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COMMUNICATION NETWORK SURVIVABILITY

by

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Communication Network Survivability

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ABSTRACT

A communication network is composed of communication links and processing nodes. The effective design of a survivable communication network requires a means of determining the structural connectivity of the network both as a whole and with respect to individual resources: links and nodes. In this thesis we represent the connectivity evaluation from two perspectives. The first pertains to considerations applicable to the design schema of the network, and the second deals with an improvement of connectivity in an existing network. We then present and analyze a practical synthetic approach to a communications network's survivability profile by using the example of SACS (the Saudi Arabian Communication System). Finally, we evaluate the difference between the theoretical and practical approaches to survivability.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

A. PURPOSE

The intention of this thesis is to identify and analyze the essential components that contribute to, and produce as the sum of their interrelationship, a profile or quotient of survivability for high-tech military communications networks that will be able to encounter an adversary of roughly equivalent characteristics. In doing so, we hope that we may contribute to a developing theory of survivability that allows systems designers to approach their task with a greater degree of clarity than is currently the case.

B. BACKGROUND

A given military communications network should be able to function along a continuum that extends from the low-stress nature of peacetime to one of intense hostility in the onslaught of full battle engagement. At the peacetime end of the continuum, processing and operations functions are generally considered to be of the greatest importance. In battle, essential functions are compressed into the ability to effect command and control communications under hostile conditions. Of course, both of the above functions are employed at any point along the continuum.

As a general characteristic, we should note that all of the military networks which have access to current electronic technology display an evident progression toward greater complexity. A case in point may be observed through a simple comparison of traditional telephone systems to those currently employed, wherein entire sets of complex and elaborate data are often transmitted over the same modalities simultaneously; still more options are available with the use of either fixed or mobile access.

If a system's functions do not reflect a rigorous application of design and planning, by which alternate routing and the expansion of capabilities are strategically planned, the result may be vulnerability as a by-product of the ever-increasing complexity of an integrated multi-functional network. Yet our reliance upon communications systems has increased along with their complexity.

Since World War I, there has been a virtually exponential acceleration in the lethality of weaponry and the techniques of mobile deployment. This acceleration parallels technological applications of scientific advancement, e.g. machine guns, poison gas, guided missiles, and so on. The resulting combination of greatly enhanced destructive capability and mobility means that lethality may also be accelerated relative to historically prevailing conditions.

The logistical, tactical, and strategic functions of a military unit must be coordinated vis-a-vis the command and control apparatus in order to achieve its goals and potentials. The communications network of that unit is of paramount importance: it represents the physical and electronic transmission and reception of orders by command and control. Thus the capability of a communications network to reconfigure and continue operations within a modern warfare environment is essential to the functioning of the command and control center as a whole.

In light of the previous statements, it is important to note that most of the approaches employed in modern network design are weighted toward specific processing, performance, and cost requirements as their working parameters, rather than a rigorous schematic analysis of basic node and link connections. Under these parameters, systems have been developed in the past which have impressive optimized high processing capabilities, but low quotients of survivability.

C. SCOPE AND ORGANIZATION

We will begin the process of identification and analysis by examining and assessing the substance of connectivity theory (Chapter II). With this approach, we evaluate survivability in terms of a composite measure of how well nodes and links contribute to network configuration. Since the issue of connectivity and its measure is significant in all of the components we will examine, our treatment shall attempt to be as exhaustive and as definitive as possible.

Chapter III will examine a process of enhancing the application of the connectivity measure through the aggregation of additional links, based on their economic utility.

The third part of our data presentation, Chapter IV, will consist of an analysis of the communications network currently being put into use in Saudi Arabia. The Saudi system has been designed assuming a "worst-case" scenario (in other words, that end of the continuum which we described as "full battle engagement"). As such, it incorporates a number of features which are particularly pertinent to our discussion and purpose. At the end of Chapter IV, we shall attempt to establish a relationship between the essential elements which contribute to survivability. Chapter V contains our conclusions and recommendations.

II. CONNECTIVITY APPROACH

A. INTRODUCTION

In the past, military networks have been designed primarily to meet specific organizational and operational requirements. The organizational hierarchy is usually the basis for the network's interconnection structure, and various operational requirements dictate any modifications and/or additions. The communications links follow operational reporting requirements. Limited (if any) alternate routing capability is available. A problem with this type of network is its poor survivability.

The effective design of survivable communication networks requires a means of accurately evaluating their structural connectivity [Ref. 2:p. 4]. In this chapter we will employ two methods for the network connectivity evaluation. The first approach is based upon the graphic connectivity parameters, namely edge connectivity and vertex connectivity [Ref. 1:p. 60]. The second approach is an extension of the first method, with the process involving multiple stages of network decomposition [Ref. 2:p. 3]. This approach quantifies the connectivity by four parameters: NCF (node connectivity factor) and LCF (link connectivity factor) as global measures, and NDI (node decomposition index) and LTI (link tree index) as local connectivity measures which give the individual link/node contribution to the network structures' survivability.

1. Connectivity Evaluation

The first step in the evaluation of a network's connectivity is the conversion of that network to graphic form, which is composed of edges (link) and nodes (vertex). The graph is commonly represented by $G = (N,E)$ where N is a set of vertices and E is a set of edges (links). The graph G is said to be "connected" if there is at least one path between every pair of the nodes in G [Ref. 3:p. 60]. Furthermore, G is said to be "completely connected" if there exists a unique edge (link) between each pair of the nodes in the set N of G. A graph is said to be "disconnected" if it consists of two or more disjoint subgraphs G_k, such that $G = G_1 \cup G_2, ..., G_n$ (implying $N = N_1 \cup N_2, ..., \cup N_n$, $E = E_1 \cup E_2, ..., \cup E_M$ and $G_K \cap G_j$ is empty for all k,j. By definition, each of these subgraphs of G is to be termed a "component" of the disconnected graph G. Two additional concepts, cut-vertex sets and spanning trees, are also of direct importance to the connectivity of Graph G. A node (or vertex) of a connected graph G is said to be a "cut-vertex" at G if and only if its removal from G (along with any edges connected to it) will cause the G to become disconnected. Furthermore, a "minimum cut-vertex set" of G represents the minimum number of nodes and associated edges that must be removed from G to make it a disconnected graph [Ref. 1:p. 75]. A "spanning tree" T of a connected graph G is defined to be a minimum set of edges in G that connect all nodes within the graph without forming any closed paths from a given node back to itself.

- The connectivity [Ref. 1:p. 78] of graph G is measured by two parameters called the edge connectivity and vertex connectivity parameters, defined as follows:

- •• The edge connectivity of a connected graph is defined as the minimum number of edges whose removal reduces the rank of the graph by one where the rank of the connected graph is defined as [Ref 1:p. 72]:

$$\text{rank } r = n - k$$

n is the number of vertices in G.

k is the number of G's components. If $K = 1$, G is connected.

- •• Vertex connectivity is the minimum number of vertices whose removal from G leaves the remaining graph disconnected.

For example, the graph G shown in Figure 2-1 consists of six vertices and nine edges. From the graph shown in Figure 2-1 we see that the minimum edges whose removal causes a disconnected graph are edges (a,b) or (h, k). Therefore the edge connectivity is 2. For the vertex connectivity, we see that the removal of N_2 and N_3 or N_4 and N_5 causes G to be disconnected. Thus the vertex connectivity is 2 in this case as well.

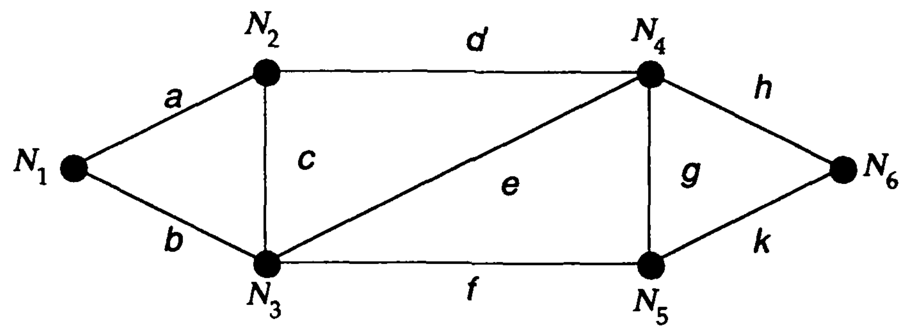

Figure 2-1. Fundamental Cut-Sets of Graph

We can ascertain if the graph is separable by utilizing graph theory.

Definition [Ref. 3:p. 68]

Separable Graph: A connected graph is said to be separable if its vertex connectivity is one.

Suppose we are given n stations that are to be connected by e links where $e \geq n - 1$. What is the best way of connecting the network so that the network is invulnerable to the destruction of individual stations and individual links? We construct a graph with n vertices and e edges that has the maximum connectivity edge and vertex, since the edge and vertex connectivity are the minimum number of edges or vertices whose removal causes a disconnected graph.

For example, given $n = 8$ and $e = 16$, we can have a graph as shown in Figure 2-2, which has an edge connectivity of three and a vertex connectivity of one.

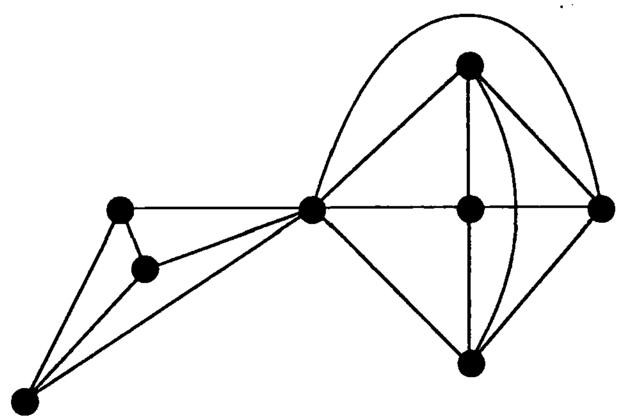

Figure 2-2. Separable Graph

But if we configure the graph as in Figure 2-3, we will have edge and vertex connectivities equal to four and consequently, even after any three stations or three links are destroyed, the remaining stations can still communicate with each other.

Thus Figure 2-3 is better connected than that of Figure 2-2. From graph theory [Ref. 1:p. 65], we see that the highest connectivity we can get is limited to the following equations:

vertex connectivity $\leq$ edge connectivity $< \frac{2e}{n}$

Max vertex connectivity $= \frac{2e}{n}$

Applying these equations to the preceding example, the maximum vertex connectivity $= \left(\frac{2e}{n} = \frac{2*16}{8}\right)$. The preceding approach equates the network connectivity to the likelihood of maintaining communication either between selected node-pairs or until the first occurrence of network disruption due to critical node and/or link losses.

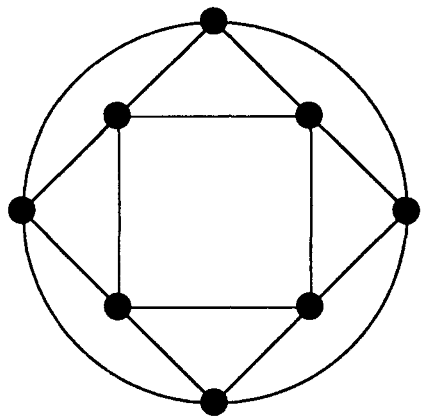

Figure 2-3. Graph with Eight Vertices and 16 Links

The second method is an extension of the above results in equating connectivity quantification to a process involving multiple stages of network decomposition resulting from the loss of link and/or node resources.

The connectivity evaluation of network is quantified for the network both as a whole and with respect to its individual resources (node/link).

Global Connectivity Measure

The overall connectivity level of a network may be quantified by a pair of factors: the node connectivity factor (NCF) and the link connectivity factor (LCF) [Ref. 10:p. 5].

The NCF represents the physical stability of a network in terms of the average number of nodes that must be destroyed in order to force its remaining nodes into a stand-alone configuration. Calculation of the NCF is begun by first determining all possible sequences of critical cut-vertex set removals that could lead to a completely disconnected state. The likelihoods of each of these decomposition sequences occurring, along with the total number of critical nodes removed, are then combined. The NCF calculation is outlined in the following steps:

1. Determine the minimum cut-vertex sets for the first component of graph *G*.
2. Determine the likelihood of occurrence for each potential cut-vertex set.
3. Generate subgraphs resulting from the removal of each possible cut-vertex set and their associated links.
4. Determine if the resulting subgraphs are completely disconnected. Repeat steps 1–3 for those subgraphs which are still partially connected.
5. Compute the component NCF.
6. Repeat steps 1–5 for each component of graph *G*.
7. Compute the composite NCF from component NCFs by summing.

The above procedure produces a decomposition diagram for each component of graph *G* (if the network is not represented as a single graph). The decomposition diagram represents all possible sequences of cut vertex set losses that could result in the complete disconnection of the component.

The computation of the component NCF from this decomposition diagram is defined by the following equation:

$$\mathrm{NCF}_i = \sum_{j=1}^{N_t} N_j P\left(N_j\right) \tag{1}$$

where

NCF_i = NCF associated with component i of graph G

N_j = Number of nodes removed for the j^{th} decomposition path

$P(N_j)$ = Likelihood of the j^{th} decomposition path occurring

N_t = Total paths or leaves formed in the component decomposition tree diagram

The overall NCF for the network is then computed by summation of the individual NCFs for each component.

The LCF represents the electronic stability of the network in terms of the average contribution of each link to maintaining a minimally connected configuration. Calculation of the LCF is begun by determining the total number of spanning trees contained in each component of the network graph. From this the average contribution of any given link to the total number of spanning trees can be calculated. The contribution of each component to the overall network LCF is then determined. The procedure for calculating the LCF of a network involves the following steps:

1. Compute the total number of spanning trees, T, for the first component of graph G.
2. Compute the total number of spanning tree branches in the component by multiplying by $(N-1)$, where N equals the number of nodes in the component. [Note that $(N-1)$ represents the minimum number of links needed to connect the nodes of the component, i.e., the minimum spanning tree.]
3. Compute the average number of spanning trees in the component to which each link in the component contributes by dividing $T(N-1)$ by the total number of links in the component (E). [This represents the component LCF.]
4. Repeat the first three steps for each component of graph G.
5. Compute the overall LCF for the network by summing individual component LCFs, each weighted by a proportionality factor, S_i/S, that accounts for the component's relative contribution to the network's overall link connectivity.

Calculation of the composite LCF for the network is defined by the following equation:

$$\mathrm{LCF} = \sum_{i=1}^{n} \mathrm{LCF}_i \left(\frac{S_i}{S}\right) = \sum_{i=1}^{n} \frac{T_i(N_i - 1)}{E_i} \left(\frac{S_i}{S}\right)$$

where

LCF_i = LCF for component i

S_i = Number of edges in a spanning tree for component i

S = Number of edges in a spanning tree for graph G

T_i = Number of spanning trees in component i

E_i = Number of edge in component i

$\mathrm{N_i}$ = Number of nodes in component i

n = Number of components

Example: given the graph G shown in Figure 2-4, find the global connectivity measures NCF and LCF.

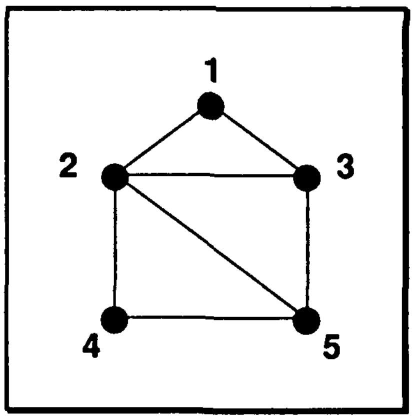

Figure 2-4. Graphic Representation of the Network

- First of all, the graph G has one component, since the it consists of a single connected graph. In this example, one individual component NCF will be computed to form the overall NCF for Graph G.
- The NCF computation procedure generates the decomposition diagram shown in Figure 2-5, as seen at level L_0. Either of the two possible

minimal cut-vertex sets, (2,5) or (2,3), can be disconnected. Removal of these sets results in two possible subgraphs at level L_1.

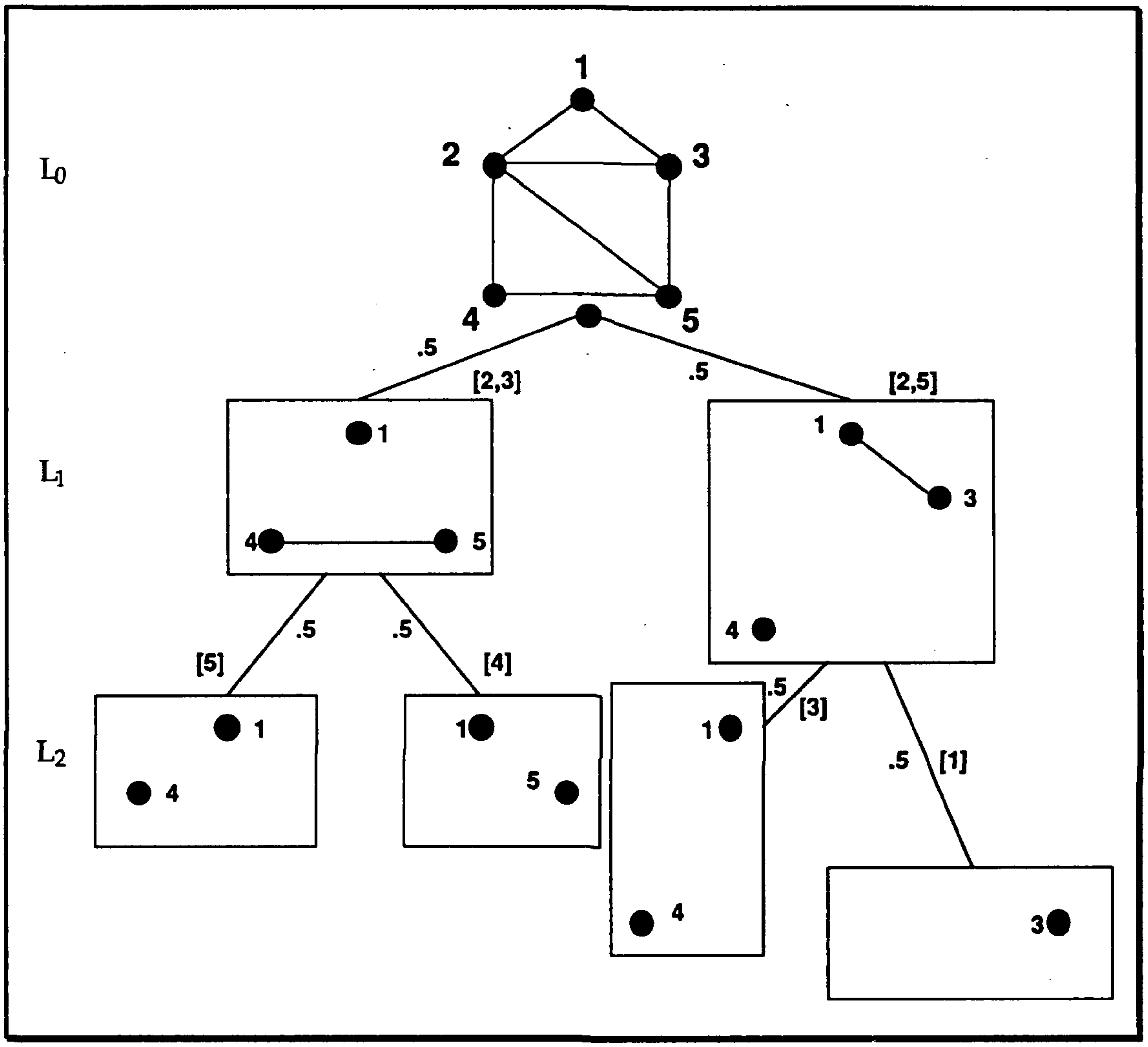

Figure 2-5. Decomposition Diagram

- For this example, the likelihood of occurrence for each of the subgraphs has been assigned a value of .50, representing an equal likelihood of each occurring.
- Both of the subgraphs of level L_1 are now further decomposable, resulting in a set of four possible subgraphs, shown as Level L_2. At this point it can be noted that all of the subgraphs generated for Level L_2 are completely disconnected, defining the end of decomposition diagram.

- Each path in the decomposition diagram from L_0 to level L_2 represents one possible sequence for the complete disconnection of the nodes.
- Each decomposition sequence can be evaluated to determine the total number of nodes that must be removed to cause this disconnection and the overall likelihood of its occurrence.
- For this example, each sequence requires the loss of three nodes and has a likelihood of occurrence of 0.25, resulting in the following NCF calculation for G, using Equation 1:

$$\begin{aligned} NCF_1 &= \sum_{j=1}^{4} N_j p(N_j) \\ &= 3(.25) + 3(.25) + 3(.25) + 3(.25) \\ &= 3 \end{aligned}$$

and in this example the overall NCF = NCF_1 since we have but a single component.

LCF calculation:

$$LCF = \sum_{i+1}^{n} \frac{T_i(N_i - 1)}{E_i} \left(\frac{S_i}{S} \right).$$

Since the graph has but a single component, $\frac{S_i}{S} = 1$. T_i is the total number of spanning trees in the graph, as determined by the following method [Ref. 1:p. 58]. We start with spanning tree T_1 (a,b,c,d) formed from graph G. Then add a chord (say h, to the tree T_1 as shown in Figure 2-7), forming a fundamental circuit. Removal of any branch from the fundamental circuit will create a new spanning tree, T_2. This generation of one spanning tree from another, through addition of a chord and deletion of an appropriate branch, is called a cyclic interchange.

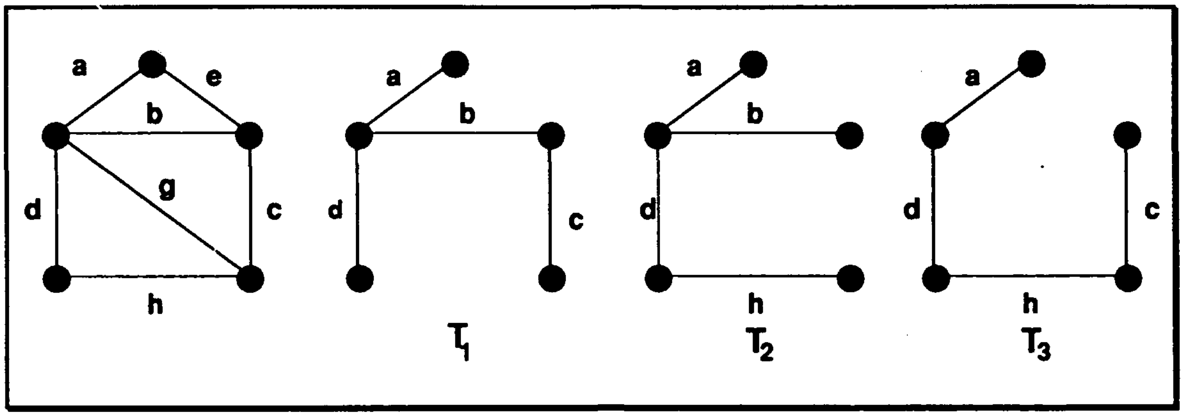

Figure 2-7. Graph and Three of its Spanning Trees

Applying the previous procedure to our example, we find the total number of spanning trees = 21 as shown in Figure 2-8, and $E_i = 7$, $N_i = 5$, $\frac{S_i}{S} = 1$.

$$LCF = \frac{21(5-1)(1)}{7} = 12$$

Local Connectivity Measures

The individual values assigned to each node and link determine the best network structure to generate. The importance of these individual nodes and links is quantified through the node-decomposition index (NDI) and link tree index (LTI) [Ref. 11:p. 6].

An NDI for each node in a network can be determined from the decomposition diagram generated during the computation of the global NCF value. A computation of the exact number of appearances of a given node in each of these decomposition paths is particularly significant. Such a

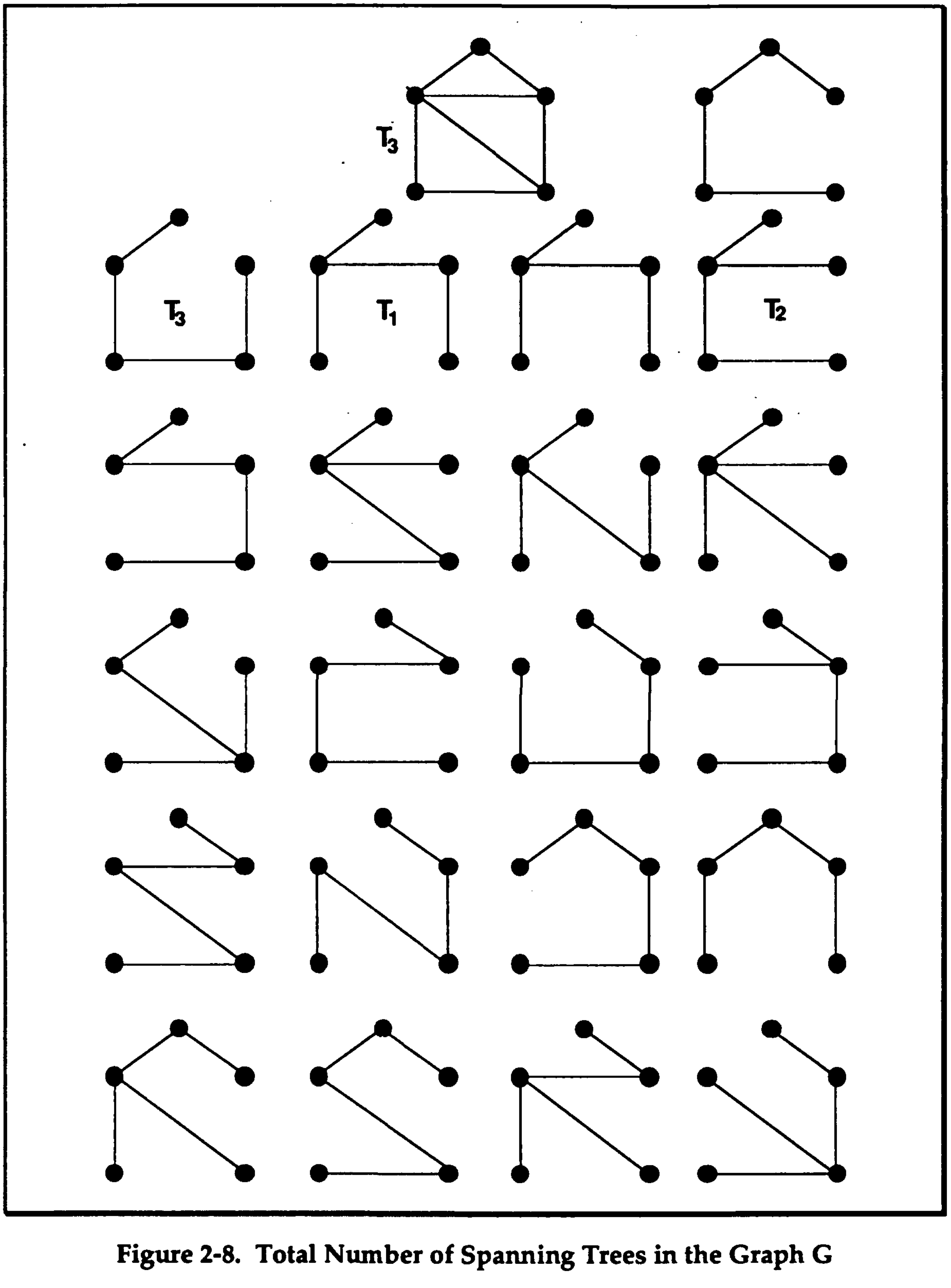

Figure 2-8. Total Number of Spanning Trees in the Graph G

computation provides a measure of the relative importance of each node to the network's connectivity by determining the degree to which that node contributes to the network decomposition process. The degree to which a given node contributes to the decomposition process is related to the total number of decomposition paths in which it occurs. Since N_j can vary from path to path, the percentage contribution C_i^n of a node n to paths of length K_i in the decomposition tree is weighted by the cumulative likelihood W_i. K_i is the number of different lengths of paths. For example, in Figure 2-9, $k_i = 1$ since all paths have length 2. The summation of these weighted contributions for all unique path lengths K_i produces a node decomposition index of node n, defined as $ND(n) = \sum_{i=1}^{m} C_i^n W_i$ where

m = number of unique path lengths K_i

C_i^n = percentage of decomposition paths of length k_i containing node n

W_i = cumulative *likelihood* of a path of length K_i occurring.

Example: to determine the NDI (node decomposition index) for the previous example. The decomposition diagram is shown in Figure 2-9.

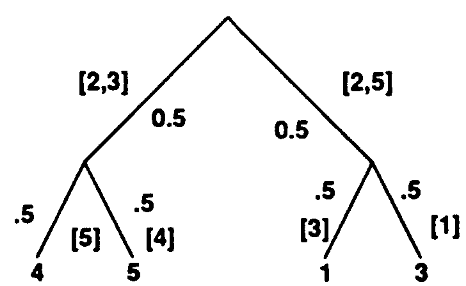

Figure 2-9. The Graph Decomposition Diagram

From Figure 2-9 we see that we have four paths of length 2; the total number of nodes in each path is 3; and we have one unique path length 2. Combining the $P(N_j)$s for each of the 3-node paths results in a cumulative likelihood weight $W_1 = 0.25 \cdot 4 = 1$.

Next, the percentage contribution C_i^n of a node n must be computed for each path of length 2. For example, node N_2 occurs in all four paths of length 2, resulting in:

$$C_1^{N_2} = \frac{4}{4} = 1.$$

Substituting the cumulative likelihood weights and the node percentage contributions into the ND(n) equation:

$$\mathrm{ND}(N_2) = C_1^{N_2} \cdot W_1 = 1 \cdot 1 = 1$$

Node N_1 occurs only in one path out of the four paths of length 2, resulting in:

$$C_1^{N_1} = \frac{1}{4} = .25$$

$$\mathrm{ND}(N_1) = \frac{1}{4} \cdot 1 = \frac{1}{4}.$$

Similarly, $\mathrm{ND}(N_4) = \frac{1}{4}$, and $\mathrm{ND}(N_3) = \mathrm{ND}(N_5) = \frac{3}{4} \cdot 1 = \frac{3}{4}$.

Note that the maximum ND value for a node is 1. A higher ND value indicates the higher importance of that node. The LT index for a link j has been defined to represent that link's proportional contribution to the total number of spanning trees in the network. The LT index is defined as:

$$\mathrm{LT(J)} = \frac{T_j}{T_s}$$

where

LT(J) = link tree index associated with link j

T_j = number of spanning trees containing link j

T_s = total number of spanning trees.

Determination of an LT index for a given link is performed by first removing the link from the network and computing the number of spanning trees in the remaining network. The difference between the initial number of spanning trees and those remaining after removal of the link represents the number of spanning trees to which that link contributes.

For example, from the computation of LCF we know the total number of spanning trees. The total number of spanning trees for the graph shown in Figure 2-10 is equal to 21. Now, if we remove link a, i.e., Figure 2-11(b), we find the total number of spanning trees in the remaining graph is equal to 8. Thus the number of spanning trees to which that link contributes is 21 − 8 = 13.

$$LT(a) = \frac{13}{21} = .619.$$

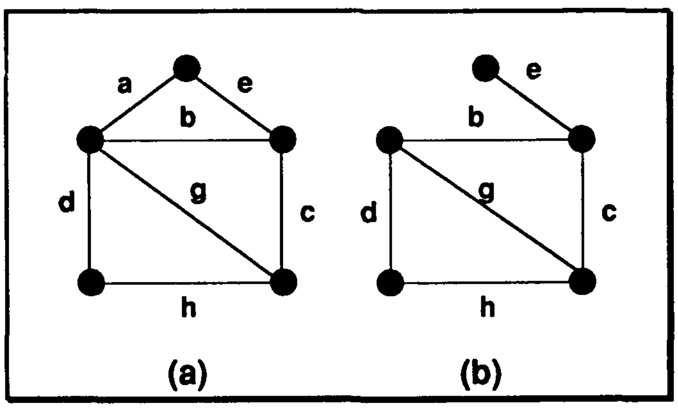

Figure 2-11. (a)—The Structure Before Removing any Links; (b)—After Moving a Link

We can determine the other link tree indices using a similar method. The connectivity values for the example we examined are shown in Table 2-1.

TABLE 2-1. CONNECTIVITY VALUES

NCF = 3		LCF = 12	
n	ND(N)	j	LT(J)
N_1	1/4	a	.619
N_2	1	b	.619
N_3	3/4	c	.714
N_4	1/4	d	.714
N_5	3/4	e	.619
		g	.619
		h	.714

Figure 2-12 displays the same information as Table 2-1: the ND and LT indices computed for the example. The ND indices indicate that N_2 is the most critical node for the topological survivability of the network. In contrast, the loss of nodes N_1 or N_4 would have minimal impact on network connectivity. The LT indices indicate that the loss of links marked with c.d.h. would result in the greatest decrease in spanning trees; thus these links would be most likely to be targeted by the enemy.

Once the connectivity measures have been determined, the network designer utilizes the values to generate the number of network configurations. He attempts to optimize the global values by relocating links with low LTIs to positions linking nodes of low NDI, repeating the process until global values are at their highest possible level.

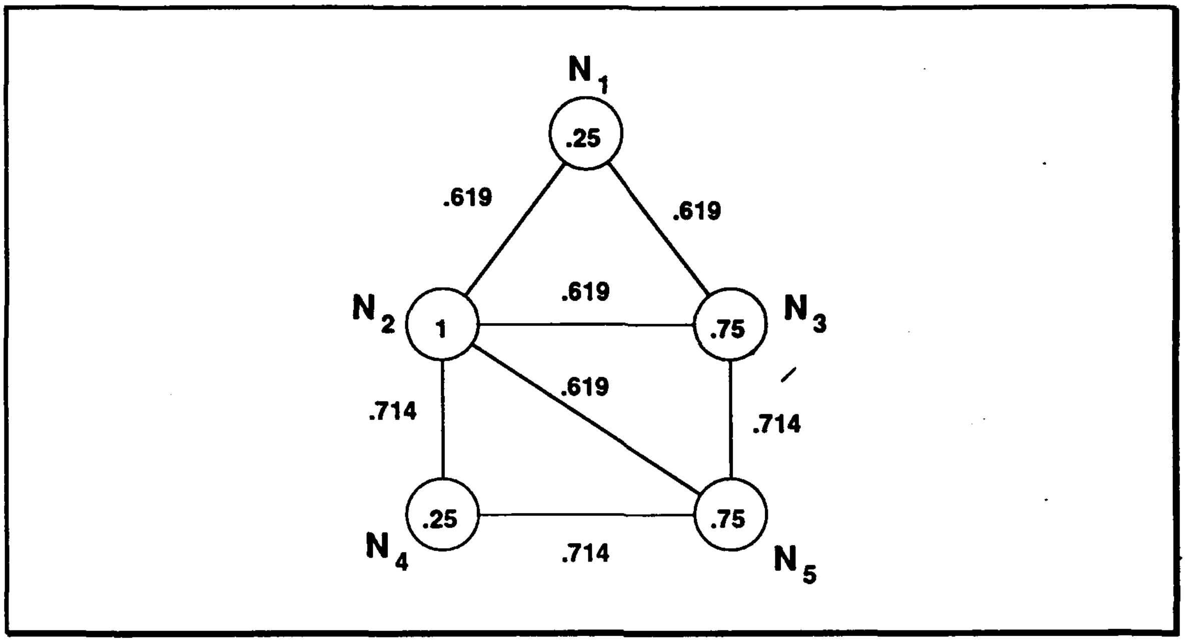

Figure 2-12. ND and LT Indices

2. Discussion

Any evaluation of the relative merits of the two approaches represented in this chapter must focus on two factors: first, their distinctive levels of complexity; and second, the practical limits involved in the effective utilization of abstract models in specific applications for network objectives.

To that end, it must be kept in perspective that human factors (that is, the ability of the cognitive process to identify, evaluate and employ such models to reasonable advantage within an environment of hostile engagement) ultimately become the determining factors of the limits and applicability of a network.

The first approach discussed in this chapter could be typified as being highly favorable in its interaction with the human factor components, in the sense that its theoretical utilization is capable of producing a rapid and readily understandable model of network connectivity. Nonetheless, the theoretical simplicity that makes this approach easy to apply is also its greatest deficiency. The first approach does not give specific indications of the contributive value of each individual node/link to the overall systemic connectivity. Because of this lack of specific indications, the first approach's operational value must therefore be consigned to a category of limited and only general applicability. It is favorable in regard to human factors, but deficient in terms of the power of its theoretical projections.

The second approach is a far more powerful theoretical tool as far as the product of its projections. Utilizing this approach is not only capable of generating the total number of connectivity configurations within a given system, but can also provide a value indicator for the contribution that each individual node/link makes within the system as a whole. With this identification of the critical or essential connections within a system, the system can then be (A) effectively and efficiently protected by an appropriate concentration of security around the critical connections (defensive mode) or (B) disabled with a minimum expenditure of resources by "surgical" destruction of the crucial node/links (offensive mode).

Taking into account the obvious theoretical superiority of the second approach, there remain several features that render its use cumbersome and only marginally effective when employed within realistic operative parameters. In order for the second approach to provide meaningful results, it must be thoroughly applied, that is, every calculation must be completely carried out. For the NCF computation, the minimum cut must be projected out from the likelihood of each potential cut-vertex set in order to generate the decomposition diagram. The LCF computation requires the determination of the total number of spanning trees contained within the graph. The complexity and extensiveness of both the NCF and LCF calculations poses significant problems for thorough application as the number of nodes grows larger.

The second approach may then be characterized as requiring significant expertise, highly accurate data input, and sufficient time and capacity to arrive at meaningful conclusions, especially as the number of nodes grows larger. We shall now consider a method by which an analytical understanding of the cost-effectiveness of internal linkage, or connectivity and its potential enhancement, may be achieved or evaluated, an important criterion in connectivity design approach.

III. LINK ENHANCEMENT

A. INTRODUCTION

We shall now introduce a specific application of another factor in the survivability profile: link enhancement. Though link enhancement is clearly an adjunct function of connectivity, its introduction as a theme in our study provides for a progression in our understanding of survivability from the theoretical to the applied.

It has been definitively shown that the problem of link enhancement is NP-complete and that BGH (Best Group Heuristic) algorithms [Ref. 13:p. 2] can supply the same solution as the optimal algorithm in 80% of its applications. In this chapter we will restate the algorithms and introduce an improvement in the methodology used in the search for the optimal solution. We shall also illustrate a method of utilizing the BGH algorithms in which the results duplicate the optimal solution with a frequency of occurrence greater than 80%.

B. LINEAR SEARCH ALGORITHMS

A communication network can be thought of as a graph G(N,E), where N are the vertices (nodes) and E are the edges (links). Suppose we have a table consisting of tuples in the form of (i, j, c_{ij}, p_{ij}) where i and j are the node numbers in the network, c_{ij} is the cost to establish the link between nodes i and node j, and the value p_{ij} is the contribution of this link enhancement. We are attempting to find a solution for a given investment C such that $\Sigma c_{ij} \leq C$ and Σp_{ij} are maximized. We can describe a generic linear search algorithm as follows. (Step 3 will not be included in subsequent discussions, since its application does not pertain to our objectives.)

1. Select (remove) a link from the set of candidate links; add this link to the current network.
2. $C \leftarrow X - c_{ij}$.
3. Update the network profile, i.e., compute p_{ij} for the new network.
4. Terminate if $C < c_{ij}$ for all links.
5. Go to Step 1.

1. One-way Linear Search Algorithms

There are three variations of one-way linear search algorithms. These three variations differ at Step 1 in the way they select a communication link, producing the feasible solution sets FS_C, FS_P, and FS_R.

To most easily apply the linear search algorithm, we first sort the table in nondecreasing order on the value of c_{ij} and extract the tuples with value of $c_{ij} \leq C$ to form a feasible solution set FS. A traditional optimal solution for the knapsack problem can be calculated by adding a field of $r_{ij} = p_{ij}/c_{ij}$ to each tuple and sorting the list in nonincreasing order of r_{ij}. This new list is designated FS_r, (consisting of tuples of (i, j, c_{ij}, p_{ij} r_{ij})). Without loss of generality, we can assign one link number to each node pair (i, j) to be considered. (Table 3-1 shows only the link numbers instead of node pairs.) Thus, in subsequent discussion, the list FS_r consists of tuples of (k, c_k, p_k, r_k) with k as the link number. Note that the value of r_k effectively measures the contribution per dollar amount. The solution is simply a selection of links from the linear search of the list FSr until C is either exhausted or becomes insufficient. If divisibility is allowed, this linear search algorithm, a solution process based on r_{ij}, gives the optimal solution for knapsack problems.

However, this solution will not give the optimal solution in 0/1-knapsack or link enhancement problems.

TABLE 3-1. EXAMPLE OF 20 LINKS TO BE CONNECTED AND THE CORRESPONDING PROFIT

LINK NUMBER	COST	PROFIT
1	1833	4140
2	1754	3506
3	1246	3819
4	1529	2310
5	2034	3370
6	2568	5276
7	1508	3859
8	1608	4477
9	1691	3269
10	2112	3807
11	1840	3661
12	1960	3560
13	2184	4440
14	2549	2899
15	2254	3643
16	2289	4224
17	1883	4368
18	1682	1922
19	1711	3844
20	1578	3484

From FS we can create two sorted lists, FS_c and FS_p. FS_c is sorted by c_{ij} in nondecreasing order while FS_p is sorted by p_{ij} in nonincreasing order. Similar to the linear search we have just described above, we can perform a linear search of list FS_c and select links one at a time until the budget is exhausted or becomes insufficient. Likewise, we can do a linear search of list FS_p and obtain the selections.

All three one-way linear search methods, i.e., based on FS_r, FS_c, or FS_p, are not optimal. We can easily construct examples that show their limitations. Table 3-2 shows the lists of FS_c, FS_p, and FS_r. Note that in FS_r we have scaled up the ratios into integers for readability at (10^3).

TABLE 3-2. FS_c, FS_p, FS_r

Link Id	FS_c	Link Id	FS_p	Link Id	FS_r
3	1246	6	5276	3	3065
7	1508	8	4477	8	2784
4	1529	13	4440	7	2559
20	1578	17	4368	17	2320
8	1608	16	4224	1	2259
18	1682	1	4140	19	2247
9	1691	7	3859	20	2208
19	1711	19	3844	6	2055
2	1754	3	3819	13	2033
1	1833	10	3807	2	1999
11	1840	11	3661	11	1990
17	1883	15	3643	9	1933
12	1960	12	3560	16	1845
5	2034	2	3506	12	1816
10	2112	20	3484	10	1803
13	2184	5	3370	5	1657
15	2254	9	3269	15	1616
16	2289	14	2899	4	1511
14	2549	4	2310	18	1143
6	2568	18	1922	14	1137

1. Example

We can apply one-way linear search to the problem of Table 3-1. For example, using FS_c alone (see Table 3-2), with a budget of 7000 we can select links {3, 7, 4, 20} and achieve a total profit of 13,472. We designate this set of links S_c (meaning the solution set based on FS_c only). The total profit that is obtained is designated P_c. Similarly, we can verify the following solutions: $S_p = \{3, 6, 8\}$ and $P_p = 13{,}572$, $S_r = \{3, 7, 8, 17\}$ and $P_r = 16{,}523$.

C. TWO-WAY AND THREE-WAY LINEAR SEARCH ALGORITHMS

In place of the one-way linear search methods described above, we can construct a search methodology whereby decisions are arrived at through simultaneous examination of two lists. For example, we may use FS_r and FS_c in conjunction to obtain the selections. Starting the linear search separately on these two lists, one link at a time, we can use a voting scheme to select the proper link. Whenever we encounter a link that has been visited in FS_r or FS_c we increment the counter associate with the link. When any counter reaches a preset threshold value, e.g., 2, we then add this link to the network. The value C is updated by subtracting the c_k of the candidate link. We continue the linear search until the C is either exhausted or becomes insufficient. This counting method is called a voting algorithm since each link accumulates votes from different lists until it obtains sufficient votes. The present threshold in two-way linear search is set at 2, since each link can only receive a maximum vote of 2.

2. Example

In the two-way search based on FS_r and FS_c we obtain the solution $S_{rc} = \{3, 7, 8, 20\}$ and $P_{rc} = 15{,}639$. Other possible methods of two-way linear search are (FS_r, FS_p), and (FS_c, FS_p). However, like their one-way counterparts, these heuristics cannot provide the optimal solution to the link enhancement problems.

To approximate the optimal solution we must add an examination of the three lists combined ($FS_{r,cp}$) to the values produced by the one- and two-way searches. Similar to a two-way search, in three-way linear searches we set the threshold value at 2. Using the two-way and three-way search methods, we obtain the solutions and the corresponding total profit: (1) $S_{rp} = \{1, 7, 8, 17\}$ and $P_{rp} = 16{,}844$; (2) $S_{pc} = \{3, 7, 8, 19\}$ and $P_{pc} = 15{,}999$; (3) $S_{rpc} = \{3, 7, 8, 19\}$ and $P_{rpc} = 15{,}999$.

D. BGH — BEST OF GROUP HEURISTIC ALGORITHMS

All the heuristic algorithms discussed above can be described as "greedy" in nature, in that each sorts the FS in a certain order and the available budget is depleted correspondingly.

Since sorting can be done in O(n log n) time, we can achieve our solution in O(n log n) time. There is, however, no single algorithm that can be shown to consistently produce superior results or outperform the others. Taking this limitation into account necessitates viewing the problem from the perspective of set selection. For instance, we may compute seven sets of solutions, using the algorithms in question, and the simply select the solution from the group that arrived at the greatest value. This process is applied to the data illustrated in Table 3-1, wherein S_{rp} provides the solution of greatest value for $P_{rp} = 16{,}844$. The other solutions of the group, S_r, S_c, S_p, S_{rc}, S_{pc} and S_{rpc}, may then be disregarded. The "best" solution of the group is then designated as the BGH.

Unfortunately, the BGH does not and cannot arrive at the value that the optimal solution provides (the optimal solution of Table 3-1 is $S_{opt} = \{3, 6, 7, 8\}$ with $P_{opt} = 17{,}431$). At a relatively high rate of occurrence, however, the BGH can attain a value that reaches or exceeds approximately 96.6% of the optimal solution (as in this example when BGH is 16,844 compared to an optimal solution of 17,431.)

Yang summarizes a set of test results where a sufficient number of cases were randomly generated so that C_k and P_k are independent and normally distributed [Ref. 13:p. 8]. A statistical comparison of the BGH solutions and the optimal solutions shows that the BGH solutions near or approximate the optimal solutions so that any distinctions are statistically insignificant in 80% of the cases.

E. IMPROVEMENT TO THE BGH

The improvement alluded to in the introduction consists of a two-part process though each part in and of itself represents a potentially significant improvement to the solution and selection methodologies currently employed.

The first part results from the introduction of an idea and method by which the area of search for the optimal solution is reduced. The imposition of limitations on the search procedure enables a better use of allocations within a given budget while avoiding significant deterioration of end solutions. Employment of this method defines the range of set exclusion as being any set where the sum of the cost of exploration is lower than the given investment or exceeds the given investment. The utilization of this maxim allows us to expend a given budget so that the range of search for possible sets of links in combinations yields the maximum profit (as previously defined).

- The upper limit (UL) = $\frac{\text{budget}}{\min C_K}$, where the budget is the given investment and min (C_K) is the minimum link cost.

- The lower limit is defined by (LL) = $\frac{\text{budget}}{\max(C_K)}$, where max (C_K) is the maximum link cost.

The reduced search range for problem size n will always be less than 2^n of possible sets and the exact parameters of exclusion will be determined by the quantity of the given budget.

Using the limited set search method described above, we were able to reduce the time frame of a search in the sets of the optimal solution algorithm 2^{20} by more than 38% in the case of Table 3-1. The first search, conducted without the constraints of limitation, required 48 hours of PC/AT time before the correct set discovery was accomplished. The second search, conducted as a limited range search on the same PC/AT, accomplished the correct set result in 27 hours. A simple comparison of area shows that the reduction diminished from an original of 2^{20} to an area of only $C_6^{20} + C_5^{20} + C_4^{20} + C_3^{20} + C_2^{20}$, since UL = 6 and LL = 2 for Table 3-1.

The second part of the improvement process displays a methodology wherein the area of search is reduced much further by utilizing the concept of limited range search. This search acts upon the set of most preferred candidates produced by the BGH solution, the best of the set of one-way, two-way, and three-way searches, which produces a minimum threshold of 80% maximum profit. We then construct a table displaying costs and profit that is comprised solely of the set union of the first sample. The limited range reduction maxim is then applied to the existing sets, followed by the application of the optimal solution algorithm (exhaustive search) to the refined sets.

Since each of the sets now undergoing exploration has an 80% basal probability of providing the correct solution and the gross number of sets undergoing exploration has been dramatically reduced, the search should conclude its exploration in a highly condensed manner.

Example.

The following results were collected from Table 3-1.

$FS_c =$ {3, 7, 4, 20}, $P_c = 13{,}472$

$FS_p =$ {3, 6, 8}, $P_p = 13{,}572$

$FS_r =$ {3, 7, 8, 17}, $P_r = 16{,}523$

$FS_{cp} =$ {3, 7, 8, 19}, $P_{cp} = 15{,}999$

$FS_{rp} =$ [1, 7, 8, 17}, $P_{rp} = 16{,}844$

$FS_{rc} =$ {3, 7, 8, 20}, $P_{rc} = 15{,}639$

$FS_{rpc} =$ {3, 7, 8, 19}, $P_{rpc} = 15{,}999$

Now, by establishing a set union from the results, we have clearly identified the most preferential candidates to provide the optimal solution {1, 3, 4, 6, 7, 8, 13, 17, 19, 20}. An application of the optimal solution algorithm search within the resulting set will now require an exploration of the magnitude of 2^{10} instead of 2^{20}.

The PC/AT computer that was used in this experiment was able to arrive at the correct result in 20 minutes as opposed to the original search time of 48 hours. (It is important to note that the same optimal solution was found in both cases).

In an informal regime of experimentation, we found that, with one exception, the derivative results of this methodology were consistently correct and reproducible. However, the one exception suggests that more thorough and formal experimentation and data analysis is called for before the methodology can be unconditionally adopted.

F. DISCUSSION

A process of link enhancement and a detailed analysis of its potential, when applied to almost any existing communications network, would unquestionably add to its potential of survivability. The end product of the enhancement can be seen as a two-fold phenomenon. The first result may be an enlargement of an analytical understanding of the expansion capacity of any given system. The second could well create a number of additional configurations which, when added to the original plane of the network, produce significantly greater routability and connectivity.

Since link enhancement is accomplished through physical installation, and installation assumes not only original costs but also continuing maintenance, it must be evaluated in regard to its practical achievement by a set of economic criteria. To date, the optimal solution, achieved through means of an exhaustive search, in whatever the format of its application, is the only known method of identifying the specific link enhancement strategy that can yield the optimal product for a given investment.

The optimal solution exhaustive search method applied in an unmodified format is a rather unwieldy device. Its consumption of time and budgetary allocations are substantive enough that employment of the method to find economic utility in link enhancement becomes especially important in that the greater the measure of time required to establish possible configurations of link enhancement, the lower the responsive capacity of a given system to reconfigure or reconstruct in the event of tactical emergency.

The above considerations have led us to seek to construct or develop the methodological improvement presented in the body of this chapter. The results of our efforts could be most briefly summarized by simply asserting that the process of link enhancement can be greatly economized in regard to both money and time if the BGH is used in a format of limited search, and the process apparently results in the same solution as would otherwise be achieved with an unmodified exhaustive search.

Though much more thorough testing will be required to refine and qualify the application of the approach, it appears that the theory of the improved method and its tentative results, contain the potential for significant progress in practical applications of link enhancement.

We have thus far considered two approaches to connectivity analysis and a process of link enhancement as a practical improvement affecting the application of connectivity evaluation. We shall now seek to enlarge the set and perspective of identifiable components directly pertinent to the parameters and objectives of survivability.

IV. THE SURVIVABILITY APPROACH OF THE SAUDI ARABIAN ARMY'S TACTICAL COMMUNICATION NETWORK

In the preceding chapters we have presented and discussed two theoretical models for measuring systemic connectivity, and a means of enhancement that essentially equate connectivity with the survivability of a given system. In this chapter we shall offer a detailed description of a system which has been derived from experiential usage (rather than a purely theoretical model) and which is specifically adapted to a known set of environmental factors.

Through empirical observation and innate knowledge of the given parameters of the operational theater, the designers of this system have chosen not to focus on an abstract measure of connectivity as the chief determinant of their system design. Rather, they have developed an approach to the objective of survivability that is focused on the dynamic responsivity of the system.

Time and accurate data input are always the twin demons facing engineers as they struggle with network configuration and re-configuration. SACS (the Saudi Arabian Communication System) has been designed to squarely address these critical and problematic issues through the structural placement of features which make the system essentially self-organizing.

Saudi Arabia is currently in the process of replacing their traditional Army multichannel network with SACS. The new system integrates the functions of transmission, switching, control, COMSEC, and terminal equipment (both voice and data) into one system. This provides the user with a switched telecommunications network that is extended through the use of mobile radio telephones and wire access.

The basic architecture of SACS has been designed to effectively support the communication needs of a division [Ref. 9:p. 27].

In addition to the feature of self-organization, we shall also discuss flexibility/adaptability and ECCM capabilities as structural components of SACS.

A. SYSTEM DESCRIPTION

Based on the nominal range of the radio relay equipment and of the mobile subscriber radio terminals, the system [Ref. 8:p. 20] is comprised of four trunk nodes and eight radio access centers (RACs) which provide service for all fixed and mobile subscribers within the brigade area. Additionally, two more trunk nodes as well as two more radio access centers are held in reserve to augment network flexibility and ease of reconfiguration in the event that their additional capacity is required. Figure 3-1 shows the system network which ensures that 100% of the area is within 25 km of at least one trunk node. Therefore, the system provides 100% connectivity to the wire users in all the command posts of the brigade, and all mobile subscribers are within range of at least one radio access center. More than 50% of these mobile subscribers are within range of at least two radio access centers, thus greatly increasing the potential of survivability.

The primary equipment components used in the construction of the system are integrated into the following six categories of function: area

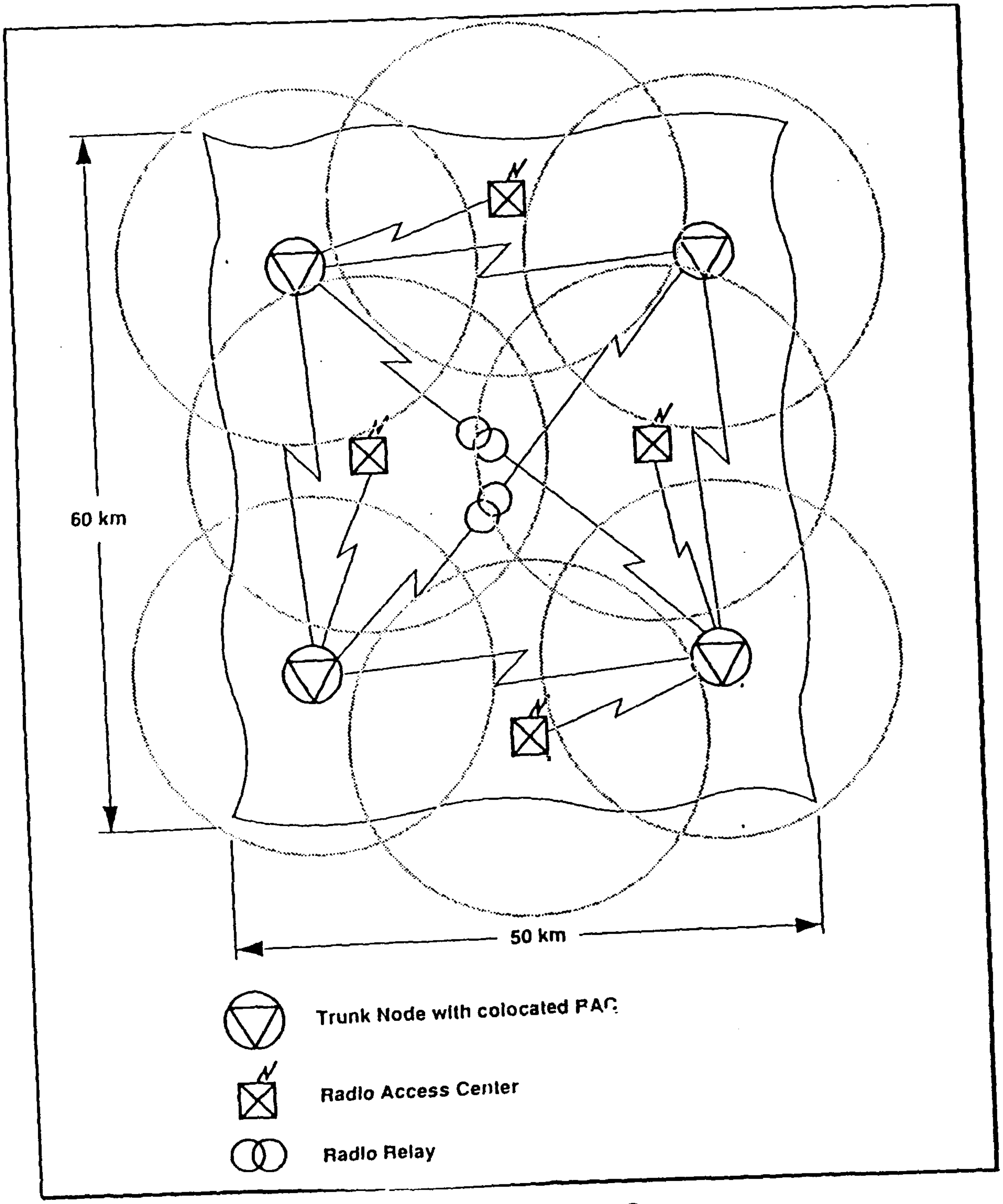

Figure 3-1. Brigade Area Coverage

coverage, wire subscriber access, mobile subscriber access, subscriber terminals, external network access and system control. (An overview of the relationships among these functions is summarized in Section B.)

1. SACS Area Coverage Function

The area of functional coverage is comprised of, and its limits defined by, two types of tactical elements: the trunk node (TN) and the radio access center (RAC). At the trunk node location are a trunk node switch and six line-of-sight (LOS) assemblages. Each radio access center is composed of one radio access unit (RAU) and one LOS assemblage, although one radio access center is normally colocated with each of the trunk nodes of the system, as shown in Figure 3-2. The primary features of the trunk node switch (TNS) are as follows:

- Automatic processing of affiliation/reaffiliation of mobile and wire users.
- Called subscriber searched through flood search technique.
- Twelve encrypted digital transmission groups operating at 512 kbps.
- Dial-up interface to the SCC. The radio access unit is enhanced by a switching device which provides the RAU with a stand-alone capability. Each RAU provides eight full-duplex, 16 kbps digital interfaces between the network and up to 20 mobile subscribers and operates in the whole VHF military band (30-38 kHz) using a high/low band concept for optimum performance.

2. SACS Wire Subscriber Access

Access to the area system for wire subscribers at the headquarters is provided by the large extension node, which comprises an extension switch and LOS assemblage. The latter allows the large extension node (LEN) to connect with two different trunk nodes for increased survivability.

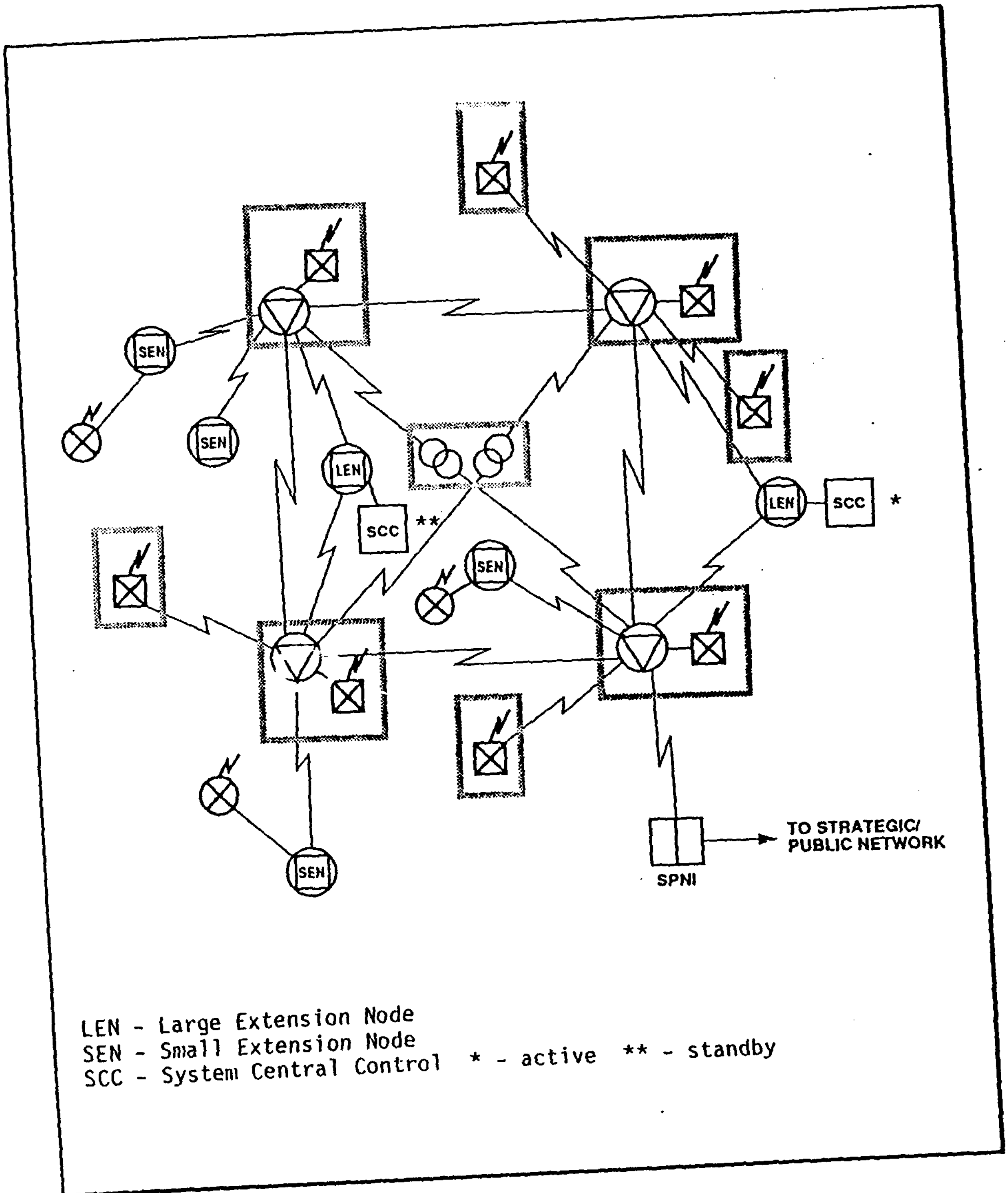

Figure 3-2. SACS Area Coverage Configuration

Access to the area system for wire subscribers at the battalion command post is provided by the small extension node (SEN), which is comprised of an extension switch and an LOS assemblage. Since the SEN is normally connected to the system backbone through one LOS link, another LOS terminal remains available and may be utilized as a flexible component (for instance, to establish a connection with a combat net radio interface). Both the LEN and SEN switches are capable of processing tandem calls, thus greatly increasing the overall survivability of the network.

3. SACS Mobile Subscriber Access

The mobile subscriber accession function is implemented through the use of a mobile subscriber radio telephone (MSRT). MSRT is an automatic radio set which provides for a total integration of the mobile user into the SACS network. Figure 3-3 shows a different mode of operation of which MSRT is capable. Some of the key features of MSRT are:

- Automatic affiliation through whichever REC offers best transmission path.
- Automatic selection of an interference-free channel among the available frequency plan.
- Automatic power/receiver sensitivity adjustments to minimize enemy detection and interference.
- Full-duplex, 16 kbps digital link to the MSRT's parent RAC.
- Direct MSRT-to-MSRT call capability to other MSRTs within radio range.

4. SACS Subscriber Terminals Function

SACS incorporates various types of user terminals in order to provide voice, data and facsimile services. For enhanced survivability, the interfaces are fully compliant with CCIT standards.

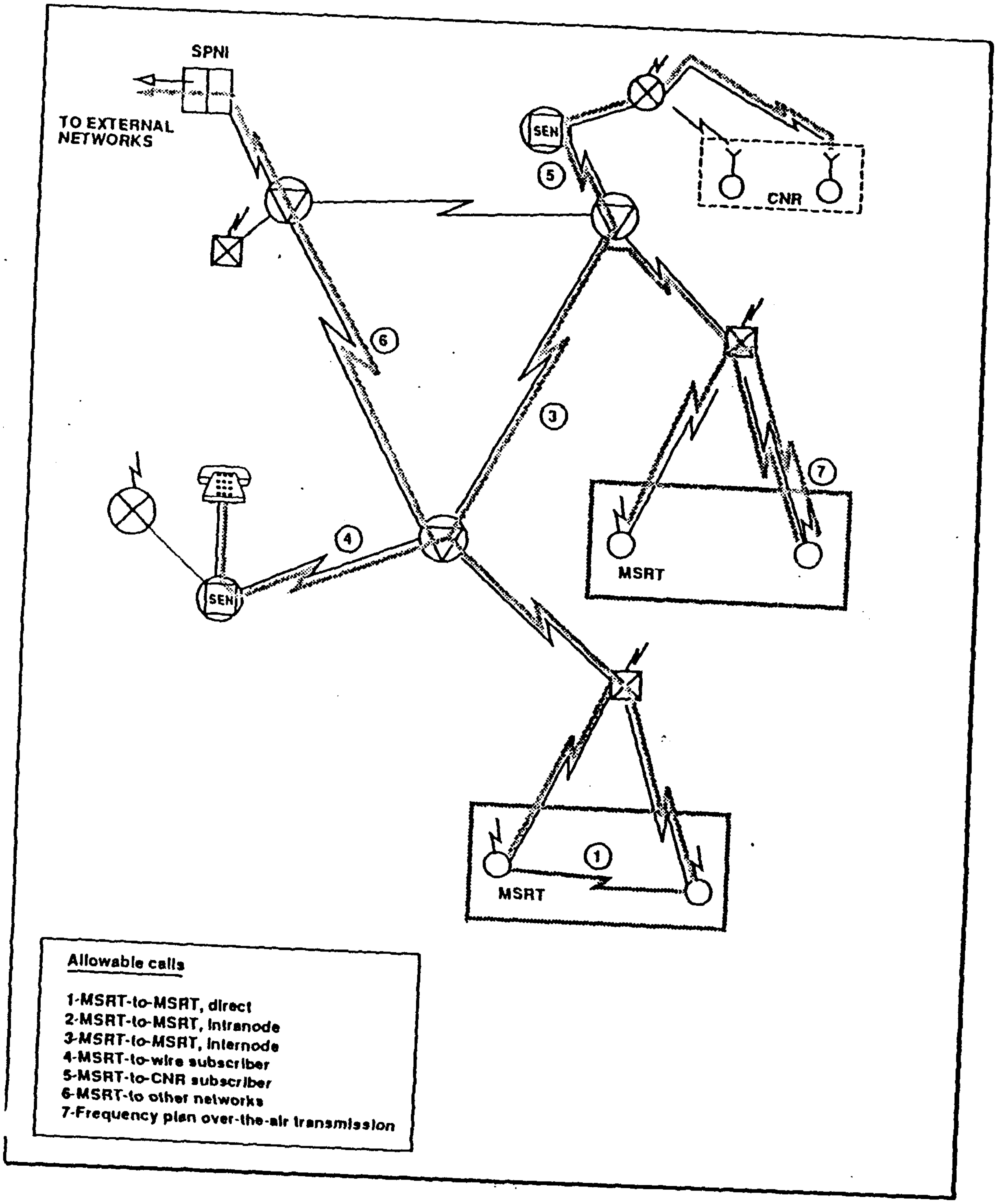

Figure 3-3. Mobile Subscriber Access Function

5. SACS External Network Access Function

A structural provision for interoperability between the system and other communication systems has been built into SACS. The external network access function is comprised of two types of tactical elements: combat net radio interface (CNRI) and the strategic and public network interface (SPNI).

The combat net radio interface is normally colocated with a small extension node, with which it may be connected via a fiber-optic cable. CNRI can interface with one or several types of combat net radios operating in different bands (VHF, HF, UHF).

The strategic and public network interface is composed of one external network interface unit and one LOS assemblage. The LOS assemblage allows us to install an element where an interface points to the availability of either a strategic or public network and subsequently establish a link between the external system and the nearest trunk node.

The SPNI switch is configured to support eight individual interfaces, which can be connected to any compatible network in any combination.

6. SACS System Control Function

The system control center (SCC) is the heart of the self-organizing SACS system and enables the signal commander to manage and control the communication assets that make up the system. The SACS has two system control centers (SCC), one in continuous activation and another preserved in a status of standby readiness, thereby insuring maximum survivability of the network control function. The SCC enables the signal commander to plan, reconfigure, and monitor the operations of the other functional areas of the SACS.

The SCC has the following operating features:

- Automatic planning and direction of the SACS network configuration and reconfiguration, including:
  - •• Area network activation, deactivation, and reconfiguration.
  - •• Transmission link activation and deactivation.
- Automatic frequency management of LOS radio terminals.
- Equipment status follow-up.
- COMSEC key management [Ref. 9:p. 77] for data security.
- Frequency coordination of RF frequencies used by both the mobile radio access subsystem and the combat net radio interface subsystem.
- Automatic dial-up interface to all the elements of the system.

B. THE SYSTEM'S FUNCTIONAL RELATIONSHIPS

The relationships between the six functional areas of SACS [Ref. 8:p. 59] are shown in Figure 3-4. This figure illustrates the vital ability of the SACS system in terms of network reconfiguration capabilities.

- The large extension nodes and the small extension nodes are normally connected to the trunk nodes, but in case of emergency, they can be connected to the radio access centers, significantly extending the coverage of the area network.
- The tactical elements that constitute the external network access function can be connected to virtually any other element of the network.
- The system control function has direct access to all the elements of the network, thus making it possible for the signal commander to directly control all the assets of the network.

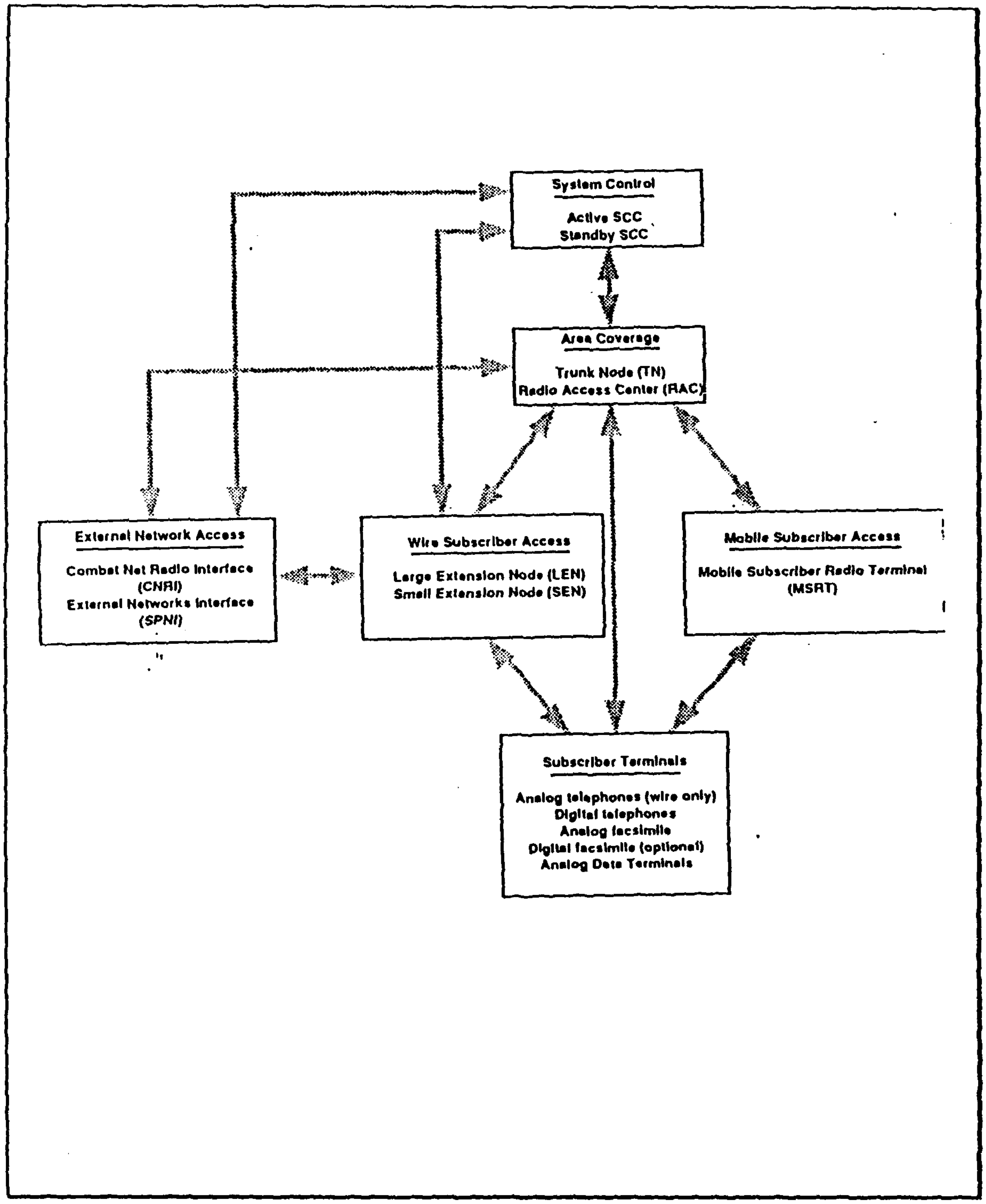

Figure 3-4. SACS Functional Area Relationships

C. SACS SURVIVABILITY

The SACS network has been designed to extend the concept of survivability to include the capability to continue its function in an intensely hostile environment without suffering a significant disruption of service. The capability of the system to function in this manner stems from the following features:

- system self-organization
- flexibility/adaptability
- ECCM features

1. System Self-Organization

a. Network Configuration and Reconfiguration

The tasks of network planning and engineering are more often than not inordinately time consuming, and consequently have a dramatic effect on network configuration and reconfiguration. The SACS system, through the structural emplacement of inherent capabilities, as shown in Figure 3-5, provides for dynamically self-organizing operation, thus considerably reducing the effect that planning and engineering tasks would otherwise have.

- The use of fixed directory numbers not only makes it easy for the SACS subscribers to place calls but also eliminates the need for maintaining directory tables in each switch of the network.
- The subscriber database contains the directory number of each subscriber of the network along with its classmark profile, which defines the services to which a subscriber can gain access. The entire subscriber database is contained in all the switches of the network and is automatically updated in case of displacement of a subscriber, thus eliminating the need for database manipulations in case of network reconfiguration.

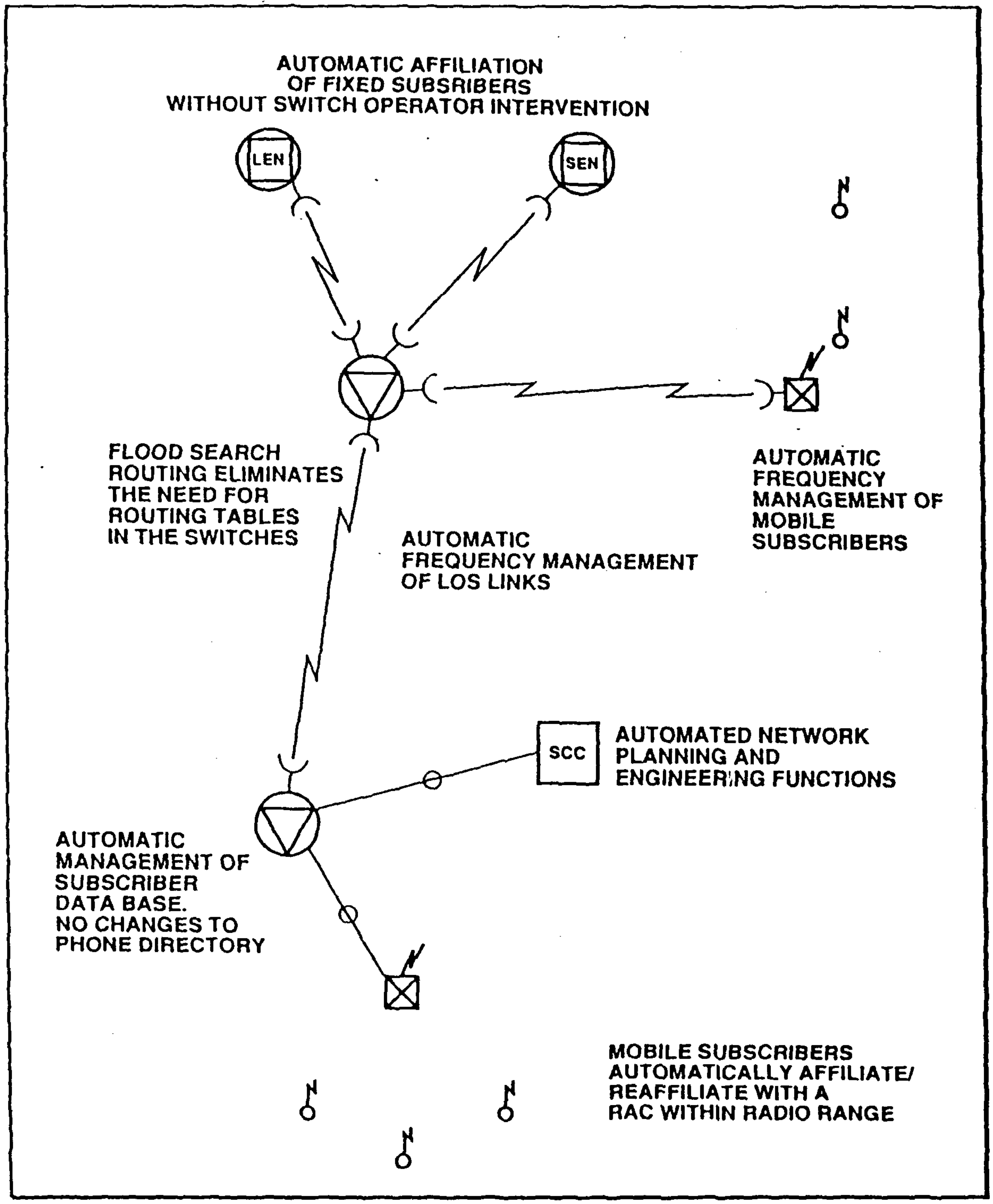

Figure 3-5. SACS System Self-Organization

- Automatic affiliation of wire subscribers as well as mobile subscribers is a key ingredient in making the system self-organizing [Ref. 8:p. 71]. This operation logs the subscriber into the network, assigns the appropriate classmarks for basic telephone services and makes the system aware of his location until he moves. A wire subscriber or CNR subscriber must affiliate each time he connects to the network and disaffiliate when he leaves the network. However, if he neglects to disaffiliate when he leaves the network, the system automatically updates the subscriber database when he reaffiliates with the network. A mobile subscriber using an MSRT is only required to activate his radio set upon power up. His equipment automatically affiliates and reaffiliates when he moves from the coverage area of one RAC to another.
- Flood search is the means by which the system determines a route between a calling and a called subscriber, regardless of network traffic, jammed transmission links or inoperable switches. In addition to considerably increasing the survivability of the network, this technique eliminates the need for maintaining routing tables as would be the case with the deterministic routing technique which is used in most networks.
- All network engineering functions are performed at the SCC which provides the computer-assisted tools required for:
  - automated planning of the deployment of the network
  - automatic network activation and deactivation
  - automatic frequency management of the transmission links
  - equipment status follow-up
  - COMSEC management
  - radio subsystem frequency management
  - automatic updating of the switch databases

These capabilities enable the Signal Commander to efficiency plan, configure and monitor the operations of the network.

b. Call Routing

All the subscribers of the SACS system, whether fixed or mobile, can initiate and receive traffic on a discrete address basis, i.e. a subscriber can initiate a call knowing only the desired party's directory number. Within the

SACS system, the calling subscriber needs only to dial seven digits plus an optional precedence digit to initiate a call. For calls to the Saudi Strategic and Public Networks, up to 13 digits can be dialed, depending upon the exact characteristics of the called subscriber's location.

If the directory number of the called party is found in the database of the switching equipment servicing the calling subscriber, it is a local call. The call is then automatically routed to the desired party and is established based upon the classmarks of both the calling and called parties. The called subscriber is preempted if necessary, depending upon the precedence level dialed by the calling subscriber.

If the directory number of the called party is not found in the database of the switching equipment servicing the calling subscriber, a flood search is initiated to locate the called subscriber. Figure 3-6 depicts the phases involved in routing a call through the SACS system:

- Search Phase. The switching equipment servicing the calling subscriber (switch A) first broadcasts a search message to all connected switches of the network. Each switch receiving this message (switches B and C) examines its subscriber database for the called directory number. If the called party is affiliated at that switch, the switch immediately initiates the return phase described below. If the called party is not affiliated at that switch, the search message is forwarded to all other connected switches (D, E, F ...). During this phase, each switch keeps track of the transmission link over which the first search message was received.
- Return Phase. The terminating switch (switch I) where the called party is affiliated sends a return message back toward the originating switch over the marked routing path (switches H, G, C), as shown in Figure 3-6b. This message reserves a channel on each traversed transmission link for further call setup, based on the precedence level of the call contained in the search message.

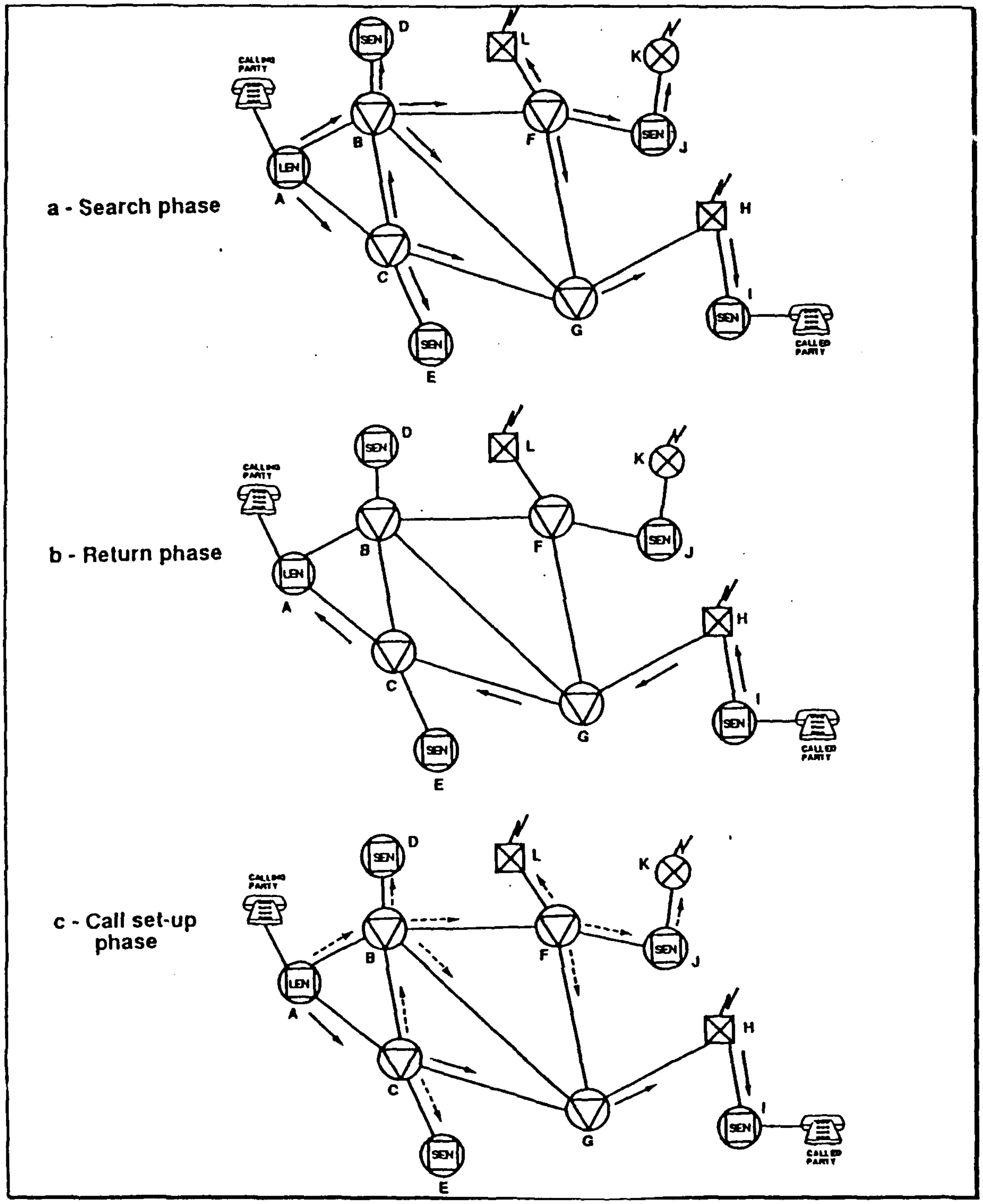

Figure 3-6. Flood Search Routing

- Call Setup Phase. Upon receipt of the return message, the originating switch broadcasts an end-of-routing message to all connected switches as depicted in Figure 3-6c. This message is progressively forwarded to all the switches of the network in the same manner as the search message. Upon receipt of this end-of-routing message, all the switches not involved in the return phase (B, D, F, J, K, L, E) clear their routing registers for that call attempt, while the switches involved in the return phase set up the call via the reserved path.

Restrictions are imposed on the broadcast of search messages to ensure network-wide traffic regulation, to provide for call precedence during route selection, and to avoid possible congestion of the switching equipment of the network.

In addition, the flood search function is programmed to automatically route calls around any blocked links or incidences of partial network destruction, providing for dynamic reconfiguration of the system. Figure 3-7 is a network diagram depicting automatic routing around blocked links and a destroyed node. Under normal circumstances, the call would be routed from the originating switch (A) to the terminating switch (B) via the shortest path (dashed line route through switch C). However, to avoid the jammed radio link, the link unavailable at the precedence level of the call, and the destroyed switch C, the flood search automatically selects an alternate path (solid line) to the terminating switch.

2. Flexibility/Adaptability

The system possesses both the ability to be easily and securely reconfigured, in order to respond to rapidly evolving tactical situations, and the ability to interface with many other communications systems.

- The complete identity of all the transmission links of the system, as well as the actual configuration of the switching equipment included in all the assemblages, makes it possible to connect the various elements of the system in virtually any configuration.

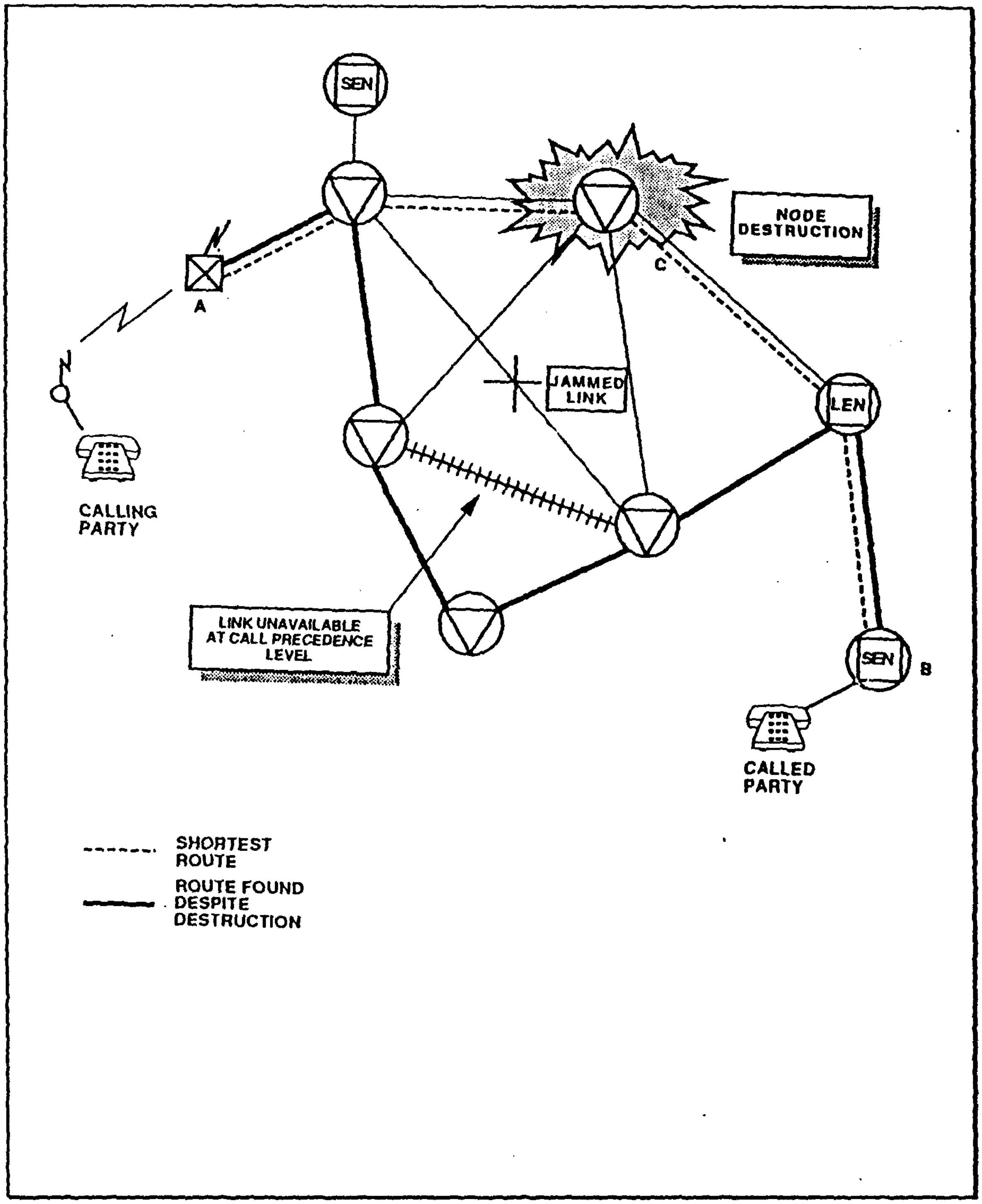

Figure 3-7. Automatic Alternate Routing

- Two trunk nodes, two radio access centers and six LOS assemblages are usually kept in reserve to face critical or unexpected situations, greatly enhancing the overall flexibility of the system.
- Reconfigurations of the network must always be engineered by the System Control Center in order to ensure that the overall performance of the rest of the network is not degraded as a result of these reconfigurations. The SCC is responsive to this requirement since it is capable of directing the relocation of the required assets, engineering the corresponding transmission links, and transmitting the related orders to the appropriate elements while still guaranteeing the proper operation of the unaffected portion of the network.
- All LOS assemblages are fully identical and operate in a unique frequency band, thus authorizing the SCC to order any node to use an LOS assemblage from another node whenever dictated by a prevailing tactical situation.
- The system provides dedicated interfaces to the Saudi Strategic and Public networks as well as to the Combat Net Radios used at lower echelons. Furthermore, these interfaces are provided by stand-alone assemblages which can be connected to any other element of the network, therefore making it possible to establish the required links.

3. ECCM Capabilities

In order to provide a high level of resistance to an enemy's ability to detect or jam SACS functions, the RF subsystems have strategically incorporated numerous ECCM features which add a significant dimension to the overall survivability of SACS.

The VHF radios of the Mobile Subscriber Access subsystem have a number of antijam features [Ref. 8:p. 107]:

- The VHF radios use a "programmable" frequency plan consisting of up to 96 duplex channels. Each channel is made up of one "high-band" frequency and one "low-band" frequency. The high-band frequency may be selected anywhere in the 59-88 MHz range and the low-band frequency may be selected anywhere between 30 and 51 MHz.

  Since any channel may be used by the radio to set up a call, an enemy jammer cannot predesignate a limited VHF band segment as that which is to be jammed, because the radio will automatically avoid the jammed channels upon call setup. In addition, even if all the channels of the current frequency plan are identified by an enemy intercept receiver, the Signal Commander may request the activation of a new frequency plan which will automatically neutralize the enemy endeavor.

- The "marker," continuously transmitted by a radio access center to allow the mobile subscribers to automatically check their affiliation state and to initiate a call to a subscriber of the network, is transmitted on a very slow frequency hopping channel. This channel changes every time a call is placed by a mobile subscriber, or in the absence of radio traffic, every 20 seconds. Consequently, it is difficult for the enemy to locate an RAC based on this signal.
- Operation of the entire Mobile Subscriber Access is based on extensive frequency reuse, since the same frequency plan is used throughout the brigade area of operation. Because of this unique characteristic, an enemy direction finding system will often be ineffective in that its directional measurements will be distorted by the simultaneous reception of several signals. Furthermore, the enemy will not be capable of selectively jamming certain communications established within the SACS system because any frequency of the currently active frequency plan may be used at a given time by any subscriber.
- If a mobile subscriber radio terminal does not receive the marker transmitted by its parent radio access center for a certain period of time, for instance in case of jamming of the RAC, it automatically attempts to reaffiliate with another RAC.
- In normal operation of the radio protocol, the excess signal level of the receivers is assessed at each end of the link during the call-initiation process. The RF power and receiver sensitivity are then adjusted to distribute the excess signal margin between the transmitter and receiver in each link direction. Thus, the receiver is desensitized to an interfering transmitter to some degree, and the transmitted signal is lowered to reduce the probability of interception of that call and to provide more opportunity for frequency reuse.
- The VHF radio of the mobile subscriber access subsystem uses link encryption during both the signaling and the traffic phases. This, along with the process of selecting an unused RF channel, means that a jammer cannot track only the most important calls and jam them. It must assume that all calls are equally important and, thus, is forced to jam targets of opportunity.
- Last, the process of discovering the channels currently in use is made more difficult for the enemy intercept receiver, because the radios of the mobile subscriber access subsystem operate in the same band as that

of the combat net radios deployed over the same area of operation. Thus, a jamming system would have some difficulty in concentrating jammer resources in a knowledgeable way on the SACS system alone.

The radio relay terminals also provide a number of antijam features.

- The highly directional antennas of the LOS subsystem have significant antijam protection (approximately 25 dB peak to sidelobe or backlobe ratio) against jamming. Additionally, the same level of protection is provided against intercept and direction-finding receivers operating in the sidelobe or backlobe direction.
- The UHF radios of the LOS subsystem operate in a full-duplex F_1/F_2 mode, with no fixed relationship between F_1 and F_2. Thus, even if a directional antenna is used by the enemy to locate the radio transmitting at F_1, this information can neither be used to jam the F_2 frequency at the same location nor to obtain knowledge of the location of the receiver operating at F_1 so as to focus the jammer power toward this receiver.
- When contact is first established between two LOS assemblages during the opening of a new radio link, both terminals transmit at full power. When operating in the automatic mode, they then start to adjust the transmitted power by 5 dB increments until a 15 dB margin above the threshold guaranteeing a bit error rate of 10^{-4}, is reached. This margin will provide adequate protection against statistical fadings while significantly diminishing the probability that an intercept receiver can find the transmitted signal.
- It is also possible to use a spread-spectrum transmission mode to further reduce the probability of interception of the transmitted signal. In this case, the transmitted signal is combined with a fast pseudo-random sequence (about 10 Mbit/second) in order to spread the transmitted spectrum and to reduce the peak power level. Although this technique reduces the receiver sensitivity by about 3 dB, it greatly increases the protection of the transmitting radio terminal, both in terms of detection of the transmitted signal and determination of the transmitter's location.

D. DISCUSSION

An analysis of the architecture and systems operations of SACS clearly suggests that survivability was considered as an equal co-function in all of the operations objectives that its designers envisioned.

In SACS' approach to survivability, the structural connectivity of the network may appear to be proportionally stronger in the function of area coverage than it is in the access function. Though this view could be supported by mathematical analysis, it is somewhat misleading since the measure of connectivity of the access area is a function of a capacity whereby the greater the number of users, the better the overall connectivity of the access area, as seen in Figure 3-2.

Furthermore, since systemic connectivity is supported by the routing algorithm and flood search technology in all switching functions, the processing performance of the entire system is greatly enhanced.

Through the utilization of a modular design concept, the capacity to establish clear identification of all the transmission links, and the capabilities of the switching equipment, a systemic capability has been created by which it becomes possible to connect the constituent elements together into virtually any configuration. The issue of connectivity is thus transposed to a plane where it can only be fully appreciated as a function of almost limitless dynamic responses.

In a system such as SACS which is fully automated, computer-driven, and self-organizing, there is always a danger that the hardware, once maximally operational under conditions of great stress, will exceed the capabilities of its human operators and so negate its effectiveness. The SACS system significantly reduces the danger of this type of result through the pivotal position that the system control center occupies. The system has been designed so that the signal commander can monitor the entire network, and has complete access to the system's data as well as the capability to modify any functions of self-organization in order to comply with a changing set of strategic objectives.

Any discussion of the survivability profile of SACS would be derelict if it failed to mention the considerable ECCM capability that the system possesses. Suffice it to say that the array of anti-jam features incorporated into the system makes it essentially impregnable within the parameters of today's available technology.

The empirical approach that SACS has taken towards survivability can best be summarized by stating the following: saturation of the system with extraordinary levels of redundancy in function, plus a synthetic capability for unlimited configuration, allows the system to operate in a mode closely resembling the organic rather than the mechanistic.

We will now attempt to identify and establish the interrelationship of those elements within SACS with regard to their contribution to survivability theory.

A quantitative analysis would of course be preferable, but lacking the means of accomplishing that at this point in time, we shall endeavor to suggest the fields of interrelationship with discoursive and deductive logic. It is our hope that the effort will assist in establishing the relevant sets for the components of survivability, which in turn may prove useful in creating a field of focus, or parameter guidelines, for later refinement and quantification.

We will begin at the level of the fundamental by asking what is the most essential element among the numerous features which directly contribute to

SACS' survivability, or in other words, which element has been assumed to enable the functions of the rest of the system? Does such an element exist?

The fact of connectivity (used here in its most basic sense of representing the sum of electronic connections within a system) in its broadest application can be said to be the precursive assumption of any and all communications networks dependent upon electronic means to accomplish their goals, since electronic systems depend upon electronic connections to establish a method of systemic operability. Connectivity, or the function of interconnections, though it is a given qualifier of the macro set to which the subset of the contents that this thesis addresses (survivability), does not necessarily translate as the precursive element of the survivability itself. We have in fact stated, in both the introduction and discussion of the SACS data presentation, that the system does not focus upon connectivity per se as the organizing principle of its design objectives. Beyond the function of macro set qualification that connectivity provides, connectivity as a feature within SACS may be characterized as a factor controlled by means of a modular design approach, thereby necessitating a systemic organization into discrete "packets" which are both redundant, hence expendable and easily managed. Connectivity as an integral feature in SACS design may then be said to be a controlled factor rather than the specific precursive element.

We have previously identified the feature of self-organization, directed towards an objective of rapid reconfiguration capability, as being the principle design objective of SACS. We have characterized this feature by the use of the term "responsivity." The feature or capability of responsivity, including all its subfeatures such as SCC, has been developed within a specific context of criteria, that while of great importance to the objectives of the system design, are more accurately qualified as an enhancement of capability rather than a precursive element.

Through a process of élimination we have arrived at ECCM capability. We will now change modes to the assertive. ECCM has developed as a response to empirical observation, which may be summarized by the following: since electronic components and their subsequent functions (transmission, reception, linkage, etc.) must be receptive to electronic impulses and interface to accomplish their ends, they are also subject to being acted upon through the same means by parties other than originally intended, that is, an enemy.

If an adversary were able to penetrate the parameters of SACS interior functions and disrupt it, then the design, content, and capabilities of its interior features would be compromised in exact proportion to the extent of penetration and disruption. Since the means of ECCM capability is the directly proportional qualifier to any and all functions of internal capability, ECCM capability is the precursive element.

We have previously noted the extensive array of ECCM capability that SACS deploys: neither expense or effort has apparently been spared. This leads us to an important qualification of ECCM capability in its function as the precursive element. Since electronic technology is an area in which innovation is constant and theoretical models are the collective property of a world scientific community, ECCM capability is inferred to incorporate the most progressive features of available technology in order to sufficiently fulfill its functions within the schema of high-tech communications networks.

Having identified the precursive element, we may now posit the following: *E* represents ECCM capability, relative to state-of-the-art technology, acting as a proportional qualifier on the set of interior functions of a communications network, here represented as X since it is as yet unqualified, and *S* represents survivability:

$$(E)\cdot(X) = S.$$

We will now attempt to identify and qualify the features contained within X. As X represents the interior functions of a communications system, it must include a measure of the functions of connectivity, since the method of achieving interconnections within a system is an application of connectivity in its capacity as the macro set precursive. Furthermore, the approach to achieving and maintaining the connectivity of a system defines the options and character of its internal organization.

The effect of connectivity approach in its function of defining internal organization is quite clearly exemplified within SACS. As a response and method of controlling the problems associated with a viable measure of systemic connectivity, the SACS system has been organized as a series of subdivided modules. Connectivity is established within each module, and the modules are then, in turn, integrated into the whole of the system, affecting and defining the entire character of internal systemic organization.

We may then assert that among whatever other features *X* contains, it also contains *C*, where *C* represents both the measure and approach to systemic connectivity, or:

$$(E) \cdot (X,C) = S.$$

Moving toward further qualification of the contents of *(X,C)*, we may note that the entire internal organization of the SACS system has been designed to achieve an objective of rapid reconfiguration capability. This is largely due to the defensive vulnerability of Saudi Arabia. Given that Saudi Arabia's potential adversaries are either numerically superior (such as Iraq or Iran) or possess greater offensive capacity (such as Israel or the USSR), the posture of SACS has been to assume the "worst case" scenario. If an enemy has the capacity to initially inundate the theater of operations with offensive weaponry, the communications network must have a dynamic capacity for rapid reconfiguration or it will prove deficient through the attrition of its physical apparatus. The ability of the network to reconfigure relative to a field of time is thus clearly an essential feature of its internal design, using the criterion of survivability. SACS strives to achieve this objective by means of systemic self-organization, since self-organization represents the most effective means of optimal reconfiguration within the least amount of time.

We may then assert that as *R* represents the capability of reconfiguration in a time field accomplished by means of dynamic self-organization:

$$(E) \cdot (X,R,C) = S.$$

Since *R* and *C* are interdependent functions within SACS, each structurally reflective and assumptive of the other function, a clearer representation of their interrelationship would be achieved by positing the assertion as:

$$(E) \cdot \left(X\frac{C}{R}\right) = S.$$

Furthermore, since at this point all other features within SACS can be accounted for as subordinate to those we have thus far identified, X may be dropped from the set of internal functions, so that we may conclude by stating:

$$(E) \cdot \left(\frac{C}{R}\right) = S$$

V. CONCLUSIONS AND RECOMMENDATIONS

The increasing complexity of military networks dictates that survivability considerations such as those introduced in this thesis be made an integral part of the communication network design process, rather than an application to be added after satisfying operational and organizational requirements. The exponential growth in the lethality of weaponry that has occurred since World War I, e.g., mobile artillery, aircraft, guided missiles, etc., has been compounded by the simultaneous appearance and function of greatly increased mobility. The effect of these two factors has meant a dramatically heightened potential for the concentration of destruction in both time and space.

If a campaign or a battle is to be determined by processes other than the random interaction of opposing lethal forces, which has often been the case throughout the history of warfare, an effective command and control apparatus must be in place and employed. A communications network is the physical extension of command and control. The survivability of that communications network in the face of intense lethality and the factor of mobility is the ultimate determinant of the effectiveness of command and control.

The connectivity approach quantifies the profile of survivability by four parameters: the factors of node connectivity and link connectivity (NCF) as global measures (LCF), and the node decomposition index (NDI) and link tree index as local measures. These parameters provide the theoretical basis from which network design proceeds, as well as a continuing means of network effectiveness evaluation and configuration expansion. The practical application of these theoretical assumptions, however, has encountered numerous difficulties when confronted with operational requirements.

An additional and recurrent problem occurs as the number of nodes in the network grows larger. The process employed to decompose the graph and determine the total number of spanning trees becomes unwieldy and ineffective when working with a large quantity of network nodes. As a consequence, the theoretical parameters of connectivity are therefore now seen as only being of practical value when applied to networks of relatively small size.

Though another simplified model of connectivity exists (which we referred to as the First Approach in the chapter on connectivity), its premises essentially equate connectivity with the likelihood of maintaining communication between selected node-pairs. The simplified model avoids the network decomposition analysis. Because of this critical avoidance (or oversight) the simplified theory is not adequate as a tool for rigorous design applications, though it can be highly useful in supplying a cursory overview of a given system.

Given the problems associated with the application of the theoretical models of connectivity, a practical approach has developed. This approach is well illustrated by the features incorporated within SACS. In SACS, the survivability objective of the system is attained through a design method that consists of subdividing the system into functional modular arenas. Each module meets its own connectivity-survivability requirement, and all the modules are deployed in a configuration through which they can be fully integrated to form an overall system.

In a practical modular approach such as SACS, the design begins by plotting an area course. Resources (nodes, links, etc.) are then embedded to establish and quantify full connectivity for the entire array of the network's usage, fixed and mobile. The area coverage is then interfaced through an on-line control and monitor pivot (SCC) which orchestrates the operations of a system that is otherwise self-organized in its design and technical capacity for reconfiguration. The capacity of the system for self-organization deserves considerable attention in and of itself, since such a capability (or lack thereof) effectively becomes the measure of tactical responsivity in an environment in which time is an important factor.

Modularity as a precursive and conscious design element not only reduces the calculations of connectivity down to a workable dimension, but also allows for a more efficient planning of resources. The SACS system, for example, exhibits a basal level of connectivity that is higher in its trunk area than its access area. Access can be reconfigured, and the SACS system makes ample provision for the likelihood of that eventuality; the trunk area is more indispensable to the continuing survival of the system's functions.

Whether a system has emanated from a modular design as a controlled strategic application or simply as a function of encountering the physical limitations of transmission, all communications networks can be described as modular. Any given module can be assessed or evaluated in regard to a quantifiable measure of connectivity. Regardless of whatever shortcomings presently exist in the application of connectivity theory, one salient feature is eminently observable from an application of connectivity theory—nodes do not contribute equally to systematic connectivity and some nodes are far more valuable in their systemic contribution than others.

Link enhancement analysis, whether applied in physical form or utilized as an analytical tool, is a means whereby the relative contribution of nodes and the resulting links can be more precisely assessed and/or reconfigured in accordance with their optimal economic contribution to systemic connectivity. The means of accomplishing this analysis (the exhaustive search) is unwieldy, costly, and too time-consuming to be effectively employed within the conditions of high-tech warfare. We have therefore expended considerable space and effort to refine an application of link enhancement analysis that would allow for the utilization of its results within a reasonable computation time.

Another extremely important component of a realistic survivability profile is the ECCM capabilities of a system. Note that all features of a system, such as connectivity, adaptability, self-organization, etc., are essentially qualified by its ECCM capabilities, since penetration and disruption can render a system's potential functions inoperable and thus irrelevant. In the SACS system we have seen the proportionate concentration of resources that results when ECCM capabilities are clearly identified as a qualifying prerequisite to systemic design objectives.

A summary of our thesis is as follows. In our introduction, Chapter I, we provided a rationale for our study into the question of survivability as a factor in communications networks that defines survivability as an important element in the capacity to implement the strategic functions of command and control.

Chapter II presented two theoretical models of connectivity in rigorous detail and discussed the problems associated with their application. The First Approach was found to be too simplistic a model to be sufficiently empowered as an effective design mechanism, and the Second Approach proved too unwieldy to be readily applied.

In Chapter III we presented a method of link enhancement analysis accomplished through the means of the optimal solution algorithm, an important practical application in regard to maximizing profit in economic contribution to systemic connectivity. We also introduced an improved methodology for utilizing the results of the optimal solution algorithm, based upon a method wherein BGH results are applied in a limited range of preferred candidates.

In Chapter IV we presented an overview and analysis of the SACS system. Of special interest to its contribution to understanding the issue of survivability were SACS' features of self-organization as a means of achieving highly responsive automatic reconfiguration in a time-space field of intense hostility, and its extensive array of ECCM capability.

We now summarize the recommendations that may be useful for further research.

- In our study we notice that a quantification of connectivity alone is not an adequate measure of survivability. A more realistic view of survivability might include the following relationship of components. Where *C* represents connectivity both in measure and approach, *R* represents the capability of reconfiguration in a time field, accomplished through means of dynamic self-organization, *E* represents ECCM capabilities relative to state of the art technology and S represents survival,

$$(E) \cdot \left(\frac{C}{R}\right) = S.$$

The equation is not intended to establish or assert a hardened definition, but simply to suggest a more realistic way of looking at the relationship between the components of survivability. Or, at least, it initiates a more productive line of analysis that draws upon empirical observation of emplaced systems as much as it does from theoretical models.

- Our second recommendation is that the suggestions for an improved methodology in utilizing the optimal solution algorithm, which was introduced in our chapter on link enhancement, be more thoroughly and rigorously tested on the appropriate equipment.

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