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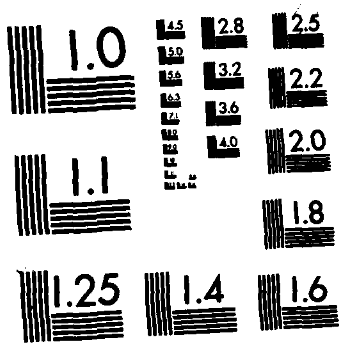

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Technical Report

Steady State Performance of Survivable Routing Procedures for Circuit-Switched Mixed-Media Networks

29 December 1982

Prepared for the Defense Communications Agency
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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS

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STEADY STATE PERFORMANCE OF SURVIVABLE ROUTING PROCEDURES FOR CIRCUIT-SWITCHED MIXED-MEDIA NETWORKS

R.P. LIPPMANN

Group 24

TECHNICAL REPORT 633

29 DECEMBER 1982

LEXINGTON MASSACHUSETTS

ABSTRACT

New mixed-media routing procedures are presented for networks with both broadcast and point-to-point transmission media. These procedures are designed for application in the Defense Switched Network, a planned new circuit-switched network, which will include both broadcast satellite and point-to-point terrestrial connections. Three new classes of procedures are presented, (1) mixed-media routing, (2) adaptive-mixed-media routing and (3) precedence flooding. All procedures treat satellite and terrestrial links separately and uniquely both when routing tables are created and when calls are routed. All procedures also use common channel signaling to pass call setup information between switches. This information includes a list of all switches and satellites already in the call path, a list of unavailable earth stations and satellites, and satellite hop and link limits. Mixed-media routing procedures use fixed routing tables and three different call processing rules (spill forward control, remote earth station querying and single-stage crankback). Adaptive-mixed-media routing procedures adapt routing tables when parts of the network are destroyed. Precedence flooding procedures route high priority calls using flooding techniques alone or in combination with mixed-media routing procedures. Low priority calls are routed using mixed-media procedures.

An existing steady state network analysis program was modified to evaluate the performance of (1) mixed-media routing with spill-forward control (2) mixed-media routing with remote earth station querying and (3) adaptive mixed-media routing. These new routing procedures were compared to modified forward routing and primary path only routing. Evaluations were

performed using 20 and 40 node mixed-media networks under overload, with various patterns of offered traffic, and with different amounts and types of network damage. Multi-level precedence and preemption (MLPP) features were not included in the comparison because of limitations in the trunk group queueing theory model used in the analysis program.

The new routing procedures studied, especially adaptive-mixed-media routing, substantially enhanced network performance after damage. These procedures did not reduce the average point-to-point blocking probability. They did, however, improve the service provided to the most poorly served group of users and they denied the possibility of call completion to the fewest users. The improvement in service to the most poorly served users provided by adaptive-mixed-media routing was slightly greater than the improvement associated with adding 10% more land trunks. Under overload conditions and when offered traffic patterns were dramatically shifted, the new procedures performed as well as or better than the best of the other procedures which were studied. All the new procedures studied are viable candidates for the Defense Switched Network. Further research is needed to evaluate the new routing procedures when MLPP features are included.

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CONTENTS (cont'd)

1. INTRODUCTION AND BACKGROUND

1.1 The Defense Switched Network

The Defense Communications Agency is developing a plan for a circuit switched network which will replace AUTOVON as the main telephone and data transmission network for the Department of Defense [1,2]. This new network, called the Defense Switched Network (DSN), must meet the dual objectives of survivable communications under stress and economical service under normal operations.

The DSN, as currently planned, will differ in a number of ways from AUTOVON. It will include many small programmable switches which exchange routing and control information over a common channel signaling network. It will also include both terrestrial connectivity and satellite connectivity obtained using many small earth stations located near switches. These earth stations will provide access to one or more broadcast satellites using Demand Assignment Multiple Access (DAMA) techniques or fixed capacity assignments. The DSN will provide better service for high priority callers by including Multi-Level Precedence and Preemption (MLPP) features which are already in AUTOVON [3,4]. These features allow a high priority call to preempt trunks used by lower priority calls when those trunks are needed to complete a call path. In addition, MLPP features provide high priority calls with much more routing flexibility than lower priority calls. The DSN will also allow calls to be least cost routed through either the backbone DSN network or through other networks such as the Bell System Direct Distance Dialing (DDD) network or the Federal Telecommunications System (FTS).

DSN requirements lead to a need for a new routing procedure. This procedure must take advantage of the mix of media and of switch intelligence to provide survivability without requiring excessive trunking capacity. It must also use distributed control, provide MLPP with a low incidence of preemption, use common channel signaling and switch processor bandwidth effectively, and be capable of sustaining network operation with intentional or unintentional signaling errors. None of the routing procedures developed previously satisfy all these requirements.

1.2 Limitations of POLYGRID and Other Existing Routing Procedures

POLYGRID routing as used in CONUS AUTOVON cannot be used in the DSN. It is too strongly tailored to the extensive POLYGRID structure of AUTOVON which is expensive because it includes not only a basic POLYGRID pattern but also a network of long-distance trunks which is overlaid on top of this pattern [5]. In addition, it is difficult to use broadcast satellites effectively with POLYGRID routing because the simple method used to limit path lengths and prevent loops (passing route control digits between switches) is inadequate in networks which include DAMA satellites. Routing procedures which are designed to make the best use of resources in such networks should consider all earth stations associated with one DAMA satellite to be the same distance apart because a short satellite hop uses no more resources than a long hop. Calls should, when necessary, be routed "backwards" to an earth station which is geographically farther from the destination than the originating switch and which is also farther via terrestrial links. This "backwards" routing is required when the shortest path to the destination includes an earth station located farther from the destination than the originating switch. It necessitates additional controls which limit the length of alternate routes and prevent loops in the call path when the earth station or satellite on the backwards path is blocked or destroyed. Backward routing and its associated controls are not possible with POLYGRID routing. POLYGRID routing also lacks two other features required by survivable routing procedures used in networks with broadcast satellites. First, it does not explicitly guarantee the existence of alternate land routes when all long-distance satellite links are destroyed at once. Second, it does not limit the total delay on voice calls by preventing these calls from traversing an excessive number of satellite hops.

None of the non-hierarchical routing procedures which are alternatives to POLYGRID routing include the features described above. We are not aware of any survivable routing procedures designed specifically for use in circuit switched networks with broadcast satellites. A number of survivable routing procedures have, however, been developed which can be used in terrestrial networks. These include the symmetric routing procedure with single-stage crankback described by Weber [6], originating office control as used in Eurpoean AUTOVON [7], a procedure to adapt routing tables in European AUTOVON based on an analysis of point-to-point blocking probabilities [8], modified forward routing as proposed for CONUS AUTOVON [9], flooding or saturation routing [10,11], adaptive routing using backwards learning based on link count [11], sequential routing [12], failsafe routing as used to establish virtual circuits [13], and a number of routing procedures designed for use in packet switched networks [14].

Some of the survivable routing procedures proposed for circuit switched networks have been evaluated using call-by-call simulations and steady state queueing theory analyses [6,11,15,16,18]. These studies demonstrate that increasing routing flexibility to improve survivability degrades network performance as measured by average call blocking probability, especially at high traffic loads. This somewhat unexpected result is caused by the creation of long alternate paths with increased routing flexibility. These paths degrade performance because the completion of one call using a [illegible] path with many tandem links often denies service to two or more addit[illegible]l calls which each require fewer links. This result suggests that the [illegible]s of economical operation and survivability are conflicting and difficult t[illegible]et simultaneously unless mechanisms such as adaptive routing or MLPP are employed. They also suggest that routing procedures should employ routing which is only flexible enough to provide the desired degree of survivability when it is needed, but not so flexible that long inefficient alternate routes are common. Similar conclusions can be drawn from research on routing procedures used in packet switched networks [19,20].

1.3 Mixed-Media Networks

Although detailed characteristics of the DSN are not known, it is necessary to create networks to compare and evaluate routing procedures for the DSN. We have created networks by extracting certain key characteristics of the DSN which affect routing and then defining a generic type of network called a mixed-media network which has these characteristics.

Mixed-media networks include many small programmable switches which exchange routing and control information over a common channel signaling network. They also include both terrestrial connectivity and satellite connectivity obtained using many small earth stations located near switches. These earth stations provide access to one or more broadcast satellites using DAMA techniques or fixed-capacity assignments.

An example of a mixed-media network which includes 16 nodes and 2 satellites is illustrated in Fig. 1. Dots in this figure represent nodes without earth stations, and solid triangles represent nodes with earth stations. Implicit in this figure is a common channel signaling network which parallels the network of voice trunks and which may be obtained using voice trunks and part of the satellite bandwidth. Two nodes in this mixed-media network (nodes 1 and 4) include earth stations which can acccess satellite S1, and three nodes (nodes 9, 15, and 16) include earth stations which can access satellite S2. DAMA access to satellite S2 allows the number of calls routed over S2 between nodes 9 and 15, nodes 9 and 16, and nodes 15 and 16 to vary dynamically depending on the offered traffic. Access to S2 via fixed-capacity assignments involves assigning a fixed proportion of the satellite bandwidth representing a fixed number of voice trunks separately to link nodes 9 and 15, nodes 9 and 16, and nodes 15 and 16. These satellite links are then used as "wires in the sky" with fixed capacities.

Mixed-media networks are more general than the above example indicates. Other types of broadcast and point-to-point transmission media besides DAMA satellites and terrestrial links can also be used. For example, microwave and high-frequency radio point-to-point links can be included as well as line-of-sight broadcast transmission similar to that used in broadcast radio networks.

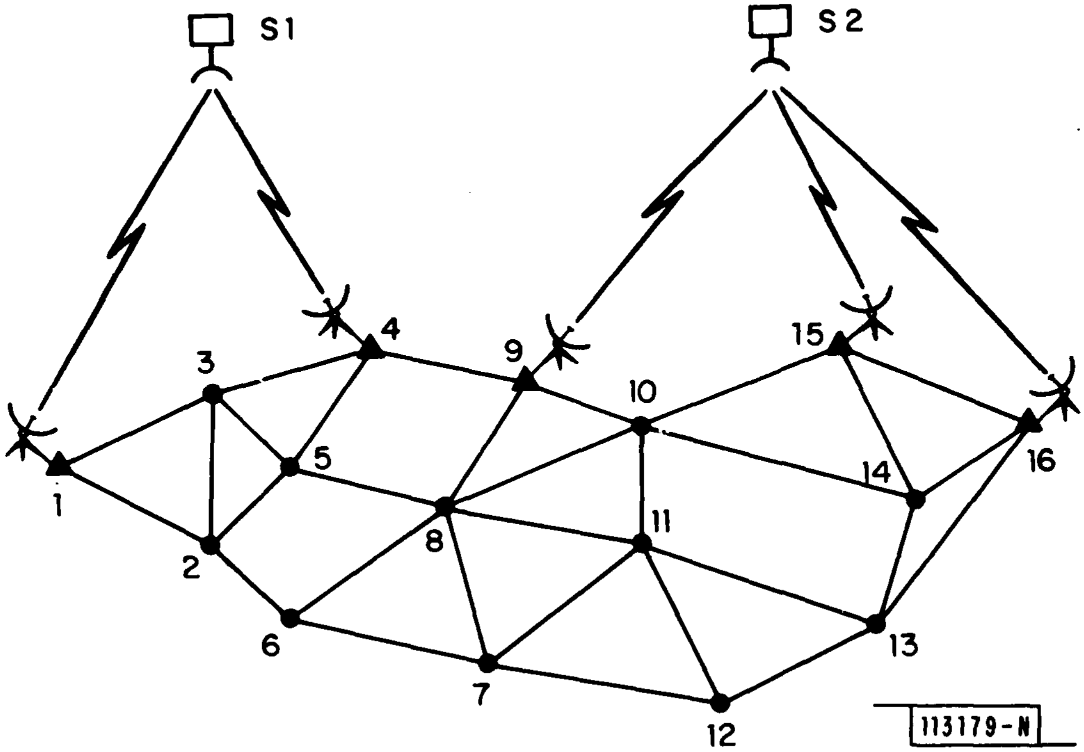

Fig. 1. A mixed-media network with 2 satellites, 5 earth stations, and 16 nodes.

In the remainder of this report we focus on the problem of developing survivable routing procedures for mixed-media networks. Three general classes of routing procedures are described and procedures from the first two classes are compared using a steady state network analysis program.

2. ROUTING PROCEDURES FOR MIXED-MEDIA NETWORKS

2.1 Mixed Media Routing

The simplest routing procedures which have been developed for use in mixed-media networks are called mixed-media procedures. These procedures use fixed routing tables and call-processing rules which employ either spill-forward control, a new type of control called remote earth station querying, or crankback. The major distinguishing characteristic of mixed-media procedures is that satellite and land links are treated separately and uniquely both when routing tables are created and when calls are actually routed through a network. For example, call-processing rules use information about the status of key nodes with satellite earth stations to route calls. In addition, routing tables indicate whether the shortest path to the destination switch via a given outgoing link includes a satellite hop. The use of fixed routing tables and local signaling in these procedures enhances routing security and automatically protects unaffected parts of a network when intentional or unintentional signaling errors occur in specific locations. These procedures also tend to minimize signaling and switch CPU processing bandwidth requirements and to minimize switch and signaling hardware requirements in general. These simplifications may, however, result in the necessity of larger and more trunk groups than are required by procedures which automatically adapt routing tables or by procedures which use flooding techniques to route calls.

Routing tables and call-processing rules used in mixed-media routing procedures attempt to maintain a balance between the conflicting goals of providing routing flexibility for survivability and limiting routing flexibility to use network resources effectively. They attempt to select those routes which use as few network resources as possible, to sustain network operation to the extent possible when all satellite links are destroyed, and to provide enough alternate land and satellite routes to guarantee survivability. Mixed-media routing procedures: 1) allow alternate earth stations to be used when the most desirable receiving or transmitting earth station is not available, 2) limit the total number of satellite hops allowed in voice and data calls, 3) prevent loops in call paths, 4) prevent excessively long routes and 5) allow more routing flexibility for high-priority calls.

2.1.1 Routing-Table Generation

All mixed-media routing procedures use routing tables which are produced automatically using a three-stage process. Figure 2 and Tables 1, 2, and 3 illustrate how a routing table for use in node 10 of the network shown in Fig. 2 is produced when the destination is node 16. The numbers in parentheses in Fig. 2 are link lengths in miles.

In the first stage of the routing-table generation process, the shortest path to the destination via each outgoing link of the originating node is found using a shortest path algorithm [21]. The outgoing links are then ordered on the basis of path lengths and placed in a list. The list for the network of Fig. 2 is presented in Table 1. This table does not contain a complete description of each shortest path. It only contains the first links in each path and some additional information on path length and on the first earth station and satellite in each path. For example, this table indicates that the first link on the shortest path to node 16 (10-9-S2-16) is link 10-9, and that this path uses two links, is 316 miles long, uses satellite

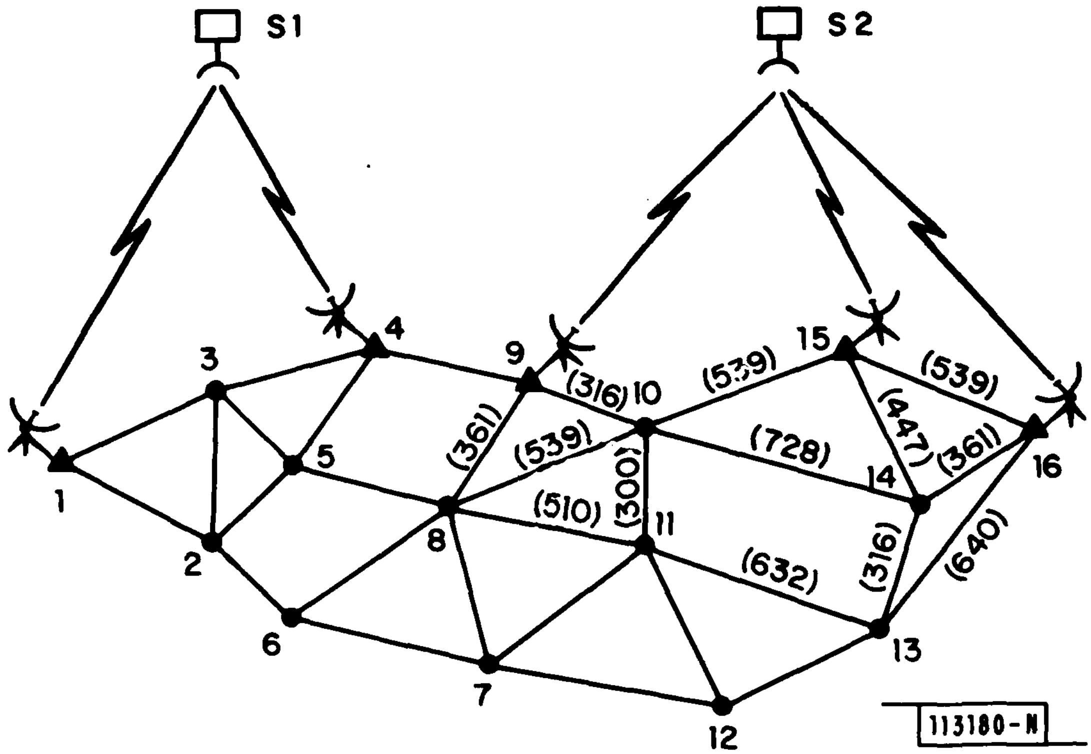

Fig. 2. A mixed-media network with the lengths of links used to route calls from node 10 to node 16 indicated in parentheses.

TABLE 1

OUTGOING LINKS FROM NODE 10 OF FIG. 2 ORDERED BY THE NUMBER OF LINKS IN AND TOTAL LENGTH OF THE SHORTEST PATH TO NODE 16

Link	Number of Links in Path	Total Length of Path (mi)	Use Satellite	Earth Station
10-9	2	316	Yes (S2)	9
10-15	2	539	Yes (S2)	15
10-14	2	1089	No	-
10-8	3	900	Yes (S2)	9
10-11	3	1572	No	-

TABLE 2

OUTGOING LINKS FROM NODE 10 OF FIG. 2 ORDERED BY THE NUMBER OF LINKS IN AND TOTAL LENGTH OF THE SHORTEST LAND PATH TO NODE 16

Link	Number of Links in Path	Total Length of Path (mi)
10-15	2	1078
10-14	2	1089
10-11	3	1572
10-8	4	2321
10-9	5	2459

TABLE 3

FINAL ROUTING TABLE USED IN NODE 10
OF FIG. 2 FOR DESTINATION NODE 16

Link	Use Satellite	Earth Station
10-9	Yes (S2)	9
10-15	Yes (S2)	15
10-15	No	-
10-14	No	-
10-8	Yes (S2)	9
10-11	No	-
10-8	No	-

Shortest Land Route = 2 Links
Shortest Satellite Route = 2 Links, 1 Hop

S2, and uses the earth station at node 9. In this and in following tables, first links are ordered primarily by the total number of links in the associated shorted path. A further ordering by total path length is made if link counts are equal. This ordering metric attempts to use the least number of switches and links to complete each call. The length of a satellite hop used to create Table 1 was zero and a satellite hop was counted as one link. In an operational network, the length assigned to a satellite hop could be adjusted to be high enough to prevent calls between nearby users from being routed over a satellite but low enough to load the satellite to capacity. In addition, the lengths assigned to links connected to vulnerable or overloaded switches could be increased to divert traffic away from such switches. Table 1 could be used as a routing table except it only applies to a network in which all satellites and earth stations are operating and not destroyed or blocked.

In the second stage of the routing-table generation process a list is produced as in the first stage, but all satellites are removed from the network and only land paths are considered. The list produced for the network in Fig. 2 is presented in Table 2. Note that the first link on the shortest path to node 16 (10-15-16) is now link 10-15. Table 2 could be used as a routing table except it applies only when satellite S2 is blocked or destroyed.

In the third stage of the routing-table generation process, the lists produced in stages one and two are combined to form a final routing table. The routing table for the network in Fig. 2 is presented in Table 3. First links on shortest land and satellite paths are entered separately in this table. This provides alternate land routes when satellites or earth stations are destroyed. For example, link 10-8 appears in both the fifth and seventh positions of this table. The lower numbered position corresponds to a satellite path and the higher to a land path. The maximum number of entries allowed in this routing table was eight and four of these eight had to be associated with land routes. These numbers were chosen to prevent excessively long routes but to provide adequate alternate routing when satellite S2 is destroyed. Only seven entries are included because some of the entries in Tables 1 and 2 are duplicates and use identical paths and because the first link on the longest land path (entry five in Table 2) was excluded to prevent excessively long routes. Such routes must be prevented because they can greatly degrade network performance, especially when the offered traffic load is high. The number of links in the shortest land path and the number of links and hops in the shortest satellite path are included in the routing table. This supplementary information is used by call processing rules to limit the length of alternate paths and to prevent excessive delay.

The above routing-table generation process is characterized by the maximum number of routing-table entries allowed, by the number of entries associated with shortest land paths, by the maximum allowable path length, and by the metric used to order paths. These characteristics depend on network loading and topology and must be determined empirically. The link count biased by distance metric used above is simple and similar to the metric used in AUTOVON and in a number of packet-switched networks. Other metrics which use information on sizes, loading, and survivability of links and switches can also be used.

2.1.2 Call-Processing Rules

All call-processing rules used with mixed-media routing require a common-channel signaling network in which switches automatically sense failure or destruction of attached links and adjacent switches and in which earth stations sense the failure of associated satellites. Call request messages are sent over this network to establish call paths. These messages contain a special header in addition to the called number and call priority. A variable-length component of this header includes a trace or list of switches and satellites currently in the call path. It also includes a list of known blocked or destroyed earth stations and satellites. Each switch in the call path adds data to this part of the header. A fixed-length component of the header contains the maximum number of links allowed in the land and satellite routes to the destination and the maximum number of satellite hops allowed. Only the originating switch places data in this part of the header. The limits on path lengths and number of satellite hops are calculated using the supplementary data stored in routing tables and detour lengths. These limits vary for calls with different priorities and for voice and data calls. Information in the call request header is used by switches to prevent loops and shuttles (a loop between two nodes), to route calls away from or avoid blocked or destroyed earth stations and satellites, to limit the length of alternate routes, to prevent excessive delay, and to direct the cranking back of calls.

2.1.2.1 Spill-Forward Control

Spill-Forward control either blocks a call at a switch or it routes a call to another switch not yet in the call path. The next switch in the call path is selected by sequentially examining the links listed in the routing table. A link is skipped if (1) it leads to a switch already in the call path, (2) its associated shortest path includes any of the blocked or destroyed earth stations and satellites listed in the call request header, (3) no more satellite hops are allowed and the links' associated shortest path includes a satellite, (4) no free or preemptable trunks are available on the link or (5) the link is destroyed. A call is blocked if no acceptable routing table entry is found after examining as many entries as is allowed for the call's priority or if only one more link is allowed in the call path and the next switch is not the destination. All tests are performed using only the local information available to the switch and the more global information contained in the call request header.

Call paths established using spill-forward control are illustrated in Figs. 3 and 4. The mixed-media network in these and the following figures includes 14 switches, 2 earth stations, and 1 satellite. The call path in Fig. 3 illustrated by a dotted line is the path established when no links are busy. Starting with switch 1, each switch places itself on the trace in the header and routes the call using the first routing-table entry. When the call request arrives at node 14, the trace includes 1-2-3-S1-11 and the list of unavailable earth stations and satellites is empty. The first switch in the call path (switch 1 in Fig. 3) uses supplementary data in the routing table and stored limits to compute the maximum number of links allowed in land routes (5 + detour of 2 = 7), the number of links allowed in satellite routes (4 + detour of 2 = 6), and the number of satellite hops allowed (1).

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ROUTING TABLE IN NODE 1
FOR DESTINATION NODE 14

LINK	USE SATELLITE ?	EARTH STATION
1-2	YES (S1)	3
1-4	YES (S1)	3
1-7	NO	–
1-4	NO	–
SHORTEST LAND ROUTE=5 LINKS		
SHORTEST SATELLITE ROUTE = 4 LINKS, 1HOP		

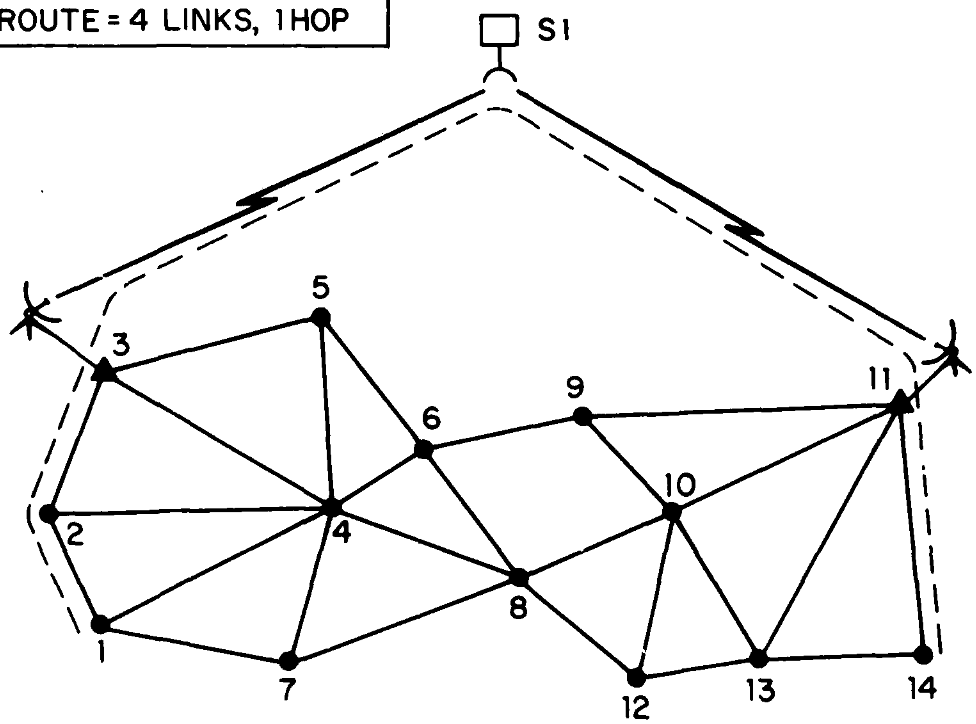

Fig. 3. Call path from node 1 to node 14 when the earth stations and the satellite are available and mixed-media routing is used.

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ROUTING TABLE IN NODE 3
FOR DESTINATION NODE 14

LINK	USE SATELLITE?	EARTH STATION
3-11	YES (S1)	3
3-4	NO	–
3-5	NO	–

ROUTING TABLE IN NODE 4
FOR DESTINATION NODE 14

LINK	USE SATELLITE?	EARTH STATION
4-3	YES (S1)	3
4-5	YES (S1)	3
4-2	YES (S1)	3
4-8	NO	–

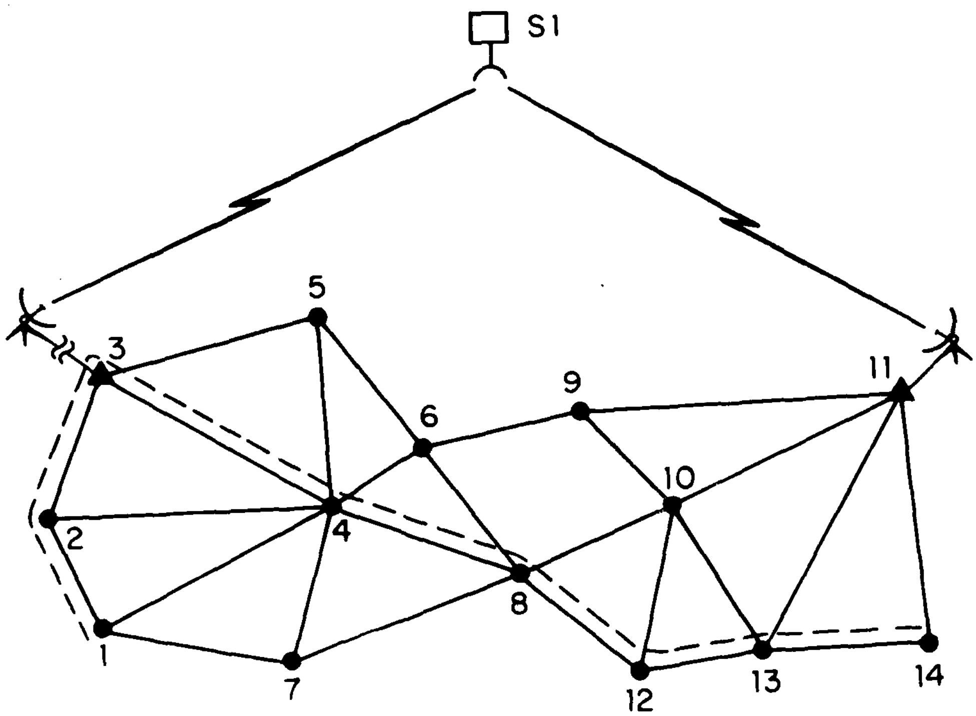

Fig. 4. Call path from node 1 to node 14 when mixed-media routing with spill-forward control is used and the earth station at node 3 is blocked.

The call path in Fig. 4 was established when the earth station at node 3 was busy. The call request message travels to switch 3 as in Fig. 3. Here link 3-11, the first routing-table entry in node 3, is blocked. Switch 3 recognizes this, places the earth station in node 3 onto the list of unavailable earth stations in the call request header, and routes the call to node 4 using the second routing-table entry, 3-4. The switch at node 4 skips the first three routing-table entries because they lead to shortest paths which include the blocked earth station at node 3 (this earth station is on the list in the call request header). The switch at node 4 routes the call to node 8 using the last routing-table entry, 4-8. All other nodes route the call using the first entry in their routing table for destination node 14.

When the call request arrives at node 14, the trace includes 1-2-3-4-8-12-13 and the list of unavailable earth stations includes the earth station at node 3. Note that if the list of unavailable earth stations had not been passed to switch 4 the call would have been routed from switch 4 to switch 5 on link 4-5, the first routing-table entry which does not lead to a node in the trace. The call would then have been routed to nodes 6 and 8. At node 8 it would have been blocked and lost because the next node wouldn't have been the destination and the call path length would have been one less than the maximum allowable length stored in the call request header (seven links).

The above example demonstrates that including a list of unavailable earth stations and satellites in the call request header can prevent a call from being lost. In general, including this list reduces path lengths by preventing calls from wandering around a network to reach blocked or destroyed earth stations. In the above example, calls had to detour to node 3 to find out that the earth station at node 3 was busy. This detour can be prevented with remote earth station querying.

2.1.2.2 Remote Earth Station Querying

Remote earth station querying is a new type of call processing made possible by common-channel signaling. If the shortest path to the destination includes a satellite, then a common-channel signaling query message is sent to the first earth station on this path to determine its status and the status of the associated satellite. If the earth station and satellite are available, the call is routed normally as with spill-forward control. If not, the earth station or satellite is added to the list of unavailable earth stations and satellites stored in the call request header and then the call is routed normally as with spill-forward control. Remote earth station querying prevents calls from being routed toward blocked or destroyed earth stations and satellites without increasing signaling or switch CPU bandwidth excessively.

Figure 5 illustrates a call path when remote earth station querying is used and the earth station at node 3 is blocked. The detour evident in Fig. 4 has been completely eliminated, and the call is routed directly to node 14. In Fig. 5, the first node in the call path (node 1) sends a query message to the earth station at node 3 because this earth station is on the shortest path to the destination (see first routing-table entry). The return message from switch 3 indicates that the earth station is blocked. Switch 1 thus adds the earth station to the list of unavailable earth stations in the call request header and routes the call on link 1-7, the first routing-table entry not associated with a path that includes the earth station at node 3.

ROUTING TABLE IN NODE 1
FOR DESTINATION NODE 14

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LINK	USE SATELLITE?	EARTH STATION
1-2	YES (S1)	3
1-4	YES (S1)	3
1-7	NO	–
1-4	NO	–

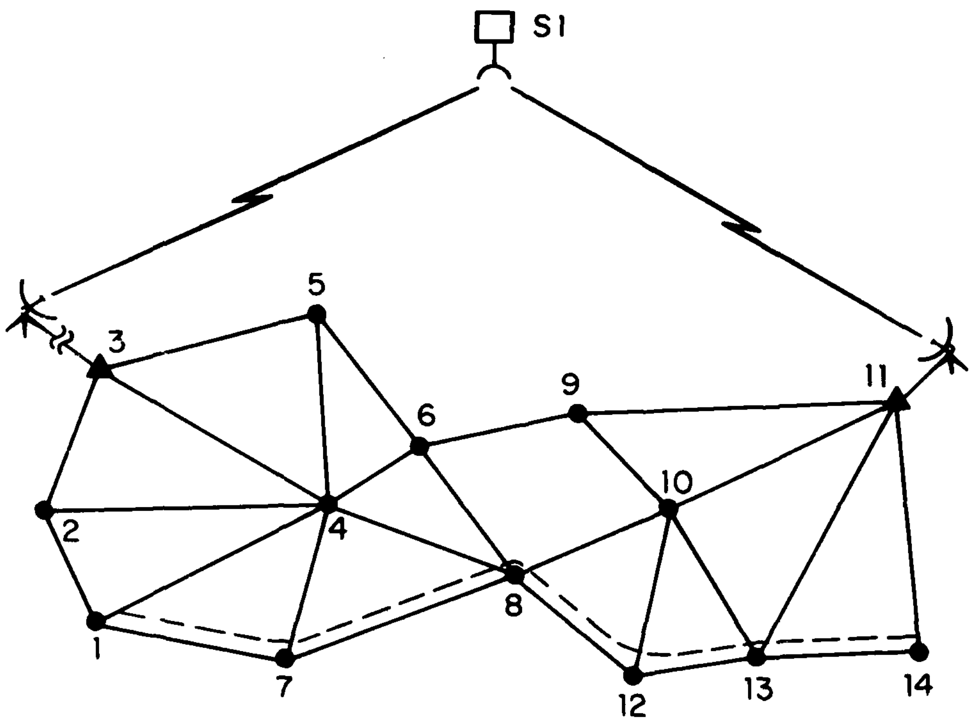

Fig. 5. Call path from node 1 to node 14 when mixed-media routing with remote earth station querying is used and the earth station at node 3 is blocked.

The other switches also route calls using routing-table entries not associated with paths that include the earth station at node 3. When the call request arrives at node 14, the trace includes 1-7-8-12-13 and the list of blocked earth stations includes the earth station at node 3.

2.1.2.3 Single-State Crankback

Single-stage crankback is similar to spill-forward control except a call request blocked at a node is routed backwards to the previously visited node. This type of crankback searches many more alternate paths than spill-forward control. It is identical to sequential routing [12] except controls have been added to prevent loops and shuttles, limit path lengths, and prevent routing to blocked earth stations. These controls are needed to prevent excessively long alternate routes which could degrade network performance. In addition, the routing-table generation process has been defined.

Figure 6 illustrates the call path when the earth station at node 3 is blocked, links 3-4 and 3-5 are blocked, and single-stage crankback is used. The call request message travels first to node 3. Here no outgoing links are available and the call would be blocked if spill-forward control were used. Single-stage crankback, however, allows the call to crankback to node 2. Before it is cranked back, switch 3 adds the earth station at node 3 to the list of unavailable earth stations in the call request header. When the call request arrives back at node 2, it thus indicates that the earth station at node 3 is busy. This prevents the call from being routed toward node 3 and causes the call to be routed over land links to node 14. The trace when the call arrives at node 14 includes 1-2-3-2-4-8-12-13 and the list of

ROUTING TABLE IN NODE 2
FOR DESTINATION NODE 14

LINK	USE SATELLITE?	EARTH STATION
2-3	YES (S1)	3
2-4	YES (S1)	3
2-4	NO	-
2-1	NO	-

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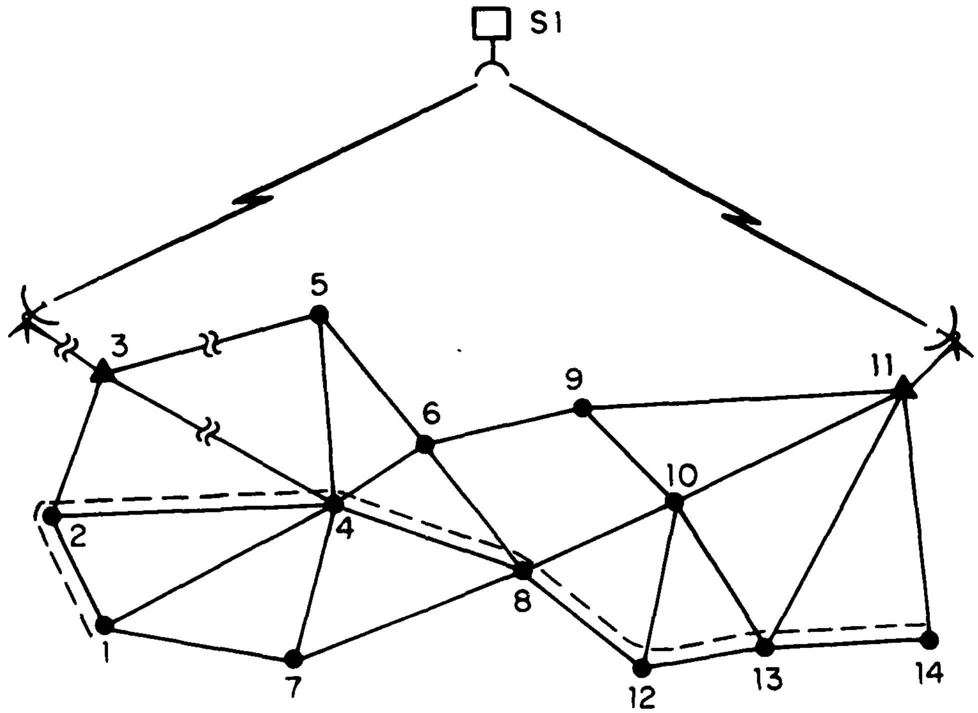


Fig. 6. Call path from node 1 to node 14 when mixed-media routing with single-stage crankback is used, the earth station at node 3 is blocked, and the links between nodes 3 and 4 and between nodes 3 and 5 are blocked.

unavailable earth stations includes the earth station at node 3. Note that the call path would have been identical to that in Fig. 4 if link 3-4 had been free.

2.2 Adaptive-Mixed-Media Routing

Adaptive-mixed-media routing procedures are identical to the previously described static mixed-media procedures under normal operating conditions. When the network is damaged, however, routing tables are automatically updated to enhance survivability.

The procedures used to update routing table in adaptive-mixed-media routing are similar to those currently used in the ARPANET [22]. Each node stores global information which describes the network topology. This information is updated only when the network topology changes (switches or links are added, removed, or destroyed). Updated information is transmitted from nodes which detect a change using flooding on a secure common-channel signaling network. Routing tables are recomputed in each node when an update is received using the three stage algorithm used to generate the original set of routing tables. This procedure is relatively simple, but it has many advantages over other adaptive procedures. It provides adaptive, distributed routing based on global information, but does not suffer from any inherent adaptation rate, stability, or convergence problems. Such problems could occur in procedures such as the failsafe protocol [13] or the old ARPANET routing procedures [23] which adapt continuously on the basis of network performance. Other advantages of this procedure are that routing tables for users with different priorities are easy to maintain, a table of unreachable nodes is automatically provided, and the two main components of the procedure have been tested in operational networks. The flooding scheme used to transmit database updates has been used since 1979 in the ARPANET (the required signaling bandwidth in the ARPANET is less than 250 bps). The procedure used to calculate new routing tables is similar to that used in AUTOVON, in the network analysis programs developed at DCEC [24], and in the ARPANET. Conservative assumptions concerning switch processing capabilities lead to times to compute new routing tables of from half a second to a few minutes.

The main disadvantage of adaptive-mixed-media routing is the extra complexity in switches it requires and the necessity of transmitting global information describing topological changes around the network. This information must be transmitted and received accurately to sustain network performance. Although it can be heavily encrypted and protected and switches can employ defensive programming to protect themselves against intentional or accidental signaling errors, it would be difficult to completely eliminate the possibility that such errors could significantly disrupt network operation. Evidence that this would occur infrequently is available in the relatively good performance of the ARPANET. The possibility of network disruption caused by signaling errors and the increased complexity and cost of this adaptive procedure must be weighed against its improved capability to reconstitute the network. The major goal of our evaluation of this procedure in this paper is thus to determine the extent of this improvement.

2.3 Precedence Flooding

Precedence Flooding routes high-priority traffic using flooding techniques alone or a combination of mixed-media routing backed up by flooding. Low-priority calls are routed using mixed-media routing. The flooding scheme used is tailored to mixed-media networks. Whenever the destination of an originating high-priority call is more than one link away, the originating switch sends a SEARCH message for the destination to any adjacent switch with free or preemptable trunks to the originating switch. SEARCH messages are transmitted over the common-channel signaling network. Each switch adds information to the SEARCH message and forwards the new message to adjacent switches. The modified SEARCH message is not sent back over the link used by the incoming SEARCH message and it is not forwarded over links containing no free or preemptable trunks.

Switches forward the first SEARCH message received and any following SEARCH message received which came over a shorter, but not necessarily quicker, path. This prevents SEARCH messages delayed on a satellite hop from being discarded when land routes are also available. The information contained in SEARCH messages is updated at each switch. It includes the number of satellite hops and links traversed, the number of links where preemption is required, and an overall measure of link loading on the SEARCH message path. Switches store this information and the incoming link for as many as N SEARCH messages received for each call, where N is an empirically selected number. Information is stored only for those N SEARCH messages with the shortest distance to their source.

The path selection process begins at the destination switch. This switch waits a short prespecified time after receiving the first SEARCH message for a given call and then attempts to route the call over that link which leads to the path with the fewest links. If paths including the same number of links are available, then link loading, delay, and the number of preempted calls on each path are taken into consideration. This metric is similar to the metric used to order paths in mixed media routing except link loading is considered, as is the number of low priority calls which are pre-empted. In addition, paths which use a given number of links more than the number of links used by the shortest call in progress to or from the source can be eliminated. This control tends to prevent excessively long routes under normal operation but allows long routes after network damage. If the link selected no longer includes a usable trunk, then the link with the next shortest path to the destination is chosen. This process is initiated at tandem switches by a backwards call setup message which starts at the destination and stops at the source. Tandem switches prevent loops and shuttles in the call path by skipping over links which lead to nodes already in the call path. These switches also reserve trunks on the selected links.

After the backwards call set-up message reaches the source, a forward call setup message is sent over the established path and the call begins. A call is blocked if the originating switch times out and doesn't receive a backwards call setup message after a given period of time.

Precedence Flooding is attractive because the shortest path is actually found by an exhaustive search. Its intuitive appeal is also supported by the good performance of flooding in [11]. Flooding provided the best grade of service when compared to the routing procedures currently used in CONUS and European AUTOVON and to an adaptive procedure which used backward learning based on link count. Flooding performed better than these procedures under normal traffic loads, overloads, and when the simulated network was damaged. It also adapted quickly and automatically after damage.

Flooding is reasonable in the DSN only for high-priority traffic because of its large signaling and switch CPU processing requirements. Conservative assumptions similar to those made in [10] indicate that 2400-baud common-channel signaling links (obtained, for example, from single voice trunks) and PDP-11/34-type switch controllers could support at most only the projected high-priority AUTOVON traffic for 1985 (roughly 1300 Erlangs). The use of 4800-baud common-channel signaling links would increase the allowable traffic which can be routed using flooding to 2500 Erlangs. More than 1300 Erlangs could be supported by 2400-baud common-channel signaling links if flooding is only used for high-priority traffic when no path is available with mixed media routing. This mixture of routing procedures is very attractive. It does not require critical topological information to be transmitted securely and accurately throughout the network and it does not require the excessive bandwidth required by pure flooding. Switches must, however, be capable of processing SEARCH and call set-up messages and the extra delay caused by the two step routing (mixed-media, then flooding) must be acceptable.

3. STEADY-STATE ANALYSIS

Two simple reference routing procedures and the three mixed-media procedures which could be analyzed using the steady state network analysis program were compared using twenty and forty node test networks with various traffic conditions. Comparisons were based primarily on the distribution of the point-to-point blocking probabilities between node pairs. All traffic was assumed to have the same priority and MLPP features were not included because of limitations in the trunk group queueing theory model used in the analysis program.

The two simple routing procedures used as references were primary path only routing and modified forward routing [9]. Primary path only routing was included because it provides a baseline performance limit to which more sophisticated routing procedures can be compared. Calls can be routed on only one path to each destination with primary path only routing. If any link in that path is blocked, the call is blocked. Modified forward routing was included because it is a previously used variant of the simplest non-hierarchical routing procedure which allows alternate routes. That procedure, forward routing, routes calls only to switches which are closer to the destination than the current switch. Loops and excessively long paths are prevented with forward routing by selecting routing table entries which conform to this rule. Modified forward routing differs from forward routing in that a call may be routed backwards once to a switch directly connected to the destination via a land link or a satellite. Loops are prevented by passing along an extra bit as the call path is set up. This bit is normally zero, but it is set to one when a backwards link leading away from the destination is selected. Any switch receiving a call setup message with this bit set blocks the call if it can't be routed directly to the destination. Modified forward routing has been used extensively in network design programs by the Defense Communications Agency and was previously found to be as survivable as POLYGRID routing in an AUTOVON-like terrestrial network [9]. The distance metric used with modified forward routing and primary path only routing in this study was identical to that used with mixed-media routing.

The three mixed-media routing procedures compared were (1) mixed-media routing with spill-forward control (2) mixed-media routing with remote earth station querying and (3) adaptive mixed-media routing. The performance of these three procedures could be determined using the queueing theory model of trunk group operation incorporated in the analysis program.

3.1 Test Networks

The minimum cost design of survivable mixed media networks is a difficult non-linear optimization problem. This design should be based on the offered traffic, the routing procedure, allowable node, earth station and satellite locations and capacities, damage scenarios, and desired point-to-point blocking probabilities before and after damage. The approach taken in this study was to design mixed-media test networks which are not optimal but are realistic in terms of offered traffic, node and earth station locations, and link capacities.

Two twenty node and two forty node mixed-media test networks were created to evaluate routing procedures. Characteristics of these networks are presented in Table 4. Link and switch locations of networks DSN1 and DSN2 are presented in Figs. 7 and 8. Dots in these figures represent

TABLE 4

CHARACTERISTICS OF FOUR TEST NETWORKS

NETWORK	DSN1	DSN2	DSN3	DSN4
Switches	20	40	20	40
DAMA Satellites	1	1	1	1
Earth Stations	5	9	5	9
Terrestrial Links	118	355	121	361
Terrestrial Voice Trunks	1992	4620	2120	4852
Satellite Capacity (Voice Trunks)	450	930	450	930
Offered Traffic (Erlangs)	1450	2960	1450	2960

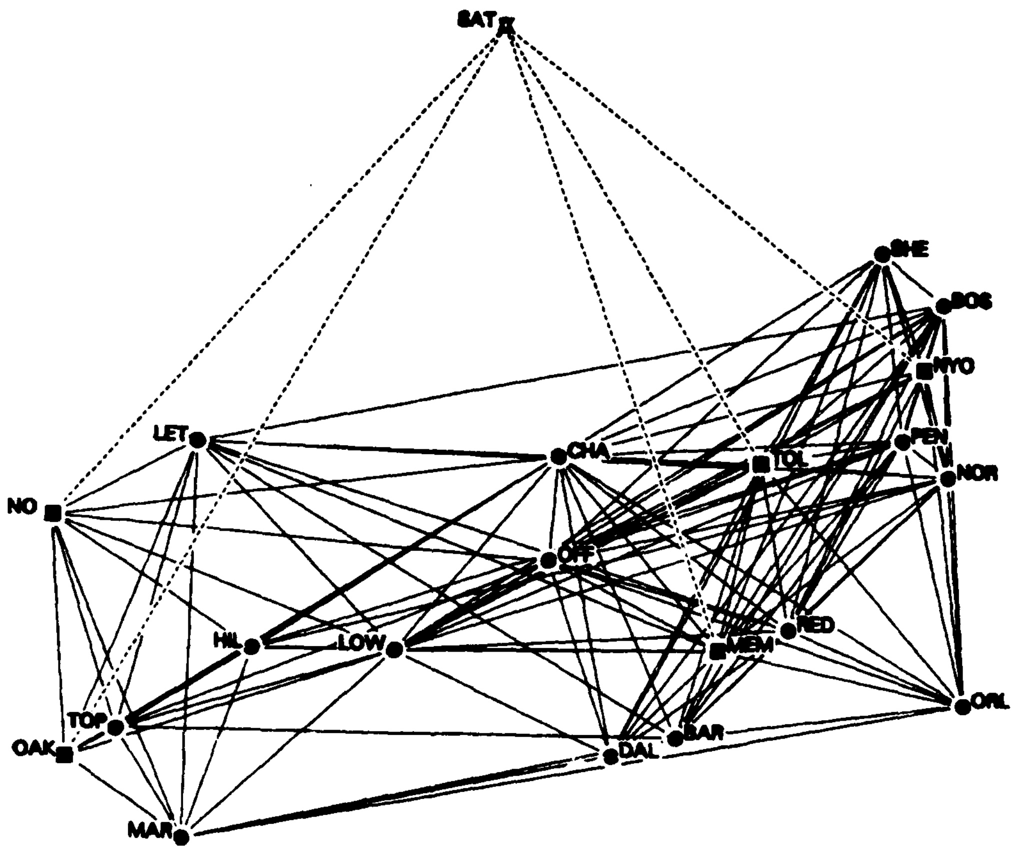


Fig. 7. Test network DSN1.

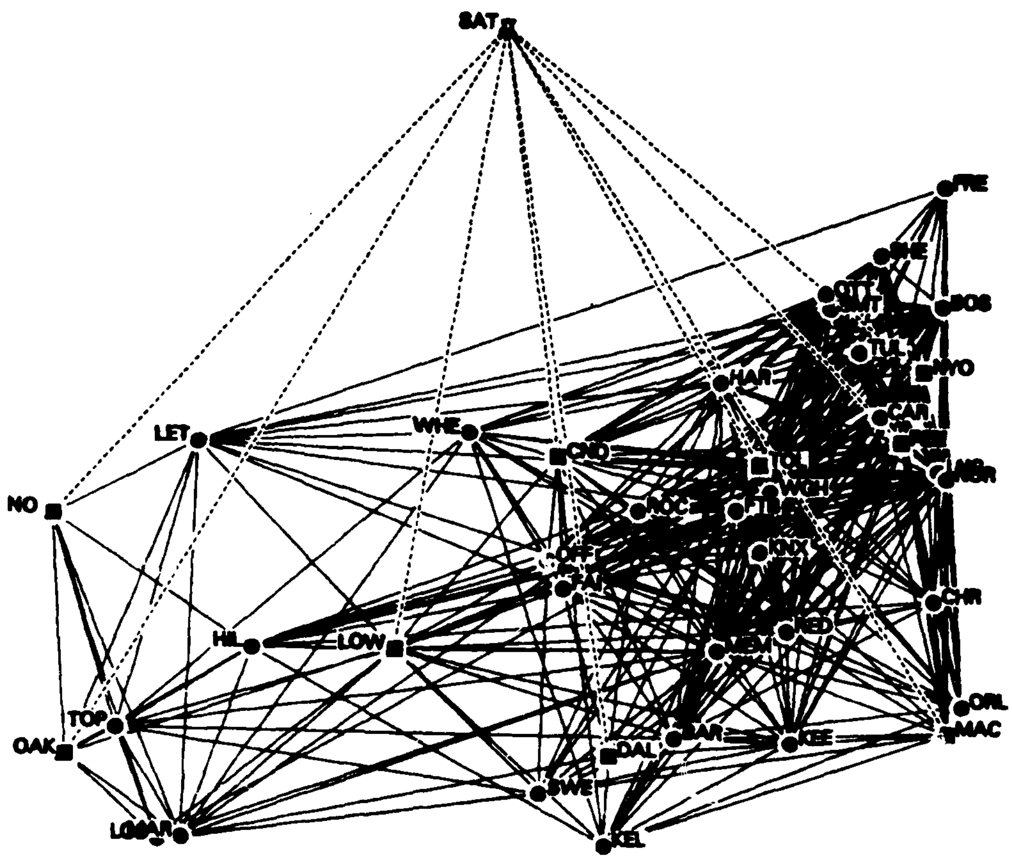


Fig. 8. Test network DSN2.

switches without earth stations and squares represent notes with earth stations. Solid lines represent land links and dashed lines represent links to the one DAMA satellite. Networks DSN1 and DSN2 are minimum cost networks without any spare trunking to improve survivability. Network DSN3 was designed by adding spare terrestrial trunks to DSN1. These trunks provide supplementary paths when the satellite in DSN1 is destroyed. Likewise, network DSN4 was designed by adding spare trunks to DSN2.

All network designs were based on the projected offered traffic and node locations in one tentative 100 node DSN configuration which was under investigation at the Defense Communications Engineering Center. The 20 and 40 nodes with the most originating traffic were first selected. Earth stations were then positioned on those nodes with the most offered traffic with the constraint that earth stations should be distributed throughout the network. All earth stations accessed one DAMA satellite. Land links and link capacities were assigned using a minimum cost network design program [24] modified to allow a DAMA satellite. The cost assigned to a satellite hop in this program was selected iteratively to route roughly 1/3 of all the offered traffic over the satellite and the desired link blocking probability was set to 0.1. The cost assigned to land trunks included mileage and termination charges representative of current tariffs. Following this initial design, link and the satellite capacity were resized to provide a link blocking probability of 0.1 when mixed-media routing with spill-forward control was used. Resizing was performed iteratively using the network analysis program described below. This procedure was used to create networks DSN1 and DSN2.

The above design procedure is not optimized to create survivable networks. Such networks should be designed using a more complex procedure which adds spare capacity to provide the desired point-to-point blocking after various amounts and types of damage. A crude approximation to such a procedure was used to design test networks DSN3 and DSN4. These networks contain spare trunking and cost roughly 10% more than networks DSN1 and DSN2. They were designed by first removing the satellite and earth stations from DSN1 and DSN2 and repeating the design procedure described above with these two all terrestrial networks. New long-distance terrestrial links were created during this design to compensate for the missing satellite capacity. The largest, most efficient long-distance links were added to the original networks one at a time until the cost of all terrestrial trunks in the new networks exceeded the cost of the trunks in the original networks by 10%. Network DSN3, based on DSN1, includes three new terrestrial links containing 128 new voice trunks. Network DSN4, based on DSN2, includes six new terrestrial links containing 232 voice trunks.

3.2 Analysis Program

A steady state network analysis algorithm first presented by Katz [25] was used to determine network performance. A program which implemented an updated version of the algorithm developed by Fischer and Knepley [26] and Fischer et. al. [24] was obtained and modified to include the new routing procedures. Some of the important assumptions of these algorithms are that the network is in equilibrium, that traffic is adequately characterized by its means and variance, that the time required to set up a call is zero, that no congestion occurs in switches, and that blocked calls are immediately cleared from the network and not offered again. The algorithm computes all point-to-point and link blocking probabilities, the traffic offered to each link, and the average number of links seized per completed call. It requires as inputs the network topology, link capacities, the offered traffic matrix, and the routing procedure. Results obtained using this algorithm in the past agree closely with results obtained using event-by-event simulations of circuit-switched networks [24,25,26].

The analysis algorithm is described in detail in [26]. It uses an iterative procedure with two phases in each iteration. In the first phase offered traffic is distributed over the network for every source-destination pair using the given routing procedure and link blocking probabilities computed on the previous iteration (these probabilities are initially set to a fixed value between zero and one). Traffic is distributed between each source-destination pair separately and lost traffic is monitored to compute point-to-point blocking probabilities. In the second analysis phase, link blocking probabilities are computed using the total traffic offered to each link and dual moment queueing theory models of link operation. The algorithm converges when link blocking probabilities on successive iterations differ by less than a given amount. This algorithm was modified by adding mixed-media routing with spill-forward control to the first traffic distribution phase of each iteration and by modifying the second phase to allow a DAMA satellite Controls used in the traffic distribution phase block calls with paths that are more than one link longer than the shortest land path to the destination.

A new routing table generation program was written which implements the two stage routing table generation process described previously. The metric used to order paths in this program is the total number of links biased by total distance. A satellite hop was counted as one link and the distance assigned to a satellite hop was adjusted to route roughly 1/3 of all traffic over the satellite. Whenever possible, routing tables included ten entries for each source-destination pair with five or more entries corresponding to land routes. First links of paths which were more than one link longer than the shortest land path between each source-destination pair were excluded from routing tables.

The routing table generation program and network analysis program were written in RATFOR and FORTRAN. RATFOR is a modern structured "C" like language. Programs written in RATFOR are much easier to write, debug, and maintain than programs written in FORTRAN. RATFOR programs can, however, be run through a preprocessor to produce FORTRAN programs. In this form they are highly portable and compatible with existing FORTRAN programs. All programs were run on an AMDAHL 470 computer under an IBM VM/CMS operating system. CPU times for the analysis program ranged from 1 to 260 seconds and the number of iterations required for convergence ranged from 5 to 19. CPU times for routing table generation ranged from 2 to 64 seconds.

3.3 Analysis Conditions

Networks were analyzed under normal operating conditions, and (1) with different types of network damage, (2) when the traffic was uniformly increased and decreased, and (3) when traffic patterns between source-destination pairs were varied in a number of ways while the total offered traffic was held constant. The performance of adaptive-mixed-media routing was examined when parts of the network were destroyed by creating a new routing table for the damaged network and using the analysis program with this routing table. The performance of remote earth station querying was examined when both the satellite and terrestrial links and switches were destroyed and when the satellite alone was destroyed by using a new routing table for the network being analyzed created with the satellite omitted.

Four patterns of network damage were examined. First, from 10% to 40% of all terrestrial voice trunks were destroyed. The largest terrestrial links were destroyed one at a time until the desired percentage of trunks were destroyed. Second, the satellite and from 10% to 40% of all terrestrial trunks were destroyed. Third, from two to eight of the busiest switches were destroyed. These switches were those which originate and terminate the most offered traffic. Fourth, the satellite and from two to eight switches were destroyed. The offered traffic was held at a normal value under all damage conditions except when switches were destroyed. In this case the traffic to and from destroyed switches was lost and the total traffic offered to the network decreased.

Network performance was examined with four deviant traffic patterns. The first was an increase in the offered traffic between all node pairs of 5% to 25%. This examines the behavior of routing procedures under overload. The second traffic pattern (RANDOM +/-100%) randomly varied the offered traffic between each node pair. Traffic values were chosen using a uniform distribution ranging from zero to twice the normal values and then all offered traffic values were multiplied by a constant to maintain the total offered traffic at a normal value. Four different randomizations of traffic pattern two were used to evaluate the ability of routing procedures to shift traffic from overloaded trunks to available trunks when traffic patterns vary over a moderate range. The third and fourth traffic patterns varied traffic over large unexpected extremes to examine routing performance when traffic is chaotic. The third pattern (UNIFORM) applied an identical amount of traffic between each node pair but maintained the total offered traffic at a normal value. The fourth pattern (REVERSE MAX/MIN) applied the maximum offered traffic between any node pair to that node pair which normally has the minimum offered traffic, the second largest offered traffic between any node pair to that node pair with the second least offered traffic, etc.

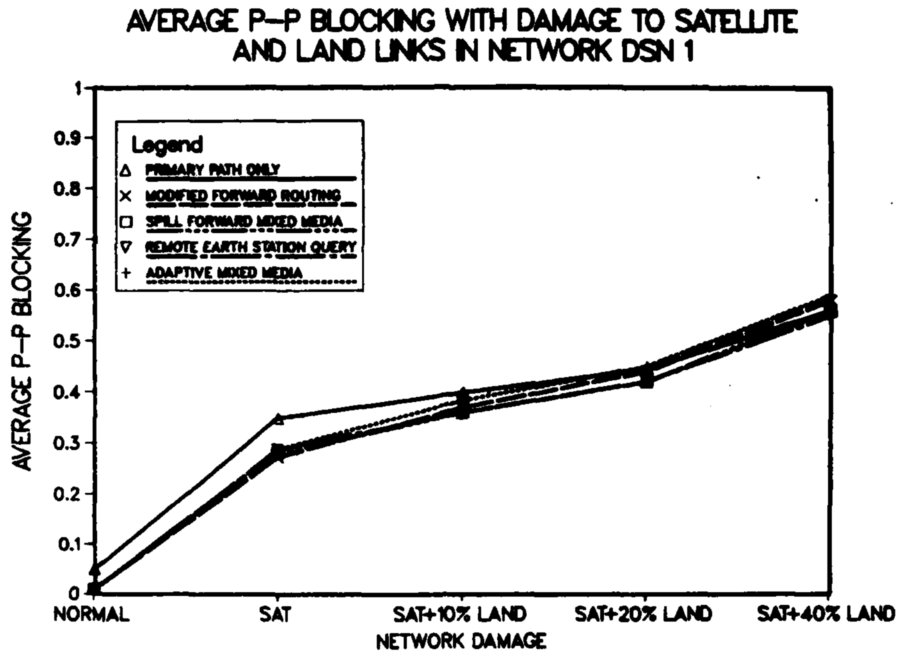
4. RESULTS

Results are presented separately for the three major analysis conditions described previously: (1) network damage, (2) traffic overload, and (3) chaotic traffic patterns. The sections describing results obtained with damage include a discussion of performance measures used to compare routing procedures and of performance under normal operating conditions. Damage scenarios are examined in the following order: (1) damage to the satellite and then land links (2) damage only to land links (3) damage to the satellite and then to switches and (4) damage only to switches.

4.1 Performance Under Conditions of Network Damage

4.1.1 Damage to Satellite then to Land Links in Networks Without Spare Capacity

The average traffic-weighted point-to-point blocking probability in networks DSN1 and DSN2 under normal operation and when the satellite and 0% to 40% of all land trunks are destroyed is presented in Fig. 9. These values were computed by multiplying the point-to-point blocking probability between each node pair by the traffic between that node pair, summing these values and dividing by the total offered traffic. Under normal operation all routing procedures except primary path only routing provide an average blocking of less than 0.02. After the satellite is destroyed blocking increases substantially. This increase is followed by further increases as more and more land trunks are destroyed. Blocking is generally highest for primary path only routing, especially when only the satellite is destroyed and all traffic normally routed over the satellite (roughly 1/3 of all offered traffic) is blocked. There are, however, no major differences between the other routing procedures evident in these Figs. In addition,



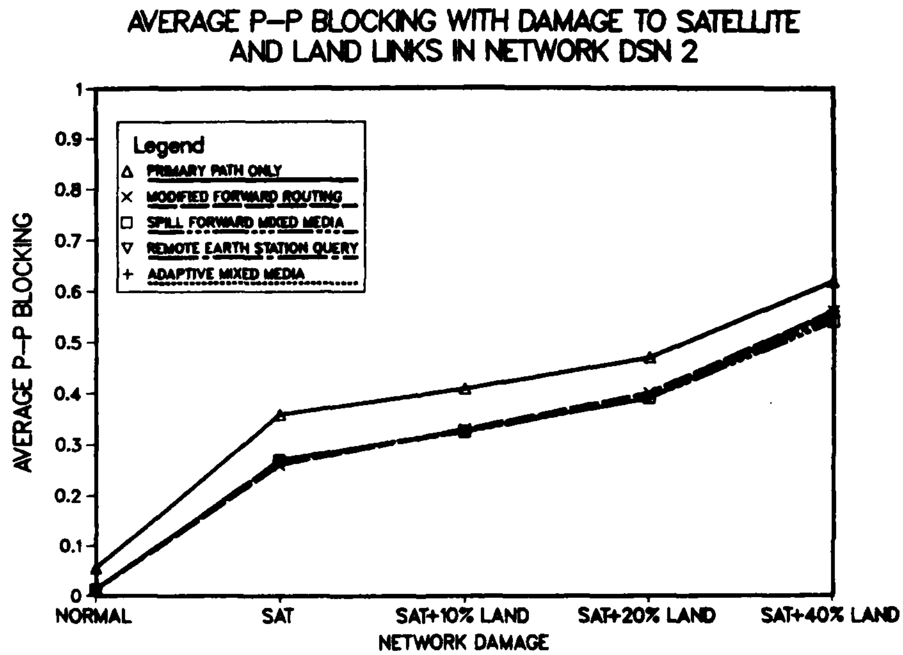
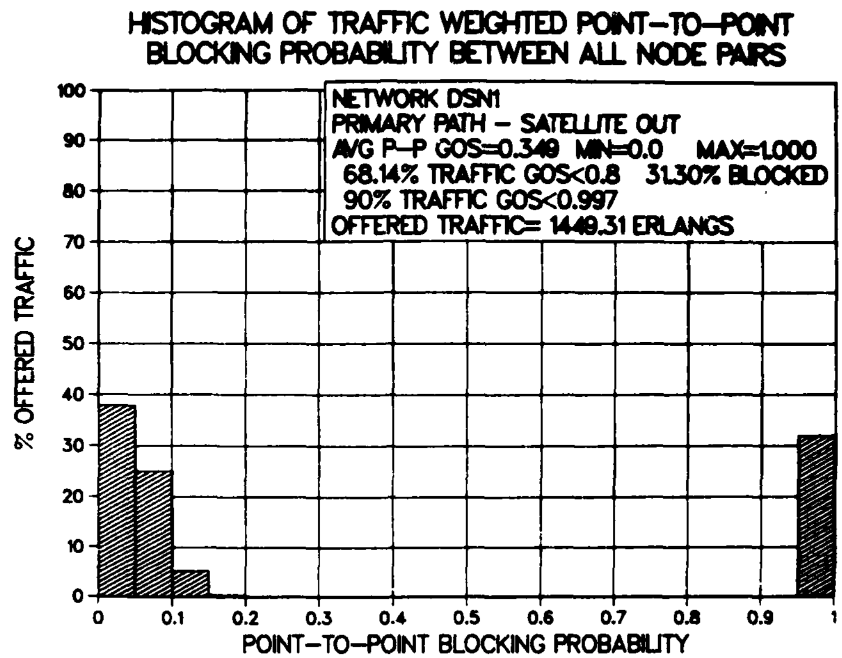


Fig. 9. Average point-to-point blocking probability under normal operation and then the satellite and then 10% to 40% of the largest land links are destroyed (a) in network DSN1 and (b) in network DSN2.

primary path only routing appears to be as effective as the other routing procedures for DSN1 under the most extreme damage condition. These results are misleading because they are based only on average blocking probabilities. It is important to examine point-to-point blocking probabilities between all nodes in a network.

Histograms of traffic weighted point-to-point blocking probabilities in DSN1 for primary path only routing and adaptive-mixed-media routing when the satellite is destroyed are presented in Fig. 10. These histograms were created by first placing the offered traffic between every node pair in the bin corresponding to that node pair's point-to-point blocking probability. The total traffic in each bin was then normalized to be a percentage of the total offered traffic. For example, the histogram in Fig. 10b indicates that roughly 25% of all offered traffic experiences a blocking of 0.0 to 0.05, that roughly 9% of all offered traffic experiences a blocking of 0.05 to 0.1, etc. Under normal conditions with adaptive-mixed-media routing all traffic experiences a blocking probability less than .05 and the bin extending from 0.0 to 0.05 contains 100% of the traffic.

A comparison of Figs. 10a and 10b indicates that although the average blocking probabilities of the two routing procedures are not dramatically different, the treatment of the node-to-node pairs with the worst service is extremely different. Roughly, 31% of all offered calls experience a blocking probability greater than 0.95 (in this case 1.0) with primary path only routing. It is impossible to place a call between those node pairs in the bin ranging from 0.95 to 1.0. Users placing calls between those pairs (representing 31% of all users if each user originates the same number of



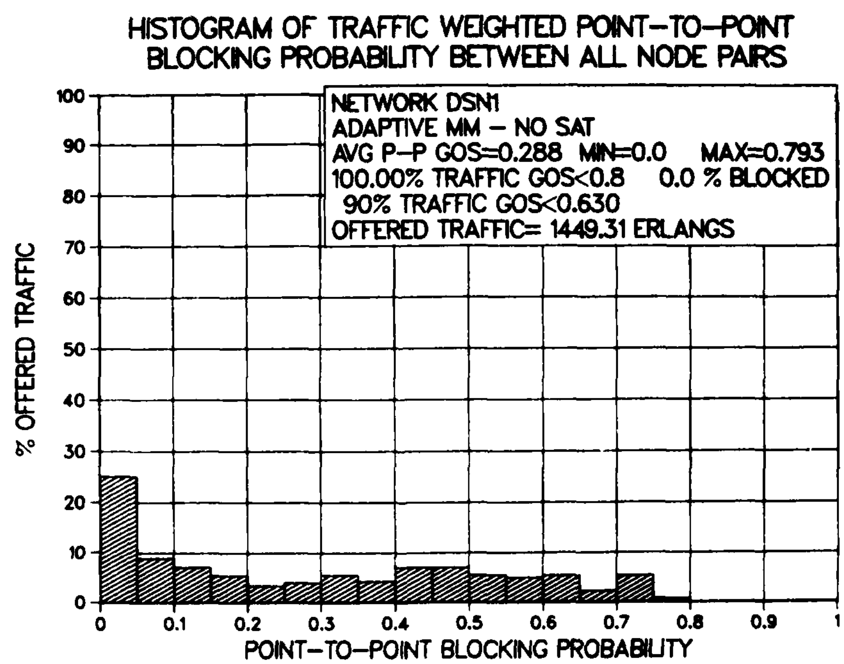
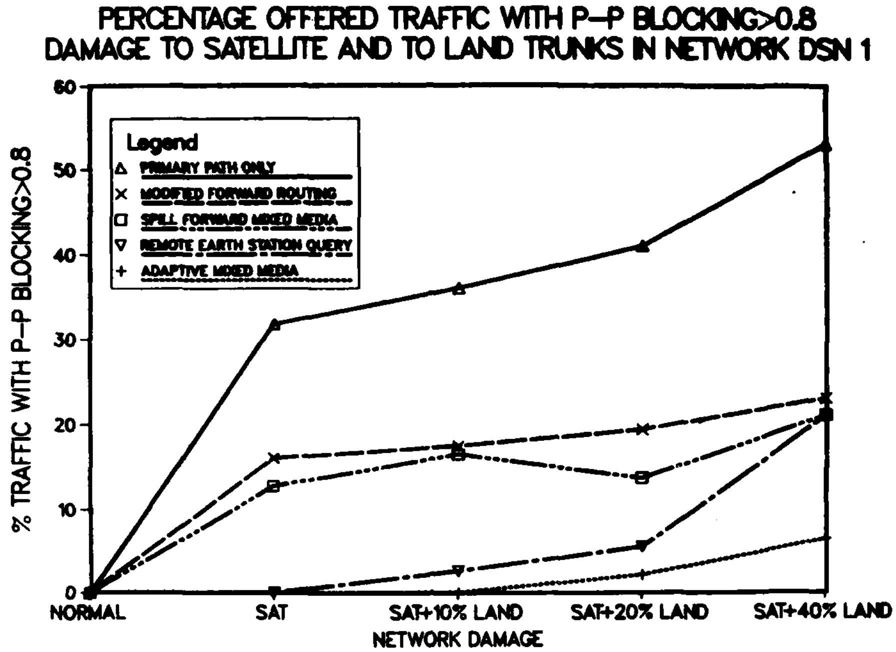


Fig. 10. Histogram of traffic weighted point-to-point blocking probabilities between all node pairs in network DSN1 when the satellite in destroyed (a) with primary path only routing and (b) with adaptive mixed-media routing is used.

calls) are treated unfairly and provided unsatisfactory service. Adaptive-mixed-media routing, however, treats all nodes more uniformly and doesn't block communcation between any nodes. The highest blocking between any two nodes is less than 0.8 and it is possible, but sometimes difficult, to place a call between all nodes.

The average blocking is similar in the above cases because traffic which is completely blocked with primary path only routing does not enter the network and thus does not tie up network resources. More resources are left for the remaining traffic which experiences little blocking. Adaptive-mixed-media routing doesn't completely block any traffic. All traffic competes for limited resources and the range of blocking probabilities experienced is larger. The effect of primary path only routing in this case is similar to that of a congestion control mechanism which blocks all long-distance calls at their source. Although such controls may minimize the average blocking, they are unacceptable because they may deny service to critical users and they unfairly penalize users placing long-distance calls.

A comparison between routing procedures based on the percentage of offered traffic provided with unacceptable service is presented in Fig. 11. Here it is assumed, as in [9], that service is unacceptable if the probability of blocking on the first attempt of a call is greater than 0.8. Figure 11 clearly illustrates the large differences between routing procedures evident in the traffic weighted histograms of Fig. 10. When the satellite is destroyed service is unacceptable for roughly 31% of all traffic with primary path only routing but service is acceptable for all traffic with adaptive-mixed-media routing. Figure 11 indicates that service is acceptable



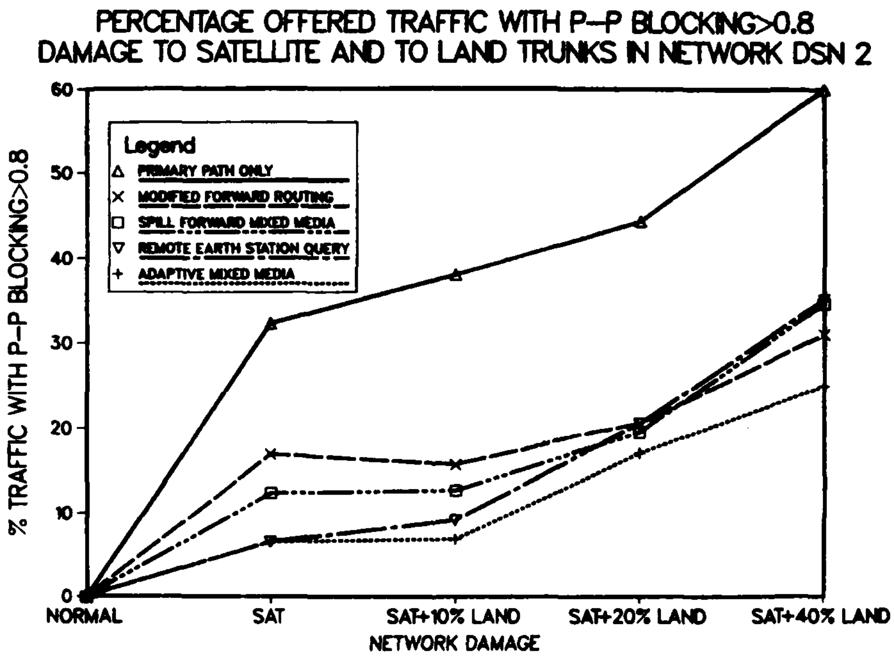
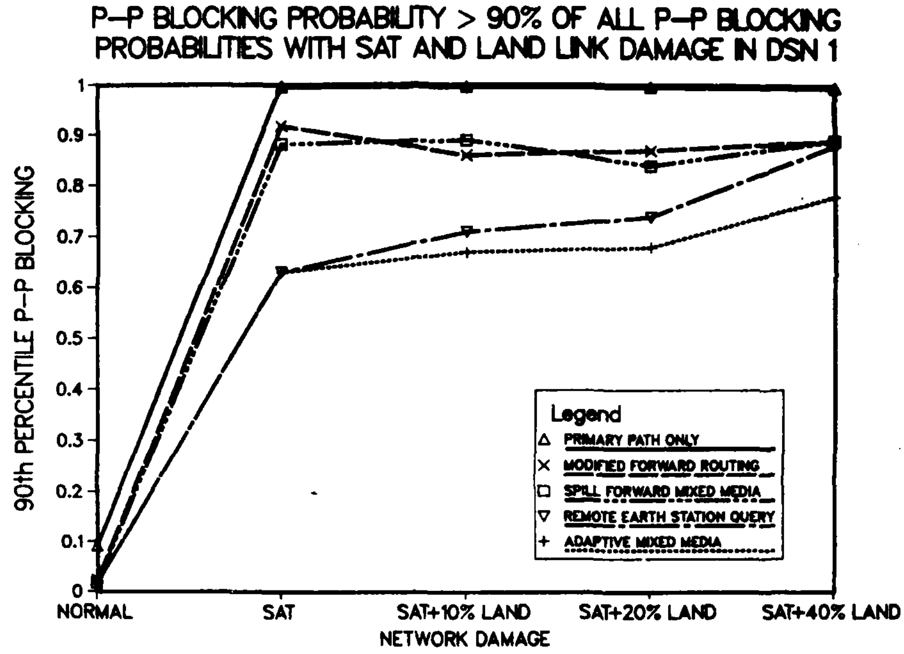


Fig. 11. Percentage offered traffic which experiences a point-to-point blocking probability greater than 0.8 when the satellite and then 10% to 40% of the largest land links are destroyed (a) in network DSN1 and (b) in network DSN2.

for all traffic under normal operation with all routing procedures but that the percentage of traffic provided with unacceptable service increases rapidly when the satellite is destroyed and then more slowly as land trunks are destroyed. Primary path only routing is clearly unacceptable. From 31% to 60% of all traffic is provided inadequate service when the network is damaged. Adaptive-mixed-media routing provides the best performance, followed by remote earth station querying, mixed-media-routing with spill forward control, and modified forward routing. The differences are most dramatic when only the satellite is destroyed and in DSN1. Here both remote earth station querying and adaptive mixed-media-routing provide acceptable service for all traffic, service is unacceptable for 13% to 16% of all traffic with spill forward mixed-media routing and modified forward routing, and service is unacceptable for 31% of all traffic with primary-path only routing. The advantage provided by adaptive-mixed-media routing is maintained as land trunks are destroyed. The advantage of remote earth station querying diminishes as more and more land links are destroyed and no new information about this destruction is obtained. In addition, spill forward mixed-media-routing performs slightly better than modified forward routing under almost all conditions.

A comparison between routing procedures based on the 90th percentile blocking level of traffic weighted histograms is presented in Fig. 12. The 90th percentile values plotted represent the lowest blocking probability experienced by the 10% of the offered traffic provided with the worst service. Ninety percent of all traffic experiences a blocking less than these values. Fig. 12a indicates that when the satellite is destroyed 90% of



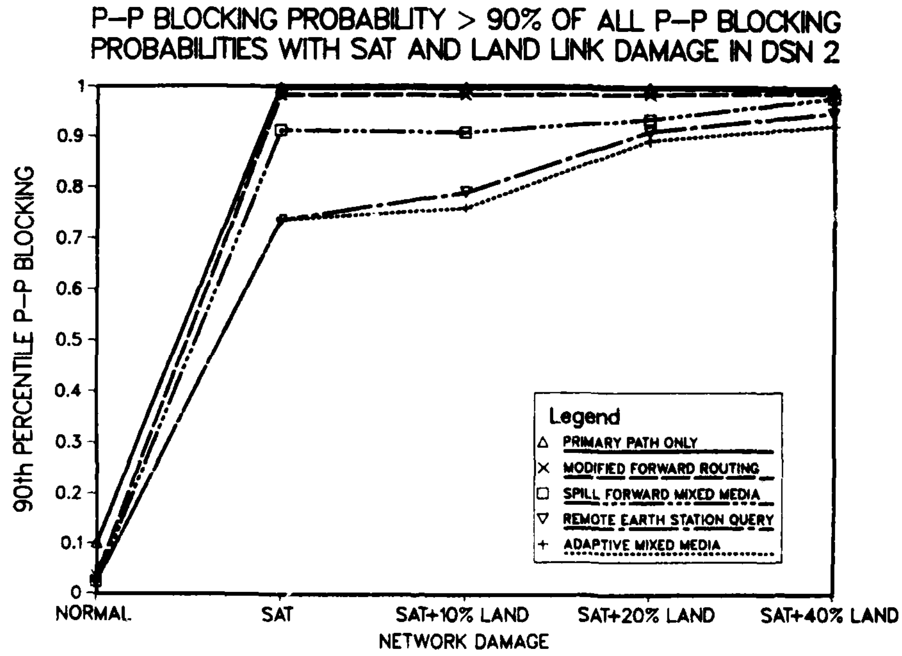


Fig. 12. 90th percentile point-to-point blocking probabilities when the satellite and then 10% to 40% of the largest land links are destroyed (a) in network DSN1 and (b) in network DSN2.

all traffic experiences a blocking less than 0.63 with adaptive mixed media routing but more than 10% of the traffic is completely blocked with primary path only routing. This method of comparing routing procedures is more informative than examining the percentage of traffic with blocking greater than 0.8 when network damage is milder and with traffic overload. In those situations the maximum blocking between any node pair is frequently less than 0.8.

Figure 12 again illustrates the advantage of the new routing procedures. Adaptive-mixed-media routing and remote earth station querying provide the best performance followed by spill-forward mixed-media routing, modified forward routing, and primary path only routing. The same general trends evident in Fig. 11 are evident in this figure. The better performance of spill forward mixed-media routing relative to modified forward routing in Fig. 12b is caused by small differences in the amount of traffic which was totally blocked by these procedures. Modified forward routing couldn't find routes for 9.7% to 10.3% of all calls with damage while spill forward mixed media routing couldn't find routes for 6.1% to 7.5% of all calls. The 90th percentile point was thus near 1.0 with modified forward routing but below 1.0 with spill forward mixed-media routing.

Figures 10 and 12 indicate that the advantage of the routing procedures is greater in DSN1 than in DSN2. The main difference between DSN1 and DSN2 which caused this result is the existence of long-distance land links to mid-western switches in DSN1. These links provide alternate land routes for coast-to-coast calls when the satellite is destroyed and when the routing procedure is flexible enough to use the routes. The land links were not included in DSN2 because new midwestern earth stations not in DSN1 were available and traffic from the two coasts to the midwest was routed through these earth stations. This result demonstrates the need for more advanced network design procedures. These procedures should provide spare trunking which the routing procedure can use after network damage. They should also provide equitable blocking between all node pairs after damage. A procedure with these goals was used to design networks DSN3 and DSN4.

4.1.2 Damage to Satellite then to Land Links in Networks with Spare Capacity

Networks DSN3 and DSN4 are similar to DSN1 and DSN2 but they include roughly 10% spare land trunks for use when the satellite is destroyed and they cost roughly 10% more than DSN1 and DSN2. Under normal conditions, performance of all routing procedures is similar in all four networks. The average blocking probability with all routing procedures except primary path only is less than .02 and the maximum blocking between any node pair is less than 0.10. Performance with all networks when the satellite is destroyed is compared in Figs. 13 to 15.

The average blocking presented in Fig. 13 is reduced in DSN3 and DSN4 by roughly the same amount for all routing procedures except primary path only routing. Averaging over all routing procedures except primary path only, the average blocking is roughly 0.28 with both DSN1 and DSN2 and 0.22 with both DSN3 and DSN4. The percentage of traffic provided with unacceptable service presented in Fig. 14 is also reduced in DSN3 and DSN4. Traffic between no node pairs experiences a blocking greater than 0.8 in DSN3 and DSN4 with remote earth station querying and adaptive-mixed-media routing. The

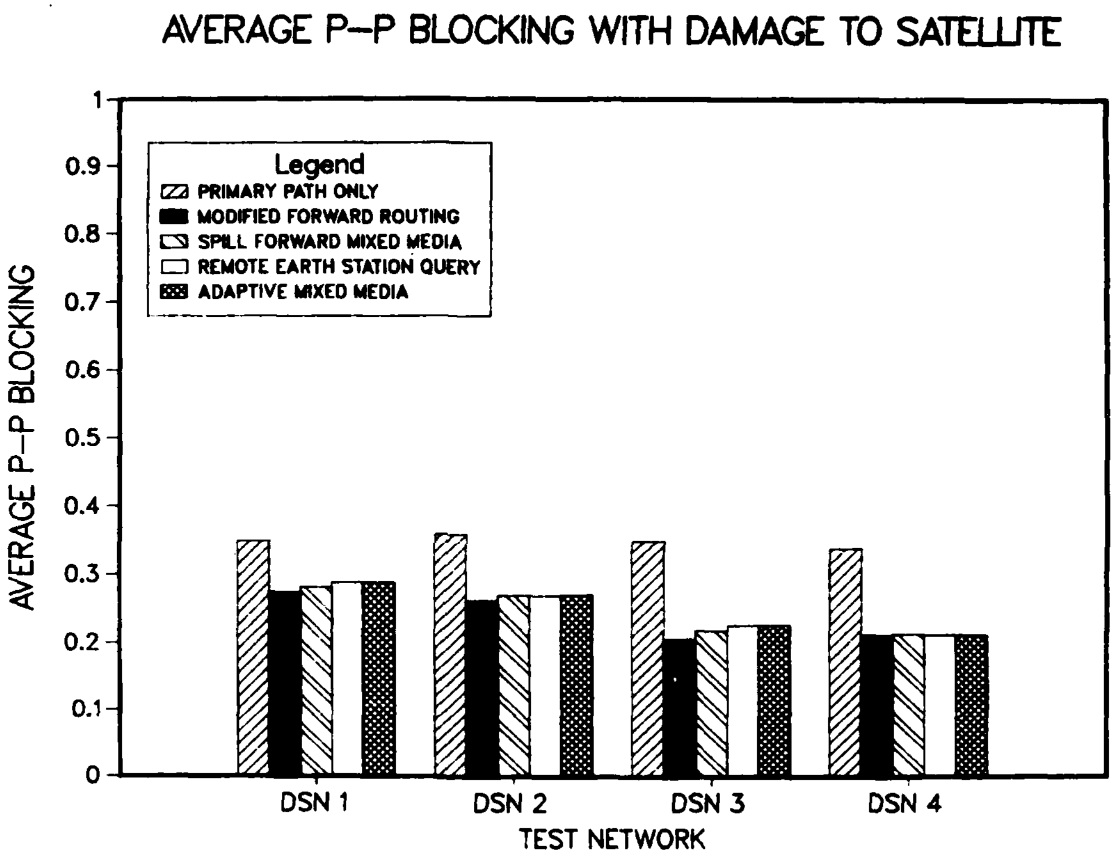


Fig. 13. Average point-to-point blocking probability when the satellite is destroyed for all networks.

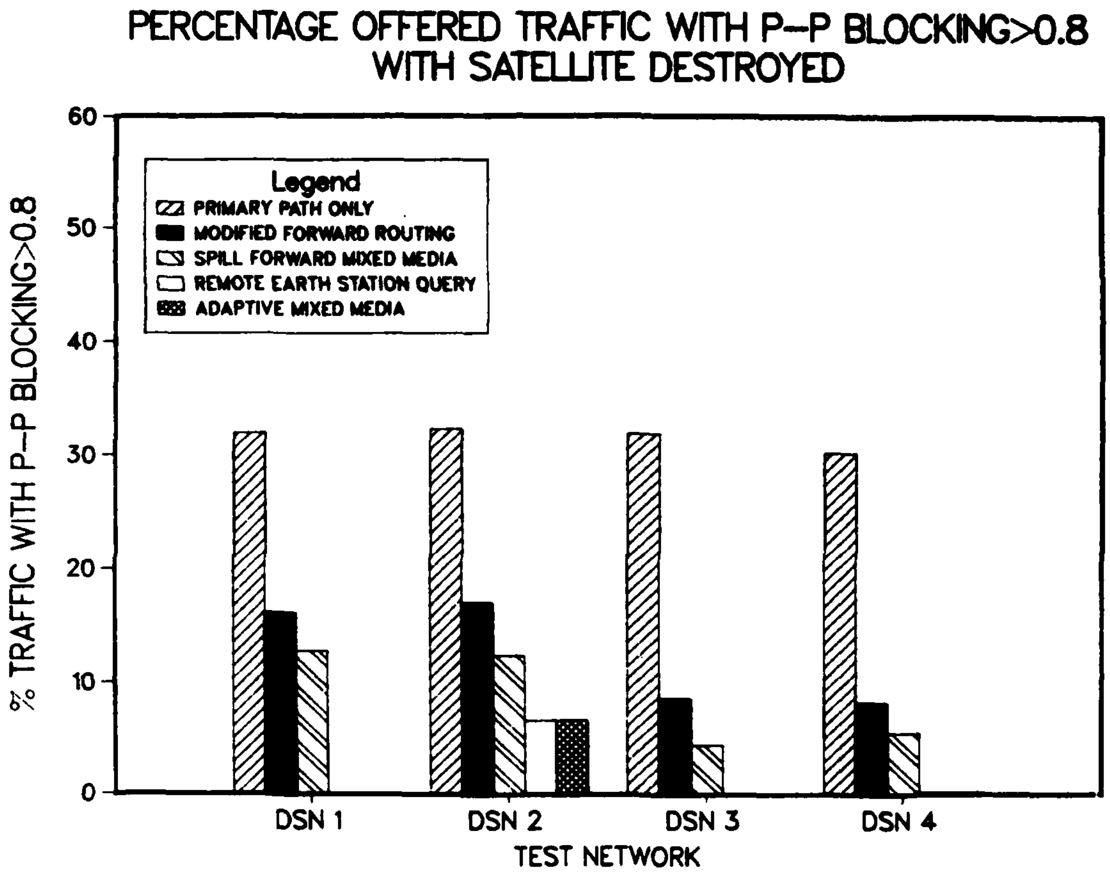


Fig. 14. Percentage offered traffic which experiences a point-to-point blocking probability greater than 0.8 when the satellite is destroyed for all networks. Bars are missing with remote earth station querying and adaptive mixed-media routing in networks DSN1, DSN3, and DSN4 because traffic between no node pairs experienced blocking greater than 0.8 under these conditions.

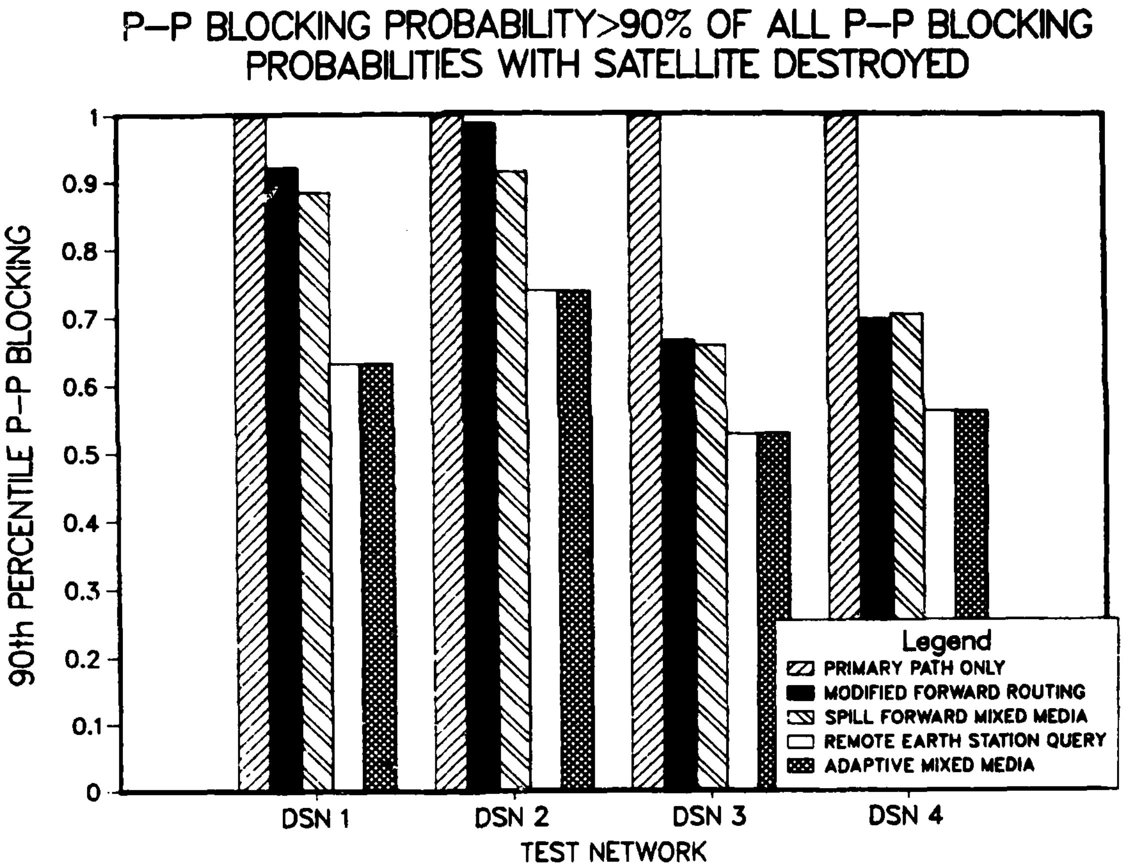


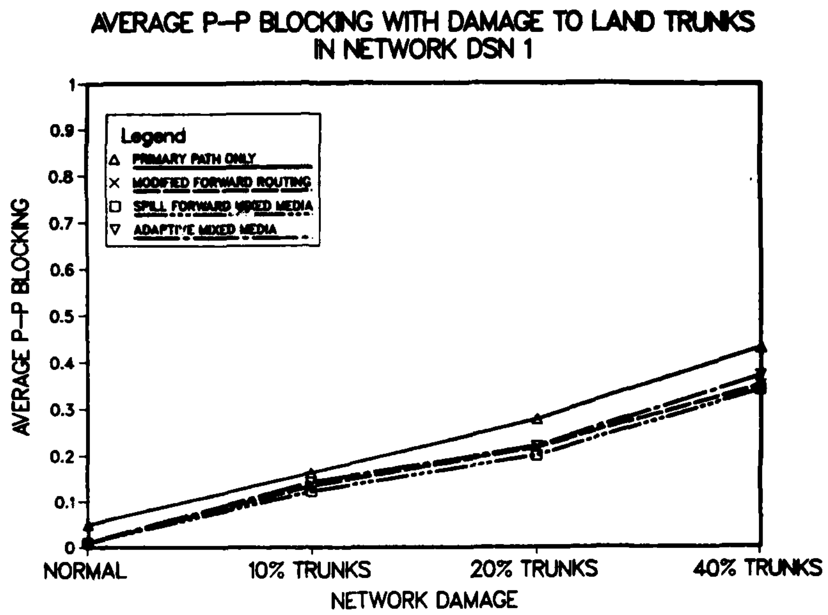
Fig. 15. 90th percentile point-to-point blocking probabilites when the satellite is destroyed for all networks.

percentage of traffic with unacceptable blocking when spill-forward mixed-media routing is used drops from roughly 13% in both DSN1 and DSN2 to 5% in both DSN3 and DSN4. With modified forward routing this percentage drops from roughly 17% in DSN1 and DSN2 to 8.5% in DSN3 and DSN4. The 90th percentile cumulative blocking levels presented in Fig. 15 also drop substantially in DSN3 and DSN4.

The relative performance of the different routing procedures in Figs. 13 to 15 when the satellite is destroyed is similar in all networks. All procedures except primary path only routing provide roughly the same average blocking probability. Remote earth station querying and adaptive-mixed-media routing provide acceptable blocking for the largest amount of traffic and also the lowest 90th percentile levels. Spill-forward mixed-media routing provides the next best performance followed by modified forward routing. Primary path only routing provides the poorest performance. The advantage of remote earth station querying and adaptive-mixed-media routing over modified forward routing and spill-forward mixed-media routing evident in Figs. 14 and 15 is substantial. It is equal to or greater than the improvement in performance obtained by adding spare trunking and increasing the network cost by 10%.

4.1.3 Damage to Land Links Only

Results obtained with networks DSN1 and DSN2 when land links only are destroyed and the satellite remains intact are presented in Figs. 16, 17, and 18. Note that these figures differ from Figs. 9, 11, and 12 in that now only land links are damaged whereas before both the satellite and land links were damaged. Average blocking in Fig. 16 increases slowly as more and more land



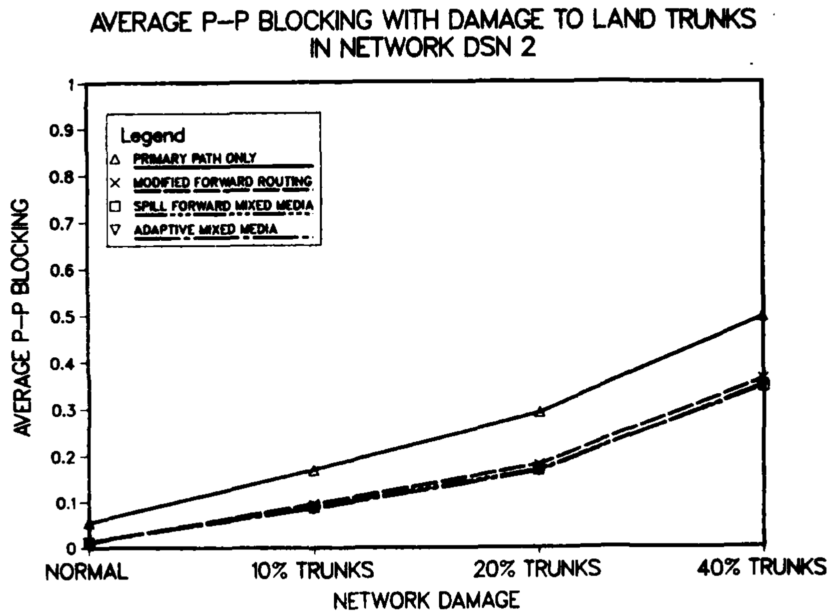
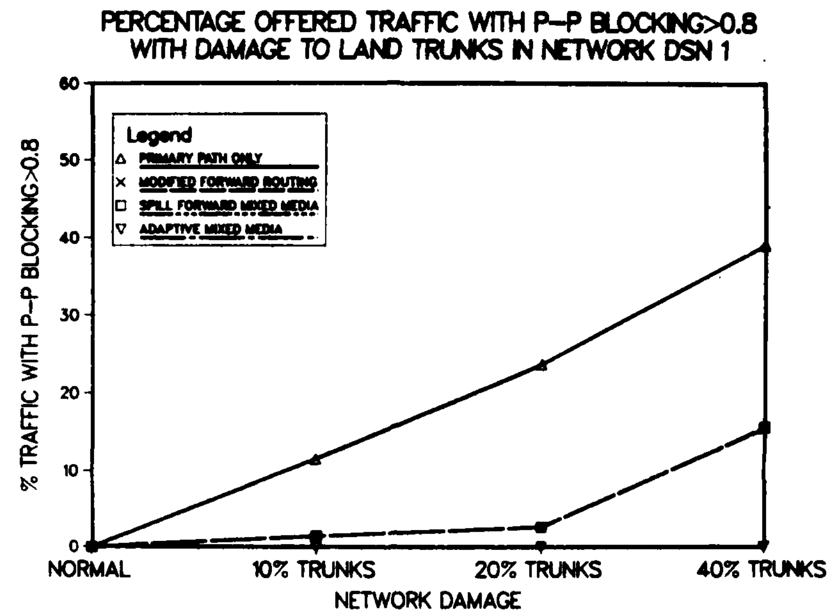


Fig. 16. Average point-to-point blocking probability when 10% to 40% of the largest land links are destroyed (a) in network DSN1 and (b) in network DSN2.



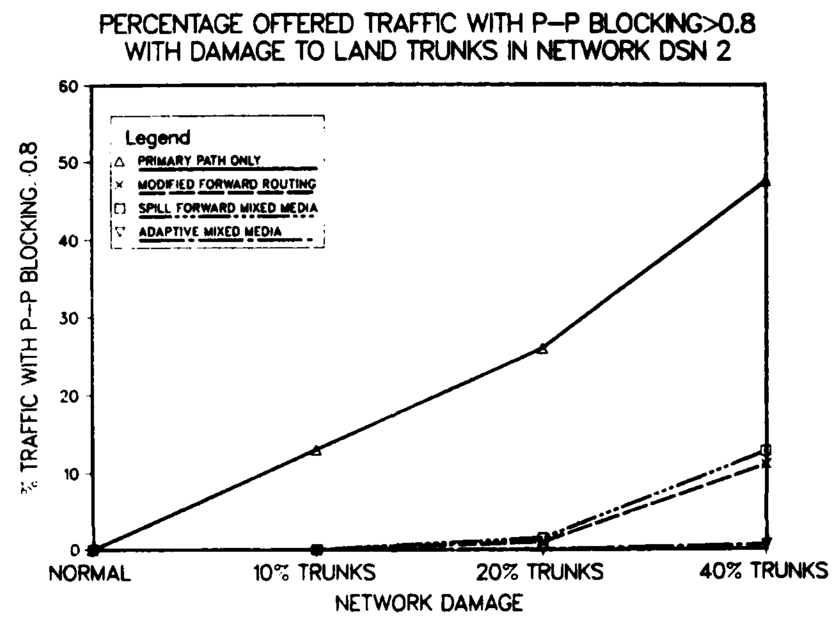
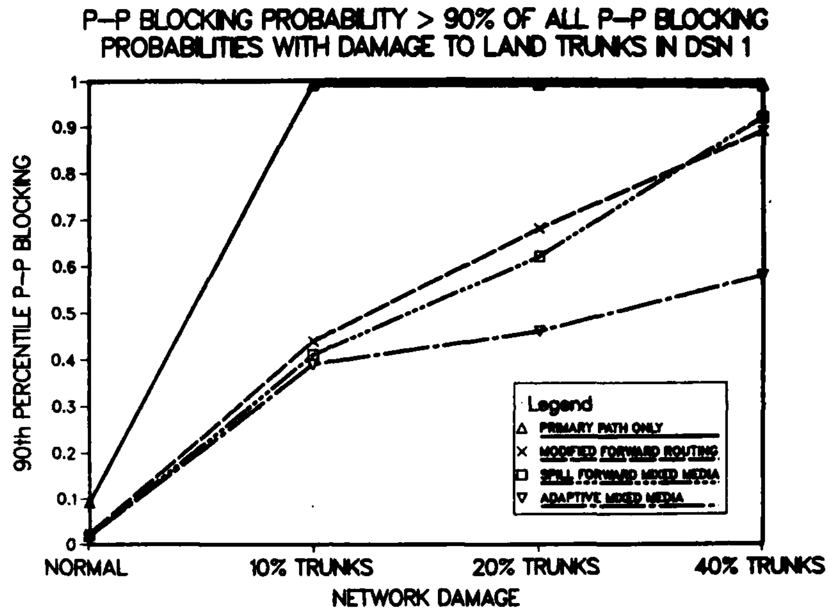


Fig. 17. Percentage offered traffic which experiences a point-to-point blocking probability greater than 0.8 when 10% to 40% of the largest land links are destroyed (a) in network DSN1 and (b) in network DSN2.



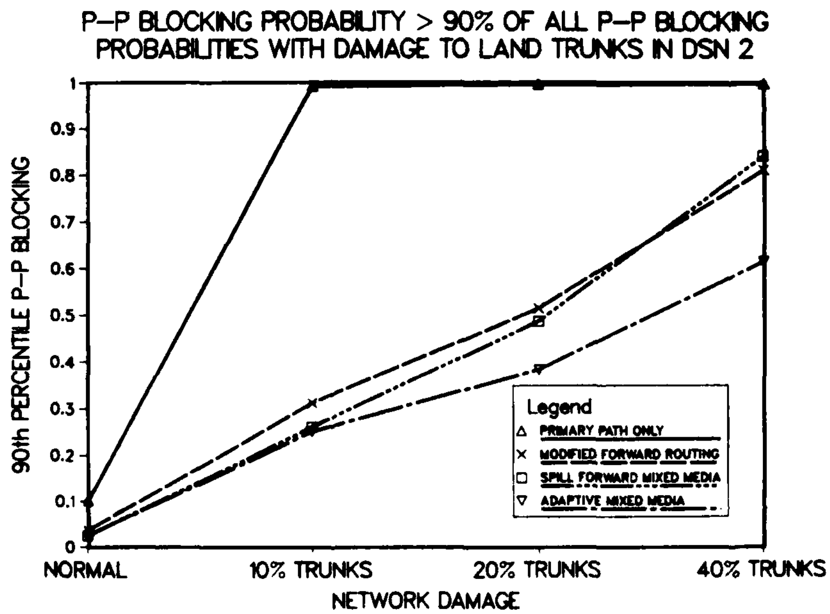


Fig. 18. 90th percentile point-to-point blocking probability when 10% to 40% of the largest land links are destroyed (a) in network DSN1 and (b) in network DSN2.

links are destroyed. Once again blocking is highest for primary path only routing and lower but roughly equivalent for the other types of routing. The percentage of offered traffic provided inadequate service in Fig. 17 differs significantly between the various routing procedures, especially at the highest level of trunk destruction. This percentage is lowest and near zero with adaptive-mixed-media routing under all damage conditions. It is highest for primary path only routing and intermediate with modified-forward routing and spill-forward mixed-media routing. Similar and somewhat stronger orderings are evident in the 90th percentile curves of Fig. 18.

4.1.4 Damage to Satellite then to Switches

Results obtained with network DSN1 when the satellite and then switches are destroyed are presented in Figs. 19, 20, and 21. The data in these figures are only for the traffic offered between switches remaining in the network. This offered traffic drops from 1450 Erlangs under normal conditons and when the satellite is destroyed to 862 Erlangs when two switches are destroyed, 536 Erlangs when four switches are destroyed, and 187 Erlangs when eight switches are destroyed. The average blocking in Fig. 19 first increases when the satellite is destroyed but then decreases when switches are destroyed. The decrease is caused by the rapid drop in remaining offered traffic when the most heavily loaded switches aren't present.

Average blocking in Fig. 19 is again highest for primary path only routing and similar for the other routing procedures. The percentage offered traffic provided inadequate service in Fig. 20 is lowest for adaptive-mixed-media routing and remote earth station querying. The blocking between all node pairs is less than 0.8 with these routing procedures under all

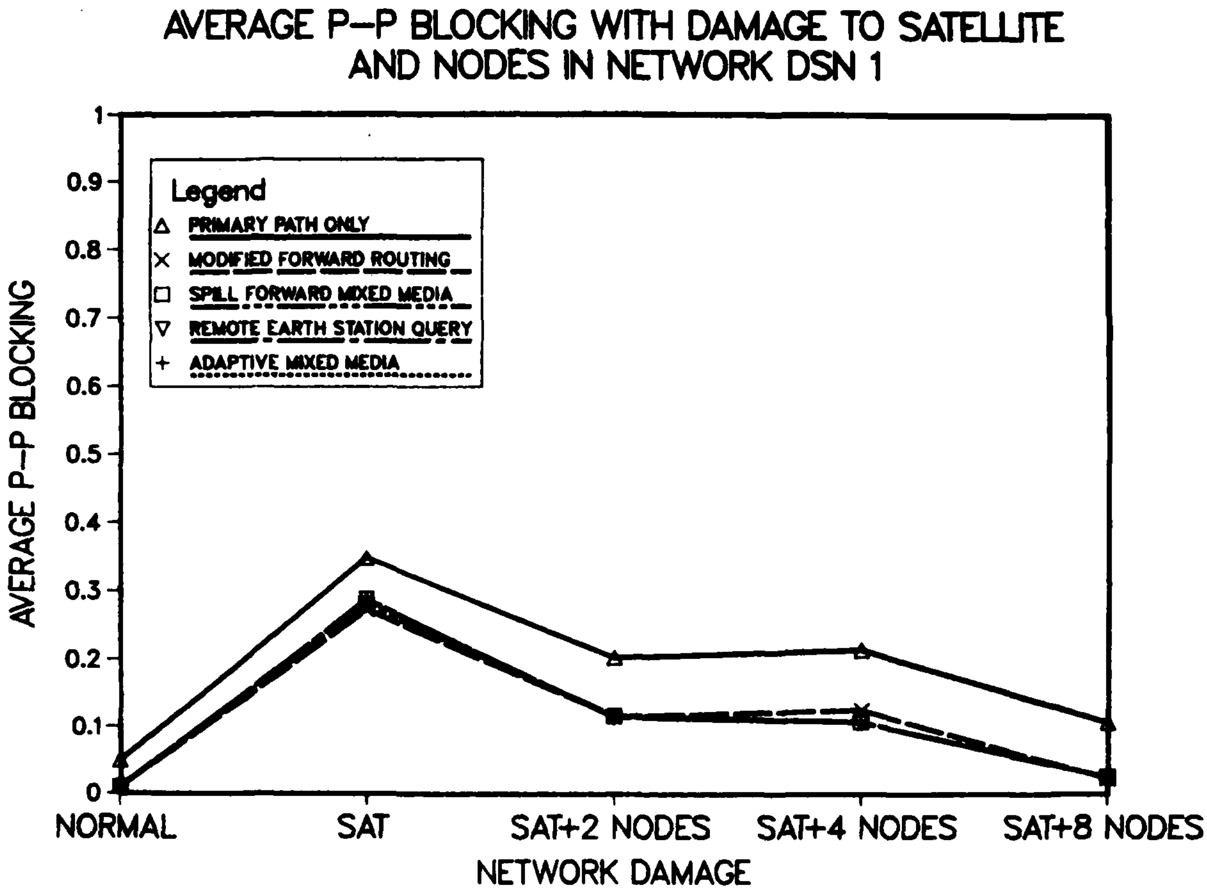


Fig. 19. Average point-to-point blocking probability when the satellite and then 2 to 8 of the largest switches are destroyed in network DSN1.

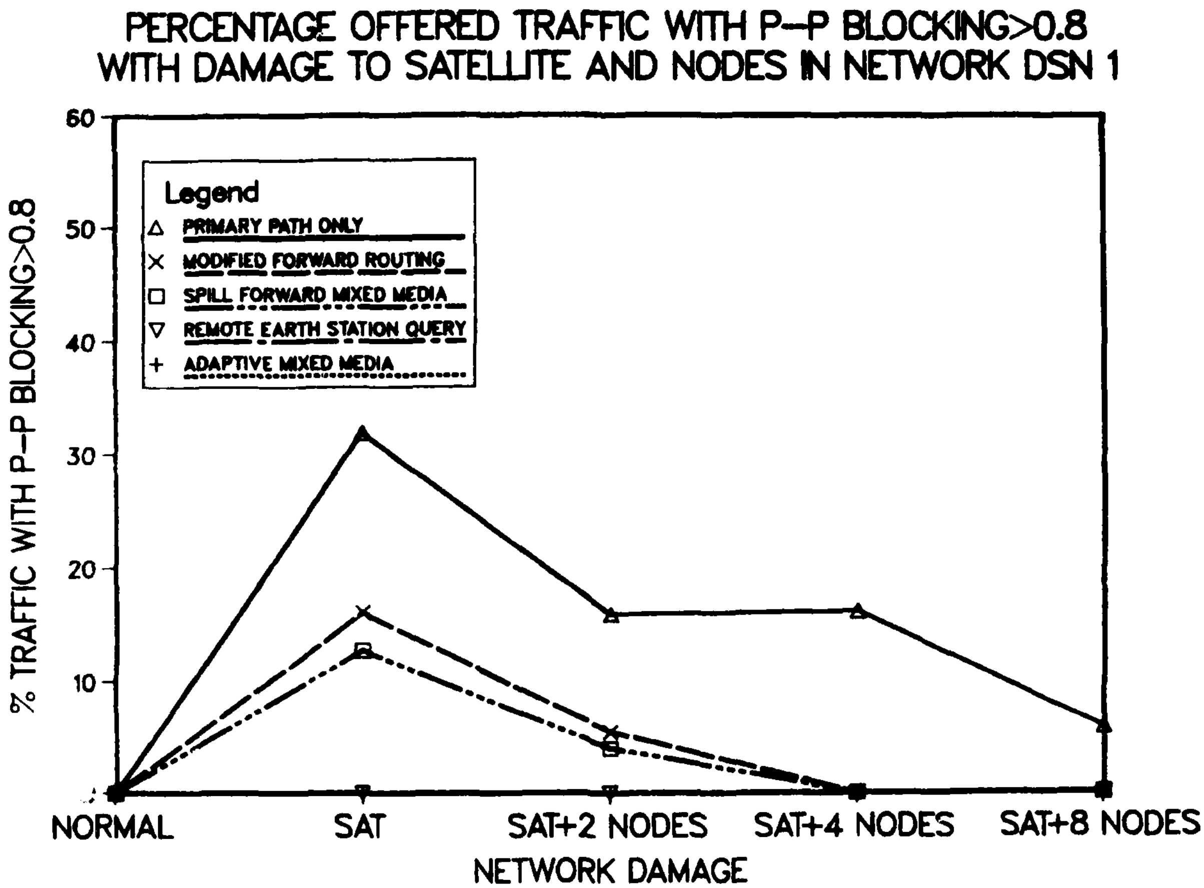


Fig. 20. Percentage offered traffic which experiences a point-to-point blocking probability greater than 0.8 when the satellite and then 2 to 8 of the largest switches are destroyed in network DSN1.

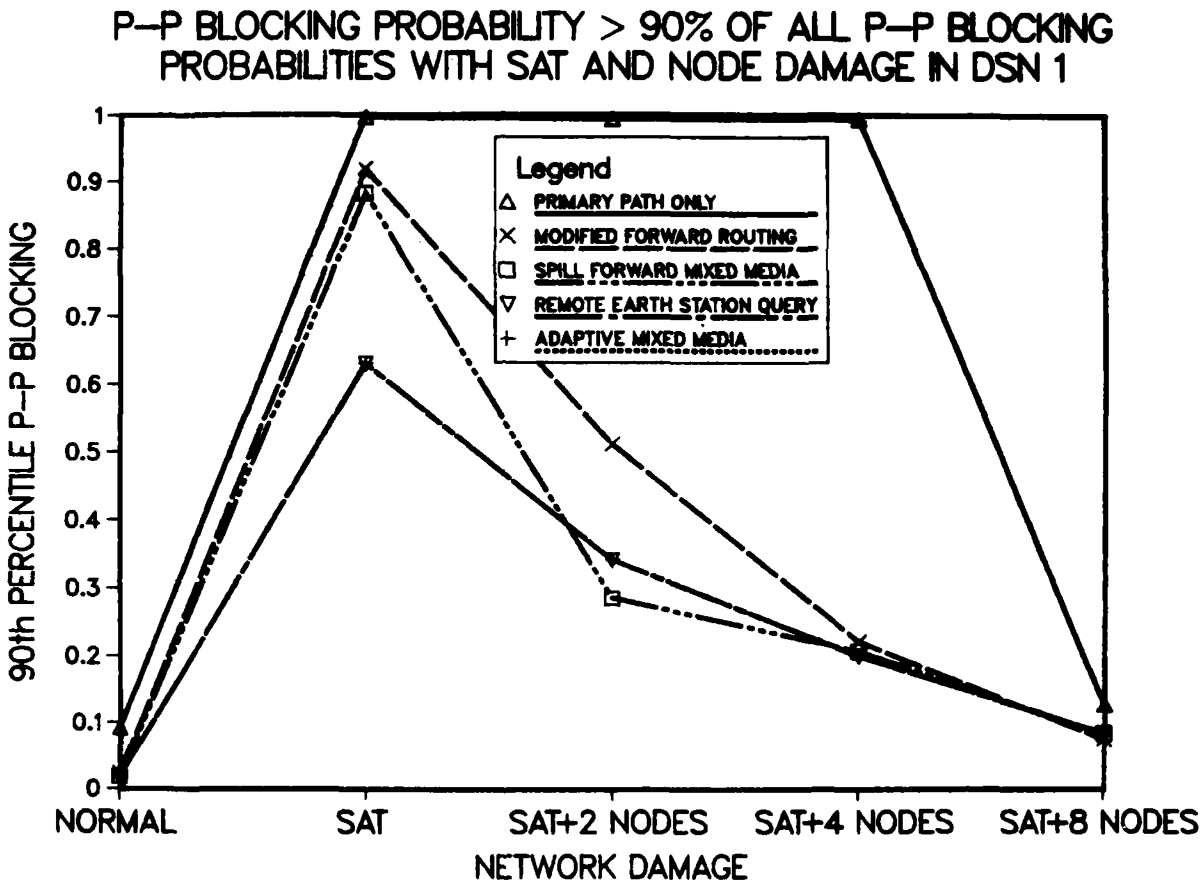


Fig. 21. 90th percentile point-to-point blocking probability when the satellite and then 2 to 8 of the largest switches are destroyed in network DSN1.

conditions. Spill-forward mixed-media routing provides the next best performance followed closely by modified forward routing. Performance is poorest with primary path only routing. Similar orderings are evident in 90th percentile curves of Fig. 21. The drop in the curve for mixed-media routing in Fig. 4 when the satellite and two nodes are destroyed is caused by the bimodal nature of the traffic weighted histogram. Roughly 4% of all the traffic experiences a blocking greater than 0.9 and 90% of the traffic experiences a blocking less than 0.29 with spill-forward mixed-media routing under this condition. Adaptive-mixed-media routing, however, treats all node pairs more equitably. The maximum blocking pairs between any node pair is less than 0.54 and 90% of all traffic experiences a blocking less than 0.34. The 90th percentile point is slightly less with spill-forward mixed-media routing because the 4% of all offered traffic which is essentially blocked doesn't compete for network resources. The remaining 96% of the offered traffic experiences a blocking low enough to lower the 90%th percentile level below that provided by adaptive-mixed-media routing.

4.1.5 Damage to Switches Only

Results obtained with network DSN1 when only switches are destroyed and the satellite remains intact are presented in Figs. 22, 23, and 24. Data are again only for traffic between remaining switches. The average blocking in Fig. 22 indicates that adaptive-mixed-media routing provides the best performance under all levels of damage. Spill-forward mixed-media routing and modified forward routing provide the second best performance followed by primary path only routing. The same ordering is evident in Figs. 23 and 24. The inversion of curves in Fig. 24 when 2 switches are destroyed is caused by

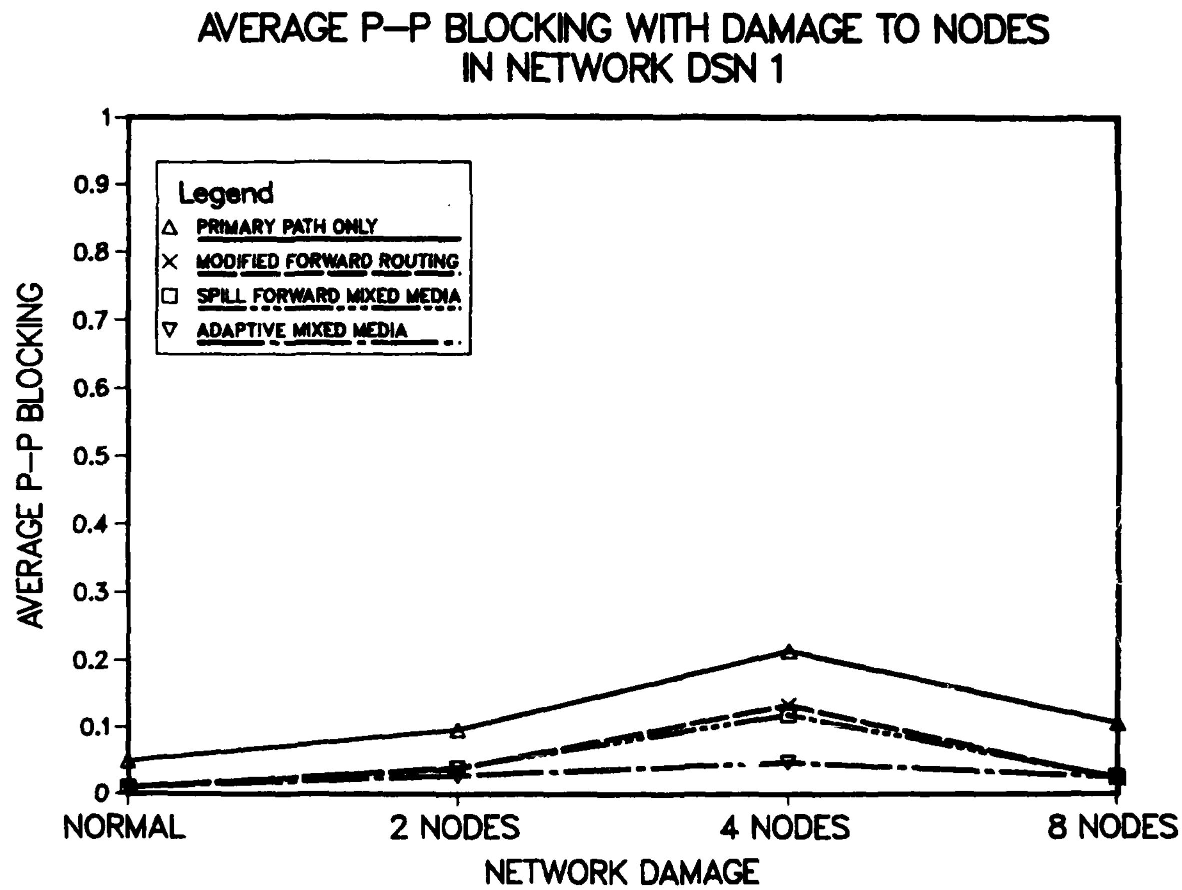


Fig. 22. Average point-to-point blocking probability when 2 to 8 of the largest switches are destroyed in network DSN1.

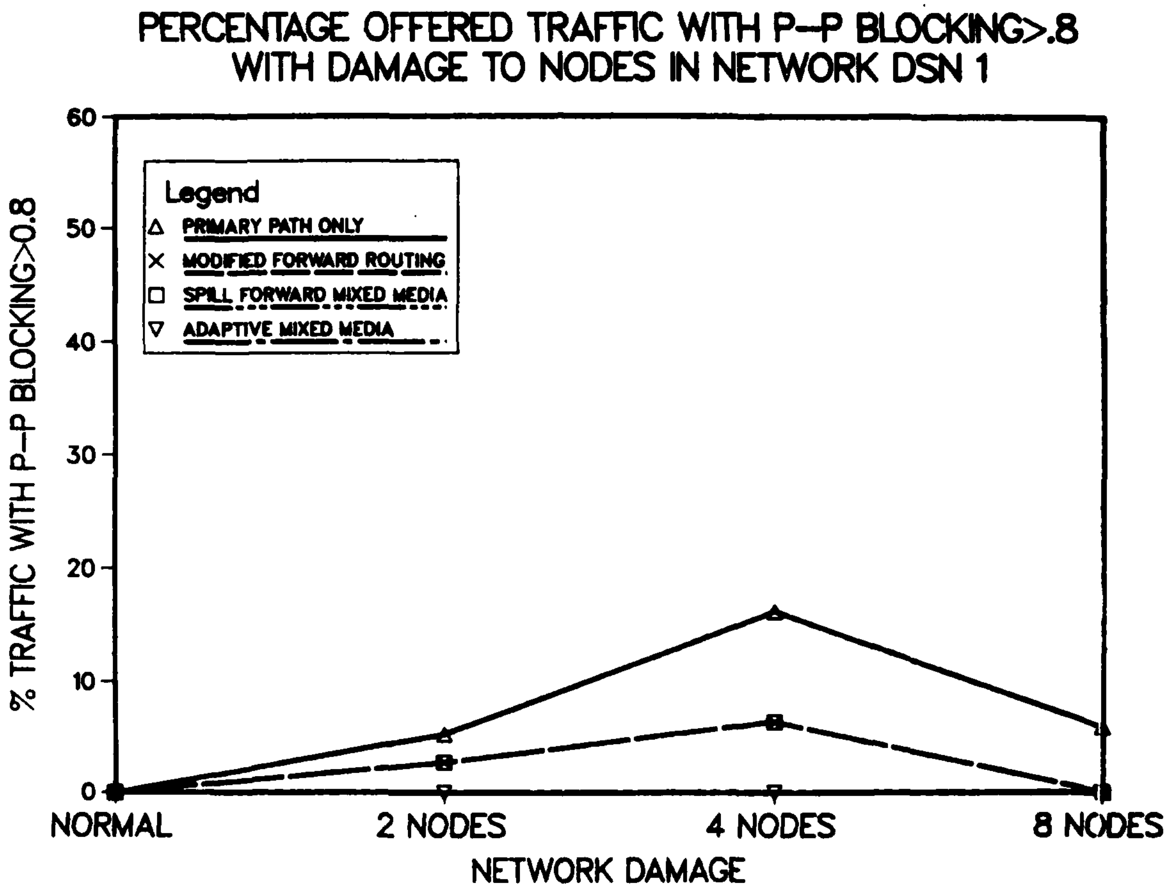


Fig. 23. Percentage offered traffic which experiences a point-to-point blocking greater than 0.8 when 2 to 8 of the largest switches are destroyed in network DSN1.

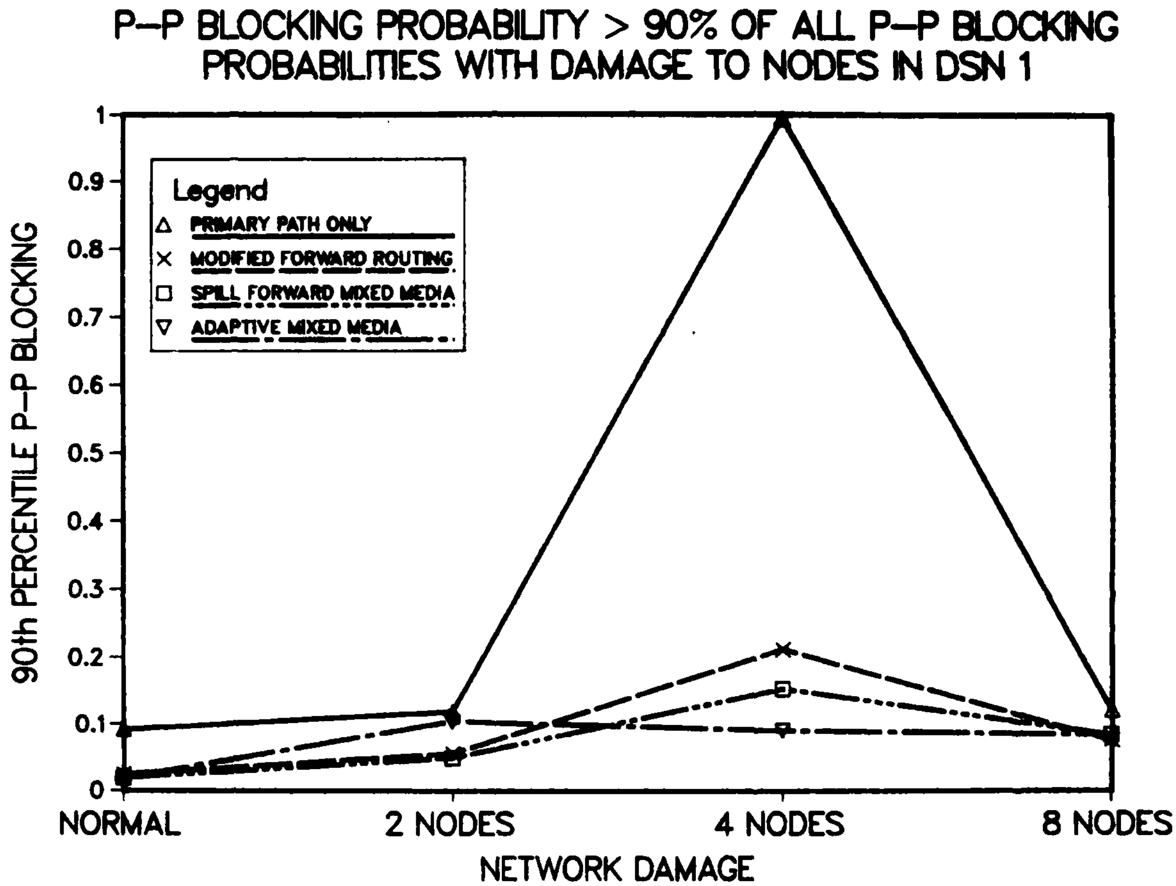


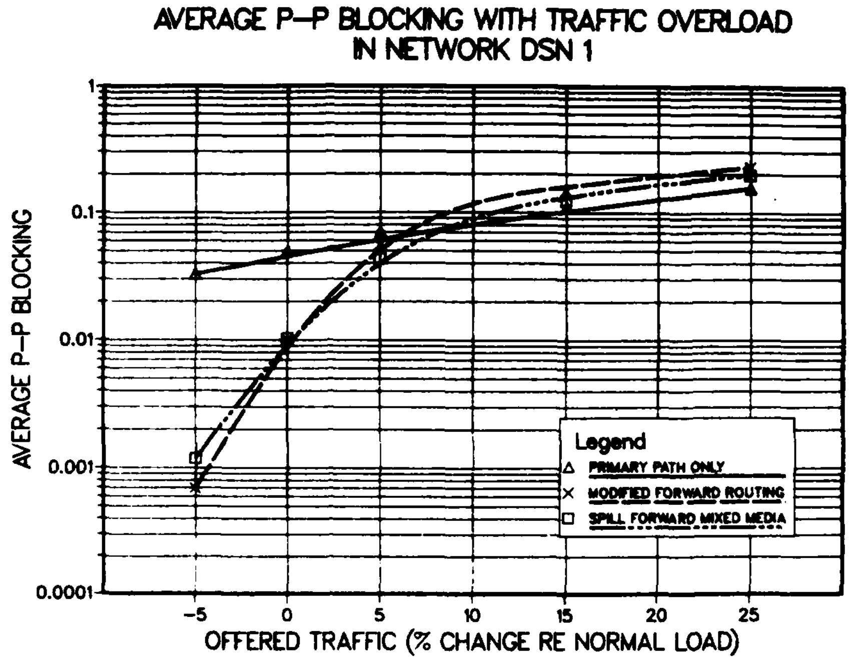
Fig. 24. 90th percentile point-to-point blocking probability when 2 to 8 of the largest switches are destroyed in network DSN1.

the bimodal nature of the traffic weighted histograms. Adaptive mixed-media routing allows all nodes to communicate under this condition and completely blocks no traffic. Spill forward routing and modified forward routing completely block roughly 3% of all offered traffic. The large jump in the 90th percentile curve in Fig. 24 for primary path only routing when 4 nodes are destroyed occurs because the percentage of calls which require alternate routing and are completely blocked exceed 10%.

4.2 Performance with Traffic Overload

Results obtained with networks DSN1 and DSN2 when the traffic offered between all node pairs was increased uniformly are presented in Figs. 25 and 26. Spline curves have been fit to the data points in these figures. A curve is not included for adaptive-mixed-media routing because in an undamaged network adaptive-mixed-media routing is identical to spill-forward mixed-media routing.

The average blocking in Fig. 25 increases as the offered load increases and the relative performance of the different routing procedures varies as a function of offered load. At normal loads the average blocking with modified forward routing and spill-forward mixed-media routing is similar and much lower than the average blocking with primary path only routing. At overloads blocking with modified-forward routing and spill-forward mixed-media routing increases rapidly until it equals or exceeds blocking with primary path only routing. Blocking with spill-forward mixed-media routing is generally less than blocking with modified forward routing. Similar trends are evident in the 90th percentile curves of Fig. 26 except the improved performance of spill-forward mixed-media routing relative to modified forward routing is more evident.



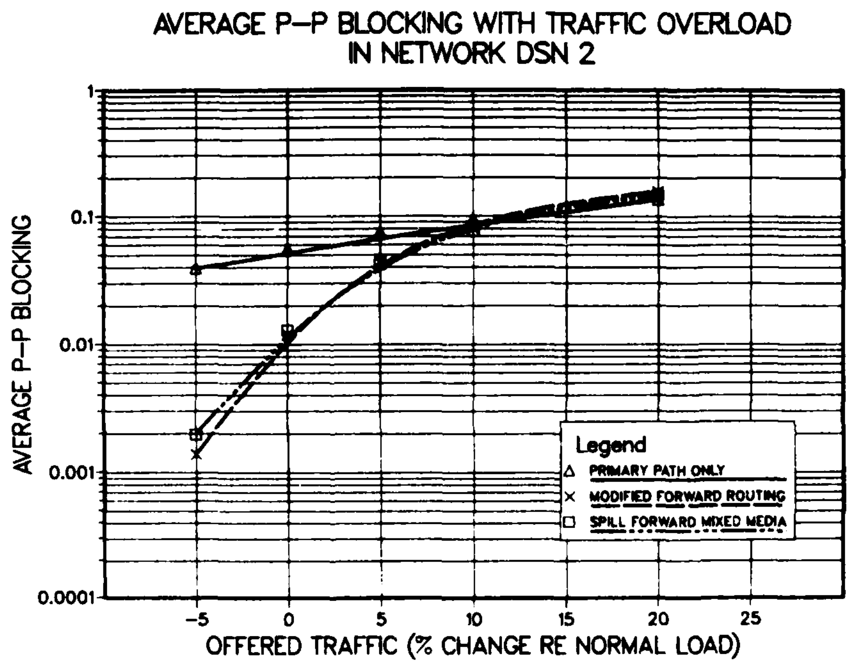
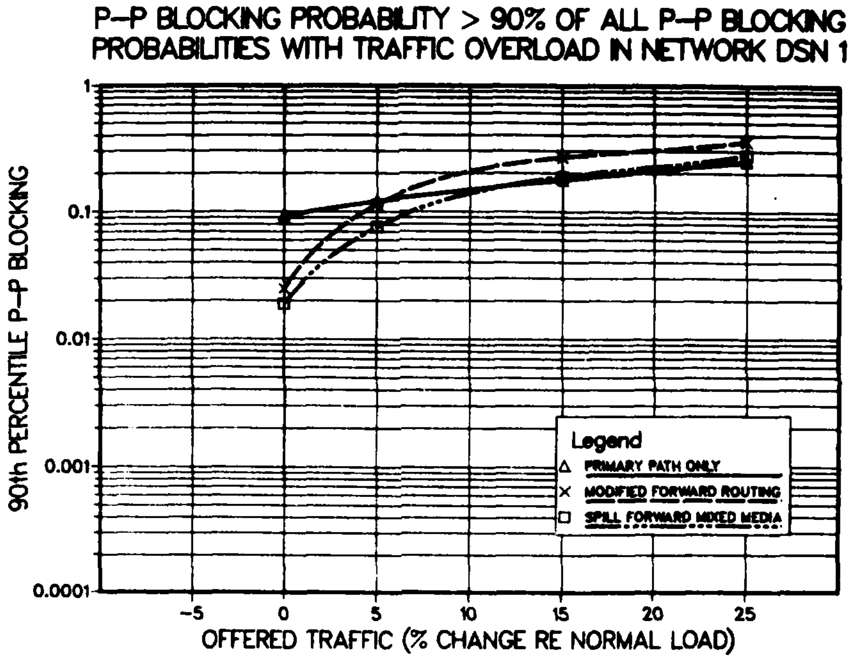


Fig. 25. Average point-to-point blocking with 5% underload and 0% to 25% uniform traffic overload (a) in network DSN1 and (b) in network DSN2.



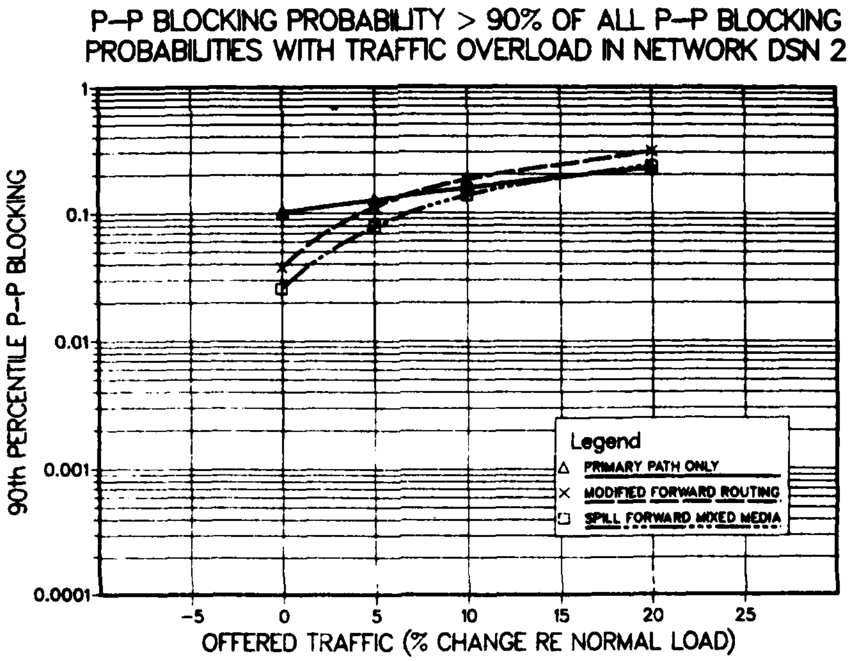


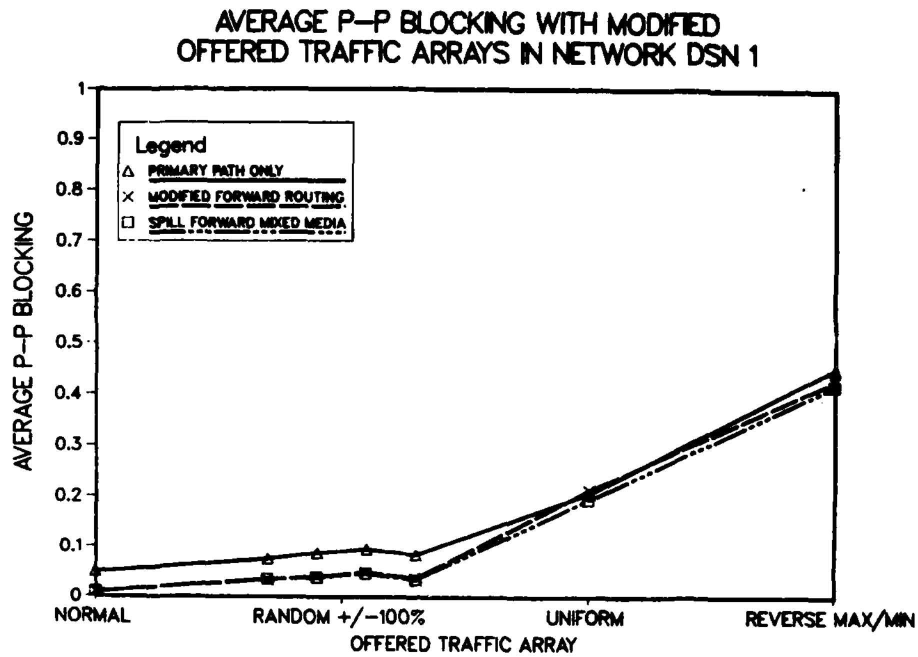
Fig. 26. 90th percentile point-to-point blocking probability with 0% to 25% uniform traffic overload (a) in network DSN1 and (b) in network DSN2.

Figures 25 and 26 indicate that primary path only routing performs equal to or better than complex routing procedures with more routing flexibility when networks are overloaded. Similar results are presented in [15,16]. At high offered loads, flexible routing procedures alternate route many calls, the average call path length increases, and network utilization is reduced. Primary path only routing, however, blocks those calls with long path lengths which would normally be alternate routed and network utilization remains high. In DSN1, for example, the average path length remained at 1.27 links per call when the offered load increased with primary path only routing. Path length increased from 1.39 to 1.64 links per call with modified forward routing and from 1.38 to 1.56 links per call with spill-forward mixed-media routing. The improved performance of spill-forward mixed-media routing relative to modified forward routing at high offered loads is caused by the controls used in mixed-media routing to limit call path lengths. The path length of every call is examined and calls with more than one extra link in an alternate route are blocked. Modified forward routing, however, does no explicit checking of path length.

Spill-forward mixed-media routing performed best with varying loads. It provided the lowest average and 90th percentile blocking at normal loads and with small overloads. At high overloads it provided performance similar to that of the best routing procedure examined.

4.3 Performance with Chaotic Traffic Patterns

Results obtained with networks DSN1 and DSN2 when traffic patterns were varied but total offered traffic remained constant are presented in Figs. 27 to 29. The three new traffic patterns are RANDOM+/- 100% (randomly vary the



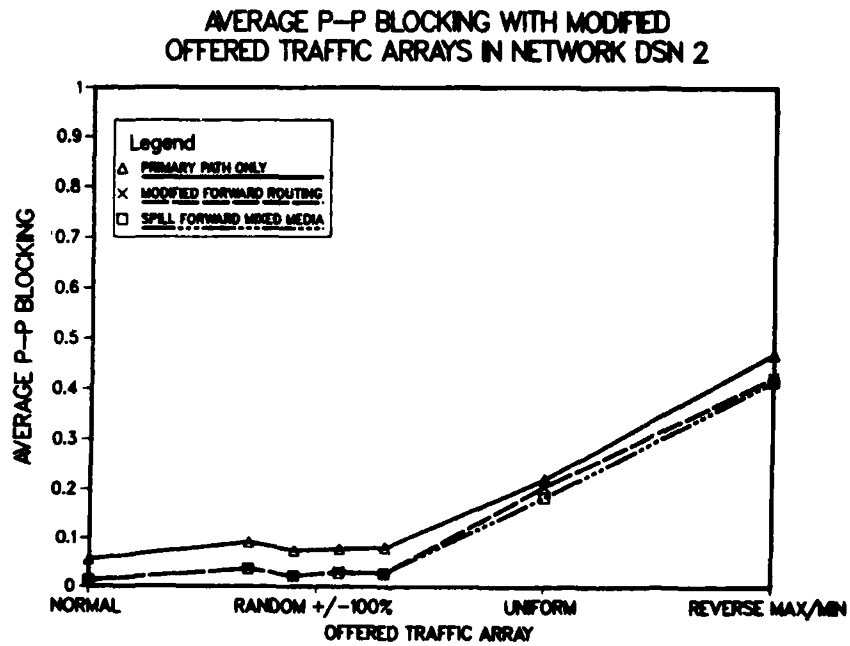
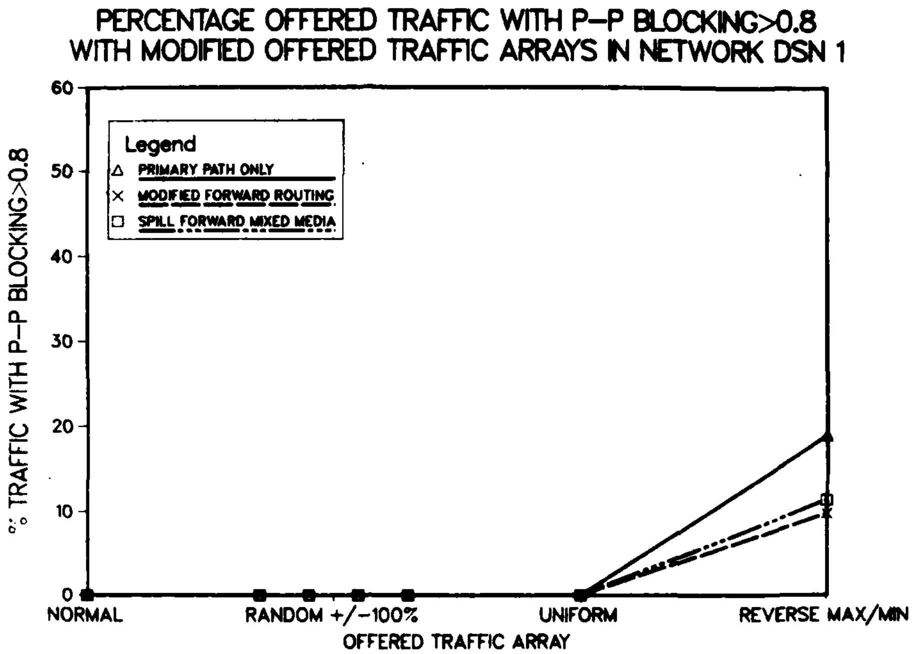


Fig. 27. Average point-to-point blocking with caotic traffic patterns (a) in network DSN1 and (b) in network DSN2.



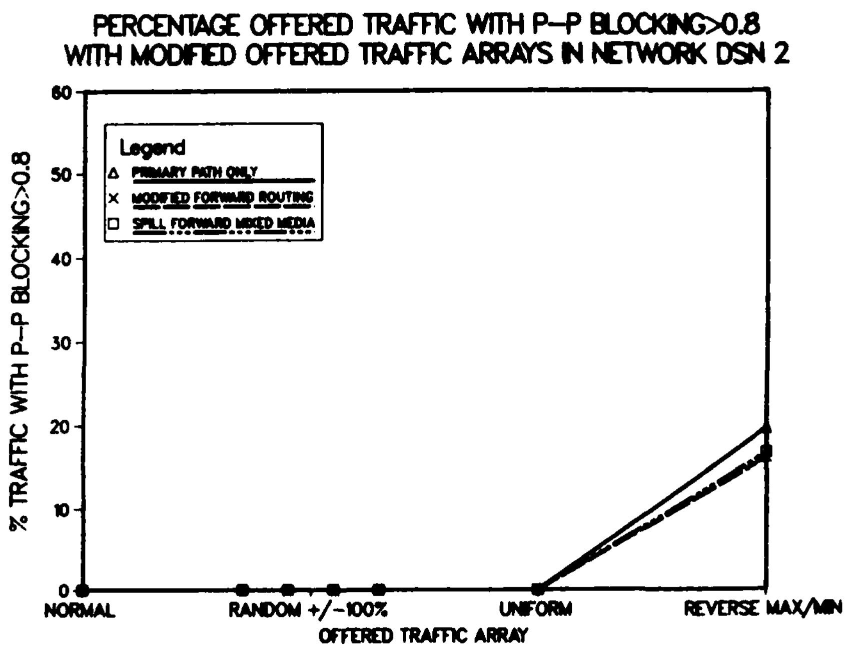
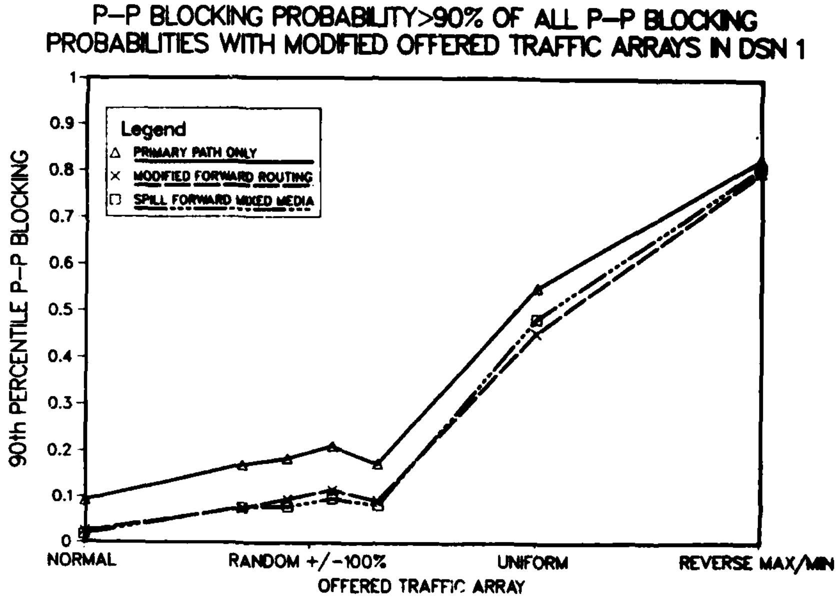


Fig. 28. Percentage offered traffic which experiences a point-to-point blocking greater than 0.8 with chaotic traffic patterns (a) in network DSN1 and (b) in network DSN2.



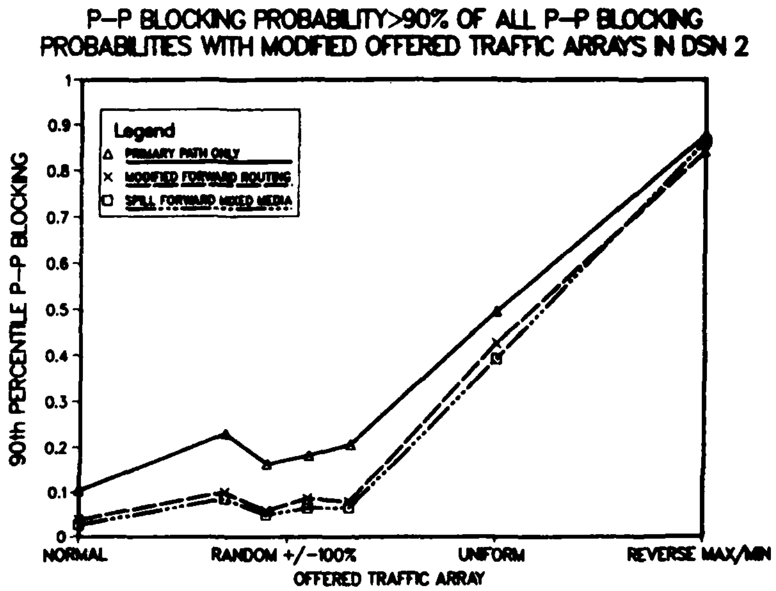


Fig. 29. 90th percentile point-to-point blocking probability with chaotic traffic patterns (a) in network DSN1 and (b) in network DSN2.

offered traffic between all node pairs from zero to twice the normal value: four randomizations), UNIFORM (traffic between all node pairs is identical) and REVERSE MAX/MIN (the switch which normally has the least offered traffic has the traffic normally offered by the switch with the most offered traffic, the switch which normally has the second least offered traffic has the traffic normally offered by the switch with the second most offered traffic, etc.).

The average blocking in Fig. 27 is lowest under normal operation, increases slightly under the somewhat realistic RANDOM +/- 100% condition, and increases dramatically under the less realistic UNIFORM and REVERSE MAX/MIN conditons. Primary path only routing provides the poorest performance while modified forward routing and spill forward mixed-media routing are roughly equivalent. Similar orderings are evident in Figs. 28 and 29. Note that since adaptive mixed media routing adapts only to network damage and not to link overloading, its performance although not plotted would be identical to that of spill forward mixed-media routing.

5. DISCUSSION AND SUMMARY

5.1 Results with Network Damage

New routing procedures were evaluated using a steady state network analysis program and networks with various types and amounts of damage. The new routing procedures were more survivable than modified forward routing under all damage conditions in both 20 and 40 node networks. The average point-to-point blocking probability was similar for both the new procedures and for modified forward routing except when switches were destroyed and average blocking was substantially lower with adaptive-mixed-media routing. The number of node pairs with unacceptable communications (point-to-point blocking greater than 0.8), the percentage of traffic experiencing unacceptable blocking (greater thn 0.8), and the 90th percentile cumulative blocking level (90% of all offered traffic experiences blocking below this level) were all, however, substantially lower with the new routing procedures. Greatest reductions in these measures were obtained (1) with adaptive mixed-media routing under all damage conditions and (2) with remote earth station querying when the satellite alone was destroyed and when the satellite and then land links or switches were destroyed. The new routing procedures were fairer in that the most poorly served group of users was provided with a better chance of call completion and all users were provided with a non-zero probability of completing a call. Modified forward routing, and to a lesser extent mixed-media routing, blocked all calls between node pairs which required excessively long alternate routes, making it impossible to communicate between these node pairs. The percentage of traffic completely blocked ranged from roughly 0% to 10% with modified forward routing and from 0% to 7% with spill forward mixed media routing. No traffic was completely blocked with adaptive mixed media routing and from 0% to 4% of all offered traffic was completely blocked with remote earth station querying. New routing procedures provided the greatest reduction in the percentage of traffic experiencing unacceptable blocking when the satellite was destroyed. Averaging over all four networks, this percentge was 32% with primary-path-only routing, 12.4% with modified forward routing, 8.7% with spill-forward mixed-media routing, and 1.7% with both adaptive-mixed-media routing and remote-earth-station querying. In this same condition, 90% of all offered trffic experienced blocking less than; 1.0 with primary path only routing 0.81 with modified-forward routing, 0.79 with spill-forward mixed-media routing and 0.61 with both adaptive-mixed-media routing and remote earth station querying.

Adding roughly 10% more trunks to improve performance after the satellite was destroyed lowered the average point-to-point blocking with satellite damage from 0.28 to 0.22 for both modified forward routing and the new routing procedures. In addition, improved service was provided to the most poorly served users when the satellite was destroyed. The percentage of traffic provided unacceptable blocking (greater than 0.8) averaged over all routing procedures except primary path only decreased from 9% to 3% with extra trunking and the 90th percentile cumulative blocking level averaged over all routing procedures except primary path only decreased from roughly 0.8 to 0.6 with extra trunking. The relative performance of routing procedures was similar in normal networks and in networks with supplementary trunking. Adaptive mixed media routing and remote earth station querying provided unacceptable blocking (greater than 0.8) for smallest amount of traffic and also resulted in the lowest 90th percentile cumulative blocking levels. Furthermore, the reduction in these measures caused by using adaptive mixed media routing instead of modified forward routing or spill forward mixed media routing was slightly greater than the reduction associated with adding 10% supplementry trunks.

5.2 Results with Overload and Chaotic Traffic Patterns

The new routing procedures performed better than the other procedures examined when 20 and 40 node networks were uniformly overloaded by from 5% to 25%. At small overloads (5% to 10%) these procedures provided the lowest average and 90th percentile cumulative blocking levels. At high overloads (10% to 25%) the peformance of these procedures was similar to that of primary path only routing which provided the best performance under this conditon. This good performance is presumably caused by the controls included in mixed media routing which explicitly check and limit the path length of alternate routed calls. The performance of the new routing procedures was similar to that of modified forward routing when offered traffic patterns were varied dramatically.

5.3 Conclusions

The results presented in this report demonstrate that new routing procedures developed for mixed-media networks significantly enhance network performance after damage. These procedures provide improved service to the most poorly served group of users and allow more users to communicate. The improvement in service to the most poorly served users provided by the best of the new routing procedures was slightly greater than the improvement associated with adding 10% more land trunks. The new procedures also perform as well as the best procedure studied under conditions of traffic overload and when traffic patterns change dramatically. Best performance was provided by adaptive-mixed-media routing and remote earth station querying. Spill-forward mixed-media routing performed better than modified forward routing but not as well as the other two new procedures. All three new routing procedures are viable candidates for use in the Defense Switched Network.

Further research is needed to examine the performance of the new routing procedures when MLPP features (preemption, more routing flexibility for high priority traffic) are available. Further research should also compare the routing procedures evaluated in this study to those new procedures which could not be evaluated with a steady state network analysis program. Those new procedures include mixed-media routing with single-stage crankback and the various precedence flooding procedures. All new procedures should be evaluated when MLPP features are available. The dynamic behavior of these procedures after damage and overload should be examined and the incidence of preemption, signaling traffic, call completion times as well as the point-to-point blocking probability distribution should be compared. Current work is underway to develop a call-by-call simulator which will be used to examine these issues.

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

routing	mixed-media	communications	traffic overload
network	defense switched network	adaptive routing	chaotic traffic
circuit-switching	POLYGRID	preemption	satellite communications
circuit-switch	AUTOVON	network damage	telephone network
performance	DSN	flooding	saturation routing
network analysis			

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Three classes of new mixed-media routing procedures are presented for networks with both broadcast and point-to-point transmission media such as the Defense Switched Network. All procedures treat satellite and terrestrial links separately and use common channel signaling to pass call setup information between switches. *Mixed-media* routing procedures use fixed routing tables and three different call processing rules. *Adaptive-mixed-media* routing procedures adapt routing tables when parts of the network are destroyed. *Precedence flooding* procedures route low-priority calls using mixed-media procedures and high-priority calls using flooding techniques. A steady state network analysis program was

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18. Abstract (Continued)

modified to evaluate the performance of (1) mixed-media routing with spill-forward control, (2) mixed-media routing with remote earth station querying and (3) adaptive mixed-media routing. These new routing procedures were compared to modified forward routing and primary path only routing using 20 and 40 node mixed-media networks under overload, with various patterns of offered traffic, and with different amounts and types of network damage. The new routing procedures studied, especially adaptive-mixed-media routing, substantially enhanced network performance after damage. These procedures did not reduce the average point-to-point blocking probability. They did, however, improve the service provided to the most poorly served group of users and they denied the possibility of call completion to the fewest users. The improvement in service provided by adaptive-mixed-media routing was slightly greater than the improvement associated with adding 10% more land trunks. Under overload conditions and when offered traffic patterns were dramatically shifted, the new procedures performed as well as or better than the two reference procedures.

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