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COST EFFECTIVENESS PROGRAM PLAN FOR JOINT TACTICAL COMMUNICATIONS. VOLUME II. SYSTEM EFFECTIVENESS

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

System Effectiveness, Cost Effectiveness, System Effectiveness Methodology, Tactical Communications, Grade of Service, Speed of Service, Information Quality, Availability, Survivability, Vulnerability, Interrupt Rate, Lost Message Rate, Mobility, Transportability, Spectrum Utilization, CASE, SIMSE, NuSAP, Network Models, Reference Circuits, Reference Nodes.

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

This Volume contains the following information:

1. A conceptual model of system effectiveness for Joint Tactical Communications Systems and Equipment.
2. An approach to system effectiveness modeling.
3. A system effectiveness methodology.
4. Techniques for measurement and analysis.
5. Measures of effectiveness.

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VOLUME II

SYSTEM EFFECTIVENESS

COST-EFFECTIVENESS PROGRAM PLAN

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VOLUME II

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VOLUME II

System Effectiveness
for
Joint Tactical Communications
Systems/Equipment

1.0 INTRODUCTION

Volume I of the Cost-Effectiveness Program Plan, which was issued by the TRI-TAC Office with Service/Agency inputs, describes the fundamental concepts and general methodology for estimating and analyzing life cycle costs (LCC) and measures of effectiveness (MOEs).* It also describes their general use for cost-effectiveness studies, economic analyses, trade-offs, and other management and engineering investigations associated with the development and acquisition of joint tactical communications systems/equipment.

Volume II provides a conceptual model useful for performing effectiveness analyses at the system level for planning studies of joint tactical communications. It also provides guidelines for the modification and application of this model to similar types of problems at the equipment level. The model is applicable to the design of test programs.

Volume III provides methodology for Life Cycle Cost analysis.

1.1 Background

The TRI-TAC Office was established by DoD Directive 5148.7 to achieve interoperability among tactical communications systems and other DoD telecommunication systems; to provide for timely fielding of the most effective tactical telecommunications technology; to eliminate duplication in the development of service equipment; and to accomplish these objectives in an economical manner.**

The Cost-Effectiveness Program Plan was initiated to assist in achieving these objectives by developing an analytical methodology, which would be coordinated among the Services and Agencies and which would

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* Joint Tactical Communications Office, Cost-Effectiveness Program Plan for Joint Tactical Communications; Vol I - Management Overview, December 1973.

** DoD Charter for the Joint Tactical Communications (TRI-TAC) Program, DoD Directive, 5148.7, 27 May 1974.

be applied in a consistent manner to appropriate joint planning studies. This Program Plan comprises a series of methodology documents on various aspects of cost-effectiveness analysis and contemplates the use of a coordinating committee of Service/Agency representatives.

1.2 Approach and Organization of Volume II

Volume II was prepared by the TRI-TAC Office based on the following steps of background work. The first step surveyed the methods used by the Services and Agencies to estimate and evaluate system effectiveness of applicable communication programs. The more significant communication studies considered in this survey were the Mallard Project, USAF Mission Analysis, and the Marine Corps LFICS Study. The second step drew upon this survey and developed a consolidated and comprehensive list of categories and elements of effectiveness which would relate to the TRI-TAC plans and equipment programs. The third step reviewed existing computational models for estimating values of these elements. The fourth step identified applications of these elements to management and engineering problems of the TRI-TAC equipment programs and developed guidelines for these applications.

The main body of Volume II is organized into five sections. Section 1 is the Introduction. Section 2 presents a brief discussion of cost-effectiveness analysis and the general concept of system effectiveness. Included is a discussion of this concept related to joint tactical communications and the application to several types of studies.

Section 3 presents a discussion of the elements of systems effectiveness for joint tactical communications and an approach to modeling these by a variety of computational techniques.

Sections 4 and 5 provide further details concerning general methodology and flow of steps of analysis. Included is a discussion of techniques of estimating particular MOEs using existing Service/Agency computational models.

Discussion of the COMSEC system effectiveness will be issued under a separate classified cover at some later date. Techniques and models for specific elements will also be published as soon as development efforts are completed.

1.3 Implementation

This volume has been prepared with Service and Agency inputs concerning their concepts, techniques and application for effectiveness analysis. It is, therefore, a composite of both theory and practice and occasionally, a compromise between different Service approaches.

The Services and Agencies should distribute Volume II to their teams of managers, engineers, and operations research analysts who are involved in joint tactical communications analysis. It should be used by these teams for analyzing system effectiveness of the alternatives under evaluation in the cost-effectiveness studies, economic analyses and contractual efforts, arising out of the TRI-TAC equipment programs. This volume must be applied with judgment and careful consideration of the specific planning problem at hand.

It is intended to serve as guidance for analytical studies and is not intended to be a directive of rigid procedures. The concepts, and guidelines of this volume will be reviewed periodically and modified to reflect new insight and updated information.

2.0 THE CONCEPTUAL MODEL OF SYSTEM EFFECTIVENESS OF JOINT TACTICAL COMMUNICATIONS

2.1 Cost-Effectiveness Analysis

The analytical technique called Cost-Effectiveness Analysis is a type of systematic study "designed to assist a decision maker in identifying a preferred choice among possible alternatives."* With reference to the application of the techniques in the Department of Defense (DoD), these decision makers are the long range planners, managers, and engineers at a variety of organizational levels in the Office of the Secretary of Defense (OSD) and the Services. They also include those in the Program Offices who are assigned responsibilities for developing and acquiring specific equipments and systems. In appropriate cases, the engineers and engineering managers of industrial contractors may also be considered the decision makers, particularly in reference to specific equipment design trade-off problems.

Cost-Effectiveness Analysis is being used to assist in planning joint tactical communications. It has and is being applied in various ways to the TRI-TAC Office System and Subsystem Plans and to the individual equipment programs.

The Cost-Effectivenss Program Plan for Joint Tactical Communications, as presented in Vol I, Management Overview, was initiated by the TRI-TAC Office and published with Service and Agency comments and inputs, in order to provide a consistent analytical foundation for application to

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* Quade, E. S., Cost-Effectiveness Analysis, edited by Goldman, T. A., Washington Operations Research Council, Praeger Publications, N. Y., 1967, Chapter 1, "Introduction & Overview", p. 1.

future equipment programs by the Services/Agencies, and to related joint studies. Vol I provides only the basic principle of cost-effectiveness and the fundamental concepts of life cycle costs and system effectiveness. It is a synthesis of system optimization ideas well recognized throughout DoD for many years for weapon system planning, and a reorientation of these ideas to the planning problems of joint tactical communications.

2.2 The Concept of System Effectiveness

System effectiveness or benefit, as referred to in DoD Directives and studies, plays an important part in the optimization process inherent in cost-effectiveness analysis. It is one of two major conceptual parts of an analytical criteria, for identifying the preferred choice (e.g., optimum system design) among possible alternatives. The other major conceptual part is the total life cycle cost.*

System effectiveness is often defined in general terms as "a measure of the extent to which a system can be expected to achieve a set of specific mission requirements."** A "system" can be defined as a composite of equipment and associated personnel and facilities required to operate and maintain the equipment. "Mission requirements" may be defined in terms of performance specifications for the individual items of equipment and/or in terms of overall operational accomplishments and goals for a Service user.

This measure of achievement is considered to be a function (i.e., often a mathematical function) of at least three important operational aspects. These are:***

1. Availability is:

a measure of the system condition at the start of a mission and is a function of the relationships among hardware, personnel, and procedures.

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* For information see Vol III, Life Cycle Costs, TRI-TAC Office, August 1974.

** MIL-STD-721B, "Definitions of Effectiveness Terms for Reliability, Maintainability, Human Factors and Safety." 25 August 1966.

*** Used by both MIL-STD-721B and the earlier studies of the Weapon System Effectiveness Industry Advisory Committee (WSEIAC) sponsored by the Air Force System Command in 1965. See References for WSEIAC publications.

2. Dependability is:

a measure of the system condition at one or more points during the mission; given the system condition(s) at the start of the mission and may be stated as the probability (or probabilities or other suitable mission oriented measure) that the system (1) will enter and/or occupy any one of its significant states during a specified mission and, (2) will perform the function associated with those states.

3. Capability is:

a measure of the ability of a system to achieve the mission objectives; given the system condition(s) during the mission, and specifically accounts for the performance spectrum of a system.

A cost-effectiveness analysis of a specific weapon or support system would rarely use these three sub-measurements just as they have been defined above. They would, however, be carefully reworded so as to relate directly to the management and/or engineering design problem at hand and to the nature of the equipment and operational environment of the system.

More likely, the concept of a Figure or Figures of Merit (FOMs) would be used to serve as an index of the estimated quality of the system as it might operate under some assumed scenario. Stochastic models and expected value models are sometimes developed to predict this quality. These models might reflect or incorporate the three previously mentioned operational aspects of availability, dependability, and capability. Occasionally, an entirely qualitative approach to the FOMs must be taken because of insufficient data, e.g., incomplete equipment designs, insufficient logistic support plans, or absence of a scenario.

Sometimes a concept of "accountable factors" is used computationally to relate the FOMs and MOEs to significant characteristics of the equipment and deployment under study. A check list for identification of accountable factors includes such things as:

a. System Hardware Description

b. Compatability

c. Survivability

d. Vulnerability

e. Deployment

f. Geographic Factors

g. Personnel

h. Spares

i. Transportation

j. Support Equipment

k. Procedures

l. System Interface

The type of weapon system, i.e., bomber, missile, tank, or fast patrol craft, has usually determined the kinds of system effectiveness elements, Figures of Merit, accountable factors, and the mathematical modeling used to evaluate alternative designs. The aggregate FOMs for weapon systems may be bombs on target or percent target destroyed.* For communication systems such FOMs are much more complex, primarily because of the multiple kinds of support provided to a great variety of users. Joint tactical communications compound the complexity because of the differences in which Services will deploy and use the equipment.

2.3 System Effectiveness for Joint Tactical Communications

For modeling purposes, joint tactical communications systems can be defined as a composite of TRI-TAC equipment in a network, nodal, and/or circuit configuration. The"equipment" may be one item or a string of equipments and will depend upon the nature and goals of the study. The "system" might be an equipment at a node or all equipment from subscriber to subscriber in a network, including perhaps a mix of TRI-TAC and Service inventory items.

The system has a mission to provide subscriber-to-subscriber communications on a demand basis for the transmission of information. This equipment passes a variety of information in support of the missions of the using Services and Agencies. Depending upon the specific Service/Agency, this information can be generated by a wide range of peacetime and wartime situations. Usually, the support mission of providing minimum essential channels for command and control of combat and related emergency actions has the highest priority. However, there are many other support functions which must be included.

The effectiveness of a joint tactical communications system is a measure of the expected adequacy of these services rendered in an assumed operational environment. There are several ways of expressing this measure of adequate service. It may be expressed as a probability of achieving certain levels of performance. It may be a ratio of perfect, uninterrupted, unfailing, service to degraded service. It may be a ratio of specification service to degraded service based on some alternative scenario.

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*For additional information see WSEIAC, Final Report of Task Group II, Prediction-Measurement, Jan 1965, AFCS-TR-65-2-Vol II.

The general elements which are appropriate for evaluating the expected effectiveness at the system level are as follows:

1. Grade of Service
2. Information Quality
3. Speed of Service
4. Call Placement Time
5. Index of Availability
6. Lost Message Rate
7. Index of Survivability (Overt Attack)
8. Index of Survivability (Jamming)
9. Interrupt Rate
10. Mobility
11. Transportability
12. Service Features
13. Ease of Reconfiguration
14. Spectrum Utilization
15. Interoperability
16. Ease of Transition (Design Growth)

These particular 16 elements represent a concensus after careful review of previous studies and planning efforts of the Services/Agencies and the TRI-TAC Office. These earlier efforts used various measures and attributes of hardware performance in order to distinguish among proposed alternative tactical communication systems. Based on this review, these 16 elements represent a generalization, consolidation, and compromise of many approaches to system effectiveness. The 16 were also reviewed in an earlier draft of Volume II by the Services/Agencies and their comments were incorporated. Therefore, the above is the best available, jointly acceptable, list for current and future studies at the system level of TRI-TAC equipment programs and architecture.

The 16 elements are intended conceptually to be reasonably exhaustive and each element independent of others. No rigorous proof can be offered. Application of the 16 to some specific study may well disclose inherent mathematical interdependence and even the need to add new elements.

2.4 General Application of System Effectiveness

There are several applications and/or objectives of the concept of system effectiveness. The WSEIAC effort noted the following objectives:*

1. Evaluate system designs and compare alternative configurations.
2. Provide numerical estimates for use in defense planning.
3. Provide management visibility at every phase of a system's life cycle of the extent to which the system is expected to meet its operational requirements.
4. Provide timely indication of the necessity for corrective actions.
5. Compare the effect of alternative corrective actions.

Volume II is aimed primarily at objectives 1 and 2, with some implication on the early development and acquisition phases of equipment programs as indicated in part by objective 3. The definitions of system effectiveness, the concept of MOEs, and the simplified conceptual models for many of the MOEs in this volume, have been prepared with system and equipment design problems in mind.

Some of these design problems and trade-off issues already have been resolved. The TRI-TAC Office System and Subsystem Plans have reported on preferred alternative configurations and have described the use of the concept of system effectiveness in making these selections. Specifications have been proposed for some of the TRI-TAC equipment programs and the range of possible design issues have been narrowed down to those which specific contractual efforts are, or will be, solving in the near time period. However, some of these major design issues continue to be reevaluated and the specifications once considered firm require appropriate changes based on more rigorous analysis and updated inputs.

It should be emphasized that the evaluation of system designs and the comparison of alternative configurations in the case of the TRI-TAC programs are not likely to be one time events never to be restudied. The long term DoD budget and the allocation of development and procurement funds by each Service/Agency to the TRI-TAC program are not certain. Technological advances a few years from now may shed new light on some current design engineering features. The threat may significantly change.

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* ibid, page 3.

These and many other uncertainties about the future will create continued needs for design studies and cost-effectiveness analyses for which system effectiveness plays an important role.

Objectives 3 and 4 of the WSEIAC system effectiveness concept alludes to the usefulness of the MOEs and their modeling techniques for development and operational testing programs. Some of the MOEs of Volume II play significant roles in the IOTE phase of the Test Plans for TRI-TAC equipment.* In a more general sense, a few of the Test Plan objectives for the AN/TTC-39 which are relevant, are:

1. For DTE -
    a. Verify traffic handling capability---through real and simulated traffic loading.
2. For IOTE -
    a. Evaluate operational effectiveness when the system is employed in an operational environment.
    b. Evaluate reliability, operational availability, and maintainability and assess operational impact.
    c. Provide information on operational effectiveness of logistic support.
    d. Provide information on survivability when employed in an operational environment.

Volume II may also serve to guide analytical work associated with WSEIAC objective number 5. The need for corrective action might stem from failures or discrepancies of IOTE, OTE, and early operational experiences. Alternative design changes may require reevaluation of system effectiveness and costs. Such evaluations of the impact of proposed ECP changes may be of particular interest and help to Configuration Control Boards for their review and decision.

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*For additional information see particularly Vol III, (Draft), IOTE, Joint Test of Central Office, Communication, Automatic, AN/TTC-39 ( )(V), Test Design Plan, 12 July 1974, proposed by US Army Op. Test & Evaluation Agency, Fort Belvoir.

3.0 AN APPROACH TO SYSTEM EFFECTIVENESS MODELING

3.1 The Conceptual Model

A conceptual model is one which describes overall logic, principle elements, basic parameters, important assumptions, and "defining equations", which serve as guidance for follow-on preparation of more detailed models for specific design optimization problems. In the case of system effectiveness, such a model helps to scope the degree of visability used for reporting of results of comparisons of trade-offs and design alternatives as well as the validation/evaluation of test results.

The 16 general elements of system effectiveness presented in Section 2.3 are used in Volume II as the skeletal structure for this type of model. The elements are used in two ways; 1 - as Measures of Effectiveness, where quantitative estimates or"cardinal values" can be prepared for each design alternative, and 2 - as Attributes, where word descriptions can be prepared so as to permit intuitive ranking of the alternatives in terms of "ordinal values". Most of the remaining portion of Volume II addresses them as MOEs.

Figure 1 shows these MOEs segregated into four groups, which are internally relatable. These groups are significant to various types of management planners.

The Communications Group is an index of the capability of a system to perform the necessary information transmission. It consists of the time limited ability to establish a link between two subscribers and then transmit information over that link. Examples of MOEs that describe the ability of the system to establish a link are call placement time, speed of service, and grade of service. Another measure is information quality which measures how well information is transferred once a link has been established.

The Stability Group deals with the capability of a communications system to continue to function while being subjected to both external and internal stresses. Two examples of external influences are the destruction of nodes by a variety of causes and radio jamming by an enemy. The ability of the communications system to function while nodes are being destroyed or rendered inoperable, temporarily or permanently, is measured by the index of survivability (overt attack) and the ability of the communications system to function while being jammed is measured by the index of survivability (jamming). Internal influences are principally equipment failures. The susceptibility of a system to equipment failures is measured by the index of availability which is a function of the reliability and maintainability of equipments.

FIGURE 1

MEASURES OF EFFECTIVENESS HIERARCHAL STRUCTURE

- System Effectiveness
  - Communication Measures
    - Grade of Service
    - Information Quality
    - Speed of Service
    - Call Placement Time
    - Service Features
    - Lost Message Rate
    - Spectrum Utilization
  - Stability Measures
    - Index of Survivability (Overt)
    - Index of Survivability (Jamming)
    - Index of Availability
    - Interrupt Rate
  - Reorganization Measures
    - Transportability
    - Mobility
    - Ease of Reconfiguration
    - Ease of Transition
    - Interoperability*
  - Security*
    - X
    - Y
    - Z

NOTE: *Will be covered in separate Appendix D to this Volume.

The Reorganization Group describes the capability of a communications system to relocate, expand, contract, and to adapt itself to satisfy the requirements of a variety of tactical situations. Measures that describe the ability of a communications system to relocate are mobility (the amount of time it takes to prepare for a move) and transportability (the ease with which a system can be moved once it is prepared to move). Another measure is the ease of reconfiguration which describes the ability of a communications system to expand, contract and adapt to satisfy the requirements of a variety of tactical situations.

Each of the three categories relates system effectiveness to different kinds of interest. The Communications Group identifies those aspects of the communication systems and equipments that are of primary interest to the Service communicators and to the communications engineer. The Stability Group is of primary interest to the operators of the system, as well as the reliability and maintainability engineers and logistics support designers. The Reorganization Group is of interest to commanders who are forced to move parts of a system during conflict, and to the mechanical designers and engineers who must design equipment for ease of movement.

The Security Measures Group treats those COMSEC MOEs which consider how well a system can protect information that is being transported through the system from unauthorized personnel or otherwise be compromised or spoofed.

3.2 An Analytical Approach

The conceptual model of MOEs represents a systematic framework to be used for analytical studies (e.g., design optimization studies) of joint tactical communications. The way in which it should be used should be approached in logical sequence of major categories of methodology:

a. Determine orientation of communication system scope.

b. Identify study objectives, define alternatives and criteria.

c. Select applicable MOEs and develop models.

d. Prepare estimates, comparisons, and sensitivities.

Items "b" through "d" are described in Section 4.

3.2.1 Conditions of Orientation

Expansion and tailoring of the conceptual model for practical applications depend initially upon proper orientation to certain broad conditions which set the stage, or scope, or boundaries of the follow-on methodologies. These are:

a. Tactical Scenario

b. Network and Traffic

c. Assumptions Concerning Operations

3.2.1.1 The Tactical Scenario

System Effectiveness, as defined earlier, implies a concept of operations. A tactical communication system is operated to provide communications support for military organizations during peacetime and wartime deployment for some period of time. These organizations, deployments, and periods of time must be explicitly defined.

The first step required for such a definition usually concerns the geographical part of the world that the analyst wishes to assume to be the future operational environment. A map of that particular area may be used to more easily visualize and keep track of locations and movements of both combat and communications organizations. The second step is to assume a level of combat intensity and/or peacetime training. The third step is to assume or estimate the number and type of troop organizations and units (i.e., force structure) that would be required to carry on such a deployment. These organizations must be positioned throughout the tactical area in some command hierarchy that is dictated by expected military doctrine.

It is customary to identify time phased snapshots during the total operational period. The deployment of troop units can be considered as overlays on a map. Each overlay can depict one snapshot in time. The first snapshot can be considered as the positioning of the force structure on D-Day (e.g., peacetime posture) or the day that the conflict starts. Other snapshots can be postulated for other points in time after the war has commenced. These portray how the various units, including the communication units, either advance or pull back in accordance with the assumed plan of battle.

Scenarios for joint tactical communications should be based at least upon joint Service deployments. Separate Service deployments are also important. Such scenarios may be provided by National Policy Guidance documents.

3.2.1.2 Communication Networks and Traffic

The military tacticians and communications analysts next should determine the amount and types of communications that are required to permit the force structure to communicate and move within the contraints of the plan of battle.* A second type of overlay can be used on the map which will show the type of communication systems links and connectivity that will be provided. This information may be based on Service and Agency requirements studies and reports.

The basic information required for the development of the communications overlay is projected traffic data. In general, this information takes the form of a specific subscriber having a need to talk

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*Derived by or from user needs and requirements.

to other subscribers. The number of calls between any two subscribers must also be forecasted as well as the length of the call and the mode of the communication. The mode being either voice, teletype, data, facsimile or video.

Once this information is available, the communications engineer can design a system that will handle the required amount of traffic. The network would include switching centers, trunks to interconnect these switches, and control units that are required to control and monitor the operation of the system. The necessary equipment required to connect the various units or subscribers to the various switching centers must also be postulated.

The communication network designers are constrained by military doctrine, by the projected requirement of the user, by existing inventory equipment as well as the state of the art. However, within these constraints there are many alternative ways of providing the required total network communications. Normally, several alternative approaches are designed. System/cost effectiveness analysis can then be employed to select the most desirable alternative.

Diagrams of communication networks can be called models. These define the connectivity of communications systems/equipment needed to satisfy the communication requirements of a particular tactical operation. Further, models of this type provide a structure for assessing the values of the MOEs within the system effectiveness model. Network connectivity diagrams can be divided into four types:

a. Total networks

b. Reference networks

c. Reference circuits

d. Nodal access configurations

Total networks are those which describe entire communications networks based on a particular tactical scenario such as for Europe or Asia. These models are usually very complex and require large amounts of data and time to construct. This type of network is necessary for evaluating total system measures such as grade of service, availability, and survivability.

Reference networks are a representative part of a larger network. These are used to simplify the calculations and evaluations of the same measures as the complete network models. Extreme care must be used to insure that the selected reference network is a representative segment of a larger network from which it was derived.

Reference circuits represent a very small part of a complete network. The reference circuits represent a set of single needlines through the system and are used to evaluate "point-to-point" types of measures such as information quality, speed of service, and call placement time.

Nodal access configurations are small parts of complete networks, which represent typical nodal deployments. They represent the relationship between a node and associated subscribers, trunks and smaller static access switches and their subscribers. These configurations are used to evaluate measures such as mobility, transportability and ease of reconfiguration. Specific examples of the models are given in later portions of this document.

3.2.1.3 Assumptions Concerning Operations

Analyses of system effectiveness, like analyses of life cycle costs, rest on the validity and reliability of the computational assumptions. Once the scenario, network and traffic conditions are established, there are a number of detailed factors, constraints, and variables, which require consideration.

Factors that can influence the analysis include:

a. Deployment and ILS environment

b. Enemy capabilities (threats)

c. System and equipment operational data

Assumptions must often be made to investigate uncertainties in these areas. In order to evaluate certain MOEs, an assumption must be made as to the environment that will exist in that part of the world where the force structure has been positioned. Measures such as survivability (overt and jamming) require assumptions that describe the enemy capability to destroy or jam areas of the communication system. Assumptions on system data must be made depending on the availability of quantitative descriptions of equipment parameters primarily during the early stages of system development. The analyst is forced to either make assumptions concerning the value of equipment parameters or conduct qualitative effectiveness analysis. The approach adopted depends on the kinds of decisions that must be made and the time frame in a system/equipment life cycle when an analysis is required.

Assumptions are often made for the sake of introducing mathematical simplicity. Extremely complex models are difficult to employ and make sensitivity analysis extremely difficult.

4.0 SYSTEM EFFECTIVENESS METHODOLOGY

4.1 General Flow of Steps

The methodology for system effectiveness is an inherent part of the overall approach and concept of cost-effectiveness analysis. The initial steps are identical to those in the overall cost-effectiveness methodology. The remaining steps pertaining primarily to effectiveness modeling depend to a large extent upon straightforward mathematical techniques of several professional disciplines (e.g., operations research and engineering).

The general flow of steps of system effectiveness methodology as a part of cost-effectiveness is shown in Figure 2. The basic steps are shown in the upper half of the Figure. The interplay with cost analysis is shown in the lower half.

These general steps must be further modified to reflect special circumstances of the system optimization vs equipment suboptimization for each application. These modified methodologies are described later in this Section in reference to performance trade-off studies, equipment specification reviews and design of tests.

4.1.1 Describe Alternatives in Detail

The overall objectives of the cost-effectiveness study as well as the basic alternative plans, designs, and trade-offs will probably have been established and defined before any analyses are made on the system effectiveness portion. If not, these objectives and alternatives must be the first step of the methodology. The definition of the study objectives and definition of the alternatives to be evaluated by the study must be examined to make sure that it will be possible to formulate a model which will discriminate among them and assist in identifying the best alternative. Some of the general steps of this examination are:

a. Check system optimization objectives and relate them to any suboptimization objectives.

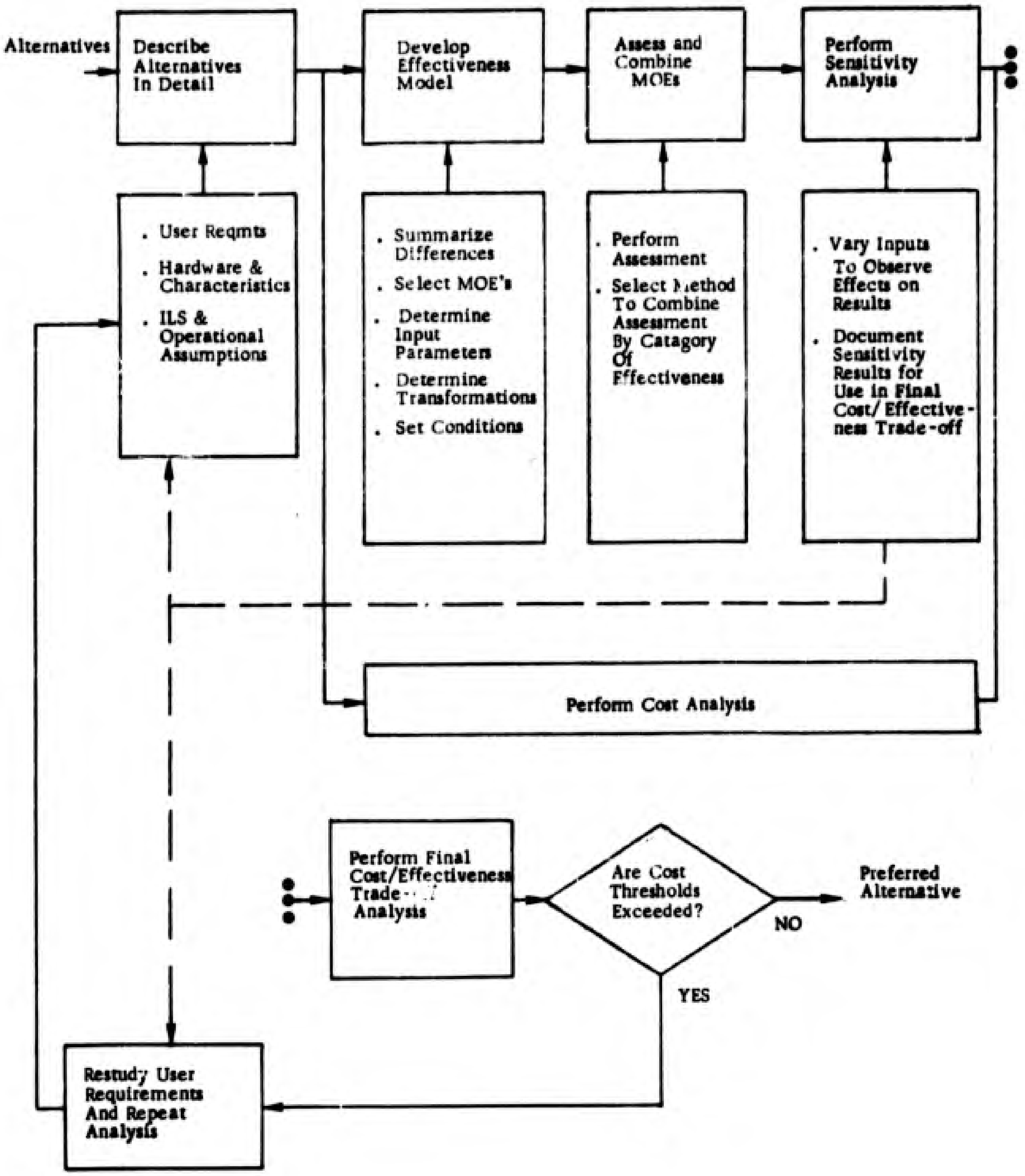
b. Make sure the alternatives are technically and operationally feasible (i.e., satisfy user requirements).

c. Describe hardware to include software and management characteristics so as to identify variables among the alternatives.

d. Describe ILS and other operational assumptions which will vary.

FIGURE 2

COST-EFFECTIVENESS ANALYSIS FLOW CHART



The first two of these actions are of paramount importance in the analysis of joint tactical communication systems. The Service or Agency that is developing a TRI-TAC subsystem or equipment is responsible for collecting all user requirements and incorporating them into the evaluation. A successful program and evaluation is contingent upon communication and coordination between all Services and concerned Agencies.

The third action lists the actual characteristics and other information on the alternatives being evaluated. This list must include the generic equipments necessary to implement each alternative together with their characteristics. The level of detail provided here will control the level of the evaluation, as far as choice of the type of transformations that will be used. Care should be taken to provide the same level of detail for all of the components of the system or equipment.

The last step is to list the integrated logistics support (ILS) and operational assumptions adopted. These represent the general conditions under which the analysis will be conducted. It is important that the rationale for the assumptions be stated. Preferably, they should be supported by factual evidence, but as a minimum, they should be based on an informed concensus. With this type of information associated with the assumptions, the degree to which errors might be introduced into the analysis can be more easily assessed during sensitivity analysis.

4.1.2 Develop an Effectiveness Model

The next step in performing the effectiveness evaluation is to develop an appropriate effectiveness model using the basic structure and procedures described in Section 3. The model should be developed to assess the relative effectiveness of each of the alternatives. Having described the alternatives in detail, the relative differences between alternatives can be summarized. Based on this information the model can be tailored to highlight these differences by selecting only the MOEs that will yield different values for the alternatives. For example, if the alternatives being evaluated require an identical number of shelters, all of which have the same weight and require equal amounts of power, then the transportability MOE would be eliminated from the analysis. On the other hand, if switching were manual in one alternative and automatic in another, the MOE "call-placement time" would be relevant. Another important aspect in developing the model is to insure that the basic definitions of the MOEs are customized to suit the particular subsystem or equipment that will be evaluated. The MOEs, as defined in Section 5, sometimes need to be refined to adapt them to a particular analysis. Examples of this will be given in Section 5.

After the MOEs have been selected to highlight the alternative differences, the procedures in Section 5 should be followed to complete the development of the effectiveness model to be used in the analysis.

4.1.3 Assess MOEs and Select Method of Combining Assessment

After the development of an appropriate model for analysis, each of the alternatives is assessed with respect to the selected MOEs. During the development of the model for analysis, the decision to use qualitative or quantitative assessment should have been made on the basis of the level of detail included in the description of alternatives. Quantitative assessment involves using transformation equations to obtain values for the MOEs after setting conditions for the evaluation under the various network/reference circuit models.

Qualitative assessment will consist of taking each MOE and breaking it down into its aspects. The assessment is accomplished by a discussion of how well each alternative performs under each aspect, and ends with a ranking of alternatives from best to worst. Each MOE is assessed in this manner, until all qualitative MOEs are analyzed.

Once the assessment of MOEs is completed, the results must be categorized and evaluated to provide input to the decision maker. To categorize results, the MOE assessments should be placed in their respective groups of communications, stability, reorganization, and security measures. Having completed this step, the various methods described in Section 4.4 can be used to combine the assessments within the categories of effectiveness to form one representative assessment for each category. These four combined assessments will then represent the effectiveness results that will be analyzed and traded off in the final cost-effectiveness trade-off analysis.

The purpose of representing effectiveness in the four categories is twofold. First, the decision maker would have a nearly impossible task, in handling the individual assessments of possibly sixteen or more MOEs per alternative in order to make a choice. Second, the four areas depicted represent different functional design areas that must be considered, and inspected separately to insure that all general requirements are met. For example, a communication system alternative can have high communication and stability effectiveness ratings, but a very poor reorganization rating. Since there are only three reorganization measures and thirteen communication and stability measures, an overall assessment would probably be erroneously high for this alternative. However, a communication system with the best communications and stability properties is of little value to a tactical user who must be able to relocate easily. Therefore, having these four separate areas to inspect provides a better representation of system effectiveness for the decision maker.

The combining of the assessments mentioned above can be accomplished using any of the methods described in Section 4.4. However, these methods possess certain shortcomings that are pointed out in the descriptions provided in that section. The recommended method is a hybrid developed at TRI-TAC, especially developed for combining multi-MOE assessments that are qualitative, quantitative, or a combination of both. This method is called the TRI-TAC Figure of Merit (FOM) and is presented in Section 4.4.4.

4.1.4 Perform Sensitivity Analysis

The last step in conducting system effectiveness analysis of alternatives is to perform a sensitivity analysis. Sensitivity analysis consists of varying the various inputs to observe the way the results obtained will vary. Inputs that can be varied are assumptions and subjective judgments. The assumptions can be changed slightly to observe the way the results are affected. By investigating assumptions in this manner, the degree to which errors might have been introduced into the evaluation can be assessed. If subjective judgments were used in the case of qualitative assessment, the strength of such assessments can be varied to observe changes in results. Subjective judgments might also have been used in combining the MOE assessments. In the TRI-TAC FOM, for example, weighting and utility assignment should be investigated for sensitivity.

Sensitivity analysis describes for the decision maker the changes in preferred alternatives resulting from changes in the variable factors affecting the analysis. A well documented sensitivity analysis can be a valuable asset to the decision maker, as he proceeds to combine the effectiveness results with the cost results in final cost-effectiveness trade-off analysis.

The flowchart in Figure 2 shows a dotted line connection from the sensitivity analysis block back to the input block, and to the restudy of user requirements block. The input connection represents the varying process that is performed in conducting sensitivity analysis.

4.1.5 Perform Final Cost-Effectiveness Trade-Off Analysis

Final trade-off analysis is the combining of the effectiveness and cost results to select the preferred alternative. The specific instructions for compiling and analyzing the cost and effectiveness information are not included in this volume. However, the use of the effectiveness sensitivity analysis is a part of this step, and will be discussed here.

The final analysis will result in the selection of a preferred alternative that best meets the user requirements at a given cost. However, this cost must be compared with the availability of monetary resources to fund this choice. Should this cost threshold be exceeded, as illustrated by the flowchart in Figure 2 , a modification of requirements to reduce the cost might be in order. Potential reduction in the requirements can be found by analyzing the sensitivity results, to see what variations can be made to affect the effectiveness assessment least. The cost sensitivity analysis can also provide information as to which requirements have caused the cost to be so high. Using this information, the requirements can be modified and the analysis can be repeated to find a more reasonable cost-effective solution.

4.2 Performance Trade-Off Methdology

The second application of system effectiveness is in conducting performance trade-off studies. This application represents the use of system effectiveness as a design tool. During the development of specific equipments, particular design parameters can be identified that affect the value of more than one MOE. These MOEs are called functionally dependent MOEs, and the purpose of performance trade-off studies is to determine the value of the design parameters that impact on the effectiveness of the system. The general procedure for conducting performance trade-off studies consists of the following steps:

a. Develop an effectiveness model

b. Identify trade-off parameters and functionally dependent MOEs

c. Establish acceptable ranges for MOEs

d. Perform sensitivity analysis

e. Select parameter values that impact effectiveness.

The remainder of Subsection 4.2 will discuss each of these steps individually.

4.2.1 Develop an Effectiveness Model

The first step in conducting performance trade-off studies is to develop an effectiveness model for the equipment, subsystem, or system being studied using the basic structure presented in Section 3. The objective of the study is to optimize effectiveness by varying the values of design parameters. The development of this model is an important step because it will serve two purposes during the study. First, it will provide the relationships between the MOEs to be traded off, and second, it will provide the vehicle for assessing the overall effectiveness. This model should use the equipment design parameters as its inputs and should provide an overall system effectiveness assessment. In this manner, the equipment design impact can be assessed with respect to the overall system effectiveness. It should be noted that the MOE definitions in Section 5 might also have to be customized to meet the needs of the particular analysis at hand.

4.2.2 Identify Trade-Off Parameters and Functionally Dependent MOEs

The next step in conducting performance trade-off studies is to identify the trade-off parameters and the functionally dependent MOEs. The trade-off parameters can be given either at the start of the study, or they might have to be determined as part of the study. To determine the parameters, each design parameter can be screened to determine if it affects two or more MOEs selected for the effectiveness model. If this is the case, then both the parameter and the MOEs have been identified. As a hypothetical example, Figure 3 shows a number of MOEs that are affected by various parameters. Notice that P_1 affects MOEs A, B, and C, and P_2 affects MOEs B, D, and E. Both P_1 and P_2 affect MOE B in this case. Notice also that as P_1 increases, MOE B increases, but that as P_2 increases, MOE B decreases. This relationship makes all of the concerned MOEs functionally dependent, and the values for P_1 and P_2 can be optimized. Figure 3 also shows that MOEs F and G are affected by parameter P_3 in such a way that MOE F increases with an increase in P_3, while MOE G decreases with this increase. This relationship makes these two MOEs functionally dependent. These are the types of relationships that must be established when considering minimum acceptable values for MOEs.

4.2.3 Establish Acceptable Ranges for MOEs

After the functionally dependent MOEs are identified, acceptable ranges for the MOEs and the design parameters involved must be established. The group conducting the study can either obtain minimum MOE requirements or they can establish them during the study. Preferably,

FIGURE 3

FUNCTIONALLY DEPENDENT MOEs

	Parameters		
MOE s	P_1	P_2	P_3
A	X		
B	X	●	
C	X		
D		X	
E		X	
F			X
G			●

● Increase in parameter results in worse performance

X Increase in parameter results in better performance these minimum requirements should be based on the requirements contained in the requirements documents such as Joint Operational Requirements (JORs). If no formal document exists, requirements should be postulated by user requirements personnel. If quantitative transformations are desirable, ranges for the input parameters can be established from the MOE requirements. These ranges are required to provide boundaries for the varying process described in the next step.

4.2.4 Perform Sensitivity Analysis

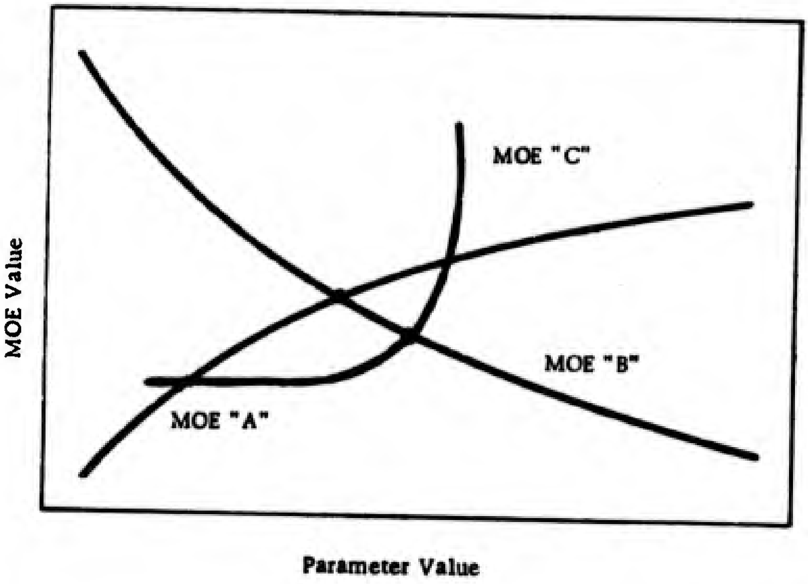
The fourth step in performance trade-off studies is to perform sensitivity analysis. Sensitivity analysis can be defined as varying input variables and observing the effects on the output variables. In the case of performance trade-off studies, the input variables are the design parameters, and the output variables are the MOEs. In order to perform sensitivity analysis, a baseline effectiveness evaluation must be performed. The average value between the minimum and maximum acceptable value for each parameter can be used to provide this baseline evaluation. Once the baseline assessment is completed, the functionally dependent parameters can be varied within the ranges specified and data should be collected on each group of functionally dependent MOEs. The data obtained can be compiled in terms of overall effectiveness by combining the respective MOE assessments obtained using the methods presented later in this section. This compilation will relate the varying of input parameters to overall system effectiveness, and can be used to provide the output of the next step.

4.2.5 Select Parameter Values that Result in Maximum System Effectiveness

The final step in performing trade-off studies is to determine the parameter values that will yield the maximum system effectiveness. The output of sensitivity analysis will provide information that can be plotted as MOE values versus parameter value. In the case where one parameter affects two MOEs, the curve intersection should be investigated as a possible optimum solution. A good method to arrive at this solution is to investigate and compare the slope of the tangents of both curves at the point of intersection (mathematically this would be the value of the first derivative of each curve). Should the absolute value of these slopes be approximately equal, the probability of the point of intersection being optimum will be high. Figure 4 shows the curves of MOEs A, B and C. In comparing MOE A with MOE B, the intersection can be considered an optimum solution because the slopes of the tangents at the point of intersection appear to have equal absolute values. However, a comparison of MOE B and MOE C will yield very different results. The slope of MOE C has a much higher absolute value at the point of intersection than does the slope of MOE B. The curves also show that by increasing the parameter value slightly above the value at the point of intersection will cause a large increase in MOE C with only a small decrease in MOE B. Therefore,

FIGURE 4

MOE VALUE vs PARAMETER VALUE



the optimum solution must be chosen by trading off the amount that MOE B should be reduced as opposed to the amount MOE C would be increased.

The discussion above applies only to MOEs that are considered to have equal weight. In some cases, however, some MOEs are considered to be more important than others, and a weighting factor can be incorporated such as that used in the TRI-TAC FOM in para 4.4. If such a weight is incorporated, it could be introduced by multiplying the equation for the MOEs by their respective weights and then plotting curves such as those in Figure 4. The investigation procedure described above can be employed to find a weighted optimum solution. In the case where many MOEs are involved, more complex methods using linear or dynamic programing techniques for optimization can be employed. In any event, the type of curves and the display of the data from the sensitivity analysis will vary with the particular equipment/system being studied.

As mentioned in the previous subsection, the MOE assessment data can be combined into an overall system effectiveness assessment using one of the methods described in Section 4.4. The choice of the final value of the parameters can be accomplished by investigating a few curves on overall system effectiveness versus parameter value. In this way, parameters can be chosen for the optimum value of overall system effectiveness.

4.3 Equipment Specifications and Design of Test

This section discusses the advantages of using system effectiveness concepts in the development of equipment specifications and design of test and presents the general method for applying these concepts.

Specifications and test designs, although they appear chronologically apart in a development program, are closely related functions since the satisfaction of the specification should be determined during the test program. Therefore, if a specification is written in terms of MOEs, the test program must be formulated to measure the value of the MOEs.

The concept of using the effectiveness model in specifications and test designs is an important one. In addition to specifying parameters or equipment characteristics, and testing for them after development, the specifications should contain required levels of performance that are correlated with the pertinent MOEs. The test designs then become procedures for measuring the value of the MOEs after development. This technique insures that the equipment will perform as an integral part of a communication system, since the equipment level MOE is derived from a system level MOE.

The remainder of Subsection 4.3 will discuss the way the method of System Effectiveness can be applied to specifications and test designs and the advantages realized by its use.

4.3.1 Specifications

At the present time, specifications are written in terms of performance capabilities. The preparing agency identifies capabilities or characteristics considered essential or desirable in the new item of equipment. After some form of requirements validation and study of the approach, a firm specification is developed. This method of writing specifications results in a document written in a somewhat fragmented and non-cohesive format that does not indicate to the contractor the relationship between ultimate equipment characteristics and the system level parameters. No indication is given to the contractor concerning the relative importance of each of the desired characteristics.

System effectiveness can be used to specify systems or equipment requirements by using MOEs and MOE values in addition to system or equipment characteristics. This procedure would provide the following advantages:

a. A more unified and coherent description of required system capabilities

b. A framework within which the contractor can make trade-offs

c. Less likelihood of over-specification resulting in excessive costs

d. Higher likelihood that the newly developed system or requipment meets the ultimate user needs.

The following paragraphs will illustrate the way the effectiveness model can be applied to specification writing and the way these advantages will be achieved.

In general, a quantitative MOE will be defined by some mathematical equation of the form:

$$MOE_1 = a . x + b . y + c . z$$

where

a, b, and c are constant multipliers, and
x, y, and z are equipment or system parameters.

Under current practice, specifications are written that define the minimum or maximum acceptable value of x, y, or z. Using this practice, the value MOE_1 becomes a computation after the fact. Since the equipment designer does not have the MOE or equation to work with, he has no control over the value of the MOE that will result from his design. However, using the MOE approach to writing specifications, this problem can be alleviated, resulting in the benefits mentioned above.

Two alternative approaches to writing specifications based on MOEs are possible. The first of these alternative approaches is to only specify a maximum or minimum acceptable value (bands of performance) and specify the equation that is to be used to determine the value. This approach allows the equipment designer the maximum degree of latitude in designing equipment to meet the specification. He can freely trade off between the various equipment parameters to achieve the desired MOE value. To some extent, this is the method currently used to specify equipment reliability. A required value for the reliability is specified along with a formula for determining equipment reliability. It is generally left to the equipment designer to achieve the desired reliability using any required trade-offs during his design effort.

The second alternative is basically a compromise between the current approach to writing specifications and the approach described above. A maximum or minimum value for the MOE and the equation defining the MOE is specified as above. In addition, a range of values is specified for each of the equipment parameters used to calculate the MOE. Using this procedure, the specification writer sets acceptable limits for the value of each equipment parameter, while still affording the equipment designer latitude in his design. To a degree, such a procedure is currently employed when specifying equipment availability. A desired value for the equipment availability is specified. In addition, a minimum value for mean time between failures is called out, a maximum value for mean time to restore is specified, along with various support system response times. The equipment designer is free to achieve the desired availability within the constraints imposed on the equipment parameters. In this manner, the user is assured of getting the level of performance desired and the contractor can trade off design parameters to meet the prescribed performance level.

4.3.2 Test Design

The primary purpose of a test program is to determine whether an item of equipment or system meets the minimum requirements of the specification. Therefore, the individual tests must be specified to determine the actual values of the parameters stipulated in the specifications. With the specification in terms of MOEs, the test program design will merely require the determination of the actual MOE value. This task is relatively easy because the MOE equations are given and the acceptable values are specified. In the case that the specifications are written in terms of parameters and equipment characteristics, the procedure for designing tests becomes a little more difficult. This case would require developing a system effectiveness model for the particular system to convert the existing specification into one that specifies MOE values, rather than equipment or system characteristics. This task can be completed by following the basic steps of the System Effectiveness method that appear in the beginning of this section. The test must then be designed to measure the parameters required to calculate the MOEs as given by their equations.

While tests are primarily designed to determine compliance with specifications, the test results can also provide other valuable information. When a specific piece of equipment is tested, it will be tested either alone or as a part of an assemblage. At this time, certain measurements of equipment performance are made to insure proper functioning of the equipment. Once this procedure has been completed, the piece of equipment can be tested in a system configuration to insure a high degree of confidence about its ability to contribute to overall system performance. This type of testing will correlate particular equipment performance to overall system performance.

4.4 Methodology for Combining Multi-MOE Assessments

The purpose of this paragraph is to present methods for choosing a preferred alternative that is described by multi-attributes. These multiple attributes arise when the decision making process has multiple goals, and consequently uses multiple criteria. Since multiple attribute values are cumbersome for the decision making process, methods have been developed to reduce the number of dimensions that represent the overall assessment.

In the case of effectiveness analysis, the multi-attributes are the various MOEs that have been chosen to represent the effectiveness of the alternatives. This paragraph will present the various methods employed in decision theory to combine the multi-attribute assessments for the selection of a preferred alternative. The methods presented fall into the following categories:

a. Full dimensionality

b. Single dimensionality

c. Intermediate dimensionality

The methods contained within each category are discussed in Sections 4.4.1 through 4.4.3. Section 4.4.4 presents a hybrid method, developed at TRI-TAC which combines the best of the various methods presented, and is very well suited for combining MOE assessments.*

4.4.1 Full Dimensionality Methods

Full dimensionality consists of starting with n-attributes (dimensions) and reducing the dimensionality to some lower value. In full

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*Decision Making Among Multiple-Attribute Alternatives: A Survey and Consolidated Approach, ARPA Order No. 189-1, The RAND Corporation, December 1968.

dimensionality techniques, the attributes must be considered separately and independently (one attribute value cannot offset another attribute value); they can be described quantitatively, qualitatively, or by a combination of both. Two methods that utilize all of the attributes are the dominance method and the satisficing method. These two methods are effective in reducing the number of alternatives, but usually do not result in the selection of a preferred alternative.

4.4.1.1 Dominance

When comparing alternatives (by attributes) and one alternative clearly has higher ranking attribute values for all attributes, then this alternative "dominates" the others. In the dominance method the decision maker relies on intuition as to whether one attribute value is more preferred than another. If one alternative does not dominate the others, then a "modified-dominance method" can be employed. That is, if one attribute value is identical for two alternatives, and all other attributes are dominated by one alternative then one can eliminate the inferior alternative. The dominance method is a useful tool in reducing the number of alternatives however, very rarely will the preferred alternative be identified, since there are usually a number of alternatives left after the method is applied. Dominance is one of the most easily applied and accepted decision making methods.

4.4.1.2 Satisficing

The satisficing method requires that the decision maker establish the minimum attribute values that an alternative's attributes might have. Any alternatives that do not meet these requirements are immediately withdrawn from consideration. If none of the alternatives meet the specified criteria, then an alteration to the requirements could be made and the process is repeated. Like dominance, satisficing generally leads to a reduction of dimension size; however, when it is used in an iterative fashion a single choice can be obtained. Satisficing does not require that the attribute values be in numerical form, but like dominance, it has intuitive appeal. Satisficing is a stronger decision making tool than dominance because it can be used iteratively.

4.4.2 Single Dimensionality Methods

The application of single dimensionality methods reduces n-dimensions to one-dimension by removing all but one dimension. Transformations that map into a single dimension and perform this reduction are:

a. Maximin

b. Maximax

c. Lexicography

d. Additive weighting

e. Effectiveness index

f. Utility theory.

These methods will now be discussed with the objective of n-dimensions mapping into one kept clearly in view.

4.4.2.1 Maximin

The maximin method reduces n-dimensions into a single dimension by examing attribute values across alternatives and noting the lowest value (minimum) for each alternative. Then by selecting the alternative with the most acceptable value across the lowest attributes, a preferred alternative is selected. This procedure is called the maximum of the minimum or the "maximin". Indeed a reduction to a single alternative is obtained by this procedure, but major drawbacks are clearly visible. First, a high degree of comparability must exist among all attributes; second, all attributes must have a common scale (either qualitatively or quantitatively) and third, one alternative might be superior in all attributes except the minimum one and still be discarded by an alternative that is average in all but the minimum attribute in which it has the higher value. The maximin procedure is very reasonable if all the attributes held the identical weight in the performance of the system under consideration.

4.4.2.2 Maximax

Maximax methodology characterizes alternatives by their best attribute (again a subjective process) and then compares them by selecting the highest attribute value across alternatives. Here again, a high degree of comparability and a common scale is needed among all attributes. The disadvantages of maximax are similar to those of maximin. For example, an alternative might have one attribute value of ten and all other attributes a value of five, and be chosen, while another alternative might have one attribute value of nine and all others a value of eight and although obviously the better selection, this one would be discarded.

4.4.2.3 Lexicography

This method is a single-dimensional technique because one dimension at a time is considered. In a dictionary like manner, the attributes are ranked with respect to relative importance as viewed by the decision maker. The attribute values are now compared across alternatives starting with the number one ranked attribute. If one alternative dominates the most important attribute, then the second most important attribute is considered and the process continues until a final alternative is selected. Again, a high degree of comparability is needed and this method also suffers from the same type of incompleteness as the maximin and the maximax techniques.

4.4.2.4 Additive Weighting

Additive weighting consists of assigning weights to all attributes that reflect the relative importance of each as a percentage of the total. For comparability, the summation of the weights are normalized to one. Multiplying these weights by the corresponding attribute values for each alternative and then summing (across attributes) gives a weighted average for that alternative. The alternative with the highest weighted average is then selected.

The method does not disregard any of the original n-attributes, because all attributes are used in forming the weighted area; however, all of the attribute values must be numerical and comparable. This technique is considered a very powerful tool for decision making.

4.4.2.5 Effectiveness Index

The effectiveness index method uses weights in a functional form, fitted for the system and, unlike additive weighting, need not be a summation operation. That is, the function is defined in terms of the attributes associated with the system under consideration and this function might be an exponential, logarithmic, or any other mathematical operation. Then, like additive weighting, the decision maker assigns attribute values to all attributes comprised within the alternatives and proceeds to input them into his general weighting model(functional form). The general weighting model will then respectively generate an effectiveness index for all of the alternatives' input. Again, the alternative with the highest effectiveness index is chosen. Clearly, all n-attributes are considered and a final decision results in this methodology which is more rigorous than additive weighting, since the function is fitted to the system under consideration. Like additive weighting the attributes must be numerical and comparable.

4.4.2.6 Utility Theory

Utility theory considers the effect of multiple events rather than multiple attributes to select the best alternative. This method is usually employed when there is a great amount of uncertainty about the outcomes of the various attributes. The uncertainty is overcome by postulating certain events in lieu of these attributes and then by using a utility function to assign a value to each alternative. These values are assigned by close examination of the information known about each alternative. This assignment is performed separately for each event. Following the assignments, an expected utility value is computed for each alternative and the alternative with the highest value is chosen. The above utility function can be a mathematical probability of success or a subjective probability provided by the decision maker.

4.4.3.0 Intermediate Dimensionality

Between the two major dimensionality categories lie procedures that deal in more than one but less than the full n-dimensions. Two methods that address the multiple attribute problem under this constraint are trade-offs and nonmetric scaling. These methods are discussed in the following paragraphs.

4.4.3.1 Trade-offs

Performing trade-offs consists of asking the question: if an attribute value is lowered for a certain attribute, then how much of an increase in value will another attribute be raised? For example, if we trade-off power for bandwidth in an amplifier one attribute value can be lowered, in order to raise the other, which one depends on what the decision maker is trying to accomplish. The consideration of trade-offs that can be implemented are given by $\binom{n}{2}$, which is the number of attribute combinations taken two at a time. Unfortunately, trade-offs are most useful in designing alternatives rather than selecting them.

4.4.3.2 Nonmetric Scaling

Nonmetric scaling consists of taking k-attributes that have been chosen from the original n-attributes and comparing or "measuring" them to an ideal alternative that lies in the k-dimensional space. By placing alternatives in their perspective places in the k-space (using its attribute values), a determination of the relative distances that these alternatives deviate from the ideal can be obtained. Then the alternative that is spatially closest to the ideal one would be selected. For nonmetric scaling the attribute values might be in any form; however, they must be independent.

4.4.4.0 TRI-TAC FOM

The TRI-TAC FOM was developed to specifically combine multi-MOE assessments for subsystem planning evaluations. The method is a combination of additive weighting, effectiveness index and utility theory, and can be used to produce a single numerical effectiveness result from quantitative assessments, qualitative assessments, or a combination of both types of assessments. The method consists of the following basic steps:

a. Establish MOE weights

b. Assign utilities to MOE assessments

c. Calculate the FOM.

The remainder of this section will describe the steps for obtaining the FOM.

4.4.4.1 Establish MOE Weight

The first step in obtaining a FOM is to establish relative weights for the MOEs in the evaluation. A logical approach to achieving this task is to first rank the MOEs by importance and assign the most important a weight of 10. The next step involves assigning values between 0 and 10 to the remaining MOEs in accordance with their relative weight with respect to the most important.

This portion of the procedure reflects the additive weighting properties of the FOM.

4.4.4.2 Assign Utilities to MOE Assessments

The next step in obtaining a FOM is to assign utilities to the MOE assessments. A utility is a dimensionless number that is used as a vehicle for combining assessments that are measured in various, incompatible units and in some cases in subjective terms. The utility will reflect the relative performance of an alternative with respect to a baseline alternative that can be chosen as the middle ranking alternative with respect to one MOE. Utility assignment requires some sort of utility function. In the case of the TRI-TAC FOM, the function was subjectively assigned in accordance with Table 1.

To use Table 1 to assign utilities, the following procedure can be employed:

a. Rank alternatives in accordance with their relative performance under the MOE (can be quantitative or qualitative)

b. Assign the median alternative a utility of 5; this becomes the baseline alternative

c. Assign utilities to the remaining alternatives in accordance with the table.

To demonstrate this approach, consider the following example: assume speed of service utilities are to be determined for five static access alternatives: A, B, C, D, and E. Assume also, that rank ordering the alternatives, for the best speed of service to the worst, results in the rank ordering: D, E, A, C, B. A is automatically assigned a utility of 5 and becomes the baseline from which other utility assessments are made. If alternatives C and B have speeds of service less than alternative A, but not sufficiently less so as to result in a decrease in effectiveness, a utility assignment of 4 (high side of the less effective category) might be assigned. Similarly, if alternative E has a better speed of service than A but not significantly better, a utility of 6 might be assigned.

TABLE 1

UTILITY ASSIGNMENT CRITERIA

Utility	Criteria
0-2	Barely meets minimum essential requirements
2-4	Less effective than the baseline
5	Baseline
6-8	More effective than the baseline
9-10	More effective to the extent that the MOE should be a principal consideration in the selection of a preferred alternative.

If alternative D has a speed of service that should be a principal consideration in the decision process, a utility of 9 or 10 might be assigned. In summary:

Alternative	Utility
D	9
E	6
A	5 (baseline)
C	4
B	4

The utilities assigned should reflect the relative effectiveness of each of the alternatives with respect to the baseline. This process is carried out separately for each of the MOEs selected for comparing alternatives.

Following this procedure, both quantitative and qualitative assessments can be converted into a numerical index of performance that reflects the relative performance of each alternative under the MOE. The step represents the effectiveness index and utility theory properties of the TRI-TAC FOM.

This process can be employed whether a qualitative or quantitative assessment of the MOEs is being made. The method is also useful if the approach is a hybrid one in that some MOEs are being treated qualitatively while others are being subjected to quantitative assessments.

In the quantitative case, each alternative may generate a numeric value for each MOE. These numbers can be normalized to a 0 to 10 scale in accordance with the method illustrated in Table 1. The qualitative assessment is done by a verbal analysis of the attributes of each MOE. The results of this analysis are directly in line with the Table 1 method.

In the case of a hybrid approach, each MOE, whether it be qualitative or quantitative, can be normalized into the 0 to 10 numerical rating. The weighting and addition of the MOE values then can be handled by the following method.

4.4.4.3 Calculate the FOM

The last step in obtaining a FOM is to combine the weighting and utility information using the following formula to calculate the FOM of each alternative:

$$FOM_i = \frac{\sum_i W_j U_{ji}}{\sum_i Wj}$$

where,

FOM_i = the figure of merit for the i^{th} alternative

W_j = the weight of the j^{th} MOE

U_{ji} = the utility assigned to the i^{th} alternative with respect to the j^{th} MOE.

To demonstrate the way the above equation is utilized to calculate an effectiveness FOM, consider the following example: assume grade and speed of service and information quality are the MOEs selected to evaluate the relative effectiveness of three alternatives. Also assume, the steps described in Section 4.4.4.1 and 4.4.4.2 result in the following:

	W_j	U_{j1}	U_{j2}	U_{j3}
Grade of Service	10	5	10	9
Speed of Service	6	6	3	5
Information Quality	3	2	5	6

$$\sum W_j = 19$$

$$FOM_1 = \frac{(10 \times 5) + (6 \times 6) + (3 \times 2)}{19} = 4.8$$

$$FOM_2 = \frac{(10 \times 10) + (6 \times 3) + (3 \times 5)}{19} = 7.0$$

$$FOM_3 = \frac{(10 \times 9) + (6 \times 5) + (3 \times 6)}{19} = 7.26$$

Therefore, the relative ranking of these alternatives with respect to effectiveness would be 3,2,1.

As mentioned previously, this procedure can be used to provide a single representative number for each category of effectiveness. The result is that the original 16 measures have been reduced to three which together provide an assessment of systems effectiveness for each alternative. In this case, the other thirteen MOE's values were the same for all alternatives.

Note: It should be noted that this approach magnifies the differences between alternatives. An alternative method would be to consider the weights and utility values of all MOEs. This technique would result in the same ranking but the differences would be less significant. The time required for the analysis could also be increased by a factor of five.

5.0 TECHNIQUES FOR MEASUREMENT AND ANALYSIS

5.1 Introduction

Sixteen elements of system effectiveness, called Measures of Effectiveness (MOEs),for joint tactical communications were briefly described in the previous sections. These MOEs are of a mixed nature. Most lend themselves to quantitative analysis resulting in estimates with various general units of measure (e.g., Probabilities, Ratios, Percentages, and Time). Other MOEs lend themselves only to qualitative analysis which can be utilized for intuitive ranking of alternatives when applied to specific plans and designs.

Design and trade-off problems requiring application of these MOEs will dictate the way in which they should be used. The scope of the tactical communication system and/or equipment being evaluated will determine, in part, which MOEs are applicable. The time during the development cycle (i.e. architecture, specification, or contract trade-offs) when the study is conducted will determine whether quantitative plus qualitative or only qualitative methods can be followed.

The sixteen MOEs are presented in detail in this Section. Each one is described in a similar outline format beginning with the formal definition. Additional information concerning defining equations, important parameters, and example techniques and models are included as appropriate.

5.2 Mathematical Optimization Orientation

Cost-effectiveness analysis and its two major elements (i.e., Life Cycle Costs and System Effectiveness) of the TRI-TAC Cost-Effectiveness Program are oriented toward mathematical optimization techniques. There are many of these techniques, including various mathematical/statistical theories. These can be found in numerous Operations Research and Statistical texts, and will not be reviewed here. It is sufficient to note at this point, that "mathematical optimization techniques" lead to the same goals as cost-effectiveness, (i.e., for guiding the problem solver to that choice of variables that maximizes the goodness measure ... or that minimizes some badness measure ...*). **

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*Carnahan and Wilkes, Digital Computing and Numerical Methods, John Wiley & Sons, N. Y., 1973. Chapter 10.

**System Effectiveness and the MOEs are also applicable to the TRI-TAC Test Program; however, standard mathematical techniques are not referenced here.

For application to engineering design problems, such as addressed in Volumes II and III of the Cost-Effectiveness Program, the analyst's objective is to find and identify the one design vector, X', out of all feasible alternatives, which maximizes some objective function f(X), that is:

$$f\ (X') = \max_{X \text{ feasible}} f\ (X)$$

subject to some suitable constraints. It is essential that this objective function be a meaningful, computable, quantitative, and single-valued function, in order to be able to use certain root-finding procedures or searching schemes which yield the maximum or minimum values.

In the case of Volume II, life cycle costs can be assumed to be the first major constraint. The analytical objective is to identify the design, among proposed alternative designs, that maximizes system effectiveness; subject to the cost constraint plus other constraints, perhaps (e.g., quantity of equipment, time schedule, and risk).

The MOEs are useful in defining the above objective function. Thus, system effectiveness is a function of such MOEs as grade-of-service, information quality, etc., as are appropriate to the particular study at hand. They may be used singly or in some combination (e.g. additive) along with appropriate weights so as to constitute a meaningful Figure or Figures of Merit (See Section 4.1). Some of these MOEs must be analyzed by models of an entire network while others need only reference circuits as typical nodes for their evaluation. Examples are discussed in Appendix C.

5.3 GRADE OF SERVICE (GOS)

5.3.1 Definition

Grade of Service is an estimate of the probability that a request for communication service (i.e., placement of a call or message) will be blocked.* For a network, it may be computed as a weighted average of blocking probabilities over all user pairs. The weights are computed based on selected characteristics of traffic needs for each user pair.

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* For general background, see: D. H. Hamsher, Communication System Engineering Handbook, McGraw Hill Book Co., 1967, pages 1-15. and R. B. Cooper, Introduction to Queueing Theory, MacMillan & Co., N. Y., 1972, pages 65-71.

5.3.2 Conditions of Evaluation

Some of the general conditions limiting or bounding the definition for application to design optimization problems of joint tactical communications are as follows:

a. The type of elements of service requested are:

1. Voice, data, TTY, or facsimile
2. Direct, indirect, broadcast, or conference
3. Direct dialed, preprogrammed conference, or dedicated circuits
4. Precedence level
5. Secure, approved, or non-secure

b. GOS is applied to peacetime steady-state operations. For combat or other stressed operations, see MOEs for Survivability and Vulnerability, which treat how GOS degrades as a function of these stresses. See Sections 5.9 and 5.10.

c. Blockage is defined to:

1. Include calls preempted by higher priority users
2. Exclude calls incompleted to busy subscribers (This blockage is a function of end instrument usage rather than an overloaded trunk)

d. GOS is computed for blockage occuring during the estimated peak period of traffic, called the "busy-hour".

5.3.3 Defining Equation

$$G_i = f\ (T,\ C,\ R,\ A,\ D)$$

where:

G_i = Grade-of-Service for a Joint Tactical Communications system defined as G_f = Total network for a given deployment and force level; G_l = Link; G_d = Node; or G_c = Reference Circuit.

T = Traffic Volume by Type of Service (Erlangs)*

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*The symbol "E" will be used throughout for Erlangs.

C = Channel Capacity (No. of)

R = Alternate Routing Capability (No. of)

A = Call or Message Arrival Probability Distribution (Assumed to be Poisson Distributed for Commercial Communications, some modified Poisson may be more appropriate for Tactical Communications during Combat)

D = Call or Message Duration

5.3.4 Background

Grade of service is often used as a circuit/network sizing parameter. It permits the evaluation of how much capacity is required to handle estimated traffic loads.

Grade of service can be used as an indication of the effectiveness of a system network design which is constrained to a certain cost level. System parameters, including quantitives, are varied with total cost and the grade of service calculated for each design. The network design with the best grade of service is the optimum for the fixed cost.

Precedence of calls is a critical aspect in joint tactical communication calculations. The higher precedence levels such as Flash Override and Flash can preempt all other types of calls. These high priority service requests will rarely be blocked; therefore, their probability of blocking approaches zero. The lowest precedence level, routine, can be preempted by all others. These calls compete for the circuit capacity that is not being occupied by the higher priority users. Their probability of blocking can be relatively high.

5.3.5 Quantitative Approach

Grade of service estimations can be made separately for each type of service request, such as are listed in 5.3.2. However, in order to limit the scope of the analysis, an evaluation by precedence level should be adequate. It should be noted that messages cannot be blocked in systems that employ store and forward type message switches.

As stated in the definition, methods for calculating GOS average the grade of service for all pairs of subscribers as weighted by the magnitude of the traffic needs.

The following equation can be written if the probability of blocking is considered to be the ratio of blocked calls to the total offered traffic:

$$\overline{GOS_j} = \frac{\sum_i (e_i \; GOS_i)}{\sum_i \; e_i}$$

where:

$\overline{GOS_j}$ = the network grade of service

GOS_i = the grade of service of the i^{th} needline

e_i = the traffic offered to the i^{th} needline

5.3.6 Isolation of Contributing Equipment Factors

Some TRI-TAC equipments contribute to network grade of service while others do not. As a general rule, multi-channel and pooled equipment significantly effect the GOS of a network. Switches such as the AN/TTC-39, which are normally described as non-blocking switches, also effect GOS in that inter-matrix blocking can result from various traffic conditions. An equipment such as a facsimile set can indirectly influence GOS in that one type of design can generate more erlangs of traffic for a specific picture transmission than an alternative design.

5.4 INFORMATION QUALITY (IQ)

5.4.1 Definition

In general, Information Quality is the fidelity or exactness with which the received signal represents the transmitted signal.

5.4.2 Conditions of Evaluations

Some of the conditions and qualifications that may be useful are:

a. The information is transmitted during busy-hour traffic

b. All equipments are in perfect working order

c. Important aspects of information quality include:

   1. Intelligibility - sentence or word recognition percentage as determined by test-subjected listeners, when standard text is spoken.

   2. Speaker Recognition - the probability that the speaker can be identified by a listener, who is familiar with the speaker's natural (untransmitted) voice.

3. Naturalness - the degree to which the received speech sounds like the speaker's natural (untransmitted) voice.

4. Bit Error Rate (BER) - the expected fraction of bits sent that are incorrectly received.

d. The "fraction of transmitted information" means:

1. "Voice intelligibility" for voice calls

2. "Character error" for TTY calls

3. "Fraction of received bits" for data calls

5.4.3 Defining Equation

Information Quality may be defined in the most general sense as follows:

$$I = f(S, W, K, D, P, M)$$

where:

I = Estimate of Information Quality for Each Relevant Item of Equipment in a Netowrk, I_N, or an equipment string, I_g

S = Signal to Noise Ratio

P = Power Level

W = Band Width (RHz)

K = Cross Talk (db)

D = Percent Distortion

M = Modulation Scheme and Coding

5.4.4 Example Methods for Estimating IQ for Analog Voice Circuits

Information quality estimates are made separately for each mode of information transfer. Reference circuits such as those described in Appendix C are required for these analyses.

The fraction of transmitted information that is received correctly is usually measured through an intelligibility test for analog voice circuits. Intelligibility tests have listeners attempt to identify received words. The percentage of words heard correctly is a measure of speech quality, and is termed the "percent-word articulation". A technique such as the Fairbanks Rhyme Test requires the listeners to identify the transmitted word as one of several rhyming words differing only in the initial consonant.

Without a test circuit, it is impossible to conduct an articulation test such as the Fairbanks Rhyme Test. However, the DCA Engineering Installation Manual lists a number of electrically measurable parameters that affect telephone circuit intelligibility and could be used in lieu of an articulation test. These are:

a. Received speech power

b. Bandwidth transmitted

   1. Amplitude versus frequency distortion

   2. Delay distortion (envelope delay)

c. Amount and character of noise, including tones

e. Crosstalk, especially that which is intelligible or nearly so

f. Echo

   1. Magnitude

   2. Delay

g. Frequency displacement

These parameters are not easily combined so that an overall estimate of intelligibility can be made. Each must be evaluated separately and compared to values found to be acceptable in circuits that do have acceptable intelligibility.*

Of the above DCA parameters, delay distortion and frequency displacement are not normally detectable by the human ear; therefore, a measurement or estimation of these quantities are necessary.

The amplitude versus frequency distortion measurement actually consists of a number of measurements made for frequencies from 300-to 3400-Hertz. For each frequency, the net loss is measured as referenced to a 1000-Hertz signal.

The power levels along a transmission path are controlled as part of system design. For a four-wire system, power losses or gains are more dependent upon the loop equipment than on the switch or trunk equipment. This is because the loop equipment varies considerably and cannot be easily adjusted and controlled.

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*For additional information see DCA -330-175-1, DCS Engineering Manual, April 1973.

If the power gains for each of the equipment in a string from the Zero Test Level Point to the subscriber terminal is known, then the power level (dBm) can be found by the summation of power gains of each equipment.

The major contributions to the noise in the circuit are thermal and intermodulation noise. Noises of these varieties are usually measured in decibels above the referenced noise level. If the noise gains for each of the equipments in a string are known, then the total noise contribution in that circuit is the sum of the contributed noise for each equipment.

Crosstalk is minimized by insuring that a large loss occurs among channels so that coupling will not result. Crosstalk is measured by the crosstalk index. The crosstalk index (in percent) is the probability that a listener will hear intelligible crosstalk.

An important parameter in computing the crosstalk index is the coupling loss. The coupling loss is related directly to the value of the crosstalk index. As such, the coupling loss can be used as an index of crosstalk.

Echo is a problem on circuits utilizing two-wire loops. On these circuits, excessive echo is reduced by the insertions of transmission losses. The transmission losses are an index of echo suppressions on circuits that use two-wire loops. If a circuit is entirely four-wire, echoes do not appear.

It is desirable to use one parameter to represent the measure for analog voice instead of the several parameters that have been discussed, one most encompassing is the received voice power. By including unintelligible crosstalk and echo in the noise measurement, intelligible crosstalk and intelligible echo can be accounted for to some extent. Using only received noise power as the desired parameter means that other measures of voice quality are not excessive.

5.4.5 Example Method for Estimating IQ for Analog Voices

The suggested equation for estimating IQ for analog voice circuits is:

$$\overline{IQ_i} = \frac{1}{e_i} \sum_{l} e_{il} \sum_{r} n_{ilr}$$

where:

e_i = Total i^{th} needline traffic

IQ_i = Information Quality for a selected mode of information transfer for a selected needline

e_{il} = Total l^{th} route, i^{th} needline traffic

n_{ilr} = Noise power contribution of the r^{th} subsystem of the l^{th} route of the i^{th} needline

The subsystem parameter necessary to calculate $\overline{IQ_i}$ is n_{ilr}. The system level inputs necessary are the subsystem connectivity, routing procedures, and needlines.

5.4.6 Evaluation for Digital Voice Circuits

As with the measurement of intelligibility of analog voices, intelligibility of a digital voice circuit cannot be done directly without an actual test circuit. Six measures have been identified that contribute to intelligibility on a digital voice circuit. These measures are as follows:

1. Signal-to-Noise Ratio (SNR)
2. Binary signaling rate
3. Dynamic range
4. Effect of bit errors
5. Degradation resulting from tandeming
6. Quantizing errors in A/D and D/A conversion

The major contribution to the SNR of an A/D converter is the quantizing noise. The quantizing noise includes the effects of the binary signaling rate and the dynamic range. For a well designed digital system, the transmission bit errors will probably not contribute significantly to the noise. As such, the SNR, due to back-to-back quantizing noise, is an adequate quantifiable indication for information quality for nontandem digital voice connection. Nonregenerative tandeming can be included by adding in the quantizing noise for each tandem connection. The quantizing noise is entirely allocatable to the A/D converters.

5.4.7 Example Method for Estimating IQ for Digital Voice

The method is:

$\overline{IQ_i}$ can be determined thru the following equation

$$\overline{IQ_i} = \frac{1}{e_i} \sum_{l} e_{il} \sum_{r} n_{ilr}$$

where:

e_i = Total i^{th} needline traffic

e_{il} = Total l^{th} route, i^{th} needline traffic

n_{ilr} = Noise power contribution due to A/D converters of the r^{th} subsystem of the l^{th} route of the i^{th} needline

The subsystem parameter necessary to calculate IQ_i is n_{ilr}. The system level inputs necessary are the subsystem connectivity, routing procedure, and needlines.

5.4.8 Evaluation for Digital Data Circuits

The most general measure of information quality is the bit error rate of the information delivered to the digital terminal by the transmission system. The bit error rate delivered includes any error rate reduction by error control devices. For a particular terminal and data format, it might be appropriate to express the error rate in terms of character, block, or message error rate.

5.4.9 Example Method for IQ for Digital Data

If the bit error rate is known for a particular link, then $\overline{IQ_i}$ can be approximated by,

$$IQ_1 = \frac{1}{e_i} \sum_{l} e_{il} \sum_{r} P_{ilr}$$

where:

e_i = Total i^{th} needline traffic

e_{il} = Total l^{th} route, i^{th} needline traffic

P_{ilr} = Probability of a bit error being introduced by the r^{th} subsystem, l^{th} route, of the i^{th} needline. P_{ilr} is assumed to be <<1.

The above method is given because it is a good estimator, when error correction codes and data format are not specified.

The subsystem parameter necessary to calculate $\overline{IQ_i}$ is P_{ilr}. The system level inputs necessary are the subsystem connectivity, routing procedures, and needlines.

5.4.10 Qualitative Analysis

A qualitative analysis of this MOE can be made by selecting an appropriate sample of reference circuits as discussed in Appendix C and analyzing them with respect to the following parameters.

Analog Voice Circuits

- Received speech power
- Bandwidth transmitted
- Amplitude vs. frequency distortion
- Delay distortion
- Noise Characteristics
- Crosstalk
- Echo delay and amplitude
- Frequency displacement

Digital Voice Circuits

- Signal-to-noise ratio
- Binary signaling rate
- Dynamic range
- Effect of bit errors
- Degradation resulting from tandeming

Digital Data Circuits

- Bit error rate

Separate analyses are required for Analog Voice Circuits, Digital Voice Circuits and Digital Data Circuits.

5.4.12 Isolation of Contributing Factors

Components considered in information quality estimates are loop equipment, switching equipment and trunking equipment. Certain of the factors discussed in Section 5.4.2 are likely to be controlled by only one of the above components. Crosstalk, for example, will be generated in switching equipment and in trunk groups. The list below shows the components that are likely to control each parameter:

- Received speech power - transmission loss in loops and trunks
- Bandwidth transmitted frequency and amplitude distortion - all components
- Noise characteristics - all components
- Crosstalk - switching and trunking
- Echo delay and amplitude - switching and end equipment and transmission length
- Frequency displacement - switching

5.5 SPEED OF SERVICE (SOS)

5.5.1 Definition

Speed of service is the expected time a message requires to move through the network from the last bit out of sending terminal to the last bit into the receiving terminal. This is an average over all user pairs weighted in accordance with the traffic-demand matrix.

5.5.2 Conditions of Evaluation

Some of the conditions that may be important for evaluation are:

a. The connection is attempted during busy-hour traffic

b. All equipments are in perfect working order

c. The precedence of call is specified (see grade of service)

5.5.3 Background

The speed of service is the time required to move a message through a network. This implies that the message must pass through either a store and forward module (message switch) or through a torn tape relay.

The time for a message to pass through a network is a function of the following parameters:

- Switching rate
- Routing Plan
- Human message handling speeds
- Dialing method
- Precedence levels
- Processor speed and capacity
- Queueing

This measure must be distinguished from "Call Placement Time" (CPT) which treats the time required to connect one subscriber to another. In the case of a message, the time required to dial the message switch or access a torn tape relay station can be considered an analogous to the time required to place a voice call which is call placement time. The CPT, which is usually under five seconds for an automatic system, is so much smaller than the speed of service, that CPT can normally be considered to be negligible for message traffic.

5.5.4 Example Methods for Analysis

The procedure for analyzing this MOE is to estimate the speed of service between each subscriber pair, and then to average over all subscriber pairs for each precedence level. The SOS for the j^{th} precedence level is:

$$SOS_j = \frac{\sum_i \left[e_i \, (SOS_{ij}) \right]}{\sum_i e_i}$$

where:

e_i = Total j^{th} precedence messages over the i^{th} needline

e_i = 0 if no j^{th} precedence messages go over the needline

SOS_{ji} = Average speed of service of the i^{th} needline for j^{th} precedence messages

$\overline{SOS_{ji}}$ can be estimated with the following equation:

$$\overline{SOS_{ji}} = \frac{1}{e_i} \sum_i e_{il} \times \sum_r t_{ilr}$$

where:

e_{ie} = Average delay of the r^{th} subsystem, 1^{th} route, i^{th} needline from final transmission of the end of the message to receipt of the end of the message for the j^{th} precedence message.

5.5.5 Quantitative Analysis

In the most rigorous sense this MOE should be analyzed at the network level under a busy hour traffic load. Such an analysis can give a true picture of the network speed of service since the interplay of the difference precedence level messages can be analyzed. The CASE model as described in Appendix B is capable of making such an analysis.

In cases where traffic data is not available for the analysis a more simplified approach is possible. The time delays that contribute to the speed of service are a function of the equipment that a message must pass through in going from the source to the sink. The strings of equipment that are required to pass the messages can be correlated with specific needlines. A finite number of types of equipment strings can be identified by analyzing the system and subsystem under study. These will be referred to as reference circuits. Appendix C discusses the construction of these reference circuits.

The speed of service can be calculated for each reference circuit and the arithmetic average of these estimates will represent the system speed of service. This analysis should be performed for each precedence level.

5.5.6 Qualitative Analysis

If sufficient detail is not contained in the identification of alternatives, a qualitative analysis may be based on consideration of the following aspects:

a. Switching Rate
b. Routing Plan
c. Human message handling aspects
d. Signaling Procedure
e. Precedence levels
f. Processor speed and capacity
g. Queueing

5.5.7 Isolation of Contributing Equipment Factors

The most critical equipment in the speed of service analysis are normally the message switch and the torn tape relay assemblage.

5.6 CALL PLACEMENT TIME (CPT)

5.6.1 Definition

Call placement time is the average time required to establish a circuit from sender to receiver, measured from the time the calling party goes off hook until the first ring or its equivalent at the called party. The average is weighted in accordance to the traffic demand matrix.

5.6.2 Conditions

a. The connection is attempted during busy-hour traffic

b. All equipments are in perfect working order

c. The type of call is specified (see grade of service)

d. "Total time" is the time from completion of dialing until the initiation of the ring signal at the called terminal

5.6.3 Background

CPT is of primary significance to calls that are placed and completed in real time. It does contribute to the speed of service for messages that pass thru a message switch but as discussed in Section 5.5, CPT is normally negligible due to the time that can be consumed when a message is in a queue.

This MOE considers the total time required to place a call. The more significant time delay could be the time waiting for a dial tone or operator, the dialing time and the time required to process a call through a system.

Call placement time if normally controlled by the switch either through processing delays or by a delay in providing dial tone. As such it is dependent on the switch specifications and the number of switches that the call must pass through. If the system under analysis employs satellite trunking, the up link/down link delays also come into play.

5.6.4 Example Methods

The procedure for calculating this MOE is to estimate the call-placement time between a particular pair of subscribers, and then to average over all subscriber pairs.

$$\mathrm{CPT}_j = \frac{\sum_i \left[e_i \quad (\overline{\mathrm{CPT}_i}) \right]}{\sum_i \quad e_i}$$

where:

e_i = Total i^{th} needline traffic if the needline is a j^{th} service request

e_i = 0 if the needline is not a j^{th} service request

$\overline{\mathrm{CPT}_i}$ = Average call placement time for the i^{th} needline

$\overline{\mathrm{CPT}_i}$ can be estimated from the following equation:

$$\overline{\mathrm{CPT}_i} = \frac{1}{e_i} \sum_{l} e_{il} \times \sum_{r} t_{ilr}$$

where:

e_i = Total i^{th} needline traffic

e_{il} = The total needline traffic of the l^{th} path of the i^{th} needline

t = Average delay of the r^{th} equipment l^{th} route, i^{th} needline in processing the call set up

5.6.5 Quantitative Analysis

The time delays that contribute to the call placement time are a function of the equipment that a call must pass through in going from the source to the sink. The strings of equipment that are required to pass the calls can be correlated with specific needlines. A finite number of types of equipment strings can be identified by analyzing the system and subsystem under study. These will be referred to as reference circuits. Appendix C discusses the construction of these reference circuits.

The speed of service can be calculated for each reference circuit and the arithmetic average of these estimates will represent the system speed of service.

The recommended analysis is based on the reference circuit concept. These circuits should be identified in accordance with the concept expressed in Appendix C.

5.6.6 Qualitative Analysis

If adequate data is not available for a quantitative analysis, the different alternatives should be examined in terms of the following aspects.

a. Switching rate
b. Routing Plan
c. Processor Speed and Capacity
d. Manual/Automatic Switching
e. Number of switches thru which the call must pass

5.6.7 Isolation of Contributing Equipment Factors

The equipment that significantly influence this MOE are circuit switches, switchboards and communication satellite equipments.

5.7 INDEX OF AVAILABILITY

5.7.1 Definition

The weighted average over all subscriber pairs of the ratio of accepted traffic of a specific type over an imperfect system to accepted traffic over a perfect system, when an imperfect system has equipment failures but a perfect system has none. The average is weighted in accordance with the traffic demand matrix.

5.7.2 Conditions

a. The measurement is made during busy hour traffic.

b. The system is not subjected to enemy overt or covert action.

c. All system executions are normal except those caused by faulty equipment.

d. Traffic blockages do not contribute to unavailability.

e. The type of call is specified.

The above definition, coupled with the qualifying conditions, form the point of departure for the analysis of the index of availability MOE. The conditions and delineations are meant to restrict the study of this MOE to the normal operating stress on the system that results from equipment failure and to eliminate from consideration any other stress situations.

It may be, that during a wartime situation, the extreme stresses placed on communications equipment would degrade the mean times between failure (MTBF) by a significant factor. If calculations of availability are assumed to be made for such an environment, the MTBF could arbitrarily be reduced by some factor. For TRI-TAC equipment, a reduction by a factor of two is recommended.

5.7.3 Background

Availability treats the basic problem of what fraction of the time a system or equipment is in an operational state as opposed to the time that it is in a down state as a result of equipment failure.

The mathematical equation that expresses the above concept is:

$$\text{Availability (A)} = \frac{\text{Uptime}}{\text{Total Time}}$$

It can also be written as:

$$A = \frac{\text{MTBF}}{\text{MTBF} + \text{MDT}}$$

where,

MTBF = Mean Time Between Failure - a function of reliability

MDT = Mean Down Time - a function of maintainability

There are three forms of availability - inherent, achieved, and operational. These three categories are a function of how the MDT is defined.

<u>Inherent Availability</u> (A_I)

$$A_I = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}}$$

where,

MTTR = Mean Time to Repair

MTTR includes only down times associated with the performance of unscheduled maintenance actions.

<u>Achieved Availability</u> (A_A)

$$A_A = \frac{\text{MTBF}}{\text{MTBF} + (\text{MTTR} + \text{MTTP})}$$

where,

MTTP = Mean Time to Perform Scheduled Maintenance

Operational Availability (A_O)

$$A_O = \frac{MTBF}{MTBF + MDT}$$

where,

MDT = Mean Down Time. It includes all times associated with the repair of equipment, such as maintenance, supply and administration.

Operational availability is the more meaningful category of availability in cost effectivess analysis since it considers all aspects of the supply and maintenance system.

5.7.4 System Availability

A communication system will never fail but it can be degraded as a result of failures of some of its component equipments. Several methods can be used to estimate the degree of degradation. One concept is the use of a non-dimensional number such as is normally used in system/equipment specifications, e.g., an availability of 0.9999.

This approach can have meaning for a piece of equipment which has only two states, either up or down. For a communication system, such a specification becomes almost meaningless because the basic problem to be addressed is the amount of degradation that exists in an operating system.

The TRI-TAC approach is to measure how much system capacity has been lost due to equipment failures. This is done by estimating the degradation of the average link grade of service that results from equipment failures. Mathematically, this can be expressed as:

$$A = \frac{1 - GOS_{ai}}{1 - GOS_i}$$

where,

GOS_{ai} = average link grade of service that includes the impact of equipment failures

GOS_i = average link grade of service for a system without failures

Two calculations are required to estimate this ratio. The first is to estimate the grade of service for a system that is assumed to have no failed equipment. The second calculation is a repeat of the first, but in this case, equipment failures are assumed based on the MTBF of the associated equipments.

A second concept that must be considered in an availability analysis is redundancy. The objective of redundancy is to minimize the effect of a failure. For example, a piece of equipment may have an MTBF of 5,000 hours. If two of these equipments are provided, when only one is required to perform the function, the effective MTBF becomes 10,000 hours. Redundancy therefore can have a tremendous effect on availability.

5.7.5 Equipment Availability

The equations presented in Section 5.7.3 can be used to calculate the availability of communications equipment. However, due to the degree of redundancy that can exist in specific equipments, each analysis should be done on an individual case basis.

The basic question that should be examined is that of downtime. Normally, it can be assumed that when a failure occurs in an equipment, it should be repaired immediately. This is the case for items such as a handset. However, if one line in a 300-line switch fails, must the switch be put into a non-operational state and the failure repaired?

This latter problem is a significant one in an equipment such as the AN/TTC 39 switch. The preferred method for accruing downtime is listed in the specifications for the switch. It is presented in the following paragraph. The method can be modified for other equipments where a high degree of active redundancy exists.

Circuit Switch Downtime Accrual

By equipment category, downtime (t_d) accrues as follows:

a. Common equipment (i.e., affecting all terminations) $t_d = T$ where T is the duration of the fault (time to correct).

b. Equipment affecting n terminations, $t_d = nT/300$ for the 300 termination configuration.

c. Pooled equipment accrues downtime on the basis of the reduction in peak hour traffic handling capacity. If the peak hour traffic handled by the pooled equipment is e Erlangs with the design grade of service, the failure of some of the pooled equipment will reduce the amount of traffic which can be handled with the same grade of service to e' Erlangs. The accrual of downtime is then proportional to the reduction in traffic handling capacity at a fixed grade of service, $t_d = (e-e')T/e$.

d. When multiple faults occur, downtime shall accrue as the sum of the separate accrual rates except that downtime cannot accrue at a rate greater than real time.

e. When a fault or combination of faults reduces the system's capabilities by greater than 20 percent, downtime shall accrue as real time, $t_d = T$.

The downtime accrued on peripheral equipments which do not directly affect line circuit quality is excluded from system downtime. It is accrued separately, by function, at a rate equal to the proportion of the function which is degraded ($t_d = \%$ degraded T). Each peripheral function shall meet an availability standard equal to that specified for the line circuit related equipments.

5.7.6 Quantitative versus Qualitative Analysis

The type of analysis that can be performed is dictated by the amount of information and data that is available on the alternative under study. In general, it can be stated that quantitative analysis is required to perform a study on availability at the system level. This is true even for postulated systems. At the equipment level, a quantitative analysis is desirable and can be done in most instances. However, in certain cases, such as a comparison of one equipment conceptual alternative to another, a qualitative study may be dictated.

5.7.6.1 Quantitative Analysis

An availability analysis at the system level requires a computerized model. The problem that must be investigaged could be as follows: Determine the index of availability for a system which provides communications for a two-corps field army supported by ten tactical air bases. This force structure can require approximately 200 automatic circuit switches, 25 message switches, 30,000 telephones, plus appropriate crypto devices, line of site and troposcatter radios, technical control facilities, et al. The traffic demand matrix would probably identify more than 30,000 subscriber-to-subscriber need lines.

One model that was developed for the analysis of such a system was the Mallard System Availability Model for Communications, (SAM-C). This model was constructed in two parts, the trunk model and the access model. The trunk model was designed to analyze the availability of the trunk network that included the trunk switches and the various multichannel trunk radios. It considered the high degree of redundancy that exists in the network as well as the alternative routing capability of the switches. The access portion of the model was designed to analyze the access strings of equipment required to connect a subscriber to a trunk switch. This model could analyze the series type of availability problem that was encountered in the string, and, also, it could be used to investigate the redundant units that appeared in the strings, such as switch boards, down the hill radio, etc. The output of the model was an availability numeric and grade of service for each need-line, plus the system figure of merit.

A much less sophisticated model is required to analyze the availability of a piece of equipment. It would have to be customized for each use but would contain the basic relationships that were discussed in paragraph 5.7.5.

5.7.6.2 Qualitative Analysis

A qualitative analysis of a system may be possible in certain situations. However, most qualitative analyses would be performed on an equipment in the early conceptual stages for this item. The method used would be to assemble a panel of experts and discuss the pros and cons of the various alternatives. An "aide memoir" consisting of a list of questions would be used to lead the discussion. The resultant ratings would be handled in accordance with the methodology proposed in Section 4.4.1 A series of potential discussion areas is listed below.

a. Mean time between failure

b. Mean time to repair

c. Equipment redundancy and simplicity of functions performed

d. Component availability/reliability

e. Duty factors of equipment

f. Ruggedness of equipment

g. Number of maintenance personnel required

h. Network configuration (redundancy, etc.)

i. Administrative maintenance procedures

j. Time required to identify equipment outage or degradation

5.7.7 Isolation of Contributing Equipment Factors

All equipments contribute to system unavailability.

5.8 LOST MESSAGE RATE

5.8.1 Definition

The lost message rate is the percentage of data messages or calls that are accepted by the system, but are lost or misrouted.

5.8.2 Conditions of Evaluation

a. The attempt is made during the busy-hour traffic.

b. The system is not subjected to overt or covert enemy attack.

c. All system executions are normal except for:

   1. Disruptive executions caused by software errors or information incorrectly stored in memories.

   2. Disruptive executions caused by incorrectly received information that was correctly transmitted.

d. The type of call or message is specified.

5.8.3 Background

The lost message rate is defined herein to measure those messages lost due to equipment or software design errors. As a system received field testing this rate will decrease as errors are identified and corrected. However, some errors may never be detected. The lost message rate will therefore, approach a rate due only to component failures. This rate is included in the MOE "Availability" and is not in the lost message rate.

Lost message rate estimates are made separately for each type of service request on the j^{th} type of service request and is denoted as LMR_j. The procedure for estimating LMR_j is to estimate the lost message rate between a particular pair of subscribers, and then to average overall subscriber pairs.

$$LMR_j = \frac{\sum_i e_i \overline{LMR_i}}{\sum_i e_i}$$

where,

e_i = Total i^{th} needline traffic if the needline is a j^{th} service request

e_i = 0 If the needline is not a j^{th} service request

$\overline{LMR_i}$ = Average lost message rate for the i^{th} needline.

It seems reasonable to assume that any "disruptive execution" will result in a lost call. For small processing error probabilities,

$$\overline{LMR_i} = \frac{\sum_{l} e_{il} \sum_{r} P_{ilr}}{\sum_{i} e_i}$$

where,

e_i = Total i^{th} needline traffic

e_{il} = Total l^{th} route traffic of the i^{th} needline

P_{iir} = Probability that the r^{th} subsystem of the l^{th} route, i^{th} needline will have a processing error.

5.9 INDEX OF SURVIVABILITY (OVERT ATTACK)

5.9.1 Definition

The ratio of the average number of calls per unit time completed after damage to the average number of calls completed before damage, when the traffic demand is specified and held constant before and after attack.

5.9.2 Conditions of Evaluation

a. The call attempts are made during the busy hour.

b. The type of call is specified (see grade of service).

c. A blockage is not considered to occur, if the called subscriber is busy.

d. There is no partial damage to equipment. It either functions properly as it did prior to the attack or it is completely destroyed.

5.9.3 Background

The index of survivavility (overt attack) assesses the ability of a communication system to continue to operate after certain of its component equipments have been damaged by enemy action. The damage can be caused by either nuclear or conventional weapons. The conditions mentioned above limit the problem to this particular stress for purpose of cost-effectiveness analysis.

5.9.3.1 The Concept of Survivability (Overt Attack)

The definition of this MOE can be represented by the equation:

$$SUR_o = \frac{1 - \overline{GOS_{si}}}{1 - GOS_i}$$

where,

$\overline{GOS_i}$ - Average link grade of service before attack

$\overline{GOS_{si}}$ = Average link grade of service after attack

The estimation of this MOE requires two separate calculations. GOS_i is first calculated for an unstressed system. This is the identical problem that is addressed for grade of service in Section 5.3. The second calculation is to estimate the grade of service for the damaged network. This should be done for varying intensities of conflict. In this second calculation, the grade of service will be degraded since basically, the same amount of traffic will be offered to the system that now has a reduced capacity. The alternate routing capability of a system is one parameter that must be investigated to the fullest so that the operation of the degraded system can be optimized.

Philosophically, it can be stated that a communication <u>system</u> cannot be damaged by enemy action, but that its performance is degraded due to the damage inflicted on its component equipment by the enemy.

The problem that must be analyzed for the equipment is their ability to withstand a variety of enemy threats. Two conditional probability functions come into play in determining the survivability of equipment operating as part of a system. The first is the probability of hit, given the probability of the equipment being selected as a target, $(Ph|Ps)$. The second is the probability of kill, given the probability of hit, $(Pk|Ph)$.

The $(Pk|Ph)$ parameter is the critical parameter for the analysis of the equipment level problem. Resistance to blast, overpressure, and EMP (Electromagnetic Pulse), are some of the inputs that come into play in this analysis.

The (Ph|Ps) statistic couples equipment level survivability to the system level problems.

5.9.3.2 Quantitative versus Qualitative Analysis

The type of analysis that can be performed is dictated by the amount of data that is available on the alternatives under study. In general, it can be stated that quantitative analysis is preferrable for studies at the system level. It is desirable that quantitative analysis be done for equipments, but in some cases, this may be a difficult problem.

5.9.3.3 Quantitative Analysis - System Level

The analysis of this MOE at the system level is a two step process. First, the system must be stressed in accordance with a postulated enemy scenario. The scenario should consider the types and number of weapons available to an enemy, and the tactical doctrine that a foe would be assumed to follow, such as the priority he would place on communications type targets. Specific information on the individual weapons is required such as their circular error probable and the inflight reliability for aerodynamic weapons or the beaten zones for artillery shells.

The (Ph|Ps) and (Pk|Ph) probabilities are derived from the above information. These statistics plus the doctrine of attack, are used to stress the communication system in terms of which nodes and links would be destroyed in the postulated attack.

In order to make the problem one of manageable proportions, certain constraints are arbitrarily imposed. Some examples are: that small arms do not impose a threat since TRI-TAC equipment will never be close enough to the FEBA to be exposed to such a threat; or Armed Tactical Reconnaissance Teams will never penetrate more than five miles beyond the FEBA.

The analysis of survivability (overt attack) requires a two part computerized model. The first segment is designed to impose a stress on the network and to estimate the resultant damage. Inputs to the model are the force structure to be analyzed plus the enemy scenario and the necessary enemy weapons statistics. The weapons probabilities must be developed external to the model and inserted as input data. A model such as NuSAP is required for this analysis.

The second part of the analysis requires that the grade of service of the damaged network be estimated. A grade of service model such as CASE is required for this analysis. This part of the problem is discussed in Section 5.3 and need not be repeated.

5.9.3.4 Quantitative Analysis - Equipment Level

This analysis must be based on (Pk|Ph) probability. This probability takes on varying connotations for different weapons. Some items such as an artillery shell basically must make a direct hit on an equipment or an assemblage of equipment to destroy the unit; NAPALM bombs have a wide area of destruction and in effect do not require that a direct hit be made; and atomic bombs have a wide radius of destruction.

A second concept that should be considered in calculating the probability of kill is that some equipment, such as an antenna, will be mounted external of a shelter, while other items are housed within a shelter. Consideration must be given to this situation.

The parameters of weapons effects, such as overpressure, EMP, and radiation, must be quantified. A structural analysis must be made on the equipments/shelter to determine if they can withstand the different stresses. Circuit analysis is also required to assess the effects that the electrical or radiation effects can have on the semiconductor devices within an equipment, as well as deleterious effects on software.

5.9.3.5 Qualitative Analysis

The following statements are a sample of the aspects of a system/equipment that could be discussed in a qualitative analysis of this MOE.

a. Pressure hardness of system equipment to nuclear/non-nuclear attack.

b. Enemy weapon yields

c. Accuracy of enemy weapons

d. Defenses protecting that part of the system being evaluated

e. Network redundancy

f. Impact of destruction of one node on system traffic handling capabilities

   1. Connectivity

   2. Flexibility in reallocating terminal capacity

g. Degree of centralization of control

5.9.4 Isolation of Contributing Equipment Factors

Destruction of each piece of equipment contributes to a degradation of system survivability.

5.10 INDEX OF SURVIVABILITY (JAMMING)

5.10.1 Definition

The ratio of the average number of calls per unit time completed during a jamming stress to the average number of calls completed in an unjammed system, when the traffic demand is specified and held constant before and during attack.

5.10.2 Conditions of Evaluation

a. The call attempts are made during the busy hour.

b. The type of call is specified (see Grade of Service)

c. A blockage is not considered to occur, if the called subscriber is busy.

5.10.3 Background

The index of survivability (jamming) assesses the ability of a communication system to continue to operate during a jamming attack. The conditions listed above limit the problem to this particular stress for purpose of analysis.

5.10.3.1 The Concept of Survivability (Jamming)

This MOE treats two aspects of a communication system. The first aspect is how well can the system continue to function when it is being electromagnetically jammed by an enemy. The second problem that is considered is that of self-jamming where radiations from one part of the system interfere with the operation of other components within the system.

The definition of this MOE can be represented by the following equation:

$$SUR_j = \frac{1 - \overline{GOS_{ji}}}{1 - \overline{GOS_i}}$$

where,

$\overline{GOS_{ji}}$ = Average link grade of service during jamming.

$\overline{GOS_i}$ = Average link grade of service before jamming.

5.10.3.2 Quantitative versus Qualitative Analysis

The evaluation of a system operating under a jamming attack may require the processing of large quantities of data. It can best be done with a computerized model. The analysis of the anti-jam aspects of an equipment can be done quantitatively if the necessary data is available. When sufficient information is not available, a qualitative analysis is possible.

5.10.3.3 Quantitative Analysis - System Level

The estimation of this MOE requires two separate calculations - the first is the grade of service for an unstressed network. This problem is discussed in Section 5.3. The second requires that the network be stressed in accordance with a jamming scenario and the grade of service recalculated for the degraded network.

In the case of enemy jamming, a scenario must be developed that would include the number and type of jammers possessed by an enemy, their geographical location, power output, types of antennas, frequency ranges and type of jamming signal produced. The enemies concept of jamming must also be developed and inputted into the scenario. The communication system is then stressed in accordance with the scenario so that the estimate can be made of those links that are made inoperative. It should be noted that only radio links can be jammed and not equipment such as switches. Moreso, the part of the link that is jammed are the receivers not the transmitters. Information required for development of this scenario is contained in TRI-TAC Cost Effectiveness Program Plan, Vol IV, Threat Forecast. This evaluation can be made through a model such as the MALLARD Vulnerability Model which can evaluate the threat as well as the resultant grade of service. An alternative approach would be to use the MALLARD model for the threat assessment and calculate the grade of service with a model similar to CASE. A discussion of CASE can be found in Appendix B.

The estimation of self-jamming is a similar problem in that the same parameters are required for the analysis but in this case they are required for friendly forces emitters as opposed to enemy jammers. The self-jamming concept can be considered as part of this measure of effectiveness where two competing alternative system designs would have a different figure of merit in this regard. However, normally this type of analysis is done on postulated systems as part of the system engineering process so that corrections can be made prior to the start of the effectiveness analysis of the system.

5.10.3.4 Quantitative Analysis - Equipment Level

It must be assumed that all receivers can be jammed if their antennas are pointed in the direction of the FEBA. The analysis of the receivers should take the form of how well they are designed to minimize the effect of a specific threat. Spread spectrum, frequency hopping and other anti-jam techniques should be considered.

5.10.3.5 Qualitative Analysis - Equipment Level

The following subject areas should be considered in performing a qualitative analysis of this MOE.

a. Signal-to-jammer power ratio

b. Jamming signal type

c. Transmission medium

d. Channel capacity loss for given level of jamming attack

e. Ease of control under jamming attack

f. System sensitivity to jamming

g. Ease of providing A/J capability

5.10.4 Isolation of Contributing Equipment Factors

Radio receivers are the equipment that are jammed. Other equipment may suffer secondary effects from this type of threat.

5.11 INTERRUPT RATE

5.11.1 Definition

The interrupt rate is the percentage of calls that are interrupted inadvertently by the system for reasons other than preemption. Included in the interrupt rate are calls interrupted or garbled beyond acceptable limits by atmospheric effects.

5.11.2 Conditions of Evaluation

a. The call is attempted during busy-hour traffic.

b. The system is not subjected to overt or covert enemy attack.

c. All system executions are normal except for disruptive executions caused by environmental disturbance outages.

d. The type of call is specified.

e. Traffic blockages do not contribute to the value of interrupt rate.

5.11.3 Background

5.11.3.1 The Concept of Interrupt Rate

The interrupt rate measures two probabilities, namely the probability of:

- Losing bit synchronization, system timing (TDMA framing and buffer overflow) and crypto synchronization.
- Signal fading (Multipath or weather conditions).

Interruptions to messages or calls due to equipment failures are measured under the Availability MOE.

Interrupt rate estimates are made separately for each type of service request with the j^{th} service request being designated IR_j.

IR_j is determined by estimating the interrupt rate between the i^{th} pair of subscribers and then averaging over subscriber pairs.

$$IR_j = \frac{\sum_i e_i \overline{IR_i}}{\sum_i e_i}$$

where,

e_i = Total i^{th} needline traffic if the needline is a j^{th} service request

e_i = 0 if the i^{th} needline is not a j^{th} service request

$\overline{IR_i}$ = The probability that a call connection will be disrupted by propagation outages.

If the probability of an outage in one subsystem is small and independent of other subsystems, then the outage probabilities can be added along each route.

$$\overline{IR_i} = \frac{\sum_l e_{il} \sum_r u_{ilr}}{e_i}$$

where,

e_i = Total i^{th} needline traffic

e_{il} = Total 1^{th} route traffic of the i^{th} needline

u_{ilr} = The probability that a call connection will be disrupted by propagation outages by the r^{th} subsystem, 1^{th} route, i^{th} needline.

5.11.3.2 Quantitative Analysis

This MOE pertains to instabilities that occur in strings of equipment that include one or more radio paths. These paths when tied together form a system. The Interrupt Rate MOE therefore can be based on an analysis of those strings that are defined as reference circuits in Appendix C. Reference is made to this appendix for details in identifying pertinent reference circuits.

The two probabilities identified in Section 5.11.3.1 should be estimated for each type of reference circuit. The system interrupt rate (IR) can then be calculated by averaging the IR estimated for each circuit.

The calculation of these parameters requires the following data:

- The synchronization scheme of the system
- Effects of bit errors on system synchronization
- Propogation effects on bit error rate

5.11.3.3 Qualitative Analysis

If adequate data is not available for a rigorous analysis, a qualitative investigation of the various alternatives should consider the following aspects of the various reference circuits.

a. Probability of losing bit synchronization, system timing (TDMA framing and buffer overflow).

b. Probability of signal fading (multipath or weather conditions).

5.11.4 Isolation of Contributing Factors

The more significant equipments that must be studies in this evaluation are the nodal switches, crypto equipment, transmitters and receivers.

5.12 MOBILITY

5.12.1 Definition

Mobility is the setup time plus the teardown time of the network or parts thereof, as directed by the system planners. Setup time is the elapsed time to set up an equipment from the time of arrival, at a new site until the equipment is operating as part of a system. Teardown time is the elapsed time of equipment removal from an operational state until the equipment has been prepared for a move.

5.12.2 Conditions for Evaluation

a. The conditions necessary to begin communication activities are specified.

b. The conditions necessary to begin transportation activity are specified.

5.12.3 Background

Occasionally a requirement will exist for an entire communication system to be moved at the same time into a new combat theater. Usually, the realistic situation is that a node, be it either a switching or transmission node, will be the basic unit for movement. In certain cases a requirement that individual equipments be shifted from place to place will occur. The calculation of the mobility of a node requires basic set up and tear down data on equipments.

5.12.3.1 Qualitative Analysis

The defining equation for this MOE at either the equipment or nodal level is:

$$MOB = T_s + T_t$$

where,

T_s = Set up time

T_t = Tear down time

At the equipment level,

$$T_s = T_s' + \sum_i (N_i \times T_{si})$$

$$T_t = T_t' + \sum_i (N_i \times T_{ti})$$

where,

T_s' = Basic set up time for an equipment

T_t' = Basic tear down time for an equipment

N_i = Value of i^{th} sizing parameter (trunks, lines, terminals)

T_{si} = Set up time required per unit of the i^{th} sizing parameter

T_{ti} = Tear down time per unit of the i^{th} sizing parameter

In general, N_i will be small for most TRI-TAC equipments. For example, two sizing parameters would be sufficient for the AN/TTC-39 switch. These being the number of loops and the number of trunks.

The objective is to estimate the mobility of a node. This analysis must be based on the set up and tear down time of the component equipments. A Performance Evaluation Review Technique (PERT) chart is one way recommended as the analytic medium. First, individual PERT charts should be developed for each piece of equipment. As an example, the AN/TTC-39 switch analysis requires the following information:

a. The basic set up time including such activities as power set up and memory loading

b. The basic tear down time

c. The time to get individual lines operational

d. The time to get individual trunks operational

e. The size of the switch in terms of lines and trunks

With the above as input data, the set up time (T_s) and tear down time (T_t) are identified by determining the critical path through the PERT for each of these parameters. The T_s and T_t for each type equipment contained in the node are inputted into a nodal level PERT. In constructing this PERT chart, the estimated numbers of personnel available to do the required tasks must be considered since personnel considerations can dictate whether all tasks can be done in parallel or that some work may be done in a serial fashion. The T_s and T_t parameters for the node are then quantified by another critical path analysis.

5.12.3.2 Qualitative Analysis

If sufficient data is not available, a qualitative analysis may be made of the mobility of a node by considering gross estimates of the following:

a. Physical set up/tear down time

b. Electrical set up/tear down time

c. Set up/tear down crew required

d. Size and weight of equipment evaluated

5.12.4 Isolation of Contributing Equipment Factors

Normally individual equipments contribute to the mobility of a node in proportion to their size, weight and complexity. If sufficient personnel are available to set up or tear down the particular equipments in a node in parallel, the equipment requiring the longest time establishes the nodal set up or tear down time. If certain equipments must be handled sequentially, then each item in this time chain contributes proportionately to nodal mobility.

5.13 TRANSPORTABILITY

5.13.1 Definition

Transportability is the ease with which the network or parts thereof can be moved as directed by the system planners. Weight, volume and the number of transport vehicles are primary considerations.

5.13.2 Discussion

This MOE addresses the problem of how well the system, equipment assemblage or equipment can be moved from one point to another. The basic parameters that must be addressed in this area are size, weight and volume.

5.13.2.1 Concept

The transportability MOE has little meaning at the system level since it would be unusual that an entire system would ever be picked up and moved. The MOE becomes very meaningful when nodes and assemblages (shelter with equipment) are being considered. A node will normally consist of several assemblages.

The node, be it a switching or a transmission node, should be used as the basic organization for analysis. Academically, it would be nice to study each type of node and permutation therein. The practical approach that is recommended is that two or three typical nodes of each type be identified by the appropriate service for the analysis.

The nodes should be described in sufficient detail to include the number of shelters, the number of non-sheltered mounted equipment, the number of vehicles and power units, the numbers and type of materiel handling equipment, as well as the number of personnel required to operate and maintain the node. The volume and weight of all equipment must be given.

Many effectiveness studies encountered in the past listed electrical power as a separate MOE. These approaches in reality considered the power problem twice. It was evaluated under the power MOE and reevaluated under the transportability MOE. The TRI-TAC concept is to count it once, under transportability, since the output power can be correlated with size, weight and volume.

The personnel required to operate the node are considered under this MOE only from the standpoint that they have to be transported. The primary consideration is the question whether additional vehicles, over and above those required for moving or installing the equipment, are needed for personnel transportation.

A transportability analysis can be meaningful at the equipment level for some equipments but for others such a study would be trivial.

An equipment such as the AN/TTC-39 switch that requires one or more shelters should be evaluated in terms of this MOE. In such a case, caution is recommended since other equipments such as certain TENLEY items may also be housed in these shelters. The other extreme example is a subscriber sub-set. Its small size makes a transportability analysis meaningless.

A traditional analysis of this MOE has been based on such questions as: can a shelter be transported in a C-130; can it be lifted by a helicopter; will it fit into the hold of a ship? The size and volume problem should be bounded by constraints in that shelters must be a standard height, weight and length.

This section does not address the effectiveness of shelters since it must be assumed that the final decisions on future shelter dimensions will be strongly influenced by International Standards Organization requirements.

5.13.2.2 Quantitative Analysis

Transportability is estimated by totaling the adjusted total equipment volume for each subsystem.

T_j = Transportability index of the j^{th} subsystem.

If the average density of the equipment for the j^{th} subsystem is less than the packing density of the transporting vehicles, then T_j is the total subsystem volume. If, however, the density of the j^{th} subsystem is greater than the optimum packing density of the transporting vehicles, then the weight of the subsystem is the determining factor, and the total volume must be adjusted.

$$T_j = m_j \frac{d_{ej}}{d_{tj}} \text{ if } d_{ej} \geq d_{tj}$$

$$T_j = m_j \text{ if } d_{ej} < d_{tj}$$

where:

m_j = Total j^{th} subsystem volume

d_{ej} = Average density of j^{th} subsystem

d_{tj} = Maximum load density for a fully loaded vehicle.

5.13.2.3 Qualitative Analysis

If adequate data is not available for the above analysis, qualitative aspects such as the following can be considered in the evaluation.

a. Equipment size and weight

b. Number and size of transport vehicles required to transport equipment

c. Packaging

d. Terrain specified for effectiveness evaluation

5.13.3 Isolation of Contributing Equipment Factors

Each item of equipment must be analyzed separately and a determination made as to the penalty it imposes on the transportability of the node.

5.14 SERVICE FEATURES

5.14.1 Definition

Service features are a qualitative assessment of the services available, e.g., direct distance dialing, conference call capability, priorities, et al.

5.14.2 Background

Service features is an MOE that is not quantifiable. Its scope includes certain features that can or can not be performed by a communication system such as a conference call capability. The evaluation of a system in this MOE area is primarily a binary assessment, the feature exists or it does not.

5.14.3 Qualitative Analysis

The following aspects should be investigated in this analysis:

a. Abbreviated Dialing
b. Compressed Dialing
c. Call Hold
d. Call Transfer
e. Line Grouping
f. Hands Free Operation
g. Conference Calls
h. Broadcast
i. Operator Recall
j. Bridging
k. Unique Address Numbering System for Selected Subscribers.

5.14.4 Isolation of Contributing Equipment Factors

The type of service features that can be provided in a system is a function of switch design and the associated software package.

5.15 EASE OF RECONFIGURATION

5.15.1 Definition

Ease of Reconfiguration is the ability of the system to expand, contract, and reorganize to satisfy the range of subscriber demands.

5.15.2 Conditions for Evaluation

a. The initial traffic needs are specified along with the initial arrangement plus a new set of traffic needs.

b. The module sizes are specified.

c. The type of call is specified.

d. Communication control procedures are specified.

5.15.3 Discussion

The Ease of Reconfiguration measures the adaptability and flexibility of equipments that comprise the system. This measure was chosen to highlight the ability of a tactical communications system to operate under varying traffic demands and changing numbers of subscribers. This MOE can be measured either quantitatively or qualitatively as discussed below.

5.15.3.1 Quantitative Methods

Two estimating procedures are presented. The first estimate measures the time required for the system to respond to changing traffic needs by utilizing equipment modules. The second estimate measures the degree to which equipment modules are efficiently used to meet traffic needs.

a. Elapsed Time Estimating Procedure

This estimating procedure measures the average time necessary for communication control to modify the system to meet new traffic needs. This measurement requires that initial traffic needs are specified along with an initial system arrangement plus a new set of traffic needs.

The measurement consists of measuring the system modification time for each new set of traffic needs. This measurement can be done utilizing PERT chart methodology whereby replacement of modules would be milestones and communication control procedures would describe the PERT chart structure.

b. Uniformity Estimating Procedure

This estimate measures the variance in the way similar modules are utilized in the system. A system configuration which uses the same module in the same way throughout the system is flexible because there are enough module sizes to meet each local traffic need. Utilizing too large of a module size must indicate that sufficient flexibility in module selection has not been given by the system designer.

This estimate is the average percentage of unused traffic capability for the i^{th} modular equipment. The average percentage of unused traffic capability for the i^{th} needline is:

$$EOR = \frac{1}{e_i} \sum_{l} e_{il} \sum_{r} \left\{ \frac{E_{ilr} - e_{il}}{e_{il}} \right.$$

where:

e_i = Total traffic for the i^{th} needline

e_{il} = Total traffic for the l^{th} path of the i^{th} needline

E_{ilr} = Maximum value of all total traffic through subsystems which are identical in capacity and are interchangeable with the subsystem identified with the set (i, l, r).

EOR is the average of $\overline{EOR_i}$ weighted by the traffic on each needline.

$$EOR = \frac{\sum_{i} \sum_{l} \sum_{r} E_{ilr} - e_{il}}{\sum_{i} e_i}$$

The quantitative evaluation of the Ease of Reconfiguration MOE presupposes that certain data are available such as:

a. Total system configuration to include nodal connectivity, size of switches, size of trunks, etc.

b. Routed traffic figures through this system.

c. Communication control procedures.

d. Assumed change in traffic demand.

The first two sets of data are required to evaluate the uniformity method described above. The last two sets of data are needed to evaluate the time elapse method. Perhaps the most difficult sets of data to obtain are the first two sets. The configuration of the system can be a result of a computer simulation which has been run to support a force deployment and traffic data base such as a SIMCE Model run. If modularities were assigned to the network configuration, the uniformity method could be evaluated.

The elapsed time method requires the definition of communication control procedures and assumed changes in traffic demand. Nodal access configurations can be used to advantage to define the initial configuration of a node which must undergo modification to meet additional traffic demand or additional subscribers. The data for changing numbers of subscribers could be taken from a tactical scenario. The movement of troops from one area to another can be translated to changing subscriber demands placed on area switches located in the theater. The nodal access models, the scenario data, and communication control procedure can be used to estimate the time elapse to satisfy changing requirements.

5.15.3.2 Qualitative Method

When the quantitative data is not available, qualitative assessment must be employed as a fallback position. The procedure is to take the qualitative aspects described below and make a subjective evaluation of how well the system, subsystem or equipment performs with respect to each aspect. A utility score can be assigned to each evaluation with respect to an accepted baseline and the scores may be combined to represent the assessment.

a. Ability to add and subtract nodes without intefering with the communications capability of other connected nodes.

b. Ability to add functions in a modular fashion.

c. Ability to add access functions.

d. Ability to add links.

e. Ability to change connectivity (redundancy of connections) and capacity.

f. Ability to update routing and directory.

g. Ability to change loop/trunk ratio.

h. Growth potential by voice bit rate reduction.

i. Ability to add service features.

j. Ability to accomodate all data rates.

k. Variability of interfacing locations.

l. Variability of traffic nodes.

m. Modularity of equipment.

n. Ease of adding and removing subscribers.

o. Ease of accommodating various traffic nodes.

Each of the aspects above contribute to the overall measure of Ease of Reconfiguration. By evaluating each aspect subjectively a qualitative assessment of this MOE can be obtained.

5.15.4 Isolation of Contributing Equipment Factors

In many instances, entire systems or subsystems can not be evaluated as a whole and the analysis must focus on a particular piece of equipment in the system. This instance calls for taking the basic system level MOE definition and customizing it to highlight the contribution of the equipment to the value of the MOE at the system level. The procedure is to isolate the contributing factors of a particular equipment to the MOE.

5.16 SPECTRUM UTILIZATION

5.16.1 Definition

Spectrum Utilization is the efficiency with which the system uses the available electromagnetic spectrum.

5.16.2 Conditions of Evaluation

a. All equipments are in perfect working order.

b. The System is not subjected to enemy attack or jamming.

c. Maximum information rate, bandwidth and frequency band of all radio links in the system be specified.

5.16.3 Background

The spectrum utilization MOE assesses two important areas within communication system design. The first area concerns the efficiency of bandwidth utilization for radio transmission techniques with respect to the maximum information rate that can be passed for a given bandwidth in the case of digital transmission or in channels for a given bandwidth in the analog case. The second area concerns the frequency band crowding problem that is becoming of increasing concern to military communication system planners. For example, the X-Band satellite allocations are inadequate for the planned systems that intend to operate in that band. The probability of obtaining an allocation in that band is relatively low. The spectrum utilization MOE combines these two factors to indicate the most efficient bandwidth utilization techniques that operate in frequency bands where frequency allocations are available.

Spectrum Utilization estimates are made separately for each subsystem requiring radio spectrum and then are weight averaged in accordance with the number of radio links in each subsystem. The general equation for system spectrum utilization is:

$$\text{SPEC} = \frac{1}{\sum_i R_i} \sum_i \left(R_i \ \overline{\text{SPEC}_i} \right)$$

where:

R_i = Total number of radio links in the ith subsystem

$\overline{\text{SPEC}_i}$ = Average spectrum utilization of the ith subsystem

$\overline{\text{SPEC}_i}$ is estimated by averaging the efficiency of bandwidth utilizations of each radio link of the ith subsystem and multiplying by the probability that the required bandwidth and frequency will be available. These products are summed over all links of the subsystem and averaged for each link. The equation for $\overline{\text{SPEC}_i}$ is:

$$\overline{\text{SPEC}_i} = \frac{1}{R_i} \sum_r \frac{I_{ri}}{B_{ri}} P_{ri}$$

where:

R_i = Total number of radio links in the ith subsystem

I_{ri} = Maximum information rate or number of channels of the rth radio link of the ith subsystem

B_{ri} = Bandwidth required by the r^{th} radio link of the i^{th} subsystem

P_{ri} = The probability that the bandwidth and frequency band will be available for the r^{th} radio link of the i^{th} subsystem.

The maximum information rate I_{ri} is not necessarily the maximum bit throughput rate of the radio link, but is the true information rate excluding overhead bits required for certain types of error correction codes, etc. The S_{ri} term was added to bring forth the problem of spectrum crowding and the increasing unavailability in certain frequency bands.

It should be noted that the higher the number achieved for SPEC, the more effective the system design.

5.17 INTEROPERABILITY

5.17.1 Definition

The degree to which the system is capable of interfacing with external systems, e.g., DCS, NICS and commercial systems.

5.17.2 Background

This MOE can be addressed from two separate levels. This can be illustrated by two questions. First, can two systems interoperate? Secondly, if they can, what is their degree of interoperability? This section addresses the second situation.

The degree of interoperability is addressed by analyzing the interfacing point between two systems in terms of how transparent is the interface. This evaluation should be done primarily in terms of those MOEs that are categorized as communication measures. The stability type of measures are not pertinent. The Mobility and Transportability MOEs could be considered if the physical size of the interfacing units are significant.

5.18 EASE OF TRANSITION

5.18.1 Definition

The inherent ability of a given system design that permits major modifications to be performed on the system without degradation in its overall performance during the period of change. The changes could be either by a smooth and gradual phasing in of new or modified equipment or by phasing out old equipment.

5.18.2 Background

This MOE treats the inherent capability of a system to be modified either by the upgrading of existing equipment or the replacement of these equipments with new items without its overall performance being degraded. Conversely, the performance should be expected to improve for each change.

The approach that should be followed in assessing this MOE is to postulate an equipment change and estimate the resultant system performance. Since the performance figure of merit is a composite of the evaluation of all other MOEs, the analysis of the ease of transition could require a total effectiveness analysis for each change in the system.

Extreme caution is required to constrain the analysis to manageable proportions. Only those MOEs that will show a significant change as a result of the modifications should be selected for the evaluation.

APPENDIX A

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APPENDIX B

EXAMPLE NETWORK MODELS

1.0 GENERAL

This appendix provides an overview of various network models that are available for use in estimating certain MOEs at the system level. The network models described in this appendix are:

a. CASE

b. SIMCE

c. NuSAP

d. MALLARD Vulnerability

e. Katz

f. AFCTC

Each model review includes information on the custodian of the model, where the model is operational, the kind of simulator, and its basic outputs. Also provided are the capabilities of each simulator with respect to estimating certain MOEs and the limitations that are inherent to the model design.

The purpose of these short overviews is to provide basic information about these simulators to aid in the selection and use of these analytical tools for application in system effectiveness evaluation by the Services and Agencies. A more complete description of these models can be found in the references listed in Appendix A.

2.0 CASE MODEL

2.1 General Description

The Communications Analysis and Systems Evaluation (CASE) model is a dynamic simulator that is under the custody of the U. S. Army Electronics Command, Fort Monmouth, New Jersey. This model was originally run on the Univac 1108 computer at Edgewood Arsenal, Maryland, from a remote terminal at Fort Monmouth. It can also be run on a CDC 1110.

The simulator consists of approximately forty modular programs that are written in FORTRAN language. CASE simulates a tactical Army communications system by synthesizing input data and employing an event-by-event simulation process. The data base currently being used for CASE is the Army COMSR (Communication Support Requirements) data base, with unit-to-unit traffic compiled by the SIMCE simulator.

2.2 Capabilities

CASE provides three important measures of System Effectiveness - Grade-of-Service (GOS), Call Placement Time (CPT), and Speed-of-Service (SOS). GOS is computed for voice traffic by counting the number of blocked calls during the call-by-call simulation, and expressing this data as the probability that a call is not blocked. CASE permits rerouting in the event of blockage at a node. In this instance, blockage occurs (for systems GOS) only if all reroutes fail. GOS is computed for the system, individual nodes, links and loop group to loop group.

TTY messages are not blocked but remain in queue until a connection is successfully established for transmission. Therefore, upon termination of the simulation phase of the model, a number of TTY messages may still remain in queue. System GOS for messages is actually the message completion rate, calculated by dividing total messages delivered by the total number of messages generated. The message completion rate is also provided for nodes and loop groups of originating TTY traffic.

CASE measures call placement time as a cumulative probability of delay. For example, the analyst may discover that 60% of the calls required 18 seconds or less to make the connection, 80% required 20 seconds or less, and so on. A cumulative distribution is provided for the system, for nodes and loop groups which originate calls, and for nodal and loop group needlines.

CASE measures speed of service as a cumulative probability of total transmission time. For example, 70% of the messages may have required 180 seconds or less to be transmitted, 85% may have required 190 seconds or less, and so on. A cumulative distribution is provided for the system and for each node and loop group originating TTY traffic.

CASE simulates Army tactical communications for Voice and TTY traffic and in separate runs allocates channels to Voice, TTY and data. The model incorporates such aspects of the system as communication center personnel, equipment types, and patching thresholds. The basic model can be supplemented by a fading model to add transmission realism to the simulation exercise. Resource utilization and message transmission statistics are provided among the outputs of the model. In addition, the CASE model can be used to calculate many of the GOS related MOEs such as the survivability and availability.

CASE is compatible with the Army COMSR data formats. It can also directly use the sized networks that are produced with the SIMCE model.

2.3 Limitations

The CASE model has several drawbacks that limit its usefulness in system effectiveness evaluation. A few such limitations are:

a. The model assumes two separate communication systems within the overall system, one for voice, data and facsimile and the other for teletype.

b. The need for security in transmitting messages is not addressed in CASE.

c. No special queue exists for secure messages awaiting the availability of a secure transmission capability.

d. The model was designed to simulate manual systems, but can be used for automatic switching systems with some limitations.

e. A complete set of user manuals are not owned by the government.

Within the above limitations, the CASE simulator can be used to evaluate GOS, GOS related measures, CPT, and SOS.

3.0 SIMCE MODEL

3.1 General Description

The Simulation Communications-Electronics model (SIMCE) is a static simulator used primarily for configuring and sizing communications networks. The model is under the custody of the Combat Training and Doctrine Group, U. S. Army Southeastern Signal School, Fort Gordon, Georgia. The model is run from a remote terminal at Ft. Gordon on the IBM360/65 computer located at Fort Monmouth, New Jersey. It is presently being converted for use on the CDC 6500 computer located at Fort Leavenworth, Kansas, and is programmed to be moved there in the future. The Simulator contains 20 or more programs written mostly in FORTRAN IV. Some newer programs have been developed and they are written in ANS Cobol. The current SIMCE data base is the Army COMSR data base.

3.2 Capabilities

The SIMCE Simulator processes its data base into the following inputs:

a. Unit-to-unit needlines

b. Unit locations

c. Node locations

d. Unit-to-node connectivities

e. Nodal needlines

f. Routed nodal needlines

g. Link sizing requirements and blocking probability

h. Routed nodal needline blocking probabilities.

These outputs are generated by using a statistical approach to assigning traffic and computing traffic statistics rather than using a call-by-call approach. Unit-to-unit needlines are identified from the data base and each of the units are placed geographically on a set of grid coordinates. A nodal location plan is then overlaid on those grid coordinates. The straight line distance of each unit from each node is then calculated and each unit is assigned to its closest respective node. A nodal needline file is then generated by properly aggregating the unit-to-unit needline file. The link connectivities are given to the model and all nodal needline traffic is then routed over the proper links. Links are then sized by erlang statistics to reflect the specified blocking level.

The model is useful for sizing communication systems to a specified blocking level. It can also be used to assess the blocking level (GOS) of a given system. Another very important application of this simulator is that the outputs listed under a, d, and g are used for input to the CASE Simulator. These inputs were formerly manual inputs to CASE.

3.3 Limitations

The SIMCE Simulation model has various limitations as follows:

a. The model does not consider all precedence levels (only two - urgent and routine).

b. The model does not consider all levels of security, however, it does consider whether traffic is secure or nonsecure.

c. Calls are not time ordered, therefore, making it impossible to determine number of required needlines for conference calls.

d. The model can only handle 60 nodes in one run.

Despite these limitations, the SIMCE model is very useful as a data manipulator and system configuring tool.

4.0 NuSAP MODEL

4.1 General Description

The Nuclear Survivavility Assessment Program (NuSAP) model is a static simulator that is under the custody of the Joint Tactical Communication Office (TRI-TAC) at Fort Monouth, New Jersey. The model is run on the Burroughs 5500 computer at Fort Monmouth. Its program is written in FORTRAN IV and the purpose of the model is to assess the impact of worst case nuclear attack on communications systems.

4.2 Capabilities

The NuSAP model is designed to assess the resultant damage to a network for varying levels of nuclear attack. The major output is a survivability index as a function of attack level. It also identifies links in the communication system that have been lost as a function of attack level.

The communication inputs required to exercise the model are node locations, node connectivity and switch sizes. Also required is the percentages of local calls, one link calls and long distance calls.

Basically, the NuSAP model performs the following steps to calculate survivability index:

a. Define the equipment system configuration and establish a node/link model of equipment/interconnections.

b. Analyze the enemies threat capabilities and formulate an attack strategy.

c. Rank the nodes/links in the model according to the order of attack dictated by the attack strategy.

d. Determine the critical nuclear effect on which to base the simulation - air blast damage for most cases of electronic equipment.

e. Establish lethal radii - the lethal area of a nuclear effect encompasses all equipment with less than a 50-percent probability of survival. The radii are functions of weapon sizes and hardness levels.

f. Calculate node/link destruction - the identification of nodes destroyed (including bonus targets) from weapons delivered against a deployment according to the attack strategy.

g. Formulate a survivability index - a separate index may apply to different electronic systems. In the case of a communications network, the index must consider the effects of local, one link, multi-link, and satellite traffic.

h. Conduct detailed analysis as nodes/links are destroyed. The survivability index, as each weapon is delivered, reflects the effect of the attack upon the system survivability. A plot of survivability index versus attack level are the results of this analysis.

4.3 Limitations

The NuSAP model has various limitations that could prevent it from providing a rigorous assessment of survivability. These are:

a. Does not consider precedence levels

b. Does not consider routing schemes

c. Does not consider security

d. Does not address attacks with conventional weapons.

The main advantage of this model, however, is that it can quickly approximate the nuclear survivability of large communication networks up to 200 nodes in just a few minutes of computer time.

This model is presently being modified so that it will be useful for the analysis of conventional weapons as well as nuclear attacks. A further modification allows the model to be coupled with a grade of service model so that the results of an attack can be expressed in terms of how the damage affects the system/link grade of service.

5.0 MALLARD VULNERABILITY MODEL

5.1 General Description

The MALLARD Vulnerability Model is a dynamic model that was developed for the MALLARD project. The model is presently under the custody of the TRI-TAC office and is run on the Burroughs 5500 computer at Fort Monmouth and also can be run on the IBM 360/65. The model is a call-by-call simulation that is written in FORTRAN IV language. The model basically assesses the vulnerability of a network to jamming.

5.2 Capabilities

This model is capable of providing detailed analysis of the vulnerability of traffic within a network to jamming. The outputs of the model are:

- a. Jammer effectiveness by types and area
- b. Network traffic loading by links and call types
- c. Traffic statistics by area and call types
  - 1. Number of calls requested
  - 2. Number of successful connections
  - 3. Average number of links per call
  - 4. Number of unsuccessful call requests
  - 5. Calls interrupted by jamming
  - 6. Calls interrupted by pre-emption
  - 7. Calls Completed

Inputs that are required for the simulator are:

- a. Network deployment and configuration
  - 1. channel capacities
  - 2. frequency assignments
  - 3. node locations
- b. Equipment parameters
  - 1. antenna patterns
  - 2. ECCM capabilities
- c. Traffic data
- d. Jammer Deployment

The model consists of three main programs. The first checks input data and computes link signal-to-noise (S/N) ratios. The second program assembles traffic needline and priority data and generates message traffic over the busy hour. The third program uses the link and traffic data from the first and second programs to assess the impact of jamming on the network in terms of the degradation of the grade of service.

5.3 Limitations

The main limitation of the MALLARD model is that it is a very tedious model and run times for typical simulation last about 12 hours. The model can handle up to 500 nodes and it does consider precedence levels and alternate routes. The model is a very rigorous and detailed tool for evaluating survivability to jamming provided the required inputs are available for use in the model.

6.0 KATZ MODEL

6.1 General Description

The Katz Model as it exists to day is a static model that is in the custody of the Defense Communicatiion Agency, Washington, D. C. The model is run on an IBM 360/65 computer and is written in FORTRAN IV language. The TRI-TAC office has acquired the model and has made it operational on the Burroughs 5500 computer at Fort Monmouth. The model basically assesses network performances for various traffic loading conditions.

6.2 Capabilities

The Katz Model can be used to predict the performance of a circuit-switched communications network in a fraction of the time required by a call-by-call simulation model. It involves an iterative procedure which estimates such traffic parameters as point-to-point loss probabilities, trunk group blocking probabilities, and network GOS. The model assumes that traffic can be adequately described by its mean and variance.

The model relates the mean and variance of node-to-node traffic to the corresponding moments of the total traffic offerred each trunk group. At each iteration, a two-step procedure is implemented. First, for a given traffic demand matrix and routing plan the load assignment process distributes the traffic throughout the network based on the traffic parameters determined at the previous iteration. After all node pairs have been considered, various performance statistics are computed. Based on the network GOS, a convergence criterion is then used to stop the model. Input requirements of the model are:

a. The number of trunks in each trunk group of the network

b. The nodal originating-destination traffic demand matrix in Erlangs

c. The routing doctrine for the network.

The outputs of the model are various traffic parameters for point-to-point traffic, trunk group loading, and the overall network. For each node pair, the following two parameters are computed for node-to-node traffic:

a. Node-to-node blocking probability

b. The average number of trunk groups seized per completed call.

For each trunk group the model computes:

a. Average blocking probability

b. Average trunk occupancy

c. Proportion of first offered and alternate routed traffic

d. Mean and variance of offered load.

Using the above results, the model computes the following traffic parameters for the overall network:

a. GOS

b. Overall trunk occupancy

c. Average number of trunk groups seized per call.

The Katz model is well suited to assess traffic disruption. In this sense it is very useful for estimating grade of service related measures such as the survivavility and availability.

6.3 Limitations

The Katz model has the following limitations in its present form:

a. Does not distinguish between:

1. Precedence levels

2. Modes of traffic

3. Secure and nonsecure traffic

b. If routing is not used as an input, the model will generate its own; however, the routing that results is far from optimum and may be incompatible with the channel capacities input for the network.

c. For large networks, the running time may be considerable. It is estimated that a 70 node network will require 20 minutes. Running times for larger networks can increase as the square of the number of nodes.

The Katz model can be used to assess GOS and GOS related MOEs.

7.0 AFCTC (MTC) MODEL

7.1 General Description

The Air Force Combat Theater Communications Model (AFCTC) is the property of the U. S. Air Force. Several modifications have been made to increase the statistical accuracy of the model outputs. The model is now in custody of ESD, Hanscomb Field, Bedford, Massachusetts, but it is not considered active and has not been used in recent months. The model is run on the IBM 370. Total running time is excessively high.

The computer simulation model is essentially a static simulator. A series of twelve computer programs produce two categories of output communication load information (grossly defined as 'static' and 'dynamic'). Static output consists of busy hour total summaries of node-to-node and link traffic statistics broken down into various categories. The dynamic portion supplies grade-of-service information, such as blocked calls, link utilization, and node queuing statistics for a peak period for 'busy hour'.

The original "Indian" two-Corps Field Army deployment has been modified to show locations without respect to particular geography. Unit locations are given in terms of the distances from other units. The force model has also been modified to show eight Tactical Air Bases instead of the original ten. The latest version of the force model is consistent with the Army's EAD concept in that the field army echelon has been eliminated. This force model version, however, has not been prepared for input to the simulation model, and there are no current plans to do so.

7.2 Capabilities

Force model input formats include unit designations, machine identifier codes, nodal connections, place name locations, and unit level codes. Unit locations in the form of map coordinates are not required. Distance plays no part in the computer model.

Traffic demand data is defined in terms of message length and number of messages flowing between units. Several files are used to input traffic data and to show generic and specific unit connectivity.

The principal files are:

- Message Characteristics File listing the various types of messages, message number, average length (words or pages), coding, precedence, security, mode, and a special identifier if the message is a specialized intelligence type.
- Generic Link File which shows connectivity and message types between typical units.
- Flow Restriction File which further defines the general Generic File instructions to make specific modifications in connectivity.
- Routing Matrix which shows node-to-node connectivity.

Force model and traffic data can be changed, but each change must be input manually in the form of a punched card. The model generates specific unit connectivity and loading and produces the Message Load Table which is used for computation of node-to-node traffic. The ultimate outputs of the AFCTC model are (1) link loading from node to node and (2) source to sink nodal traffic loading. The busy hour rate is assumed to be 10 percent of total daily traffic.

A primary and alternate DCS interface are included in the model together with input and output traffic flow. Some allied interface is indicated in the form of air traffic control and air defense messages, but no NATO type links are included.

7.3 Limitations

The AFCTC Model has a number of limitations for system assessment. Among these are:

a. Does not consider routing schemes.

b. Is essentially a static simulator and has only limited dynamic simulation capability.

c. Does not consider distance in computational assessments.

d. The force model has not been modified under the latest "Army EAD Concept" for input to the simulator.

The main advantage of this model however, is the fact that the deployment depicts Army and Air Force units in a doctrinal combat situation.

Within the above limitations, this model can be used to evaluate GOS and GOS related MOEs.

APPENDIX C

1.0 COMMUNICATION NETWORK CONFIGURATIONS

The MOEs defined in section 5 were designed to analyze the effectiveness of alternative communication system designs. This appendix discusses methods that can be used to postulate or structure the system to be analyzed.

For certain MOEs, the effectiveness analysis can be simplified by examining reference circuits that are derived from the overall network. Another approach to simplification for other MOEs is that reference nodes can be examined rather than total networks.

Three categories of MOE can therefore be postulated. The appropriate MOEs are listed under each category.

a. Network Measures

    1. Grade of Service
    2. Index of Survivability (Overt)
    3. Index of Survivability (Jamming)
    4. Index of Availability
    5. Ease of Transition
    6. Service Features

b. Reference Circuit Measures

    1. Information Quality
    2. Speed of Service
    3. Call Placement Time
    4. Interrupt Rate
    5. Spectrum Utilization

c. Nodal Measures

    1. Mobility
    2. Transportability
    3. Ease of Reconfiguration
    4. Interoperability

5. Lost Message Rate

The remainder of this appendix treats the suggested methods for the construction of:

a. System Networks

b. Reference Circuits

c. Typical Nodes

2.0 SYSTEM NETWORKS

A communication system can be described as a conglomerate of equipment which when connected together form a system that can provide the necessary communications for a force structure. In the abstract sense, an infinite set of force structures can exist and it follows that an infinite set of systems can be postulated to provide the required communications.

In order to make an analysis manageable, one force structure should be postulated along with alternative systems designed that can provide the required communications. A scenario that includes several snapshots should also be developed for this force structure so that the communication system overlays can be evaluated to determine their effectiveness at various stress levels.

The communication system overlays are in reality a connectivity diagram of the system that shows the location of nodes, the transmission media that interconnect the nodes and the various types of equipment strings that connect subscribers to the nodes. The following information is required in order to design these communication overlays. Some of this data must be provided in terms of User Communication Requirements (UCRs), while other information must be synthesized by geographically placing a force structure on a map.

a. Equipment lists

b. Unit-to-unit needlines

c. Unit locations

d. Node locations

e. Unit-to-unit connectivities

f. Nodal needlines

g. Routed nodal needlines

h. Link sizing requirements and blocking probability

i. Routed nodal needlines blocking probabilities

A model such as SIMCE is required to assimilate the above information and to translate it into a properly sized communications network model. A brief synopsis of this model is presented in Appendix B. A more detailed description of SIMCE can be found in Ref 8 of Appendix A. The detailed procedures on how to establish the basic connectivity diagram for a communication system and how to use the SIMCE model to size the system can be found in this reference. These details will not be repeated in this appendix.

3.0 REFERENCE CIRCUITS

Reference circuits are another means for setting conditions to evaluate MOEs. A reference circuit can be considered as a single thread taken through a communication system to represent a subscriber to subscriber link. By inspecting what occurs in setting up and maintaining the link, "point-topoint" measures such as speed of service, call placement time and information quality can be evaluated. The method of evaluation in this manner is described in the paragraphs which follow.

3.1 Development of Reference Circuits

The object of developing reference circuits is to represent all types of subscriber calls through a larger network to exercise the system being evaluated. To illustrate this concept, reference circuits that were developed for evaluation of the Static Subscriber Access subsystem at TRI-TAC are presented in Figure C-1 and Table C-1. Figure C-1 represents a small piece of a larger network from which the reference circuit routes given in Table C-1 are derived. The 12 reference circuits described in Table C-1 represent various types of service requests through the system ranging from local subscriber calls, to multi-link calls, to external interface type calls from Autovon or Autodin.

3.2 Evaluation Example

Once the reference circuits are set up, evaluation of the MOEs becomes a matter of adapting the quantitative equation for the appropriate MOE to the reference circuit and averaging the values obtained over all of the reference circuits. For example, taking the equation for call placement time from section 5 and applying it to a reference circuit it reduces to:

$$CPT = \sum_r t_r$$

This simplification is possible because the total traffic over the reference circuit is equal to the traffic over the route and, therefore, both cancel. The evaluation procedure is to add the time delays experienced at each point through the reference circuit. In the case of the Static Subscriber Subsystem, 12 values will be calculated for CPT. These values can then be averaged for the final value of CPT for the equipment/subsystem being evaluated.

4.0 NODAL ACCESS CONFIGURATIONS

Nodal access configurations are used to set conditions of evaluation of MOEs that are associated with typical configurations at a node. TRI-

FIGURE 5 Reference Circuit Configurations for Static Subscriber Access

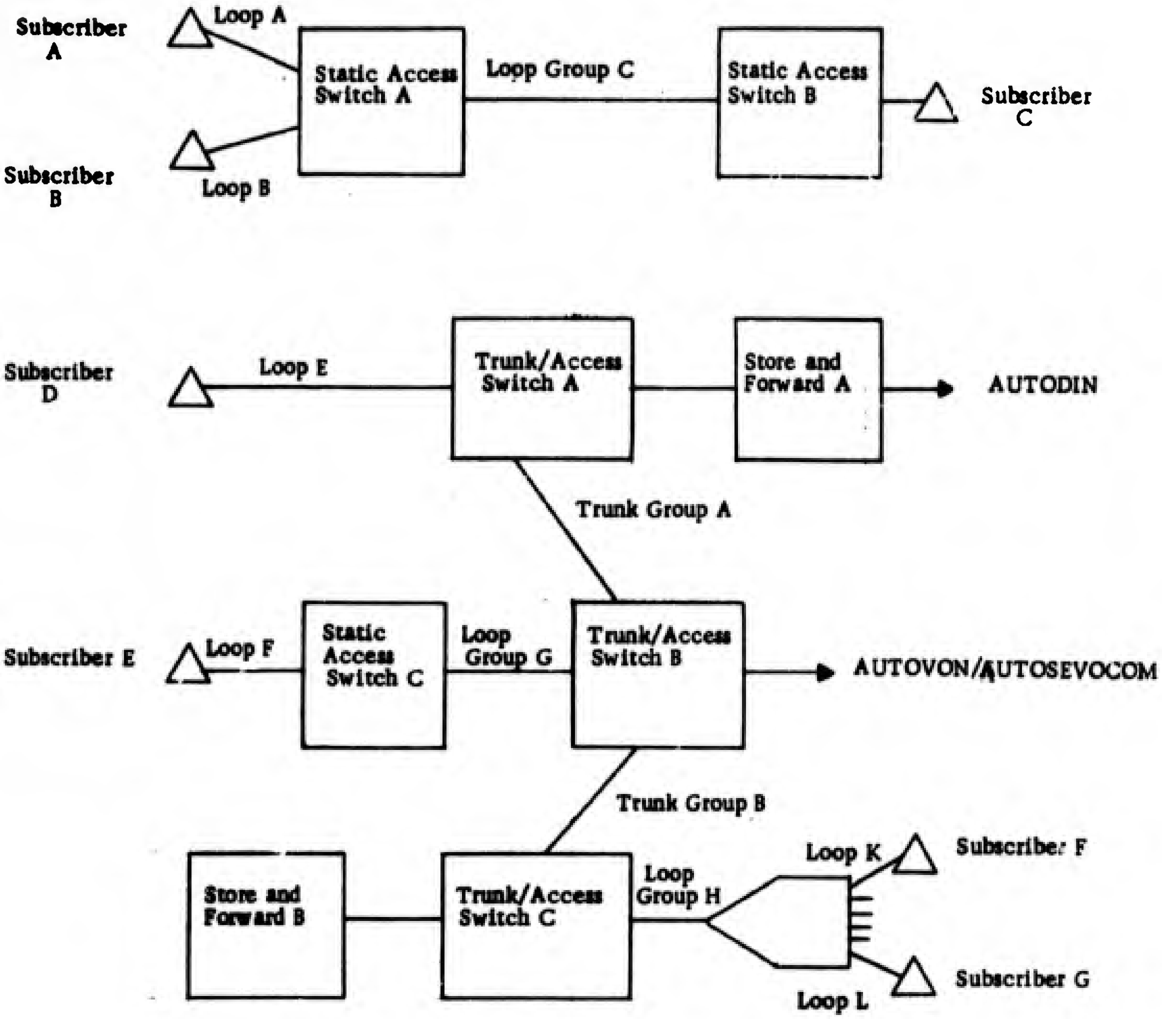


TABLE 2
Reference Circuits

REFERENCE CIRCUIT NUMBER	FROM	TO	ROUTE
1	SUBSCRIBER-A (ANALOG VOICE TERMINAL)	SUBSCRIBER-B (DIGITAL VOICE TERMINAL)	SUBSCRIBER-A/SAS-A/SUBSCRIBER-B
2	SUBSCRIBER-A (ANALOG VOICE TERMINAL)	SUBSCRIBER-C (DIGITAL VOICE TERMINAL)	SUBSCRIBER-A/SAS-A/SAS-B/SUBSCRIBER-C
3	SUBSCRIBER-B (DIGITAL VOICE TERMINAL)	SUBSCRIBER-C (DIGITAL VOICE TERMINAL)	SUBSCRIBER-B/SAS-A/SAS-B/SUBSCRIBER-C
4	SUBSCRIBER-D (DIGITAL VOICE TERMINAL	SUBSCRIBER-E (ANALOG VOICE TERMINAL)	SUBSCRIBER-D/T/AS-A/T-AS-B/SAS-C/SUBSCRIBER-E
5	SUBSCRIBER-D (ANALOG VOICE TERMINAL)	SUBSCRIBER-E (DIGITAL VOICE TERMINAL)	SUBSCRIBER-D/T/AS-A/T/AS-B/SAS-C/SUBSCRIBER-E
6	SUBSCRIBER-D (TTY TERMINAL)	SUBSCRIBER-F (TTY TERMINAL	SUBSCRIBER-D/T/AS-A/S/F-A/T/AS-A/T/AS-B/T/AS-C/S/F-B/T/AS-C/SUBSCRIBER-F
7	SUBSCRIBER-E (TTY TERMINAL	SUBSCRIBER-F (TTY TERMINAL)	SUBSCRIBER-E/SAS-C/T/AS-B/T/AS-C/S/F-B/T/AS-C/SUBSCRIBER-F
8	SUBSCRIBER-D (DIGITAL VOICE TERMINAL)	SUBSCRIBER-F (DIGITAL VOICE TERMINAL)	SUBSCRIBER-D/T/AS-A/T/AS-B/T/AS-C/SUBSCRIBER-F
9	SUBSCRIBER-D (DATA TERMINAL)	SUBSCRIBER-F (DATA TERMINAL)	SUBSCRIBER-D/T/AS-A/T/AS-B/T/AS-C/SUBSCRIBER-F
10	SUBSCRIBER-F (DIGITAL VOICE TERMINAL)	SUBSCRIBER-G (DIGITAL VOICE TERMINAL)	SUBSCRIBER-F/T/AS-C/SUBSCRIBER-G
11	AUTODIN	SUBSCRIBER-F (DATA TERMINAL)	AUTODIN/S/F-A/T/AS-A/T/AS-B/T/AS-C/S/F-B/T/AS-C/SUBSCRIBER-F
12	AUTOVON	SUBSCRIBER-F (DIGITAL VOICE TERMINAL)	AUTOVON/T/AS-B/T/AS-C/SUBSCRIBER-F

TAC measures such as mobility and transportability and ease of reconfiguration are examples. The nodal access configurations represents a model of a node and its associated equipment such as subscribers, associated trunk equipment, and unit level switches with their subscribers. In the following subsections these nodal configurations are described along with the procedure for evaluation.

4.1 Development of Nodal Access Configurations

Nodal access configurations are developed by choosing representative deployments at particular nodes that cover the most likely conditions under which the equipment or subsystem being evaluated will be placed. For example, the static subscriber access subsystem had the five nodal access configurations chosen for its evaluation. They described the potential nodal deployments of the following units:

a. Army Corps Main Configuration

b. Army Brigade Configuration

c. Air Force Tactical Air Base Configuration

d. Naval Basic Access Node (BAN)

e. Marine Division Configuration

4.1.1 Army Corps Main Configuration

A typical command node, Corps Main, is characterized by the following type and quantities of equipments:

a. 289 subsets

b. 69 data adapters

c. 43 teletypewriters

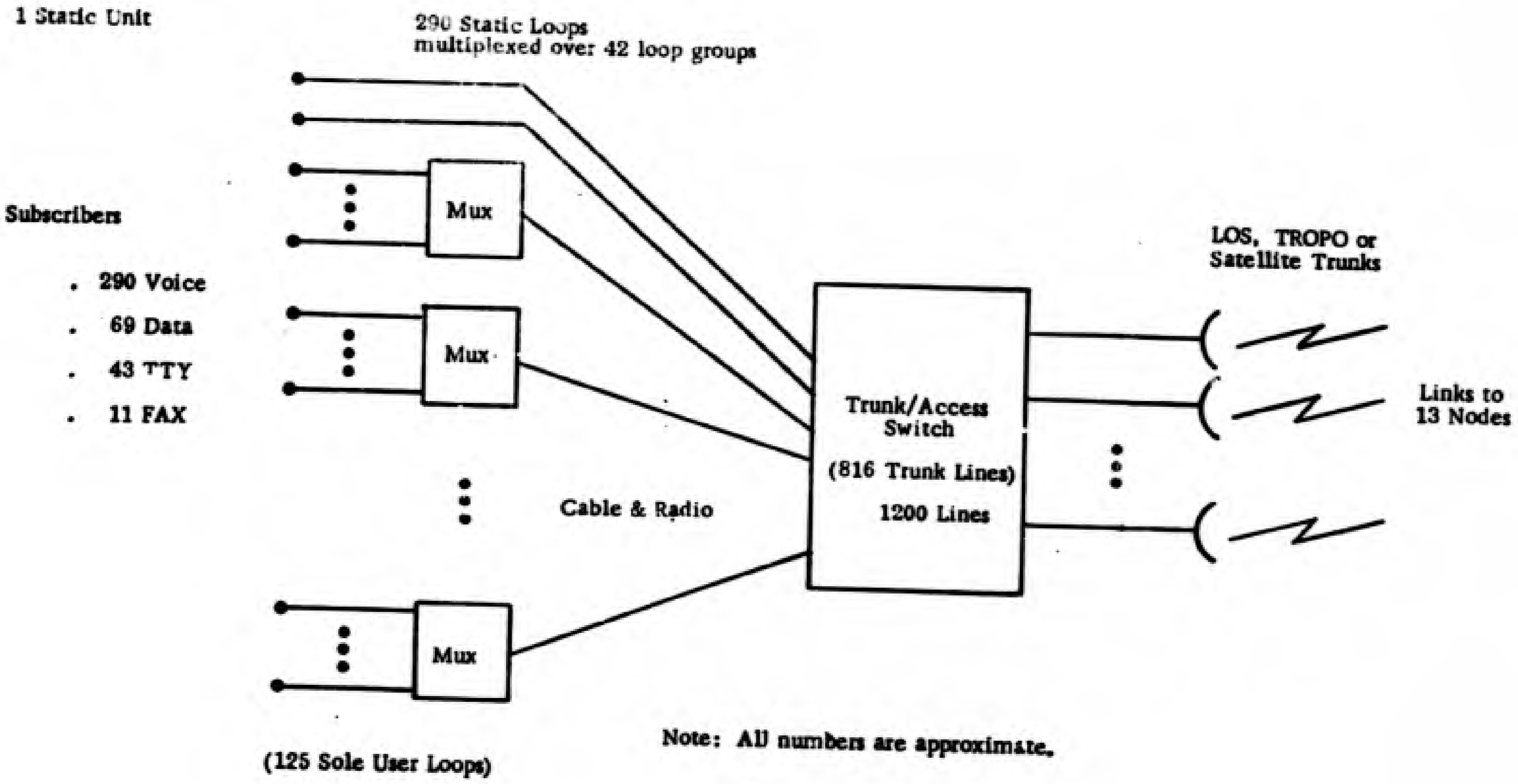
d. 11 facsimile terminals

A 1200-line switch and store-and-forward facility will be required at Corps Main. Trunk links exist from Corps Main to 13 other nodes. The average trunk length is about 50-km, and transmission is accomplished by either LOS or Tropo. Corps Main requirements are illustrated in Figure C-2.

4.1.2 Army Brigade Configuration

Communications facilities at a typical brigade node are quite different than at Corps Main. At Corps Main, for example, the trunk/access switch is utilized to a great extent while at the brigade level, the emphasis is towards the utilization of a static access switch. Typically, a 120-line switch at a brigade node would be linked to several battalion level static access switches. Links also exist back to trunk/

FIGURE 6 Subscriber Access Configuration At Corps Main



Note: All numbers are approximate.

access switches at Division Main and Division Alternate. Typical terminal equipments would include:

a. 80 voice subsets

b. 9 TTY

c. 15 data

d. 2 fax

Figure C-3 depicts typical Army Forward Brigade communications.

4.1.3 Air Force Tactical Air Base Configuration

Figure C-4 details intranodal requirements at a typical Tactical Air Base. The 400 common-user and sole-user subscribers are equipped with:

a. 400 voice subsets

b. 35 data adapters

c. 30 teletypewriters

d. 9 facsimile facilities

A store-and-forward facility is provided for data and TTY traffic. A 600-line switch provides switching over a total of 120-trunk channels that are connected to four nodes via troposcatter links.

4.1.4 Naval Basic Access Node (BAN)

A typical Naval subscriber access configuration is that of a Basic Access Node (BAN) that can be located, for example, on a destroyer. Typically, it can be expected that subscriber equipment includes approximately:

a. 30 voice terminals

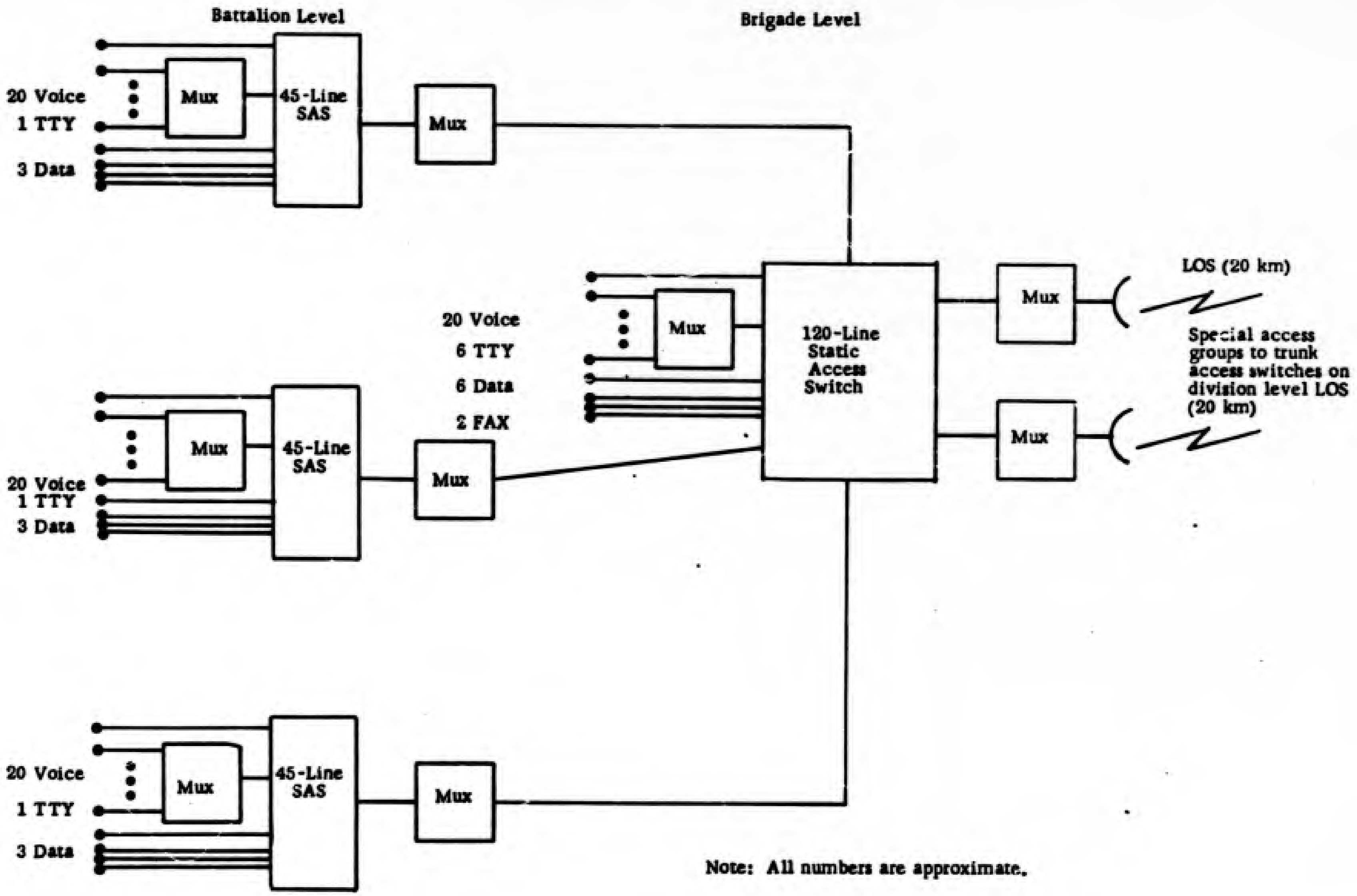
b. 2 or 3 message terminals

c. 2 data terminals with voice capability

d. 1 facsimile terminal

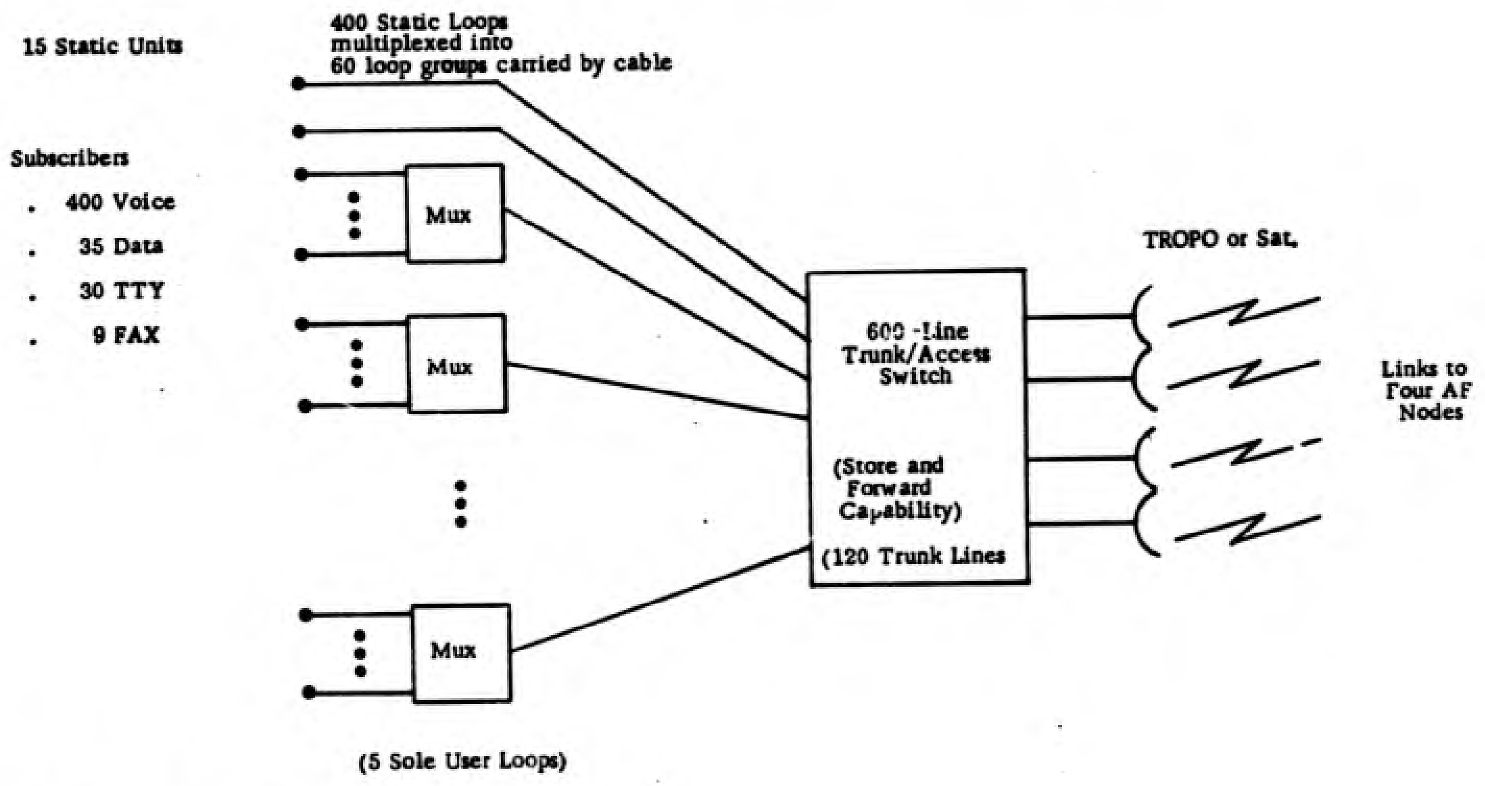
Most of the switching is internal. Typically, only three or four subscribers are authorized access to the external system. Figure C-5 shows the salient features of the typical BAN.

FIGURE 7 - Typical Army Forward Brigade Configuration



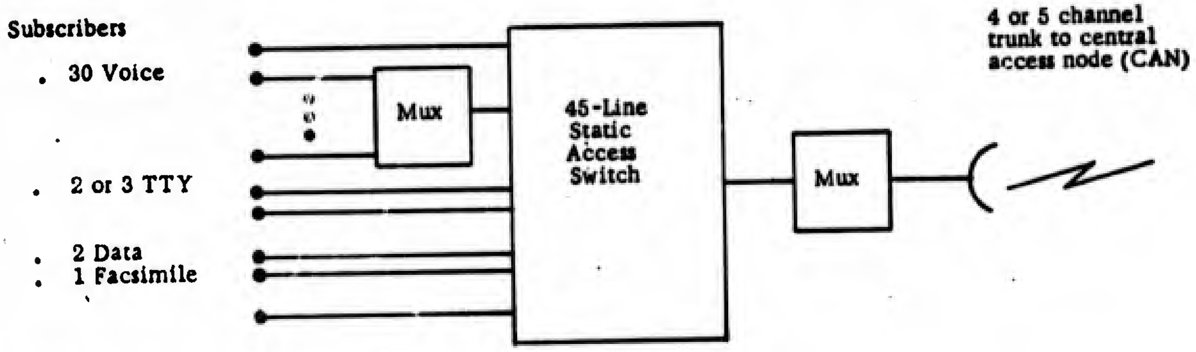
Note: All numbers are approximate.

FIGURE 8 - Typical Air Force Tactical Air Base (TAB) Configuration



Note: All numbers are approximate.

FIGURE 9 Naval Subscriber Requirements At a Basic Access Node (BAN)



Note: All numbers are approximate.

4.1.5 Marine Division Configuration

Net radios are used extensively in Marine Corps deployments. Wire is restricted to the confines of a command post, and occasionally between units of the MAW and the Force Logistics Support Group that is relatively immobile about an airfield or a supply point. Trunks are primarily oriented along command lines rather than located geographically.

The Marine Division Headquarters (MARDIV) communications complex represents a typical configuration. The requirements of MARDIV consist of:

a. 72 digital telephones

b. 44 teletype terminals

c. 2 message entry terminals

d. 5 data terminals

e. 8 facsimile terminals

f. A digital switchboard with 71 local loops and 12 interface channels to the switched network.

g. 5 smaller switchboards

h. Links to 10 other nodes

i. Accommodation of remote subscriber terminals

Figure C-6 illustrates the typical configuration at MARDIV.

4.2 Evaluation Example

The evaluation of MOEs using nodal access configurations is the same as that of reference circuits presented in subsection 3.2. The quantitative equation of the MOE is adapted to the configuration and it is used on each configuration to calculate a value for the MOE. These values are averaged and the final value of the MOE is obtained for the subsystem or equipment being evaluated. For example, the MOE mobility.

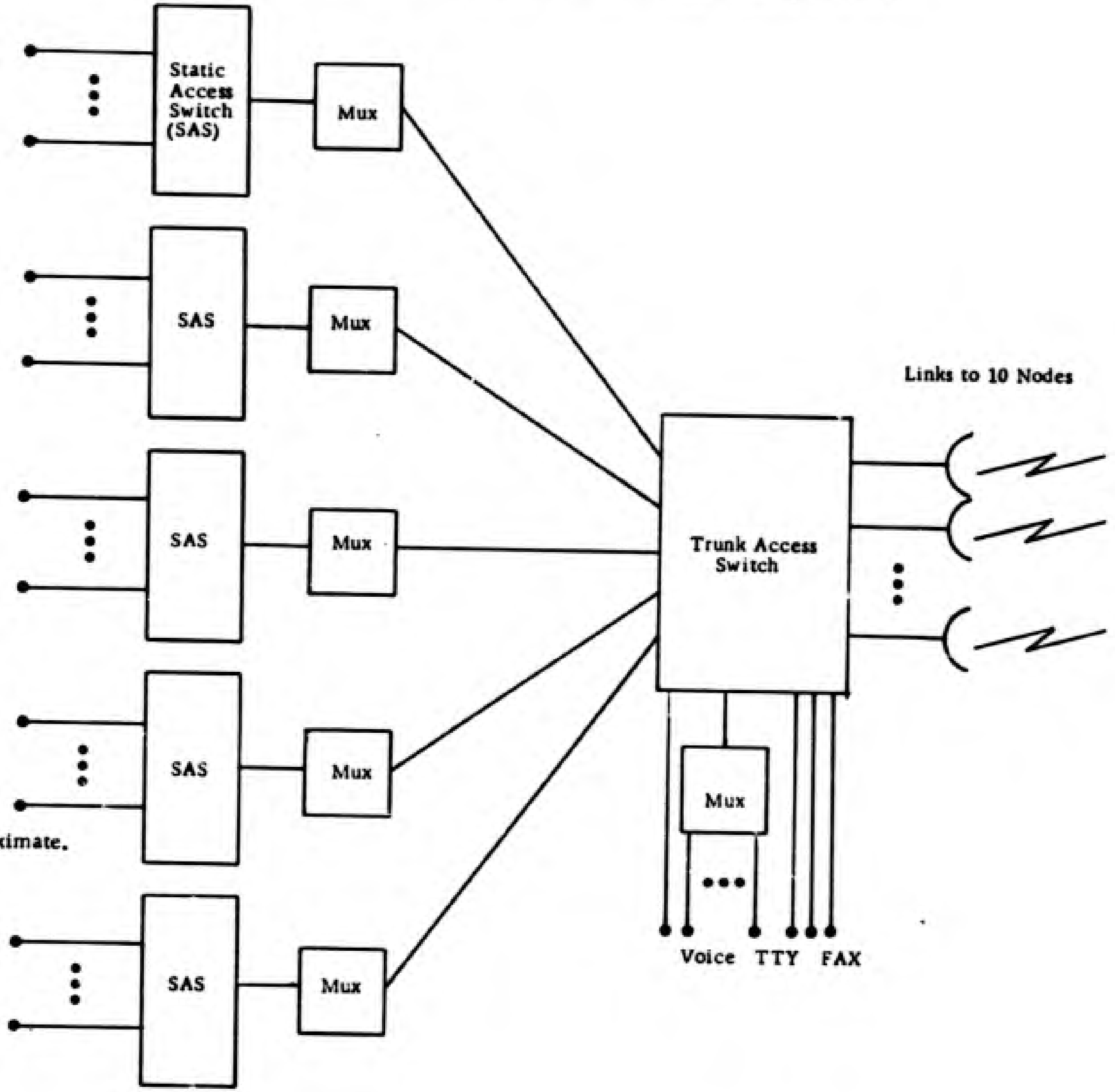
$$MOB = T_s + T_t$$

Where $T_s = T_s' + \sum_i (N_i \times T_{si})$

$$T_t = T_t' + \sum_i (N_i \times T_{ti})$$

The MOB MOE can be evaluated by estimating the appropriate values for the critical paths of the PERT charts for equipments of the particular configuration. After this procedure is repeated for the number of configurations used, the values are averaged for the final MOE value.

FIGURE 10 Marine Division Static Subscriber Access Configuration



Total Subscribers:

- 72 voice
- 44 TTY
- 8 FAX
- 5 Data

Note: All numbers are approximate.