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ANALYSIS AND DESIGN OF FULLY SHARED NETWORKS

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CONTRIBUTION STATEMENT: Presents a new dynamic network concept which combines dynamic traffic routing performed by switch network elements with dynamic transport routing performed by digital cross-connect network elements. Describes mathematical models to design such fully shared networks (FSN), which achieve efficient and highly robust capacity design, and simplified network operation. Demonstrates significant network efficiency and performance improvements of FSN designs for normal daily traffic loads, network failures, unexpected traffic overloads, and peak day traffic overloads.

ABSTRACT: Dynamic routing in telecommunications networks has been the subject of worldwide study and interest. Service providers, equipment providers, and academic institutions throughout the world have active research programs in this area. Dynamic routing networks have been in operation for nearly 10 years and many such networks are in the planning or deployment stage. First implemented during the 1980s, dynamic routing is now deployed in three major networks (AT&T USA, TCTS Canada, and NTT Japan) and has provided considerable benefits in improved performance quality and reduced costs [1]. These benefits have motivated the extension of dynamic routing to integrated networks with multiple classes-of-service and to networks with rearrangeable transport capacity, which is the subject of this paper. The fully shared network (FSN) is a new dynamic network concept which combines dynamic traffic routing with dynamic T1/T3 transport routing. FSN uses automatic control of DCS3/1 and DCS3/3 (digital cross-connect systems 3/1 and 3/3) to achieve dynamic bandwidth allocation of T1/T3 transport and switch capacity. It provides robust network design, T3-level capacity engineering, and automatic T1/T3 provisioning to achieve increased revenues and significant savings in capital and operations costs. The FSN concept builds on class-of-service dynamic routing capabilities in the switched network by allowing automatic implementation of self-healing network strategies such as T1 transport diversity, multiple homing, and T1/T3 restoration. Automatic control of DCS3/1 and DCS3/3 allows rapid provisioning and rearrangement of interswitch T1 capacity, access T1 capacity, and switching capacity in much shorter time periods than is possible today. An FSN design module receives daily network traffic data, designs and allocates T1/T3 transport capacity based on traffic levels, calculates an efficient rearrangement strategy, interfaces with the switches and DCSs through a control channel, and automates the provisioning and control of T1/T3 transport and switching capacity within the FSN.

1. FSN CONCEPT

Fully shared network (FSN) is described in Reference [2] as an evolutionary dynamic routing strategy for rearrangeable transport networks, including both circuit-switched and ATM-based networks. As illustrated in Figure 1, the FSN concept includes electronic switches (SWs), digital cross-connect systems (DCSs), and access nodes (ANs). Access nodes include end-offices, access tandems, customer premises equipment, and overseas international switching centers. Access nodes connect to DCS3/1 by means of access T1 links such as link AD_1. Switches connect to DCS3/1s by means of links such as SD_1. A number of T3 backbone links interconnect the DCS3/1 network elements, such as links DD_1, and DD_2. T3 backbone links are terminated at each end by DCS3/1s, and are routed over fiber spans on the physical transport network on the shortest physical paths. T1 interswitch links (T1-ILs) are formed by cross-connecting T1 channels through DCS3/1s between a pair of switches. For example, the T1-IL from SW_1 to SW_3 is formed by connecting T1 terminal equipment between SW_1 and SW_3 through links SD_1, SD_3, DD_1, DD_2, by making appropriate cross-connects through DCS_1, DCS_2, and DCS_3. T1-ILs have variable T1 bandwidth capacity controlled by the FSN design module. Access T1 links are formed by cross-connecting T1 terminal equipment between access nodes and switches, for example, access node AN_1 connected on links AD_1 and SD_1 through DCS_1 to SW_1, or alternatively, access node AN_1 connected on links AD_1, DD_1, and SD_2 cross-connected through DCS_1 and DCS_2 to SW_2. For additional network reliability, switches and access nodes are dual homed to two DCS3/1s, possibly in different building locations.

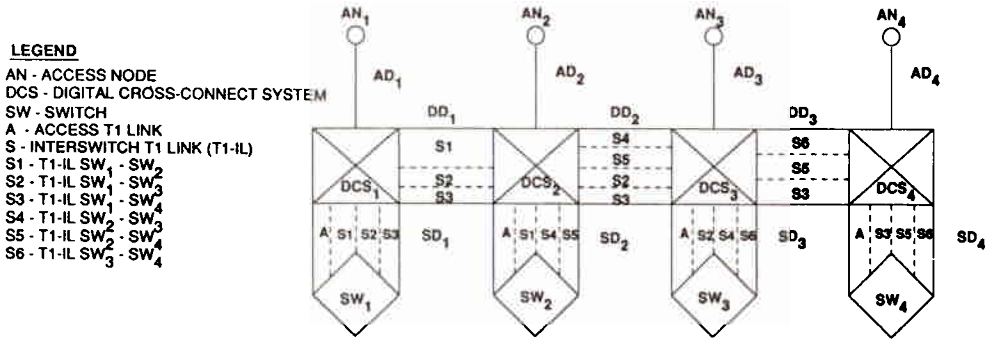

FIGURE 1. FULLY SHARED NETWORK CONCEPT

Figure 2 illustrates an example set of T3 backbone links that overlays the physical fiber transport network. Some T3 backbone links, called T3 express links, overlay two or more T3 backbone links. Therefore T3 express links traverse longer distances before terminating on DCS3/1s. These T3 express links are included in a T1-IL if the T3 express link is fully traversed by the T1-IL transport path between network switches.

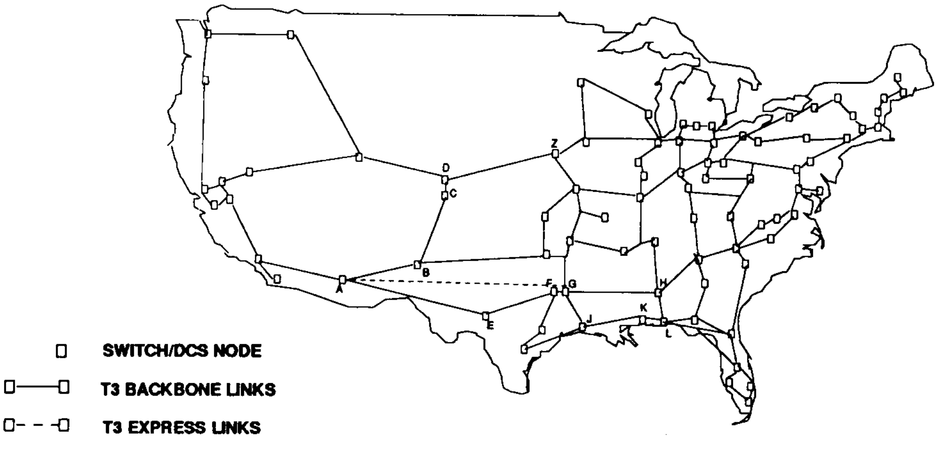

FIGURE 2: FULLY SHARED NETWORK: T3 BACKBONE/EXPRESS LINKS

For example, in Figure 2, T3 express link AG is on the T1-IL transport path between switches A and H, which consists of T3 express link AG and T3 backbone link GH. Here T3 backbone links AE, EF, and FG are traversed by T3 express link AG on the T1-IL transport path, which avoids demultiplexing at DCS3/1s E and F to the T1 level by only going through DCS3/3s at these locations. Hence use of T3 express links leads to fewer DCS3/1 terminations and associated multiplexing and demultiplexing stages. Although only one express link is shown in Figure 2, the network design would have many express links.

Figure 3 illustrates the relationship of the DS0, T1, and T3 dynamic routing strategies used in the FSN. Dynamic traffic routing, that is class-of-service real-time network routing (RTNR) [3], is used at the DS0 level to route calls comprising the underlying traffic demand. DS0-level capacity allocations, denoted as $VTeng^i$, are made for each virtual class-of-service network on the T1-IL capacity. For each call the originating switch analyzes the called number and determines the terminating switch, class-of-service, and virtual class-of-service network. The originating switch tries to set up the call on the direct T1-IL, if one exists, to the terminating switch, and if unavailable tries to find a two-link path using RTNR state dependent routing logic. FSN dynamic transport routing is used at the T1 level to rearrange the T1-IL capacity as required to match the traffic demands, and to achieve interswitch T1 diversity, access T1 diversity, and T1 restoration following switch, DCS, or fiber transport failures. The T1-IL capacities are allocated by the FSN design module such that the bandwidth is efficiently used according to the level of traffic between the switches. FSN dynamic routing is used at the T3 level to aggregate the Interswitch and access T1-IL demands to the T3 backbone/express link level, and then to aggregate the backbone/express link T3 demands to the physical fiber link level. T3 restoration is used to restore T3 capacity through control of DCS3/3s in the event of transport or equipment failures.

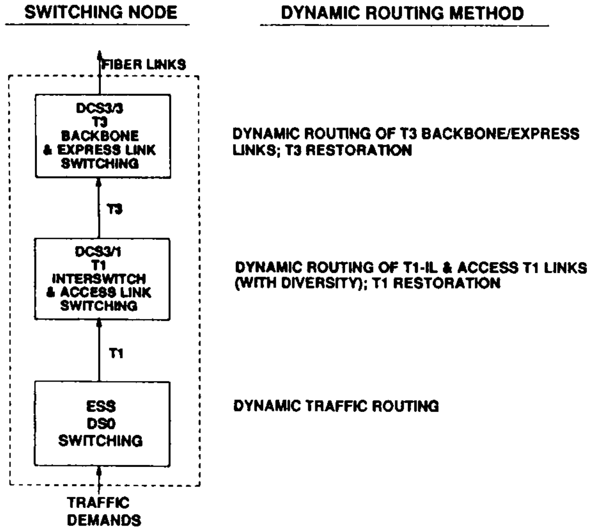

FIGURE 3. FSN DYNAMIC NETWORK CONCEPT

2. FSN DESIGN MODELS

Each night the FSN design module obtains traffic data for the past 24 hour period, smooths and updates its current traffic estimates, allocates T1 bandwidth requirements to T1-ILs and access T1 links, allocates T3 bandwidth requirements to backbone/express links, routes T1-IL capacity on diverse routes through the backbone/express link network, computes a rearrangement strategy to minimize cross-connect activities in switches and DCSs, and populates the routing, trunking, and cross-connect data structures in the switches and DCSs to implement the new network map. Bandwidth allocation is controlled in the FSN through a) dynamic adjustment of T1-IL capacity based on traffic requirements and $VTeng^i$ DS0 bandwidth allocation, b) T1-IL and access T1 bandwidth allocation and routing on the T3 backbone/express link capacity, and c) backbone/express link T3 bandwidth allocation and routing on the physical fiber capacity. Here the design objective is to meet network performance objectives for the estimated traffic loads with minimum cost, and provide a robust design in the event of unforeseen load patterns and network failures.

The mathematical models given in this section are used to estimate traffic, size T1-IL capacity, reallocate access T1 capacity between overloaded and underloaded switches, compute diverse T1-IL capacity requirements, size backbone/express link T3 capacity, and rearrange network capacity. See Figure 4 for an illustration of the FSN design module and design steps. Further details of FSN design models are now given.

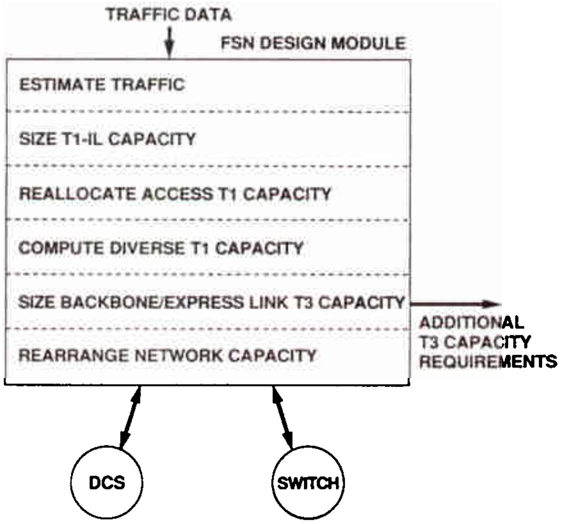

FIGURE 4. FULLY SHARED NETWORK DESIGN

2.1 Estimate Traffic

Based on traffic data received each day, the FSN design module keeps a) running estimates of average daily loads, by day of week and peak day, b) statistical day-to-day variation of the daily and peak day load patterns, and c) seasonal variation of load patterns. With these data the FSN design module estimates the hourly load patterns and day-to-day variation parameters for the next several days interval.

2.2 Size T1-IL Capacity

Here we compute T1-IL capacity demand. We note that T1 demand for dedicated services can be included with the switched T1-IL demand. Switched T1-IL demand is determined by a traffic flow model [4] which computes network flows as well as switch-to-switch blocking probabilities for networks with RTNR. An assumption of the model is that the stationary behavior of RTNR networks can be computed based on the stationary, independent link state probabilities, and on via switch selection probabilities, which are based on the link state probabilities and switch-to-switch blocking probabilities. An iterative erlang fixed point approach [5] is used and all overflow traffic is assumed to be poisson.

Three steps are performed iteratively by the algorithm. The link state probability model derives the link aggregate state probabilities from the link arrival rates, the link arrival rates are the outcome of the network flow model. The traffic flow model uses the link aggregate state probabilities to derive the path state probabilities and the route state probabilities. With these state probabilities, the flow model determines the route flows, path flows, path arrival rates, and the link arrival rates, where the latter are used in the link state probability model to compute the link state probabilities. Finally the adaptive trunk reservation and adaptive path selection depth model computes the switch-to-switch blocking probability distribution, and from that models the path selection depth and the link reservation levels. A model of calls-in-progress is used to determine the probability that reservation and path selection depth are enabled. The convergence criterion is the sum of the squared differences in link state probability levels from the previous to the current iteration, summed over all links in the network. Our numerical experience shows that, when RTNR trunk reservation is applied, the approximation method converges quickly to the fixed point solution. At each iteration, the traffic flow model is used to compute blocked traffic for a given T1-IL capacity level, and then the T1-IL capacity is re-engineered to meet the objective blocking performance. T1-IL capacity is modularized to the nearest modular T1 capacity.

Bandwidth is allocated for every class-of-service on the T1-IL capacity. The bandwidth allocations for individual virtual class-of-service networks, denoted as $VTeng^i$ for class-of-service i, are shared amongst classes-of-service under normal network conditions, but are dedicated to class-of-service i under congestion. The originating switch collects traffic data in real time and determines the level of VT traffic demands to each destination in the network for each class-of-service i. Based on these estimated demands and available capacity in the network, the switch allocates the DS0 capacity on the T1-IL capacity. $VTeng^i$ is a minimum guaranteed bandwidth for a class-of-service if there is blocking for the class-of-service and sufficient traffic to use the $VTeng^i$ bandwidth. If a class-of-service is meeting its blocking objective, other classes-of-service are free to share the $VTeng^i$ bandwidth allocated to that class-of-service. The quantity $VTeng_k^i$ is calculated for virtual class-of-service network i on link k, as follows:

$$VTeng_k^i = d_k \times [\ \sum_{h=1}^{H} D_k^{hi} \,/\, \sum_{n=1}^{M} \sum_{h=1}^{H} (D_k^{hi\bullet})\ ].$$

Here classes-of-service n are numbered 1 to M, hours h are numbered 1 to H, d_k is the modular T1-IL capacity for switch pair k, and D_k^{hi} is the offered traffic load for switch pair k in hour h for class-of-service i.

2.3 Reallocate Access T1 Capacity Between Overloaded and Underloaded Switches

If the total interswitch termination capacity available on a switch is exceeded by the estimated interswitch T1 capacity demand, then additional interswitch termination capacity is generated for the switch by rehoming (rerouting) access T1 capacity to underloaded switches having spare termination capacity. This access T1 rerouting frees terminations on the overloaded switches, which can then be used to satisfy the interswitch T1-IL demand. After terminations are rehomed to underloaded switches, switch-to-switch traffic loads are adjusted according to the number of access terminations moved, and through use of a Kruithof iteration procedure [6]. After the switch-to-switch traffic levels are adjusted, the T1-IL capacity requirements are re-computed. In this model, additional switch termination capacity requirements are determined to achieve sufficient capacity to meet network demands up to a specified level of overload. Current switch termination inventory is determined directly from network elements.

2.4 Compute Diverse T1 Capacity

The T1-IL sizing model provides for diverse sizing of the T1-IL capacity in the hour of maximum T1-IL traffic load, in order to achieve a traffic restoration level (TRL) objective under network failure. The TRL objective specifies that for single fiber transport link or switch failures, that the T1-IL capacity of the network is sized to carry at least a certain minimum percentage of the engineered traffic load denoted as the TRL objective. For example, if the TRL objective is 0.5, this means that following any single fiber cut in the transport network that at least 50 percent of the engineered traffic is still carried after the failure.

The model used for the TRL design of the T1-IL links is as follows:

TRL = traffic restoration level objective
$trlcap_k$ = minimum T1-IL capacity required for switch pair k to meet the TRL objective
$trlcap_k \le d_k/2$

Then the required number of surviving T1-IL capacity after a fiber transport failure is given by

$$trlcap_k = \text{TRKRQS}(\max_h D_k^h, 1\text{-TRL})$$

where the function TRKRQS gives the trunks required for a given offered load and blocking objective. Here a minimum of $trlcap_k$ trunks of the T1-IL capacity are routed if possible over each of two diverse T1 paths, while insuring that T1 modularity conditions are met. A further constraint is that $trlcap_k$ is equal to or less than half the total T1-IL capacity d_k. If that is possible it ensures that a failure of either path allows enough T1 capacity to survive to meet the TRL objective. At times, however, because of modularity constraints, it is not possible to achieve this diversity condition on the T1-IL capacity (e.g., if the T1-IL capacity only requires one T1, it is not possible to achieve the condition). Diverse T1 capacity is allocated and if possible the $trlcap_k$ diverse T1-IL capacity is realized on the diverse path. Similarly the diverse access T1 capacity required to be split between network switches to achieve TRL objectives for switch failure is calculated in the same way. This same procedure is followed whether the access T1 capacity is brought into one building location or routed diversely into multiple DCS3/1 building locations.

Other related models for reliable network design are given found in [7,8]. In Reference [8], linear programming models are formulated for diverse capacity design, in contrast to the TRL method presented above.

2.5 Size Backbone/Express Link T3 Capacity

In this section we first describe the topological design of the FSN transport network in terms of backbone links, express links, and diverse paths. We then formulate the T3 capacity sizing model for FSN. The FSN transport network is comprised of DCS3/1s, DCS3/3s, and fiber links between them. Each DCS3/1 is co-located with a corresponding DCS3/3, although DCS3/3s may exist without corresponding DCS3/1s. To design candidate FSN backbone links, we first find all the shortest paths between the DCS3/1s on this fiber network. We then break each shortest path into unique segments beginning and ending on a DCS3/1, and these segments are then the candidate backbones links. Diverse T1 paths through the T3 backbone link network are designed by first constructing a "violations matrix" for the each T3 backbone link. This matrix describes the degree of physical overlap between any pair of T3 backbone links. The set of candidate backbone links defines a connectivity among the DCS3/1s. We also have the underlying fiber link topology for all the backbone links, and from physical routing information we can compute span violations between all backbone links. We use a span diverse algorithm to find a set of candidate span diverse shortest paths between all DCS3/1s. This algorithm allows for both node and span violations with a weighted penalty function. Each T1-IL capacity requirement is split on two or more diverse T1 transport paths, such that typically the diverse T1 capacity ($trlcap_k$) is routed on the longer T1 path. For example, in Figure 2, the T1-IL capacity between switch J and switch L is split between T1 transport path JK-KL and T1 transport path JG-GH-HL, in which the diverse T1 capacity routed on the JG-GH-HL path and the remaining T1-IL capacity is routed on the JK-KL path.

An express link is a "through T3" in that if there is more than one T3 of demand between DCS3/1 A and DCS3/1 B, and the path between them passes DCS3/1 Z, for example, we do not cross-connect the T3 at DCS3/1 Z. Instead we bypass DCS3/1 Z by cross-connecting at the T3 level through the DCS3/3, thus saving DCS3/1 terminations. We use a greedy heuristic to eliminate candidate express links that can never carry enough T1 demand to fill a T3. We do this by examining each candidate express link one at a time, and flowing the T1-IL demand for the entire network. If the particular express link candidate carries less than one T3 of T1 flow, we discard it from the candidate list. We order the set of candidate express links in decreasing order by hop count. These are then inserted into the set of diverse paths starting with the one with the largest hop count, and thereby we repace the backbone links in the diverse paths with express links.

A minimum cost linear programming (LP) model is solved for sizing backbone/express link T3 capacity, in which the T1-IL demands d_k are routed on the fiber link network, as follows:

$$\text{Min} \sum_{f=1}^{F} \Delta F_f \times C_f$$

such that

$$\sum_{k=1}^{K} \sum_{j=1}^{J} P_{jkb} y_{jk} \le f_b$$

for each backbone/express link b.

$$\sum_{b=1}^{B} Q_{bf} f_b \le F_f + \Delta F_f$$

for each fiber link f.

$$\sum_{j=1}^{J_k} y_{jk} = d_k$$

for each switch pair k.

$$\sum_{j=1}^{J_k} \sum_{b=1}^{B} P_{jkb} Q_{bf} y_{jk} \le d_k - trlcap_k$$

for each switch pair k and fiber link f.

$$y_{jk}, f_b \ge 0$$

for each path j for switch pair k and backbone/express link b.

Here fiber links f are numbered 1 to F, backbone/express links b are numbered 1 to B, T1-IL paths j are numbered 1 to J_k, and switch pairs k are numbered 1 to K. In the above model

P_{jkb} = 1 if path j of T1-IL k routes over backbone/express link b
= 0 otherwise

Q_{bf} = 1 if backbone/express link b routes over fiber link f
= 0 otherwise

y_{jk} = flow assigned to path j of switch pair k

$trlcap_k$ = minimum T1-IL capacity required by switch pair k to meet the TRL objective

f_b = capacity assigned to backbone/express link b

F_f = existing transport capacity of fiber link f

ΔF_f = added transport capacity on fiber link f

C_f = cost per T3 of added transport capacity on fiber link f

T3 transport capacity requirements are determined to achieve sufficient capacity to meet network demands up to a specified level of overload. Current fiber link T3 capacity is determined directly from network elements. The above model is solved for the required capacity additions and achieves substantially increased fill rates over current levels. Since transport and equipment demands are aggregated to the fiber link level and total switch level, this provides a simpler and more robust network design.

Either Karmarkar's algorithm and/or a heuristic technique can be used to solve the LP flow model. One heuristic solution method that works well is as follows. First the T1-IL demands are flowed over two diverse backbone/express link paths. We then find a minimum cost alternative T3 path (MCAP) for each express link that minimizes DCS3/1 terminations. For a given express link, its MCAP is the concatenation of two or more shorter express or backbone links. Topologically the MCAP comprises the same underlying fiber links as the shortest T3 backbone path. We then move traffic off an inefficient express links onto its MCAP, starting with the longest express link and rounding the T1 flow down to a multiple of full T3s. The "overflow" T1 demand is split off and routed onto the corresponding MCAP. This procedure is repeated for each express link in the greedy ordered list, and must terminate on backbone links. Backbone link capacity is then rounded up to the next T3 module of capacity.

2.6 Rearrange Network Capacity

Once the bandwidth allocation design is completed for the estimated traffic, a combinatoric optimization algorithm computes the rearrangement strategy which minimizes cross-connect activities by first recognizing common route segments between the existing and target network arrangements, and then finding the cross-connect actions which maximally re-use these common segments. In the model we compute a sequence of T1-IL disconnect and connect orders so as to always maintain the maximum capacity connected throughout the network rearrangement. The FSN design module communicates with the network elements to make the necessary rearrangement and cross-connect changes.

3. ANALYSIS OF FSN DESIGNS

The implementation of FSN allows significant reductions in capital costs and operations expense with new FSN routing and capacity design methods. Automated T1 provisioning and rearrangement leads to very significant annual expense savings. Other major operational impacts, leading to additional reduction in operations expense, are to simplify T1 provisioning systems; absorb pre-service trunk testing and simplify maintenance systems; absorb current trunk forecasting, administration, and bandwidth allocation into T3-level capacity planning and delivery; simplify switch and facility planning; and automate inventory tracking. FSN design allows more efficient use of switch capacity and transport capacity and leads to reduction of network trunk capacity by about 10 percent, while improving network performance. This translates into a significant reduction in capital expenditures. FSN T3 network design achieves 90%+ average T1 to T3 fill rates, which further reduces transport costs. FSN implements automated interswitch and access T1 diversity, T1 restoration, and switch backup restoration to enhance dramatically the network survivability over a wide range of network failure conditions. We now illustrate FSN design performance under design for normal engineering traffic loads, fiber transport failure events, unpredictable traffic load patterns, and peak day load patterns.

3.1 Analysis of FSN Capacity Design for Engineered Traffic Loads

A full-scale network model of 129-switches is designed for normal engineered traffic loads with the methodology described in the above sections, and results in a 15.0% savings in total trunk capacity over the base network model. In addition to this large savings in network capacity, the network performance under a 10% overload results in the following performance comparison:

TABLE 1. NETWORK BLOCKING PERFORMANCE FOR 10% TRAFFIC OVERLOAD (129-NODE NETWORK DESIGN FOR ENGINEERED TRAFFIC LOADS)

Hour of Day	Base Network (% Network Blocking)	FSN Design (% Network Blocking)
9 to 10 AM	0.19	0
1 to 2 PM	0.30	0
8 to 9 PM	0	0
Average	.11	0
Node-Pair Maximum	17.3	0

Hence FSN designs achieve significant capital savings while also achieving superior network performance.

3.2 Analysis of FSN Designs for Network Failures

Simulations are performed for the base and FSN network performance for the 1/4/91 fiber cut in Newark, New Jersey, in which approximately 70,000 trunks were lost. The results are as follows:

TABLE 2. NETWORK BLOCKING PERFORMANCE FOR 1/4/91 FIBER CUT IN NEWARK, NJ

	Average Network Blocking (%)	Number of Switch Pairs with Blocking > 50%
Base Network	14.4	963
FSN Design	4.2	0

Here a threshold of 50 percent or more switch pair blocking is used to identify switch pairs that are essentially isolated; hence the FSN design eliminates all isolations during this network failure event.

An analysis also is performed for the network performance after T3 transport restoration, in which the base and FSN design networks are simulated after 29 percent of the lost trunks are restored. The results are as follows:

TABLE 3. NETWORK BLOCKING PERFORMANCE FOR 1/4/91 FIBER CUT IN NEWARK, NJ (AFTER T3 RESTORATION)

	Average Network Blocking (%)	Number of Switch Pairs with Blocking > 50%
Base Network	7.0	106
FSN Design	.6	0

Again the FSN design eliminates all network isolations, some of which still exist in the base network after T3 restoration. From this analysis we conclude that the combination of dynamic traffic routing, T1-IL diversity design, and T3 transport restoration provide synergistic network survivability benefits. FSN design automates and maintains T1-IL diversity as well as access T1 diversity in an efficient manner, and provides automatic T1/T3 transport restoration after failure.

3.3 Analysis of FSN Designs for Unexpected Traffic Overload Patterns

FSN design provides load balancing of switch traffic load and T1-IL capacity such that sufficient reserve capacity is provided throughout the network to meet unexpected demands on the network. The advantage of such design is illustrated in the following table, which compares the simulated network blocking for the base network and FSN design during the evening hours of 8/19/91, when Hurricane Bob caused severe overloads in the Northeastern United States.

TABLE 4. NETWORK BLOCKING PERFORMANCE FOR UNEXPECTED TRAFFIC OVERLOADS (8/9/91 HURRICANE BOB)

Hour of Day	Base Net (% Network Blocking)	FSN Design (% Network Blocking)
6 to 7 PM	.01	0
7 to 8 PM	1.15	.85
8 to 9 PM	.44	.21
Average	.34	.23
Node-Pair Maximum	22.7	13.3

Such unexpected focused overloads are not unusual in a switched network, and the additional robustness provided by FSN design to the unexpected traffic overload patterns is clear from these results.

3.4 Analysis of FSN Designs for Peak Day Traffic Load Patterns

An FSN design is performed for the Christmas, 1990 traffic loads, and simulations performed for the base network and FSN design for the Christmas Day traffic. Results for the interswitch blocking are summarized in the following table:

TABLE 5. NETWORK BLOCKING PERFORMANCE COMPARISON FOR CHRISTMAS 1990

Hour of Day	Base Net (% Network Blocking)	FSN Design (% Network Blocking)
9 to 10 AM	17.2	0
10 to 11 AM	22.2	0
11 to 12 AM	29.7	0

Clearly the FSN design eliminates the interswitch network blocking, although the access network blocking may still exist but is not quantified in the model. Given this interswitch blocking reduction resulting from FSN peak day design, we estimate annual revenue increases of $3.5M in recovered lost revenue. Customer perception of network quality also is improved for these peak day situations.

4. SUMMARY

We present results of a number of analysis, design, and simulation studies related to a dynamic network concept called fully shared network. FSN dynamic routing is a new routing and bandwidth allocation strategy, which combines dynamic traffic routing with dynamic transport routing, and for which we provide associated network design methods. A call-by-call simulation model is used to measure the performance of the network for FSN dynamic routing design in comparison to the base network design, under a variety of network conditions including normal daily load patterns, unpredictable traffic load patterns such as caused by Hurricane Bob, known traffic overload patterns such as occur on Christmas day, and network failure conditions such as the 1/4/91 Newark New Jersey fiber cut. We find that FSN dynamic routing design improves network performance in comparison to the base network for all network conditions simulated. In particular, the ability of FSN to enhance network performance under abnormal and unpredictable traffic load patterns results from the improved robustness of the network design, which is achieved while significantly reducing network capital and expense costs. The ability of FSN to enhance network performance under failure is significant in that it provides automatic interswitch T1 and access T1 diversity in combination with the network-wide path selection and immediate adaptation to failure available with RTNR and T1/T3 transport restoration. We show that higher network throughput and enhanced revenue should accrue from deployment of FSN, and at the same time capital and expense savings should result. Overall, FSN provides a new dynamic traffic and transport routing concept that meets customer oriented goals of service flexibility and performance quality.

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