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OBJECT-ORIENTED MODELLING AND ANALYSIS OF
A MARINE CORPS COMMUNICATIONS ARCHITECTURE

by

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Thesis Advisor: Michael P. Bailey

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The Marine Corps Communications Architecture Analysis Model (MCCAAM) presented in this thesis gives Marine Corps decision makers, analysts, and communications officers the ability to quantify the effectiveness of alternative tactical radio system configurations within a given Marine Air-Ground Task Force (MAGTF) environment. The Marine Corps will be fielding the SINCGARS frequency-hopping radio system during the next five years. During the transition period, there will be units that will employ both the conventional fixed-frequency radios and the SINCGARS radios in the same area at the same time. Marine Corps decision makers and communications officers can use MCCAAM performance results to determine where best to allocate the new frquency-hopping radios, as they become available, in order to maximize the overall frequency-modulated communications performance of a MAGTF. Using a unique traffic workload paradigm to generate realistic message traffic, this object-oriented simulation model assesses the overall performance of a given architecture through a penalty accrual process and through aggregating traditional communications measures of effectiveness. The results of system performance rankings and associated sensitivity trade-off analyses provide the analyst with a powerful and easy-to-use decicison making aid.

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Object-Oriented Modelling and Analysis of a Marine Corps Communications Architecture

by

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ABSTRACT

The United States Marine Corps (USMC) will be fielding the SINCGARS frequency-hopping radio system during the next 5 years. There will be units within the Corps during the transition period in which both the conventional fixed-frequency radio and the SINCGARS radio will be employed in the same area at the same time. The Marine Corps Communications Architecture Analysis Model (MCCAAM) presented in this thesis will give Marine Corps decision makers, analysts, and communications officers the ability to quantify the effectiveness of alternative tactical radio system configurations within a given Marine Air-Ground Task Force (MAGTF) environment. Using a unique traffic workload paradigm to generate realistic message traffic, this object-oriented simulation model assesses the overall performance of a given architecture with a specified mix of fixed-frequency and frequency-hopping radios through a penalty accrual process or through aggregating traditional communications MOEs. USMC decision makers and communications officers can use the results of the system performance rankings and associated sensitivity trade-off analysis to determine where best to allocate the new frequency hopping radios, as they become available, in order to maximize the overall FM communications performance of a given MAGTF.

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THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all the cases of possible interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

I. INTRODUCTION

A. BACKGROUND

> The problem of commanding and controlling armed forces, and of instituting effective communications with and within them, is as old as war itself. A Stone Age chieftain had to devise the optimal organization and find the methods and technical means to command the forces at his disposal. From his day to ours, failure to consider and to solve the problem was to court disaster—indeed, to make it impossible for the forces to exist. [Ref. 1]

Success in future conflicts at all levels of intensity will depend on the ability of Marine commanders to gather, store, display, and forward information and operational orders at a faster and more efficient level than ever required before. The strategic significance of communications superiority lies in its potential to create major asymmetries in the distribution of information in any given situation [Ref. 2]. Recognizing this, the Marine Corps is moving toward automation by introducing computer-based systems and digital communications into virtually every area of command and control. [Ref. 1]

The recent emphasis on rapidly evolving military technology raises a major issue for the United States and, specifically, for the Marine Corps. At what pace should we pursue the new technology, possibly at the expense of the full completion of current or proposed programs? To answer this and similar questions in this time of rapidly changing technologies and limited defense budget, it is more important than ever for the Marine Corps to have an analytical methodology and complementary modeling technique that can quickly and thoroughly compare and contrast new or anticipated tactical command, control and communications (C3) systems [Ref. 3]. To ensure that only the most cost effective changes are implemented, the Marine Corps needs the specific capability to:

- compare proposed C3 architectures;
- allocate new resources optimally in existing network structures; and
- appraise the change in performance that will result from implementing specific improvements in equipment, doctrine or training [Ref. 4].

As part of a needed modernization of its communication technology, the Marine Corps will be fielding the SINCGARS frequency-hopping radio system as a replacement for the VRC-12 family of single channel radios during the next five to ten years. Over the transition period, there will be units in which the current, conventional, fixed-frequency radios and the SINCGARS radios will be employed in the same geographical place at the same time. Knowing that there will not be enough money in the budget to totally replace all the older radios at one time, and given an imperfectly specified enemy jamming, interference, and interception capability, one of the Marine Corps' current challenges is the allocation of the new SINCGARS radios within the Marine Air-Ground Task Force (MAGTF) structure to provide the most reliable, robust, and effective architectures possible.

B. PURPOSE

The purpose of this thesis is to design and implement a simulation model to provide Marine Corps decision makers, analysts, and communications officers the ability to quantify the effectiveness of alternative tactical radio system configurations within any specific MAGTF environment. The Marine Corps Communication Architecture Analysis

Model (MCCAAM) presented in this thesis uses a unique traffic workload paradigm to generate realistic network traffic and assesses the overall performance of a given architecture (a specified mix of fixed-frequency and frequency-hopping radios) through a penalty accrual process or through aggregating traditional communications MOEs. This object-oriented simulation model will allow Marine Corps decision makers to determine the best allocation of the new frequency hopping radios, as they become available, in order to maximize the overall communications performance of a MAGTF.

As an example of how MCCAAM can be used, this thesis presents a statistical analysis of four different SINCGARS allocation schemes that might be considered by the Marine Corps. The objective of this analytical example is to determine whether there is any real difference in the tactical radio system performance between the different allocation schemes, to estimate those differences using two different performance measuring approaches, and to assess the precision of the estimates.

C. OUTLINE OF THESIS CHAPTERS

Given the thesis background and purpose described above, the first step pursued in this thesis is to completely describe and frame the problem under consideration. Chapter II gives the necessary background information to bound the Marine Corps' communication architecture analysis problem. We illustrate the complexity and scope of the problem by briefly describing the unique communication needs presented by the expeditionary nature of the various MAGTF levels of organization. The many factors that contribute to the complexity of any communications analysis are highlighted by discussing general Marine Corps communication principles, equipment, and information requirements. This information is important because it drives much of the modelling that is implemented. To provide the necessary background for the measures of effectiveness used in this analysis, the key characteristics of the VRC-12 family of radios currently in use and the new frequency-hopping radios is presented. Basically a facts and figures section, Chapter II concludes with a description of the analysis process that was used in approaching this problem.

Chapter III explains why simulation was used for this analysis and describes the key features of object-oriented simulation and how they made this approach the best analysis tool for our problem. A brief argument is given in support of the decision to use the MODSIM II language instead of a graphically oriented product. Following the essential aspects of the modelling language, the modular approach we used in writing code is described, and the model development phases are described (because they were a key part of the whole problem solving process). To provide a general understanding of the actual model used for this analysis, the essential message traffic paradigm is presented and the key module contents are highlighted. The way the many different modules interact during an actual simulation run is presented next as a typical scenario "flow." The chapter concludes with a discussion of the model data requirements and how they were met. A reasonable defense of most assumptions is presented to fully define those areas that are not fully addressed or modeled. Model resolution is re-addressed. Chapter III is essential because it highlights the areas of the model development, implementation, and analysis that are not readily apparent.

Chapter IV starts the transition from the model to the analysis through a full discussion of measures of performance, measures of effectiveness, and measures of force effectiveness. By highlighting the characteristics of the desired MOEs, a case is made for those specific MOEs used in the analysis. The MOE aggregation approach we adopted is discussed with advantages and disadvantages presented. The penalty process used to assess the overall performance of a given network is described and the accompanying output analysis is briefly highlighted.

Chapter V specifically ties the chosen MOEs to the actual simulation runs through the experimental design that was established to capture and measure system differences for our example. Also in this chapter, the alternate SINCGARS allocation schemes are described and we present the way the simulation model was used to compare them.

Chapter VI begins by illustrating how the model output was used to verify the model. After model verification is established, the experimental results are detailed and a claim is made that the effectiveness of the alternative communications systems has been sufficiently quantified. The alternative communication system performance results are presented in a manner that allows a decision maker to readily see the origins and significance of the differences. Before Chapter VI closes with a three step approach to model validation, we discuss the use of variance reduction techniques.

Finally, Chapter VII recaptures the highlights of our model development work and its applicability to the current Marine Corps communications analysis problems. Concluding comments regarding model validation and usefulness are followed by a discussion of potential model embellishments.

II. PROBLEM APPROACH AND FRAMEWORK

A. THE ANALYSIS PROCESS

The previous chapter presented the problem background and the focus of this thesis. The current section describes the analysis process used in approaching our problem. We accomplish this by focusing on the different steps undertaken throughout MCCAAM model development and application.

> In any analysis supporting decisions during the life cycle of a system, it is essential to be able to relate the contribution of the various alternatives under consideration to the desired objectives of the system, or military force. The mechanism by which this relationship is established is referred to as "the analysis process." [Ref. 5]

Proper selection of the criteria to be used in comparing alternatives is more an art than a science and is treated as one of the most important steps in developing an analysis plan. Our ability to specify the values of these criteria heavily influences the efficacy of the analysis to accomplish the objectives defined during problem formulation.

The Modular Command and Control Evaluation Structure (MCES) developed by a joint working group [Ref. 5] is a general approach for evaluating C3 systems that has been successfully applied to a number of issues concerning C3 systems planning, acquisition, testing and operation. It incorporates all of the previously mentioned basic analysis activities in a series of seven steps or modules (Figure 1) to evaluate alternative C3 systems and architectures. The following paragraphs describe how these modules were used as guidelines in developing and evaluating the MCCAAM model.

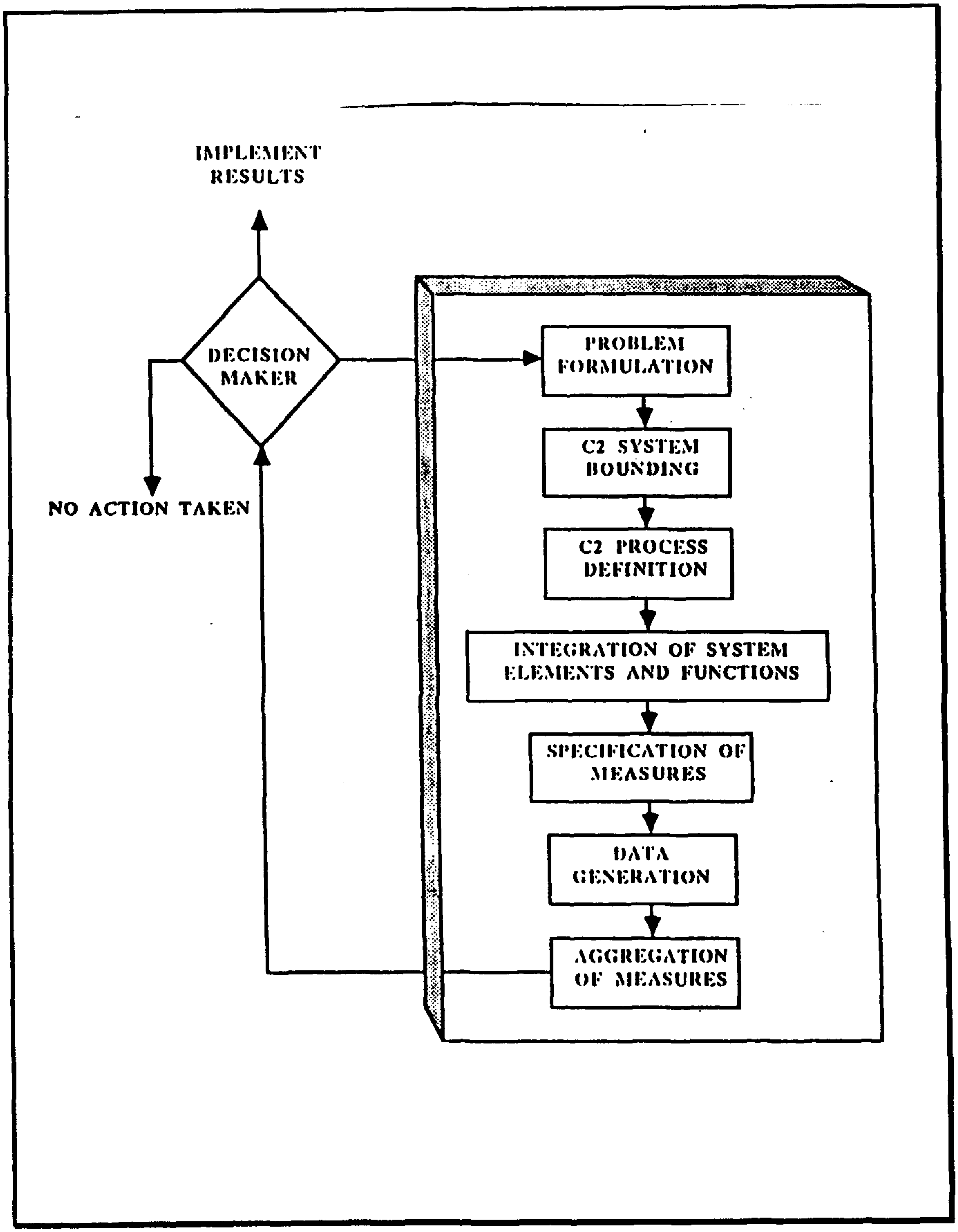

Figure 1. Modular Communications Evaluation Structure (MCES)

PROBLEM FORMULATION MODULE. In this module, the Marine Corps decision makers were identified and their objectives were described. Next, the alternatives for the SINCGARS allocation problem were identified so they could be modelled in later steps, and the various mission areas affected were detailed. As a result, the scope and depth of the Marine Corps analysis needs were defined and basic assumptions were agreed upon.

SYSTEM BOUNDING MODULE. Here the MAGTF elements that would be affected by the SINCGARS allocations were identified from doctrinal publications. C3 system statics (units & radios) were distinguished from system dynamics (activities & procedures), and physical units were defined along with their associated command structures. Marine Corps standard operating principles were investigated to provide needed guidance for proper modelling of message durations, protocols, and reporting requirements.

PROCESS DEFINITION MODULE. In this phase, the dynamic C3 processes of the Marine Corps tactical FM radio networks were identified by looking at the functions of the C3 cycle (sense, assess, generate, select, plan, and direct) as performed by the units identified in the previous phase. Since the SINCGARS system is most concerned with the conveyance of sensed information, plans, and direction, the model developed is actually a communications model more than an overall C3 system model. The assessment, generation, and selection functions are not really addressed in MCCAAM.

INTEGRATION MODULE. In this module, basic communications functions (enter net, transmit, receive, change frequency, etc.) were mapped to the command system elements (specific units or command and control facilities). In this modeling context, the message traffic flow represents most of this mapping. This integration is the combination of the results of steps two and three: integrating the system elements and the process functions into a valid simulation model.

SPECIFICATION OF MEASURES MODULE. At this stage, Measures of Effectiveness (MOEs) and Measures of Performance (MOPs) were identified and agreed upon with the Marine Corps project officers. The MOEs selected measure aspects of the communication system functions that contribute to the overall accomplishment of critical missions while the MOPs quantify critical capabilities of the radios.

DATA GENERATION MODULE. Here values for the MOPs and MOEs were obtained from the simulation model (MCCAAM). This is accomplished by generating traffic with different rates of occurrences. This traffic is simulated as it works through the given force architecture where relevent net and radio statistics are collected. Many simulation test runs under a specific experimental design yield the data ultimately used in our analysis.

AGGREGATION AND INTERPRETATION MODULE. The numerical results obtained from the simulation runs as MOPs and MOEs were aggregated under a scheme described in Chapter III to provide an overall quantifiable measure of system effectiveness.

In the SINCGARS allocation application, the measures would ideally be measures of force effectiveness (MOFEs) that reflected the effect better communications had on the outcome of battles. But the Marine Corps desired a flexible, scenario-independent model which, of necessity, excludes battle outcomes. Therefore, measures of communications effectiveness were selected in two major categories: timeliness of message receipt and reliability of network connectivity.

B. USMC MAGTF STRUCTURE

To understand the specific areas of our simulation model development it is necessary to understand the building blocks that were used to model the MAGTF communications architecture. These building blocks are the MAGTF force structure and how units are related organizationally, the communications principles dictating how, when, and why units communicate, and the physical equipment that is used to actually establish the essential communication lines. Figure 2 [Ref. 5] illustrates how these building blocks exist within a framework that contains not only the equipment sub-systems, but the forces and environment as well.

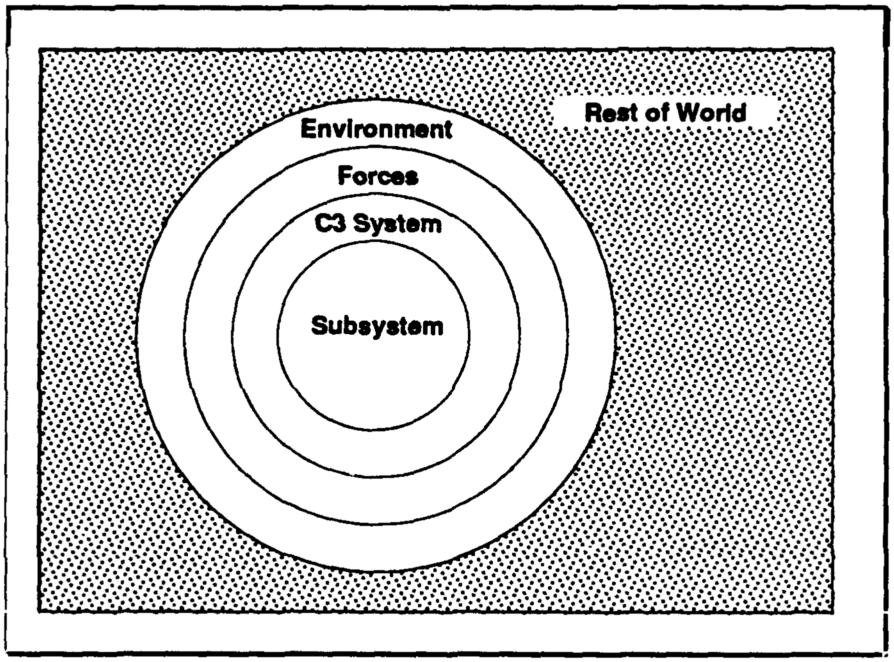

Figure 2. Communication System Bounding

This section briefly discusses these building blocks as motivation for how and why our model was developed the way it was.

A Marine Air-Ground Task Force (MAGTF) is the organizational structure used for nearly all operations conducted by United States Marine Corps forces. Independent of the size of the force, MAGTFs are combined arms organizations composed of a command element, a ground combat element, an aviation combat element, and a combat service support element (See Figures 3 & 4).

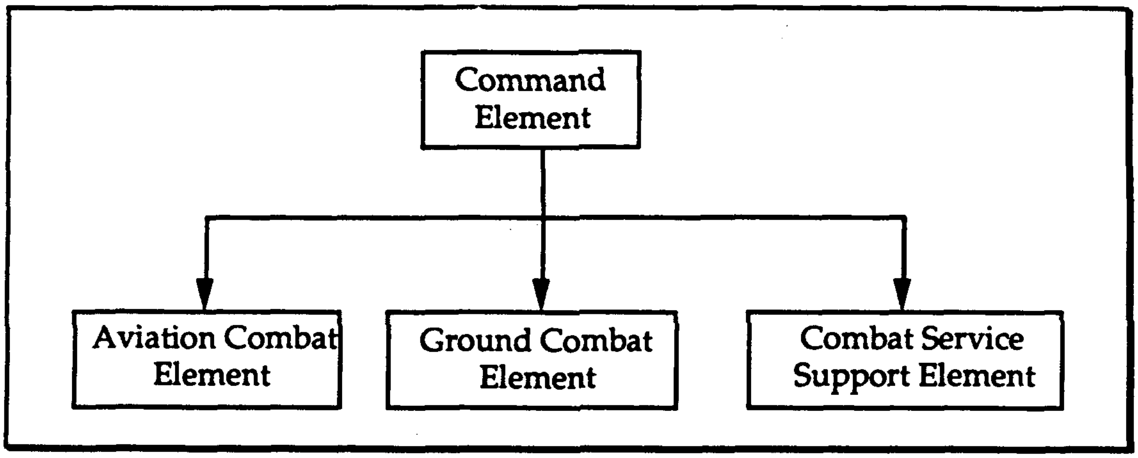

Figure 3. MAGTF Element Sizes

In order to support combined air, ground and logistics operations, four (or more) distinct command and control systems which differ in degree of centralization, automation, mobility, and complexity must be integrated. These distinct systems are composed of heterogeneous links and widely shared network resources which, when combined, form the key neurological component of a MAGTF. [Ref. 11]

The three sizes of operational MAGTF's are the Marine Expeditionary Unit, Marine Expeditionary Brigade, and Marine Expeditionary Force (MEU, MEB, MEF). From the smaller, more mobile MEU to the massive MEF, these MAGTFs are formed for specific operational requirements from various available units as illustrated in Figure 4.

	ACE	GCE	CSSE
MEU	Squadron	Battalion	CSSD
MEB	Group	Regiment	BSSG
MEF	Wing	Division	FSSG

Figure 4. MAGTF Element Sizes

The purpose of system bounding (third step in the MCES process) is to explicitly define the organizational scope of the problem. The result of this problem scoping step are lists or tables of the physical elements and structures that enumerate the levels of the problems. The complete list of all units involved in this specific MEB analysis is provided in Appendix D.

The *system* of focus is the MEB C3. The conceptual name for this system is the Marine Corps Tactical Command and Control System (MTACCS). It consists of the people, the hardware, and the software systems in the operational headquarters or command and control facilities (C2FACs) of the MEB. There are subsystems of the MTACCS for ground C3, aviation C3, combat service support (CSS) C3, and intelligence. Table 1 shows some of the major systems under each of these. Some of these are currently under development while others are in place. The communications elements of these systems are represented in the Marine Corps Tactical Communications Architecture overview chart which cannot be reproduced at this scale but which would be familiar to anyone involved in Marine Corps C3 discussions. [Ref. 18]

TABLE 1. EXAMPLE MTACCS SYSTEMS

Ground C2 System
- Tactical Combat Operations (TCO)
- Fireflex System

Aviation C2 System
- Advanced Tactical Air Command and Control Central (ATACC)
- Tactical Air Operations Module (TAOM)

Combat Service Support System
- Marine Integrated Personnel System (MIPS)
- Logistics Automated Information System (LOGISTATS)

Intelligence System
- Tactical Electronic Reconnaissance Process and Evaluation System (TERPES)

MCCAAM is currently being used to analyze only the ground C3 systems, but by design it can easily be modified and enlarged to incorporate aviation and combat service support systems that are key parts of a complete MEB communications architecture. Figure 5 [Ref. 17] provides another view of MCCAAM's current scope—the tactical, voice radio systems.

C. MAGTF COMMUNICATIONS

1. General

A command and control system is defined [Ref. 6] as consisting of the facilities, equipment, communications, procedures, and personnel essential to a commander for planning, directing, coordinating and controlling operations of assigned forces pursuant to the missions assigned. The functions of this system are to:

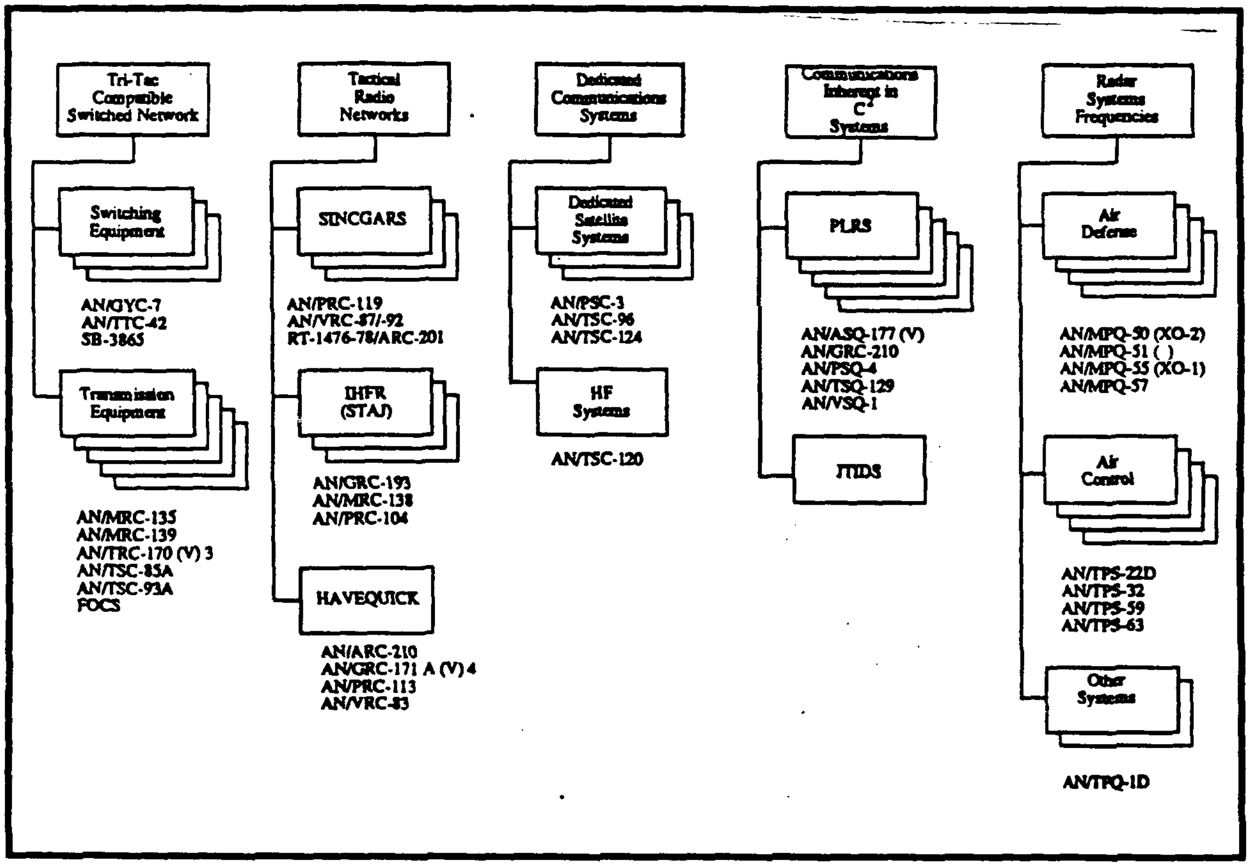

Figure 5. MAGTF Communications Systems

- Provide the commander accurate and timely information and ideas for developing courses of action and making decisions.
- Translate the commander's decisions into plans and orders.
- Communicate those plans and orders to subordinates.
- Provide required information to and respond to tasking from higher and supported commands.

To build a simulation model of a MAGTF tactical communications network in all of its dynamics, it was first necessary to understand all the mathematical model underpinnings that would be used to structure the simulation process. First, a brief discussion of the communications process is presented. This process must be understood to effectively model any communications architecture.

Each unit within a MAGTF possesses specified radio resources which individually compete for transmission time over their assigned nets. Over time, each radio receives messages which are classified according to priority, and higher priority traffic usually gets transmission precedence. When the respective radio operators receive written messages to be transmitted to higher, subordinate and adjacent units, they wait until the tactical net is free of traffic and then attempt to reach the receiving units with their highest priority message. If a radio operator receives messages of the same priority, he usually transmits them in the order he receives them. This discipline is commonly referred to as *store-and-forward* switching. [Ref. 32]

Delay of the messages may, in practical military networks, vary from a fraction of a second to several hours, measured from the time the message is first received by the initial radio operator. This delay consists of the times for the unit operators to store and retrieve the message along the various links, the times that the message sits in storage queues at the unit nodes waiting for the net to become available, and the often extensive time required to just make radio contact with the intended receiver. The first types of delays (node processing and net transmission) can be made relatively small in digital communications relative to the maximum tolerable delay. In voice communications, the net transmission time is often much larger. The unit-to-unit message delay, which is typically the principal criterion of performance, depends largely on the queuing delays at the various units.

Modelling all forms of these delays is a central focus of our programming effort. [Ref. 32]

Given the communications problem stated above, it was natural to approach our modelling task from the queueing theory perspective where a large number of alternative mathematical models have been produced for various waiting line situations. We initially focused on the single unit queuing system and then branched out to model the entire communication architecture as a network of queues.

The operating characteristics of queuing systems are determined by two key distributions: the probability distributions of the inter-arrival times and of the service times. To build a simulation model as a representation of the real tactical communication system we were interested in, it was first necessary to specify the assumed form of these two key distributions. To be useful in any form, the assumed distributions had to be sufficiently realistic so that the model provides reasonable predictions, while at the same time being feasible to work with. A discussion of the distributions used to provide randomization in MCCAAM is provided in section C of Chapter III.

2. Communications Principles

This section addresses MAGTF command, control and communication principles applicable to operation of communications and computers in task forces at all levels of warfare. This material is presented to motivate and explain the Measures of Effectiveness (MOEs) selected and to illustrate the type of information that was considered during the modelling process. To build a communications architecture which will serve the needs of a wide variety of users and communications managers, it is essential that the complex communications possible with today's technology be guided by fundamental doctrine. Nearly all of the principles which follow have been drawn verbatim from doctrinal publications and are categorized into two categories: those applicable to organizations and those inherent in the communications process. [Ref.8]

Principles applicable to organizations [Ref. 7: par 1008] are essentially rules of the road. They state which commander has the responsibility for establishing and maintaining communications when units work together. Since these are conventions established to place responsibility, no elaboration is necessary.

- Communications between a senior and subordinate unit are the responsibility of the senior commander.
- Communications between adjacent units are the responsibility of the first common senior commander.
- Communications between a supporting and supported unit are the responsibility of the supporting unit commander.
- Communications between a unit and an attached unit are the responsibility of the unit to which the attachment is made.

Principles applicable to the communications process that were considered in modeling the MAGTF C3 architecture and which are important to MOE selection are the following [Ref. 7: par 1004, 1005]:

- Communications must be **reliable**. Communications which enable a commander to plan, direct, coordinate and control forces in combat must be fully dependable and accurate. Reliability is attained through dependable equipment, excellent planning and execution techniques, and first class communications training of all personnel.
- Communications must be **secure** from all except intended recipients. All unauthorized persons and organizations must be denied information about a command's activity and status. This results in an enhanced operational security (OPSEC) posture and, at the same time, denies the enemy information. Security includes safeguarding the

physical equipment, documents, and personnel as well as the cryptographic, transmission, and emission security.

- Communications must be **timely**. Command and control communications must arrive at the intended user's location in time to be made useful. Speed of communications refers not only to the ability of hardware to transmit and receive data, but to the use of efficient methods and procedures.
- Communications must be **flexible**. FMFM 3-30 states that "Flexibility is the ability to support wide dispersion of units under adverse and varying conditions. A flexible communications system is achieved by detailed advanced planning, anticipation of the commander's needs, and provisions for the installation and maintenance of a responsive communications system."
- Communications must be **interoperable**. For communications systems to transfer data successfully, it is obviously essential that message standards, protocol standards, and data standards be established and adhered to.
- Communications systems must be **mobile**. Combat operations, especially Marine Corps offensive combat, requires rapid maneuver of forces. A communications system must be capable of full support of force maneuver. The amount of time involved in the set-up and establishment of a network is an important factor of this criteria.
- Communications systems must be **survivable**. Vital to the maneuver of forces, communications must be invulnerable to interruption on any battlefield and at any level of warfare. Inherent in this criteria is the need for a communications system to be able to operate in the midst of jamming, interference, direction finding and other enemy electronic activities.
- Communications must be **economical**.
- Communications must be **simple**. Simplicity promotes smooth, efficient operation for users and communications personnel who must establish, maintain and use systems. Even though the technical aspects of communications systems become complex, it is essential to keep procedures and techniques as simple as possible in order to meet the objectives of the command and control system.

3. Characteristics of FM Voice Transmission

Within the infantry, artillery, and mechanized units of a Marine Corps MAGTF, the primary method of communications between elements is typically single-channel, frequency modulated (FM) radios utilizing voice transmission. While this mode is easy to use, reliable, and fast, it does suffer from certain limitations. U.S. Marine Corps tactical FM radios generally operate in the frequency range of 30 to 76 megahertz (MHz) with typical output powers ranging from 3-5 watts in portable man-packed radios to 33 watts for the vehicular radios. Since radio waves above 30 MHz primarily travel by line-of-sight paths and since power outputs of 3 to 33 watts are not high, these radios are generally reliable only for short distance transmissions. Also, single channel tactical FM radio equipment is characteristically half duplex. That is, all tactical radios are push-to-talk and release-to-listen radios. They can only transmit or receive, but not both at the same time. When only one station transmits a message on a given frequency at a time, assuming that no jammers are active and an acceptable propagation path exists, then any station within range of that transmitter will receive its transmissions. If, however, two or more stations attempt to transmit simultaneously on the same frequency, interference may occur and the receiving stations may not be able to discern the intended signals. Furthermore, FM radios tend to capture the strongest signal transmitted on their respective listening frequencies. This characteristic, known as FM capture, tends to make single channel radios very susceptible to jamming. [Ref. 10]

Based on the limitations and characteristics of FM radios discussed above, the following simplifying assumptions were made for this model and analysis:

- Transmissions under way in a net will not be interrupted by other stations in the net desiring to use the net.

- When a message is transmitted over a net, all stations that receive the message will interpret that message correctly. This assumption is that human error in interpretation is negligible.

The human factors being assumed away are not trivial but are so complex that attempts to simulate them would detract from the overall modelling effort. Proper training and motivation of radio operators will eliminate much of the human factor problems [Ref. 9:pp. 17-18].

4. The Commander's Critical Information Requirements

To further motivate the structure and background of our communications model, this section highlights the necessity for a dependable C3 architecture that processes traffic in a timely manner. We then present an overview of how current technology is being used to achieve these goals in military communications. It is our intent that the MCCAAM model will be expanded to test and predict the impact of some of these current changes.

Fundamental to any discussion of command, control, and communications is the commodity of information. Since time is always working against the commander's ability to analyze information for the purpose of decision making, the keystone of any successful command and control system is an efficient communications backbone. "On today's battlefield, the ability of a commander to pass information among his forces is critical to the outcome of any engagement [Ref. 7]." Given this truth, our model *structures and measures of effectiveness are highly time sensitive.*

In amphibious operations, the single channel radios (SCRs) are the principal means of communication during the assault phase. SCR configurations supporting high frequency (HF), very high frequency (VHF), and ultra high frequency (UHF) communications are found throughout all elements of a MAGTF. Though these radios have been designed and traditionally used for voice communications, computer technological advancements have introduced the capability to transmit computer-generated information, such as a situation report typed on a word processor, over tactical radio systems.

A significant advantage of computer-to-computer communications instead of voice is the speed of information that is transferred and the fact that operator intervention is kept to a minimum. For example, in the time it takes one to read this paragraph, an entire Size, Activity, Location, Unit, Time, Equipment (SALUTE) report of over 300 words can be transmitted. This ability to transmit high volumes of information in a short time is called burst transmission, and time on the air is significantly reduced with this capability. Consequently, the opportunity for the enemy to successfully locate a position is minimized. [Ref. 1]

As the Marine Corps and other services continue to incorporate technological advances like digital communications terminals (DCTs) and packet radio modems in their communications architectures, it will be essential that the services have the means to assess their contribution to the overall communication system performance. Though not currently modelling these aspects of modern military communication, MCCAAM can be easily modified to test the effects of such technology on a given architecture's message throughput, efficiency, and resistance to intervention.

C. SINCGARS/VRC-12 CHARACTERISTICS

This section provides the reader with a general description of the physical characteristics and functional parameters of the current AN/VRC-12 and

AN/PRC-77 radios compared to the SINCGARS-V replacement configurations. The differences between the two radio technologies affect the overall FM communication system performance, and thus serve as the foundation for the subjective MOE assessments presented in Chapter IV.[Ref. 10]

1. Conventional Fixed-Frequency Radios

a. General

The AN/VRC-12 series radio and AN/PRC-77 family radio are the primary radios in current use by the U.S. Marine Corps for the VHF-FM tactical communications. Throughout the remainder of this thesis, the phrase "conventional, fixed-frequency radio" will pertain to these two types of radios currently employed by the Marine Corps.

b. Capabilities

The radio sets in the AN/VRC-12 family are short-range, vehicular radio sets. The AN/PRC-77 is a compatible, short range, man-packed radio. These radios provide FM voice and telephone (MUX) communications and can be used with secure voice and digital data equipment. Two of the sets (VRC-45 and VRC-49) have re-transmission capability. The radio sets of the AN/VRC-12 family are used in nets with the AN/PRC-77 radio sets within the 30.00 to 75.95 MHz frequency range. The conventional radios are capable of transmitting and receiving on one of 920 frequency channels separated by 50 KHz, and have a planning range of 8 to 41 kilometers. Range depends on power out, antenna type and height and terrain/atmosphere conditions.

c. *Establishing a Fixed-Frequency Net*

The radio links established between designated radio stations can be categorized as a broadcast communication network. Each radio station is attached to a transmitter/receiver that communicates over a medium shared by other stations. All radio stations that are tuned to the same channel and that are within transmission range of each other will be able to receive a broadcast from a transmitting station. Two observations are in order for broadcast communications networks:

- Since the transmission medium is shared, only a single station can successfully transmit at a time. This requires some mechanism for controlling access to the shared channel. The net control station (NCS) offers a centralized scheme of control. The NCS can direct that a "free net" be established which is also known as the ALOHA access control technique. The ALOHA method is a first come, first served process.
- Establishment of radio links is limited by the nature of the broadcast medium. The weather, terrain, and link distance affect the signal transmission loss between stations in the broadcast communications network.

To establish a radio net with the conventional, fixed-frequency radios, the operator of a radio set must first locate his designated frequency in a Communications-Electronics Operation Instruction (CEOI). The frequency changes once every 12 hours. The operator then, using the lowest power setting available (to prevent unwanted transmission range/exposure to enemy listening or DF devices), makes radio voice contact with the net control station (NCS), asks permission to enter the net, authenticates, and waits for instructions from the NCS. The NCS, when given a correct authentication, grants the operator permission to enter the net, and informs the operator of net procedures (if any special ones exist). The NCS can either establish a directed net where the radio operator must make all communication links through the NCS, or a free net can be established where any station in the net can call any other station in the net without going through the NCS. [Ref. 10]

2. SINCGARS-V Frequency-Hopping Radio

a. General

SINCGARS-V is scheduled to replace some of the USMC configurations of the AN/PRC-77 and AN/VRC-12 family radios over the next five years. Limited by a budget that is traditionally very "tight," the Marine Corps does not have the luxury of replacing all the older radios at one time, though that is understood to be the eventual goal. With obvious emphasis on providing for the combat arms first, the infantry, armor, and artillery units will receive the first SINCGARS radios. See page 21 of [10] for the nomenclatures of the SINCGARS-V radio configurations which are scheduled to replace the conventional, fixed-frequency radios. This new radio will serve as the main tactical voice radio for the MAGTF when fully allocated, and therefore will be critical to successful operations ashore. As mentioned previously, since there will not be a total one-time replacement of the older radios, there will be many situations over the next few years when conventional radios and SINCGARS will be operating in the same area. Though not discussed in this thesis, this will undoubtedly provide many interoperability, maintenance, and supply challenges.

b. Capabilities

SINCGARS is a VHF-FM radio system, electronically tuned and controlled, which operates in the 30 to 88 MHz frequency band. It is able to transmit analog voice, tactical analog data, and 16 kilobit-per-second digital data record traffic. The transmission range for SINCGARS is similar to that of the AN/VRC-12 family radios. This new system provides approximately 2320 discrete channels in the VHF spectrum compared to the 920 provided by the current radios. It can be configured in man-pack, vehicular, and airborne versions and it features operational upgrades through various means to include:

- Push button tuning via keyboard
- Single Channel to frequency hopping by single switch operation
- Automatic identification of voice or data
- LED display provides comprehensive status information

The SINCGARS is lighter and about half the size of its current counterparts (See Figure 6 for a summary of technical characteristics). Some models of SINCGARS have a re-transmission capability similar to that of the present system that uses two receiver-transmitters in a special configuration to transmit to units out of normal communications range.

The primary ECCM (Electronic Counter-Counter Measures) technique for SINCGARS is its ability to frequency hop. An ECCM device can be fixed to the radio to give it six ECCM channels in addition to two fixed-

SYSTEM SPECIFICATIONS:

Frequency Range	30.00 to 87.975 MHz
Modulation type	Frequency modulation (binary or analog) 10 Hz to 8.0 kHz
Channels	2320
Channel spacing	25 kHz
Modes of operation	Single channel and frequency hopping
Preset channels	6 for single channel operation
Frequency Hopping Preset Radio Nets	6 each from front panel selector switch
Frequency Offset Capability	± 5 and ± 10 kHz to any manual or preset frequency
Frequency Entry	Through the keyboard
Frequency Stability	± 5.0 PPM
Communications Security Capability	Will operate with current U.S. inventory COMSEC equipment
Digital Capability	16 kbps and FSK (with optional data rate adapter)
Self Test	Microprocessor controlled in conjunction with LCD display
Radio tuning	All electronic

RECEIVER CHARACTERISTICS:

Noise Figure	10 dB
Image Rejection	80 dB minimum
IF Rejection	100 dB minimum
Audio output	50 mW or 1 mW/150 ohms (selectable)

TRANSMITTER CHARACTERISTICS:

Power output	10 watts nominal
Harmonic suppression	MIL-STD-461A
Transmitter spurious responses	100 dB
Frequency deviation	± 6.5 kHz

INPUT POWER:

Primary Power	+28 Vdc per MIL-STD-704 (3.5 Amps Max.)
Lighting	0-115 Vac 400 Hz (Electroluminescent)

ENVIRONMENTAL:

Specification	MIL-E-5400 Class IA

INTERFACE CHARACTERISTICS:

Interfaces with the following Avionics equipment:

- CV-3885/ARC-201 Data Rate Adapter
- KY-58, Z-AHQ, Z-AHP COMSEC Equipment
- ID-1351A Homing Meter
- C-1611, C-6533, C-10414 Intercoms
- AM-7189A/ARC 50-Watt Power Amplifier

Figure 6. SINCGARS Technical Characteristics

frequency channels. The system uses a number of separate frequencies, and one channel is established by synchronizing the transmission and reception of these frequencies. The frequencies to which the signal can be hopped can follow an ordered or random sequence called a hop set.

The band-width is increased due to the use of a multiple number of frequencies per channel. More users can operate within the same band employing this technique since they are only on one specific frequency for a very short period of time. Though there have been several proposals for different algorithms to deal with this problem, assignment of these frequencies remains a difficult challenge. [Ref. 10]

The SINCGARS radio system is interoperable with the current inventory of radios in both the plain text and cipher modes on a single fixed channel. Communications security (COMSEC) equipment will be internal or external to the radio system and both are compatible with the current radio/COMSEC configurations.

Some additional features of the SINCGARS radio are [Ref. 10] :

- Balanced nuclear hardening to include Electromagnetic Pulse (EMP) and Transient Radiation Effects on Electronics (TREE) protection.
- Modular components which provide commonality among all configurations.
- A high power amplifier (HPA) module used with the SINCGARS to provide a power output of 50 watts.
- Any one of six frequency pre-sets may be switch-selected by the operator.
- Built-in-test (BIT) unit to detect failures in equipment modules or cards.

c. Establishing a Frequency-Hopping Net

Similar to the current radio system, a broadcast communication network will be used to establish the frequency-hopping SINCGARS radio nets. However, the procedures for establishing the SINCGARS radio nets is a much more complicated process, as described below.

The technical characteristics of the frequency-hopping radio requires multi-frequency management on a decentralized basis. As a result, the procedures required to establish a radio net become much more complicated. The NCS must distribute five variables required for frequency-hopping operation to each radio station in the net. The required variables are:

- TRANSEC Key
- Hopset/Net ID
- ERF Frequency
- Cueing Frequency
- Mission Day/Time of Day

A battlefield electronic CEOI system (BECS) electronic notebook is used to generate, store, display, or transfer the five variables required for SINCGARS frequency-hopping net operation to the radio sets. [Ref. 10]

There are two methods for loading the data into the radio sets. The NCS can use either a local fill procedure or an electronic remote fill (ERF). A local fill procedure is accomplished by physically connecting an ECCM fill device or a tape to the radio while electronic remote fill is performed by electronically transmitting frequency hopset variables between SINCGARS radios. (Since much of the data needed by SINCGARS is based on the time of day variable mentioned above, any inconsistency in the filling procedure can lead to a rather time consuming set-up time for a tactical SINCGARS net).

In summary, the existing VRC-12 radios are not as flexible and reliable as the new SINCGARS radios, but they are simpler to set up and use.

III. SOLUTION METHODOLOGY

Working from our problem framework outlined in the previous chapter, Chapter III explains how the MAGTF structure, communications principles, and equipment were incorporated into our model development. We begin by giving our rationale for choosing simulation as the appropriate modeling tool, and then briefly discuss our choice of a simulation language. The key sub-models of MCCAAM are then presented as a preliminary to describing the overall simulation flow. We detail how messages are handled within the simulated communications architecture to show the reader the key logic that allows for accurate analysis of alternative architectures. This chapter concludes with a description of the model's data input requirements and assumptions.

A. WHY SIMULATION?

A subjective allocation of SINCGARS radios could be made by asking experienced officers to review existing architectures and traffic requirements and then allocate the available SINCGARS radios to the VHF networks that need them most (highest traffic and most vulnerability). However, even experienced officers would have difficulty comparing the operational tradeoffs offered by different allocations and determining how the various nets would actually perform in different environments. Therefore, a quantitative model, such as discussed in this Chapter, is desirable. [Ref. 18]

Over time, much effort has been expended evaluating the performance of military organizations' communication systems. Typically, these efforts have involved modelling the workload the communications system must handle. The performance is evaluated using analytic, approximation, Monte Carlo, or system simulation methods. To a large degree, the following aspects of a model are dictated by the degree to which the workload model reflects reality [Ref. 11]:

- the choice of evaluation technology,
- the development and implementation costs, and
- the degree of acceptance and usability of the end product.

One of the main strengths of the *analytical* approach is that it abstracts the essence of the problem and reveals its underlying structure, which provides insight into the cause-and-effect relationships within the system. These methods attempt to find and solve mathematical equations in a closed form solution to accurately describe the behavior of a system under different circumstances. If it is possible to construct an analytical model that is both a reasonable idealization of the problem *and* amenable to solution, this approach is usually superior to simulation. However, many problems are so complex that they cannot be solved analytically. This is because these systems (including C3 systems) are composed of a variety of subsystems that, even when viewed individually, are extremely difficult to analyze by conventional methods. Additionally, the choice of MOEs often drives us to use simulation, independent of the system's complexity.

If a conventional approach is pursued to keep the problem within a tractable domain, assumptions must be made that could distort the physical reality of the system. *Simulation* is a versatile tool that is typically used when the system involved is too complex to be analyzed satisfactorily by analytical models. [Ref. 12]

With this in mind, we view simulation as a controlled statistical sampling technique for estimating the performance of a complex stochastic communications system. We simulate the actions of the communications system over time and record its aggregate behavior to estimate performance. We understand and want to make clear that "simulation is inherently an imprecise technique that provides only statistical estimates rather than exact results. It compares alternatives rather than generating an optimal one." [Ref. 13:pp. 857 & 887]

After choosing simulation as our modelling technique, we examined the full range of the simulation fidelity spectrum. A brief discussion of models found at the extremes of this fidelity spectrum will help clarify the strengths of our approach.

At one end of the simulation fidelity spectrum, there exist models which have stationary arrival processes of message-sending requirements. These processes are typically stationary Poisson. This simple workload model is used because evaluating the resulting communications traffic process is sometimes analytically tractable. This approach usually allows for relatively inexpensive development at the expense of reality, usability, and user acceptance. Examples of this approach can be found in [Ref. 14].

At the other extreme are models which attempt to simulate the evolution of combat, thereby inducing a realistic communications workload. Some of the drawbacks of this approach are readily apparent. In order to generate the communications traffic, the combat simulation must be of high resolution. Thus, reality comes with significant model development costs, and programming costs. Such models require voluminous input data, to which confidence in model output is very tightly linked. Conclusions drawn from the results of high resolution combat models are valid only for the specific scenario used. [Ref. 11] Furthermore, inclusion of details costs computational effort with each replication of the (obviously terminating) scenario, resulting in extremely large computing requirements for meager accuracy. These types of models display hard-to-quantify effectiveness, as the engagement modeled can take several distinct turns during its evolution. Most frustrating, it becomes very difficult to attribute changes in performance to variations in input. Examples of high resolution combat models for communications performance analysis can also be found in [Ref. 14].

In this thesis, we describe a model of MAGTF communications traffic which occupies the middle ground of the simulation fidelity spectrum between the extremes of simple, analytically tractable Poisson models and high resolution combat models. Our model uses a paradigm of Marine Broad Operational Tasks (MBOTs), Broad Operational Subtasks (BOSTs), and Message Exchange Occurrences (MEOs) to avoid the weak points of the simulation extremes described above. This paradigm is described in section C.1 of this chapter.

In summary, it is clear that a simulation model is the appropriate tool for analyzing the complex military communications process. It provides a means to experiment with proposed systems or architectures without actually implementing them. With proper experimental design and sound statistical analysis, the results of a simulation can, and often do, provide decision makers with a very effective decision-making aid.

B. OBJECT ORIENTED PROGRAMMING

Object-oriented programming is a design and programming discipline that focuses on the objects that make up the system rather than on the overall function of the system. While this is at odds with traditional top-down design techniques, we will see that there are excellent reasons for adopting this point of view. [Ref. 22]

This introductory section is presented since object-oriented programming is fairly new to the military and the selection of a modelling language is a key part of any computer modelling problem. It highlights object-oriented programming's many strengths and the reasons for choosing MODSIM II as our simulation language. [See reference 15 for details of the MODSIM programming language]

1. MODSIM II

The result of evolutionary language developments, the Modular Simulation language, MODSIM II, is a general-purpose, modular, block structured language which provides support for object-oriented programming and discrete event simulation. It has several advantages over non-object-oriented simulation languages when used in modelling complex, interactive sytems like military communications architectures. [Ref. 15]

- **Modularity**: Programs may be (but are not required to be) divided into modules. Each module is stored in a separate file. The advantages of this approach are that these modules can be compiled separately, saving time when only one of them is edited. Modules can import constructs and definitions from each other. This modularity allows one to easily model real-world sub-systems as separate parts of a large model and lends itself to multiple programmers.

- **Block-Structured**: A block is made up of declarations and executable statements. It may contain smaller blocks. The important feature of block-structured languages is that the scope or visibility of variables is restricted to the block in which they are declared and any subsidiary blocks. This feature helps to make programs very reliable and easily modifiable.
- **Object-Oriented** : An object is an encapsulation of a *data record* (obejct's fields) which describes the state of the object and *procedures* called methods which describe its behaviors. (See Fig. 7) Objects are more concrete than most programming constructs in that they exist as individual entities throughout a program execution. They interact through a clearly defined protocol, and the fields of an object instance can only be changed by its own methods.

```
UnitObj = OBJECT
  name            : STRING;
  unitType        : UnitDesignationType;
  loc             : UnitLocationRec;
  echelon         : EchelonType;
  division        : INTEGER;
  regiment        : INTEGER;
  battalion       : INTEGER;
  company         : INTEGER;
  platoon         : INTEGER;
  numRadios       : INTEGER;
  radio           : ARRAY INTEGER OF RadioObj;
  netType         : ARRAY INTEGER OF NetDesignationType;

  ASK METHOD   ObjInit;
  TELL METHOD  ReceiveBostInstance (INIncomingBostPack: BostInstanceTxObj;
                                    IN IntendedReceiver : INTEGER;
                                    IN SelectedRadio    : RadioObj;
                                    IN ReceiptStatus    : ReceiptStatusType);
  TELL METHOD ExceptionHandlingRoute
               (IN IncomingBostPack : BostInstanceTxObj);
  TELL METHOD KnowAboutJamming  (IN Radio : RadioObj;
                                    IN Index : INTEGER);
```

Figure 7. Example of MODSIM Object with its Fields and Methods

There are other key object-oriented constructs of MODSIM II that make it such a powerful and flexible tool. These other constructs are detailed in [15] for those readers who are interested, but a few are simply listed here:

- single and multiple inheritance
- dynamic binding of objects
- polymorphism
- data abstraction and information hiding
- dynamic memory management capability

As an example of some of the features mentioned above, we might have two unit types, rifle company and tank platoon, which are object types derived from the more general unit object type. If we ascribe a method called *receive.order* to the unit object, then we can invoke *receive.order* for any object whose type inherits the unit object type. If, at some point in future development, we wish to add a Light Armored Vehicle (LAV) platoon to the simulation, we may choose to inherit the properties of the tank platoon object as a starting point and then modify the fields and methods as necessary. [Ref. 11]

MODSIM II's structure and syntax were based on that of Modula-2, so programmers familiar with Pascal, Modula-2, or Ada would have little difficulty in learning the language. Since it is a strongly typed language, (all variables must be declared by type), MODSIM II promotes consistency and reduces errors in user code. This strong type checking ensures errors are caught at compilation time rather than at run time when they would be much harder to find. [Ref. 15]

The speed and portability of MODSIM II are a result of the C code which is created by the system's C compiler. Compiled code means faster execution times, and allows it to be highly portable across mainframe, work-stations, and PC's. Because MODSIM II supports automated separate compilation and importation of code from modules and libraries, the language is ideal for large projects with multiple programmers. [Ref. 15]

The same modularity that facilitates multiple programmer projects promotes easier code maintenance and improves reliability and code reusability. Objects and routines performing related functions can be grouped into modules which can be put into libraries for reuse by other programs. In this manner, such common simulation requirements as statistic collecting and queue management are already standardized and available with the language's built-in library.

A key area for future MCCAAM development work is the integrated dynamic graphics available in MODSIM which can substantially reduce the time and effort required to display results. Only a few lines of code are needed to create dynamic icons, histograms, clocks and meters that change as the program runs. With graphics, many results are easier to explain and understand.

2. Object Oriented Simulation

Object-oriented simulation and object-oriented programming are both based on the principle that the design of a system should be based on the objects that make up the system. Three concepts characterize the difference between object-oriented programming and object-oriented simulation: entities, events, and simulation time. [Ref. 22]

In an object-oriented simulation some of the objects are active. They execute independently of, and concurrently with, other active objects. These active objects are called entities. They are used to model the physical processes in the system being simulated. In our case, the unit, net, and radio objects are all examples of entities and a physical process that they model is transmitting and receiving messages.

An event represents a change in the state of one of the objects in the system being simulated. Entities schedule events for each other to mark when these state changes are to occur. Events are used either to synchronize the actions of two entities or to pass information from one entity to another.

Entitity actions and event scheduling are both tied to a logical clock called *simulation time*. Simulation time is an arbitrary, application defined time scale that is independent of real time. Each event is tied to the logical clock through a scheduled event time. This event time corresponds to the actual time in the physical system when the corresponding physical event would occur. [Ref. 22]

Given the three concepts briefly explained above, constructing object-oriented simulations involves: [Ref. 22]

- Identifying the physical processes that make up the system being defined.
- Defining an entity class to model each type of physical process.
- Identifying all circumstances that can lead to changes in the state of the system and characterize these as events.
- Determining when events occur and tieing them to simulation time by means of their scheduled event time.

Like all process oriented (i.e. not discrete event) simulation paradigms, the object-oriented simulation modeling framework has occasion to freeze a process until some time passes, some condition becomes true, or some resource is available. The utility offered by object-oriented simulation is that this waiting is done by a method of an object. In MODSIM II, an object can have several concurrent methods waiting for different things. This allows for autonomy of objects, promoting reusable object code.

In summary, MODSIM II is a complete, powerful, general purpose programming and simulation language. Its features reduce design and coding effort and improve reliability. As mentioned previously, its modularity allows any simulation programmer to expand a simple model into a more complex one with ease. This degree of modularity has enabled us to quickly develop MCCAAM using three programmer authors with a graceful buildup. [Ref.11] The degree of dynamic interaction between many varied units in real-world military communications requires the flexibility and structure that object-oriented simulation affords.

C. MODEL DEVELOPMENT

In order to theorize about military communications and the complex military C3 process and to construct an appropriate model, it is useful to have a definition of a C3 system. For our evaluation, and in concert with the MCES system bounding requirement, a C3 system possesses the following components [19]:

- **physical entities**—refers to equipment (computers and peripherals, modems, jammers, antennas, batteries, vehicles), software, facilities, and people.
- **structure**—identifies the arrangement and interrelationships of physical entities, procedures, protocols, concepts of operation, and information patterns. (This frequently reflects doctrine and may be scenario dependent.)
- **process**—identifies the functions of the system as tasks that are being carried out (receiving, queueing, transmitting, routing, jamming, waiting, etc.)

These three components were used as a baseline for modeiling the MAGTF communications architectures. The external stresses that affect all of these basic components were another foundational consideration in developing MCCAAM and are discussed in the following sections.

MCCAAM is intended to be used by the Marine Corps Warfighting Center to measure communications network and architectural performance under a variety of possible stresses, as shown in Figure 8.

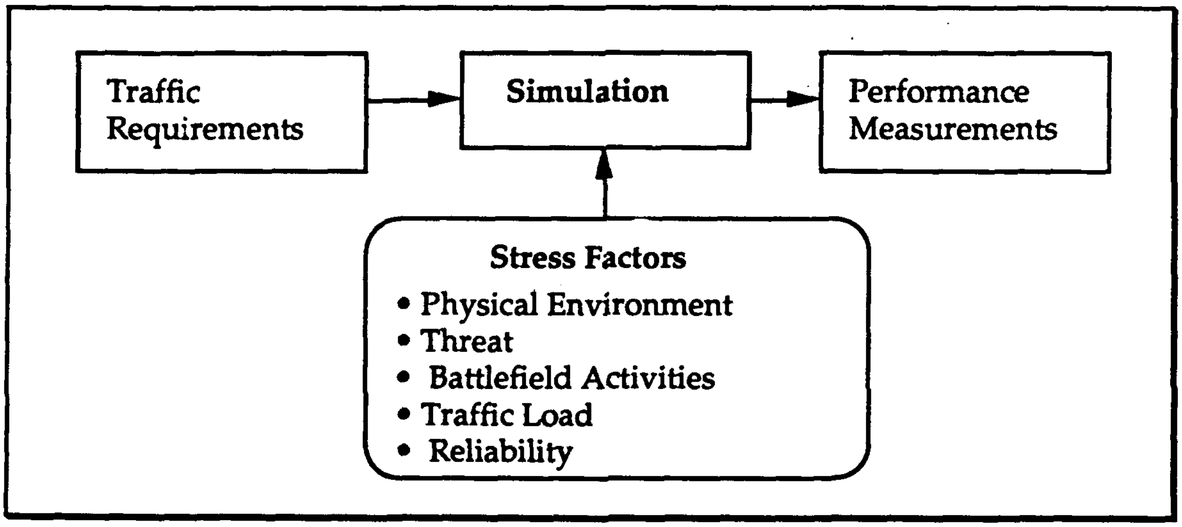

Figure 8. External Model Stresses

Of the 5 major stresses listed, MCCAAM currently only models traffic, reliability, and a limited threat. It will be useful for system engineering functions, such as network sizing and configurations, as well as operational planning. In can also be modified to support interoperability analysis, threat analysis, test and evaluation planning, and any application where a communications network ability to move traffic under battlefield conditions is a consideration.

The model design is based on the premise that the major mission of a MAGTF communications network is its capability to move message traffic during combat. Actual performance is a function of numerous battlefield factors that affect network throughput. The main subsystems of our MCCAAM model that simulate these battlefield factors are the communications model, the workload model, the jamming model, and the reliability model.

1. Communications Model

Communications requirements within a MAGTF are outlined in [Ref. 20, 21] and depicted in MCCAAM in terms of needlines. A needline is a series of related data elements which describe a requirement to communicate information between two or more battlefield communicators, hereafter described as Command and Control Facilities (C2FACs). The makeup of these "needlines" is described in the following paragraphs which detail the workload modelling.

The *five* major Marine Corps mission areas are air operations, ground operations, intelligence, fire support and combat service support. The MAGTF Interoperability Requirements Concepts (MIRC) contains the tasks performed by Marine Corps communicators which are similar to the MCES standard functions of sense, assess, generate, plan and direct. Each of these functions is performed by a subset of the C2FACS in a MAGTF in a sequential fashion to accomplish tasks in the five mission areas above.

To capture the sequence of message traffic required to accomplish certain operational tasks, the Marine Corps Technical Interface Design Plan for Marine Tactical Systems (MTS-TIDP) defines three levels of functions in

Volume II entitled Multiple Agency Message Exchange Sequences (MAMES) At the top level for each of the five mission areas are Marine Broad Operations Tasks (MBOTS) such as artillery call for fire in the fire support mission area. Each MBOT is then subdivided, for example standard fire mission, check fire etc. These subdivisions are called Broad Operational Subtasks (BOSTs). Each BOST is further subdivided into Message Exchange Occurrences (MEOs). Each MEO explicitly identifies the origin and destination C2FAC, the type of message sent and the net used for each MEO in accomplishing the BOST as illustrated in Figure 9. In addition, each MEO cross-references the interface task which created it and the next interface task which its receipt supports. The normal sequence of the MEOs is roughly indicated for each BOST. There are as many as 50 MEOs for a BOST.

The following paragraphs discuss how the actual communications architecture was modeled in MCCAAM primarily through the interaction of Unit, Radio, and Net Objects. Figure 10 lists the primary network objects in MCCAAM with most of their accompanying fields(attributes) and methods(activities).

a. Command and Control Facilities (C2FACs)

C2FACs are the agencies that process command and control communications and are modeled as Unit Objects in MCCAAM. Since MCCAAM simulates actual procedures to generate and route message traffic, it needs to know what C2FACs are in the architecture, where they are located, the single-channel nets they guard, and a few additional pieces of information.

The Unit Object is the base type from which we create all of the C2FACs in MCCAAM. Instances of C2FACs range from a platoon headquarters (~ 2 radios) to a Brigade headquarters (~ 20 radios). The communications equipment owned by a C2FAC is stored in a radio array which is a field of each unit object. Each radio, in turn, is a doctrinal

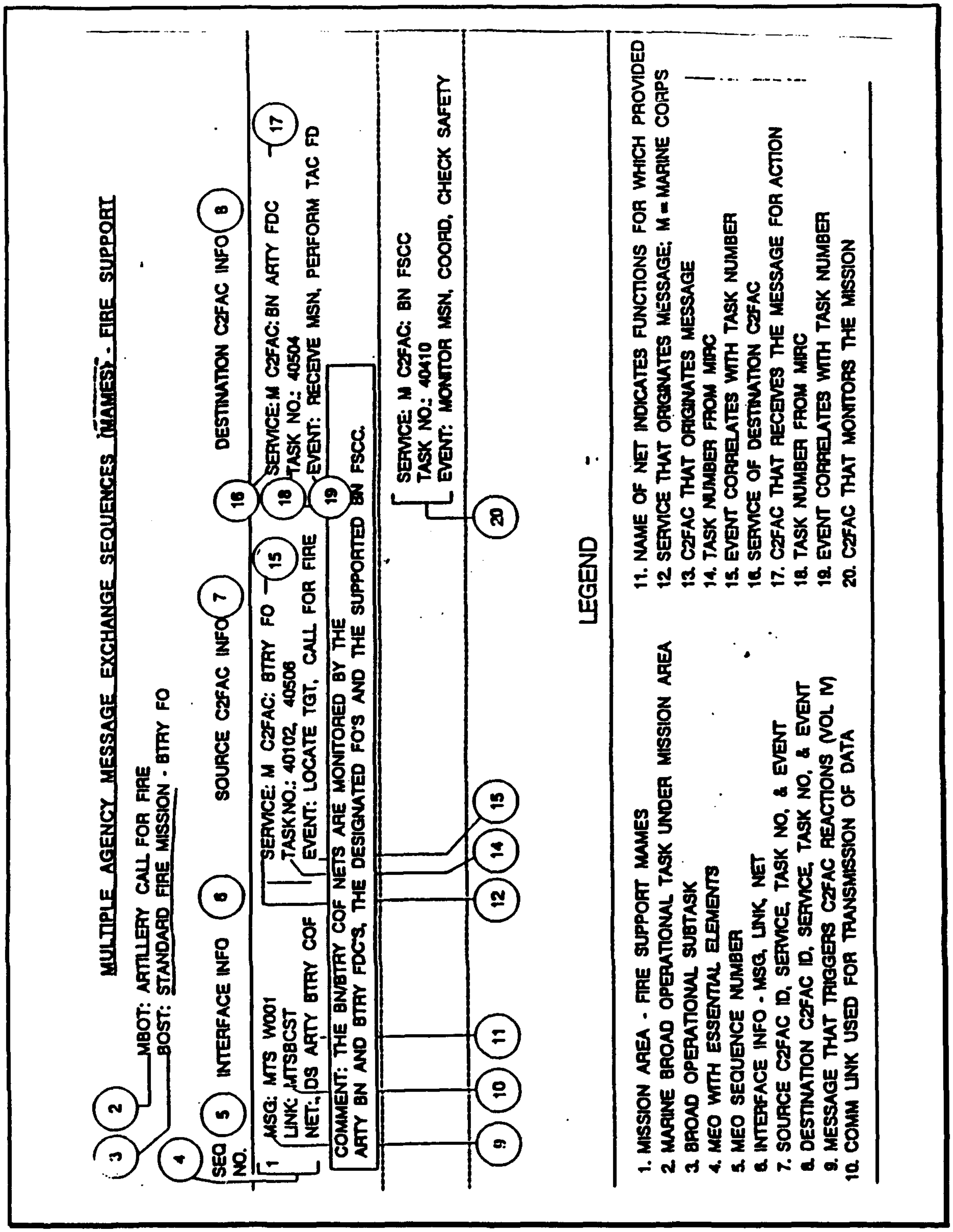

Figure 9. Message Exchange Occurrences Between C2FACS

subscriber of a given net. Section (b) further illustrates the features of the radio objects. The differences between unit types are found in the composition of the radio array, the rate of BOST initiation for each type of BOST, and the particular nets that the unit is a subscriber of.

OBJECTS (ENTITIES)	FIELDS (ATTRIBUTES)		METHODS (ACTIVITIES)
Units	name	numRadios	TELL ReceiveBostInstance
	location	netType	TELL ExceptionRoute
	echelon	radio (array)	TELL KnowAboutJamming
Radios	unitLoc	NetType	TELL Fail
	netIndex	Equipment	ASK Start(Stop)Receiving
	queue	Available	ASK RequestTransmission
	Jammed	Transmitting	ASK SubmitBost
	Receiving	MTBF	ASK Start(Stop)Transmit
	NumInQ	NumMessAtt	ASK Become(Un)Jammed
Nets	NetIndex	NetDescriptor	TELL EnterNet
	Type	PropagateMode	TELL ChangeFreq
	NetIdle	Equipment	TELL ExecuteBusyPeriod
	Frequency	NetJammed	ASK SelectRadio
	Mean AcknowledgeTime		ASK NextTraffic
	RadioList (linked list)		ASK ConstructWaitingList
	SelectedRadio		TELL TransmissionDelay
Jammers	Name	IDNumber	TELL Jam
	XCoord	YCoord	PROCEDURES:
	Range	JamBandLow	ReadJammer
	Active	JBandWidth	SelectTarget
	NumJammed		CalcDistance

Figure 10. Partial Attribute and Activity Summary for Major MCCAAM Network Objects

Each BOST is pursued via the execution of MEOs between units. After a unit receives an MEO, it checks the BOST to determine the next MEO and determines the appropriate net using the route procedure. Figure 11 shows the interactions between the units, nets, and the traffic generator. [Ref. 11]

As currently modeled, the main method that the Unit object owns is the **ReceiveBostInstance** method which takes an incoming MEO, checks it for accuracy, and then takes appropriate action as required. There are circumstances under which the unit will not be able to reach some of the intended receivers on the net specified in the BOST. Thus, the **ReceiveBostInstance** method makes a call to a complex routing routine which determines the sequence of units who will relay the BOST to the intended receiver.

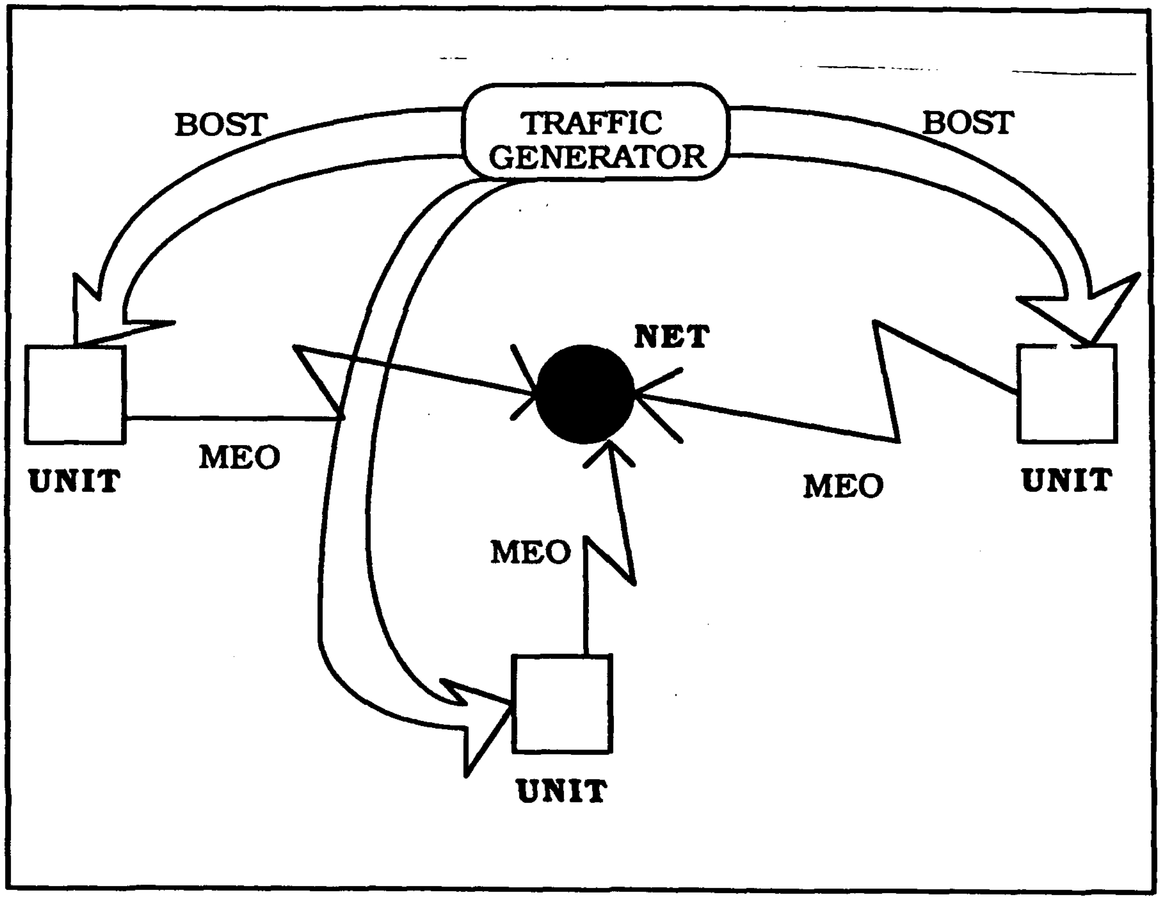

Figure 11. Interaction Between TrafficGenerator, Units, and Net

b. Radios

The radio object, as mentioned earlier, models the actual characteristics and actions of the tactical radios in our simulation. Each radio object has its own fields and methods which distinguish its existence and performance capabilities within the simulation model. Fields which identify whether or not the radio is down for repair, currently being jammed, or currently transmitting all help to track the individual performance of each radio. Instances of the radio object in MCCAAM currently are the members of the VRC-12 family and the SINCGARS radio as well as HF radios which are often used as an alternate route for VHF traffic. The main field that the radio object owns is a prioritized queue which is used to hold the MEOs that the radio is waiting to transmit. By means of this queue, we are able to monitor the number of waiting messages and, over time, gather a picture of which radios are used the most. From within the radio object, we also track the number of message attempts and completions for each radio. As illustrated in the unit description section, each radio object is owned by a unit and is located in that particular unit's radio array where it can be accessed when needed.

The main methods that the radio base-type owns are the RequestTransmission method, the SubmitBost method, BecomeJammed method, and the Fail method.

c. Nets

Voice radio nets are central to our problem; as part of their respective object descriptions, they have access to the different radio object types that we are concerned with (VRC-12 family and SINCGARS). They are a target of enemy jamming, a resource that is tied up by a message transmission, and a method for re-routing traffic when a primary net is not available between any two C2FACs. For the results of any MCCAAM analysis to be meaningful, it is imperative that the nets and the units that are subscribers of these nets reflect the actual nets and net memberships that are relevant to the question at hand. In this case, the allocation of new SINCGARS radios.

The net object is the base type from which all the various MAGTF nets are created and linked together to form the communications architecture of MCCAAM. Since radio net transmission time is the only limited resource in our model (besides radios) the modeling of this resource is key to how the model simulates the actual message handling of specified nets.

A net may be thought of as a one-talker-at-a-time party line where all the unit subscribers of the net have the opportunity to hear every message that is transmitted on the net, but only one subscriber may transmit at any time.

The nets in our model use a highest-priority-first discipline, which may be slightly more orderly than an actual tactical communication process. When an opportunity for transmission takes place, (i.e. the net becomes idle), the net polls each of its subscribers using its NextTraffic method and randomly chooses one of the units with a highest priority message waiting in queue This reflects reality in that if several units are all trying to gain access to a net with equal priority traffic, the winner really is a random draw. This queueing discipline is easily varied by changing the ExecuteBusyPeriod method of the net.

The other main method that the net objects own is the ChangeFreq method which causes the current net frequency being used by fixed frequency radios to change in a user-defined periodic fashion. This method is also called when a fixed frequency radio is jammed and cannot work through the jamming. The jammer objects, as defined later, check specific frequency bands and if no net is transmitting in that range band while the jammer is scanning, the net avoids being jammed. See Figure 11 on page 47 for an illustration of the jammer/net/unit interaction.

2. Workload Model

Stochastic workload models are normally used to drive communication system models. As mentioned previously, these range from simple low-resolution models that generate messages according to stationary Poisson processes to extremely high-resolution models that try to simulate the actual evolution of combat with all of its inherent communications. [Ref. 29]

In order to test the value of a specific communications architecture, we must stress the system in a realistic fashion. However, we want our conclusions to be independent of a specific scenario of events. Through application of the Modular Command and Control Evaluation Structure (MCES), we have developed a paradigm for workload modeling that lies between the extremes mentioned above. It exploits the information promulgated in the Technical Interface Design Plan (TIDP) Vol II as described in the section on the communications model. The structure of this document, which clearly defines each of these items and their interdependencies, makes it possible to generate realistically interdependent message traffic without resorting to a specific scenario. This generation process is detailed in the following paragraphs. [Ref. 29]

To generate traffic for the MAGTF communication system, we generate a sequence of BOSTS which are initiated by specific units within the force. Each unit, j, in the MAGTF has a particular rate of occurrence, $\lambda_{i,j}$, for each of the BOSTs, i, that it could possibly originate. Each Bost-Unit combination (i,j) initiates a particular BOST with its own rate relative to the other BOSTs and other units within MCCAAM. For our current model, the rates that are employed are best estimates from a surveyed panel of officers.

For efficiency and centralization of control, we generate instances of BOSTs from a BOST master list (which is easily manipulated as a data file) in a central process:

```
while (not TIME's UP)
sample DELAY with mean = 1/λr
wait DELAY
choose a BOST and UNIT
tell UNIT to INITIATE BOST
end while
```

where $\lambda = \sum_{(i,j)} \lambda_{i,j}$. For a straightforward initiation with no intensity factor, r=1. Given BOST i and unit j, the BOST-unit combination (i,j) is chosen from a multinomial distribution with probability $\lambda_{i,j} / \lambda$. If the central delays are chosen to be exponential, then each BOST-unit initiation is a filtered Poisson process. Otherwise, each time between BOST-unit initiation is a sum of a geometric number of *iid* delays.

An example of an operational task in offensive operations is Artillery Call For Fire, with the constituent BOST, Standard Call For Fire. This BOST might be initiated by a Battery Forward Observer (BTRY FO), and it involves the cooperation of the Artillery Battalion Fire Direction Center (BN FDC), the Battalion Fire Support Coordination Center (BN FSCC), and the Artillery Battery Fire Direction Center (BTRY FDC). The MEOs which are required to complete the Standard Call for Fire BOST include the original call for fire, the clearing of the fire mission up the chain of command, the replaying of the clearance back down the chain, the spotting and firing directions exchanged between the BTRY FO and the BTRY FDC, the end of mission and surveillance messages. This BOST is a good example of how realistic traffic is produced in that there are concurrent messages that go out over monitored nets, conditional response type messages, and a real-world precedence structure between the MEOs. [Ref. 11] The MEOs that need to be sequentially accomplished for this BOST are illustrated in Figure 12.

Each specified message within a BOST has associated with it a message format which identifies the message originator, receivers, net to be used, and a duration. The duration is a modelling addition which allows us to control how long the particular message will "occupy" or tie-up a radio net. A list of the specific MEOs required for the completion of each BOST is given in the TIDP Vol II along with a comprehensive description of the MEO. Therefore, the workload of our communications network is the complete set of message durations of all the MEOs that must occur to complete all of the BOSTs initiated by all the units in the simulation.

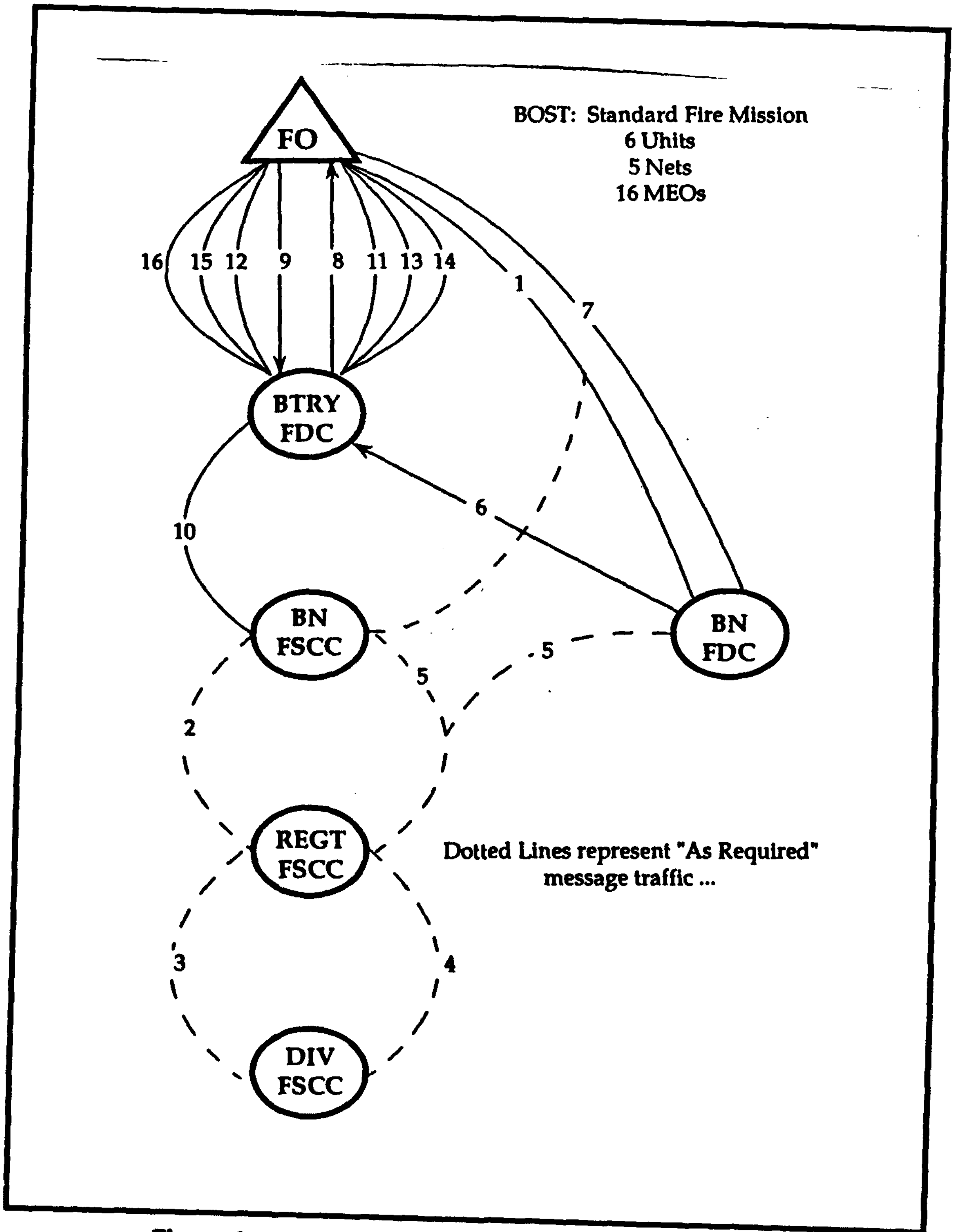

Figure 12. Example BOST: Standard FO Fire Mission

An interesting challenge in modelling military communications beyond the usual deterministic point-to-point, one-level message traffic, is that many times messages are intended as broadcast type messages which are intended for all children nodes on a family tree. We model this facet of military communications with a simple BOST designation: PointToPoint or Broadcast. The MEOs within a Broadcast BOST are cloned on-the-fly to meet the intended receiver requirements. In this manner, the conditional nature of our workload paradigm is greatly magnified and exercised. This facet of MCCAAM alone distinguishes it from normal communication simulation models.

To achieve realism, we specify several aspects of a general situation for our MCCAAM environment that help determine the extent of the MBOTS that will be involved. For example, the assumption that our MAGTF is already ashore and engaged eliminates the use of the MBOT "Warfighting Ship to Shore Operations." Based on the assumed information about the units involved in the MAGTF simulation (i.e. location and mission), we can more realistically specify the relative frequency with which each unit initiates each type of BOST. For example, an infantry battalion in reserve will not be initiating as many calls for fire as will a battalion engaged in a forward area of operations. The object-oriented nature of our model will allow very easy and graceful upgrades to include any level of detail desired in the actual simulated environment. As mentioned before though, our emphasis in modeling was only to include those elements of the tactical environment that would directly affect the communications process.

The use of the MBOT/BOST/MEO framework briefly discussed above allows us to model the tasks that any given MAGTF communications network would be required to undertake without mimicking detailed attrition engagements. We initiate BOSTs according to a static, stationary process and let the workload paradigm provide the realism; we get the communications realism of a combat model without the large development costs or narrow focus. This structure also allows us to compare alternative architectures under varying workloads without sacrificing realism; we simply adjust the rate (intensity) of the BOST initiation process. [Ref. 29]

3. Jamming

Significant radio jamming threats exist in several of the world's areas of interest. MCCAAM includes a model of these threats to provide a realistic environment for communications system evaluation. This is especially important because the SINCGARS radios, with their frequency hopping capability, are much more resistant to jamming than the current radios as Figure 13 illustrates. Thus, the relative value of a specific architecture of old and new radios is largely measured in the ability to perform critical communications in the presence of jamming.

a. *EW Definition and Scope*

Electronic Warfare is any military action involving the use of electromagnetic energy to exploit, reduce, or deny the enemy use of the electromagnetic spectrum. Normally, the electromagnetic warfare arena is broken down into three separate functional areas. The first, electronic support measures (ESM) pertains to those measures related to electronic search, interception, and location. The second area is that of electronic counter measures (ECM), which is the active portion of the electronic warfare arena. ECM involves jamming employment and the use of other equipment to disrupt the use of communications or noncommunications devices in the electromagnetic spectrum. Imitative deception falls into this category. The third functional area is that of electronic counter counter measures (ECCM). ECCM deals with those measures that a force takes to ensure friendly use of the electromagnetic spectrum and to reduce enemy ESM and ECM effectiveness. [Ref. 9:p. 60]

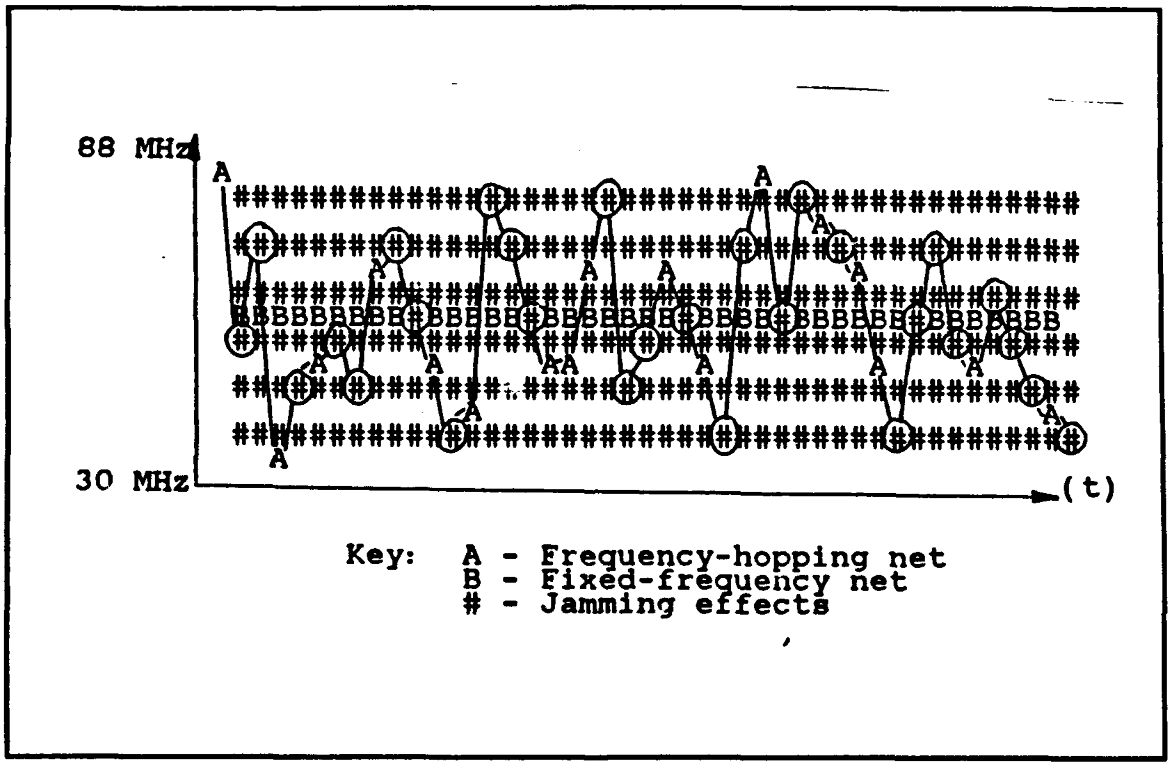

Figure 13. Effects of Jamming on Fixed Frequency and Frequency Hopping Radios [Ref. 10]

b. Enemy EW Techniques

To provide an example of how enemy ESM and ECM resources are expected to be utilized, Figure 14 is provided. Note that within 25 seconds after transmitting, a station is expected to be intercepted and its approximate location identified. Within three minutes, some type of ECM action such as incoming artillery fire or jamming can be expected. [Ref. 10] These times, of course, are based on optimal conditions favoring enemy electronic warfare efforts. Terrain obstacles, transmission time, power output, antenna directivity, and movement all play important roles in the success of electronic warfare. All are variables that can be modeled to reflect reality more closely, but the important factor that we considered was this: does it help to delineate between competing radio architectures?

There are many types of jamming signals that may be used against a targeted receiver. Some will be quite difficult to detect and in some cases impossible. For this reason, an operator must always be alert to the probability of jamming and react according to local unit standard operating procedures (SOP). Other jamming signals are clearly noticed as such. The more commonly used types are [Ref. 27]:

- Random Noise
- Recorded Sounds
- Random Pulse
- Stepped Tones
- Pulse
- Tone

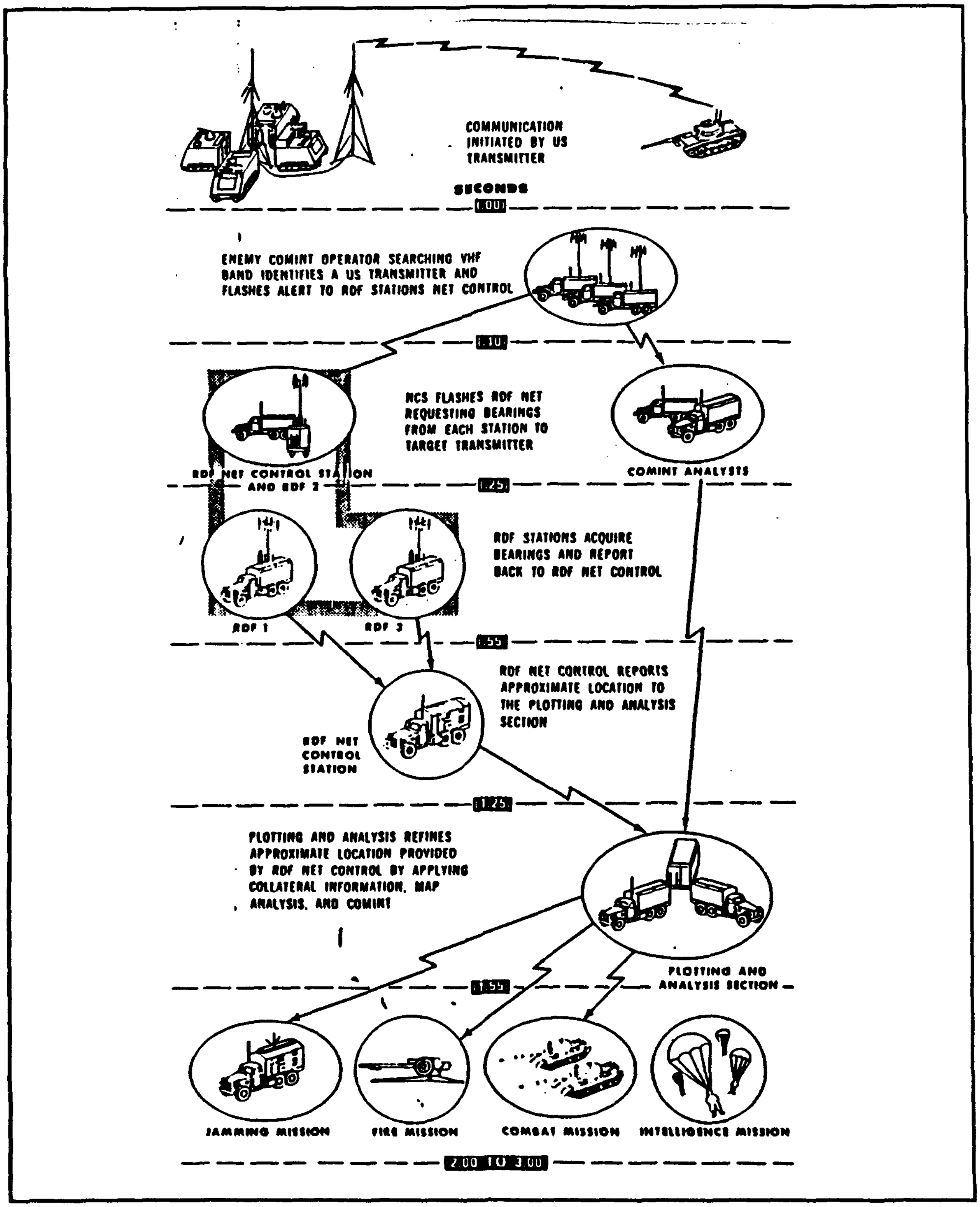

Figure 14. Example Threat Jamming Procedures

c. *Enemy EW Impact on Communications*

Radio operators must be able to determine whether or not their radios are being jammed. As was mentioned in the previous paragraph, this is not always an easy task. Threat jammers may employ obvious or subtle jamming techniques. These techniques may consist of powerful unmodulated or noise-modulated carrier signals transmitted to the operator's receiver. Unmodulated jamming signals are characterized by a lack of noise.

If radio operators suspect that their radios are the targets of threat jamming, there are many procedures which help them to make this determination and re-establish communications. If tests indicate the probability of jamming being present, the operator would follow local SOP to reestablish communications and also to initiate a Meaconing, Intrusion, Jamming and Interference (MIJI) Report informing highter headquarters of the jamming. [Ref. 27]

As difficult as it can be to detect jamming, even more so, the modeling of the many possible forms of jamming is very complex and difficult to implement. The next section details how we implement the jammer/receiver interaction and the subsequent communications time delay that results.

d. *Modeling Enemy EW*

As mentioned previously, the only electronic warfare modelled in this thesis focuses primarily on the enemy's ability to jam friendly transmissions. The modeling of interception and direction finding will add to the resolution of the model, but we assumed it would not necessarily help to distinguish between alternative system configurations.

To include the enemy jamming threat and resultant stress in our network model we developed the jammer object. We describe its fields and methods in Appendix A. The JammerMasterList is an array in MCCAAM that contains references to all the specific jammers included in any given simulation run and is used to access specific jammers by name or location throughout the simulation run. The user controls the modeling of jammer interaction with a simple boolean variable in the run data file.

If jamming is to be incorporated in a given run, the jammers residing in the jammer data file are created and can be activated at any particular time. After creation of each jammer object, the SelectTarget procedure is called to find all the units currently within the jammer's range and operational sector. If a unit is within range and sector and is transmitting over any fixed-frequency radios, the JammerObj then checks to see if those radios are operating within the frequency range he is currently monitoring. If so, the jammer then proceeds to jam those radios for a user determined length of time. The effect of this jamming is to make the radios unavailable for *receiving* any more MEOs from the particular net that it is a subscriber of. Note that as in the real EW environment, the jammer only affects the receiving radios—not the transmitters. This will have the effect of slowing down the BOST completion times and create delays throughout the network. To what extent this jamming will impact the architecture's overall accumulated penalty is one of the chief design questions of the MCCAAM model.

4. Reliability

There is a significant improvement in mean time between failures (MTBF) with the adoption of the new SINCGARS radios. This improvement is discussed in Chapter IV. MCCAAM reflects this improvement in terms of the overall system's operation through reduced radio failures and down time. This section provides some brief background into how we approached the modelling of this critical area.

Generally, it is more informative to study times between failures, rather than numbers of failures, for a continuous time communication system. The most commonly used model for describing the times between failures for such a continuous time system is the exponential model. In order to model a radio system's failure as an exponential distribution, the following conditions are required and were assumed to be true in MCCAAM:

- the radio system is as good as new after each repair,
- the probability of failure in any given interval of time is the same no matter how old a system is and no matter how many failures it has experienced.

The second condition above is an intuitive description of the memory-less property. For electronic oriented hardware like the radios in our model, this memory-less property is not an unrealistic assumption since modern day electronics, once past burn-in, tend to exhibit a no wear-out lifetime. A future embellishment in this area would be to model the reliability failures with some form of Weibull distribution where the radios would exhibit some form of wear-out over time. The possible benefits from such a model embellishment are the topic of another current thesis. [Ref. 23]

Given the reliability background above, we proceed now to briefly discuss the implementation of reliability modelling in MCCAAM.

Initial reliability failures are generated/scheduled to occur for each radio in the simulation at the beginning of each simulation run based on a random draw from the exponential distribution. The mean time between failures (MTBF) for the given type of radio is used as the mean parameter for the exponential draw. When a scheduled reliability failure comes up on the simulation "calendar," the boolean AVAILABLE field of the radio is changed to FALSE. This causes an interruption in traffic transmission if the radio is in use at the time. If the radio was not in use at the time of the failure, its unavailability is modeled by causing that radio object to wait for that radio type's mean time to repair. Once a radio's modeled repair time is completed, it becomes available again for processing further traffic. It is at this point that modelling redundancy, in the form of radio spares, would impact communications performance.

Although we collect the number of radio failures for each type of radio in MCCAAM, a measure of effectiveness of our communications *system reliability* is not implemented in this analysis. Analysis of system reliability, availability, and maintainability is a recommendation for future study discussed in Chapter VII.

5. Random Variables

The necessary stochastic elements of MCCAAM are obtained through random number draws from the following distributions:

- Relative frequency of BOSTs is obtained by drawing the mean inter-generation time from a gamma distribution with mean and shape parameter determined by the user.

- NextTraffic. When a net is polling all of its subscribers to see who will have the next opportunity to send traffic, if there is a tie for highest priority traffic, then there is a random draw to determine which unit gets the privilege. The random draw is from a uniform distribution [0, number of subscribers].
- Message durations are currently deterministic, but the code is in place to allow messages to vary according to a normal distribution with mean and variance defined by the user.
- Radio failure times are drawn from an exponential distribution with mean time between failures as key parameter.
- Jamming sector and frequency band are random draws from a uniform distribution.
- Frequencies of fixed-frequency radios are drawn from uniform distribution [33.0, 88.0].

D. MODULE DESCRIPTIONS AND RESOLUTION

As described in section B of this chapter, MODSIM is a modular language which allows separate compilation of blocks of code. Once a module has been compiled, its routines, types, variables, and data structures may be imported and used by other modules. [Ref. 15]

There are two major types of modules in MODSIM:

- Main Modules
- Library Modules

Since MCCAAM takes full advantage of MODSIM's modularity and is not housed in one large main module, the bulk of the simulation code is found in the library modules. There are two parts to a Library Module: the DEFINITION MODULE and the IMPLEMENTATION MODULE. The definition module contains descriptions of those aspects of the library module which can be imported by other modules and it acts as a type of summary for a particular object's characteristics and abilities. The implementation module contains the code which implements the functionality of the module; this is where the main logic and conditioning procedures and methods are detailed.

Although a very significant amount of this thesis work was in the actual development, writing, compiling and debugging of the MODSIM code that makes up MCCAAM, the extensive number of modules that are used (more than 70) will not be detailed here in the body of the thesis. Appendix G is a listing of all the modules and gives an indication of the nature of the modules that were created. Module summaries listing the fields and methods of the key objects are found in Appendix D. For those that are interested in the actual implementation code, the MCCAAM users manual [Ref. 32] contains a synopsis of the tasks each of the modules performs within a simulation run.

The level of resolution, (the level of detail that was modeled in the communication process) found in MCCAAM was dependent on whether or not the added detail would affect the system 's performance when different radio technologies were used. Resolution is summarized for MCCAAM's major objects below:

- **Units** : Simply a base object for the C2FACs, only the location, number of radios, types or radios, nets subscribed to and echelon of the unit are modeled. No movement or firepower attributes modeled.
- **Nets** : Besides name, propagation mode, frequency and subscriber radio types, the Net Obj keeps track of whether it is idle or not and if it is being jammed. It maintains a linked list of all subscriber radios.
- **Radios** : The radios are modeled at the operational level. No specific internal functions are modeled. The Radio Object keeps track of whether it is transmitting, receiving, being jammed, or idle. It tracks the number of messages waiting in its transmission queue and how many transmissio attempts it has made. It knows its type, frequency, location, parent unit and whether or not it is "down" for a reliability failure. Antenna types, heights, and radio power are not brought into

the model yet. Effects of terrain and weather are not considered as impacting transmissions.

- **Jammers**: Leaving much room for embellishment, the jammers are also modeled at the operational level,. The jammers have an operating band width, a max range, a location, and an alternating sector of search. They keep track of the number of attempts and successed when jamming units within range, sector, and band width. The direction finding process is not modeled in detail. Different types of jamming are not modeled. Jammer movement is not modeled. Jammer knowledge of high priority target nets is not modeled.

E. MCCAAM PROGRAM FLOW

1. Model Runtime Environment

MCCAAM is embedded in a run-time environment (Figure 15) which includes:

- database creation, manipulation, and maintenance;
- model control;
- model execution;
- output analysis.

The MCCAAM **database** consists of specifications of the units, nets, and BOSTs which are to be examined for potential use. The user has the opportunity to adopt a baseline MEU, MEB, or MEF configuration, and then to revise these configurations to suit the precise force or architecture under study. The user can save the constructed system under a user-specified name for future use. All of the database functions are menu driven and self explanatory.

Model control is the stage where the user may exert control on the behavior of some of the objects. There are several ON/OFF choices to be made such as whether to model radio failures, whether jammers are present

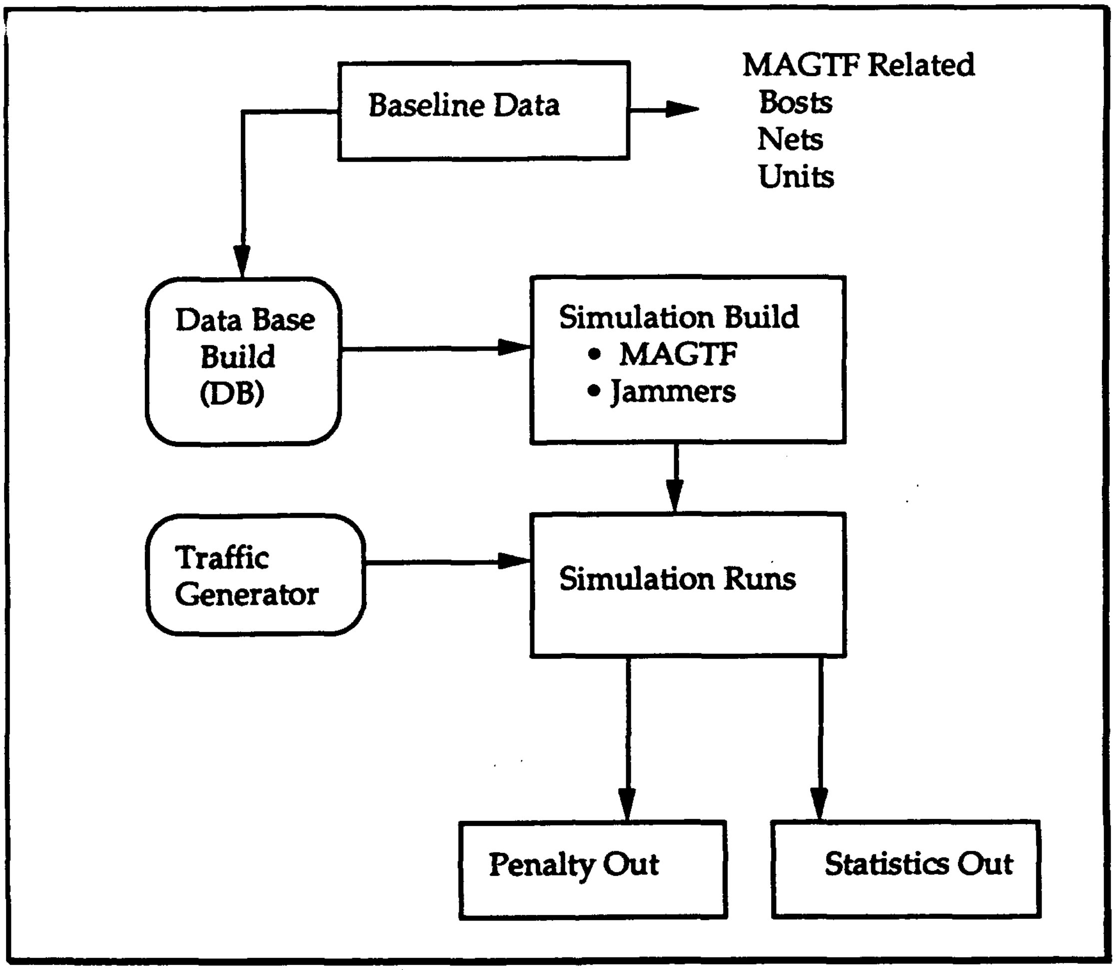

Figure 15. MCCAAM Simulation Flow

for the run, the method of jammer target selection, and several other features. The user also specifies the duration of the model run, and the initial value of the traffic workload rate.

Model execution is the phase where the model constructs sample paths of communications network specified. MCCAAM differs from most computer simulations in that all of the objects in the simulation are dynamically constructed using the data found in the database. That is, the program itself has no units, nets, radios, or C2FACs. The simulation contains only specifications of the behavior of these objects. Thus, the program *instantiates* the MAGTF communications network, the BOSTs, and the traffic generator with whatever size, scope, and relationships are described in the database. [Ref. 11]

The output analysis stage of the run-time environment is described in Chapter VI.

2. MCCAAM: An Inside View

To further detail the events that comprise an instance of MCCAAM, the following list shows the general order that is followed upon execution:

a. SimBuild

Events occuring prior to simulation start:

- Global variables initialized and read in from data files.
- Traffic Generator and Penalty Accumulator created and initialized.
- All nets created based on user chosen data file.
- For each unit that is created:
  - i) Radios are created and initialized
  - ii) Units are made subscribers on appropriate nets.
  - iii) Appropriate BOSTs are connected to units for future traffic.
- For each BOST, MEO durations are read in from data file and specific messages are initiated.

b. SimRun

The following events occur during execution:

- Traffic Generator initiates BOST occurrences at BOST specified rates
- Units are selected to initiate respective BOSTs
- BOST transmission packet and associated records created from BOST master file.
- Appropriate MEOs for BOST obtained for transmission by Unit.
- Timers for BOSTs created and all fields assigned.
- All Units that will initiate BOSTs are told to receive BOST "instances"

- For each BOST, the following cycle occurs:
  - + Completion status checked and updated.
  - + Route procedure called to begin transmission of MEOs
    - * Transmission Radios on proper net obtained (wait if not available).
    - * Net entered.
    - * Destination location obtained
    - * Destination radio checked to see if active and on the net.
    - * Alternate route determined if appropriate.
  - + MEO transmitted—if more than one receiver, MEO is cloned.
  - + Appropriate message duration time ties up net, then net is released and MEO terminated.
- Repeat cycle from the top.

While the cycle of MEO transmission, reception, routing, and waiting is going on, each BOST's Timer is running. A method periodically checks each BOST to see if all of its MEOs are completed. If they are, and all were completed before the allowed time for that BOST, the Timer is interrupted and disposed of. Otherwise, penalty information is obtained from the Timer object and assessed until the BOST is either completed or perishes, or the simulation ends.

F. DATA INPUT, REQUIREMENTS, AND ASSUMPTIONS

As with any simulation model that desires to reflect reality in some respect, one of the most difficult areas to overcome in developing MCCAAM was the collection and construction of data needed to drive the simulation sub-systems. When we learned that the Warfighting Center could not provide the workload data base, we selected the BOST, MEO workload structure as described previously. Using the Marine Corps Tactical Communications Architecture (MCTCA) and the Technical Interface Design Plan (TIDP), we discovered that the selection of appropriate nets, BOSTs, and message lengths to include in the analysis was not a straightforward process. [Ref. 28] Typical difficulties we encountered were:

- The documents provided (MCTCA, TIDP, and MIRC) were written for a MEF sized MAGTF. Therefore considerable expert screening, alteration, and augmentation was required to build the information for a MEB.
- Each MEO requires transmission between two command and control facilities (C2FACs), but messsage numbers and durations were often missing.
- Expert judgment was required to select a subset of the BOSTs to include in the analysis. If no net for any MEO in a BOST was to be involved in the SINCGARS architecture, the BOST was not included.
- Some non-VHF/FM nets should be included as alternative routes when the primary net is being jammed, but the proper subset requires expert judgment based on the BOSTs and C2FACs already selected.

The following bullets highlight the major areas of data input requirements and our corresponding assumptions[Ref. 29]:

- **Requirements**: BOST applicability to model level, relative frequencies of BOSTs for particular types of units, allotted time for each BOST, one-time penalty, penalty rates, perishability point.

  Assumptions: Since no sources could be found for determining doctrinal relative frequencies for these BOSTs, (Desert Storm data is a future, possible lead) we have made best guess estimates. These relative frequencies of occurrence can be easily changed by any analyst, and since our focus is architecture selection, not precise modeling of the real traffic, the frequency information need only be reliable enough to judge the *relative* worth of different architectures. Easily modified, these input data values are the same across simulation runs comparing different architectures.

- **Requirement**: Intensity of overall traffic flow

  Assumption: Given that we are interested in a given network's operational capacity at times of intense stress, this parameter is easily modified to provide increasing message traffic.

- **Requirement**: Sufficient, pertinent message traffic to stress network

  Assumption : Of the 184 BOSTs listed in the TIDP Vol. II, only a limited subset of BOSTs is included, but those that are have been screened to ensure applicability to the nets included in the given network. Since all possible messages are not being stimulated and we need to sufficiently stress the network, we increase the rate that the limited BOSTs are generated until we can analyze periods of heavy traffic.

- **Requirement:** Scenario Data

  Assumption: MEB sized MAGTF is engaged in desert combat. Unit locations and collocations per general doctrine. Radio allocations made within doctrinal table of organization (TO) to support respective analysis objectives.

- **Requirement:** Appropriate Jammer data

  Assumption: Since not modelling the direction finding equipment or process, we assume that the target selection has already taken place. This is modelled in zero-time. Once the threat jammer has targets in range, in sector, and in band-width, we assume each jammer is only effective in his specified range and jamming band width. We assume all jammers use an overt jamming method such as barrage jamming with noise.

Our model is intentionally designed to facilitate easy specification, modification, or re-specification of the input data. This is accomplished through an extensive, interactive, menu driven program called DB (Database Build) which allows a user to choose any MAGTF level (MEU,MEB, or MEF) and any of the main building block areas of data specification (Unit, Net, Bost, MEO, Jammer) to input, alter, or cross reference. Through the use of this very helpful set of data manipulation routines, the Warfighting Center (WFC) or any other user can verify which units are attached to which nets, and which units generate specific BOSTs as well as a host of other items of interest.

The following list itemizes most of the input variables that a MCCAAM user might be interested in changing:

Units: name, location, number of radios

Nets: name, number of subscribers,

Radios: MTBF, type, net index

Jammers: name, location, range, effective band width

Messages: descriptor, duration

BOSTS: descriptor, precedence, alloted time, one-time penalty, penalty rate, perishability, number of MEOs, initiators

Simulation Run Data: scenario stop time, number of replications, model jammers, model failures, max message re-trials, MEO duration variabilily, mean acknowledgement time, acknowledgement variability, time between frequency changes, net entry times by radio type

Traffic Generator: pace, interstimulation time, intensity rate

G. MODEL SPECIFICATION SUMMARY

The following bullets provide a brief summary of interesting model specifics:

- IMPLEMENTATION LANGUAGE: **MODSIM II** vs. 1.6 with **SIMGRAPHICS** vs. 1.3
- SIMULATION CLASSIFICATION: Process-oriented, discrete event
- Effective for Terminating and Steady-State Analysis
- More than 70 modules
- More than 30,000 lines of code
- Portable across computing architectures:
  - * Initially developed on PC (DOS)
  - * Moved to SUN workstation (UNIX)
- Extensive, menu-driven data base manipulation program

IV. MEASURES OF SYSTEM PERFORMANCE

A. GENERAL

Judicious use of operational systems, such as a MAGTF communications architecture, requires an understanding of how to measure the performance and relative contributions of sub-system components to mission success. This understanding is greatly enhanced by the proper selection and study of appropriate measures of effectiveness (MOEs). In dealing with the issues of system performance, the analytic community has developed the following set of inter-related terms to use when evaluating the behavior of system: [Ref. 5]

- Dimensional Parameters
- Measure (Variables) of Performance (MOPs)
- Measures of Effectiveness (MOEs)
- Measures of Force Effectiveness (MOFEs)

Agreement has not been reached about how the general terms mentioned above can be explicitly defined to be comprehensive and distinguishable from one another. Therefore, the following definitions are presented for use in this thesis [Ref. 5]:

- **Dimensional Parameters**—Properties or characteristics inherent in the radios whose values determine communication behavior and the structure under question, even when at rest (size, weight, number of frequencies, power output).
- **Measures of Performance**—Closely related to inherent parameters (physical and structural) but measure attributes of independent radio behavior (gain, throughput, signal-to-noise ratio).
- **Measures of Effectiveness**—Measure of how the system performs its functions within an operational environment (speed of service, percentage of transmissions jammed, number of messages requiring re-routing).

- **Measures of Force Effectiveness**—Measure of how a given communication system and the force (sensors, weapons, vehicles) of which it is a part performs missions (i.e. how does it contribute to battle outcome). This thesis, as mentioned before, does not attempt to determine directly any such force effectiveness measures.

MOEs are measured relative to some standard, which is often implicitly how a perfect system would perform. We use a variation of this standard in that a baseline system's performance is used to compare system performance across the areas of interest. Since the VRC-12 family of radios have been around for a long time and there is much corporate knowledge, both technical and subjective, about its strengths and weaknesses, we use it as the standard when assessing the qualitative MOEs. [Ref. 5]

It is an accepted fact that MOEs, as well as MOFEs, are related to the operational context of the model and to assumed enemy actions. As such, they are always inherently scenario dependent to some extent. To help avoid this problem in MCCAAM, we allow the user complete freedom to change those factors that will impact communications performance. For example, we focus on jamming as the key aspect of enemy electronic counter measures (ECM) abilities. The amount and extent of enemy jamming can be quickly changed to provide easy sensitivity analysis as this factor is changed.

B. CHARACTERISTICS OF MEASURES

Performance and effectiveness measures can be characterized by their physical and analytic attributes. [Ref. 5:p 6-12] Analytic attributes are desirable characteristics that can serve as a useful guide to analysts in selecting appropriate measures. The following four characteristics are considered by many to be particularly critical to a successful analysis and were used in deciding which measures to apply to MCCAAM analysis. Additional criteria for evaluation measures are listed in Table 2.

- **Mission Oriented**—The measure selected should be related to a clearly defined statement of the mission, or objective, of the system under analysis. This statement provides explicit or implicit information regarding the standards involved.
- **Discriminatory**—Measures must discriminate sufficiently so that real differences among alternatives can be readily identified. Without this measurement capability, important information can be obscured.
- **Measurable**—A measure must represent a measurable concept. Data collection must be possible in some form. As a general rule, values are assigned to measures on the basis of observations acquired through the use of a broad range of analytic tools. As in the case of three of our MOEs, the historical availability or ease of acquiring extensive data necessary to quantify a measure often precludes assigning objective values.
- **Quantitative**—It is preferable for ease in analysis that measures be quantifiable. For example, a numerical one-dimensional measure facilitates both the (univariate) ranking of alternatives and the (multivariate) combination of measures. The process by which the measures are combined is generally made easier (but certainly not trivial) if the values of the various measures can be specified as numerical quantities.

TABLE 2. CRITERIA FOR EVALUATION MEASURES [REF. 5]

CHARACTERISTICS	DEFINITION
Realistic	Relates realistically to the C2 system and associated uncertainties
Objective	Can be defined or derived, independent of subjective opinion
Appropriate	Relates to acceptable standards and analysis objectives
Sensitive	Reflects changes in system variables
Inclusive	Reflects those standards required by the analysis objectives
Independent	Is mutually exclusive with respect to other measures
Simple	Is easily understood by the user

As an application of the need for mission-oriented and discriminatory MOEs, consider the fact that measures used for communications acquisition management would probably be inappropriate for evaluating communication system performance for jamming robustness. With this in mind, we don't view the measures specified in Section C as any sort of super set, but simply a set that seems to meet the need for this particular application. A careful review of current and alternative measures would be needed if a different decision problem was in question.

C. SELECTION AND SPECIFICATION OF MEASURES

Since the actual system we are concerned with does not yet exist (a fully integrated SINCGARS and VRC-12 family MAGTF architecture), the only approach to assigning values for the MOEs we selected is through simulated data and conditions and historical data from existing systems. The process we followed for obtaining the quantitative MOEs from MCCAAM is illustrated in Figure 16.

The Measures of Effectiveness (MOEs) we use to evaluate the level of performance of distinct tactical FM communication configurations in a given MAGTF are listed below. ("S" denotes MOEs measured on a qualitative scale while "Q" indicates quantitative measures from MCCAAM simulation runs.)

- (S) Network Construction (NC)
- (S) Net Maintenance (NM)
- (S) Information Protection (IP)
- (Q) Timeliness (T)
- (Q) Protection from Jamming (PJ)
- (Q) Grade of Service (GOS)
- (Q) Radio Reliability (R)

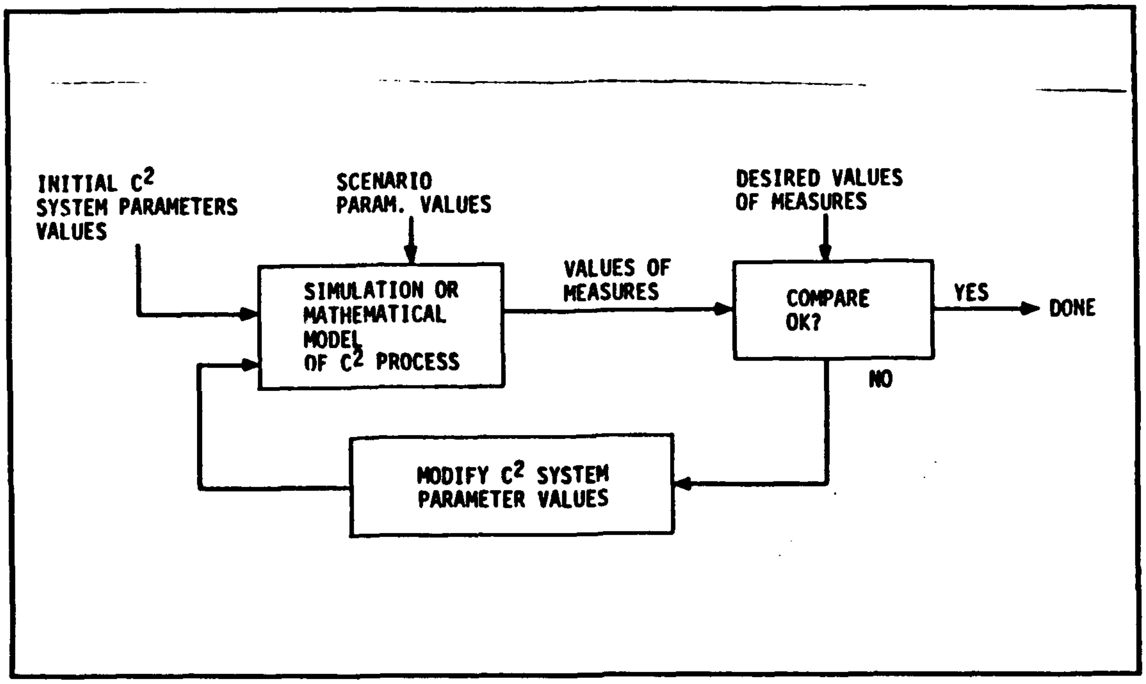

Figure 16. Modelled System Analysis [Ref. 5]

The seven MOEs we chose are a subset of many that could be included for a tactical communications system. Only those that met the characteristics listed in section B were selected for this analysis. Emphasis was placed on measures that would discriminate between the radios of interest. For a more complete list of possible communication MOEs, see [10] and [33].

Three of the seven MOEs chosen are *qualitatively* assessed while the other four are assessed *quantitatively*. The four MOEs judged to have the most significant impact in evaluating communications performance are quantitatively assessed using MCCAAM. Through the use of our communications model, we can more adequately compare the major differences between competing architectures. The remaining 3 MOEs are qualitatively assessed using the criterion scale illustrated in Table 3 since no means currently exist to capture these measures from the model. The baseline for the criterion scale listed in Table 3 represents the minimum U.S. Army Training and Doctrine Command (TRADOC) performance criteria for a tactical FM communications system. This criteria is used because the Army has performed the most extensive testing and analysis of current U.S. radio systems. Historical performance criteria of the AN//VRC-12 series and the AN/PRC-77 family radios are used for the baseline value when the minimum TRADOC criterion is classified or if the standard was not available. [Ref. 10:p. 70]

TABLE 3. CRITERION SCALE

Weight	Criteria
10	Superior (MOE is the most important factor which causes system to outperform baseline).
8	Much more effective than baseline.
7	More effective than baseline.
6	Slightly better than baseline.
5	Baseline.
4	Slightly worse than baseline (marginally acceptable).
3	Less effective than baseline.
2	Much less effective than baseline.
0	Inferior (MOE does not meet minimum essential requirements, unacceptable).

D. DESCRIPTION AND RELEVANCE OF MEASURES

The seven MOEs identified in the section above will now be examined individually by definition and by identification of those variables that affect the level of MOE assessment. The standard that is used as a baseline for each measure is also identified for those three measures not obtained through

MCCAAM. Though not explicitly discussed, the mission oriented, discriminatory, measurable nature of the MOEs is illustrated in each case.

1. Network Construction

a. Definition

Network construction is defined as those actions that are required to make network frequency assignments at a decentralized level, the effort required to train net control station (NCS) operators on the procedures to establish a net, and the performance of the radio operator during network establishment. In the FM communications system described in this thesis, the Brigade and Regimental Communications-Electronics Officers are responsible for managing frequencies in their designated geographical areas. The NCS operators control and manage the operation of specific nets, and radio operators are responsible for understanding and executing proper network procedures.

Technological advances are usually accompanied by an increase in operational and procedural complexity. The Network Construction MOE is used to discriminate between the operational and procedural complexity differences of the AN/VRC-12 radios and the SINCGARS radios. It is a subjective assessment of the increased training effort required at all levels of operation within the FM communications system to implement the new SINCGARS radios.

b. Variables Affecting the Network Construction MOE

The amount of effort required to establish a net can be determined from the amount of time that it takes to enter each radio station into the net. The variables that influence the amount of time are [Ref. 10] the skill levels of the radio operators, NCS operators, and communications officers, the amount of training that they have received, the complexity of the equipment, and the procedural complexity of operation.

A subjective evaluation of this MOE will be made with the following assumptions:

- The administrators and users of the FM communications system have an average skill level compared to all Marines.
- The complexity of equipment and procedural operation determines the amount of required training.

c. Baseline Criteria

The amount of time required to train general purpose users on AN/VRC-12 series radios is used as a baseline criteria. Specific figures for testing requirements and scores collected by various Army testing agencies are detailed in [Ref. 10].

d. Alternative Radio Assessments

The following findings and observations were used to make a subjective evaluation, and determine criteria scores for the alternative radio configurations examined in this thesis.

- Electromagnetic Compatibility Analysis Center (ECAC) personnel feel that the electronic remote fill (ERF) capability of the frequency-hopping radio requires an NCS operator with special training commensurate with an additional skill identifier. They cite the SINCGARS-V Maturity Operational Test (MOT) [Ref. 35] as an example where there was a high net establishment failure rate, and some net operators with a rank of E-6 took as long as eight hours to give all stations in the net the correct ERF variable. [Ref.10: p 87]
- SINCGARS NCS operators need a higher skill level and require more intensive and repetitive training that normal radio operators.
- SINCGARS frequency-hopping operator skills require extensive hands-on training to acquire, and repetitive application to retain.

- Net establishment times have been reduced, however the times still remain greater than for single-channel operation. Operators are not able to commit frequency-hopping skills to memory because of their complexity and number of precise actions required to complete them.
- The 49 SINCGARS radio human engineering problems identified during the MOT will unnecessarily increase training time and requirements.

The MOE criterial score for each radio alternative configuration is based on the information presented in this section. The values were obtained from MOP utility values published in the Concept Formulation Package for SINCGARS [Ref. 3]. The results from testing the AN/VRC-12 radio represent the baseline criteria for the Network Construction MOE.

DESCRIPTION	SCORE
Conventional Single-Channel FM w/COMSEC[1]	5
SINCGARS-V w/imbedded COMSEC, Frequency Hopping	3
Mixed SINCGARS and Conventional FM Environment	3-5

The criteria score for the mixed environment is determined by the number of subscribers on SINCGARS nets and the number of subscribers on conventional AN/VRC-12 series nets.

For example, if 60 percent of an architecture's nets were conventional fixed-frequency nets and this totaled 120 fixed-frequency subscribers, then each of those subscribers would have to join its given net with a score of 5. If the other 40 percent were SINCGARS nets with 80 subscribers, then each of the SINCGARS subscribers would be able to join

[1] COMSEC refers to Communications Security equipment which encrypts messages before they are transmitted.

their nets with a lower score of 3 to reflect a more complex, time-consuming net construction process.

The resulting Network Construction MOE would be:

$$(120)*5 + (80)*3 = 840/200 \text{ subscribers} = 4.2$$

and would reflect the fact that this architecture was closer to the baseline standard of 5.0 than the all-SINCGARS architecture score of 3.0.

2. Network Maintenance

a. Definition

The Net Maintenance MOE is the measure of the administrative traffic that is required to retain network connectivity after the net has been established. Examples of administrative traffic are radio checks, frequency changes, and net procedural traffic.

b. Variables Affecting the Net Maintenance MOE

The tactical and environmental situation, the probability that COMSEC and frequency-hopping operational variables will be lost, and the degree of confidence that the NCS has in the equipment and its operators are all variables that affect the amount of time an NCS must dedicate to maintaining a given net.

To compare alternative radio configurations, this thesis will only consider the loss of essential radio variables to assess Net Maintenance. It is recognized that the tactical situation and environmental factors can change the degree of net maintenance, however the change will be primarily relative to the situation, and not to the radio configuration employed. Similarly, the variable of confidence is likely to change from unit to unit, so it is not considered in developing this MOE. (Here we could incorporate a factor that distinguishes the greater training and availability c' knowledgeable operators at higher unit levels)

c. *Baseline Criteria*

The net operation of the AN/VRC-12 series radio is used as the baseline criteria from which to make qualitative assessments of utility rankings for alternative radio configurations.

d. *Alternative Radio Assessments*

Since the AN/VRC-12 series radio and SINCGARS radio will use similar COMSEC devices, the loss of this equipment variable is not addressed. Everything else remaining equal, the SINCGARS frequency-hopping radio has five additional equipment variables required to insure proper operation in the frequency-hopping mode. These additional variables were described in section C of Chapter II.

Below are the results of the Maturity Operational Test and Operational Assessment (O/A) showing the average number of times that a radio experienced the loss of one or all of the frequency-hopping variables [Ref. 10: p. 1].

PROBLEM	MOT RESULTS	O/A RESULTS
Loss of variables	21/week/radio	1.4/week/radio

When these SINCGARS variables are lost for whatever reason, the recovery process is quite time consuming and can take from thirty to fifty steps to reload the lost variables [Ref.10:p. 13]. Since radios using the fixed-frequency mode of operation do not require these five variables, performance in terms of increased administrative time is reduced. Therefore, the Net

Maintenance MOE receives a marginally acceptable criteria score of 4 for alternatives employing frequency-hopping operation. The criteria score for the mixed radio configuration is determined by a percentage of SINCGARS and fixed frequency nets in the given architecture as demonstrated previously.

DESCRIPTION	SCORE
Conventional Single-Channel FM w/COMSEC	5
SINCGARS-V w/imbedded COMSEC, Frequency Hopping	4
Mixed SINCGARS and Conventional FM Environment	4-5

3. Information Protection (IP)

a. Definition

The Information Protection MOE is defined as the effectiveness of the design parameters that have been built into the network's radio equipment that allows it to conceal transmitted information from unauthorized users. It is a measure of the architecture's electronic counter-countermeasure (ECCM) ability.

This MOE is often used with an ECCM encryption MOE which would be assessed by comparing information scrambling (COMSEC) techniques and devices.

b. Variables Affecting Information Protection MOE

The design parameters of antennas, the power output control parameters, and the frequency modulation/spread spectrum techniques employed by the radio technology are the variables used to develop a Information Protection (IP) MOE assessment.

All of these design parameter variables can be used to conceal the transmitted information from unauthorized users. Directional antennas transmit a signal in only one limited sector forward of friendly position, thus reducing the chance of detection by the enemy. Power output, when reduced to the minimum strength necessary to establish a link, will also reduce the probability of being detected by the enemy because the transmission range is reduced.

The most important variable required to assess the IP MOE is the frequency-hopping capability of the new radio systems. The information transmitted over a frequency-hopping radio (when hopping more than 200 hops per second) cannot be captured by unauthorized users unless they know the exact hopping pattern and hopping rate, and can synchronize equipment to receive these transmitted signals.

c. Baseline Criteria

The conventional single-channel FM radio configuration is used as a baseline measurement.

d. Alternative Radio Assessments

Alternative one has a criteria score of five as the baseline. The AN/VRC-12 series radios can transmit on a low power setting of 3-5 watts, and are capable of using directional long wire antennas cut to the desired frequency.

DESCRIPTION	SCORE
Conventional Single-Channel FM w/CRYPTO	5
SINCGARS-V w/imbedded CRYPTO, Frequency Hopping	9
Mixed SINCGARS and Conventional FM Environment	5-9

SINCGARS operating in the fixed-frequency mode would have a slight advantage over the conventional system in that power output can be adjusted down to four watts. This feature allows the SINCGARS fixed-frequency user to have more flexibility in providing protection for his transmitted message.

The frequency-hopping capability of the SINCGARS radio provides state-of -the-art protection against unauthorized users intercepting a transmitted message. This alternative did not receive a utility rating of 10 for the IP MOE because the efficiency of directional antennas is decreased in the frequency-hopping mode of operation. Antennas are adjusted for one specific frequency. They cannot provide maximum efficiency for frequency-hopping radios which transmit multiple frequencies over one channel. The criteria score for the mixed environment is determined by the percentage of SINCGARS radios and conventional AN/VRC-12 series radios assigned to the same unit. For example, if 60 percent of a force's radios were conventional fixed-frequency and the other 40 percent were SINCGARS, then the resulting force IP MOE would be: $(.60)*5 + (.40)*9 = 6.6$.

4. Radio Reliability (R)

a. Definition

Though we initially intended to develop a measure of overall *system* reliability (an additional MOE that could be used to discriminate between architectures) time prevented us from including that in the current version of MCCAAM. Instead of calculating some measure of overall system reliability, we simply collect the number of radio failures for each type of radio in a given architecture. The total failures for an architecture give some indication of reliability at the component level.

MCCAAM collects radio failure statistics on all the individual radio objects (AN/VRC-12 family or SINCGARS) throughout the simulation run. Assumptions in the collection of this data include:

- Radio equipment configurations and operations are in accordance with published operating instructions.
- All the radios of same type have the same MTBF.

b. *Variables Affecting the Reliability MOE*

The assumptions made in modelling radio reliability (i.e. exponential, no wear-out lifetimes) preclude anything within the current model environment from really affecting the reliability measure. We understand that we are simply sampling failure times from an exponential distribution and then collecting those failures. The only factor influencing the number of failures within a simulation run is the user defined MTBF values for the various radio types.

c. *Alternative Radio Assessments*

Recent upgrades and redesign have greatly increased the MTBF factor for the SINCGARS from an initial value of 1250 hours. For example, a 1988 follow-on operational test and evaluation (FOT&E) demonstrated an MTBF exceeding 5,000 hours for 100 radios in operation for over 20,000 operating hours [Ref. 37]. More recently, preliminary reports from the Gulf War proclaim SINCGARS MTBFs were around the 7,000 hour mark, whereas the VRC-12 family of radios experienced an MTBF average range of 250 - 300 hours. Using the definitions and equations outlined above, MCCAAM allows an assessment of radio reliability for any given mixed radio environment by randomly generating reliability failures and repairs from exponential distributions with appropriate means from recent test results and then aggregating the results for all the radios in the system.

5. Grade of Service (GOS)

a. Definition

The probability that a message that is transmitted from an FM communications station is received by the intended recipient. This will be assessed quantitatively in MCCAAM by tracking the number of message transmission attempts and completions by each radio. The percent transmissions completed will reflect this measure.

GOS = (# messages completed/# messages attempted) * 100.0

As in all aspects of modelling a complex system, definitions are key to implementation of a process. For collecting statistics from the myriad of radios in a MCCAAM run, the following definitions were used:

- **Attempt**: any time that a radio tries to perform the acknowledgement and transmission sequence with another radio.
- **Success:** an attempt that culminates in the information transferred to the intended receiver radio (note distinction between intended receiver and destination of message for the case where a message is routed through an alternate net)

Thus, a radio which attempts to transmit a MEO to two receivers in which

- receiver 1 acknowledges contact, receives full transmission, and acknowledges receipt would be counted as (1 attempt, 1 success)
- receiver 2 does not acknowledge contact until the transmitter has pursued the acknowledge process two times and then acknowledges contact and receives full transmission. This would be counted as (3 attempts, 1 success).

6. Protection from Jamming (PJ)

a. Definition

Electronic countermeasures (ECM) is defined [7] as those actions taken to reduce effective use of the electromagnetic spectrum. These actions include *jamming,* electronic deception, and emitter direction finding.

Of the three major areas mentioned above, only jamming will be considered in the evaluation of the jamming protection MOE. The vulnerability of a given radio configuration to direction finding (DF) can be represented by an equation taking into account such factors as power output, transmitter and receiver antenna gain, thermal noise, environmental noise, and path loss of the signal, but these factors are not currently incorporated into MCCAAM. [Ref. 10]

b. Variables Affecting the Protection from Jamming MOE

An equation that represents how well a given architecture continues to function when it is being jammed by enemy electromagnetic activity is:

$$PJ = GOSj/GOS$$

where:

PJ = Assessment of architecture's resistance to jamming
GOSj = Average link grade of service during jamming
GOS = Average link grade of service before jamming

c. Alternative Radio Assessments

MCCAAM is used to measure the effects of jamming by running a given scenario and collecting required data to calculate the grade of service (GOS) for that architecture. A user specified level of jamming is then introduced and the simulation is run again with the same traffic workload sample path. The grade of service is calculated and the difference is attributed to the jamming effect on the communications architecture.

7. Timeliness (T)

a. Definition

Timeliness is described by the average amount of time a message has to wait for delivery by a given architecture. We calculate average message wait time as the difference in message delivery time and message duration.

W = average message wait time

W = Message Delivery Time–Message Duration

W = (Msg Stop Time–Msg Start Time)–Msg Duration

We define the message delivery time as beginning when a message is pulled out of its radio queue and a transmission is attempted. The completion time is defined when a message is successfully received by its intended receiver. So, for a single simulation run, each radio will have its own average message delivery time. By defining timeliness in this manner, we take into account the fact that different radios will be processing different BOSTS with different message durations.

After we calculate each radio's average message wait time, we sum over each type of radio to obtain an average message wait time by radio type. We then aggregate to the architecture level and obtain an overall average message wait time.

Since an architecture's average message wait time will depend greatly on the amount of traffic it handles, we need to scale the average message wait time by the number of messages successfully transmitted.

$$W^* = \text{Adjusted } W = W/\#\text{ Messages}$$

Our Timeliness MOE is then defined as one over the adjusted wait time. This convention makes the larger valued MOE more desirable.

$$T = 1/W^*$$

b. Variables Affecting Timeliness

Any network subjected to any type of stresses at all will not be able to process traffic in a perfectly timely manner. In MCCAAM, the stresses of jamming, radio failures, and heavy contention for a given net all contribute to a message not being transmitted in exactly its message duration time. For example, suppose a battalion Fire Support Coordination Net radio pulls its top priority message out of its queue and attempts to transmit it to a jammed intended receiver. That message's delivery time will incorporate all the waiting, re-trials, and possible re-routing time that is necessary to get the message to the intended receiver.

c. Alternative Radio Assessments

The average message delivery time is collected by radio type, so comparisons between radio types within a given architecture are available. Since the SINCGARS radios have a smaller MTBF and are essentially jam-proof, the average message delivery time will be lower for a SINCGARS radio when compared to a PRC-77 radio in the *same communications environment*. Because some messages have much longer transmission times than others, a SINCGARS radio might have a longer average message time than a PRC-77 if it processed many BOSTS with longer than average message lengths. For this reason, the message durations were all set to an arbitrary four minutes in duration for our comparative analysis. As a result of this control over the simulation, we can confidently attribute any variations in average message time to different radio types.

E. AGGREGATION APPROACH

The common problem is this: given a set of MOEs $m_1, m_2, m_3, \ldots, m_n$ we wish to combine them into an overall MOE, E. There are traditionally two approaches to this problem [26]:

- Define E by some mathematical function
- Develop the relationship of E and $m_1, m_2, m_3, \ldots, m_n$ using expert judgment

When the first approach is used, the most common method is to assume a linear combination:

$$E = w_1m_1 + w_2m_2 + w_3m_3 + \ldots + w_nm_n$$

where the *w*'s are relative measure *weights* which reflect the amount of importance attributed to each measure by the user or modeler. The positive features of this approach are:

- Simple, easier to sell than other approaches.
- No data needed to build the relationships except the weights.

and the negative features are [26]:

- It is an arithmetic average of the measures and hard to justify the averaging idea.
- Substitutability (often unwanted) exists in that while relationships should evaluate tradeoffs, the trade-off should be designed in and not there as a whim of the function.
- This approach does not provide diminishing marginal return (second derivative < 0)
- Unresolved dimensionality problems almost always exist ... i.e. combining time, number of messages, penalty rates, etc.

- No consideration of variance (or recognition of uncertainty) in the measuring process.
- This approach gives E *by definition* and is not an approximation to a real world number; therefore, we cannot test it.
- Assumes the MOEs are mutually exclusive in what they measure!

To avoid some of the pitfalls described above, we have decided to use a variation of the linear combination approach where E is defined as the weighted linear combination of the *utilities* of the given measures, where the utilities are measured on a 0 -1 scale.

$$E = \sum w_i * U_i$$

This approach handles the diminishing marginal return problem and this, in turn, helps a bit with the basic substitutionality problem. It also alleviates the dimension problem, but it is still an average and there is still no consideration of variance on the weights assigned.

For such a small number of MOEs, we have elicited the weights to be used in the aggregation from select experts by having them use a commercial software product, *Expert Choice* [Ref. 39], to make paired comparisons of the MOEs (each MOE is compared against every other). The Analytical Hierarchy Process (AHP) used by *Expert Choice* is a well known procedure which derives relative scales using judgments from experts in the form of these paired comparisons. AHP background and examples can be found in [38].

The first step in using *Expert Choice* is the structuring of the problem as a hierarchy of nodes or leaves. Figure 17 illustrates our problem levels. The first (or top) level is the overall goal. In our case, it is the selection of the best communications architecture. In the second level we have three categories which contribute to the goal. Each of the three categories has two or more

MOEs, or criteria, beneath them to form level three. The second step is where each expert is asked to make decisions about the relative importance of each MOE (as compared to each other MOE) with respect to the overall goal of selecting the best architecture. This judging is conducted in a structured environment in *Expert Choice* where the decision maker is presented with a sequence of all possible MOE pairs.

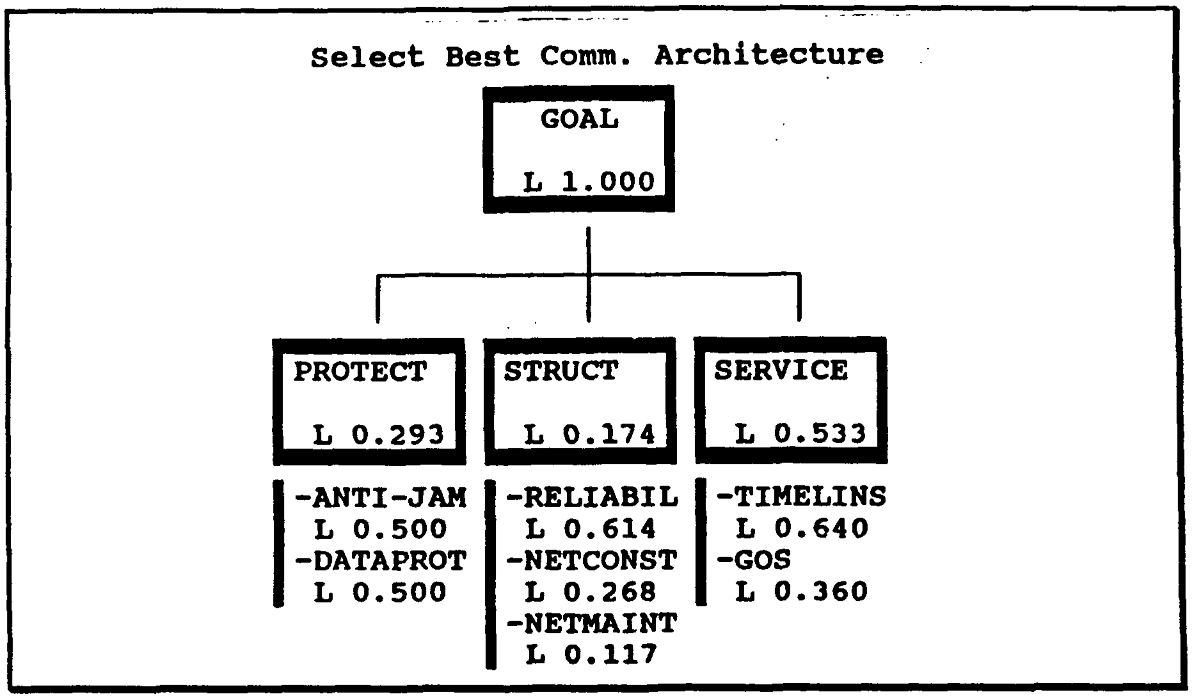

Figure 17. Problem Hierarchy

Once all possible pair-wise comparisons have been made within each level, *Expert Choice* produces the unique MOE weights based on the comparisons made by the expert. Figure 18 shows one of the many forms out output that *Expert Choice* provides in the form of a sorted synthesis of the leaf nodes with respect to the overall goal of selecting the best architecture.

The consensus on the order of importance for the seven MOEs and the accompanying weights assigned are as follows:

		MOE	WEIGHT
•	(GOS)	Grade of Service	0.299
•	(PJ)	Protection from Jamming	0.191
•	(T)	Timeliness	0.176
•	(R)	Radio Reliability	0.141
•	(NM)	Network Maintenance	0.084
•	(IP)	Information Protection	0.064
•	(NC)	Network Construction	0.045

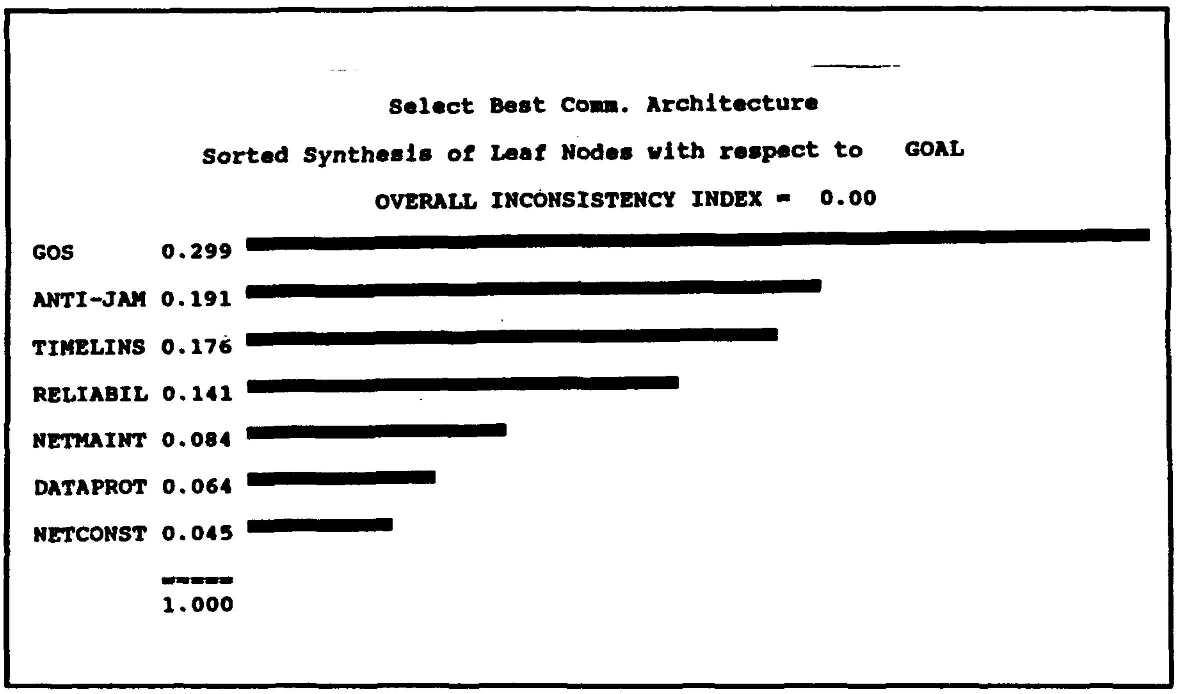

Figure 18. Sorted Synthesis of Leaf Nodes

1. Utility Theory

"If a man will begin with certainties, he shall end in doubts; but if he will be content to begin with doubts he shall end in certainties."

Francis Bacon

MCCAAM users will most likely be using the simulation model to help select one alternative out of several. When the alternatives lead to payoffs that are random, one would like to select the alternative for which the expected mean value of the payoff is the largest, but many decisions are too complex to make decisions by comparing payoff averages directly.

Decisions can be simplified though, provided payoffs are measured by their *utilities*. Von Neumann and Morgenstern [1944] showed that if a decision maker is rational[2], there exists a function U (the decision maker's utility function) having the property that the best alternative is the one for which the expected utility is largest. In other words, a rational decision maker will make decisions as if he were ranking them by expected utility, even if he never actually makes the computation. Personal preferences enter through utility functions. Utility functions can be measured, but we will not discuss methods for eliciting the utility functions of actual, human decision makers in this thesis. Utility functions will always be assumed to be known, sometimes with an argument as to plausibility.

If $U' = aU + b$, then the linearity of the expectation operator implies that $E(U') = aE(U) + b$. It follows that $E(U')$ and $E(U)$ rank alternatives in the same order as long as $a>0$, and therefore that U' is operationally the same utility function as U. Therefore the origin and unit of utility can be selected

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[2] "Rational" means that certain postulates of rationality are satisfied. Rational decision makers, for example, are assumed to have transitive preferences: if A is preferred to B and B to C, then A must be preferred to C.

for convenience—letting the worst outcome have a utility of 0 and the best a utility of 1.0 is common.

Figure 19 illustrates the characteristics of the three basic utility preference curves: *risk averse, risk neutral,* and *risk prone.* The real value, or utility of an additional increment of a measure of effectiveness depends on how much you already have.

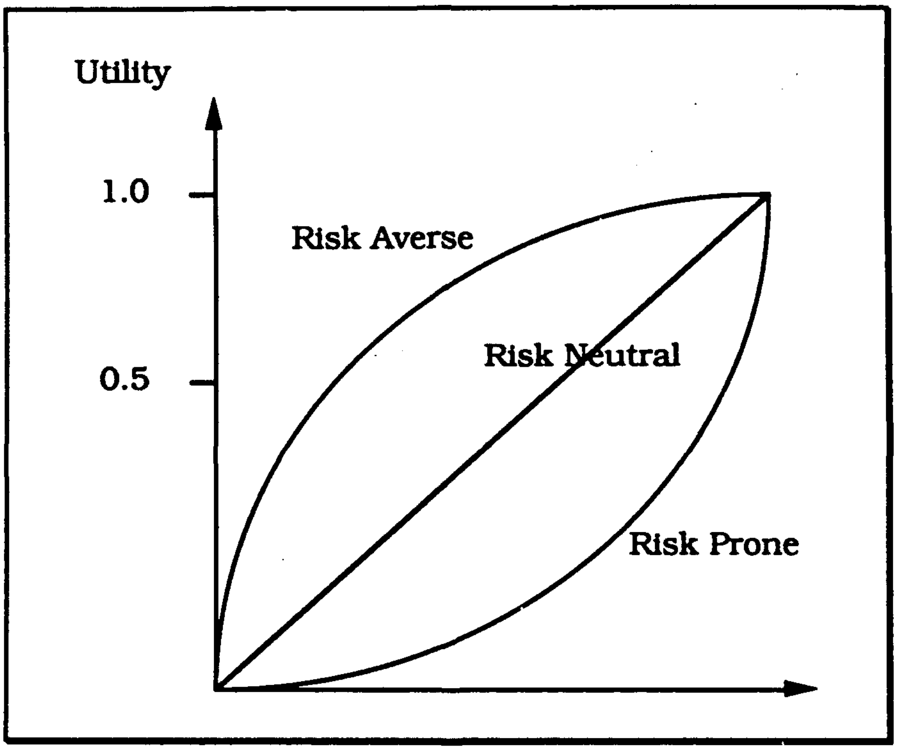

Figure 19. Utility Curve Classifications

The risk averse decision maker exhibits a diminishing additional utility for increasing levels of the item of interest, once beyond a given point. As an example, the log function, y = log x, is concave downward, consistent with the idea of diminishing additional utility as one's wealth increases from each increment of added money. The risk neutral decision maker exhibits a linearly increasing utility for increasing levels of the item or quantity of interest. The risk prone decision maker exhibits a rapidly increasing utility for increasing levels of the quantity of interest.

To illustrate the use of utilities with respect to our measures of effectiveness, an example is presented for the qualitatively assessed Network Construction MOE.

For each net in a given architecture, the criterion scale values defined by Table 3 are assigned. Next, for each type of net in the architecture the scale values are summed and then divided by the total number of nets. This gives the architecture's Network Construction score, which is then applied to the decision maker's specified utility curve.

Example: Given 200 MEB Single-Channel Nets

140 Conventional	*	Scale Value of 5	=	700
60 SINCGARS	*	Scale Value of 3	=	180
				880

Dividing the sum of 880 by total number of nets, 200, yields 4.40, which is this architecture's raw Network Construction score.

Assuming a risk prone utility curve, $U(x) = x^2$, we see (Figure 20) that the utility of a Network Construction value of 4.4 is 0.194 when the baseline value of 5.0 would give a utility of 0.25.

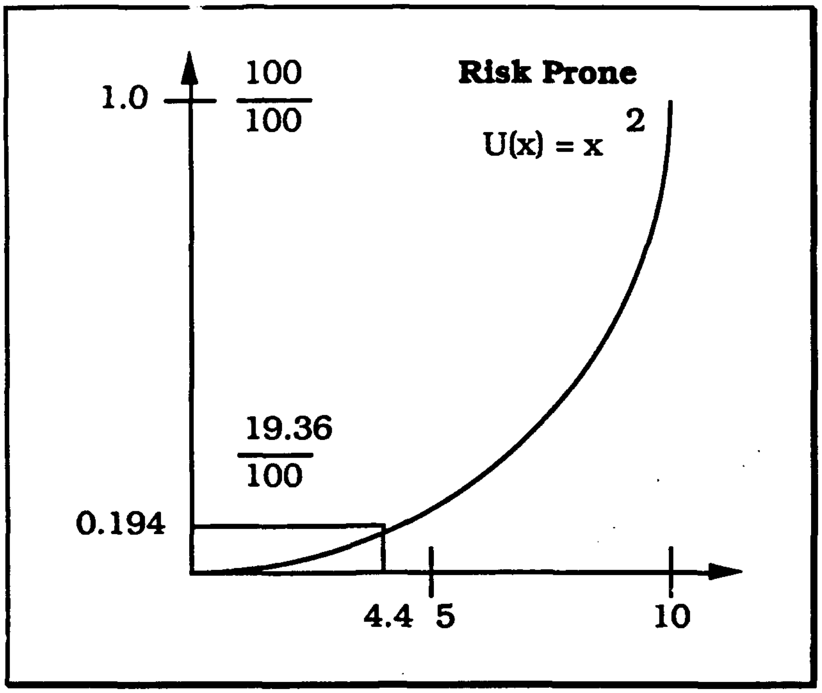

Figure 20. Utility of Network Construction MOE

Clearly, the choice of utility curve as well as the choice of weighting and criterion scale for the subjective MOEs will have definite impacts on the calculated utilities. When the same decision environment must be faced on multiple occasions, ranking outcomes according to *expected utility* is definitely a more comfortable idea, but there is no logical requirement for that to be the case.

The assumption that the seven MOEs are mutually exclusive is one that could be argued against fairly easily, and if a decision maker doesn't like that approach, the individual MOEs can be assessed individually for each architecture examined.

F. PENALTY PROCESS

A more direct way to measure the overall effectiveness of a given communications network is through a unique penalty accrual process we have developed which is directly related to the *system's* timeliness. Timeliness, of course, is affected by all the previous MOEs in some manner or another, and thus is a good natural aggregation measure.

Each BOST which is undertaken has a time within which all of the tasks associated with it (MEOs) must be completed. As described in Chapter III, these times are not available from any doctrinal source, so professional best guess values were specified based on fleet experience in the Marine Corps. These values are some of the many available for easy manipulation within MCCAAM. Since these times are common to architectures being compared in MCCAAM, and no real-world values exist, only their magnitudes relative to one another are of any importance.

If a given BOST is not completed within its user-defined allotted time, a one-time penalty is recorded. This penalty's value is determined by the nature of the BOST and the particular unit that is originating it. Additionally, some designated BOSTs will continue to accrue additional penalties for each time unit they proceed beyond their given allotted times. Collectively, these penalties reflect the system's ability or inability to process traffic in a timely manner. [Ref. 11]

The *stationary* mean rate of penalty accrual will reflect the degree to which the network is functioning properly. If a large amount of penalty is being accumulated constantly, the BOST deadlines are consistently being violated. The analyst or model user then identifies the sources of largest consistent penalty accrual and determines if the given deadlines are unrealistic, if certain nets or units are consistently resource constrained, or if some BOSTs need to be redesigned. By analyzing the penalty choke points, an analyst might improve the doctrinal structure for a given BOST by increasing task concurrency or changing traffic routing to ensure more timely dissemination.

Beyond the stationary mean rate of penalty accrual mentioned above, we know that to fully stress a given network architecture, we would need to test many different traffic intensity patterns before we found one to break the network. By linearly increasing the traffic workload intensity, we can obtain a measure of effectiveness that is less straightforward than the stationary case but one that provides some very good insights into network performance. Recall that in our central traffic generation process described in section C of Chapter III, the delays between BOST generations had a mean $1/\lambda r$. We will call r our workload intensity, and we consider the case $r=1$ to be our baseline. As previously discussed, the BOST initiation rates do not come from any doctrinal or scenario specific source and thus do not reflect an actual system's fluctuating intensity. Any given real-time communications network's traffic is going to be highly dependent on the level of unit engagements, movement, enemy EW action, the time of day, and the terrain and weather. Not wanting to be tied to a scenario or attrition type model, we allow the traffic intensity to continuously increase over time to give a picture of network performance through all ranges of possible stress.

When we use r as our workload intensity variable, we believe that, for each communications configuration, there exists a threshold workload intensity r^* such that for $r < r^*$, the penalty accumulating rate, $\partial p(r)/\partial r$, is fairly small, and as the workload intensity grows above r^*, $\partial p(r)/\partial r$ rapidly becomes much large. Thus a communications network can handle its workload fairly well until *the workload intensity* passes r^*, at which point the system breaks and can no longer handle the offered traffic. Analysis of this increasing workload intensity is not covered in this thesis.

To summarize, our penalty MOE (P) is the sum of all one-time penalties and accrued penalty rate for a given simulation run. Since the overall penalty will be a direct function of the number of BOSTS that get processed, we scale the accumulated penalty by that number of BOSTS. This provides a more accurate relative measure of an architecture's penalty.

$$P^* = P/\#\,\text{BOSTS}$$

G. SUMMARY

In most simulation programs, model parameters, when related to physical entities, are as objective and quantified as they would be in an engineering sense, and can be measured or estimated. When equipment parameters have not been clearly defined for all ranges of a system or are unavailable, measures of performance (MOP) for these items are not as easily measured. In these cases, MOP's are often subjective and qualitative, e.g., ordinal ranking by experts, and may or may not be assigned numerical values. MOEs and MOFEs are heavily judgmental even when they are numerical, since choosing system boundaries, particular functions to be evaluated, and the reference standards can greatly influence particular numerical calculations. When based on models, they are highly dependent on the model assumptions, simplifications, values of input parameters, and the selection of output measures to be estimated. [Ref. 5]

This is one reason MCCAAM can be so effective for studying the large, complex communications process. If a particular analyst or decision maker does not think the input parameters are accurate for a given simulation/analysis scenario, sensitivity analysis can easily give insight into the effects of changing assumptions or values of those input parameters. An example of the possibilities afforded in this area with MCCAAM is presented in the next chapter.

V. ANALYSIS EXAMPLE

A. GENERAL

> Because simulation involves statistical sampling from waiting time distributions, repetition of a simulation under a fixed set of factor conditions produces variable results. Thus we have a situation in which (1) we have a large number of variables to consider and (2) the variation cannot be ignored. This is exactly the situation for which experimental designs were invented. [Ref. 30]

> Even a well documented model may generate non-credible results without an appropriate experimental design which can establish the statistical validity of the model under varying environments. [Ref. 18]

Since we want to investigate how the various parameters and particular structural assumptions of MCCAAM affect its measures of performance, we need a structured experimental environment to conduct intelligent analyses.

In the simulation context, experimental design provides a means to decide beforehand which system parameters to use or change so the desired information can be obtained. As we learn more about the behavior of a model (in particular, which factors really matter and how they appear to be affecting the response), we may want to move on and become more specific with our goals. [Ref. 30]

To begin our experimental analysis, it is necessary to define the type of simulation we are going to run.

B. TERMINATING OR STEADY-STATE ?

"The two types of simulations with regard to analysis of output data are *terminating* and *steady-state* simulations." [Ref. 34] We begin this section by defining what we mean by these two terms.

- "A terminating simulation is one for which the desired measures of system performance are defined relative to the interval of simulated time [0, T], where T is the instant in the simulation when some specified event, E, occurs. (Note that T may be a random variable.) Since measures of performance for terminating simulations explicitly depend on the state of the simulated system at time 0, care must be taken in choosing initial conditions." [Ref. 34]
- "A steady-state simulation is one for which the measures of performance are defined as limits as the length of the simulation goes to infinity. Since there is no natural event E to terminate the simulation, the length of *one* simulation is made large enough to get "good" estimates of the quantities of interest. Steady-state does not mean that the actual delays in a single realization (or run) of the simulation become constant after some point in time, but that the *distribution* of the delays becomes invariant" [Ref. 34]

From the definitions above, it is clear that for some systems either type of simulation might be appropriate, *depending on what the analyst wants to learn about the system*. For example, in a complex communications model like MCCAAM, a steady-state simulation might be designed to estimate the penalty accrual rate after the user-defined MAGTF has been operating long enough for the exercise/battle to have progressed through all possible phases of operation. Another application could be to estimate the steady-state expected average message completion time for an architecture if the MAGTF was to operate at a high traffic intensity for an indefinite period of time.

To use MCCAAM as a terminating simulation tool, consider the analyst who wants to look at starting a network cold and then study the measures of effectiveness after one twenty-four hour period of normal activity. The initial conditions in this case, empty and idle, would provide a realistic assessment of the normal beginning of an operation when all concerned units are just establishing communications.

Another terminating application could be the analysis of a short war where the traffic intensity was a non-homogeneous Poisson process. Creating cycles of high intensity traffic in the early morning and late evening hours for each twenty-four hour period would provide a realistic traffic environment, where most intense conflicts might take place outside of the middle of the day. The end of the three days would terminate the simulation and the resulting MCCAAM penalty statistics and other measures of effectiveness could provide comparative insight when examined against a competing architecture pushed through the same simulation environment. Scripted message traffic from an actual exercise would provide a great example of this type of terminating analysis.

A major consideration in how we approached our analysis was the need to eliminate as much unwanted variability as possible in our model. Variability that just adds fog to a model, without affecting any measures of effectiveness in a significant way, makes any analysis task more difficult. A short run, terminating simulation would have added more traffic variability that would have detracted from our comparative analysis. Since we were not given a specific scenario to model and the goal of the study focused on the long-term effects of architecture differences, we made the decision to look at our system measures from a steady-state perspective. This decision was embraced by our Marine Corps sponsors.

C. MODEL SPECIFICS

1. Simulation Time

Since a steady-state simulation approach was taken for this example analysis, we are interested in examining the expected average MOE values after one simulation run of sufficient duration to ensure good estimates. The length of sufficient duration that is needed is dependent on how long the simulated system takes to reach steady-state conditions. The time our communication system takes to reach steady-state conditions is calculated by means of the penalty output analysis described by Bailey in [Ref. 25]. To summarize this method, we examine sequential time samples of the penalty accumulation rate at fixed intervals (starting from the end of the simulation, when the system is in steady-state) and compute F statistics to determine when the distribution changes a statistically significant amount. Since the time samples are taken from the end of the simulation run, the point at which the F statistic allows us to reject the null hypothesis, (the penalty rate samples are from the same distribution), we can mark that time as the end of the initial transient conditions and the beginning of steady-state. This method is further detailed in [40].

Using the above approach, we found that for the level of traffic intensity we were modelling (see Appendix I for Traffic Data) the simulation entered its steady-state range very quickly (approximately 2,000 minutes). Since we knew we would need to drop the output from the first 2,000 minutes and still want a good sample of steady-state output, we conducted our production runs for a 10,000 minute duration (approximately 7 days).

Because we are unable to start the simulation off at time 0 in a state which is representative of the steady-state behavior of the architecture, the output data at the beginning of the simulation are not good estimates of the steady-state MOE responses we are interested in. Since the penalty rate for each architecture was the only MOE to be statistically analyzed with a steady-state approach, the initial transient problem was dealt with by dropping the first 2000 minutes worth of penalty rate output data. [Ref. 34:p. 307]

2. Units and Nets

Figure 21 on the following page shows the sub-network of the MEB communications architecture that we are using for this analysis example. As the figure details, we are simulating only the major Fire Support nets of the Ground Combat Element of the MEB. The sub-network involves the Brigade Operations Center, the Regimental Operations Center, the three infantry battalions (each with three companies and one 81 mm Mortar Platoon), and the Artillery Battalion with its three Artillery Batteries. The fourth artillery battery, N5/11, is a self-propelled artillery battery that has been attached to the Regiment to help support the mechanized battalion in its maneuver operations. There are a total of 22 units or command and control facilities (C2FACs) using a total of 19 different communications nets with 102 radios. Each link between the units in Figure 21 actually represents all the different nets that currently connect two given units. For example, the line connecting the 3d Marine Regiment to the 1/12 Arty Battalion actually represents connectivity between these two units on an Intelligence Net, a Fire Support Control Net, a Conduct of Fire Net, and a Regimental Tactical Net.

3. Radios and Jammers

For the architecture illustrated on the next page, the 22 units own a total of 102 radios which can be designated as PRC-77, SINCGARS, or HF types in the data base manipulation program. Providing the essential threat stress, we model two jammers which are located within range of all the units modelled in this sub-network. All the jammer specific data for our analysis can be found in Appendix E.

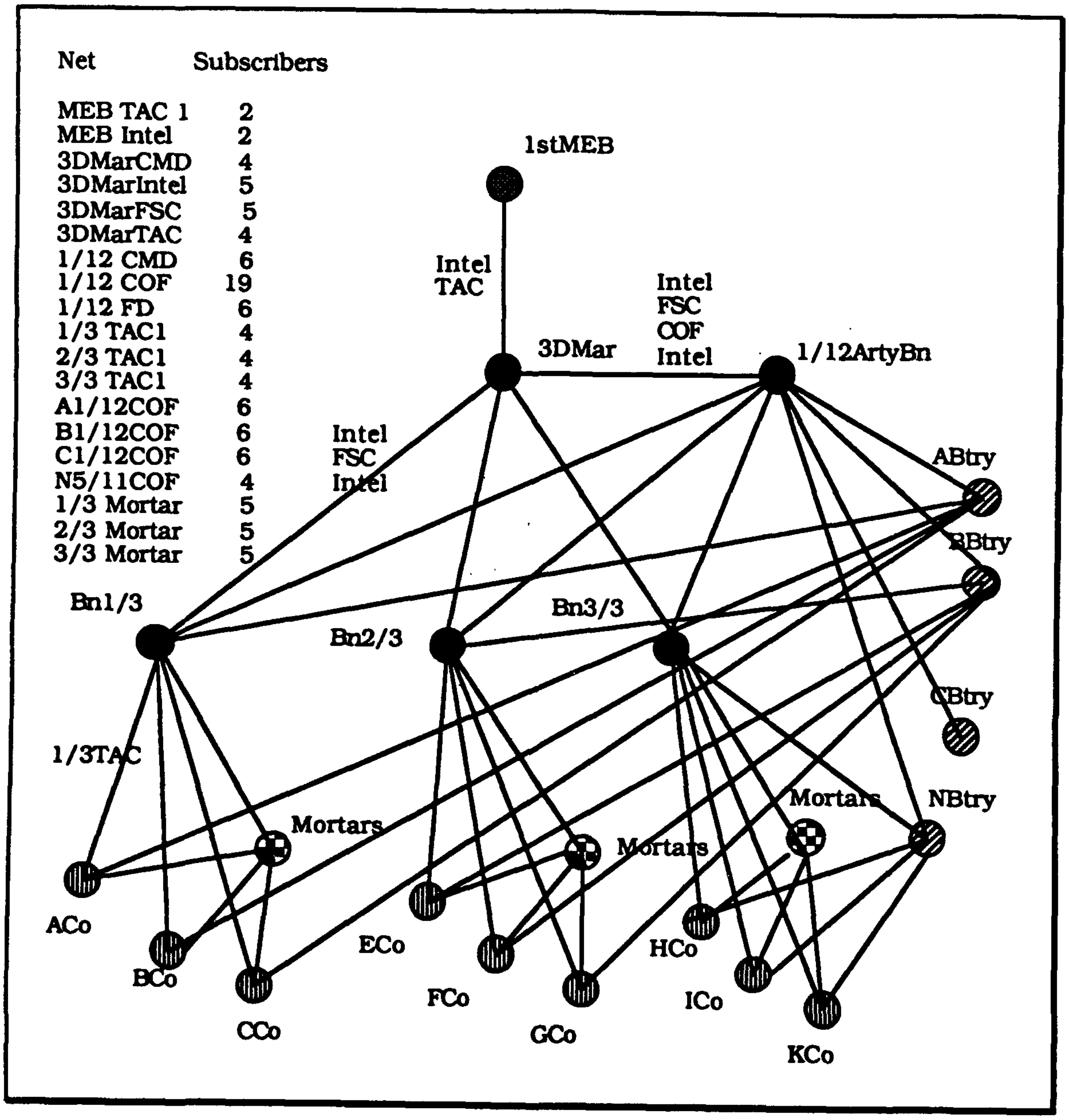

Figure 21. 1st MEB Fire Support Architecture

4. Analysis Set-Up

As an example of how MCCAAM can be used by Marine Corps analysts, the simulation experiment in this thesis compares four different SINCGARS allocation schemes for the Fire Support nets of a standard Marine Expeditionary Brigade (MEB) architecture. The object of this experiment is to determine whether there is any difference between the communication abilities of this portion of the MEB for the different allocations, to estimate the differences, and to assess the precision of the estimates. A short description of each of the allocation schemes follows:

- **Allocation Scheme 1** is the standard benchmark for the analysis. It represents the way the Marine Corps MEBs currently communicate. All the MEB units are using only the fixed-frequency VRC-12 and PRC-77 family of radios.
- **Allocation Scheme 2** represents the philosophy that the higher level nets are carrying more important information and therefore need the protection that SINCGARS provides. Therefore, under this scheme, SINCGARS are issued to the high level nets first and then down the architecture until depleted.
- **Allocation Scheme 3** is for those who would propose that the new, highly reliable anti-jam radios need to go to the units who operate in the field the most. Those tactical units which, in combat, will be actively engaged with the enemy the greatest amount of time. So, for a given number of SINCGARS, the subscribers on the nets at the lowest level are issued SINCGARS until the number of available radios is depleted.
- **Allocation Scheme 4** assigns the available SINCGARS radios to the nets that are used the most with the current traffic workload. This allocation obviously does not protect the most "important" traffic, but it provides yet another example for comparison, and is a potential consideration for decision makers.

The flow for each allocation scheme in Figure 22 below illustrates a simulation run in MCCAAM with the same workload sample path and jammer interaction. The output for each iteration or run are the statistics used for calculating the seven communication MOEs and the accrued penalty, P. For each allocation scheme, the seven MOE values are calculated or taken straight from the output files as described in Chapter IV. Next, the utilities of each of the MOE values is calculated with user-defined utility curves. Using weights obtained from a pair-wise comparison of all the MOEs as described in Chapter IV, we then aggregate the seven MOEs to obtain, E, an aggregate measure of that architecture's communications performance.

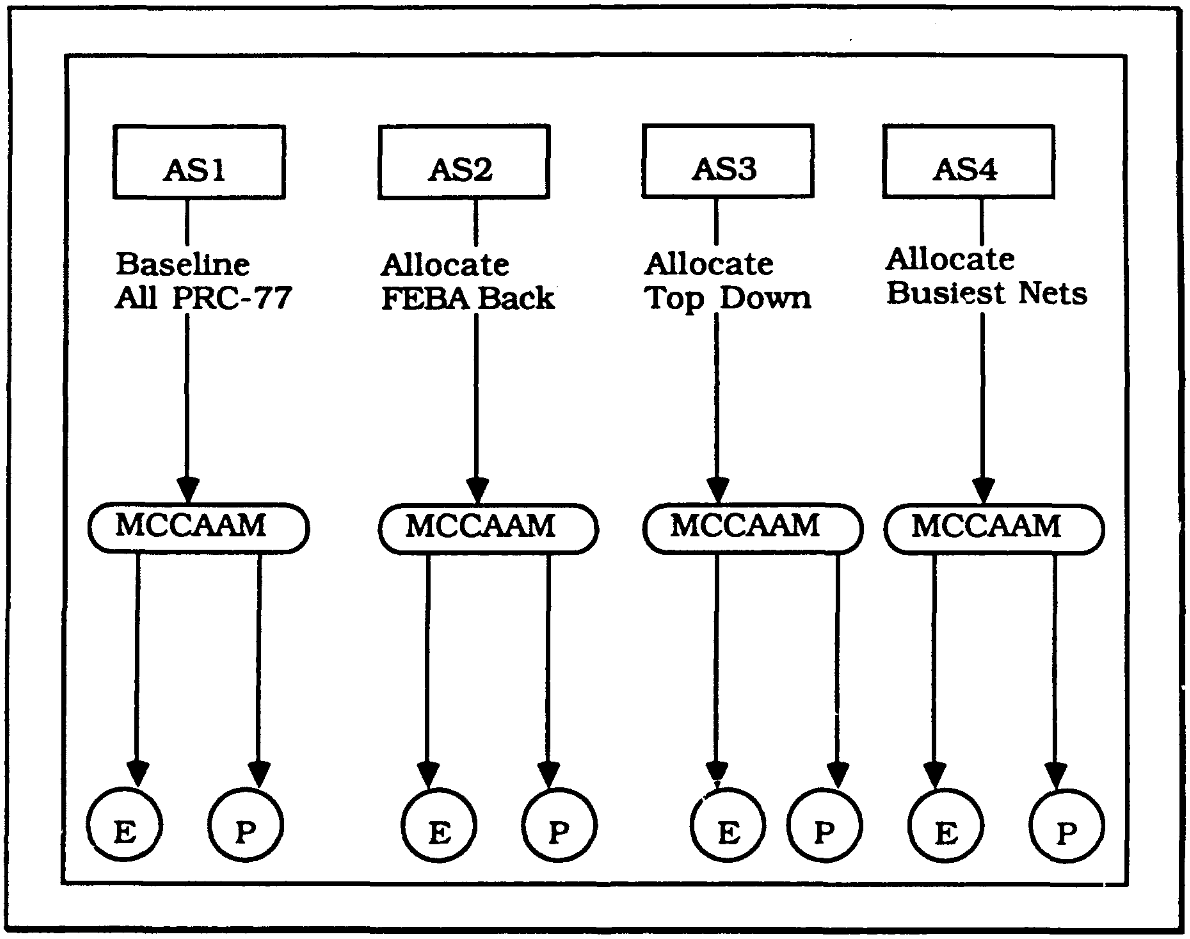

Figure 22. Experimental Flow

We would like to see that both aggregate measures of effectiveness choose the same architecture as "the best", but the aggregation of the seven individual measures considers effects of more factors than does the overall penalty MOE and might yield different results in certain circumstances.

Once we have obtained all the measures of effectiveness for each of the four allocation schemes, we are interested in choosing the architecture that gives us the best measures of effectiveness in the most areas.

The next chapter provides model results and an example of how an analyst can provide a decision maker with a quantifiable comparison of the architecture under study.

VI. OUTPUT ANALYSIS

Four example architectures were developed to demonstrate the utility of MCCAAM as both an analytic and planning tool. The baseline, model as described in the previous chapter, provides a point of reference for comparison of experimental results. The three additional scenarios demonstrate the use of MCCAAM as a planning tool and allow the user to compare results of alternative tactical plans with those of the baseline model.

A. MODEL VERIFICATION

Before describing the steps taken in verifying MCCAAM, we begin by giving some simple definitions of verification, validation, and output analysis to avoid any confusion over what is being referred to. "*Verification* is determining whether a simulation model performs as intended, i.e. properly debugging the program." [Ref. 34] Although simple in concept, this was very difficult for a large-scale simulation model like MCCAAM. "*Validation* is determining whether a simulation model (as opposed to the computer program) is an accurate representation of the real-world system under study. This is to be contrasted with *output analysis* which is concerned with determining a simulation model's (not necessarily the system's) true parameters or characteristics."[Ref. 34:p. 333]

Our model verification goal was to confirm that MCCAAM was producing the numbers that we desired when we implemented our model logic. This was accomplished in large part by five techniques [Ref. 34] briefly described below :

- **Technique 1**: In developing MCCAAM, we wrote and debugged the entire program in modules. The modular structure of MODSIM II made this very easy and natural and greatly assisted in testing subprogram structures. As the program coding progressed, additional levels of detail were successively added until the model satisfactorily represented our system of interest.
- **Technique 2**: Realizing it is advisable to have more than one person "proof" the computer program when large simulation models are being developed, we implemented this formally with periodic *structured walk-throughs*. These walk-throughs allowed the three members of the modelling team to work through modules step-by-step to reach mutual agreement on logic and implementation style.
- **Technique 3**: One of the more powerful verification techniques that can be used to debug a discrete-event simulation model is a *trace*. Once again, MODSIM made this very easy with its built-in trace stream objects. Appendix H shows one page of our c3log.out file which contains examples of statements that were written to the file throughout the flow of the program to ensure the system was behaving the way we intended it to. This trace stream was very effective in revealing areas of faulty code or problem areas. Through appropriately located comments, we could pin-point the models activities in any given area and time of interest.
- **Technique 4**: By running MCCAAM under a set of simplifying assumptions (manifest by changing input parameters) for which the model's true characteristics were known (or easily calculated), we were able to assure ourselves that from the simple level on up, the radios, nets, and messages were all behaving as intended and expected.
- **Technique 5**: Not always the easiest to incorporate, technique five involves displaying simulation output on the terminal screen as the simulation actually progresses. Though not necessarily helpful with all types of simulations, this technique was employed in MCCAAM through the graphical portrayal of the accumulating penalty for the architecture under study. Through this window, which is active while the simulation program is running, we see the the passage of time and the architecture's accumulating penalty. Graphical portrayal of any of MCCAAM's measures of effectiveness can be implemented to provide the analyst a real-time picture of the system's performance.

B. RESULTS

Once the verification steps discussed above were completed with our final version of MCCAAM, we were able to make production runs for analysis purposes. The paragraphs below list the quantifiable measures of effectiveness we obtained through MCCAAM. The measures determined through the subjective scoring (not obtained through MCCAAM) are also presented. The following list of abbreviation definitions is provided to facilitate table interpretation:

W	: Average message wait time (minutes)
#Mess	: Number of messages completed in simulation time.
T	: Timeliness measure = 1/(W/#Mess)
GOS	: Grade of Service = #Messages Comp/#Messages Att
PJ	: Protection from Jamming = GOSj/GOS
R	: Radio Reliability = Number of radio failures[3]
IP	: Information Protection (calculated from criterion scale)
NC	: Network Construction (calculated from criterion scale)
NM	: Network Maintenance (calculated from criterion scale)
E	: Sum of weighted utilities of MOEs
P	: Overall penalty accumulated by given architecture
#Bosts	: Number of BOSTS completed in simulation time.
P*	: Scaled Penalty MOE = P/#Bosts
P Rate	: Average Penalty Rate for entire simulation run.

The respective weights and utilities below are examples of values that were obtained for each of our seven measures of effectiveness as described in Chapter IV. The weights came from the paired comparisons of all MOEs using *Expert Choice* and the utility curves for each of the MOEs are just some

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[3] The radio failure numbers in Table 4 are intentionally very large. The MTBF values we used were much smaller than currently known values in order to see effects of high radio failure. Additionally, the statistic reflects *all* the radios in the MEB whether they were used or not. Since it is simply a *relative term* between allocation schemes, the magnitude is not important.

of many that could be employed. The specific utility values listed were obtained by substituting Allocation Scheme 1 MOE values into the respective utility functions.

- Weight (GOS) = .299
- Weight (PJ) = .191
- Weight (T) = .176
- Weight (R) = .141
- Weight (NM) = .084
- Weight (IP) = .064
- Weight (NC) = .045

- Utility (GOS) = GOS ^ 2 = 0.871
- Utility (PJ) = PJ^ 2 = 0.912
- Utility(T) = 2 *IN = 0.334
- Utility(R) = R/1000 = 0.173
- Utility (NM)= NM/1000 = 0.395
- Utility (IP) = IP/1000 = 0.395
- Utility (NC) = NC/1000 = 0.395

The aggregate measure E is calculated as the weighted sum of utilities as described in Chapter IV:

$$E = \sum w_i * U_i$$

$$E = .299*U(GOS) + .191*U(PJ) + .176*U(T) + .141*U(R)$$

$$+ .084*U(NM) + .064*U(IP) + .045*U(NC)$$

$$E = 0.5361$$

Table 4 summarizes all the individual and collective measures for the four allocation schemes. Our experimental results show that Allocation Scheme 3 (FEBA back) produces the overall best communications architecture with respect to the overall accumulated penalty. Allocation Scheme 4 appears to be the best architecture with respect to most of the individual MOEs and the aggregate MOE, E.

An analyst could now use these results to brief a decision maker with quantifiable results. One question remains: Are these differences in architectures statistically significant? The following sections discuss how we can formally look at the differences in some of the MOEs obtained.

TABLE 4. MOE RESULTS

MOE	AS1	AS2	AS 3	AS4	BEST
W	35.91	44.64	38.24	38.88	AS1
#Mess	5414	6387	6141	6453	AS4
T	150.83	143.20	160.59	165.98	AS4
GOS	93.36	96.83	95.89	97.83	AS4
PJ	0.955	0.980	0.975	0.976	AS2
R	1733	1372	1399	1425	AS2
IP	5	6.97	6.97	7.03	AS4
NC	5	4.01	4.01	3.99	AS1
NM	5	4.51	4.51	4.49	AS1
E	.5361	.5569	.5595	.5669	AS4
P	50,331	51,517	48,530	53,006	AS3
# Bosts	203	231	237	248	AS4
P*	247.94	223.02	204.78	213.73	AS3
P Rate	4.67	4.92	4.71	5.24	AS1

C. SELECTION PROCEDURES

The different MOEs provided in any MCCAAM run give any analyst or decision maker the ability to select a best architecture in one of any number of different areas. For example, if an analyst was only interested in how many BOSTS an architecture could process in a heavy jamming environment, then he could make his selection based strictly on the Protection from Jamming (PJ) MOE.

If there is no clear difference in the performance of competing architectures when examining all the tabulated measures of effectiveness, then there is no reason to pursue further analysis. On the other hand, if there seems to be a difference in the performance of competing architectures, we want to provide a decision maker with some sense of how much performance difference exists.

The following sections discuss statistical approaches to help assess those performance differences.

D. ANALYSIS OF DESIGN AND MOES

A natural first step is to compare all the architectures or systems to a standard or reference point to discern the magnitude of performance differences. Beyond comparison to a reference point, one of the simplest and most intuitive approaches when comparing two systems is to examine the difference in the average values of a specific measure of effectiveness. The most efficient way to look at differences is through a confidence interval approach, so this technique is presented below.

1. Confidence Intervals for Steady-State Simulations

For our analysis example, we are interested in the penalty rate output for a single steady-state simulation run. If we let the variables $p_1, p_2, \ldots, p_j$ represent this output process and p_i represent the architecture's penalty rate at time i in the simulation run, then we define the steady-state average response p^* of p_i (when it exists) by:

$$p^* = \lim_{m \to \infty} \frac{\sum_{i=1}^{m} P_i}{m} \text{ w.p. } 1$$

Of the two general approaches given in most simulation literature for constructing a confidence interval for p^*, we chose the fixed-sample-size approach. Within the fixed-sample-size approach, there are five or more techniques available. We chose the batch means technique which partitions the output data $p_1, p_2, \ldots, p_j$ into approximately IID observations to which classical statistical analyses can be applied to construct a confidence interval. [Ref. 30]

For the batch means technique, we make a simulation run of length m and then divide the resulting observations (whether they be penalty rate, grade of service, or number of BOSTS) into n batches of length l. (Assume that $m = nl$) Thus, batch 1 contains observations $p_1, p_2, \ldots, p_j$ etc. If we let $\overline{P}_j(l)$ be the batch mean of the l observations in the jth batch and

$$\overline{\overline{P}}(n,l) = \sum_{j=1}^{n} \overline{P}_j(l)n$$

be the grand sample mean, then we can use $\overline{\overline{P}}(n,l)$ as our point estimator for P^*. Thus the $\overline{P}_j(l)$'s play the same role for batch means as the individual observations do for the terminating case confidence interval.

If we choose the batch size l large enough, it can be shown that the $\overline{P}_j(l)$'s will be approximately uncorrelated. Additionally, if l is chosen large enough, there are central limit theorems for correlated stochastic processes that allow us to assume the $\overline{P}_j(l)$'s to be approximately normally distributed.

Ten differences between averages from comparable non-overlapping sequences of observations will be nearly normally distributed because of the central limit effect. Furthermore, even though successive individual batch yields are almost certainly statistically dependent, the differences between averages will be distributed approximately independently. [Ref. 30: p. 51]

Therefore, if the batch size l is large enough, it follows that it is not unreasonable to treat the $\overline{P}_j(l)$'s as if they were IID normal random variables with mean μ and to construct an approximate $100(1-\alpha)$ percent confidence interval for μ from

$$\overline{\overline{P}}(n,l) \pm t_{n-1,\,1-\frac{\alpha}{2}} \sqrt{s_{\overline{P}}^2(n)/n}$$

where the sample variance *of the mean* is

$$s_{\overline{P}}^2(n) = \frac{\sum_{j=1}^{n} \left[\overline{P}_j(l) - \overline{\overline{P}(n,l)}\right]^2}{n-1}$$

Using the approach above, we ran MCCAAM for 10,000 minutes, deleted the first 2000 minutes worth of penalty output, and then collected 31 batches of size 5 by sampling from the penalty process every 50 minutes. For each of the four allocation schemes, the global penalty rate batch means, standard deviations of the means, and associated 95% confidence intervals are listed below:

	AS1	AS2	AS3	AS4
Batch Mean*	4.67	4.92	4.71	5.24
Stand. Dev.	0.246	0.255	0.273	0.302
Conf. Interval	(4.17, 5.17)	(4.40, 5.44)	(4.15, 5.26)	(4.62, 5.86)

2. Multiple Comparisons with a Standard

Using the standard treatment (AS1 : No SINCGARS in architecture) as a benchmark against which to compare the specific allocation schemes, the question to be answered is whether or not any of the treatments may be considered to be different from the mean of the standard.

With k=4 allocation schemes, the statistic of interest is the k–1= 3 differences $\overline{AS_i} - \overline{AS_1}$ where $\overline{AS_1}$ is the observed average response for the baseline architecture with no SINCGARS. The 1–α confidence intervals for all 3 differences from the standard are calculated from Dunnett's Procedure [Ref. 30:p. 205] as given below:

$$\pm t_{k,v,\alpha/2}\, S \sqrt{\frac{1}{n_i} + \frac{1}{n_1}}$$

where $t_{k,v,\alpha/2}$ values are found in Dunnett (1964). S is the pooled sample standard deviation, obtained from the four individual standard deviations and v is the degrees of freedom of the estimate s^2.

Thus for our example with k = 4 allocation schemes and 31 batch mean observations for each allocation scheme, we have v = 120 and 95% confidence limits

$$\pm 2.51 * 1.50 \sqrt{\frac{1}{31} + \frac{1}{31}} = 0.96$$

Therefore any observed difference from the standard greater than 0.96 in absolute value can be considered statistically significant at the $\alpha = 0.5$ level. The 3 differences that follow show that none of the average penalty rates is statistically significant from the standard at the 0.05 level:

	AS1	AS2	AS3	AS4
Avg. P Rate	4.67	4.92	4.71	5.24
Difference	*	0.25	0.04	0.57

Though it is good practice to allot more observations to the control treatment than to each of the other treatments, we have 31 batch means for all four of the architectures of interest.

3. Comparison of Two Averages

The approach demonstrated here for determining if there is a significant difference between any two MOEs can be applied to most any of the statistics collected in MCCAAM to provide further insight into architecture differences.

In our example, we are interested in providing a decision maker with some idea as to the magnitude of the performance difference between the top two communication architectures. We accomplish this by constructing a confidence interval for the difference in the mean values of the two MOEs of interest. This approach provides more information than if we were to simply conduct a hypothesis test to see whether the observed differences could be distinguished from zero.

For this example, we use the thirty-one penalty rate batch means discussed above as our sample of IID observations from AS3 and AS4. For example, for allocation scheme four, we will denote the individual batch means as $X4_1$, $X4_2$, $X4_3$, ..., $X4_{31}$. We are interested in $\mu = E(XI_j)$, the global penalty rate batch mean for the entire simulation run for each of the two allocation schemes. We want to construct a confidence interval for $D = \mu(AS4) - \mu(AS3)$. By pairing each of the 31 batch means from the two allocation schemes, we define $Z_j = X4_j - X3_j$ for j = 1, 2, ..., 31 and we have IID random variables, Zj, where E(Zj) = D. So, we let

$$\bar{Z}(n) = \frac{\sum_{j=1}^{n} Z_j}{n} \quad \text{and} \quad \widehat{\sigma^2}[\bar{Z}(n)] = \frac{\sum_{j=1}^{n} [Z_j - \bar{Z}(n)]^2}{n(n-1)}$$

and we form the approximate 100(1-α) percent confidence interval

$$\bar{Z}(n) \pm t_{n-1,\,1-\alpha/2} \sqrt{\widehat{\sigma^2}[\bar{\bar{Z}}(n)]}$$

If the Zj's are normally distributed, this confidence interval covers D with probability 1–α; otherwise, we rely on the central limit theorem which implies that this coverage probability is near 1-α for large *n*. An important point here is that we did not have to assume that the allocation batch means are independent; nor did we have to assume that the variances were equal. The following paired-t confidence interval is obtained for our example:

$$\bar{Z}(n) = 0.536 \quad \hat{\sigma}^2[\bar{Z}(n)] = 51.25/31(30) = 0.055$$

$$\sqrt{\hat{\sigma}^2[\bar{Z}(n)]} = 0.235$$

These values give us a 95% confidence interval of

(0.0567, 1.015)

for D = μ(AS4) - μ(AS3). So, with approximately 95% confidence, we can say that μ(AS3) differs from μ(AS4), and it appears that AS3 is better with respect to penalty accrual rate, since it leads to a lower average penalty rate.

E. VARIANCE REDUCTION

The first (and probably most useful and popular) variance reduction technique that we considered, *common random numbers (CRN)*, applies when one is comparing two or more alternative system designs – precisely the situation in this experiment.

The basic idea with this technique is that we would compare the alternative systems "under similar experimental conditions" so that we can be more confident that any observed differences in performance are due to the differences in the system designs rather than to fluctuations of the "experimental conditions." In simulations, the experimental conditions are the generated random variables that are used to drive the models through simulated time.

The name of this technique stems from the possibility in some situations of using the same stream of basic U(0,1) random variables to drive each of the alternative models through time. In the terminology of classical experimental design, CRN is a form of blocking. This was carried out in MCCAAM by ensuring each of the radio allocation schemes was exposed to the exact same traffic workload. No formal analysis is presented to show the effects of simulating the different architectures with different variable traffic workloads.

F. MODEL VALIDATION

Though not fully accomplished with MCCAAM, the three-step approach to validation presented here is an approved approach [Ref. 34] which has been carried out to some degree. The remaining validation steps await time and future testing.

1. Develop a Model with High Face Validity

As an initial objective, we determined to develop a model which, on the surface, seemed reasonable to Marines knowledgeable about the communication system being modeled. We tried to make use of all existing information, which included the following:

- Intuition
- General Knowledge
- Observations of the system
- Existing theory
- Conversations with experts

2. Test the Assumptions of the Model Empirically

The goal of this step is to quantitatively test the assumptions made during the initial stages of model development. One of the most useful tools during the second validation step is *sensitivity analysis*. This technique was used to determine how much MCCAAM output varied with small changes in specific parameters. Another important use of sensitivity analysis is to determine the level of detail at which a particular sub-system is to be modelled.

3. Determine How Representative the Simulation Output Are

> Probably the most definitive test of the validity of a simulation model is to establish that the model output data closely resemble the output data that would be expected from the actual system. [Ref. 34]

If there was specific enough communications data available from a MEB field exercise, there are a number of statistical tests available in validation literature for comparing output data from MCCAAM to the MEB exercise data. Since the output processes of almost all real-world systems and simulations are *non-stationary* (the distributions of the successive observations change over time) and *auto-correlated* (the observations in the process are correlate with each other) the comparison would be difficult without a model like MCCAAM. Using the exercise's scripted message traffic to drive the simulation, model output could be used for validation tests.

Since MCCAAM is only an approximation to the actual communication architecture, a null hypothesis that the system and model are the same is clearly false. We believe, along with Law and Kelton "that it is more useful to ask whether or not the differences between the system and the model are significant enough to affect any conclusions derived from the model." [Ref. 34]

In addition to statistical procedures, one can use a Turing test [Ref. 34:p. 341] to compare the output data from a specific field exercise to that of a MCCAAM simulation of that exercise scenario. In a Turing test, Marines knowledgeable about the exercise and the communications involved would be asked to examine one or more sets of exercise data and one or more sets of MCCAAM results without knowing which data was which. If these "experts" can differentiate between the exercise data and the MCCAAM data, their explanation of how they were able to do it can be used to improve the model. [Ref. 34]

MCCAAM output data could be compared to communications data from a major field exercise if the particular data needed for validation was collected and made available. An immediate recommendation is to establish a MCCAAM simulation of a joint Army/Marine Corps field exercise at Fort

Irwin, California and take advantage of the Army's extensive data collection effort at their National Training Center (NTC) to compare the exercise results to the MCCAAM results. This type of validation effort would go a long way toward establishing the benefits of a communications analysis model and also provide great insight into other areas of MCCAAM development.

VII. SUMMARY, CONCLUSIONS, RECOMMENDATIONS

A. MODEL AND ANALYSIS SUMMARY

In this study, we have proposed a *new paradigm for workload modeling* in military communications systems which reflects the dynamics and dependencies of the actual system, while not requiring a complex, high resolution combat model. This workload model is facilitated by the MBOT/BOST/MEO structure previously described.

We constructed an *object-oriented simulation model* of the communications system which exploits the given Marine Corps message structure, and we measured the performance of the system through traditional communication MOEs and a penalty accumulation process. As we anticipated, both the object-oriented modelling approach and the MODSIM II language were found to be powerful and easy to use.

We have constructed a *reusable tool for analysis* of single-channel voice communications architectures. By using the model in concert with the database manipulation program as depicted in Figure 23, a communications analyst is afforded a rare opportunity to [25]:

- observe the effects of doctrinal modifications to routing, net use, or directed nets,
- improve allocation of advanced technology single channel radios in the MAGTF,
- determine the overall capacity of an architecture to handle a mixture of data and voice traffic,
- react to changing environments involving jamming and other threats within a pristine experimental environment.

To summarize the results of the limited analysis example, we re-visit the respective measures of effectiveness for the four different allocation schemes in Table 5 below.

TABLE 5. MOE Summary

	AS1	AS2	AS3	AS4	"Best"
Bosts	203	231	237	248	AS4
E	.5361	.5569	.5595	.5669	AS4
P*	247.9	223.0	204.8	213.7	AS3

As discussed in Chapter six, these measures of effectiveness might not have any significant meaning when an actual architecture of type similar to the model is observed in a given field exercise. The strength of these measures lies in their ability to provide a means for comparative analysis between two similar systems. Given the control that the simulation model provides over the communications environment, we can assess differences in performance between two competing architectures due to the differences in the architecture composition.

The results from the four different allocation schemes analyzed by MCCAAM produced distinct measures of effectiveness. The aggregation approach used in this thesis with accompanying utility curves presents a MCCAAM user with a flexible, rational means to quantify a given architecture with a single measure. The unique penalty accrual process was shown to be a ***natural*** and effective aggregate measure of overall system performance.

B. CONCLUSIONS

In order to maintain the best equipped force-in-readiness, the Marine Corps is pursuing new communications technology at all operational levels. To best implement the new communications equipment, the Marine Corps must be able to compare proposed architectures before they are purchased and fielded. Specifically, the acquisition of the new frequency-hopping SINCGARS radios over the next few years presents an allocation concern.

It was the purpose of this thesis to design and implement a simulation model to provide Marine Corps decision makers and communications officers the ability to quantify the effectiveness of alternate tactical radio system configurations. We did not attempt to simulate reality but provide instead an effective comparative analysis tool. In all cases where choices were made concerning the inclusion of certain aspects of Marine communications, the question asked was: Does it help to distinguish between different communications architectures?

Based on the research conducted and the results detailed in this thesis, it is our conclusion that:

- a comparative analysis tool for Marine Corps communication architectures is needed.
- optimal allocation of new communications resources is required
- MCCAAM is a viable tool to achieve both.

C. RECOMMENDATIONS

As with most modelling and analysis efforts, each problem solved or question answered usually generates many more to be considered. There still remains quite a bit of work that can be done to expand MCCAAM's usefulness to the Marine Corps. The following paragraphs highlight potential areas of future work or research.

- **MEB Data Base.** Our first recommendation is to complete the MEB data base files to allow for full and accurate analysis of a MEB communications architecture. This will involve extensive work inputting message workload data in the form of BOSTs and MEOs, but will provide an extremely powerful analysis tool.
- **Digital Traffic.** The current form of MCCAAM does not model all the different complexities of digital transmissions. It treats digital messages simply as burst transmissions requiring a reduced time to transmit. The effect on any analysis is to decrease the load on the affected nets because of the reduced transmission time. We currently have not provided for different protocols, routing procedures, or even interoperability considerations of digital message traffic.

Realizing that our tactical communications should support short, "bursty," critical messages in keeping with the battlefield environment, a very worthwhile extension of the current study would be to examine the capabilities of the single channel radio network to concurrently serve as a voice network and a digital data pipeline below the Infantry Regimental level. This analysis would require information to include acknowledgement, re-transmission and relay procedures, assignment of digital devices to units (C2FACs), designation of specific messages as digital, band-width capabilities of the pipelines, and limitations imposed by the equipment that is incorporated. If SINCGARS is not currently a good tool for *large* data exchange rates, then it would make sense to allocate the incoming SINCGARS below regimental level. This study extension has already received favorable approval from the Marine Corps study sponsors. [Ref. 28]

As another example of future MCCAAM analysis, consider the new tactical data systems being considered. One such tactical data system, the Portable Data Link System (PDLS), has been initiated to meet the need that exists to provide advance forces and forward aviation command elements with a compact, rapidly deployable system capable of exploiting established tactical data information links (TADIL). Once modified, MCCAAM could be used to measure the effect on force communications if such a data system was widely adopted. [Ref. 16]

- **Spares**. Combat is inefficient because of the need for redundancy (which equates to survivability) in all equipment—especially communications equipment. If we ignore this need for redundancy in any equipment allocation scheme, we are not being very realistic. MCCAAM could be used to great effect in studying the effect of different types and numbers of backup radio systems at all force levels. To further expand on the impact of modelling spares, consider the current model. When a radio fails in MCCAAM, it is not available for use until its specified repair time has elapsed. The net it was a subscriber of is totally unavailable to that unit for that period of time. More realistically, an extra (spare) radio would be brought on-line, enter the net, and prosecute any waiting messages. In this manner, the modelling of spares will reduce the penalty associated with not passing traffic in a timely manner.
- **Experimental Designs.** An unlimited number of experimental designs can now be pursued with MCCAAM to examine questions of interest. A 2^3 design, such as the following, could be used to look at the main effects of jamming, radio reliability and traffic intensity.

Test #	# Jammers	MTBF	Traff Intense	Penalty/MOEs
1	4	200	High	
2	8	200	High	
3	4	400	High	
4	8	400	High	
5	4	200	Low	
6	8	200	Low	
7	4	400	Low	
8	8	400	Low	

- **Scenarios.** Different, *specific* scenarios could be analyzed to show effects of force size and threat on communications effectiveness. Data obtained from major field exercises could be used to continue MCCAAM's validation as an effective analysis tool.

- **Movement.** Integrating unit movement algorithms would create a greater need for network construction and maintenance modelling for a given architecture. This would help differentiate between systems that have distinctly different time costs associated with net construction and maintenance.
- **Graphics.** Integrating more simulation graphics will assist users in tracking communications performance as the simulation progresses. For example, a net analysis window that reflected all the major nets' traffic volume and average priority of traffic could help shed some light on how individual nets are used over time. Further implementation of graphics in the analysis stage of MCCAAM will also greatly enhance its ready use.
- **Band-width.** MCCAAM could, with modifications, be used to assist in determining effects of changing band-width and wait time parameters for different communications channels.
- **Data problem.** During the entire modelling and analysis process, we noted the recurring need for data like that contained in the LFICS Scenario and Events Listing (ratio of different precedence traffic, average number of BOSTS for different types of units, mean time to establish various types of nets, etc.) Numerous Marine Corps analysis activities at the Research and Development center such as Wargaming, C4I Interoperability and Proponency, and the Communications School currently rely on independently gathered data for respective studies and analysis pertaining to communications equipment and doctrine. It would be a very valuable asset if summaries of C4I information from such exercises as Team Spirit, Combined Arms Exercises (CAX's), and especially Desert Storm could be permanently retained in a central repository that was accessible to all who would need it. A system similar to the Marine Corps Lesson Learned System would greatly facilitate the use of such models as MCCAAM, as the Marine Corps and the remainder of the U.S. military moves more and more toward automated, digital communications.
- **Electronic Warfare.** Much still remains to be accomplished in enriching the communications and electronic warfare modules. For instance, the limitations and capabilities of the threat environment have not been modelled in a detailed manner. The comparative analysis conducted in this thesis did not require it, but others might. Additional technical areas of the communication environment could be incorporated if a specific analysis need warranted it. Such areas of

directional antennas, antenna height, HF single side-band radio nets, and various power level effects could all be incorporated.

- **Amphibious Nets.** The modelling of the complex communications involved in amphibious operations from ship to shore would be a very involved but worthwhile project.
- **Hindsight Optimization.** An interesting and challenging project would be to develop algorithms that would allow MCCAAM to assign a set amount of communications assets to an architecture's units in a step-wise fashion that would optimize the architectures performance for a user-specified criteria (timeliness, grade of service, digital throughput, etc.).
- **System Reliability.** Not specifically addressed in this thesis but a candidate for future study is the *composite probability* that all radio sets are operational at the start of a mission, will continue to perform without failure during the mission, and in the event that radio sets do fail during the mission, can be repaired in a specified time. This type of measure would include not only the reliability of the system, but the *availability* and *maintainability* of radios as well. [Ref.10:p. VI-18]

APPENDIX A. MAIN DEFINITION MODULES

This appendix contains all the main definition modules for current version of MCCAAM. These Definition Modules give a good overview of how the communications system was modelled by listing each of the object's fields, methods, and procedures.

```
DEFINITION MODULE Globals;

FROM RandMod IMPORT RandomObj;
FROM IOMod IMPORT StreamObj;

TYPE
  PrecedenceType     = (routine, priority, immediate, flash);
  RadioType          = (PRC77, SINCGARS, HF);
  UnitDesignationType = INTEGER;
  NetDesignationType  = INTEGER;

  UnitLocationRec = RECORD
   location       : INTEGER;
   MemberNum      : INTEGER;
   XCoord         : REAL;
   YCoord         : REAL;
  END RECORD;
VAR
 BostUGenerator             : RandomObj;
 MainTrafGenerator          : RandomObj;
 InterstimGenerator         : RandomObj;
 NextTrafGenerator          : RandomObj;
 MEODurationGenerator       : RandomObj;
 AckDurationGenerator  : RandomObj;
 MTBFGen               : RandomObj;
 logFile                : StreamObj;
 ScenarioStopTime           : REAL;
 NumberOfReplications   : INTEGER;
 SendOBETraffic             : BOOLEAN;
```

```
  RadioFailure                    : BOOLEAN;
  ModelJammer                     : BOOLEAN;
  NumberAllowedRetries            : INTEGER;
  MEODurationVariability          : REAL;
  MeanAcknowledgementTime         : REAL;
  AckDurationVariability          : REAL;
  TimeBetweenFreqChanges          : REAL;
  MaxRetrialsInNet                : INTEGER;
  SingarsEntryTime                : REAL;
  PRC77EntryTime                  : REAL;
  PRCCallingSingarsEntryTime : REAL;

PROCEDURE SetUpGlobals;
END MODULE.

{-----------------------------------}
DEFINITION MODULE Unit;
{-----------------------------------}

FROM Globals IMPORT UnitLocationRec,
            NetDesignationType,
            UnitDesignationType;
FROM Radio   IMPORT RadioObj;
FROM BostInf IMPORT BostInstanceTxObj,
            BostInstanceRecType,
            BoundUnitRecType;
FROM Bost    IMPORT MEORecType;

FROM RecLL IMPORT LinkedListOfRecords;

TYPE
EchelonType = (Sldr, Plt, Co, Bn, Rgt, Div, Corps, Army, Country);
CommunicationMethodType = (RadioComm, Messenger);
ReceiptStatusType = (NewMessage, InterruptedMessage);
CommMethArray = ARRAY INTEGER OF CommunicationMethodType;
RadioListType = ARRAY INTEGER OF INTEGER;

UnitObj = OBJECT
  name       : STRING;
  unitType   : UnitDesignationType;
  loc        : UnitLocationRec;
  echelon    : EchelonType;
  division   : INTEGER;
```

```
  regiment    : INTEGER;
  battalion   : INTEGER;
  company     : INTEGER;
  platoon     : INTEGER;
  numRadios   : INTEGER;
  radio       : ARRAY INTEGER OF RadioObj;
  netType     : ARRAY INTEGER OF NetDesignationType;

  ASK METHOD ObjInit;

  TELL METHOD ReceiveBostInstance
        (IN IncomingBostPack : BostInstanceTxObj;
         IN IntendedReceiver : INTEGER;
         IN SelectedRadio    : RadioObj;
         IN ReceiptStatus    : ReceiptStatusType);

  TELL METHOD ExceptionHandlingRoute
        (IN IncomingBostPack : BostInstanceTxObj);

    TELL METHOD KnowAboutJamming(IN Radio : RadioObj;
                                 IN Index : INTEGER);
END OBJECT;

UnitLocationListRecType = RECORD
  Unit : UnitObj;
END RECORD;

{----------------------------------------}
DEFINITION MODULE Net;
{----------------------------------------}

FROM Radio   IMPORT RadioObj;
FROM Globals IMPORT RadioType,
             NetDesignationType,
           UnitLocationRec,
           PrecedenceType;
FROM Unit    IMPORT UnitObj;
FROM BostInf IMPORT BoundUnitRecType;
FROM RandMod IMPORT RandomObj;
FROM RecLL   IMPORT LinkedListOfRecords;

TYPE
WaitingListType = ARRAY INTEGER OF RadioObj;
```

```
TransmissionCompletionResult =
    (TransmitterFailed,
     TransmitterJammed,
     ReceiverJammed,
     ReceiverOutOfRange,
     ReceiverFailed,
     SuccessfulContact);

RadioNetRecType = RECORD
  Radio : RadioObj;
  Unit  : UnitObj;
  RadioIndex : INTEGER;
END RECORD;

IntendedReceiverRec = RECORD
  UnitLocRec : UnitLocationRec;
  RadioNetRec : RadioNetRecType;
  IntendedReceiverNumber : INTEGER;
  Condition : TransmissionCompletionResult;
END RECORD;

NetObj = OBJECT
  NetDescriptor     : STRING;
  NetIndex          : INTEGER;
  Frequency         : REAL;
  PropagateMode     : STRING;
  Equipment         : RadioType;
  AntennaType       : STRING;
  PowerLevel        : STRING;
  NetIdle           : BOOLEAN;
  NetJammed         : BOOLEAN;
  Type              : NetDesignationType;
  RadioList         : LinkedListOfRecords;

  ASK METHOD ObjInit;
  TELL METHOD EnterNet(IN  subscriberRadio : RadioObj;
                       IN  subscriberUnit  : UnitObj;
                       IN  subscriberRadioIndex : INTEGER);
  TELL METHOD ChangeFreq;

  TELL METHOD ExecuteBusyPeriod;

  ASK METHOD BecomeJammed;
```

```
ASK METHOD BecomeUnJammed;

 ASK METHOD UnitOnNet(IN Unit : UnitObj;
          OUT OnTheNet : BOOLEAN;
          OUT Active : BOOLEAN);

 PRIVATE
MeanAckTime          : REAL;
SelectedRadio : RadioObj;

ASK METHOD NextTraffic(OUT SelectedRadio : RadioObj);
ASK METHOD ConstructWaitingList
             (OUT WaitingList : WaitingListType;
                  OUT NumberInWaitingList : INTEGER;
                   IN HighestPrecedenceSought : PrecedenceType;
                  OUT HighestPrecedenceFound : PrecedenceType;
                         IN TestAvailable : BOOLEAN);

ASK METHOD SelectRadio(IN WaitingList : WaitingListType;
           IN NumberInWaitingList : INTEGER;
          OUT RadioChosen : RadioObj);

 ASK METHOD CollectIntendedReceivers
    (IN BoundUnitRec : BoundUnitRecType;
     INOUT IntendedReceiverList : LinkedListOfRecords);

 TELL METHOD AcknowledgementDelay
                  (IN IntendedReceiver : IntendedReceiverRec);

TELL METHOD TransmissionDelay (IN IntendedReceiverList :
                                  LinkedListOfRecords;
                                  IN MeanTransmissionTime : REAL);

END OBJECT;
{------------------------------------------------------------}
VAR
 NetMasterList : ARRAY INTEGER OF NetObj;
 NumberOfNets : INTEGER;
 FreqGen     : RandomObj;
{______stuff that facilitates I/O and Objinit of a Net_____}
 IOWhatNetType : NetDesignationType;
 IOEquip : RadioType;
 IONetDescriptor : STRING;
```

```
  IONetIndex : INTEGER;
END MODULE.

{--------------------------------------}
DEFINITION MODULE Radio;
{--------------------------------------}

FROM Globals IMPORT UnitLocationRec,
                    NetDesignationType,
                    RadioType;
FROM GrpMod  IMPORT RankedObj;
FROM BostInf IMPORT BostInstanceTxObj;
FROM StatMod IMPORT SINTEGER,TSINTEGER;
FROM RandMod IMPORT RandomObj;

TYPE
BostQueue = OBJECT(RankedObj)
  OVERRIDE
     ASK METHOD Rank(IN a, b : ANYOBJ) : INTEGER;
END OBJECT;

RadioObj = OBJECT
  unitLoc          : UnitLocationRec;
  NetType          : NetDesignationType;
  netIndex         : INTEGER;
  Equipment        : RadioType;
  queue            : BostQueue;
  Available        : BOOLEAN;   {strictly mechanical}
  Jammed           : BOOLEAN;   {being interfered with}
  Transmitting     : BOOLEAN;
  Receiving        : BOOLEAN;
  MTBF             : REAL;
  NumInQ           : TSINTEGER;
  NumMessAtt       : SINTEGER;
  NumMessComp      : SINTEGER;

  ASK METHOD ObjInit;
  ASK METHOD GETNetNum(IN i : INTEGER);
  ASK METHOD GETUnitLocRec(IN ULR : UnitLocationRec);
  ASK METHOD RequestTransmission
       (IN BostTransferPack : BostInstanceTxObj);
  ASK METHOD SubmitBost
       (OUT BostTransferPack : BostInstanceTxObj);
```

```
  ASK METHOD CleanQueue;
  ASK METHOD IncAttempts;
  ASK METHOD IncCompletions;
  ASK METHOD DecCompletions;
  ASK METHOD BecomeJammed;
  TELL METHOD BecomeUnJammed;
  ASK METHOD StartTransmitting;
  ASK METHOD StopTransmitting;
  ASK METHOD StartReceiving;
  ASK METHOD StopReceiving;
  TELL METHOD GenReliabilityFail;
  ASK METHOD FixNetIndex(IN NetIndex : INTEGER);

END OBJECT;
PROCEDURE GetMTBF(IN Radio : RadioObj;  OUT MTBF : REAL);
END MODULE.


{-----------------------------------}
DEFINITION MODULE Message;
{-----------------------------------}

TYPE
MessageObj = OBJECT;
 Descriptor   : STRING;
 Duration     : REAL;
 ASK METHOD ObjInit;
END OBJECT;

VAR

NumberOfMessages        : INTEGER;
MessageList             : ARRAY INTEGER OF MessageObj;
IODuration        : REAL;
IOMessDescriptor    : STRING;

END MODULE.

{-----------------------------------}
DEFINITION MODULE TrafGen;
{-----------------------------------}
TYPE
```

```
TrafficGeneratorObj = OBJECT
  SumOfAllRates   : REAL;
  Pace            : REAL;
  Alpha           : REAL; {Alpha controls the slope of the failure rate of the
                           overall interstimulation times.}
  MaxStimulationEpochs : INTEGER; {Maximum number of TrafGen loops.}

  ASK METHOD ObjInit;
  TELL METHOD GenerateTraffic;
  ASK METHOD AddToRates(IN Rate : REAL);
  ASK METHOD ChangePace(IN NewPace : REAL);

END OBJECT;
VAR
  TrafficGenerator : TrafficGeneratorObj;
{-----vars used to facilitate IO and OBJINIT--------------}
  IOAlpha         : REAL;
  IOInitialPace   : REAL;
  IOMaxEpochs     : INTEGER;

PROCEDURE SetUpTrafficGenerator;
END MODULE.

{----------------------------------------}
DEFINITION MODULE Penalty;
{----------------------------------------}

FROM IOMod IMPORT StreamObj;

TYPE

PenaltyRecord = RECORD;
  Time            : REAL;
  PenaltyLevel    : REAL;
  PenaltyJump     : REAL;
  PenaltyRate     : REAL;
  NextPenaltyRecord : PenaltyRecord;
END RECORD;

PenaltyAccumObj = OBJECT;
  P               : PenaltyRecord;
  PenaltyDumpFile : StreamObj;
```

```
   ASK METHOD ObjInit;

   TELL METHOD DeletePenalty(IN Penalty : REAL;
                             IN Rate    : REAL);

   TELL METHOD AddPenalty(IN Penalty : REAL;
                          IN Rate    : REAL);

   ASK METHOD UsePenaltyFile(IN FileName : STRING);
   ASK METHOD TidyAndReset;

END OBJECT;
VAR
  PenaltyAccum : PenaltyAccumObj;
END MODULE.
```

```
{-----------------------------------}
DEFINITION MODULE Jammer;
{-----------------------------------}

FROM Unit     IMPORT UnitObj;
FROM RandMod IMPORT RandomObj;

TYPE
 JammerObj = OBJECT
   Name          : STRING;
   IDNumber      : INTEGER;
   XCoord        : REAL;
   YCoord        : REAL;
   MaxPower      : REAL;
   AntennaHt     : REAL;
   AntennaGn     : REAL;
   BeamWidth     : REAL;
   Range         : REAL;
```

```
JamBandLow    : REAL;
JBandWidth    : REAL;
Active        : BOOLEAN;
NumAttempts   : INTEGER;
NumJammed     : INTEGER;

ASK METHOD ObjInit;
TELL METHOD Jam (IN CurrentUnit : UnitObj);

END OBJECT;

VAR
JammerMasterList :  ARRAY INTEGER OF JammerObj;
JFreqGen       : RandomObj;
IOName      : STRING;
IONumber     : INTEGER;
IOXCoord    : REAL;
IOYCoord    : REAL;
IOMaxPower   : REAL;
IOAntennaHt : REAL;
IORange    : REAL;
IOActive    : BOOLEAN;

PROCEDURE ReadJammer;
PROCEDURE SelectTgt(IN Jammer : JammerObj);
PROCEDURE CalcDist(IN A : JammerObj ; IN B : UnitObj) : REAL;

END MODULE.
{---------------------------------}
DEFINITION MODULE Bost;
{---------------------------------}

FROM Globals IMPORT   UnitDesignationType,
                NetDesignationType,
                PrecedenceType,
                UnitLocationRec;

TYPE
{------------------------------------------------------------}
{-------------------static Bost data structures-------------------}
{------------------------------------------------------------}

MEOReceiverRecType = RECORD
```

```
  UnitType : UnitDesignationType;
  NextMEO : INTEGER;
  SameAsSenderNumber : INTEGER;
END RECORD;

MEOReceiverRecArray = ARRAY INTEGER OF MEOReceiverRecType;
PrecConstrArray = ARRAY INTEGER OF INTEGER;

MEORecType = RECORD
  NumConstrMEOs : INTEGER;
  PrecConstrMEO : PrecConstrArray;
  MessageNumber : INTEGER;
  NumberOfReceivers : INTEGER;
  MEOReceiver : MEOReceiverRecArray;
  Net : NetDesignationType;
  Broadcast : BOOLEAN;
END RECORD;
{-------unit connection stuff-----------------------------}
BostUnitConnRec = RECORD
   nextConnectionRecord : BostUnitConnRec;
  rateOfOccurance     : REAL;
  unit                : UnitLocationRec;
END RECORD;

{-------end unit connection stuff-----------------------------}




BostMasterType = OBJECT
   Descriptor : STRING;
   Precedence : PrecedenceType;
   AllotedTime : REAL;
   OneTimePenalty: REAL;
   PenaltyRate : REAL;
   Perishable : BOOLEAN;
   PerishabilityPoint : REAL;
   NumberOfMEOs : INTEGER;
   MEO : ARRAY INTEGER OF MEORecType;
    FirstUnitConnection : BostUnitConnRec;
    LastUnitConnection  : BostUnitConnRec;
```

```
    SumOfRates        : REAL;


    ASK METHOD ObjInit;
    ASK METHOD GETMEO(IN MEORec : MEORecType;
              IN Number : INTEGER);
     ASK METHOD ConnectToUnit(IN connectingUnit : UnitLocationRec;
                 IN rate         : REAL  );
    ASK METHOD SelectUnit(OUT UnitSelected : ANYOBJ {UnitObj});

    ASK METHOD GenerateOccurance;
END OBJECT;

{------------------------------------------------------------}
VAR
{------------------------------------------------------------}
  NumberOfBostMasterRecords : INTEGER;
  BostMasterList : ARRAY INTEGER OF BostMasterType;
  IODescriptor : STRING;
  IOPrecedence : PrecedenceType;
  IOAllotedTime : REAL;
  IOOneTimePenalty: REAL;
  IOPenaltyRate : REAL;
  IOPerishable : BOOLEAN;
  IOPerishabilityPoint : REAL;
  IONumberOfMEOs : INTEGER;
END MODULE.


{----------------------------------------}
DEFINITION MODULE Bost;
{----------------------------------------}

FROM Globals IMPORT   UnitDesignationType,
              NetDesignationType,
              PrecedenceType,
              UnitLocationRec;
```

```
TYPE
{-----------------------------------------------------}
{----------------static Bost data structures-----------------}
{-----------------------------------------------------}

MEOReceiverRecType = RECORD
  UnitType : UnitDesignationType;
  NextMEO : INTEGER;
  SameAsSenderNumber : INTEGER;
END RECORD;

MEOReceiverRecArray = ARRAY INTEGER OF MEOReceiverRecType;
PrecConstrArray = ARRAY INTEGER OF INTEGER;

MEORecType = RECORD
  NumConstrMEOs          : INTEGER;
  PrecConstrMEO          : PrecConstrArray;
  MessageNumber          : INTEGER;
  NumberOfReceivers      : INTEGER;
  MEOReceiver            : MEOReceiverRecArray;
  Net                    : NetDesignationType;
  Broadcast              : BOOLEAN;
END RECORD;

{-------unit connection stuff----------------------------}

BostUnitConnRec = RECORD
  nextConnectionRecord : BostUnitConnRec;
  rateOfOccurance      : REAL;
  unit                 : UnitLocationRec;
END RECORD;

{-------end unit connection stuff--------------------------}

BostMasterType = OBJECT
  Descriptor             : STRING;
  Precedence             : PrecedenceType;
  AllotedTime            : REAL;
  OneTimePenalty         : REAL;
  PenaltyRate            : REAL;
  Perishable             : BOOLEAN;
  PerishabilityPoint     : REAL;
  NumberOfMEOs           : INTEGER;
```

```
MEO                     : ARRAY INTEGER OF MEORecType;
FirstUnitConnection     : BostUnitConnRec;
LastUnitConnection      : BostUnitConnRec;
SumOfRates              : REAL;

ASK METHOD ObjInit;
ASK METHOD GETMEO(IN MEORec : MEORecType;
                  IN Number : INTEGER);
ASK METHOD ConnectToUnit(IN connectingUnit : UnitLocationRec;
                         IN rate           : REAL   );
ASK METHOD SelectUnit(OUT UnitSelected : ANYOBJ {UnitObj});
ASK METHOD GenerateOccurance;

END OBJECT;

{---------------------------------------------------}
          VAR
{---------------------------------------------------}
NumberOfBostMasterRecords : INTEGER;
BostMasterList : ARRAY INTEGER OF BostMasterType;
IODescriptor : STRING;
IOPrecedence : PrecedenceType;
IOAllotedTime : REAL;
IOOneTimePenalty: REAL;
IOPenaltyRate : REAL;
IOPerishable : BOOLEAN;
IOPerishabilityPoint : REAL;
IONumberOfMEOs : INTEGER;

END MODULE.

{-------------------------------}
DEFINITION MODULE Route;
{-------------------------------}


FROM Globals IMPORT UnitLocationRec,
             NetDesignationType,
             logFile;
FROM BostInf IMPORT BostInstanceRecType,
                    BostInstanceTxObj,
                        BoundUnitRecType;
FROM Bost    IMPORT MEORecType;
```

```
FROM Radio IMPORT RadioObj;
FROM Unit IMPORT UnitObj,
                       RadioListType,
                       CommMethArray;
TYPE
{------------------------------------------------------------}
PROCEDURE Route(IN BostTxPack    : BostInstanceTxObj;
                IN NewMEORec     : MEORecType;
                IN InstanceRec   : BostInstanceRecType;
                IN SenderUnit    : UnitObj;
                OUT BoundUnitRec : BoundUnitRecType;
                OUT RadioList    : RadioListType;
                OUT WalkOrTalk   : CommMethArray);
{------------------------------------------------------------}
END MODULE.
```

APPENDIX B. EXAMPLE IMPLEMENTATION MODULE

One MCCAAM implementation module is provided for the curious reader to see how an object's methods are coded. The Jammer Object has several of the major methods in the simulation program and are detailed below:

```
IMPLEMENTATION MODULE Jammer;
FROM IOMod      IMPORT StreamObj,FileUseType(Input);
FROM MathMod IMPORT SQRT, POWER;
FROM Globals    IMPORT UnitLocationRec, ALL RadioType,ScenarioStopTime;
FROM Radio      IMPORT RadioObj;
FROM Net        IMPORT RadioNetRecType,NetObj, NetMasterList;
FROM Unit       IMPORT UnitObj,LocationList,UnitLocationListRecType;
FROM SimMod     IMPORT Interrupt,SimTime;
FROM RandMod IMPORT RandomObj;
FROM RecLL      IMPORT LinkedListOfRecords;

PROCEDURE ReadJammer;
VAR
  JamFile       : StreamObj;
  i,NumJammers  : INTEGER;
  Garbage       : STRING;
  Jammer        : JammerObj;
BEGIN
  NEW(JamFile);
  ASK JamFile TO Open("jammer.dat",Input);
  ASK JamFile TO ReadInt(NumJammers);
  NEW(JammerMasterList, 1..NumJammers);

  FOR i := 1 TO NumJammers
    ASK JamFile TO ReadString(IOName);
    ASK JamFile TO ReadInt(IONumber);
    ASK JamFile TO ReadReal(IOXCoord);
    ASK JamFile TO ReadReal (IOYCoord);
    ASK JamFile TO ReadReal(IORange);

    NEW(JammerMasterList[i]);
```

```
    Jammer := JammerMasterList[i];
    SelectTgt(Jammer);
  END FOR;
END PROCEDURE;

{--------------------------------------------------------------------------}
PROCEDURE CalcDist (IN A : JammerObj ; IN B : UnitObj)  : REAL;
{--------------------------------------------------------------------------}
VAR
  XDIST, YDIST  :  REAL;
BEGIN
  XDIST := ABS(A.XCoord - (ASK B loc.XCoord));
  YDIST := ABS(A.YCoord - (ASK B loc.YCoord));
  RETURN (SQRT(POWER(XDIST,2.0) + POWER(YDIST,2.0))*100.0);
END PROCEDURE;

{------------------------------------------}
PROCEDURE  SelectTgt(IN Jammer : JammerObj);
{------------------------------------------}
VAR
  Dist           : REAL;
  CurrentUnit    : UnitObj;
  LocationListRec : UnitLocationListRecType;
  i              : INTEGER;
  NumberOfLocations : INTEGER;
  FirstLLObject   : LinkedListOfRecords;

BEGIN
  i := 1;
  NumberOfLocations := HIGH(LocationList);
  OUTPUT("High LocList is : ",HIGH(LocationList));

  WHILE (i <= NumberOfLocations)

    IF LocationList[i] <> NILOBJ
     LocationListRec := ASK LocationList[i] First();
    ELSE
      OUTPUT("&&&&&&&&&&&&   i value for jammer prob is  :",  i);
    END IF;

     WHILE LocationListRec <> NILREC
       CurrentUnit := LocationListRec.Unit;
       Dist := CalcDist(Jammer, CurrentUnit);
```

```
      {Check to ensure distance is being calculated correctly}
            IF FALSE
        OUTPUT("************************");
        OUTPUT("Distance from  ",ASK CurrentUnit name," to ");
        OUTPUT(ASK Jammer Name, "  is the following :  ", Dist);
        OUTPUT;
            END IF;

      IF Dist < (ASK Jammer Range)

IF TRUE
ASK TraceStream TO WriteString("About to jam a unit");
ASK TraceStream TO WriteLn;
END IF;
        TELL Jammer TO Jam(CurrentUnit);
      END IF;
       LocationListRec := ASK LocationList[i] Next(LocationListRec);
    END WHILE;
 i := i + 1;
 END WHILE;
END PROCEDURE;
```

OBJECT JammerObj;

```
{------------------------------}
ASK METHOD ObjInit;
{------------------------------}

BEGIN
 Name          := IOName;
 IDNumber        := IONumber;
 XCoord        := IOXCoord;
 YCoord        := IOYCoord;
 MaxPower        := IOMaxPower;
 AntennaHt      := IOAntennaHt;
 AntennaGn       := IOAntennaGn;
 BeamWidth      := IOBeamWidth;
 Range        := IORange;
 Active       := TRUE;
 NumAttempts   := 0;
 NumJammed      := 0;
```

```
 JBandWidth    := 40.0;  { can move this to ReadJammer }

  NEW(JFreqGen);

END METHOD;




{------------------------------------------------------}
TELL METHOD Jam(IN CurrentUnit : UnitObj);
{------------------------------------------------------}
VAR
 CurrentRadio  : RadioObj;
 CurrentNet    : NetObj;
 RadioNet      : NetObj;
 i             : INTEGER;
 duration      : REAL;
 RadioFreq     : REAL;


BEGIN

INC(NumAttempts);
duration := 20.0;
JamBandLow  := ASK JFreqGen UniformReal(30.0,88.0);

FOR i := 1 TO (ASK CurrentUnit numRadios)
CASE (ASK CurrentUnit.radio[i] Equipment)
 WHEN PRC77:
   CurrentRadio := ASK CurrentUnit radio[i];
   CurrentNet   := NetMasterList[ASK CurrentRadio netIndex];
   RadioFreq    := ASK CurrentNet Frequency;
   IF CurrentRadio.Available
         OUTPUT("Jamming an available PRC77.. if in correct freq. range
&&&&&");
       IF (RadioFreq > JamBandLow) AND (RadioFreq < JamBandLow +
JBandWidth)
       ASK CurrentRadio TO BecomeJammed;
       INC(NumJammed);
       RadioNet := NetMasterList[ASK CurrentRadio netIndex];
```

```
      Interrupt(RadioNet, "ExecuteBusyPeriod");

      OUTPUT("**********************************************");
      OUTPUT("Just jammed a PRC-77 radio for following unit:");
       OUTPUT(ASK CurrentUnit name,"  ...on this net:  ",ASK RadioNet
NetDescriptor);
      OUTPUT("**********************************************");
      OUTPUT;

     TELL RadioNet TO ChangeFreq;
      TELL CurrentRadio TO BecomeUnJammed IN duration;
    ELSE
        ASK TraceStream TO WriteString("Didn't jam radio...freq. not in
range");
      ASK TraceStream TO WriteLn;
    END IF;
   ELSE
    OUTPUT("Attempted to jam an unavailable PRC-77");
    OUTPUT;
   END IF;
 WHEN SINCGARS:
  OUTPUT("Attempted to jam a SINCGARS Unit");
 OTHERWISE
  OUTPUT("Attempted to jam an HF radio");
END CASE;
END FOR;

IF (Active) AND  (SimTime() <  ScenarioStopTime + 100.0)
  TELL SELF TO Jam(CurrentUnit) IN (duration + 60.0);
END IF;

END METHOD;


END OBJECT;
END {IMP} MODULE {Jammer}.
```

APPENDIX C. TIME-LATE PENALTIES FOR BOSTS

The delay in performance of individual Basic Operational SubTasks (BOSTs) from jamming or simply because of traffic may have differing effects on performance of the Marine Corps missions depending upon the BOST. Delay of a reporting task will not directly cause lives to be lost but delay to a fire mission may. Therefore in aggregating total delay, the minutes of delay should be given differing weights in calculating a communictions measure of effectiveness based on timeliness. This appendix describes a set of relative weights or penalties for each of the BOSTs. [Ref. 18]

Before describing the results however, it is noted that the BOSTs have been partitioned into those that are relevant to VHF single-channel nets and those that are not. This reduces the number of penalties to be determined. The BOSTs not considered are primarily the aviation and amphibious landing BOSTs that are performed with radios of other frequencies or higher capacities and are not candidates for SINCGARs. In addition, the Combat Service Support (CSS) BOSTs are not considered in the baseline analysis.

The initial set of penalties for the SINCGARS relevant BOSTs are given in the accompanying table, Appendix E. They were estimated by relative judgments of the research team with a base penalty of 100 for the standard fire mission BOST under the call for force MBOT. Only a few BOSTs score higher than this. In general, those BOSTs that involve execution of immediate fires have about 100 points and all others have lower penalties. Coordination of fire BOSTs have the next highest penalties, followed by planning and finally reporting which have values of 5 to 10 points. This leaves room for combat service support BOSTs to be added at a later date if desired.

The point scheme was designed to give an order of magnitude difference in ratio values between the most time critical and least time critical combat operations. We believe the order of penalties would not significantly vary between individual raters although the penalty ratio might vary.

The penalties in this appendix are for each minute of delay or time late. This could be measured from either initiation of the BOST or from some threshold time after initiation based on precedence (i.e. 10 minutes for FLASH messages) or other standard operating procedure or CEOI thresholds. It would also be possible to extend the penalty structure to include a one-time penalty for any delay above a threshold. This could pr ide additional discrimination between alternative allocations but would be dependent upon setting an acceptable threshold, which may be difficult to establish. If required, the one-time penalties could be established as a multiple of the penalties estimated above. The size of the multiple could be the same for each BOST somewhere in the range of a multiple of 10 to 100 or could vary by BOST category.

An additional hierarchical dimension to the penalties could be added to reflect relative importance of the BOSTs as a function of whether they were initiated by the platoon, company, battalion or brigade. With respect to fire mission it is unlikely that there is any difference in the importance of the message according to the command hierarchy. However for planning messages or orders it can be argued that delay moving down the chain of command implies that many more units will be affected then by delay at the bottom of the chain. Therefore it may be desirable to introduce a factor to change some of the penalties based on command level. At this time the initiators of each BOST are not yet specified so this refinement must wait until data on frequencies of initiation of BOSTs by command level are known. It is likely that a BOST will ordinarily only be initiated by one level of command. The initial set of penalties are shown below as penalties per minute of delay from initiation of the BOST. For descriptions of the listed BOSTs (and all others), see [20].

#	Name	Preced.	Allotted	Penalty	P.Rate	Perish?	P.Point
1	StdFireMission	3	63	100	3	True	120
2	Dist.GCEOrders	3	36	10	2	True	80
3	FinalProtFires	4	32	150	15	True	120
4	Intel.Report	3	24	60	0.5	True	120
5	CheckFire	3	15	125	10	True	30
6	HighAngleFire	2	64	100	5	True	130
7	HighBurstReg	2	40	40	0	True	80
8	PrecisionReg.	2	72	40	2	True	145
9	MortarMission	3	52	25	2	True	104

APPENDIX D. SIMULATION SCENARIO

Our friendly situation is intended to be as general as possible and still obtain realism. We have taken the notional amphibious MEB depicted in the Marine Air-ground Task Force Presentation Team Pocket Guide of 1 October 1990 to be our base MAGTF for this analysis. Based on guidance from the Warfighting Center, we have assumed that the amphibious operation is over and the MEB is in conflict ashore.

In order to provide some general framework in which to organize our notional MEB on the ground and provide some realistic distance calculations for radio and jammer ranges, we have chosen the 1:50,000 edition 3-DMA of Twenty-Nine Palms West. This training area in southern California is one of the few areas in the Marine Corps that see large units rotate through for live fire and force-on-force exercises on a continual basis. By using this terrain for our analysis example, we provide the Marine Corps analysts with a common reference point. Additionally, the potential exists to obtain actual exercise data from this training area for model comparison.

We have task organized the Ground Combat Element (GCE) into a reinforced infantry regiment consisting of a mechanized infantry battalion, a normal infantry battalion, a heliborne infantry battalion, a direct support artillery battalion, a recon company and a light armored infantry company. The self propelled artillery battery has been attached to the mechanized battalion and the remainder of the artillery is in general support. We have not included "Bravo" or alternate command groups because displacement (units moving) is not currently included in the model and because adding displacement will not greatly help our ability to distinguish between C3 architectures.

The Direct Air Support Center (DASC) is co-located with the regimental command group, and the remainder of the Aviation Combat Element (ACE) is located at an airstrip several miles from the GCE.

The Combat Service Support Element (CSSE) is located near the MEB headquarters. Combat Service Support Detachments are not considered close enough to the maneuver units to provide alternate routing for GCE message traffic.

This task organization, including unit locations is depicted here in Appendix D. To specify a high but realistic level of activity for the individual units, we have adopted the following general scenario.

The heliborne battalion has seized its objective and is engaged in heavy combat. The battalion reserve has been committed, so all three companies are engaged. The mechanized battalion was moving up Gays Pass to link up with the heliborne battalion when it encountered stiff resistance. It is also heavily engaged and has committed its reserve. The tank company and all three rifle companies are engaged. The infantry battalion, which was following in trace of the mechanized battalion as the regimental reserve, has reinforced the mechanized battalion with two rifle companies. The third rifle company is now the regimental reserve. Thus, we have a tank company and eight rifle companies engaged in combat along with the additional units illustrated on the following page.

The purpose of detailing a general scenario like the above is to motivate a high intensity traffic environment and provide the analyst a frame of reference for making parameter changes with respect to units, jammers, and their locations. Specific unit locations used are listed on the following page.

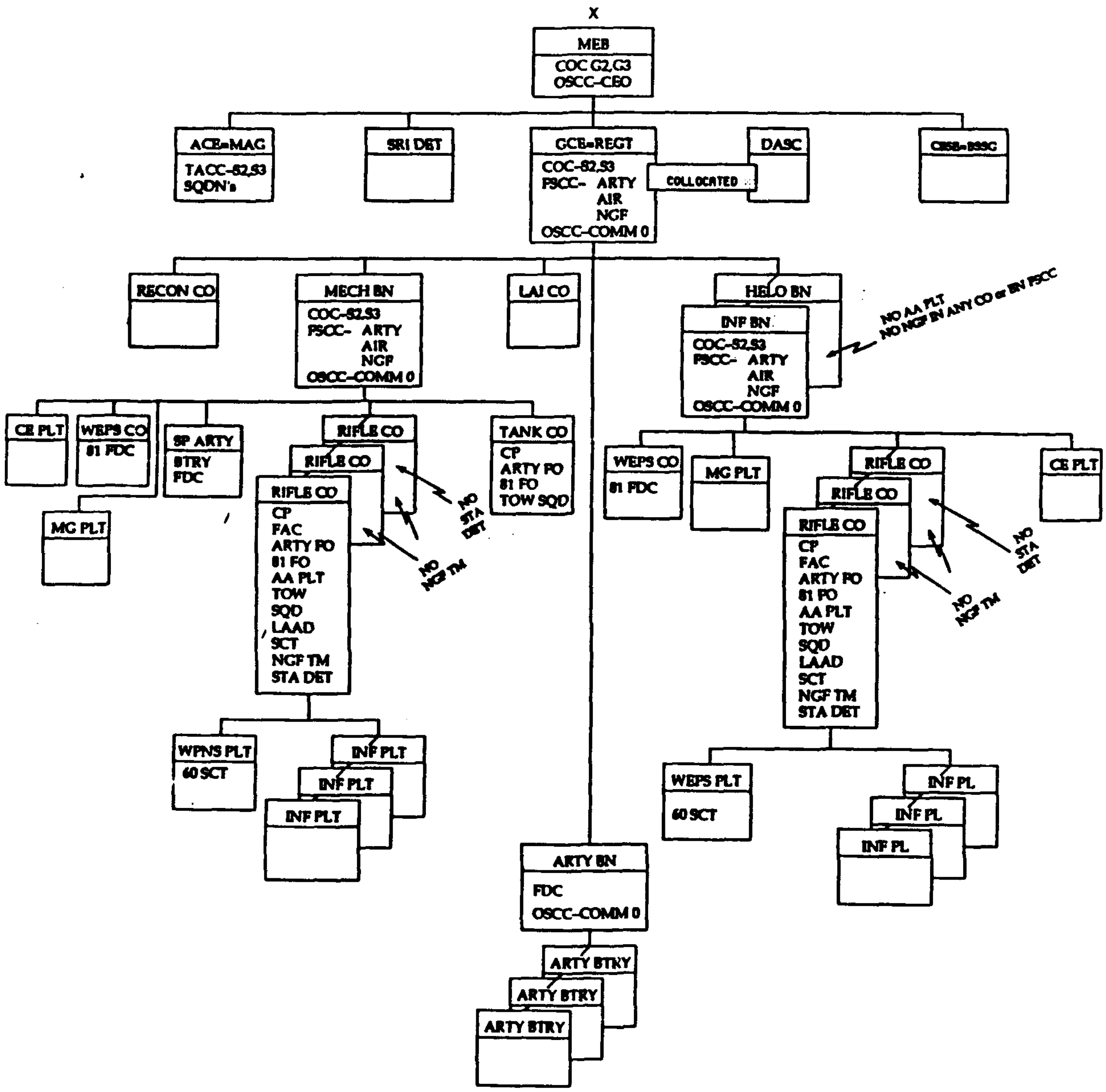

Figure 23. Example Task Organization

1st Marine Expeditionary Brigade

Unit	Location
1MEBCOC (CE)	793 068
MAG24 (ACE)	776 946
BSSG1 (CSSE)	810 038
1stSRIDet	532 276
3DMarCOC (GCE)	608 139
3DMarFSCC	
3DMarDASC	
1/12FDC (Arty)	600 086
NBttry5/11 (SP)	535 186
ABttry1/12	608 085
BBttry1/12	588 083
CBttry1/12	593 098
ACo3DRecon (CP co-loc w/Rgt)	608 139
1stPltCoa3dRecon	598 255
2ndPltCoA3dRecon	522 201
3dPltCoA3dRecon	574 271
ACo1stLAIBn	475 218
1stPltA/1/LAI	482 228
2ndPltA/1/LAI	481 218
3dPltA/1/LAI	489 219
1stBn3dMar (COC,FSCC,HST,) (Helo Bn)	465 225
1stPltCoA3dEngrBn	475 232
ACo1/3 (CP,FAC, 81FO)	472 236
1/3STADet1	
BCo1/3 (CP,FAC, 81FO)	478 230
1/3STADet2	
CCo1/3 (CP, FAC, 81FO)	470 223
1/3STADet3	
Sect1BttryA1stLAAD	468 226
3dMarTOWSect1	468 228
ABttry1/12FO (w/BCo)	478 230
HvyGuns1/3	472 240

81sPlt1/3	470 223
Dragons1/3	472 240
2ndBn3dMar (COC,FSCC,HST) (Mech Bn)	538 187
2ndPltCoA3dEngrBn	537 202
ACo1stTanks (ArtyFO, 81FO)	545 205
1stPltCoA	539 206
2ndPltCoA	545 208
3dPltCoA	549 212
TOWSquad	545 204
ECo2/3 (CP,FAC,ArtyFO, 81FO)	534 201
1stPltCoB3dTracks	534 202
2/3STADet1	555 215
NGFTeam1	534 201
FCo2/3 546 200	
2ndPltCoB3dTracks	545 201
2/3STADet2	546 200
GCo2/3 551 206	
3dPltCoB3dTracks	550 207
81sPlt2/3	554 207
HvyGuns2/3	534 198
Dragons2/3	534 194
3dMarTOWSect2	542 196
Sect2BttryB1stLAAD	539 189
3dBn3dMar (COC,FSCC,HST) (Leg Battalion)	589 225
3dPltCoA3dEngrBn	581 235
HCo3/3 (CP,FAC,ArtyFO, 81FO)	584 228
1stPltCoC3dTracks	583 230
NGFTeam2	584 229
3/3STADet1	584 228
ICo3/3 583 234	
2dPltCoC3dTracks	582 235
3/3STADet2	583 234

KCo3/3 583 234	
3dPltCoC3dTracks	583 239
81sPlt3/3	582 232
HvyGuns3/3	584 240
Dragons3/3	584 240
3dMarTOWSect3	589 239
Sect1BttryC1stLAAD	592 236

APPENDIX E. ANALYSIS JAMMER DATA

The table below lists the specific values for the two jammer objects that were modeled in the analysis example. These values are located in the "jammer.dat" file and can easily be changed using DB, the data base manipulation portion of MCCAAM. Any number of jammers can be modelled to produce a full range of interference for an architecture of interest. Only two jammers were modelled for our analysis example since we examined such a small portion of a MEB architecture.

VALUE	DESCRIPTION
2	Number of Jammers in File
USSR.KwikJam	Jammer Name
1	ID Number
504.0	X Coordinate
240.0	Y Coordinate
5000.0	Range (meters)
30.0	Jam Band Width Mhz
60.0	Sector Width (degrees)
15.0	Jamming Duration (mins)
45.0	TimeBetween Target Selection (mins)
xyzJammer	Jammer Name
2	ID Number
555.0	X Coordinate
216.0	Y Coordinate
6000.0	Range (meters)
40.0	Jam Band Width Mhz
60.0	Sector Width (degrees)
10.0	Jamming Duration (mins)
45.0	TimeBetween Target Selection (mins)

APPENDIX F. ANALYSIS RUN DATA

The table below lists the specific values for the global variables that were used in the analysis example. These values are located in the "c3run.dat" file and can easily be changed using DB, the data base manipulation portion of MCCAAM.

```
10000.00     Simulation Horizon
true     = send OBE Traffic
T     = (T/F) Do/Do Not model radio failures
T     = (T/F) Do/Do Not model jamming
     1     = # replications
  2    = # of allowed retries (in queue)
0.0000     = MEO duration variability in (0,1)
  1.0000     = Mean Acknowledgement Time
0.0000     = Acknowledgement variability in (0,1)
   1440.00     = time (mins) between freq changes
  8.00     = time (mins) to make freq changes
  2    = max retrials by a net
  2.00     = entry time for SINCGARS
  1.00     = entry time for PRC-77
  1.00     = entry time for PRC-77 on SINCGARS net
 15.00     = repair/replace time (mins) for PRC-77
 25.00     = repair/replace time (mins) for SINCGARS
 60.00     = jammer sector width in degrees
  5.00     = MIJI delay time
  5.00     = the time before retrying an impossible MEO
F    = the graphic presentation of the penalty process
4000.00     =  PRC mean time between failures (mins)
16000.00     = SINCGARS mean time between failures (mins)
4000.00     =  HF mean time between failures (mins)
```

APPENDIX G. RADIO ALLOCATIONS

The following table shows how the different types of radios were distributed for each of the four allocation schemes used in the analysis example:

Key: 0 PRC-77 radios
1 SINCGARS radios
2 HF radios

	AS1	AS2	AS3	AS4
MEB TAC 1	0	1	0	0
MEB Intel	0	2	2	2
3DMAR CMD	0	1	0	0
3DMAR INTEL	0	1	0	0
3DMAR FSC	0	1	0	1
3DMAR TAC	0	1	0	0
1/12 CMD	0	1	0	0
1/12 COF	0	1	0	1
1/12 FD	0	1	0	0
1/3 TAC 1	0	0	1	0
2/3 TAC 1	0	0	1	0
3/3 TAC 1	0	0	1	0
A 1/12 COF	0	0	1	1
B 1/12 COF	0	0	1	1
C 1/12 COF	0	0	1	1
N 5/11 COF	0	0	1	1
1/3 MORTAR	0	0	1	0
2/3 MORTAR	0	0	1	0
3/3 MORTAR	0	0	1	0

APPENDIX H. EXAMPLE TRACE FILE

The following pages give an example of the MCCAAM "c3log.out" file which was essential to all debugging efforts. By carefully placing output statements throughout the various implementation modules, we are able to track individual messages as they route through different nets.

Simulation Horizon = 1000.000 time units

```
--------simulation begins------
About to jam a unit
About to jam a unit
About to jam a unit

-----NEW BOST STARTING---------

getunit: location and membernum of input    1   1
asking timer to experience life
*********** Just Generated   StandardFireMission
* the time is now 0.000000
InterStimTime is: 41.7434
Didn't jam radio...freq. not in range
Didn't jam radio...freq. not in range
-----------------------------------
BtryFO  Receive bost: this unit's loc. =     1
intended receiver number is:      1
MEONum =        0
bost instance descriptor = StandardFireMission

-----------------------------------
getunit: location and membernum of input    1   1
getunit: location and membernum of input    1   1
we are the destination
hi from route, after operating on sender

\\\\\\\Point-to-Point Comm///////
```

finding potential receivers for MEO Receiver 1
receiver is a new player for this bost
net = 1
Unit attempting send is BtryFO
unit type AND RECEIVER NUMBER 3 1
finding potential receivers for MEO Receiver 2
receiver is a new player for this bost
net = 1
Unit attempting send is BtryFO
unit type AND RECEIVER NUMBER 4 2
Talking for receiver 1 on radio 0

BtryFO Receive bost: this unit's loc. = 1
intended receiver number is: 1
MEONum = 0
bost instance descriptor = StandardFireMission

Ghost radio in receive bost
RadioList[I] and I 0 1
cutting out of receive bost

===========Enter Net===============
this net is DsArtyBnFd number 2
entering unit BtryFDC
this net now has 1 subscribers.
===========Enter Net===============
this net is BdeFSC number 4
entering unit BdeFSCC
this net now has 2 subscribers.
unit is on the net at time 2.000000

===========Enter Net===============
this net is InfRegtTac number 5
entering unit RegtCoc
this net now has 2 subscribers.
unit is on the net at time 2.000000

===========Enter Net===============
this net is InfRegtCmd number 6
entering unit BdeCOC
this net now has 2 subscribers.
unit is on the net at time 2.000000

beginning wait for perishable, wait is 5.0000
THE TIME IS NOW 15.000

-----NEW BOST STARTING----------

getunit: location and membernum of input 1 1
asking timer to experience life
*********** Just Generated StandardFireMission
* the time is now 41.743357
InterStimTime is: 37.9275

BtryFO Receive bost: this unit's loc. = 1
intended receiver number is: 1
MEONum = 0
bost instance descriptor = StandardFireMission

----
getunit: location and membernum of input 1 1
getunit: location and membernum of input 1 1
we are the destination
hi from route, after operating on sender

\\\\\\Point-to-Point Comm///////
finding potential receivers for MEO Receiver 1
receiver is a new player for this bost
net = 1
UT1 1
UT1 2
UT1 3
Potential receiver BnFDC
UT1 4
Unique receiver determined, receiver is BnFDC
________in route___________
the RADIOLIST[I] = 1
the net used to transmit = 1
finding potential receivers for MEO Receiver 2
receiver is a new player for this bost
net = 1
UT1 1
UT1 2
UT1 3
UT1 4

Potential receiver BnFSCC
Unique receiver determined, receiver is BnFSCC
________in route___________
the RADIOLIST[I] = 1
the net used to transmit = 1
Talking for receiver 1 on radio 1
Talking for receiver 2 on radio 1
requesting that the bost work through radio 1
In the radio's request trans trying to reach net # 1
net is idle, so we tell it to xbp
in Execute busy period
net index = 1
MEONumToGo = 1
MEORec.MessageNumber = 1
getunit: location and membernum of input 3 1
getunit: location and membernum of input 4 1
0 th trial out of 2 beginning
IntendRec.IntendedReceiverNumber is 1
IntendRec.RadioNetRec.Unit name is BnFDC
----ACKNOWLEDGEMENT DELAY------
this receiver is BnFDC
netIndex for the SelectedRadio is 1
condition successful contact
IntendRec.IntendedReceiverNumber is 2
IntendRec.RadioNetRec.Unit name is BnFSCC
----ACKNOWLEDGEMENT DELAY------
this receiver is BnFSCC
netIndex for the SelectedRadio is 1
condition successful contact
----TRANSMISSION DELAY------
this receiver is BnFDC condition for receiver 1 is SUCCESSFUL CONTACT
this receiver is BnFSCC condition for receiver 2 is SUCCESSFUL CONTACT

BnFDC Receive bost: this unit's loc. = 3
intended receiver number is: 1
MEONum = 1
bost instance descriptor = StandardFireMission

----
getunit: location and membernum of input 3 1
getunit: location and membernum of input 3 1
we are the destination
meo not done yet

APPENDIX I. LIST OF ABBREVIATIONS AND ACRONYMS

AHP	Analytical Hierarchy Process
BOST	Broad Operational Sub Task
C2FAC	Command and Control Facility
C4I2	Command,Control,Communications,Computers, Intelligence
CDB	Communications Data Base
CSS	Combat Service Support
DCT	Digital Communications Terminal
DF	Direction Finding
DMA	Defense Mapping Agency
ECAC	Electronic Compatibility Analysis Center
ECCM	Electronic Counter-Counter Measures
ECM	Electronic Counter Measures
ERF	Electronic Remote Fill
EW	Electronic Warfare
FDC	Fire Direction Center
FM	Frequency Modulated
FO	Forward Observer
FSCC	Fire Support Coordination Center
HF	High Frequency
MACCS	Marine Air Command & Control System
MAGTF	Marine Air Ground Task Force
MAMES	Multiple Agency Message Exchange Occurrences
MCCES	Marine Corps Communications Electronics School
MCES	Modular Command & Control Evaluation Structure
MCTCA	Marine Corps Tactical Communications Architecture
MEB	Marine Expeditionary Brigade
MEF	Marine Expeditionary Force
MEO	Message Exchange Occurrence
MEU	Marine Expeditionary Unit
MIRC	MAGTF Interoperability Requirements Concepts
MOE	Measure of Effectiveness
MOP	Measure of Performance
MOT	Maturity Operational Test
MTACCS	Marine Tactical Command and Control System
O/A	Operational Assessment
OPFAC	Operational Facility
PLRS	Position, Location, Reporting System
RT	Receiver/Transmitter
SCR	Single Channel Radio
SINCGARS	Single Channel Ground and Airborne Radio System
SNR	Signal to Noise Ratio
SOP	Standard Operating Procedure

TIDP	Technical Interface Design Plan
TM	Threat Model
TO	Table of Organization
WFC	Warfighting Center

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