capacity and any reconnection capacity already available on this f-link. (1d) and (1e) are to specify non-negativity of the path flow variables and reconnect capacity variables. Note that this multi-commodity flow model is based on link-path formulation; this allows us to limit the number of f-links (if and when required) for a transmission path between two switching nodes.

The reconnection capacity design to consider all f-link failure (one at a time) can be addressed by solving the following heuristic algorithm. The algorithm assumes an initial circuit layout of connections in the transmission network for trunk demand generated for normal network operating conditions for a specified GoS (e.g., see [15]) and assumes no initial restoration capacity.

Algorithm:ReCap

- Step 0 Generate initial circuit layout of connections corresponding to trunks for the traffic network under normal network conditions. Set $r_\ell \leftarrow 0, \ell \in \mathcal{L}$.
- Step 1 For each f-link $m \in \mathcal{L}$ do
 - Step 1.1 Determine all the t-links affected, \mathcal{K}_m , due to this failure.
 - Step 1.2 Determine units of connections affected (lost) $d_{k(m)}$ for every affected t-links due to failure of link m
 - Step 1.3 Determine all the valid candidate paths due to the failure of link m
 - Step 1.4 Solve the reconnection capacity estimation optimization model (1) for failure of link m to determine f_ℓ .

Step 1.5 Update reconnection capacity available, $\{r_\ell\}$.

enddo

Step 2 Output $\{r_\ell\}$

Although Model (1) provides optimal placement of capacity for a specific *single* failure, the heuristic ReCap may not provide an optimal placement due to the order in which f-links are considered in Step 1 for the entire network. We discuss the implication of the order in computational work later in section 5.1. We refer the reader to other, more sophisticated, heuristics for restoration capacity design in cross-connect networks by Chujo *et al* [31].

4. RESTORATION MODELS

Now we discuss analytical models/algorithms for two restoration schemes: connection based restoration (CBR) and load directed restoration (LDR). These are aimed at generating pre-planned reconnection rerouting (of circuits) and creating a database; in the event of a failure, a database look up is triggered to look for the specific failure scenario.

4.1 Connection Based Restoration (CBR) Model

As we have mentioned before, the initial network design determines the number of trunks required for every demand pair based on the load in erlangs for a specified grade-of-service and the transmission paths through which these trunks are circuit routed. Furthermore, using the reconnection capacity design procedure, transmission capacity for restoration can be determined and placed in the network. When a facility link failure occurs, it affects the demand pairs for which the trunks are being circuit routed through the failed f-link. The connection based model tries to restore as many connections as possible in the transmission network for every affected t-link (group) based on the available reconnection capacity. If reconnection capacity is designed using CRF (α) to be one, then this model would restore the entire lost connections (hence, trunks) since there is enough reconnection capacity built-in to restore all the affected trunks; if, however, the reconnection capacity is designed with $\alpha < 1$ due to the cost for full restoration being more than budgeted for, then there is a need to make the best use of available reconnection capacity for restoration of failed connections.

The input to this problem is a set of trunkgroups affected by the failure, the connections lost at the cross-connect level due to this failure, and the units of reconnection capacity available in the network. We assume that the reconnection capacity is obtained by solving the reconnection capacity model (1) for a given CRF. The goal of the CBR algorithm is to maximize the restoration of lost connections between switching nodes by reconnection rerouting. The following notations are used in this model:

\mathcal{L} Set of facility links

\mathcal{K} Set of affected t-links (trunkgroups) due to the failure of the f-link

r_ℓ Units of reconnection capacity available on link $\ell \in \mathcal{L}$ (from model-1) except for the failed f-link for which $r_\ell = 0$.

d_k^a Units of connections affected (lost) for t-link (group) $k \in \mathcal{K}$

$d_k^{a,low}$ minimum units of connections affected to be restored for $k \in \mathcal{K}$

\mathcal{J}_k Set of valid facility paths (surviving paths) for $k \in \mathcal{K}$

δ_{kj}^ℓ Link-path indicator: 1 if path $j \in \mathcal{J}_k$ for $k \in \mathcal{K}$ uses link $\ell \in \mathcal{L}$, 0 otherwise

x_{kj} Amount of circuit routed (flow) on transmission path j for trunkgroup k (variable)

The rerouting of circuits in the CBR model can be given by the following multi-commodity model:

$$\max_{\{x_{kj}\}} \sum_{k \in \mathcal{K}} \sum_{j \in \mathcal{J}_k} x_{kj} \quad (2a)$$

subject to

$$d_k^{a,low} \leq \sum_{j \in \mathcal{J}_k} x_{kj} \leq d_k^a, \quad k \in \mathcal{K} \quad (2b)$$

$$\sum_{k \in \mathcal{K}} \sum_{j \in \mathcal{J}_k} \delta_{kj}^\ell x_{kj} \leq r_\ell, \quad \ell \in \mathcal{L} \quad (2c)$$

$$x_{kj} \geq 0, \quad j \in \mathcal{J}_k, \quad k \in \mathcal{K} \quad (2d)$$

The expression (2a) represents the maximization of the total circuits routed on the surviving paths for all groups. The expression (2b) says that all the surviving paths together are required to carry as much lost connections as possible while carrying a minimum of connections at the same time. Note that the upper bound also implies that no switching port reassignment is done in real-time. The expression (2c) refers to the total flow carried by all the demand pairs on each f-link being satisfied by reconnection capacity available on that f-link. (2d) says that the path variables are non-negative. Setting a lower bound on connections as in (2b) is to ensure that a certain minimum amount of restoration for each demand pair is attained to achieve fairness. The feasibility of this model is guaranteed when the designed α using in Model (1) for capacity design is used here to provide a lower bound, i.e., $d_k^{a,low} = \alpha d_k^a$ (or any factor smaller than designed α will also ensure feasibility). When the reconnection capacity is tight, without the lower limit as in (2b) it may be that all the trunks for a t-link are restored while another has no trunks restored at all. However, if the fairness issue is not a problem, then the lower bound can be ignored. The lower bound may not be practical in a rapidly changing network where it is difficult to pick $d_k^{a,low}$ to ensure feasibility of the problem; in that case, it may be wise to ignore it.

4.2 Load Directed Restoration (LDR) Model

This model is motivated by the offered load variation that occurs in the traffic network depending on the time of the day and taking into account dynamic call routing in the traffic network. Note that the connection based model tries to restore as many connections as possible for affected groups without considering the load variation. The idea behind the load directed model is to make better use of available reconnection capacity depending on the time of the failure. While the restoration rerouting with CBR is indifferent to load variation during the day, the restoration rerouting can be different at different times during the day with LDR.

For the load directed model the first step is to consider the offered load (in erlangs) for each demand pair at the time of failure. For pre-planned computation, this means considering the load profile if the failure were to occur at a particular time during the day. Based on the load, we then estimate the number of trunks that need to be restored on each t-link by using a two-phase process: first we estimate virtual trunks required for every demand pair for a specified Grade-of-Service in restored state (see next paragraph for explanation of virtual trunks), and then solve a multi-commodity flow model to estimate the trunks required on each t-link. The GoS goal can be classified into a desired restoration GoS (r-GoS) for the affected demand pairs in the network in the restored state; for non-affected demand pairs, we still plan to provide the normal Grade-of-Service, n-GoS, designed for normal network operating conditions in the failure state also. We first estimate the trunks required considering that the network has dynamic call routing. Then the optimization

model given for CBR is used to reroute (as much as possible) the computed requirements in the facility network.

For a given offered load and GoS level, the virtual trunk requirement is approximated as discussed in [12] and [15] which is found to work well in practice. We briefly discuss it here for completeness. The load to be carried in a dynamic call routing environment can be carried in two ways: on a direct traffic link or on two traffic links in case of alternate routing. If we assume a blocking b_d of the load to be carried on the direct path, then the overflow traffic can use two traffic links to complete the requirements. This overflow traffic shares trunks from other traffic pairs. Conceptually, although it uses two traffic links, the overflow can be visualized as being carried on a shared virtual trunk group. Thus the total requirement over the direct link and alternate two link paths is the total virtual trunk required for the offered load to be carried. Let B_p be the blocking level for the traffic demand pair p . This reflects the grade of service. Let $E(c, a)$ be the well known Erlang blocking formula (e.g., see [5]) for trunk c and offered load a defined by:

$$E(c, a) = \frac{a^c/c!}{\sum_{k=0}^c (a^k/k!)} \quad (3)$$

We denote the number of trunks necessary to carry the offered load a at a particular blocking level b by the inverse function $E^{-1}(a, b)$. Let the average occupancy of a trunk group be ρ . For traffic pair p , let the carried load be denoted by $a'_p = a_p(1 - B_p)$. Then the virtual trunk demand for traffic pair p is approximated by the following formula:

$$vt(a_p, B_p) = E^{-1}(a'_p, b_d) + a'_p b_d / \rho \quad (4)$$

The choice of b_d is observed usually from practical network by observing amount of alternate routed traffic compared to direct routed traffic. We used the parameter values as used in [12].

The input to the model is a set of switched demand pairs and the virtual trunk demand estimate computed using the above procedure for the traffic load depending on the time of the day the failure were to occur, and GoS parameters, n-GoS and r-GoS. We first present notations:

- \mathcal{K} Set of traffic links (trunk groups) in the network
- \mathcal{P} Set of traffic switching node pairs in the network
- \mathcal{G}_p Set of candidate (one/two t-link) traffic paths for call routing for node pair $p \in \mathcal{P}$
- a_p Load in erlang for pair $p \in \mathcal{P}$
- d_k Additional trunks desired for group $k \in \mathcal{K}$ (variable)
- B_p Acceptable blocking for pair p which is r-GoS for affected pairs and n-GoS for unaffected pairs
- s_k Units of trunks survived for group k after the failure
- \hat{d}_k Units of affected (or lost) trunks for group k after the failure
- y_{pi} virtual trunk flow on traffic path $i \in \mathcal{G}_p$ for pair p (variable)
- γ_{pi}^k t-link/path indicator: 1 if traffic path i for node pair p uses t-link k , 0 otherwise

The units of virtual trunks required for carrying the load are estimated as mentioned above in (4) for the specified GoS and the model below tries to find the minimum additional trunks required given the survived trunks in the network with at most two t-link call routing.

$$\min_{\{y_{pi}, d_k\}} \sum_{k \in \mathcal{K}} d_k \quad (5a)$$

subject to

$$\sum_{i \in \mathcal{G}_p} y_{pi} = vt(a_p, B_p), p \in \mathcal{P} \quad (5b)$$

$$\sum_{p \in \mathcal{P}} \sum_{i \in \mathcal{G}_p} \gamma_{pi}^k y_{pi} \leq d_k + s_k, k \in \mathcal{K} \quad (5c)$$

$$y_{pi} \geq 0, i \in \mathcal{G}_p, p \in \mathcal{P} \quad (5d)$$

$$0 \leq d_k \leq \hat{d}_k, k \in \mathcal{K} \quad (5e)$$

The expression (5a) represents the minimum additional trunks required. Expression (5b) refers to satisfying virtual trunk demand between switching node pairs on various traffic paths for a given traffic offered load (corresponding to the time of failure) in erlangs for desired blocking level. The expression (5c) refers to the total trunk flow carried by all demand pairs on each traffic link being satisfied by trunks that has survived the failure and any additional restoration trunks desired. (5d) indicates that path variables are non-negative. (5e) specifies that the maximum that can be restored for a group is the total affected, thus, not allowing port re-assignment; in particular, a trunk group can not have more trunk ports than originally assigned for.

Thus, to recap, the load directed model, LDR, has two steps: in the first step, compute (4) and solve (5) to determine d_k ; in the second step, set $d_k^q = d_k$ in (2) and then solve (2) to generate restoration rerouting of trunks. It should be noted that the CDR models does not add *additional* trunks in the traffic network (beyond originally provisioned for); it provides a directive on selective connections to be reconnected in the transmission network (triggered by the offered load in the traffic network at the time of failure) in an intelligent manner to make best use of reconnection capacity.

5. COMPUTATIONAL RESULTS

Before we present our results, we first discuss the network data and the network scenarios. We have considered a ten switching node example network for computational work. The data for this network is extracted from an actual public switched voice network spanning the continental US. The facility network for this network is shown in Figure 1 which consists of eighteen cross-connect nodes and twenty seven transmission links. Three different load periods of traffic data are considered to reflect variation of traffic during the day; they are for morning, early afternoon and late afternoon with total load of 2684.80 erlangs, 2826.16 erlangs and 3224.08 erlangs, respectively. For brevity, we refer to them as ld-1, ld-2, and ld-3, respectively. Additional discussion about the data can be found in [2], [15]. Three network scenarios are generated based on the data (see [15]):

- PMO-1 the traffic network is designed for 1 % blocking GoS (n-GoS) under normal operating conditions considering the multi-hour traffic and the facility network is designed for circuit routing based on minimum cost routing subject to f-link capacity constraints.
- PMO-2 the traffic network is designed as in scenario PMO-1 but the facility network is designed for circuit routing based on minimum cost routing subject to f-link capacity constraints *and* additional constraints that trunks between two switching nodes are split on two or more physically diverse transmission paths while none carrying more than 50 %.
- SDSN this is a unified traffic and facility network design for survivability where the traffic network is designed for 1 % blocking GoS under normal operating conditions considering multi-hour traffic and 50 % blocking GoS in case of a failure for the affected traffic pairs (see [15] for detail).

Note that while PMO-1 and PMO-2 have the same number of trunks (total: 3,863) between switching nodes, their trunk layouts on the transmission network are different. Specifically, PMO-2 provides trunk group diversity while PMO-1 does not (subject to f-link capacity constraints). On the other hand, SDSN has PMO-2 layout as the starting layout and then additional trunk capacity for the switched network to provide a specified level of survivability in the traffic network itself (total: 4,241). This additional trunking in the traffic network is sometimes referred to as the traffic restoration capacity.

5.1 Reconnection Capacity

In the reconnection capacity design procedure, ReCap, it is clear that the order of failure of f-link considered can produce different design outputs. Using distance as the link cost (c_ℓ in (1a)), we considered three rules for failure order for the test network in hand based on Step 0 in ReCap for PMO-1 or PMO-2: 1) failure is done in increasing order such that the f-link whose failure would affect the *minimum* capacity under normal condition is considered first and so on, 2) failure is done in decreasing order such that the f-link whose failure would affect the *maximum* capacity under normal condition is considered first and so on, 3) failure is done without any ordering, i.e., links are failed based on alphanumeric name of links. The linear program in model (1) is solved using MINOS [32]. Integral values for capacity are obtained at the end of ReCap by rounding the solution.

For the test network in hand, we found that the decreasing order is about 2% costlier and the alphanumeric order is about 12% costlier than the increasing order. Thus, we chose the increasing ordering in our study to determine the restoration transmission capacity. The reader should keep in mind that the outcome may be different for different network topology and traffic data. We generated reconnection capacity for two values of CRF, namely, 0.5 and 0.75 to generate two cases of tighter reconnection capacity availability for network scenarios PMO-1 and PMO-2. Note that $\alpha = 1$ produces all the reconnection capacity for any f-link failure at a time and, thus, is not of interest to us for the rest of our work. In Table I, we report the total units of transmission capacity required for CRF values of 0.5 and 0.75 with respect to scenarios PMO-1 and PMO-2. A clarification between units of trunk capacity and units of transmission capacity is in order here: a trunk to be reconnected between two switching nodes generates w units of transmission capacity if the transmission path on which it is reconnected has w number of links, requiring one unit from each f-link.

5.2 Network Performance

To observe the implication of connection based and load directed restoration in case of an f-link failure in the traffic network, we developed a call-by-call traffic simulator with dynamic call routing capabilities. We first briefly discuss the call routing scheme used. For each switching pair, the two traffic link alternate paths are ordered periodically in decreasing order based on the free trunking capacity available on them, and then a routing table is created. An arriving call (with Poisson arrival) between two switching nodes first tries the direct traffic link. If there is a free trunk, the call is connected on that trunk. If there are no free trunks on the direct t-link or there is no direct t-link, then the call first tries through the first alternate via node as given in the routing table; if it cannot find any available trunks (subject to trunk reservation [33], [34], [35]) on this alternate route then the call is crankbacked ([3]) and tried via the next alternate via node as given in the routing table. If the call cannot find any available trunks after trying all the alternate routes given in the routing table, then the call is blocked. Call holding time is assumed to be exponential with a mean of three minutes. Like dynamic non-hierarchical routing (DNHR) [3] and trunk status map routing [36], this routing has the crankback feature; while DNHR used an off-line computed routing (with some real-time network management add ons in case of overload [37]) and the Trunk Status Map Routing (TSMR) uses DNHR with some added routes computed regularly, the routing we used in our simulation updates routing table at a regular interval (every ten seconds) based on maximum free trunks and ordering, somewhat similar to Dynamically Controlled Routing (DCR) [38]. Note that the routing we use attempts various alternate routes in the order given in the routing table using crankback, if needed, while DCR uses probabilistic values to pick the alternate route from the routing table; additionally, DCR does not have crankback. More details on this routing can be found in [2] and [15].

For our study, we have chosen two different f-link failures (each considered separately in simulation). They are f-links 1–3 and 4–15. The number of trunk groups and the number of trunks affected due to each of these failures are shown in Table II. They were considered since each of them affect a significant number of trunks and trunk groups in the event of a failure. As discussed earlier in the beginning part of section 5, for each scenario, PMO-1 and PMO-2, first the layout is obtained (Step 0 of Algorithm ReCap) and then the reconnection capacity is computed for CRF values of 0.5 and 0.75 using algorithm ReCap. Reconnection rerouting in the transmission network is then generated using reconnection capacity available (depending on the value of CRF) for each of the failure scenario 1–3 and 4–15 separately as described in section 4; this is done for both the connection based reconnection and the load directed reconnection (for LDR, a separate rerouting is generate for each load period). The linear programs in (2) and (5) are solved using MINOS [32]. For LDR, typically, we have set r-GoS to be 3 % or 1 %. Since we consider CRF of 0.5 and 0.75, note that not all the trunks can be reconnected with reconnection rerouting in the transmission network. For, clarity, the trunks that can be reconnected will be referred to as *restorable trunks*, and when all restorable trunks (does not mean all affected trunks are up) are up, we call it *fully-restorable state*.

In the event of an actual failure, it may not always be possible to bring all restorable trunks up at the same time due to database look up of restoration scenarios. Thus, in our simulation, we considered another scenario where a part (partial recovery) of the restorable trunks are restored at a time. Specifically, we consider bringing back restorable trunks associated with three trunk groups at a time (staggered restoration). We will refer to the time between each such partial recovery to be a time slot without assigning a specific time amount to it. (Thus, for f-link failure 4–15 in scenario PMO-2, it takes eight time slots to bring up all the restorable trunks to the fully-restorable state, cf. Table II). If the actual time of this time slot is very small, then the order or staggering may not be an important issue — in that case, the reader may look at the average blocking at the time of failure, and the average blocking at the fully-restorable state, and ignore the blocking information in between; for example, in Figure 3, consider blocking at time slot 1, the time of failure, and time slot 13, the time of the fully-restorable state. On the other hand, if the time between successive time slots is noticeable, then the affect of giving priority in partial recovery of restorable trunks is important; in this case, the reader may look at the blocking value at each time slot from the time of failure to the time of recovery of all restorable trunks. Furthermore, this provides a comparison of CBR and LDR during the partial restoration states.

The simulation is started considering the network to be under normal operating conditions (no failure). After the transient time is over, the failure of a facility link is indicated so that appropriate trunks affected are disabled and the active calls riding on them are disconnected. Then trunks that are restorable are reconnected for this failure using pre-computed restoration (depending on whether the option for connection based restoration or load directed restoration is given) for each f-link failure; this is done for three trunk groups in each time slot. In our graphs, we show the blocking state right after failure for three consecutive time slots, and then we start restoring trunks (three trunk groups at a time) partially in each time slot where the blocking is shown. Regarding priority with CBR (recall that it does not consider load variation during the day), we considered the following: the three trunk groups with most restorable trunks computed using CBR model are restored first, and then the next three in terms of most restorable trunks, and so on. For LDR, since we have some idea about offered load at the time of failure, the intuition may be to give priority to a set of trunk groups associated with switching pairs that has the most blocking, and then the next set, and so on. However, through our initial investigation, we found that this may not be a good idea. For example, suppose a node pair with offered load of 10 erlangs is likely to face 50 % blocking immediately after failure, thus, being unable to carry 5 erlangs; however, this pair is not as important as a pair which is likely to face 20 % blocking which has, however, offered

load of 100 erlangs, thus being unable to carry 20 erlangs. Thus, for LDR, we give priority to groups associated with the node pairs that has the most load affected (in groups of three), and so on.

We have run ten replications of each simulation case and then computed 90 % confidence intervals. We found that typically the non-affected pairs have blocking in the order of n-GoS. Thus, in our figures, we opted to show average blocking only for all *affected* pairs (short vertical lines show 90 % confidence intervals).

For all three network scenarios, PMO-1, PMO-2 and SDSN under tight restoration capacity, we found that LDR has either lower affected pair blocking than CBR or about the same as CBR. A representative set of figures are included (Figures 2, 3, 4, 5, 6, 7, 8, 9, 10, 11); additional figures can be found in [39]. Our experience is that, typically, it is more difficult to see any difference under PMO-1 than under PMO-2 and SDSN. This indicates to us that in a severe failure without trunk group diversity when several groups usually lose all its direct trunks, LDR may not always be able to take advantage of the load pattern as much as when the network has some trunk group diversity (i.e, when affected trunk groups lose some of the trunks). Another area where we found LDR to do better is that it can provide lower blocking while restoring fewer trunks than CBR. For example, consider PMO-1 with CRF to be 0.5 for f-link failure 4–15 in traffic load ld-1; at fully-restorable state, LDR needs to restore 30 % fewer trunks than CBR while having an affected-pairs blocking of 4.45 ± 1.10 % compared to an affected-pairs blocking of 10.94 ± 1.24 % for CBR. In another case (PMO-2, CRF = 0.5, ld-2, f-link failure 1–3), LDR needed about 5 % less to restore than CBR while having an affected-pairs blocking of 4.81 ± 0.38 % compared to 10.07 ± 0.66 % for CBR. This implies that LDR is making better use of the resources of transmission restoration capacity than CBR while providing lower blocking; furthermore, if the (near) real-time cost of bringing each trunk up is an issue, then CBR appears to do it cheaper than LDR.

Another interesting issue is now discussed on blocking of affected pairs at the time of failure and at the fully-restorable state. This discussion is done for LDR. Consider f-link failure 1–3 in scenario PMO-1 for traffic load ld-2: since failure of an f-link under PMO-1 generally affects all direct trunks on affected groups, the blocking immediately after failure is about 92.73 ± 0.42 % for affected pairs and goes down to about 34.35 ± 0.64 % after all recoverable trunks are restored when CRF is 0.5 (Figure 3), but it can go down to as low as 9.10 ± 0.76 % when CRF is 0.75 (Figure 2). On the other hand, for the same case under scenario PMO-2, the blocking right after failure is about 34.93 ± 1.15 %, and goes down to about 4.80 ± 0.38 % for CRF to be 0.5 (Figure 5), and down to 1.59 ± 0.32 % with CRF to be 0.75 (Figure 8). For clarity, Figure 12 shows the comparion of PMO-1, PMO-2 and SDSN for CRF = 0.75. Thus, if the restoration time is noticeable and actual physical restoration can take long time (hours), it is apparent that PMO-2 is a better scenario that PMO-1; i.e., it is better to have trunk group diversity built in the network layout. Furthermore, in some instances, even tighter restoration capacity (CRF = 0.75) can bring the network back nearly to normal Grade-of-Service if the proper restoration rerouting (along with call routing) is used. Now, looking at SDSN, we can see that at the time of failure, the average blocking for affected pairs at the time of failure is 27.61 ± 1.12 %, and goes down to 0 % with CRF = 0.5. Thus, SDSN does better than PMO-2; but, the reader should note that SDSN has more trunk capacity to begin with. However, some additional trunking as in SDSN may sometimes be justifiable because this additional trunk capacity can provide better call completion rate than PMO-2 (or PMO-1) if there is overload (or focused overload) in the network (not due to a link failure) and is, thus, a part of the normal revenue producing capacity; on the other hand, the stand-by transmission restoration capacity can only be used for restoring failed trunks in the event of a failure. There is obviously an important trade-off issue here between restoration capacity in ‘different’ networks. We refer the reader to the work by Krishnan *et al* [26] for further discussion on this issue.

Now we discuss the role of dynamic call routing in restoration. We found that dynamic call routing plays an important role in reducing blocking. We have observed that both at the time of failure and at the fully-restorable state, typically, 8 to 15 % of the calls for the affected pairs are found to be alternate routed for scenarios PMO-2 and SDSN. Specifically, for f-link failure 1–3 during ld-2 in scenario PMO-2 with CRF to be 0.75, when the blocking goes down to 1.59 % at the fully-restorable state, the amount of alternate routing done for completed calls is about 12 %. Note that for PMO-1 at the time of failure, generally all the trunks on affected direct trunk groups between switching nodes are lost (no diversity); thus, all calls that are completed for affected pairs are alternate routed. When restorable trunks are restored, then some groups may get some direct trunks back. Typically, at the time of failure these affected pairs can still carry about 8 % of the calls using alternate routing. In one instance, we found that 23 % of the calls for the affected pairs were alternate routed at the time of failure (failure 4–15, load-1); for this case, at the fully restored state (with CRF 0.5), we found that affected pairs call completion rate was 89 %, out of which 28 % were alternate routed. These examples show us the interplay between restoration rerouting of failed circuits and dynamic call routing in restoring the network from a failure state.

6. SUMMARY AND DISCUSSION

In this paper, we presented a mathematical model/algorithm for reconnection capacity design for transmission network. Further, we presented two restoration rerouting models, CBR and LDR, to create restoration layout scenarios in case an important f-link fails. We then quantified network performance through network simulation where both restoration rerouting of circuits and dynamic call routing were in effect.

We summarize the main observations we have made through our study. The reader should bear in mind that this is done for a specific 10-switching node network example.

- > If staggered restoration of restorable trunks is employed for LDR, then worst-load-affected-pairs-first heuristic appears to be better than considering first the affected pairs with worst blocking.
- > LDR appears to do either better than or about the same as CBR if there is already trunk diversity and the reconnection capacity available is tight. In terms of space requirement for pre-computed reconfiguration tables in the database, LDR requires h times more space than CBR where h is the number of important load periods during the day for which LDR can be computed. Based on our experience, we think that instead of computing LDR for each load period, it is better to consider network impact under both schemes for important network link outage scenarios and at critical load change periods during the day. If LDR does noticeably better than CBR for a given load period, then this is a case to be included in the database; if there is no significant difference, then the default CBR can be used. The upshot of this hybrid approach is that the space requirement is between the requirement for CBR and LDR while at the same time maximizing the benefit in terms of network performance.
- > If restoration speed of restorable trunks is noticeable and the actual physical restoration of the failure takes considerable time (hours), then it appears that it is better to have trunk group diversity in the network to provide better restoration when the restoration capacity is tight. Additionally, if additional trunking in the traffic network can be provided (strategically by using method such as the one given in [15]), the network may be perceived to provide almost normal grade-of-service after fully-reconfigurable state is reached; one advantage of additional trunking is that it can provide better call completion rate than normal network trunking if there is overload (or focused overload) in the network (not due to a link failure) and is, thus, a part of normal revenue-bearing capacity; on the other hand, the stand-by transmission restoration capacity can only be used for restoring failed trunks in the event of a failure. We

believe that a combination of traffic restoration capacity and transmission restoration capacity based on the specific objective of a network provider may be the suitable option.

It may be noted that CRF can be provided to be different for different t-links based on how important a particular trunk group is. This requires only specific parameterization of CRF without any need to change the entire model. For example, CRF can be set to one for some important pairs, and less than one for other pairs, thus, using α_k with different value for each k , instead of using a single α for the entire network. Our restoration rerouting methods address pre-computed configurations. Sometimes, it may be preferable to compute such configuration in near real-time; this would require solving the linear programs in models (2) and (5) efficiently and/or developing a quick good heuristic; also, in this case, the estimation can be based on actual load observed in (near) real-time. Future works plan to address these issues.

Finally, we discuss the work presented here in the context of ATM-based broadband networks. If the network architecture is defined with ATM switches and ATM cross-connect nodes with virtual path (VP) switching capability as described in [40], then we can use the concept of virtual path to denote a trunkgroup. Most of the results presented here will carry through for circuit-mode traffic in uni-service broadband networks as long as the network has dynamic call routing capabilities. However, in the case of ATM-based network, it may be possible to relax assumption (A5) on port limitation. Intuitively, this would provide even better results with LDR. Finally, the concept of virtual path with zero bandwidth as proposed in [21] may be explored for restoration rerouting. Another issue is the introduction of multi-services with differing bandwidth and quality-of-service requirements, and the ability to provide priority to a service class when the restoration capacity is tight. Also, by relaxing (A4), dynamism in virtual path routing can be considered for network efficiency [41]. Further work is required for understanding of these various implications in the context of broadband networks.

ACKNOWLEDGEMENTS

The traffic data used here was provided for another work [15] by Sprint Corporation and is greatly appreciated. We thank the reviewers for their constructive comments which helped clarify several issues and for bringing several references (particularly including, [28], [31]) to our attention.

REFERENCES

- [1] *IEEE Communications Magazine*, Issue on Surviving Disaster, Vol. 28, no. 6, June 1990.
- [2] D. Medhi and S. Sankarappan, Impact of a Transmission Facility Link Failure on Dynamic Call Routing Circuit-Switched Networks under Various Circuit Layout Policies, *Journal of Network and Systems Management*, Vol. 1, pp. 143-169, 1993.
- [3] G. R. Ash, R. H. Cardwell and R. P. Murray, Design and Optimization of Networks with Dynamic Routing, *Bell Sys. Tech. Journal*, Vol. 60, pp. 1787-1820, 1981.
- [4] B. R. Hurley, C. J. R. Seidl and W. F. Sewell, A Survey of Dynamic Routing Methods for Circuit-Switched Traffic, *IEEE Communications Magazine*, Vol 25, No. 9, pp. 13-21, 1987.
- [5] A. Girard, *Routing and Dimensioning in Circuit-Switched Networks*, Addison-Wesley, Reading, Mass., 1990.
- [6] *IEEE Communications Magazine*, Issue on Dynamic Routing, Vol. 28, no. 10, October 1990.
- [7] T.-H. Wu, D. Kolar and R. Cardwell, Survivable Network Architectures for Broad-band Fiber Optic Networks: Model and Performance Comparison, *IEEE J. of Lightwave Technology*, Vol. 6, pp. 1698-1709, 1988.
- [8] C. L. Monma and D. F. Shallcross, Methods for Designing Communications Networks with Certain Two-Connected Survivability Constraints, *Operations Research*, Vol. 37, pp. 531-541, 1989.

- [9] B. Gavish, P. Trudeau, M. Dror, M. Gendreau and L. Mason, Fiber Optic Circuit Network Design under Reliability Constraints, *IEEE J. on Selected Areas in Comm.*, Vol. 8, pp. 1181-1187, 1989.
- [10] R. H. Cardwell, C. L. Monma and T.-H. Wu, Computer-Aided Design Procedure for Survivable Fiber Optic Networks, *IEEE J. on Selected Areas in Comm.*, Vol. 7, No. 8, pp. 1188-1197, 1989.
- [11] Y. K. Agarwal, An Algorithm for Designing Survivable Networks, *AT&T Technical Journal*, Vol. 68, No. 3, pp. 64-76, 1989.
- [12] G. R. Ash, F. Chang and D. Medhi, Robust Traffic Design for Dynamic Routing Networks, in *Proceedings of IEEE Conference on Computer Communications (INFOCOM'91)*, Bal Harbour, Florida, pp. 508-514, April 1991.
- [13] T.-H. Wu, *Fiber Network Service Survivability*, Artech House, Boston, Mass., 1992.
- [14] O. J. Wasem, T.-H. Wu and R. H. Cardwell, Survivable SONET Networks — Design Methodology, *IEEE J Selected Areas in Comm.*, Vol. 12, pp. 205-212, 1994.
- [15] D. Medhi, A Unified Approach to Network Survivability for Teletraffic Networks: Models, Algorithms and Analysis, *IEEE Trans. on Communications*, Vol. 42, pp. 534-548, 1994.
- [16] D. Mitra and J. B. Seery, Comparative Evaluations of Randomized and Dynamic Routing Strategies for Circuit-Switched Networks, *IEEE Trans. Comm.*, Vol. 39, pp. 102-115, 1991.
- [17] G. R. Ash, J.-S. Chen, A. E. Frey and B.-D. Huang, Real-time Network Routing in a Dynamic Class-of-Service Network, *13th International Teletraffic Congress*, Copenhagen, Denmark, 1991.
- [18] R. J. Gibbens, F. P. Kelly and P. B. Key, Dynamic Alternate Routing, in M. Streenstrup (ed), *Routing in Communications Networks*, Prentice Hall, Englewood Cliffs, NJ, pp. 13 - 47, 1995.
- [19] D. Tipper, J. Hammond, S. Sharma, A. Khetan, K. Balakrishnan and S. Menon, An Analysis of the Congestion Effects of Link Failures in Wide Area Networks, *IEEE J Selected Areas in Comm.*, Vol. 12, pp. 179-192, 1994.
- [20] B. A. Coan, W. E. Leland, M. P. Vecchi, A. Weinrib and L. T. Wu, Using Distributed Topology Update and Preplanned Configurations to Achieve Trunk Network Survivability, *IEEE Trans. on Reliability*, Vol. 40, No. 4, pp. 404-416, 1991.
- [21] R. Kawamura, K.-i. Sato and I. Tokizawa, Self-healing ATM networks based on Virtual Path Concept, *IEEE J Selected Areas in Comm.*, Vol. 12, pp. 120-127, 1994.
- [22] D. A. Dunn, W. D. Grover and M. H. MacGregor, Comparison of K -shortest Paths and Maximum Flow Routing for Network Facility Restoration, *IEEE J Selected Areas in Comm.*, Vol. 12, pp. 88-99, 1994.
- [23] R. D. Doverspike and B. J. Wilson, Comparison of Capacity Efficiency of DCS Network Restoration Routing Techniques, *Journal of Network and Systems Management*, Vol. 2, pp. 95-123, 1994.
- [24] K. Balakrishnan, D. Tipper and J. Hammond, An Analysis of the Timing of Traffic Restoration in Wide Area Communication Networks, *14th International Teletraffic Congress*, Antibes, France, June 1994.
- [25] G. R. Ash, K. K. Chan and J-F. Labourdette, Analysis and Design of Fully Shared Networks, *14th International Teletraffic Congress*, pp. 1311-1320, Antibes, France, June 1994.
- [26] K. R. Krishnan, R. D. Doverspike and C. D. Pack, Unified Models of Survivability for Multi-Technology Networks, *Proceedings of 14th International Teletraffic Congress*, pp. 655-666, Antibes, France, June 1994.
- [27] G. R. Ash and S. D. Schwartz, Network Routing Evolution, in A. Kershenbaum, M. Malek and M. Hall (eds). *Network Management and Control*, Plenum Press, New York, pp. 357-367, 1990.

- [28] T1 Committee Report, *A Technical Report on Network Survivability Performance*, Report No. 24, October 1993.
- [29] R. F. Rey (ed.), *Engineering and Operations in the Bell System*, Bell Telephone Laboratories, 1983.
- [30] D. Bertsekas and R. Gallager, *Data Networks – 2nd Edition*, Prentice Hall, 1992.
- [31] T. Chujo, H. Komine, K. Miyazaki, T. Ogura and T. Soejima, The Design and Simulation of an Intelligent Transport Network with Distributed Control, *Network Operations Management Symposium*, San Diego, February 1990.
- [32] B. A. Murtagh and M. A. Saunders, MINOS 5.0 User’s Guide, Technical Report # SOL 83-20, Department of Operations Research, Stanford University, Stanford, CA, December 1983.
- [33] J. H. Weber, A Simulation Study of Routing and Control in Communications Networks, *Bell Sys Tech Journal*, Vol. 43, pp. 2639-2676, 1964.
- [34] R. S. Krupp, Stabilization of Alternate Routing Networks, *Proceedings of IEEE International Conference on Communications (ICC’82)*, pp 31.2.1-31.2.5, Philadelphia, June 1982.
- [35] J. M. Akinpelu, The Overload Performance of Engineered Networks with Nonhierarchical and Hierarchical Routing, *AT&T Bell Labs Tech. Journal*, Vol. 63, No. 7, pp. 1261-1281, 1984.
- [36] G. R. Ash, Use of a Trunk Status Map for Real-time DNHR, *11th International Teletraffic Congress*, Kyoto, Japan, 1985.
- [37] G. R. Ash and E. Oberer, Dynamic Routing in the AT&T Network – Improved Service Quality at Lower Cost, *Proceedings of GLOBECOM’89*, pp. 303-308, Dallas, TX, November 1989.
- [38] W. H. Cameron, J. Regnier, P. Galloy and A.-M. Savoie, Dynamic Routing for Intercity Telephone Network, *10th International Teletraffic Congress*, Montreal, Canada, 1983.
- [39] R. Khurana, Optimization and Performance Analysis of Network Restoration Schemes for Teletraffic Networks, M.S. Thesis, University of Missouri–Kansas City, Kansas City, MO, June 1994.
- [40] M. De Prycker, ATM Switching on Demand, *IEEE Network*, Vol. 6, No. 2, pp. 25-28, March 1992.
- [41] D. Medhi, Multi-Hour, Multi-Traffic Class Network Design for VP-based Wide-Area Dynamically Reconfigurable ATM Networks, *Proceedings of IEEE Conference on Computer Communications (INFOCOM’95)*, Boston, MA, pp. 900-907, April 1995.

D. Medhi has B.Sc. (Hons.) in Mathematics from Gauhati University (Cotton College), Assam, India, M.Sc. in Mathematics from the University of Delhi, India, M.S. and Ph.D. in Computer Sciences from the University of Wisconsin–Madison in 1981, 1983, 1985 and 1987, respectively. He is currently an assistant professor of Computer Science Telecommunications at the University of Missouri–Kansas City (UMKC). Prior to joining UMKC, he was a member of the technical staff at the AT&T Bell Laboratories, Holmdel, New Jersey from 1987 to 1989. His current research interests are in survivable network design, dynamic routing, broadband network design, large-scale optimization algorithms, and network management. He is a member of ACM, IEEE, INFORMS and SIAM.

R. Khurana received his B.E. in Computer Science and Engineering from Regional Engineering College, Rourkela, India in 1991. He received M.S. in Computer Science with emphasis in Telecommunications from the University of Missouri–Kansas City in 1994. Since 1994, he has been a software engineer with Sprint Corporation, Burlingame, California where he is presently involved in the development of enhanced services for Sprint’s wide area networks.

	PMO-1	PMO-2
CRF, $\alpha = 0.5$	6151	4784
CRF, $\alpha = 0.75$	9227	7176

Table I: Transmission capacity required for restoration

f-link	PMO-1		PMO-2		SDSN	
	TG	tk	TG	tk	TG	tk
1-3	18	1313	20	716	20	813
4-15	12	977	23	1006	23	1101

Table II: Number of trunk groups (TG) affected and trunks (tk) lost due to a failure

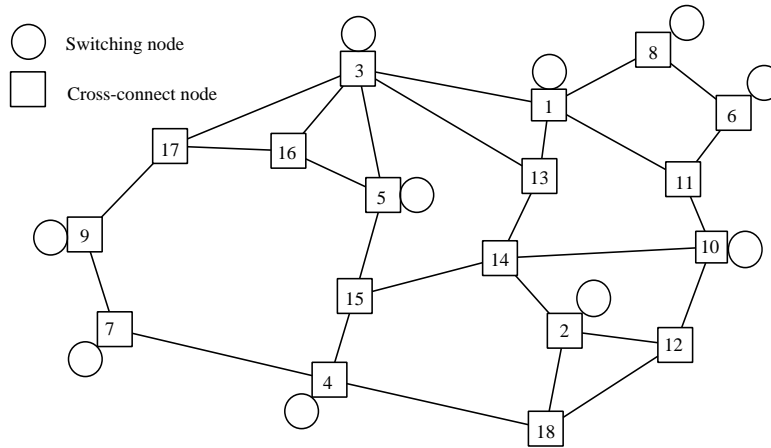


Figure 1: Network Topology of the test network

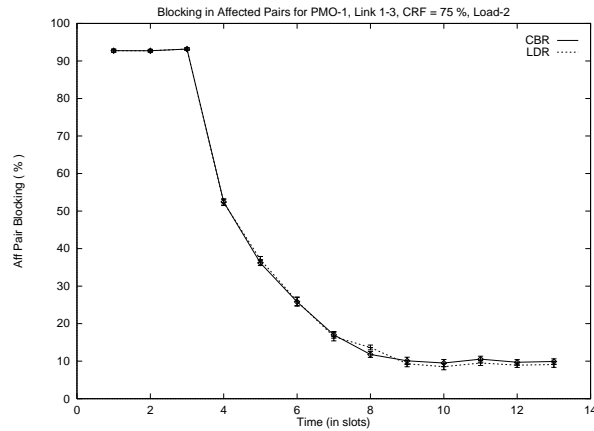


Figure 2: Affected Pair blocking for link 1-3 in load ld-2 for PMO-1 with CRF = 75 %

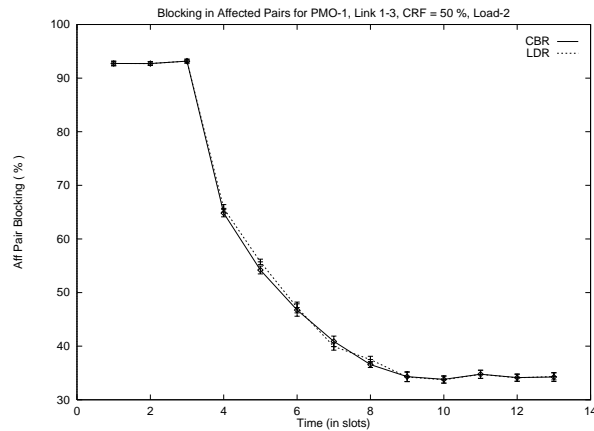


Figure 3: Affected Pair blocking for link 1-3 in load ld-2 for PMO-1 with CRF = 50 %

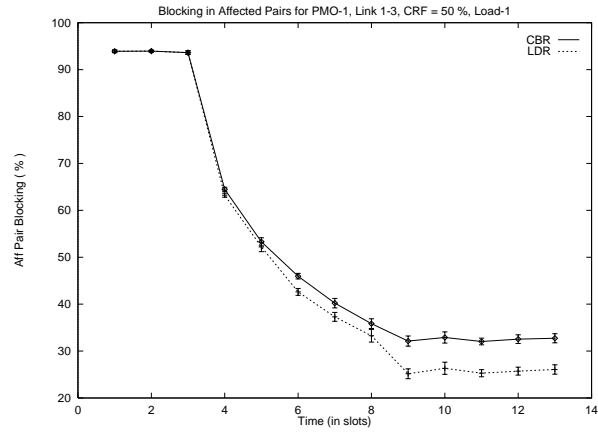


Figure 4: Affected Pair blocking for link 1-3 in load ld-1 for PMO-1 with CRF = 50 %

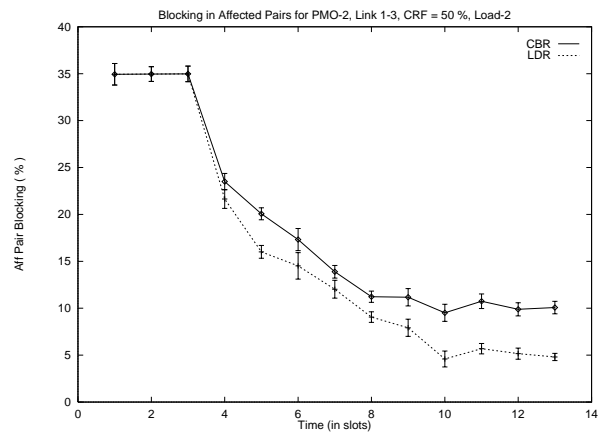


Figure 5: Affected Pair blocking for link 1-3 in load ld-2 for PMO-2 with CRF = 50 %

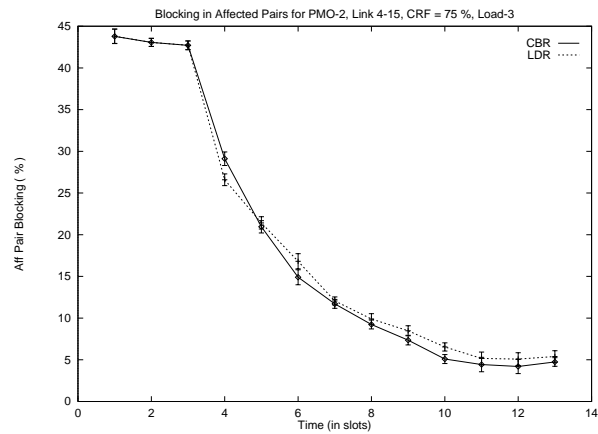


Figure 6: Affected Pair blocking for link 4-15 in load ld-3 for PMO-2 with CRF = 75 %

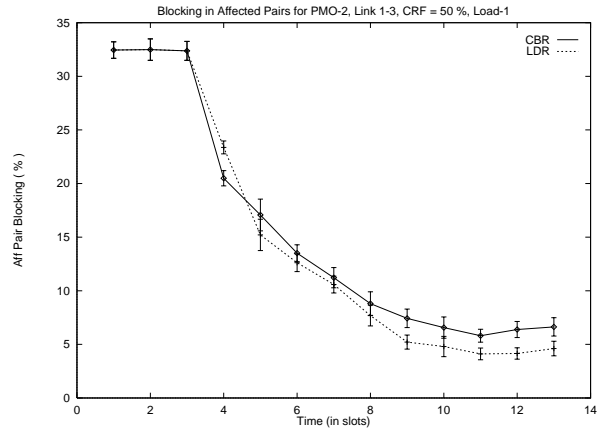


Figure 7: Affected Pair blocking for link 1-3 in load ld-1 for PMO-2 with CRF = 50 %

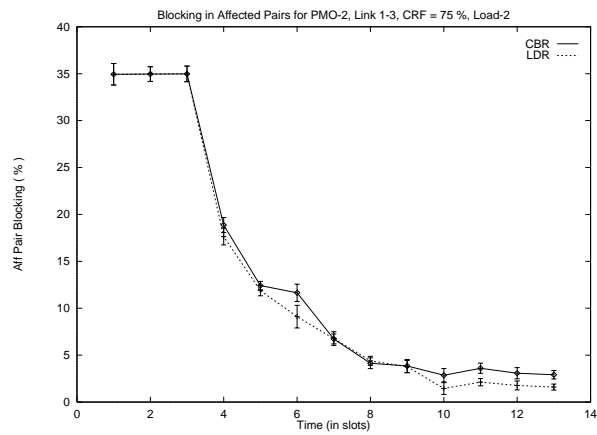


Figure 8: Affected Pair blocking for link 1-3 in load ld-2 for PMO-2 with CRF = 75 %

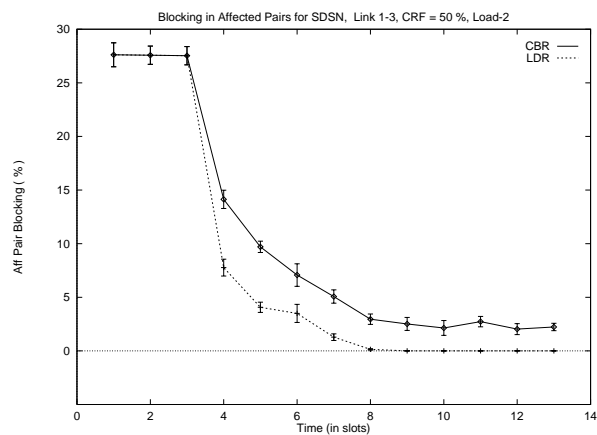


Figure 9: Affected Pair blocking for link 1-3 in load ld-2 for SDSN with CRF = 50 %

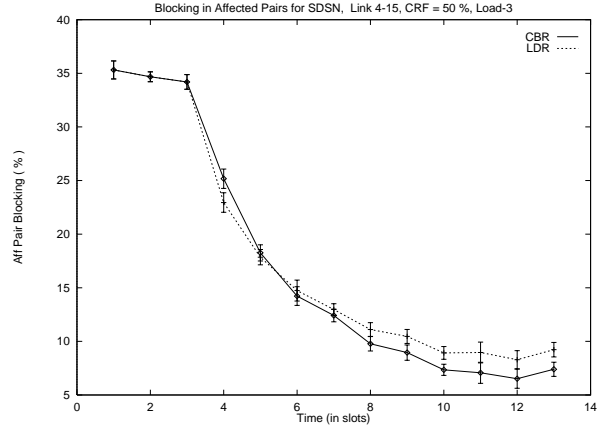


Figure 10: Affected Pair blocking for link 4–15 in load ld-3 for SDSN with CRF = 50 %

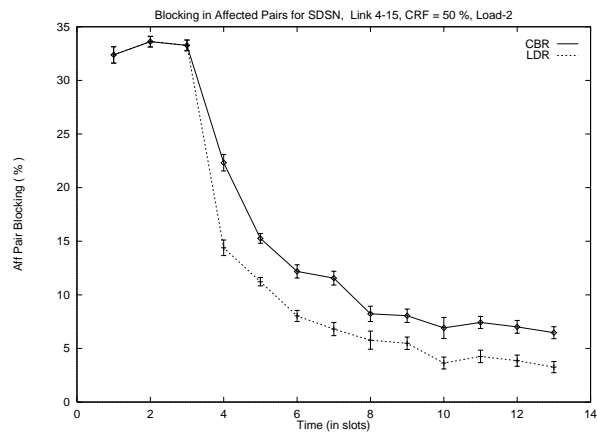


Figure 11: Affected Pair blocking for link 4–15 in load ld-2 for SDSN with CRF = 50 %

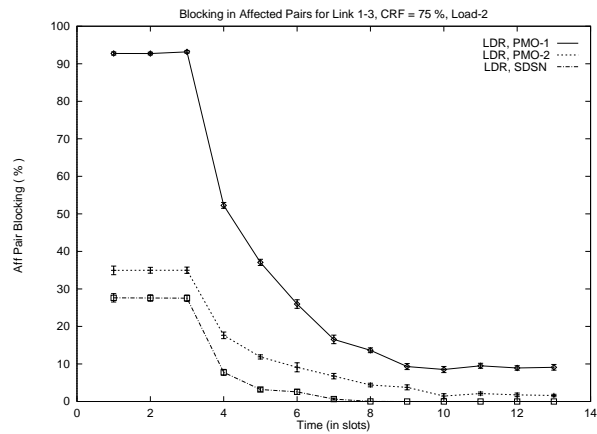


Figure 12: Affected Pair blocking for link 1–3 in load ld-2 with CRF = 75 % under three scenarios