

Computer-Aided Design Procedures for Survivable Fiber Optic Networks

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Abstract—We describe methods to design cost-effective survivable telecommunications networks which employ fiber optic transmission links. One of these methods utilizes optical switching devices to implement route diversity during cable cuts. These methods have been incorporated into a software tool consisting of three modules: a topology generator, a circuit to DS3 bundler, and a multiplex layout system. This tool is compact enough to run on a personal computer, and we describe each of these three modules and provide sample results.

I. INTRODUCTION

THE high capacity of new technology fiber transmission systems has resulted in the capability to carry many thousands of telephone conversations and high-speed data on a few strands of fiber. This situation has increased concern about the possibility of severe service loss in the event of a building or fiber link failure. Also, the economics of fiber transmission systems differ significantly from the economics of more traditional, copper-based technologies. New techniques which design optimal fiber networks considering network survivability are thus needed. This paper describes the methods and algorithms used in a series of computer program modules, collectively called Fiber Options, which were devised at Bell Communications Research as part of general research efforts into new technologies for network design.

This series of computer programs are available for Local Exchange Carriers (LEC's) to plan and engineer interoffice Local Access Transport Area (LATA) fiber optic networks. The intent is to provide insight into the cost/survivability tradeoffs of fiber networks and design cost-effective networks toward which the existing network can grow. The basic philosophy in the methods is to utilize a growth model which places all demand on new fiber facilities. It is possible, however, to consider some aspects of embedded plant through modification of the input demand and network data. The problem considered is how to design a cost-effective all fiber network; existing capacity expansion tools can then be used to consider how to grow toward this solution. The methods essentially consider broad-gauge cost factors to find and recommend reasonable networks; further study using more detailed

analysis can be used to refine the solution and ascertain a transition plan.

A. Overview of Fiber Network Design

Fiber Options makes use of facility hubbing and facility hierarchies to optimize facility networks [1]. Facility hubbing takes advantage of the fact that the cost of fiber systems is relatively insensitive to distance, while the capacity of fiber transmission systems is very large compared to building-to-building circuit quantities. As a result, a reasonable network architecture and routing strategy is to send all the demand from each building to the building selected to be its "hub." At the hub, all demand is sorted and properly assigned to get to its desired destination. A Digital Cross-Connect System (DCS) is used at the hub to rearrange DS1's (a multiplex bundle containing 24 circuits) within the DS3 signal level normally used by high-speed fiber transmission systems. The DS3 signal level contains 28 DS1's for a total of 672 circuits and is too large for most interbuilding demands which fall into the range of a few DS1's. Thus, all demand is concentrated into high capacity routes to a central location where the demands are sorted according to destination.

It is possible to take the concept of facility hubbing a step further and consider a *facility hierarchy*. That is, we group buildings together into "clusters" with each cluster having one hub building. This grouping considers such factors as community of interest and geographic area. Then we can group clusters together into "sectors" with each sector having one "gateway" which is a hub building designated to handle intercluster demands. A gateway hub can aggregate demand from several cluster hubs together to form a large demand to be routed to another gateway in much the same way as demand is aggregated to a hub building, thus taking advantage of the high capacity of fiber optic systems. Naturally, the concept of facility hierarchy discussed here can be extended to an arbitrary number of levels beyond the three-level hierarchy (building, hub, gateway) discussed here.

The survivability issues that the software modules consider is how to build cost-effective networks which are immune to unusual but catastrophic single point failures such as cable cuts [2]–[5]. Fiber networks are most economic when tree structures are used. When such tree structures are broken at any point through the failure of any link, the network may become disconnected and buildings may be isolated. In other words, the very high

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capacity of the fiber transmission systems tends to force placing large portions of the total demand into a few working systems, and thus a network may have severe problems in the face of an occurrence such as a failure in electronic components or a fiber cable cut.

The most common means to protect fiber transmission systems from failure of electronic components is to employ a *protection system* which can be switched in to replace a failed working system. There may be several working systems protected by the same protection system with an *automatic protection switch* which detects a failure of a working system and switches the working service automatically to the protection system. Fig. 1(a) shows N working systems protected by one protection system (a $1:N$ arrangement). This protection system not only serves to guarantee service should a piece of electronics fail, but also is used to maintain and modify the working service. Studies of the relative component costs of fiber networks have indicated that the majority of network cost is due to the terminal electronics of the fiber transmission systems [1], [2]. The remainder of the cost is the cost of fiber material and installation and the cost of the hub DCS. Since a protection system is normally employed to protect working service, it is natural to investigate methods by which the protection system can be used to ensure service in the event of a fiber cable cut, along with its use to protect against electronic failures. One way to do this is to route the fibers used by the protection system along a physically diverse route from the route taken by the working service. Fig. 1(b) shows an example of diverse routed protection. One would suspect, and indeed studies have proven [2]–[4], that the additional cost for material and installation of the diverse fiber routes would be acceptable for the benefits gained since the increased cost of the fiber itself is small compared to the unchanged cost of electronics.

Normally, $1:N$ protection is utilized in the design of fiber systems since the probability of two terminals failing at the same time is very small. However, a fiber cable cut is a single-point failure that can disrupt the service carried by several working fiber systems. If $1:N$ protection were employed in such a case, the service carried by $N - 1$ of the working fiber systems would be lost. It is possible to use $1:1$ protection to circumvent this difficulty, however, this may be expensive due to the cost of the fully equipped protection terminals needed. Fig. 2 shows the use of optical switches which can be employed to send the optical signal on a physically diverse path should the fiber cable be cut. These switches can be mechanical devices that choose between two optical inputs or outputs. Should the normal working path be severed, the receiving terminal can switch to get its optical input from the diverse path. The figure shows an optical switch being used at the transmit end to feed the diverse or normal fibers; an optical splitter can also be used to feed the diverse fiber continually if signal loss is not a problem. This approach results in complete restoration of working service should the fiber be cut while retaining the economy of $1:N$ terminal

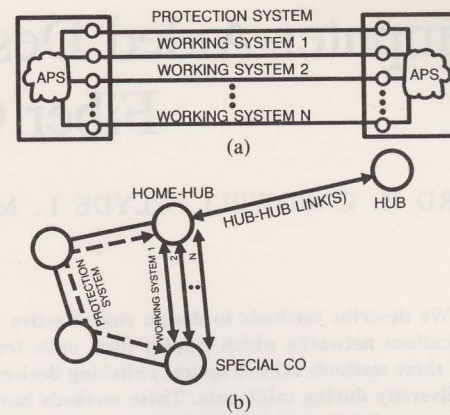


Fig. 1. Protection routing. (a) $1:N$ protection. (b) $1:N$ protection with diverse routing.

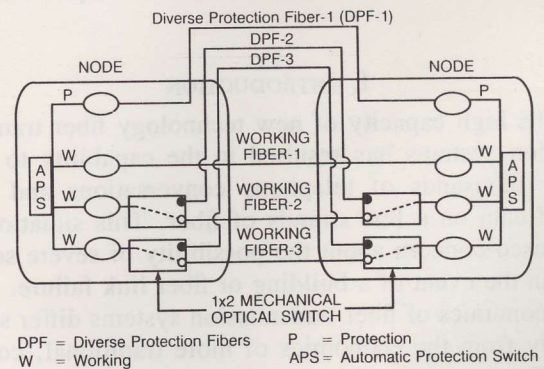


Fig. 2. Protection optical switching.

protection. The protection terminals are still needed to protect against electronics failure. The method is economic since an optical switch costs a few hundred dollars while a fully equipped protection terminal can cost on the order of one-hundred thousand dollars.

The problem of ensuring network integrity during cable cuts is thus a problem of selecting a network topology which minimizes the cost of interconnecting certain *special buildings* so that each special building has a diversely routed protection fiber as described above and the increased cost of the fiber is minimized. These special buildings are selected by LEC's on a cost/benefits basis, and are normally highly important, high revenue-producing wire centers, perhaps having a high proportion of priority services. That is, it may not be economically possible to ensure the service of small buildings in the face of fiber cable cuts, and in fact it may not be possible to ensure service to certain buildings since there may be only one path out of them. However, we can provide a diverse protection fiber route between a special building and its home hub which will protect service should a failure occur. The fiber transmission systems between hubs can be treated in a like manner.

Several architectures used to provide network survivability are shown in Fig. 3. The term *single homing* refers to concentrating all demand from a building over a single fiber span to its home hub building. As discussed, this approach can be made more survivable by diverse protec-

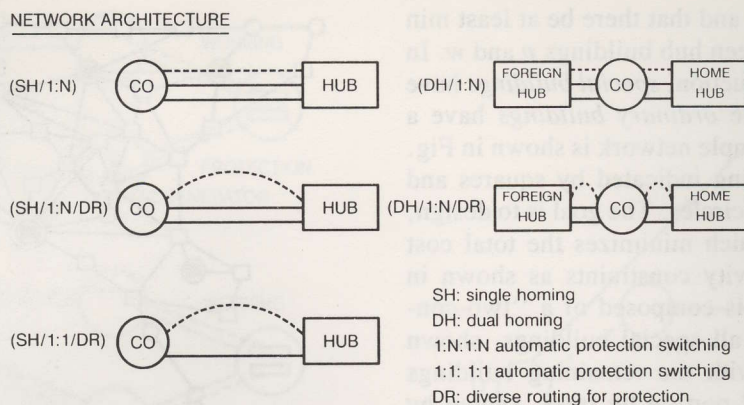


Fig. 3. Survivable architectures.

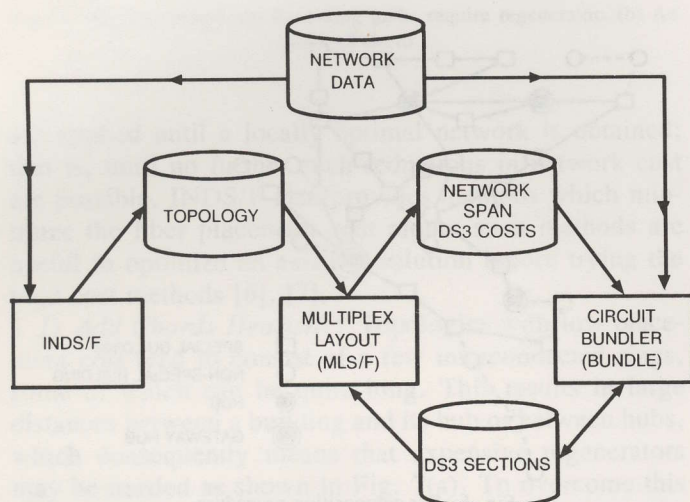


Fig. 4. Fiber Options software.

tion routing on either a 1: N or 1: 1 basis (the optical protection scheme is considered as 1: 1 here). The base case is assumed to be 1: N protection without diverse routing, as this approach is widely used in present networks. Survivability is calculated as the number of circuits that are still intact after the worst-case and average failures. Cost penalties associated with survivability are computed by comparison to the base architecture and the final design is chosen based on the cost and benefits obtained. The term *dual homing* refers to splitting the demand of a building among two hubs in an effort to avoid total failure should a hub building or DCS fail.

The Fiber Options series of software consists of three modules which communicate via data files as shown in Fig. 4. These modules operate as follows.

- 1) The Interactive Network Design System/Fiber (INDS/F) module produces a near-minimum cost fiber topology by determining which links are to be equipped with fiber while ensuring the desired diverse routes are available.
- 2) The Bundle module determines a set of near-minimum cost DS3 sections to carry the input circuit demand.
- 3) The Multiplex Layout System/Fiber (MLS/F) module is used to layout the fiber systems and compute actual

network cost for the fiber transmission components (electronics, fiber material, and fiber installation) along with the resulting network survivability.

It is recommended that several iterations on the selection of special buildings, the facility hierarchy, and the restoration strategy be used to find the solution with the best cost/survivability tradeoff.

We first describe the INDS/F module in Section II. The Bundle module is discussed in Section III, followed by a discussion of the MLS/F module in Section IV. Sample results are presented in Section V.

II. INDS/F MODULE

The INDS/F module determines which potential fiber links are to be included in the topology of a cost-effective fiber network. Inputs include the locations and connectivity requirements of the buildings, a list of the potential fiber links between buildings (available from network planners), the fiber demands for working and protection systems between buildings, and circuit demands (used to calculate survivability estimates). The potential links correspond to pairs of buildings between which fiber can be placed and each link has an associated distance. Costs considered are the cost per mile for fiber material and installation, together with the cost of a regenerator and a distance threshold beyond which a regenerator is required. Using these data, INDS/F chooses which links will be equipped with fiber so that the connectivity constraints are met and outputs the topology for the MLS/F module to consider. The user has complete control at all times and can direct or override the process; extensive use of color graphics allows easy review of the solution and aids user interaction to understand and edit the solution.

A. The Problem

We are given an undirected graph $G = (V, E)$, where V represents the set of *building* locations, and E represents the set of *edges*, or potential fiber links. Associated with each edge (u, v) between buildings u and v is a non-negative *distance* $d_{u,v}$. Each building v has an associated connectivity type r_v . The connectivity constraint requires that there be at least r_v edge-disjoint paths between a

building and its cluster hub, and that there be at least $\min\{r_v, r_w\}$ disjoint paths between hub buildings v and w . In the terminology of the Introduction, *special buildings* have a connectivity of two, while *ordinary buildings* have a connectivity of one. An example network is shown in Fig. 5 with special buildings being indicated by squares and ordinary buildings shown as circles. The goal is to design, from scratch, a network which minimizes the total cost while meeting the connectivity constraints as shown in Fig. 6. A feasible network is composed of a "two-connected" portion containing all special buildings, shown by solid lines in Fig. 6, with the remaining buildings linked to the two-connected portion by trees, shown by dotted lines in Fig. 6. We note that INDS/F considers only fiber cost and hence treats the number of protection and working fibers between buildings as the demand.

B. Algorithms for Building an Initial Solution

Any two-connected network can be constructed by an "ear-composition" procedure. First find a cycle (or, in other words, a ring) on a subset of the buildings to form a partial solution. Then repeatedly add a path, called an *ear*, to the solution until all buildings are two-connected; these paths start at a building in the present solution, continue through buildings not in the solution, and end at another building which is in the solution. Once all of the special buildings (and possibly some of the ordinary buildings) are included in the two-connected part of the solution, the rest of the ordinary buildings are linked in by spanning trees as shown by the dotted lines in Fig. 6.

1) *Greedy Ears*: This method is based on the ear composition procedure. The first step is to construct an initial cycle C spanning a subset of buildings. This is done by randomly selecting a special building v and then selecting a special building w whose shortest path P from v to w is longest among all special buildings. Let u be the building next to the special building w on the path P from v to w . We now construct a short cycle through the edge (u, w) by finding a shortest path from u to w not using the edge (u, w) . (There must be such a path; if not, there would not be two disjoint paths between u and w , and hence the problem would be infeasible.) The next step is to greedily add short ears to the solution until all special buildings are contained in this two-connected network solution. This is done by first selecting a special building z not yet in the solution whose shortest path P to the partial solution (to a building v) is longest among all special buildings not yet included. We now find another shortest path Q from z to the partial solution which does not use any edges of P and terminates on the partial solution at a node w other than v . Again, this path must exist for the problem to be feasible. The combination of P and Q must contain an ear which is added to the partial solution.

2) *Random*: This method works the same as the ear composition procedure and is provided to allow the user flexibility in obtaining different initial solutions. The first step is to construct an initial cycle C spanning a subset of the special buildings. This is accomplished by randomly

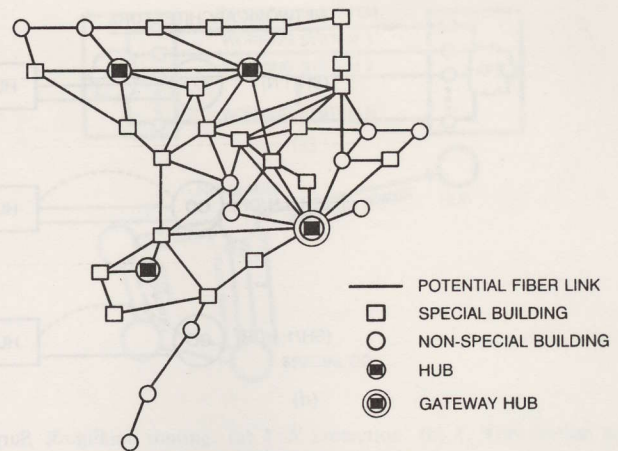


Fig. 5. Fiber topology problem.

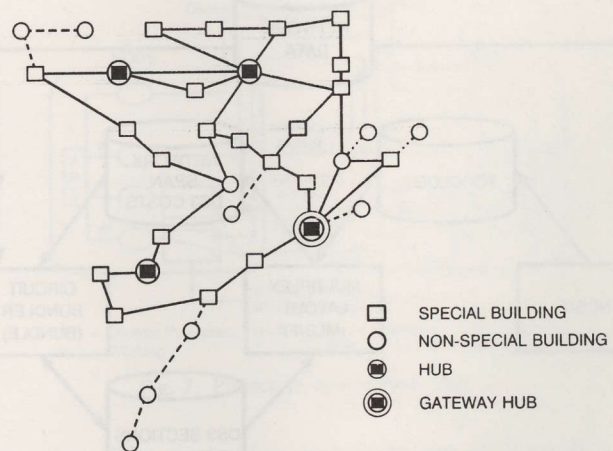


Fig. 6. Ear composition procedure.

choosing a special building v and constructing a depth-first-search tree T rooted at v . Now form a cycle by randomly choosing an edge (v, w) not in the tree T . (There must be such an edge, or else v is not on any cycle and the problem is infeasible.) Next, random ears are repeatedly added until all special buildings are on the two-connected part of the solution. This is done by initially constructing a depth-first-search forest F rooted at the buildings which are in the partial solution. A building v is said to be *allowed* if v is not yet in the solution but has an edge (v, w) not in F with w in the solution. (Again there must be such a building or else the problem is infeasible.) Let T be the tree in the forest F containing v , and let z be the root of T . Now the random ear is chosen in the path from v to z in T , together with the edge (v, w) . Since this method does not use cost information, it does not generally produce a low-cost solution. However, it is useful for generating random starting solutions on which to apply the improvement methods to be described next.

C. Improvement Methods

The improvement heuristics described here apply local transformations to any feasible network in order to reduce the total cost of placement, fiber material, and regenerators while maintaining feasibility. These transformations

further aggregate the demand. As in the case of ECCS, one could speak of an "Economic DS1," with which to judge the tradeoffs of direct routing; this concept will be discussed further in the section on cost calculations.

A. Building-to-Building DS3's

Building-to-building DS3's are generated first. We first convert the number of circuits to DS1's by simply dividing the given number of circuits by 24 (the number of circuits in a DS1) and rounding up. Naturally, one can end up with DS1's with one or two circuits, but the method seems to have sufficient accuracy for the purposes of this software, and avoids the complexity of having multiplexed DS1's. Once the number of DS1's is obtained, the economics of forming a direct building-to-building DS3 is calculated (as will be discussed later) or a user-supplied threshold is applied. If the number of DS1's is greater than the threshold, or, equivalently, the cost of the direct DS3 is deemed less expensive than the cost of the alternate hub DCS route, a direct DS3 is formed. If there are more circuits than can be carried by one DS3, the process is repeated until there is a number of DS1's remaining which are not to be carried by a direct DS3.

Now assume we are given the network shown in Fig. 9 with circuit demand as shown in Table I. We consider only the circuits from building number 1 for the purposes of this discussion; the other buildings would have circuits between them also in an actual example. Also, we consider only the case of total circuits; separation of message and special circuits is handled in a similar manner. We assume for this example that DS3's will be formed only if there are 20 or more DS1's to be routed.

For the purpose of this example, we consider that unrouted DS1's are assigned equally between the two hub DCS's if the two buildings considered are in different clusters. This method is called the *dual* bundle. It is also possible to instruct the Bundle module to assign all unrouted DS1's to the home hub of the lowest numbered building. This option is called the *single* bundle. Users can run either method and decide which yields the best results for their network.

The results of the building-to-building bundling process is shown on Fig. 9 where three building-to-building DS3's shown in dotted lines have been formed. Note particularly the parcel lists of all unrouted (unassigned to DS3's) parcels at each hub; these will be used in the next stage.

B. Building-to-Foreign Hub DS3's

After all the building-to-building circuit demand pairs have been processed, the next step is to try and form DS3's between buildings and other hub DCS's. The final, or last-choice path, from a building through its home hub DCS will be considered later; we are now only concerned with paths from a building through a foreign hub, and from that foreign hub to the endpoint of the DS1.

Consider Fig. 9 again to see how this is accomplished. We have changed the threshold for DS3 formation to 16

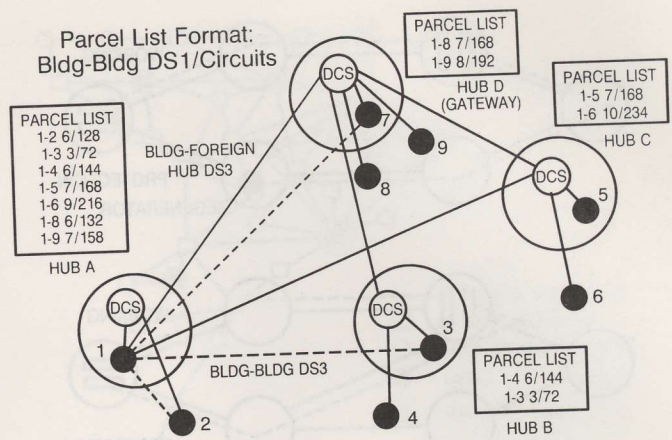


Fig. 9. DS3 formation example.

TABLE I
EXAMPLE CIRCUIT QUANTITIES

Demand Pair	Circuits
1,2	800
1,3	816
1,4	288
1,5	336
1,6	450
1,7	500
1,8	300
1,9	350

DS1's for the sake of this example. We consider for the present example that unrouted parcels at the various hubs will not be moved. Bundle also allows movement of parcels during this stage to improve fill and spread the DCS load; the methods used are similar to those reported here.

We first consider forming a DS3 between a building and first level hubs and thus consider a DS3 between building 1 and hub B in building 3. Note that the total available demand for this particular DS3 is 9 DS1's, the sum of the parcel between buildings 1 and 4 and the parcel between buildings 1 and 3. Because this demand is less than our threshold of 16 DS1's for the formation of a DS3, we leave the parcels in place and proceed to hub C in building 5. At the hub C DCS, we have a total demand of 17 DS1's for building 1. Thus, a building-to-foreign hub is formed between building 1 and the hub C DCS and the DS1's routed accordingly.

Once all the first level hub demands have been processed, the demand from any existing gateway(s) will be considered. In this example, hub D in building 7 is a gateway and has a total demand or 15 DS1's for building 1. Note, however, that there is a demand of 9 DS1's at hub B which homes on the gateway hub D. This demand can be routed from hub B to hub D, combined with the hub D demand of 15, resulting in 24 DS1's which is enough to establish a DS3 from building 1 to hub D. The procedure for considering a higher-level hub in the facility hierarchy is thus to aggregate its demand with the demand from subordinate hub DCS's, if any. We search down the facility hierarchy looking for demand which can be routed through the hub under consideration. This candidate demand is

then added to the demand in the hub under consideration before a routing decision is made.

C. Hub-to-Hub Out-of-Chain DS3's

After all the building demands have been processed, the routing of demands between hub DCS's is determined. We consider at this stage only those hub-to-hub pairs which are not finals; routing along finals will be considered next. The purpose here is to find efficient routes to decrease the demand which is routed along finals.

The procedure here is very similar to the case of building-to-foreign hub formation. Basically, we consider each of the hub DCS's at the first hub level, and consider demand between it and each other hub DCS in order of increasing hub level. Once all hub DCS's at the first level have been processed, we consider all the hubs at the next level and try to establish DS3's between them and hubs at the same level and then higher levels in ascending order. This procedure is repeated until all levels except the highest level have been processed; demand between the highest levels is handled as discussed in the next section. At each stage in processing, the parcels at each end of the prospective DS3 which have destinations below the other hub in the facility hierarchy are considered, together with unrouted parcels below the hubs in question which likewise have destinations below the other hub.

D. Final Routing

When all possible nonfinal DS3's have been formed in the facility hierarchy, we must route all remaining parcels at all hub DCS's to a hub from which they can be routed to their endpoints. With this in mind, Bundle will move all unrouted parcels which do not have *both* endpoints below the present hub up the facility hierarchy. This process is repeated until all parcels are positioned at a level high enough to have both endpoints below the hub DCS where they reside, or they are at the top level of the hierarchy. At this point, the parcels at the top of the facility hierarchy which have one endpoint in another homing chain are moved across the hierarchy on a final between the top DCS's. After completion of this step, it only remains to route the parcels *down* the hierarchy to the endpoint and assign the parcels to finals and, if possible, DS3's which economically bypass unnecessary DCS's.

E. Cost Calculations

As previously mentioned, Bundle can calculate the costs of making a direct DS3 as well as the cost of the alternate route which uses hub DCS's to improve fill. To do these calculations, cost information of the multiplex sections in the network are required; these costs are normally obtained from the MLS/F module and included the cost of fiber and fiber terminals prorated to each DS3 using a fiber span. In the case of two feasible routes through the facility hierarchy, Bundle will take as the cost estimate the cost of the least expensive route. The cost of transport of the direct route is calculated as the actual cost of the DS3

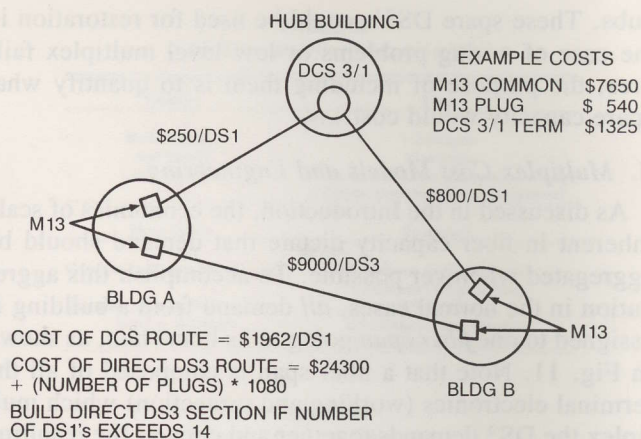


Fig. 10. Threshold example.

section involved (the sum of all the DS3's along the routing path). The cost of transport of the alternate route is calculated assuming that the use of the additional DCS will result in 100 percent fill. The cost of multiplexing to the DS3 level from the DS1 level is also included, and once again the cost of the direct route is calculated using actual demand while the cost of the alternate route is calculated assuming 100 percent fill.

Fig. 10 may make this more clear. Here the decision to be made is whether to establish a direct building-to-building DS3 from building A to building B, or use the alternate route from building A to the hub DCS shown and then to building B. The costs are as shown; note that the cost of the alternate (hub DCS) route is calculated on a DS1 basis as the fill is assumed to be perfect. The term M13 refers to a multiplexer from the DS1 signal rate to the DS3 signal rate. The numbers in the figure indicate that the direct DS3 would be formed if the number of DS1's exceeds 14. Otherwise, the hub DCS path would be utilized. The situation for building-to-foreign hub or hub-to-hub DS3 sections is similar.

IV. MLS/F MODULE

The MLS/F module calculates the cost of the fiber multiplexing network to realize the topology from INDS/F and to carry the DS3 demands from the Bundle module. Cost factors considered by this module include the cost of fiber material and installation, the cost of any required regenerators, and the cost of fiber multiplex equipment. The cost of DCS's and equipment to multiplex to the DS3 rate can be obtained from the Bundle module; we are only concerned with transport cost here. Along with the cost evaluation, MLS/F calculates the exact survivability of the resulting network using DS3 and DS1 information from Bundle.

The user can select several options. Seven architectures are provided, corresponding to those in Fig. 3 together with optical switching. Cost models for fiber electronic equipment are included; the user may enter new cost model parameters if desired. If desired, spare capacity can be included in the form of extra DS3's—one from each special building to its hub and two between each pair of

hubs. These spare DS3's could be used for restoration in the case of wiring problems or low level multiplex failures; the purpose of including them is to quantify what spare capacity would cost.

A. Multiplex Cost Models and Engineering

As discussed in the Introduction, the economies of scale inherent in fiber capacity dictate that demand should be aggregated wherever possible. To accomplish this aggregation in the normal cases, *all* demand from a building is assigned to one *fiber span* going to its home hub, as shown in Fig. 11. Note that a fiber span is composed of all the terminal electronics (working and protection) which multiplex the DS3 demands together and convert the resulting signal to light, together with the fiber itself. Note also the fibers in a span may pass through intermediate buildings on their way to the hub. As shown in Fig. 11, demands may be cross-connected at the hub building on a DS3 signal basis should the quantity of demand warrant (as decided by the Bundle module), and demand may be connected to the hub DCS to be sorted into the proper DS3 for the destination. This concept of routing all demand to the hub building is termed *hub routing*, and has proven to give near-optimal results [9]. Later optimization options are available to try multiplexing at intermediate buildings to lower network cost. Dual homing is an exception to this rule, as demand is split in the dual homing case between the home hub and a foreign hub to ensure survivability for hub failures.

MLS/F uses a simplified cost model for fiber multiplex equipment which is sufficiently accurate while still being computationally manageable. To compute the cost of fiber terminals, we assume that the cost is a function of two factors: the number of DS3's carried by each terminal, and the total number of working terminals. The former cost factor represents the cost of plug-ins, while the latter factor represents the cost of frames and common control. Naturally, the protection system is sized to carry the maximum number of DS3's carried by any working system. The cost of fiber material can be computed from the length of the working and protection paths as determined by the topology. Fiber placement cost is likewise determined by summing the length of utilized fiber links.

All demand between hub buildings is sent via the gateway unless more direct hub-hub fiber spans are economically attractive. To determine the economics of hub-hub spans, the network is engineered first with all hub-hub demand sent via the gateway. Then hub-hub spans are tried and kept if total network cost is lowered.

To engineer a fiber span for the case of 1 : N protection, the cost of using all possible data rates (for example, 45 Mbits/s, 90 Mbits/s, and so forth) considering fiber and terminal costs is evaluated, and the least expensive alternative is chosen. For the case of 1 : 1 protection, the situation is more complicated as we can use fiber spans spans of possibly different rates (say, 1 : 1 405 Mbits/s and 1 : 1 560 Mbits/s from a building to its hub) between an origin and destination. To size fiber spans in this case, we utilize

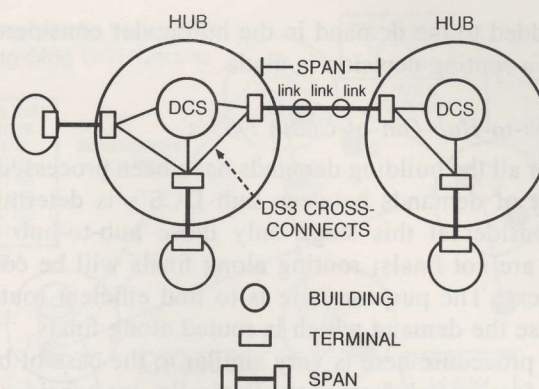


Fig. 11. Fiber span layout.

an integer programming approach to optimize the fiber rates.

B. Survivability Calculations

The survivability calculation is performed on a link, building, and hub DCS basis. That is, each link is failed in turn and the number of circuits surviving is calculated. The average and worst-case survivability are both calculated; however, the worst case is usually the more important statistic. Calculation of building and DCS failure statistics is similar. MLS/F can calculate the exact link and building survivabilities of the network using information supplied by Bundle. A unique number is assigned to each DS1, and the assignment of DS1's to DS3's is available. To calculate link survivability, MLS/F fails each fiber system carried by that link, applies the protection strategy, and counts the number of circuits carried on DS1's which have not been counted yet for this link failure. It is necessary to count in this manner because the same DS1 can be carried in more than one DS3 in the same link, and double counting must be avoided.

An interesting quantity which can be calculated by MLS/F is the *incremental cost/survivability ratio* (ICSR), which is simply the incremental cost over the base case of some survivable network architecture divided by the incremental number of survivable circuits over the base case of that survivable architecture. This measure provides insight into the relative cost and benefits of each architecture.

C. Span Layout Optimization

Although the use of dedicated fibers from each building to its home hub results in a reasonable network cost, there are situations where it is possible to decrease network cost by demultiplexing at an intermediate building and remultiplexing the total demand from that building on another fiber span to the hub. This approach is shown in Fig. 12 and is most useful in eliminating the need for regenerators since both fiber spans are now shorter than the original fiber span. MLS/F supplies two methods to minimize cost in this manner, and both operate by attempting to apply the remultiplexing technique at each building in turn; those places where a reduction in cost is observed are im-

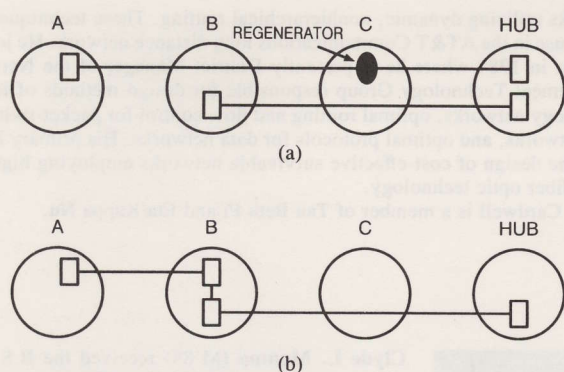


Fig. 12. Remultiplexing at intermediate buildings. (a) Dedicated fiber. (b) Remultiplexing at B.

plemented. The first method uses a heuristic which orders the search for remultiplexing sites by the cost of the regenerators used by the working and protection fiber spans passing through that building. The second, which is more accurate but much slower, utilizes a combinatorial search to evaluate all alternatives.

V. COMPUTING RESULTS

Results obtained from the Fiber Options software are presented here in the interest of completeness and in order to illustrate the usefulness of these methods. As the majority of this discussion is oriented toward methods rather than results, this discussion will be brief. Other published work [2]–[5] discusses the results of these studies in more detail. The results presented here are obtained using a model of a large metropolitan Local Access and Transport Area (LATA), composed of 36 buildings (of which 20 were special buildings) and containing about 145 000 circuits, which was obtained from a Local Exchange Carrier. Equipment costs, both electronic and fiber, were obtained from vendor price lists and typical fiber installation values. Only equipment first costs are used. These data seem to be typical of metropolitan telephone networks.

Computer run times are always of interest, and we report here on approximate times obtained using the Fiber Options software on an IBM PS 2 Model 80 PC. Various situations for the three modules are reported in Table II. The additional run time for the 1:1 protection case is due to the attempt to optimize the use of multiple technologies (fiber line rates). The heuristic was used for the MLS/F improve solution results. As an added note, it was found that the Bundle module could decrease the cost of the fiber transport network by up to 4.5 percent by using its method of calculating alternate path costs, rather than using a set of reasonable thresholds for all situations.

The second area of interest lies in the topology of fiber networks, the cost of providing survivability, and the sensitivity to the optimization methods used. A single-connected fiber topology was first constructed, followed by a two-connected topology which was engineered using two methods: the first minimizing only the placement cost (denoted OP), and the second considering the total topology cost of fiber placement together with fiber material

TABLE II
FIBER OPTIONS RUN TIMES ON A PC

Situation	Time
Build Solution	1-2 seconds
Add Chords	10 seconds
1-Opt Algorithm	2-3 seconds (consider placement cost only) 1 minute (consider all cost components)
Bundle	21 seconds
Move Option	MLS/F
Compute Dedicated Span Layout	0.2 minutes (1:N protection) 1.9 minutes (1:1 protection)
Compute Network Survivability	0.6 minutes
Improve Solution	0.8 minutes (1:N protection) 5.0 minutes (1:1 protection)

TABLE III
TOPOLOGY COST FACTORS

Cost Component	Single Connected (\$K)	Two-Connected OP(\$K)	Two-Connected OT(\$K)
Placement Cost	721.5	739.5	942.0
Fiber & Repeater Cost	956.4	3446.4	1254.4
Total Cost	1677.9	4185.9	2196.4

and regenerators (denoted OT). The total cost of the fiber network for these cases is shown in Table III.

As can be seen, the cost of a two-connected topology is about 30 percent more than a single-connected topology when the total cost is considered. As will be shown shortly, this cost penalty expressed as a percentage of *total* cost is acceptable. Optimizing only the placement cost is definitely suboptimal as this method results in large fiber material and repeater costs, with a total cost penalty of 91 percent compared to minimizing considering all costs.

The most commonly used architectures were then evaluated for the case of fiber cable cuts which are the most common form of catastrophic failure. Only transport costs are considered; other costs such as hub DCS and lower level multiplexers remain relatively constant and do not affect the result. The base case architecture was single-homing with 1:N protection and no diverse protection routing (SH/1:N). Three diverse protection cases were also evaluated: single-homing with 1:N diverse protection routing (SH/1:N/DR), single-homing with 1:1 diverse protection routing (SH/1:1/DR), and single-homing with 1:N electronic protection and optical switching (SH/1:N/OSW). One additional case was also evaluated which utilized dual homing and rehoming of several buildings to different cluster in an effort to improve building survivability (DH/1:N/DR). The results are given in Table IV.

The term "Surv." refers to survivability, or the percentage of total circuits still working after a failure. As can be seen from the data, the incremental cost of making circuits survivable can be as low as \$12–22 per additional survivable circuit. Since the total cost of a circuit is in the range of several hundred dollars (considering multiplexing to the DS3 level and channel banks), this may be a reasonable cost to pay. This penalty corresponds to a transport cost increase of about 5–12 percent, which is not very large considering the benefits gained. Also, the worst-case building survivability can be increased some-

TABLE IV
TRANSPORT COST/SURVIVABILITY RESULTS

Architecture	Cost (\$K)	Link Surv. (Worst Case %)	ICSR (\$/surv. ckt)	Building Surv. (Worst case %)
SH/1:N	9299	55.46	*	16.3
SH/1:N/DR	9785	83.12	12	21.2
SH/1:1/DR	11006	91.05	33	21.2
SH/1:N/OSW	10438	91.05	22	21.2
DH/1:N/DR	10694	79.33	40	29.8

what, along with the worst-case link survivability, at a cost penalty of about 15 percent. The final decision on what degree of survivability to incorporate lies, of course, with the users of the Fiber Options software.

VI. SUMMARY

Fiber Options is a software package which provides network planners with the flexibility to evaluate multiple fiber network architectures very quickly and easily. The methods used have proven that survivability is affordable, and future networks composed entirely of fiber technology can be made relatively immune to single point failures such as cable cuts.

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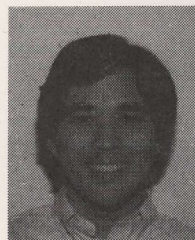


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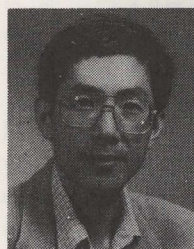
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