SIMULATION MODELING AND ANALYSIS OF MESSAGING SYSTEM OF A MECHANIZED INFANTRY BRIGADE

A THESIS

SUBMITTED TO THE DEPARTMENT OF

INDUSTRIAL ENGINEERING

AND THE INSTITUTE OF ENGINEERING AND SCIENCE

OF BILKENT UNIVERSITY

IN PARTIAL FULFILMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

MASTER OF SCIENCE

By
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August, 2003

I certify that I have read this thesis and in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

SIMULATION MODELING AND ANALYSIS OF MESSAGING SYSTEM OF A MECHANIZED INFANTRY BRIGADE

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August, 2003

The need of information on tactical battlefield will increase in future battles. Not only to gain information on battlefield, but also to convey it where it is needed on time, will be very important. The next generation mobile tactical communications systems will provide a robust, reliable, secure and flexible network to the mobile users of tactical battlefield. However, it is a question under interest to predict the impacts of different battle conditions on their performance.

In this study, a simulation study of messaging system of a model brigade in which mobile users employ TDMA (Time Division Multiple Access) radios and TDMA technique for channel access is conducted. The focus of this study is to construct a simulation model of a messaging system of a mechanized infantry brigade on tactical battlefield and to determine if the system is capable of supporting the data exchange in performance criteria under different conditions. Also, the factors that have significant effects on the system performance are investigated. The simulation is developed in Arena 7.0 simulation program and results are analyzed by using SPSS statistical package program.

Keywords : Simulation, messaging system, mobile wireless network

ÖZET

BİR MEKANİZE PİYADE TUGAYININ MESAJ İLETİM SİSTEMİNİN SİMÜLASYONLA MODELLENMESİ VE ANALİZİ

İbrahim CAN
Endüstri Mühendisliği Bölümü Yüksek Lisans
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Ağustos, 2003

Geleceğin muharebelerinde taktik muharebe sahasında bilgiye olan ihtiyaç artacaktır. Sadece muharebe sahasında bilgiyi elde etmek değil, aynı zamanda bilgiyi gerekli olan yere zamanında iletmekte önemlidir. Gelecek nesil mobil taktik muhabere sistemleri taktik muharebe alanındaki kullanıcılara sağlam, dayanıklı güvenli ve esnek bir iletişim ağı sağlayacaktır. Fakat, değişik muharebe şartlarının iletişim ağları üzerindeki etkisinin tahmini halihazırda araştırılan bir konudur.

Bu çalışmada mobil kullanıcıların TDMA (Zaman Bölmeli Çoklu Erişim) telsizlerini ve TDMA tekniğini kullandıkları bir örnek tugayın mesaj iletim sisteminin simülasyon çalışması yapılmıştır. Muharebe sahasındaki bir mekanize piyade tugayının mesaj iletim sisteminin simülasyon modelini kurmak ve bu sistemin değişik koşullarda performans kriterleri içerisinde veri alışverişini destekleme kabiliyetini belirlemek bu çalışmanın odak noktasıdır. Aynı zamanda sistem performansı üzerinde belirgin etkisi olan faktörler araştırılmıştır. Simülasyon Arena 7.0 simülasyon programı ile geliştirilmiş ve sonuçlar SPSS istatistiksel paket programı ile analiz edilmiştir.

Anahtar Sözcükler : Simülasyon, mesaj iletim sistemi, mobil kablosuz ağ

To Ebru, Umut and Kaan

ACKNOWLEDGEMENTS

I would like to express my deep gratitude to Prof. İhsan Sabuncuoğlu for his continuous guidance, attention, understanding, and patience throughout all this work.

I would like to thank to the readers Osman Oğuz and Yavuz Günalay for their effort, kindness and time.

I cannot fully express my gratitude and thanks to my family for their care, support and encouragement during preparation of this thesis.

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LIST OF ACRONYMS

ANOVA : Analysis of Variance

ATM : Asynchronous Transfer Mode

C4I : Command, Control, Communications, Computer and Intelligence

CBS : Corps Battle Simulation

CDMA : Code Division Multiple Access

DTSAP : Distributed Time Slot Assignment Protocol

GPS : Global Positioning System

FDMA : Frequency Division Multiple Access

LAS : Local Area Subsystem

LOS : Line of Sight

MRR : Multi Role Radio

MS : Mobile Subsystem

MST : Mobile Subscriber Terminal

MTWS : Marine Tactical Warfare Simulation

PST : Personal Subscriber Terminal

RAP : Radio Access Point

ROBC : Ratio of Blocked Calls

ROTC : Ratio of Terminated Calls

ROUD : Ratio of Unreachable Destinations

SMSC : System Management and Control Subsystem

TACOMS : Tactical Communications

TDMA : Time Division Multiple Access

WAS : Wide Area Subsystem

CHAPTER 1

INTRODUCTION

The success of military operations on today's tactical battlefield is closely related to the C4I (Command, Control, Communications, Computer and Intelligence) concept. Gathering, exploiting, and protecting information is critical from the view of C4I concept. To achieve the C4I functions such as maneuver control, fire support, air defense, electronic warfare and intelligence on the tactical battlefield efficiently, the existence of a secure, robust, reliable and mobile communications infrastructure is very important. This communications infrastructure should be capable of conveying messages, data, imagery, and video files as well as voice communications among the fixed and mobile components of the battle forces in a secure, and timely manner.

Historically, the components of the battle forces communicated with each other by simply speaking or delivering messengers. As the telephone and radio were introduced, the soldiers and commanders could be able to communicate more quickly in real-time and over long distances. Advances in technology affect the way that the warfare is conducted. As a result of recent improvements in information, computers and communications technology such as broadband networks, digital cellular systems, wireless computer networks, evolving computer systems, global positioning and other technologies opened new horizons in the communications systems. Electronic mail, cellular telephone for voice and data, vehicle position reporting/tracking systems, and many other products have appeared. With these evolving technologies, today, the efforts to reach the goal of "digitizing the battlefield" increased. Digitization is defined as near-realtime transfer of battlefield information between different fighting elements to permit a shared awareness of the tactical situation. Digitization of the battlefield is a viable solution for managing C4I information. "Digitizing the battlefield is the application of information technologies to acquire, exchange, and employ timely digital information throughout the battlespace, tailored to the needs of each decision maker (commander), shooter, and supporter, allowing each to maintain a clear and accurate vision of his battlespace necessary to support both planning and execution" (Driscoll, Impson, Kupst, Mehravari, Rush, 1999).

To be successful in battle, commanders must be able to make good decisions quickly. Digital information systems enhance the commander's ability to have an understanding of the current state of friendly and enemy forces and maintain the ability to see and understand the dynamic relationships between friendly and enemy forces. The intelligence about the battlefield such as the strength and placement of the enemy, the geographical positions of friendly troops are tracked and analyzed with computers and, again these computers can be used to pass the information between components of the battlefield. Through digital information exchange, systems can automatically share information between platforms and weapon systems, including relative positioning, targeting, and support. These improvements will significantly impact future military operations by providing warfighters and decision makers with accurate information in a timely manner. Integrated and digitized information systems of the future will permit commanders and decision makers to access critical information from any point on the battlefield and this situational awareness permits them to make timely decisions.

In our thesis, we develop a simulation model of the messaging system of a Mechanized Infantry Brigade on the battlefield. In the messaging system, information in forms of messages, reports and plans are accomplished with personal computers. GPS information is automatically updated, giving subordinate units complete knowledge of the friendly situation; thus a common view of the battlefield. The multimedia (video, imagery) is one of the most important part of this information. The users of the system are mobile and use Time Division Multiple Access (TDMA) radios to send this data. We examine the behavior of the messaging system to determine if it is capable of supporting the needs of the users in the battlefield. We also investigate the significant factors that affect the system performance and their relationships. Finally, we evaluate the system under different types of operations.

The outline of the thesis is as follows : In Chapter 2, brief information about tactical communications and wireless networking is presented and the system is described. In Chapter 3, a review of the literature with the simulation software and the simulation methodology is given. In Chapter 4, the simulation model is explained in details and validation and verification of the model is discussed. The results of the output analysis and experimental design are presented in Chapter 5. In Chapter 6, we model different scenarios, and finally concluding remarks and future research directions are given in Chapter 7.

CHAPTER 2

SYSTEM OVERVIEW

In this chapter, we give a brief information about the tactical communications systems on the battlefield, the wireless networking, routing and channel access in networks and finally, we describe the messaging system of the mechanized infantry brigade.

2.1. Tactical Communications Systems

The tactical communications systems on the battlefield are complex systems. The theater of war may be very large, it may include multiple theaters of operations. There may be many communication systems involving satellite communications in the theater. However, we are only interested in the communications that take part in battlefield. Thus, we focus on the communications systems on the battlefield. The subscribers of the communication systems on tactical battlefield may be command centers, infantry men, tanks, armored or other vehicles, sensors, fire support units, air defense units, antitank units, aircrafts, helicopters, etc. All these units have different characteristics in many aspects.

Today's tactical communication systems should have the following characteristics:

– It should be mobile, easily and rapidly deployable. The subscribers of the communication systems on tactical battlefield have very different mobility patterns. Some of them may be fixed in location, although some may move very fast.

- It should have electronic protection measures and provide a high level of protection against electronic warfare threats such as interruption or jamming by the enemy.

- The tactical battlefield communications occur in an unfriendly and hostile environment. There are always risk of to be destroyed. It should provide a robust and survivable network to its users.

- It should support multimedia communications, such as data, imagery and video, as well as voice communications.

- It should be highly reliable and should perform in difficult weather and terrain conditions.

- It should be integrable with other communications infrastructures.

There are many researches that have been made about the next generation tactical communications systems. Figure 2.1 illustrates the architecture of the next generation tactical communications systems which is derived from Post-2000 Tactical Communications (TACOMS) efforts (Quan and Sive, 1995).

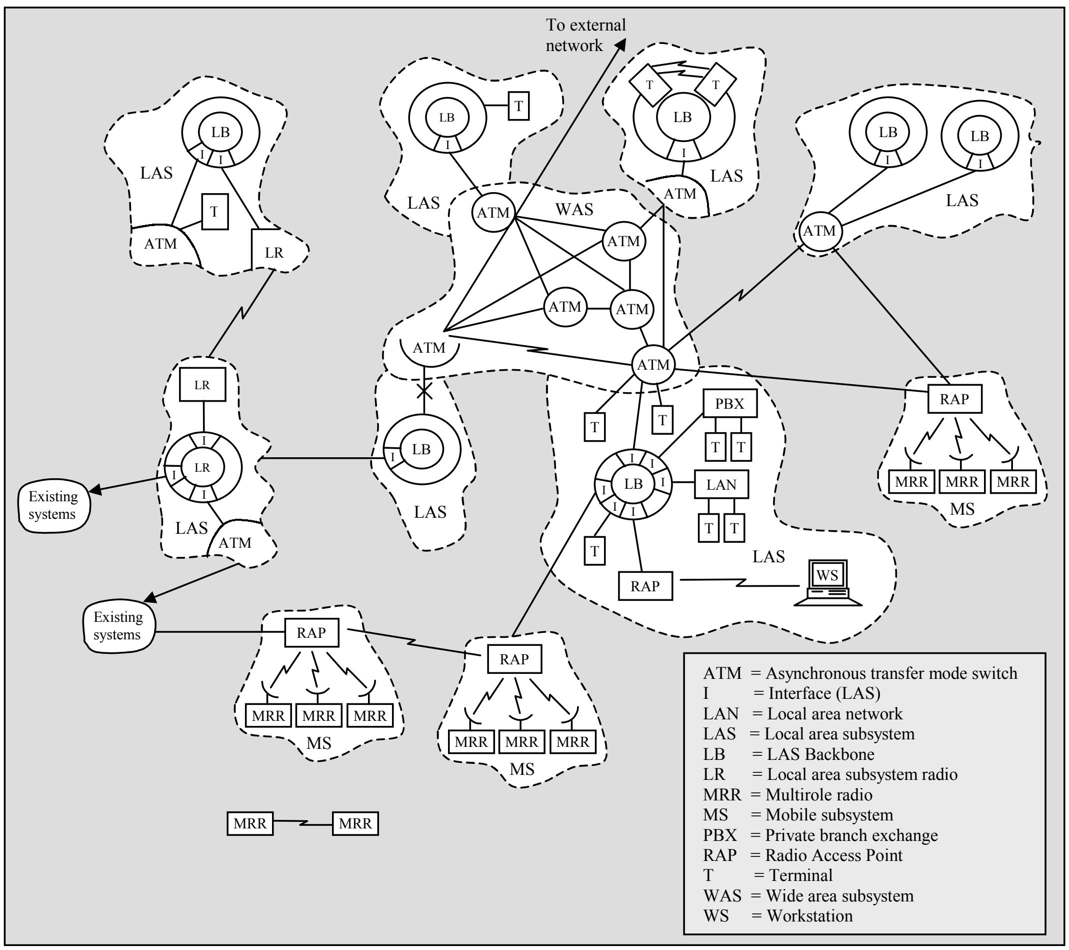


Figure 2.1. The architecture of the next generation tactical communications systems (Quan and Sive, 1995)

This architecture has four subsystems:

- The Wide Area subsystem (WAS)
- The Local Area Subsystem (LAS)
- The Mobile Subsystem (MS)
- The System Management and Control Subsystem (SMSC)

The WAS is the backbone of the system. It connects multiple LASs into a single larger network. It provides a transit function to LAS and MS users the tactical communications system. The WAS is formed of nodal points. Asynchronous Transfer Mode (ATM) is selected as the multiplexing and switching architecture of this subsystem.

The LAS supports local and internal communications of users in a geographical restricted area (e.g., headquarters). The LAS backbone provides mobile and wired communications of the overall system. It is modular in design and can be configured for various network topologies. The LAS provides users access to the WAS, interface to the strategic systems, and connection to commercial networks. The LAS is formed of Radio Access Points (RAPs). The RAP constitutes a gateway for the mobile users of the Mobile Subsystem (MS). The LAS may be wireless because of the requirement of mobility at the lower echelons such as brigades. This will limit the throughput and system facilities confined to transportable equipment such as vehicles. Where mobility is not vital, the LAS may be configured via cabling using fiber optic cables where throughput can be measured in the gigabit per second range.

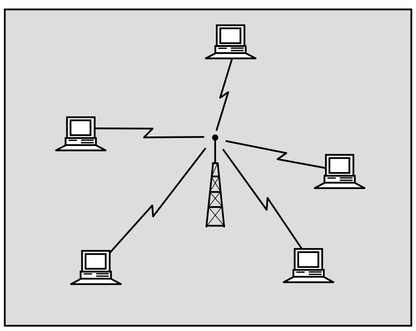
The MS is the subsystem that supports the mobile users. It may operate as an independent network or as a part of the overall tactical communication system. The MS supports three modes of operations: combat net radio, mobile telephone, and packet radio. The two major components in the MS are multi-role radio (MRR) and radio access point (RAP). The MRR will integrate user services (voice, data, imagery) including position and navigation.

In addition to these subsystems, the SMCS carries out the system management functions such as system planning, control and management. The SMCS is not a separate subsystem but is integral to the architecture.

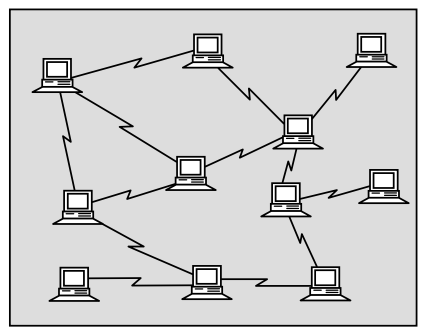
2.2. Wireless Networking

A wireless network is a set of devices with wireless adapters communicating each other using radio waves. Based on the network architecture, wireless networks can be broadly classified into two categories.

Centralized Networks : In centralized networks mobile users are connected to the fixed network with the help of a common receiver (e.g. a base station). The base stations act as the interface between wireless and wireline networks. In such a centralized topology, the base station is a common receiver that can hear all transmissions in the network. A typical centralized network is illustrated in Figure 2.2.



a) A centralized network



b) A distributed network

Figure 2.2. Centralized and Distributed Networks

Distributed Networks : Distributed networks, also known as ad hoc networks, are self-organizing networks where there is no need to a predetermined topology or a pre-existing infrastructure. A typical distributed network is illustrated in Figure 2.2. An ad hoc network has no central administration. We can classify ad hoc networks as single hop and multi hop ad hoc networks. In a single hop ad hoc network, only the mobile users that are within radio distance to each other can be connected. Mobile radio networks, including vehicular mounted and hand-held units, are classical examples of single hop ad hoc networks. Besides, in a multi hop ad hoc network, nodes can relay the messages, messages hop over several intermediate nodes in order to arrive at their destinations, since not all pairs of nodes communicate directly. This gives rise to routing issues i.e., which of the receiving users should forward a received packet towards its destination. Thus, the network connectivity increases by an order of number of hops allowed. In a multihop ad hoc network, each user is in reception range of only a subset of the users and similarly the transmission of a user is heard by a subset of all users. A transmission is successful only if it is the only transmission currently being heard by the receiving node. Multihop networks appear naturally in radio networks with low powered transmitters or in interconnected local area networks.

Ad hoc networks can be interconnected to other networks as well as they can operate themselves. Since they have the ability of self-organizing, they represent robust, flexible, rapidly deployable network characteristics which are the basic requirements of tactical battlefield communication systems.

There are many networking concepts in an ad hoc network. Some basic networking functions are; channel access, switching, routing, flow control, speed and code conversion, network management, and so on. Within the limited scope of this thesis, we will only consider the functions of channel access, switching and routing.

2.2.1. Channel Access

In an ad hoc network, a communications channel is shared by a number of independent users. When sharing a channel, there is a need to deal with conflicts. Accessing the channels can be achieved by random access schemes, fixed channel assignments to the resources or using dynamic channel access algorithms. Since we are dealing with wireless communications, one of the most important constraints is that the bandwidth is limited. To use the bandwidth efficiently a multiple access scheme required. There are many multiple access protocols in the literature. Therefore, we will not mention all multiple access protocols here. Instead, we will classify these protocols and mention shortly about classes. Figure 2.3 shows a classification of wireless multiple access protocols (Rom and Sidi, 1990).

Firstly, we can classify these protocols as conflict-free and contention protocols. In conflict-free protocols, a transmission will not be interfered by another transmission. Conflict-free transmission can be achieved by allocating the channel to the users either statically or dynamically. Static allocation means to allocate the channel resources from a time, frequency, or mixed time-frequency standpoint.

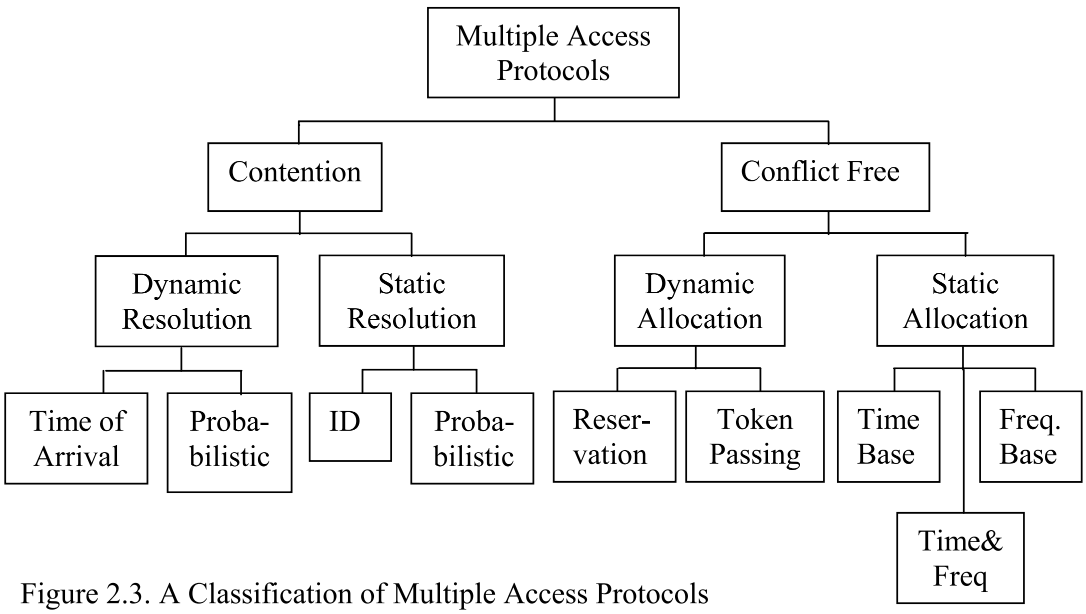


Figure 2.3. A Classification of Multiple Access Protocols

In Time Division Multiple Access (TDMA) the entire frequency range (bandwidth) is allocated to a single user for a fraction of the time. In Frequency Division Multiple Access (FDMA) a fraction of the frequency range is allocated to every user all of the time. In Code Division Multiple Access (CDMA) the entire bandwidth is allocated to all users, but the signals are distinguished by spreading them with different codes.

In contention-based protocols, a transmission may be interfered by another transmission. In this case, a conflict occurs. So, these protocols should describe a way to resolve conflicts when they occur. We can classify contention-based protocols as dynamic resolution and static resolution in respect to how they resolve conflicts. In static resolution, a conflict is resolved by user ID's or any other fixed priority assignment. In ID static resolution, whenever a conflict occurs, the user with the smallest (or highest) ID will transmit a message first. In probabilistic static resolution, the transmission schedule for the interfering users is chosen from a fixed distribution to decide which users will complete transmission first. In dynamic resolution, resolution can be based on time of arrival by giving highest (or lowest) priority to the oldest message in the system. Alternatively resolution can be probabilistic but this time transmission schedule for the interfering users is chosen from a distribution function that changes dynamically.

Since, we use TDMA in our system we will not give more details about the channel access schemes other than TDMA.

2.2.2. Time Division Multiple Access (TDMA)

In the time division multiple access (TDMA) the time axis is divided into time slots. Each user transmitting data is allocated one or more time slots. The slot assignment repeats itself periodically and each such period is called a frame. All users share the same frequency band and can transmit data using entire bandwidth during their allocated time slots. An example of allocation of time slots is presented in Figure 3.4.

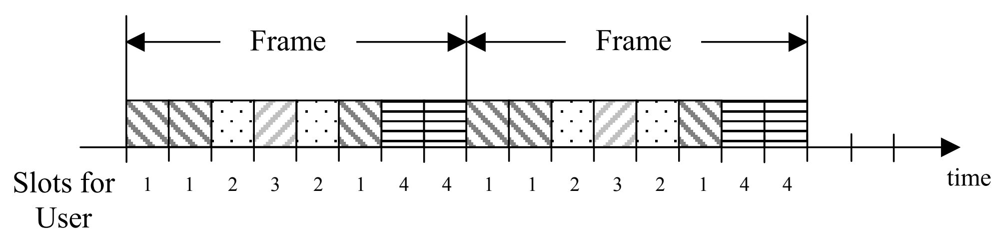


Figure 2.4. TDMA Slot Allocation

In the above figure the frame consists of 8 slots and 4 users share the channel. Slots 1,2 and 6 are allocated to user-1, slots 3 and 5 to user-2, and slot 4 is allocated to user-3 and slots 7 and 8 are allocated to user-4.

In TDMA scheme, the users must be synchronized in order to observe the same time reference and transmit at the boundary of a time slot. Thus, each user must know exactly when and for how long it can transmit.

2.2.3. Routing

There are many routing protocols in literature. These routing protocols may generally be categorized as table-driven and source-initiated (demand-driven) routing protocols.

Table-driven routing protocols attempt to maintain consistent, up-to-date routing information from each node to every other node in the network. These protocols require each node to maintain one or more tables to store routing information, and they respond to changes in network topology by propagating updates throughout the network in order to maintain a consistent network view. The areas in which they differ are the number of necessary routing-related tables and the methods by which changes in network structure are broadcast.

A different approach from table-driven routing is source-initiated on-demand routing. This type of routing creates routes only when desired by the source node. When a node requires a route to a destination, it initiates a route discovery process within the network. This process is completed once a route is found or all possible route permutations have been examined. Once a route has been established, it is maintained by a route maintenance procedure until either the destination becomes inaccessible along every path from the source or until the route is no longer desired.

2.3. System Description

In this study, we construct a model of a messaging system of a mechanized infantry brigade and conducted a simulation for the first day of a combat. A mechanized infantry brigade is a combination of mechanized infantry battalions, armor battalions and other supporting units grouped under the command of a brigade headquarters. In the brigade structure that we model, there are a Brigade Headquarters, a Communications Company, an Antitank Company, an Engineer

Company, an Air Defense Battery, an Artillery Battalion, two Mechanized Infantry Battalions, and two Armor Battalions. The organizational chart of the brigade is given in Appendix A.

There are many types of data including voice over radio, orders, operations plans, reports, maps, real-time video files, etc. that the users will exchange in the system. However, we classify these data into four groups as voice calls, messages, real-time video, and other data files. The transmission speeds for different data types and needed data channel numbers to send the data are given in Table 2.1.

Table 2.1. Transmission speeds and needed data channel numbers

Type	Transmission Speed	Needed Channel Numbers
Voice Call	4.8 Kbps	2
Message	9.6 Kbps	4
Live Video	64 Kbps	24
Other Data File	9.6 Kbps	4

2.3.1. Communication Devices in The System

All units in the brigade messaging system use mobile subscriber terminals (MST) or personal subscriber terminal (PST). A MST is a terminal which is used for both voice and data communications. It is generally mounted on a vehicle. Also, it may be connected to a computer to send data, multimedia or imagery. MSTs transmission range is maximum 10 km in the line of sight (LOS). A PST is a terminal which has the same features with MST except output power, transmission range and dimensions. Its transmission range is maximum 2 km in the line of sight. A Radio Access Point (RAP) is the gateway from LAS network to the WAS backbone. Units reach the subscribers of other networks via RAP.

All units use TDMA scheme to access the channel. Units using the same frequency band can communicate with units that are in theirs transmission ranges. Units can form a radio network automatically in the tactical field and provide integrated communication services to all the users of the network. All the radio network management functions are carried out in a distributed fashion without the need for centralized management. Also, units can act as a relay to the voice or data connections of other units without interrupting communication services to its own user. A maximum of 3 hops can be used for voice calls and 5 hops for data connections, while real-time video is only available for the destinations in the transmission range. The multi-hop feature extends the range of mobile communications and increases the survivability of the radio network.

Units contain internal GPS receivers and obtain position location information from the GPS system. The GPS information is automatically distributed in the network. This enables the formation of the real-time picture of the battlefield which is made available to the tactical commanders.

2.3.2. Routing in The System

We used a distributed asynchronous version of Bellman-Ford algorithm which is in the class of table-driven routing protocols in our study. In this protocol, each user holds a routing table containing the length of the shortest path to the every destination in the network. An update packet is broadcasted by a node when a topological change is detected. This packet consists of only changing nodes. Every node updates its routing table according to this information. When an update packet is received from a neighbor node, an acknowledgement of the update packet is sent to the neighbor node. This process will be repeated until all the nodes have updated their routing tables. Also, each node broadcasts its routing table periodically. The update data is kept for a while to wait for the arrival of the best route.

2.3.3. Channel Access in The System

We use distributed time slot assignment protocol (DTSAP) (Pond and Li, 1995) for channel access. DTSAP is in the class of conflict-free, dynamic allocation, reservation based, multiple access protocols. The frame structure is given in Figure 2.5.

In this structure every unit has its own control channel which is designated by RAP. In control channel the unit broadcasts its position information and call related information to the network. A frame consists of 28 data channels.

Using DTSAP, transmission of data or making a voice call occurs in a two-stage procedure. In the first stage, a connection between source and destination node is established and in the second stage data is transmitted through the route or voice call is made.

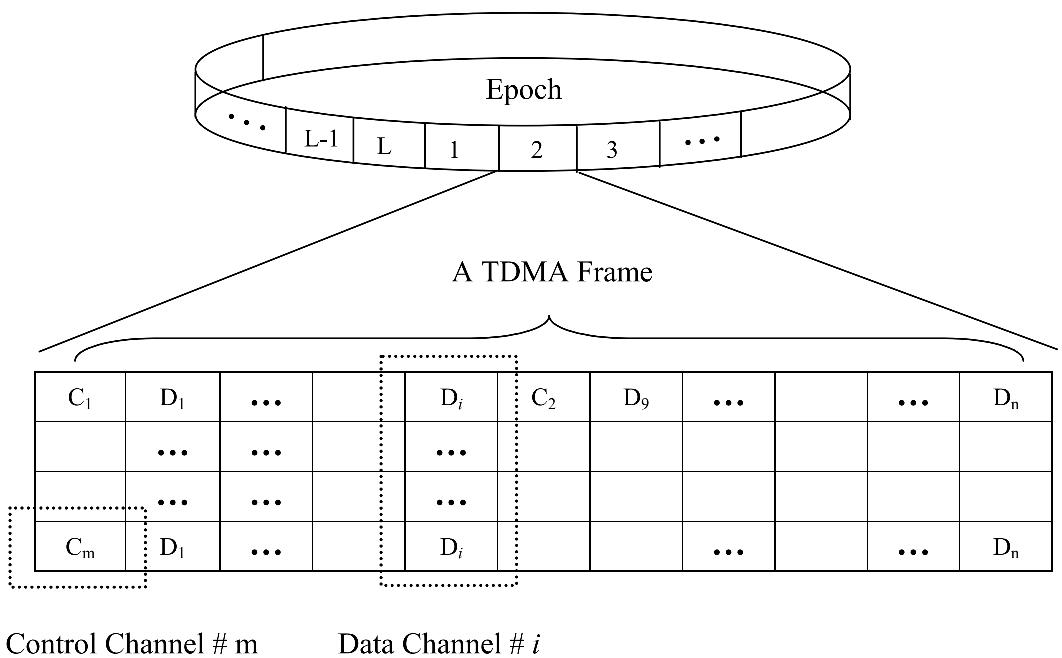


Figure 2.5. The frame structure

When a node wants to make a connection with destination node, it first sends a connection request packet to the destination node if it is in transmission range, or to the next hop in the route to the destination if it can be reachable in allowed number of hops. This call request packet involves the address of the destination node, number of the channel needed and the data channels that the node cannot broadcast and receive.

Upon receipt of connection request packet, the relay unit selects the channels for transmission under following constraints:

– The source node and relay unit cannot broadcast or receive from the data channels dedicated for other transmissions.

– The source node cannot broadcast from the data channels that its neighbors receive and the neighbors of relay unit broadcast.

– The source node cannot receive from the data channels that its neighbors broadcast.

– The relay unit cannot broadcast from the data channels that its neighbors receive and the neighbors of the source node broadcast.

– The relay unit cannot receive from the data channels that its neighbors broadcast.

If the channels are available, it sends a connection confirmation packet that includes the selected data channels. Otherwise, the connection request is rejected.

If the relay unit is not the destination, it starts the next leg of the connection towards the destination node. After a connection is established, the destination node sends a call accepted packet back to the source using data channels. After the call accepted packet is received, the source node starts transmission of data. The communications between source and destination node is full duplex which means the source and destination node can send data to each other simultaneously. At the end of every packet the destination node, if it has successfully received the packet, will return an ACK (acknowledgement) packet to the source node. The source node will retransmit the packet if it had not received an ACK packet after a defined period.

When a node detects a new neighbor during transmission, it sends a resolve conflict packet, its time slot assignment table and its routing table to the new neighbor. The neighbor terminates all connections that have a conflict and it broadcasts its revised routing and time slot assignment tables in its control channel. All nodes updates their routing tables according to new topology.

After all data transmitted or if a node determines that it has no longer connected to a node in the route, to terminate the connection, source node sends a clear request packet in the data channel. Upon receipt of clear request, the destination node and the nodes on the route sends a clear confirmation packet from their control channels consecutively, and the neighbors update their tables. This completes the data transmission.

CHAPTER 3

LITERATURE REVIEW

In this chapter we investigate the studies and researches that are related with analysis of tactical communications systems on the battlefield via simulation. We review these studies and researches under following topics:

• Simulation software and methodology

• Military simulation

• Tactical communications simulation

3.1. Simulation Software and Methodology

In this section, we first give a brief information about simulation software used to model communications. Then, we present a literature review on validation, verification and accreditation, output analysis of a simulation model and experimental design studies. There are many simulation software products to model communications. We use ARENA 7.0 and its output analyzer, since it has the desired properties for modeling our system. It has the modeling flexibility such that it can be used both for combat modeling and modeling communications. It also has an interactive debugger that helps to verify our model. The output analyzer is used to display and analyze model data after the simulation runs have been performed. It provides analysis features such as confidence intervals, analysis of variance, plots, correlograms, histograms, and more.

Balcı (1990) provides guidelines for conducting a successful simulation study. In the paper, the guidelines are provided throughout the entire life cycle of a simulation study.

Law and McComas (1994) define the types of simulation software that are available for network analyses. Three major types for simulating communications networks are general-purpose simulation languages, communications-oriented simulation languages and communications-oriented simulators. The major advantage of using a general-purpose simulation language is its ability to model almost any kind of communications network. Possible drawbacks as compared to some simulators are the need for programming expertise and possibly long time spent coding and debugging. Arena, BONeS DESIGNER, GPSS/H, MODSIM II, SES/workbench, SIMAN/Cinema V, SIMSCRIPT II.5 and SLAMSYSTEM are examples of simulations languages. OPNET Modeler is an example of communications-oriented simulation language. BONEs Planet, COMNET III, L.NET II.5 and NETWORK II.5 are examples of basic simulators.

Later, Law and McComas (1996) discuss how simulation is used to design and analyze communications networks. They present an overview of the use of simulation in the design and analysis of communication networks.

Takus and Profozich (1997) explain the ARENA software and its capabilities in their tutorial. They provide a basic overview of the ARENA simulation system.

Balcı (1998) presents guidelines for conducting verification, validation and accreditation of simulation models. Fifteen guiding principles are introduced and 77 verification and validation techniques are shown for the major stages of modeling and simulation life cycle.

Chang (1999) discusses several network simulators and presented OPNET in detail. Some examples of academic simulators discussed in this study are REAL, INSANE, NetSim and Maisie network simulators. Other examples include NS-2, VINT, U-Net, USC TCP-Vegas test-bed and Harvard simulator.

Kleijnen (1999) gives a survey on how to validate simulation models through the application of statistical techniques, such that the type of technique actually applied depends on the availability of data on the real system.

Sargent (2000) discusses validation, verification and accreditation of simulation models. In the paper different approaches to deciding model validity is presented and various validation techniques are defined.

Law and McComas (2001) present a seven-step approach for conducting a successful simulation study and discuss techniques for developing a more valid and credible simulation model. They also give guidelines for obtaining data in simulation studies.

Rathmell and Sturrock (2002) introduce the Arena suite of products for modeling, simulation, and optimization highlighting product architecture and technology features that are targeted toward successful deployment of simulation in their paper.

3.2. Military Simulation

In this section, we briefly present the research studies in the area of military simulations.

Mertens (1993) discusses the Corps Battle Simulation (CBS) which is a discrete event simulation system that was developed for use in military training exercises. He explains CBS development history, development cycle, capabilities and software arcitecture in the paper.

Garrabrants (1998) proposes an expansion of simulation systems' roles to support all levels of command and control functioning. In the paper, he explains how Marine Tactical Warfare Simulation (MTWS), an advanced simulation system, is used to model all aspects of combat and gives detailed information about its usage.

Page and Smith (1998) give an overview of military training simulation in the form of an introductory in their tutorial. In the paper, basic terminology is introduced, and current trends and research focus in the military training simulation domain are described.

Smith (1998) identifies the essential techniques necessary for modern military training simulations. The paper provides a brief historical introduction, discussions of system architecture; simulation interoperability; event and time management; distributed simulation; and verification, validation, and accreditation.

Kang and Roland (1998) stress on the differences of military simulation and classify the military simulation models in their study. They provide some explanations about simulation as a training tool and also mention a war-gaming model of joint theater level simulation.

Grabau and Payne (2000) present a model and an analysis done to predict enemy force closure. The model provides planners with the capability to assess critical factors: transportation network constraints, equipment reliability and maintainability, varying task times, nighttime operations, and the effects of air interdiction. They discuss war planning implications and notional results.

Hill, Miller and McIntyre (2001) discuss the applications of discrete event simulation modeling to military problems, the uses of military simulation and the issues associated with military simulation. Then, they focus on three particular simulation studies undertaken with the Air Force Institute of Technology's Department of Operational Science.

3.3. Tactical Communications Simulation

In this section, we give the information about the existing studies on simulation of tactical communications.

Quan and Sive (1995) discuss the NATO Post 2000 tactical communications architecture and standards, the objective and background of the project and the supporting technology. The architecture's performance was modeled via simulation and some of the results are presented in the study.

Harrington, Josephson and Paclik (1997) discuss the efforts to identify critical users requirements, enabling technologies and model their effects on the 21st century tactical warfighter communications environment. In the study a set of candidate network architecture was developed around the critical enabling technologies and user requirements then modeled using a network simulation tool.

Vigneron and Moreland (1999) describe a scheme for data transmission using a combat–net mobile radio for use on land. They present the simulation of data transmission with radios for communications in a terrestrial mobile environment.

Sanchez, Evans and Minden (1999) present some of the system level challenges encountered in highly dynamic multi-hop wireless networks that include mobile base stations and mobile hosts on battlefield. They focus on topology management, location management and routing management challenges in particular.

Hall, Surdu, Maymi, Deb and Freberg (2001) construct a model of the Land Warrior system from the soldier level to company command level using OPNET software. Land Warrior system is a project in US Army that provides each soldier in an infantry squad with a wearable personal area network consisting of various sensors, a radio system and a computer system, designed to enhance the individual soldiers awareness of his own situation and that of its units.

Maymi, Surdu, Hall and Beltramini (2002) construct a simulation study to determine the communications architecture of Land Warrior was sufficiently scalable to use in large Army units and describe the development of the simulation model used to determine the scalability of Land Warrior communications architecture. We give a summary of literature review in Table 3.1.

Table 3.1. Summary Table of Literature Review

	PUBLICATION	SUBJECT
Simulation Software and Methodology	Balcı (1990)	Guidelines for successful simulation studies
	Law and McComas (1994)	Simulation software for communications networks
	Law and McComas (1996)	Design and analysis of communication networks
	Takus and Profozich (1997)	Arena software tutorial
	Balcı (1998)	V&V&A of simulation models
	Chang (1999)	Network simulations with OPNET
	Kleijnen (1999)	Statistical techniques and data availability
	Sargent (2000)	V&V&A of simulation models
	Law and McComas(2001)	Building valid and successful simulations model
	Rathmel and Sturrock (2002)	Arena suite of products
Military Simulation	Mertens (1993)	Corps battle simulation system
	Garrabrants (1998)	Simulation as a mission planning tool
	Page and Smith (1998)	Overview of military training simulation
	Smith (1998)	Essential techniques for modern military simulation
	Kang and Roland (1998)	Military simulation
	Grabau and Payne (2000)	A model to predict enemy force disclosure
	Hill *et.al.* (2001)	Application of discrete event simulation modeling to military problems
Tactical Com. Simulation	Quan and Sive (1995)	Post-2000 Tactical communications system
	Harrington *et al.* (1997)	Modeling the 21st century tactical communications networks
	Gneron and Moreland (1999)	A scheme for data transmission using a combat-net radio
	Sanchez *et al.* (1999)	Challenges in dynamic wireless networks
	Hall *et al.* (2001)	Modeling the communications capabilities of the infantry soldier
	Maymi *et al.* (2002)	Modeling the wireless network architecture of land warrior

CHAPTER 4

SIMULATION MODEL

4.1. Formulation The Problem And Planning The Study

In this study, simulation is used to evaluate the messaging system of a Mechanized Infantry Brigade. The objectives of this study are to;

a) develop a simulation model of a brigade messaging system,

b) examine the behavior of the communication system to determine if it is capable of supporting the messaging needs under different conditions for various performance measures,

c) analyze the effects of the model parameters on the performance,

d) establish the nature of the relationships among input factors and system responses,

e) compare system responses under different circumstances.

In case that the existing system does not operate properly, we will try to identify the bottleneck factors and improve the conditions. Specifically, we will answer the following questions via simulation:

- How efficient is the system in terms of the performance measures?
- Does there exist a bottleneck in the system ?
- What happens if we change the number of MSTs and PSTs in the system ?
- What are the relationships between performance measures?
- How will the system perform when traffic load increase?
- Which factors have significant effects on the system performance?
- What are the relationships between significant factors?
- How will the system perform in different types of operations?

4.2. Why Simulation ?

It is always desirable to obtain answers to the questions by analytical solutions. But, because of the complex nature of the system and dynamic/stochastic elements, simulation model is used to model and analyze the system.

First of all, the tactical communication system under consideration has many stochastic elements such as, the call arrival rates varies for each user, the destruction of users may occur at an unknown time, the channel capacities differs according to the geographical position of users.

There are many analytical studies for queueing systems of communication networks. But the systems are mostly continuous and the state variables change continuously over time. Thus, the mathematical procedures of these analytical solutions are very complex for our network. Only steady-state results are possible for these systems. Also, it is very difficult to obtain estimates of parameters other than mean values.

Because of economic reasons and difficulties creating real world conditions, it is almost impossible to exercise the systems in the field, either. Thus, to answer a wide variety of "what if" questions is a major issue. Simulation enables us to analyze different policies and system alternatives in our study. Once a model is built, it can be used repeatedly to analyze different policies, parameters or design alternatives and answer several other questions. Simulation can also quantify the difference between the alternative systems and helps to see their advantages or disadvantages.

Consequently, for all of these reasons, simulation is the appropriate tool for our study.

4.3. Model Development

To build the model we first observe the real system and the interactions among its various components and collect data on its behavior. Then we construct a conceptual model (a collection of assumptions on the components and the structure of the system, plus hypotheses on the values of model input parameters) by carefully determining the level of details. After all, we translate the operational model into the computerized model. The stages of the model development process are given in Figure 4.1.

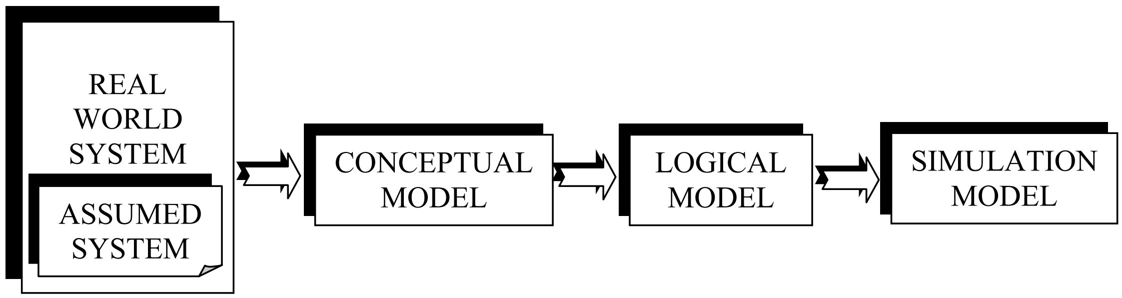


Figure 4.1. The stages of model development process

When developing a simulation model, determining the correct level of detail for the model is very important. The simulation model should have enough details to represent the real world system. There is always a trade off between accuracy and cost of the model and level of details (Figure 4.2).

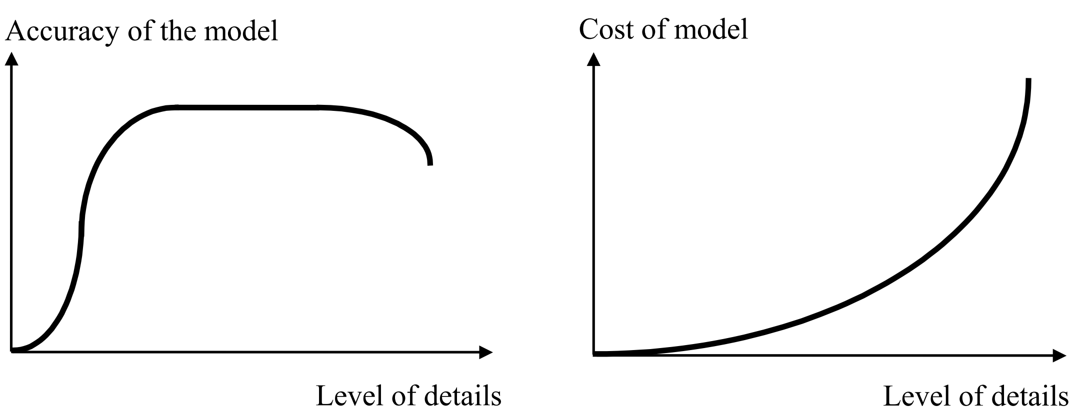


Figure 4.2. Relationship between accuracy and cost of the model and level of details (Taken from Sabuncuoğlu, 2003)

The challenge is to identify appropriate level of details so that the model can answer to the questions under consideration. Lack of details usually causes wrong answers to the questions, while, too much detail requires more time and efforts, longer simulation runs, and it is more likely to make errors. Also, it is more difficult to debug and make changes.

4.3.1. Conceptual Model

Conceptualizing a model is one of the important phases of model development. A conceptual model provides an organized way for an analyst to document the system of interest. We create conceptual models of these real world systems to examine the essential components and structures of the real world systems under consideration. Then the basic elements of this simulation model are determined by the certain characteristics, components and the structure of the assumed system. By the help of the conceptual model, we understand main structure of the system and focus on the essential components of the system. Only objects necessary for understanding of the system need to be documented. A conceptual model is not intended to be a design for a system to simulate the real world.

During conceptualization, we interview with military experts and gather enough data about real systems, then we construct the logical model (flowchart) of the systems to show relationships among the elements of the models. The code of simulation model is written by using the Arena 7.0 simulation program (the latest version of ARENA).

Conceptual model contains elements of the real system, which should be included in our model. These include events, entities, attributes, exogenous variables, endogenous variables, operational rules, initial conditions and assumptions of the existing system. The basic elements of the simulation model is given below:

<u>Entities :</u> An entity is an object of a interest in the system which requires an explicit representation in the system. In our system, entities are ;

- Voice calls
- Messages
- Live video files
- Other data files.

<u>Attributes :</u> Attributes are the characteristics of an entity. Our attributes are ;

- Source node

- Destination node
- Source RAP
- Destination RAP
- Maximum hop number
- Call duration

Events : An event is an instantaneous occurrence that changes the state of the system. The events of the system are ;

- Destruction of nodes : Any unit of brigade which is destructed cannot send or receive data.
- Call request : When a call request is done to a user, it make a transition to call establishment state.
- Call establishment : When a call is established, the data channels that are used make a transition to busy state.
- Clear request : When a clear request is done to a user, the data channels that are used make a transition to idle state.

Activities : An activity is a time period in which the state of an entity does not change.

The activities of the system are ;

- Call establishment
- Transmitting

Input Variables

a. Controllable Variable

- Number of MSTs
- Number of PSTs
- Number of RAPs
- Velocity of nodes

- Direction of nodes
- Weather and terrain conditions

b. Uncontrollable Variables

- Call establishment time
- Call duration

Output Variables

a. State Variables

- State of MSTs (idle, busy, destroyed)
- State of PSTs (idle, busy, destroyed)
- State of RAPs (idle, busy, destroyed)

b. Performance Measures

- Number of rejected calls because of insufficient data channels
- Number of rejected calls because of unreachable destinations
- Number of terminated calls because of unreachable destinations
- Total number of calls
- Ratio of Terminated Calls
- Average message delivery time
- Average call establishment time
- Unit utilization
- Channel utilization
- *Ratio of Unreachable Destinations (ROUD)* : is the ratio of number of the calls rejected because of unreachable destinations (the destination is not in the coverage area of allowed number of relay units) over total number of calls.
- *Ratio of Blocked Calls (ROBC)* : is the ratio of number of rejected calls because of insufficient radio resources over total number of calls.

The last two performance measures are important, since as these ratios get higher, the users of the system will have difficulties to establish a communication link with the destination nodes, even in some cases they cannot communicate with some of them.

<u>Assumptions :</u>

We have also made some assumptions in the model. These are :

- All units are synchronized in time.
- Every unit has a unique identification number which is known by other units.
- All links are bi-directional.
- Units detect the existence of a neighbor or a link failure within a finite time by a link layer protocol.
- Velocity of a unit is uniformly distributed between 0 and 8 kilometers per hour.
- Units cannot go out of the region defined for every hour of simulation.
- The lost packets over a link are transmitted and received again by a link layer protocol, so that transmission is completed in the call duration time.
- Packets sent in control channels are received correctly by the neighbor units in transmission range of the source node.
- There is no electronic attack measures of the enemy.

4.3.2. Logical Model

Logical model shows the relationships among the elements of the model. We construct the logical model of the messaging system of a brigade via flowcharts. A flowchart is a pictorial summary of the flows and decisions that comprise a process. It has several advantages in constructing the model such as functioning as a communication and planning tool, providing an overview of the system, defining roles, demonstrating interrelationships and promoting logical accuracy. The flowchart of the system is presented in Figure 4.3.

When a user wants to send data, it first determines the destination and type of data. After controlling the routing table, it determines whether the destination is the subscriber of the same RAP. If the destination is the subscriber of the same RAP, it first sends a connection request packet to the destination node or to the next hop in the route to the destination if it can be reachable in allowed number of hops. If the node is unreachable in the number of allowed hops, the user tries to transmit it after a random period. If the destination is not the subscriber of the same RAP, the user sends the request packet to RAP. This process is depicted in Part A of the flowchart.

Upon receipt of connection request packet, the relay unit selects the channels for transmission as explained in Chapter 2, if the channels available and sends a connection confirmation packet that includes the selected data channels. Otherwise, the connection request is rejected. In this case, the user transmits the data after a random period. In Part B of the flowchart, the connection establishment is shown.

If the relay unit is not the destination, it starts the next leg of the connection towards the destination node. If the data type is a voice call and the destination is making another voice call, the call is blocked. Otherwise, the connection is established and the destination node sends a call accepted packet back to the source node using data channels as in Part C of the flowchart. After the call accepted packet is received, the source node starts transmission of data.

4.3.3. Simulation Model

We used Arena 7.0 simulation language to model our system. There are many simulation packages that are used for modeling communications networks. Arena software is a general-purpose simulation language, that is, it can also be used for modeling manufacturing systems, for combat modeling or for modeling communications networks. It is also a powerful and flexible tool in creating animated models and offers reasonably good simulation output process.

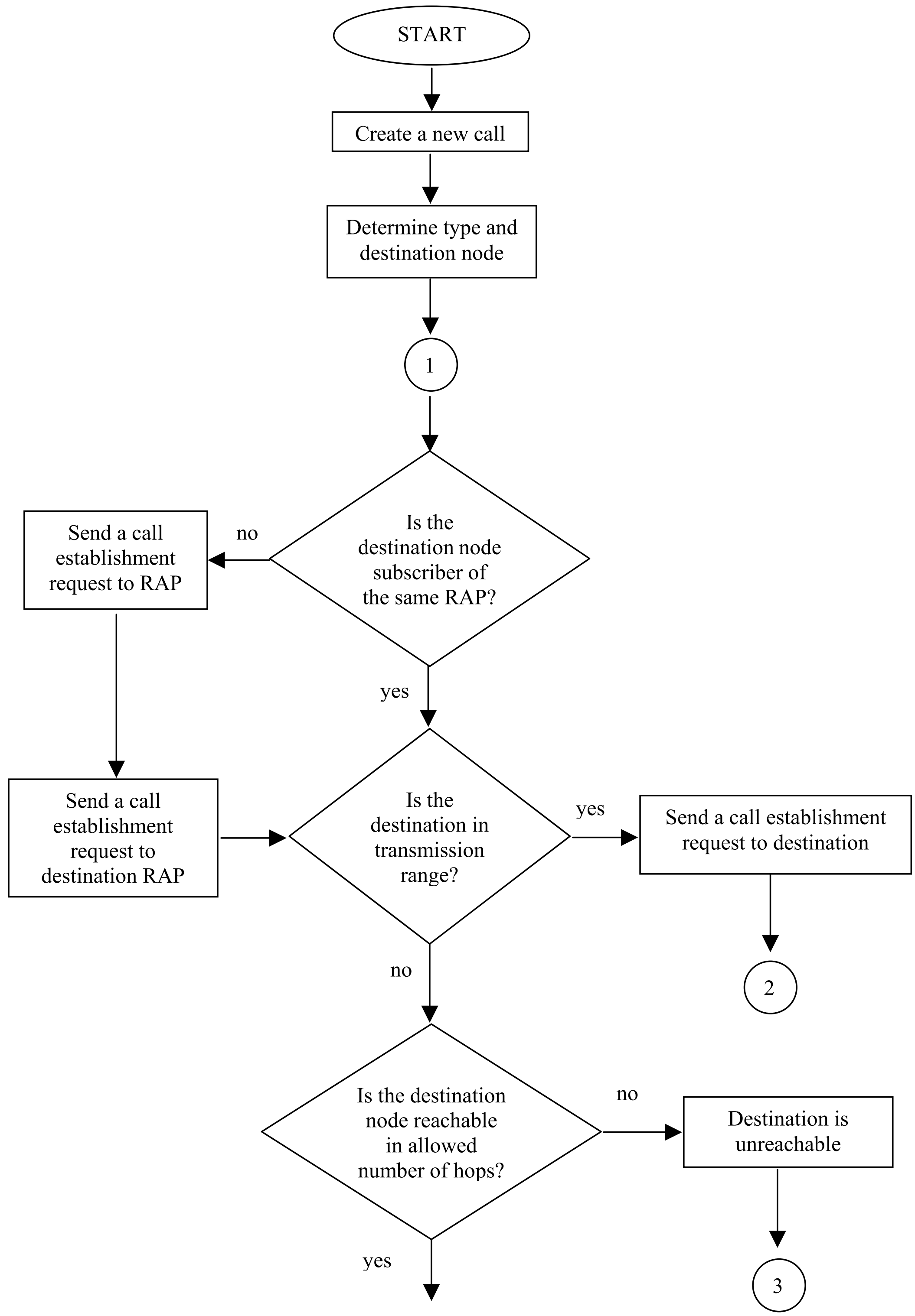


Figure 4.3. Flowchart of the system (Part A)

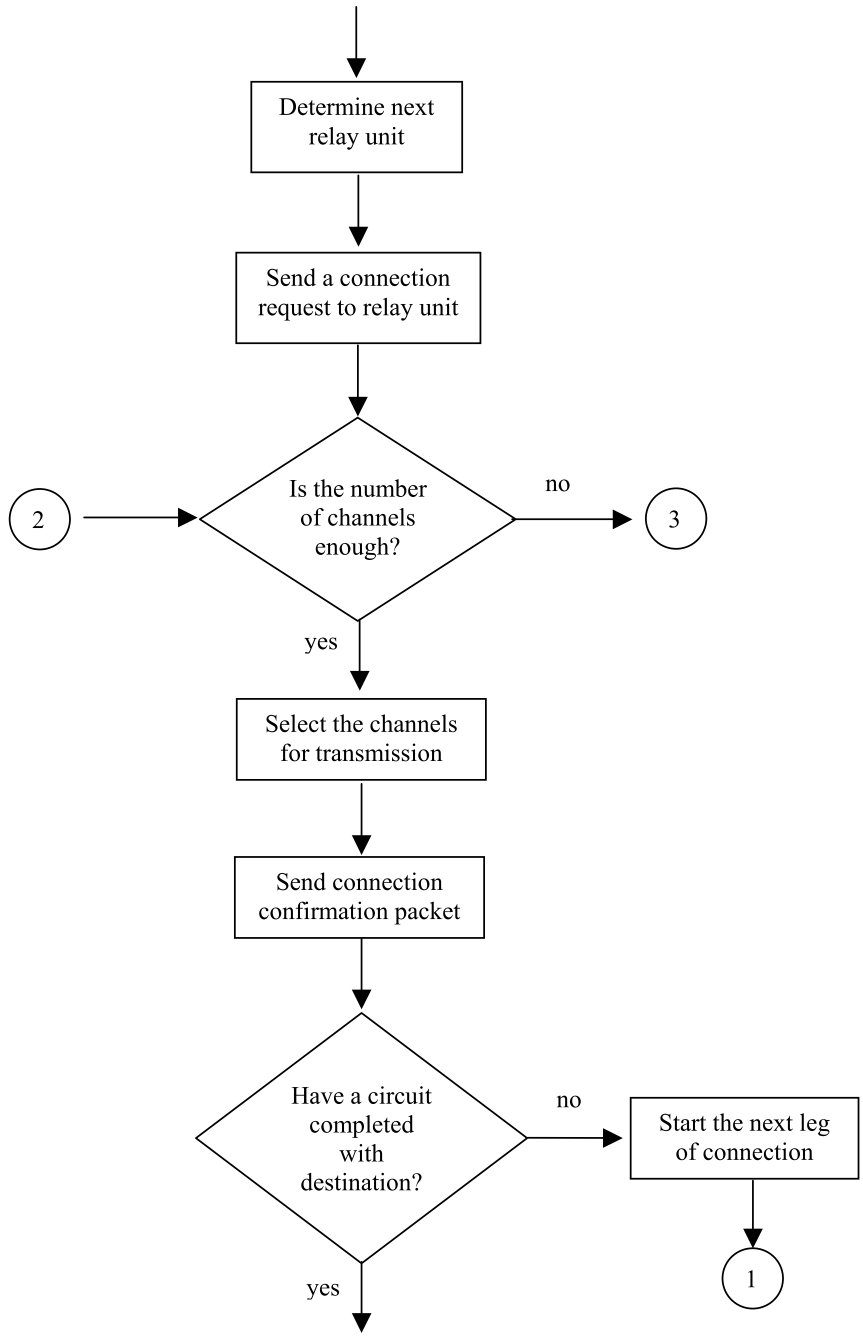


Figure 4.3. Flowchart of the system (Part B)

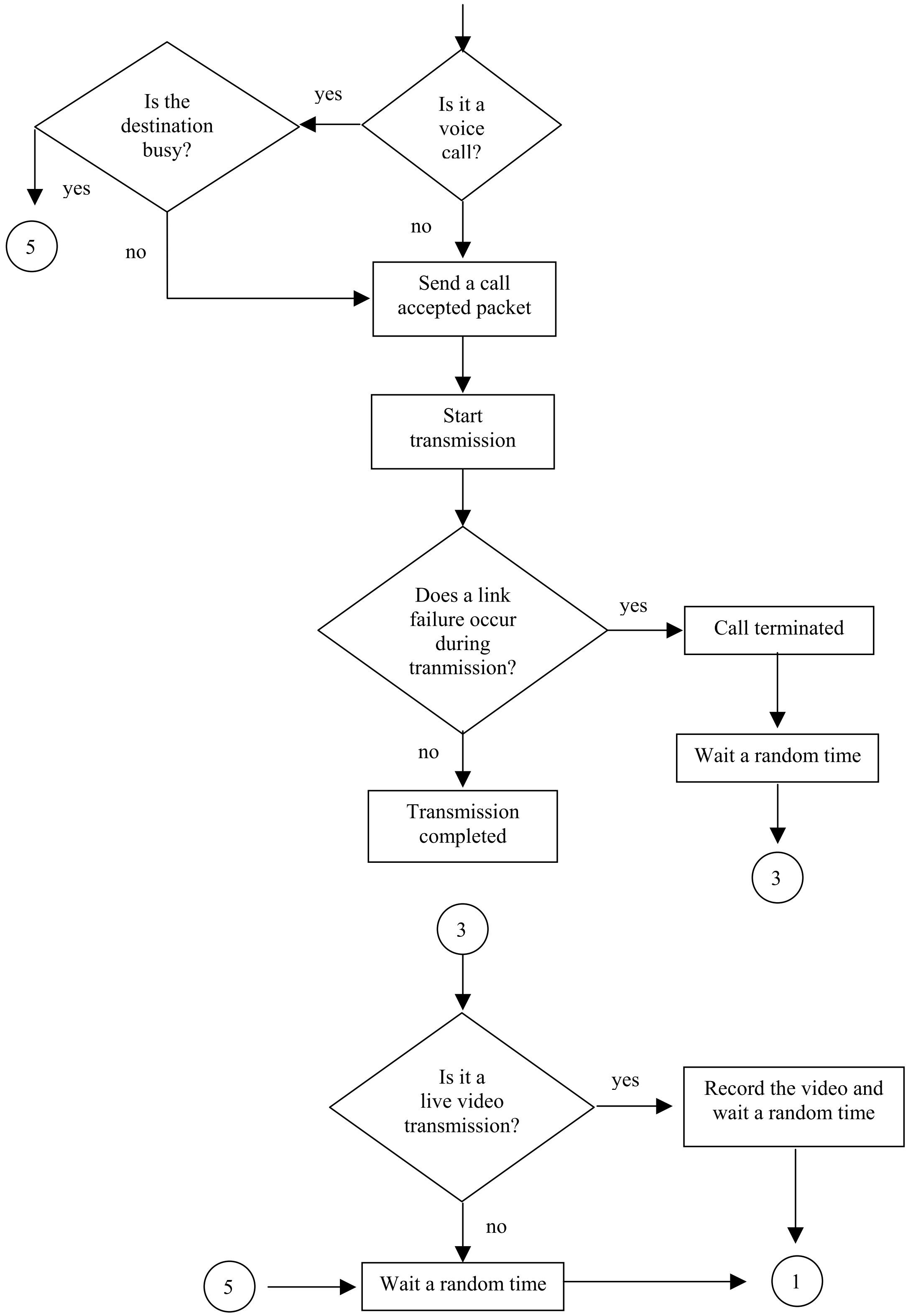


Figure 4.3. Flowchart of the system (Part C)

The major advantage of general-purpose languages is their ability to model almost any kind of communications network, regardless of its complexity. Their possible drawbacks, as compared to some simulators, are the need for programming expertise and possibly the long time spent coding and debugging that is associated with modeling complex networks (Law and McComas, 1994). Hence, to develop the model was a challenging task during our study. It took three months to develop a valid simulation model including validation and debugging, etc.

We present some technical information about the model in Table 4.1. A small part of the computer code of our simulation model is given in Appendix B.

Table 4.1. Technical Information About The Model

Size of Model	2.65 MB
Simulation Run Time	9.56 minutes
Number of Blocks In Model File	933
Number of Attributes	27
Number of Variables	38

4.4. Input Data Analysis

The communication system that we model is a new system. Since it is not tried in a war condition or in an exercise we know, it is not possible to collect required input data for our system. But, in a data network, it seems reasonable to assume that the arrival process can be described as a Poisson process. Thus, we use exponential distribution for the call interarrival times. For the call duration times, we used uniform distribution, since it provides a good approximation when it is known that the service time is random, but no information is available about the distribution. (Smith, 1998) We obtain the parameters of the distribution functions by interviewing the military experts. Some of the data points are taken from the army field manuals that are written according to the war experiences. The parameters of these distribution functions are presented in Appendix C. In the future applications, as we gather new data sets, the input data analysis techniques discussed in Law and Kelton (2000) can be employed to find correct distribution functions for random variables.

4.5. Model Verification and Validation

Verification and validation is one of the most important stage of a simulation study, since any conclusions derived from the model will not have any meaning unless the model verified and validated. We verify and validate our model by using the following techniques and considering the principles of Balcı (1998) for all steps of our study.

4.5.1. Verification of Model

Model verification is the process of determining that a model implementation accurately represents the developer's conceptual description and specifications. In other words, by using verification techniques we will check the translation of the conceptual model into a correctly working program. We use following techniques to verify the model :

• Tracing : By using Arena trace option, we observe the state of our model. The state variables, statistical counters are printed out just after each event occurs. Thus, we can easily check if the program is operating as intended.

• Debugging : In developing the simulation model of the existing system, we write a computer program that contains modules and sub-programs. First, the main part is developed and tested. Then, additional sub-program and levels of detail are added and debugged successively, until the model is matured to satisfactorily represent the existing system.

• Input and Output Control : We take a lot of simulation experiments by changing input parameters . We see that the outputs are reasonable. Because outputs of the model are as expected.

• Animation : An animation of the simulation model is performed and it is observed that the animation of the simulation output imitates of the existing system.

4.5.2. Validation of Model

Model validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model (Kleijnen, 1999). In validation process, we would like to see that the proposed model for our system is really the accurate representation of the real system. Only after the model is validated the evaluations made with the model can be credible and correct. We use the following techniques to validate our model.

• Face Validity : A model with face validity is the model that, on the surface, seems reasonable to people who are knowledgeable about the system under study. It includes conversations with system experts, observations of the system, experience and intuition. (Law and Kelton, 2000) During these stage, we consulted with the military experts and we agreed on the validity of the system.

• Sensitivity Analysis : This technique is performed by systematically changing the values of model input variables and parameters over some range of interest and observing the effect upon model behavior. Unexpected effects may show invalidity. We conduct a number of experiments by changing input variables. We changed call durations by a multiplication factor and we observed ROBC values. The results are presented in Figure 4.4.

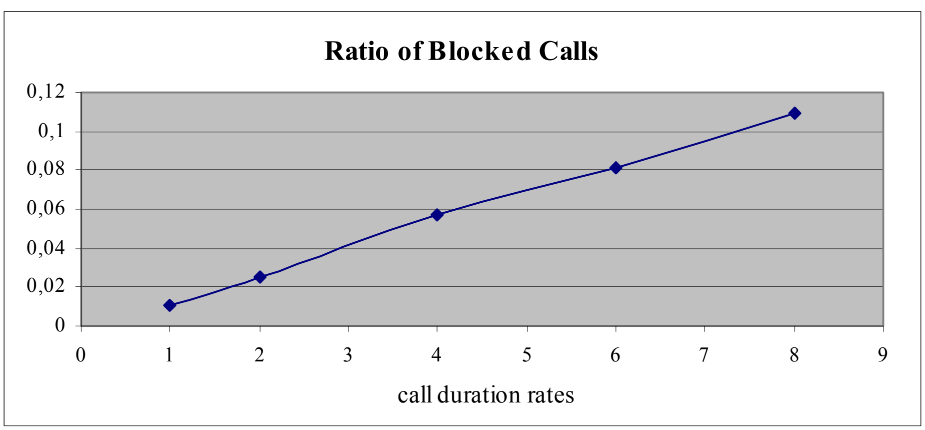


Figure 4.4. Ratio of blocked calls for different call duration rates

We also examined the other performance measures such as call establishment times, message delivery times, number of calls, number of unreachable destinations, number of terminated calls, ROTC and ROUD for all multiplication factors. In these experiments we have not meet any unexpected effect of input variables on outputs. All the results seem reasonable as expected.

• Fault/Failure insertion test : This test is used to observe the output of the model when a fault (incorrect model component) or a failure (incorrect behavior of a model component) is inserted into the model. If the model produces the invalid behavior as expected we can say that our model is valid. First we added a mechanized infantry battalion to the brigade (incorrect model component). But the interarrival time of calls for this battalion is three times shorter than the mechanized infantry battalion in the system. Then, we decreased the number of allowed hops for messages to one (incorrect behavior of a model component). We observed ROBC and ROUD values. The results are presented in Table 4.2. As expected the model produced invalid behaviors for both cases.

Table 4.2. Results of fault/failure insertion test

Performance Measures	Values for Typical Model	Values for Fault Insertion Test	Values for Failure Insertion Test
ROUD	0.0074	0.0011	0.082
ROBC	0.0106	0.025	0.379

4.5.2.1. Statistical Validation

Since we do not have any historical data we did not make statistical validation.

CHAPTER 5

DESIGN AND ANALYSIS OF EXPERIMENTS

Simulation is a computer-based statistical sampling experiment. Since some of the input processes driving a simulation are random, the output data is also random and the results are estimates of performance measures. If the results of a simulation study to have any meaning, appropriate statistical techniques must be used to design and analyze the simulation experiments (Law and Kelton, 2000).

In this chapter, we model messaging system of a mechanized infantry brigade in an attack operation. We first determine number of replications needed to achieve a desired accuracy in simulation experiments. Then we measure the system performance and finally implement factorial design to explore the significant factors and their effects. We will try to answer the following questions throughout the chapter:

- How efficient is the system for various performance measures?
- Does there exist a bottleneck in the system?
- How does the system perform when traffic load increase?
- What happens if we change the number of MSTs and PSTs in the system?
- What is the effect of mobility on performance measures?
- Which factors have significant effects on the performance measures?

5.1. Determination of Run-Length and Number of Replications

We begin the statistical procedures by determining number of replications needed to achieve a desired accuracy on the estimates of the performance measures. We use sequential procedure with relative precision criterion to determine number of replications (Law and Kelton, 2000). The specific objective of the procedure is obtain an estimate of μ with a relative error of γ ($0 < \gamma < 1$) and a confidence interval of 100(1-α) percent.

The two stage procedure is as follows :

Step 1. Make n_0 replications (more than two) of the simulation and set $n = n_0$

Step 2. Compute $\overline{X}(n)$ and $\delta(n,\alpha)$

where, $\delta(n,\alpha) = t_{n-1,1-\alpha/2}\sqrt{\frac{S^2(n)}{n}}$ is the half length of the confidence interval.

Step 3. If $\frac{\delta(n,\alpha)}{|\overline{X}(n)|} \le \gamma'$, use $\overline{X}(n)$ as the point estimate of μ and stop. This ratio is an estimate of the actual relative error.

$\gamma' = \frac{\gamma}{1+\gamma}$ is the adjusted relative error to get an actual relative error of γ.

Else make one more replication and go to Step 2.

The two main performance measures that we will evaluate are ROBC and ROUD. We choose the initial sample size as 10 and γ = 0.10 for both of the performance measures and simulate the system for one day length. The averages and variances for each performance measure are presented in Table 5.1.

Table 5.1. The averages and variances for each performance measure

	ROBC	**ROUD**
$\overline{X}(n)$	0.0106	0.0074
$S^2(n)$	3.32 E-06	1.59 E-06

We find that we need to make at least 10 replications for ROBC and 12 replications for ROUD to achieve the desired accuracy. Then we decide to make 15 replications of simulation model. After determining the number of replications to achieve the desired accuracy we construct the confidence intervals for ROBC and ROUD. In our case $\alpha = 0.05$. The half-lengths and 100 (1-α)% confidence intervals for means of ROBC and ROUD is given in Table 5.2.

Table 5.2. The half lengths and lower and upper limits of confidence intervals for each performance measure

	ROBC	**ROUD**
$\overline{X}(n)$	0.0106	0.0074
$\delta(n,\alpha)$	0.00083	0.00057
Lower Limit	0.0098	0.0068
Upper Limit	0.0115	0.008

5.2. Evaluation of System Performance

In this section, we look into the following questions:

- How efficient is the system for various performance measures?
- Does there exist a bottleneck in the system?
- How does the system perform when traffic load increase?

To evaluate the system performance, we conduct 15 simulation runs, and analyze the results. The values of average of 15 runs for different performance measures are given in Table 5.3.

Table 5.3. Results of average of 15 runs for performance measures

Performance Measure	**Average**
Total number of calls	3215.7
Number of blocked calls	34.2
Ratio of blocked calls	0.0106
Number of blocked messages	15.67
Number of blocked voice calls	3.46
Number of blocked video transmission	9.13
Number of blocked other data	5.93
Number of unreachable destinations	23.9
Ratio of unreachable destinations	0.0074
Number of terminated calls	0.67
Average call establishment time	1.91 sec.
Average call duration time	47.71 sec.

When we evaluate the system performance, it seems that the system does not have a serious problem. Approximately one percent of calls is blocked because of insufficient resources that is an acceptable value for a communications network on the battlefield. Also, the value of ratio of unreachable destinations is evaluated as in good standards.

While investigating the results of simulation runs, we see that the system is significantly affected by live video transmission. The plot of ratio of blocked calls by data types is presented in Figure 4.6. Since, live video transmission needs an important part of resources (24 data channels), over nine percent of live video transmission is blocked. Voice calls have the smallest ROBC value since this type of data use only two channels of system resources.

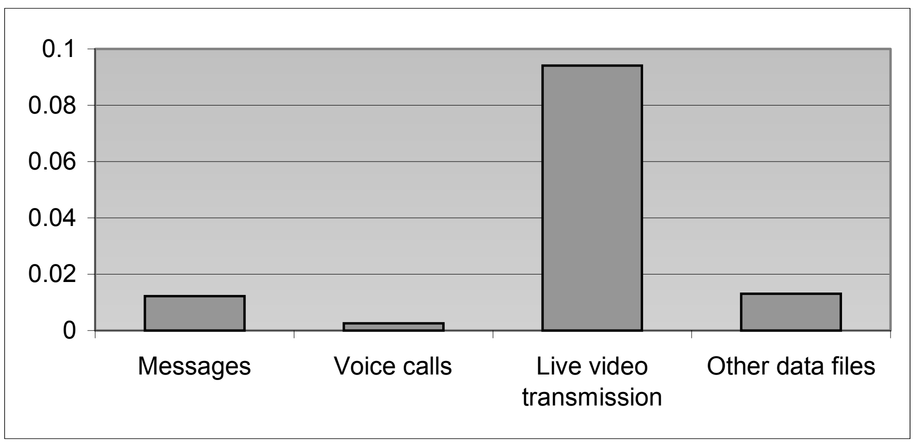


Figure 5.1. ROBC values for different types of data

Since live video transmission has the greatest ROBC value, we examine the system performance in the absence of live video transmission to see the effect of this type of data on performance measures. We see that all the messages are sent to their destinations without any type of blocking in the absence of live video transmission.

We also investigate ROBC values for different types of units. The results of ROBC values by types of units are presented in Figure 5.2.

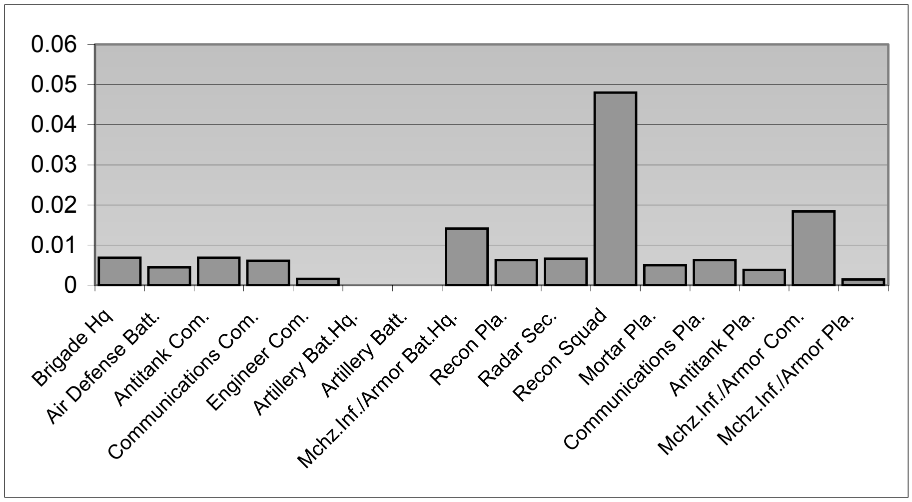


Figure 5.2. ROBC values for different types of units

The reconnaissance squad has the greatest value of ROBC. The second greatest value belongs to mechanized infantry and armor companies. In the system, only these units transmit live video. The mechanized infantry and armor battalions are the third in terms of value of ROBC since they realize the greatest data transmission in the system. The average data transmissions in megabits for different types of units are presented in Figure 5.3.

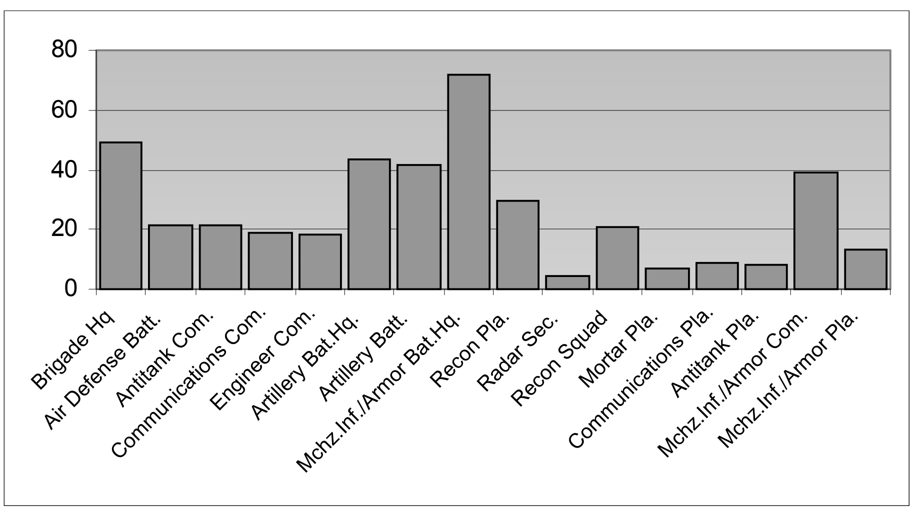


Figure 5.3. The average data transmissions in megabits for different types of units

To analyze how the system performs in increasing traffic rates, we conduct simulation runs at different message traffic rates. To evaluate the effect of traffic rate, we decrement the interarrival times of messages for each user by a multiplication factor. The results are presented in Figure 5.4.

As seen in the figure, as the multiplication factor increases, the ROBC value also increases. As the utilizations of data channels increase and the increase in ROBC becomes more significant. We can say that the increases in multiplication factors has a great effect on the system performance.

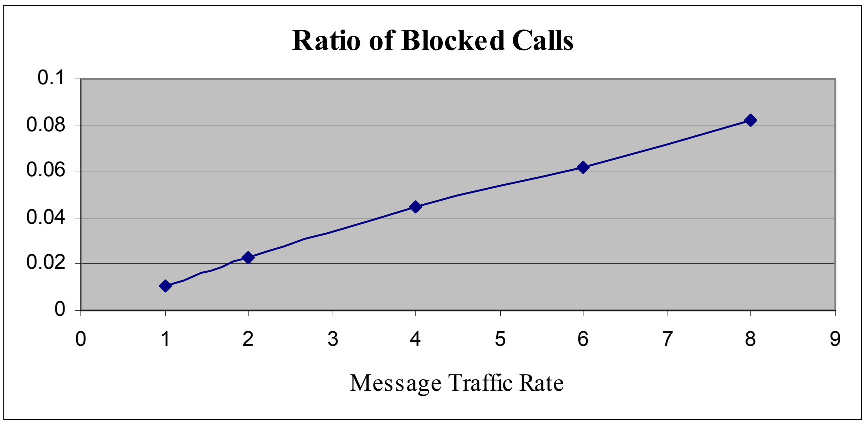


Figure 5.4. ROBC at different multiplication factors

5.3. 2^k Factorial Design

To study the effects of the factors on performance measures and the interactions between factors, we use factorial design. A special type of factorial design is 2^k factorial design which is widely used in experiments involving several factors. We implement 2^k factorial design for the model to determine the effects and possible interactions of factors on system performance considering performance measures. We particularly investigate answers of the following questions:

- What happens if we change the number of MSTs and PSTs in the system?
- What is the effect of mobility on performance measures?
- Which factors have significant effects on performance measures?
- What is the effect of traffic rate on performance measures?

- What are the effects of weather and terrain conditions on the system performance?

In our study, there are five factors under consideration. An explanation of factors and their levels is given below.

Table 5.4. Factors and their levels

FACTOR	FACTOR DESCRIPTION	LOW LEVEL	HIGH LEVEL
Factor A	Type of Brigade	With 3 battalions	With 5 Battalions
Factor B	Traffic Rate	Low (1)	High (2)
Factor C	Mobility	Low (4 kph)	High (16 kph)
Factor D	Weather and Terrain	Bad	Good
Factor E	Buffer	No	Yes

Factor A : In the existing system, the brigade has five mechanized infantry battalions and two armored battalions. We determine the high level as a typical mechanized brigade organization. To examine the effects of different number of users on the performance measures, we decrease the number of users in RAP-2 and RAP-3 by removing a mechanized infantry battalion from RAP-2 and an armored battalion from RAP-3 as the low level of factor.

Factor B : At high level of Factor B, we increment the arrival rates messages twice of typical conditions. Low level represents normal conditions.

Factor C : At the low level of the factor, the units move at a speed of 4 kph. and the brigade moves 24 kilometers per day. At the high level, mobility is high. Units move at a speed of 16 kph, and the brigade moves 72 kilometers per day.

Factor D : In bad weather and terrain conditions, the transmission range of units will decrease. We decrease the transmission range of MSTs and RAPs as the half of their actual range at the low level of the factor.

Factor E : At the low level of this factor, when the data channels are insufficient the call requests are rejected. At high level, when the data channels are insufficient the call requests are buffered and if the data channels are available, the call request is confirmed. The timeout values for request are 15 seconds for voice calls and video transmission and 60 seconds for messages and other data.

5.3.1. Implementation of ANOVA

We implement analysis of variance (ANOVA) to find out which factors and interactions have significant effects on the system performance. We run the model for 32 design points. The results are given in Appendix D (Table D.2-D.3). In the Appendix, a "0" implies the low value and a "1" implies the high value of the factor. To achieve independency, we run each of the 32 design points with different seeds and different random number streams.

First, we check the homogeneity of variances and normality assumptions which are to be satisfied to implement ANOVA.

Homogeneity of Variance

We have 32 design points, and we test the following hypothesis.

H_0 : $\sigma_1^2 = \sigma_2^2 = \sigma_3^2 = ... = \sigma_{32}^2$

H_1: Above is not true for at least one σ_i^2

To check homogeneity of variance assumption, we applied Barlett's and Levene's test. These tests are widely used to diagnose the inequality of variances. The result of Barlett's test is given in Table 5.5 and results of Levene's test is given in Table 5.6. The assumption of homogeneity of variances is satisfied for ROUD and ROBC in both tests.

We also check scatter plot of variances. The plots are presented in Appendix F (Figure F.1-F.2). We see that there is no obvious patterns or structures in these plots.

Table 5.5. Barlett's test result for ROBC and ROUD

Performance Measure	ROBC	ROUD
S_p^2	3.617 E-06	3.272 E-06
Q	19.313	18.073
C	1.0238	1.0238
X_0^2	43.437	40.647
$X_{0.05,31}$	45	45
Test Result	**Do not reject**	**Do not reject**

where, $\chi_0^2 = 2.3026 \dfrac{q}{c}$ $\qquad q = (N - a)\ \log_{10}\ S_p^2 - \sum_{i=1}^{a}(n_i - 1)\ \log_{10}\ S_i^2$

$$c = 1 + \frac{1}{3(a-1)}\left(\sum_{i=1}^{a}(n_i - 1)^{-1} - (N-a)^{-1}\right)$$

$$S_p^2 = \frac{\sum_{i=1}^{a}(n_i - 1)S_i^2}{N - a}$$

We reject H_0 when $\chi_0^2 > \chi_{\alpha,a-1}^2$

In Levene's test, a low significance value generally less than 0.05 indicates that the variance significantly differs between groups. The assumption of homogeneity of variances is satisfied for both performance measures.

Table 5.6. Levene's test results for ROBC and ROUD

Performance Measure	F	df1	df2	Significance Value	Test Result
ROBC	1.219	31	448	0.197	**Do not reject**
ROUD	1.007	31	448	0.459	**Do not reject**

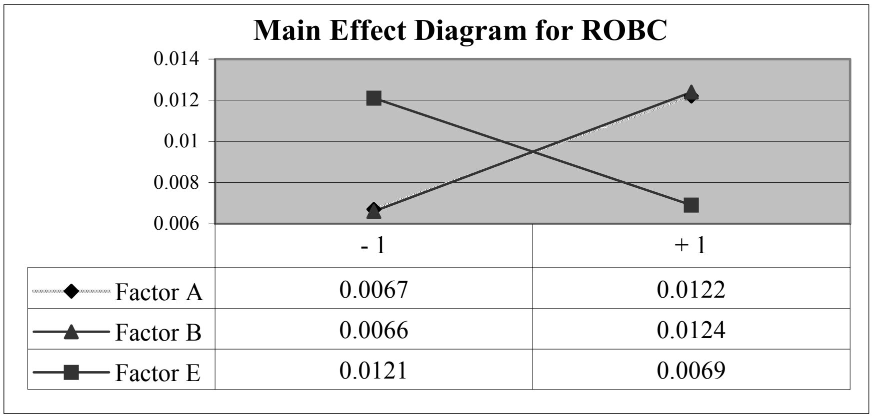
Normality

To check normality assumption, first, we compute residuals using regression model. Then, we construct a histogram of residuals. If the normality assumption is satisfied, then this plot should look like a sample from a normal distribution centered at zero. We also construct a normal probability plot of the residuals. Another procedure to check normality is to construct scatter plots of residuals. This plot of residuals should not show any obvious pattern. The residual analysis is presented in Appendix G (Table G.1). The plot of histogram, the normal probability plot and scatter plots of the residuals are given in Appendix G (Figure G.1-G.5).

Also, note that appearance of a moderate departure from normality does not necessarily imply a serious violation of the assumptions. Since the F test is only slightly affected from moderate departures from normality, we can say that the analysis of variance is robust to the normality assumption. But, gross deviations from normality require further analysis (Montgomery, 1991).

5.4. Evaluation of Main Effect and Interaction Effects on ROBC

We use SPSS software package to implement ANOVA. Then, we plot the main effect and interaction effects diagrams to evaluate the results. The SPSS output of ROBC performance measure is given in Appendix E. There are three significant factors and four two-way interaction effects on the performance measure. The main effect diagram is shown in the Figure 5.5. The significant factors are factor A, B and E. Factor E has an effect that decrease the value of the performance measure while the other significant factors have increasing effects. When a user has a buffer, if there is not sufficient data channel to confirm the call request, it does not immediately reject the call. The call request is buffered during 15 seconds for voice calls and video transmission and 60 seconds for messages and other data files. If there exist sufficient number of data channels in this period, the call is confirmed. Otherwise call is blocked. This causes a significant decrease in number of blocked calls. The effects of factor A and B cause an increase in the value of ROBC, since the data channel utilization will increase in both cases.



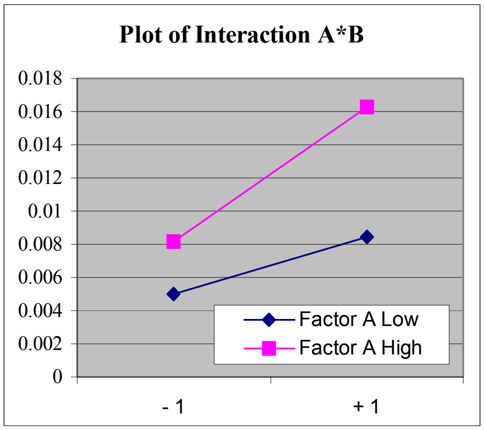
	- 1	+ 1
Factor A	0.0067	0.0122
Factor B	0.0066	0.0124
Factor E	0.0121	0.0069

Figure 5.5. Main Effect Diagram for ROBC

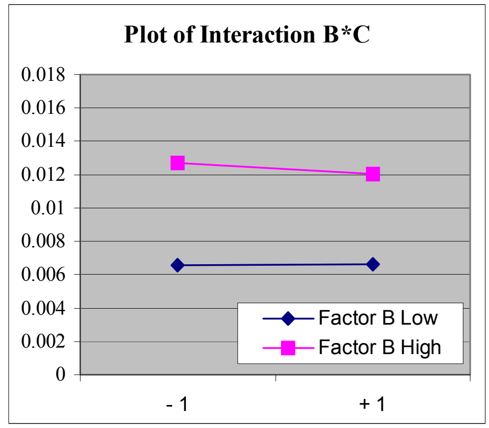
Factor C and D have not significant effects on the ROBC. The units on the battlefield are positioned close to each other and they move in their responsibility area. Hence, mobility does not affect the distance between them significantly. Bad weather and terrain conditions will affect the transmission range, but this decrease in the transmission range will not affect the number of hops from source to destination significantly.

We have also four significant two-way interaction effects. These are between factors A-B, B-C, A-E and B-E. The plots of the interaction effects are given in Figure 5.6.

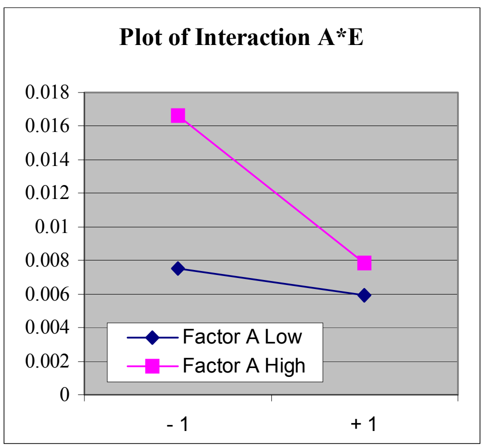
First interaction effect is between factor A and B. Both factors have effects that increase the value of ROBC. When the brigade has five battalions, utilization of data channels increase. If we increase the traffic rate while the data channels are highly utilized, increase in ROBC will be more significant. Thus, the slope of the performance measure when one factor is at its high level is more than the slope of the performance measure when the factor is at its low level. Another interaction effect is between factor B and C. Factor B has an increasing effect on the performance measure and factor C has not a significant effect. Since the lines in the plot are nearly parallel to each other, this interaction is the least significant.



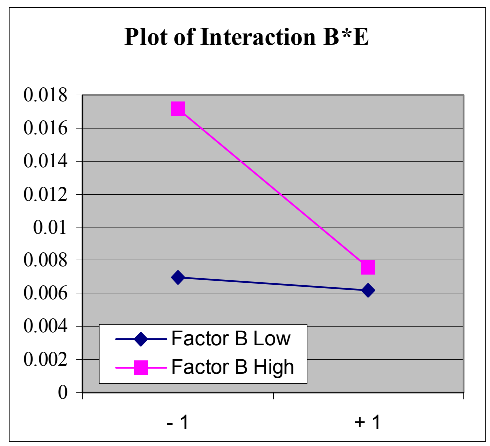
a) Plot of interaction between factor A and B



b) Plot of interaction between factor B and C



c) Plot of interaction between factor A and E



d) Plot of interaction between factor B and E

Figure 5.6. Plots of interaction effects

The other interaction is between factor B and E. The factor B has an increasing effect while the effect of factor E is decreasing. The factor E has a more significant effect on ROBC. When the utilization of data channels is high, the factor E affects ROBC more. The interaction between factor A and E can be explained in a similar way as interaction between B and E. The values of interactions between significant factors are given in Table 5.7.

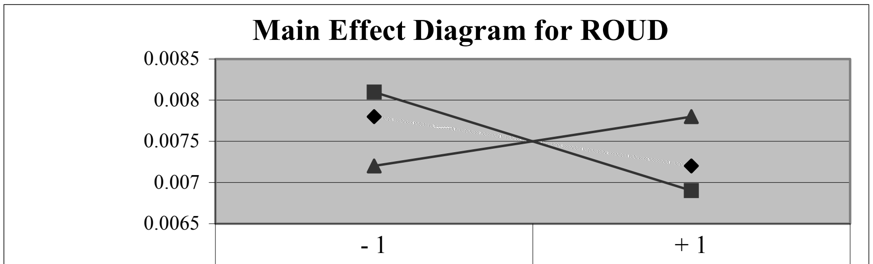
Table 5.7. Interactions between factors for ROBC

Interactions	Ratio of Blocked Calls				
AB			B		
			Low	High	Difference
	A	Low	0.0050	0.0084	0.0034
		High	0.0082	0.0163	0.0081
		Difference	0.0032	0.0079	
BC			C		
			Low	High	Difference
	B	Low	0.0066	0.0066	0.0001
		High	0.0127	0.0120	-0.0006
		Difference	0.0061	0.0054	
AE			E		
			Low	High	Difference
	A	Low	0.0075	0.0059	-0.0016
		High	0.0166	0.0078	-0.0088
		Difference	0.0091	0.0019	
BE			B		
			Low	High	Difference
	E	Low	0.0070	0.0062	-0.0008
		High	0.0171	0.0076	-0.0096
		Difference	0.0102	0.0014	
AB			B		
			Low	High	Difference
	A	Low	0.0122	0.0071	-0.0051
		High	0.0119	0.0067	-0.0052
		Difference	-0.0002	-0.0003	

5.5. Evaluation of Main Effect on ROUD

We plot the main effect and interaction effects diagrams of ROUD performance measure to evaluate the results. The SPSS output of ROBC performance measure is given in Appendix G (Table G.1). There are three significant factors on the performance measure. The main effect diagram is shown in the Figure 5.7.

The significant factors are factor A, C and D. Factor A and D have effects that decrease the value of ROUD while factor C has an increasing effect. The weather and terrain conditions is the most significant factor. Mobility factor is more significant than the type of brigade.



	- 1	+ 1
Factor A	0.0078	0.0072
Factor C	0.0072	0.0078
Factor D	0.0081	0.0069

Figure 5.7. Main Effect Diagram for ROUD

As the mobility increase, the distance between the source and destination node will also increase such that the destination is not reachable in allowed number of hops. The other significant factor is the type of brigade that has a decreasing effect on ROUD. As the number of subscribers of the same RAP increase, the network will have a more connected structure. The more connected network structure will cause a decrease in the value of ROUD. The traffic rate and existence of buffer is not significant because they do not make any change in the distance between users.

The only significant two way interaction effect is between factor A and D. The plot of the interaction effect is given in Figure 5.8.

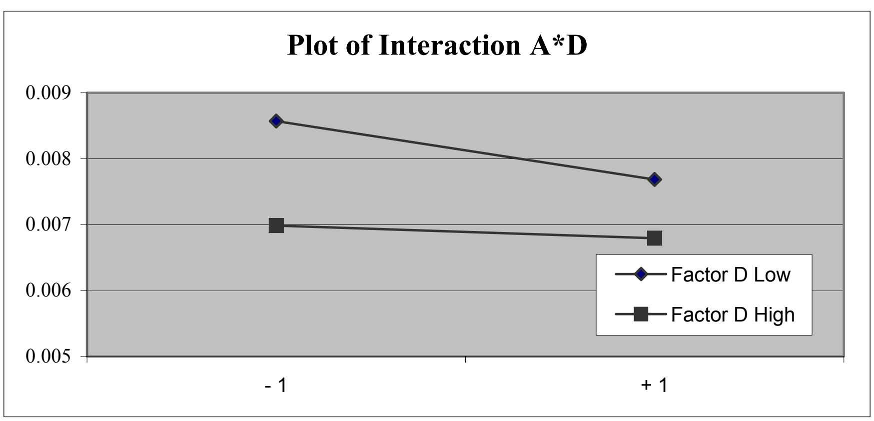


Figure 5.8. The plot of interaction between factor A and D

When factor D is at its low level, the effect of factor A is more significant. The summary of significant factors and interaction effects is given in Table 5.8.

Table 5.8. Summary table of significant factors and interaction effects

Performance Measure / Factors	ROBC	ROUD
A	***Significant***	***Significant***
B	***Significant***	Insignificant
C	Insignificant	***Significant***
D	Insignificant	***Significant***
E	***Significant***	Insignificant
A*B	***Significant***	Insignificant
B*C	***Significant***	Insignificant
A*D	Insignificant	***Significant***
A*E	***Significant***	Insignificant
B*E	***Significant***	Insignificant
A*B*E	***Significant***	Insignificant

5.6. Conclusions

When we analyze the results, we find that the significant factors on ROBC are existence of buffer, type of brigade and traffic rate factors. The existence of buffer has an effect that decreases the value of ROBC while the other factors have increasing effects. The results show us that as the number of messages increase in the system, the system robustness goes down. Since the distances between the units of the brigade in an offensive operation are not long, the effect of mobility is not significant. But as the distances get longer, this effect will increase. The interaction effects are between type of brigade-traffic rate, traffic rate-mobility, type of brigade-existence of buffer and traffic rate-existence of buffer.

The significant factors on ROUD are type of brigade, mobility and weather and terrain conditions. Mobility factor has an increasing effect while type of brigade factor and weather and terrain conditions have effects that decrease the value of ROUD. As the number of units in the same area increase, the network will be more connected because of the multi-hop capability of units. The distance between units is an important factor for this performance measure.

CHAPTER 6

DIFFERENT SCENARIOS

One of the main purposes of the simulation is to observe and understand the behavior of a system under different conditions. In this chapter, we evaluate the system performance and investigate if the system is capable of supporting different types of operations. During war, the brigade may take part in different types of operations such as offensive, defensive, retrograde operations and many other tactical operations. There may be many scenarios involving different types of the operations.

We model different scenarios to observe the system performance in different operations. Modeling all types and subtypes of operations need a great effort and time. Instead, we model a most possible scenario for main types of operations. These are a defensive operation scenario, a delay operation scenario and a movement scenario. We evaluate ROBC and ROUD performance measures for each type. In each scenario, the initial position of units, the arrival rates of messages and the mobility characteristics of the units of the brigade will differ.

6.1. Evaluation of Defensive Operation Scenario

The main purpose of a defensive operation is to cause an enemy attack to fail. The two main types of defensive operations are area defense and mobile defense. The area defense depends on protection of terrain or facilities for a specified time. The mobile defense aims to destroy enemy forces by a combination of fire and maneuver, offense, defense, and delay. The mobile defense normally conducted at higher levels than brigade. A brigade conducts an area defense or mobile defense as part a division or corps defense. In the scenario, we model a brigade conducting area defense in depth. An area defense in depth focuses on key terrain that must be controlled throughout the depth of the area of operations. It allows the defender to fight a heavy enemy who possesses shock capability.

The main differences between attack and defense scenarios are the distance between units, the mobility characteristics of units and the traffic rates. In defense operations the frontage and depth of the brigade is larger than offensive operations. The frontage and depth of a brigade will differ according to mission, enemy and terrain conditions. We assume that in defense scenario, the frontage of brigade is 12 km and the depth is 16 km while in attack scenario the brigade is initially deployed in 6x8 km area. Another difference between two scenarios is the mobility characteristics of units. In the defense scenario, the units are less mobile. In defense operations the message traffic will be lower than offensive operations since some of message traffic is achieved by wired communication systems. The message traffic will differ according to tactical situation even for the same type of operation. Since, we do not have real data, we consult the military experts for an estimate of the message traffic in different types of operations. After evaluating the estimates of message traffic, we decide to use a multiplication factor of 0.8 for defense operations.

The average of 15 runs of defense scenario for ROBC and ROUD performance measures and comparison with the ROBC and ROUD values of attack scenario are given in Figure 6.1.

When we evaluate the results of the defense scenario, we see that there is a decrease in ROBC and an increase in ROUD performance measures compared with the results of attack scenario. Since the distances between units are larger in this scenario, an increase in ROUD should be expected. We know that as the distances between units increase, the number of hops increase, and the utilizations of resources get higher. As we evaluate in Chapter 5, the distance between units is a significant factor on ROUD performance measure.

As the traffic rate decreases, the value of ROBC performance measure decreases. The effect of traffic rate is the most significant factor on ROBC as we evaluated in Chapter 5.

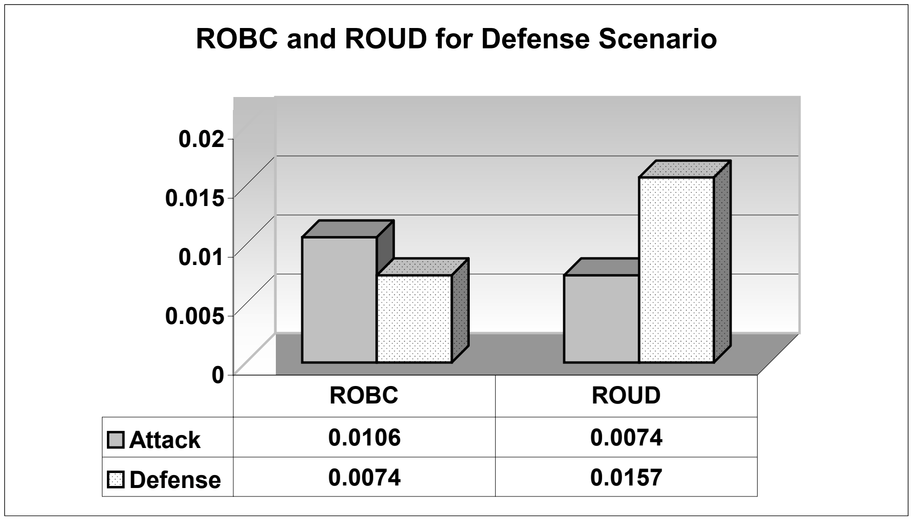


Figure 6.1. The ROBC and ROUD values for Defense Scenario.

6.2. Evaluation of Delay Operation Scenario

In this scenario, we model a delay operation. In delay operations the main purpose is to gain time. The destruction of the enemy is secondary to slowing advance of enemy to gain time. Delay operations are conducted by delaying in sector or by delaying forward of a specified line for a specified time. In our scenario, we model a brigade that conducts a delay operation in sector. In delay scenario, the distances between units are larger than defense scenario, so we model the frontage of brigade as 16 km and the depth as 20 km.

Since the delaying force must have a mobility advantage relative to the enemy, the units of brigade are more mobile than defense scenario. Finally, we assume that the traffic rate is more than defense scenario, but less than attack scenario and decide to use a multiplication factor of 0.9 for the message traffic rate.

The average of 15 runs of defense scenario for ROBC and ROUD performance measures and comparison with the ROBC and ROUD values of attack scenario and defense scenario are given in Figure 6.2.

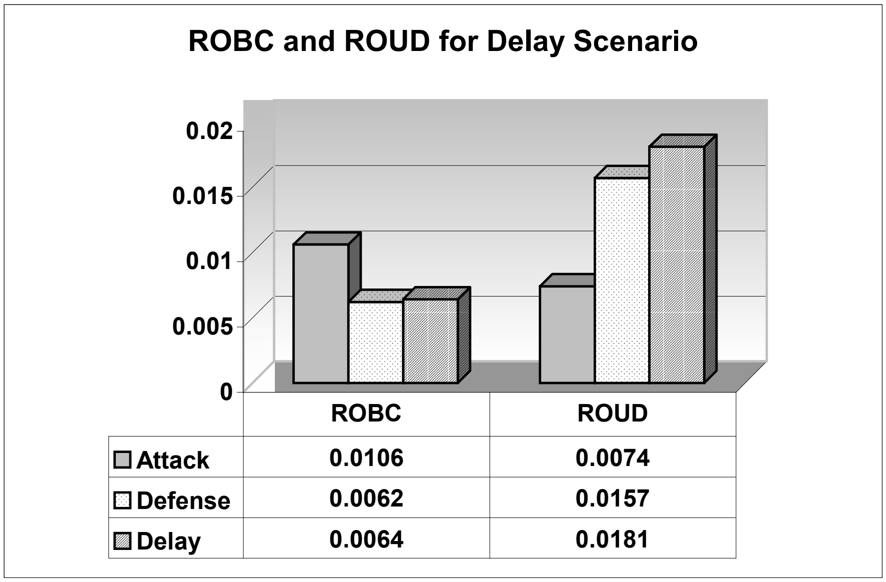


Figure 6.2. The ROBC and ROUD values for Delay Scenario.

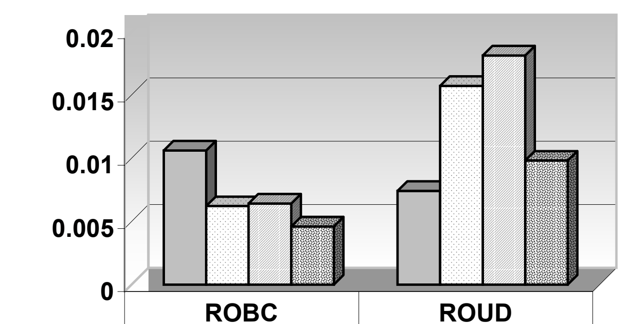
The results of delay operation scenario are similar to defense scenario. The value of ROUD is greater than attack and defense scenarios. This is a result of large distance between units. In delay operations, the distance is greater than defense scenario. As the distance between units get larger, there will be a decrease in the number of neighbors of the units. Some of the units that are in transmission range of the sending unit in defense scenario, are out of transmission range in this scenario. This causes an increase in ROUD. In delay operation scenario ROBC is slightly higher than defense scenario. This is an effect of message traffic rate. The traffic rate in this scenario is 10% more than defense scenario. As the message traffic rate increases, the value of ROBC also increases.

6.3. Evaluation of Movement Scenario

As the last scenario, we model a movement of the brigade. There are mainly two types of movement. These are tactical and administrative movements. In this scenario, we construct a model of tactical movement of brigade. In the movement, the brigade is usually column formation and establishes advance, flank and rear guards to protect the main body. As it gets closer to the enemy forces, it will make a transition to the line formation. In the scenario, the depth of brigade is 36 km and frontage is 2 km. In this scenario, the distances between units are larger than all scenarios. Although, this scenario is the most mobile among all scenarios, the effect of mobility should not be expected to cause great changes in ROBC, since all units follow each other in an order and the distance between units does not change in large values.

In this type of operations, the message traffic will be the lowest of the three scenarios since the threat of enemy is at the lowest degree. Hence, we decide to use a multiplication factor of 0.6 for the movement scenario.

The average of 15 runs of defense scenario for ROBC and ROUD performance measures and comparison with the ROBC and ROUD values of the other scenarios are given in Figure 6.3.



	ROBC	ROUD
Attack	0.0106	0.0074
Defense	0.0062	0.0157
Delay	0.0064	0.0181
Move	0.0046	0.0098

Figure 6.3. The ROBC and ROUD values for Movement Scenario.

Although the depth of the brigade is the greatest among all scenarios in the movement scenario, the distance between units that send live video is less than the defense and attack scenario. Thus, the value of ROUD is less than defense and delay scenarios but greater than attack scenario. ROBC is slightly less than defense scenario and delay scenarios. In this scenario, message traffic rate is the lowest.

Although the mobility and distance between units increase ROBC value, the effect of message traffic rate dominates the effects of mobility and distance between units.

6.4. Conclusions

We conduct simulation model and make output analysis in Chapter 5 for an offensive operation. In this chapter, we evaluate the system under different types of operations and find out the effects of different types of operations on performance measures. We model a defense scenario, a delay scenario and a movement scenario. All these types of operations have a different effect on performance measure, since each has different characteristics in terms of mobility patterns, distances to other units, and message traffic rates.

The highest value of ROBC is in attack scenario. In offensive operations, most of the message traffic is achieved by wireless communications systems. Hence, message traffic rate is the highest in this scenario. Since the message traffic rate is a significant factor as we evaluate in experimental design, the value of ROBC is higher than other scenarios.

The highest value of ROUD is in delay operation scenario. In delay operation scenario, the distance between units is higher than all other scenarios. As the distance between units get larger, the value of ROUD increases. The defense and delay operations give similar results in terms of performance measures.

Consequently, the system is capable of supporting the brigade under different types of operations.

CHAPTER 7

CONCLUSIONS

In this study we develop a simulation model for a messaging system of a mechanized infantry brigade. The objectives of this study are to;

a) develop a simulation model of a brigade messaging system ,
b) examine the behavior of the communication system to determine if it is capable of supporting the messaging system needs under different conditions for performance measures,
c) analyze the effects of the model parameters on the performance,
d) establish the nature of the relationships among input factors and system responses,
e) compare system responses under different circumstances.

We have two performance measures under interest that are ROBC and ROUD. We determined the effects of different factors on performance measures and finally construct different scenarios to examine the effects of different types of operations on performance measures.

7.1. Significant Factors on Performance Measures

We perform 2^k factorial design to determine the effects of factors on performance measures and detect interactions between factors. We choose five factors that may affect the system performance. These are type of brigade, message traffic rate, mobility, weather and terrain conditions and existence of buffer. Then, we implement ANOVA to determine the factors that have significant effects on performance measures. The significant factors on ROBC are type of brigade, message traffic rate, and existence of buffer. Existence of buffer has an effect that decreases the value of the performance measure while the other significant factors have increasing effects.

We have also four significant two-way interaction effects. These are between factors type of brigade-traffic rate, traffic rate-mobility, type of brigade-existence of buffer and traffic rate- existence of buffer. The results show us that as the number of messages increase in the system, the system robustness goes down. Since the distances between the units of the brigade in an offensive operation are not long, the effect of mobility is not significant. But as the distances get longer, this effect will increase.

The significant factors on ROUD are type of brigade, mobility and weather and terrain conditions. Type of brigade and weather and terrain conditions have effects that decreases the value of ROUD while mobility has an increasing effect. The weather and terrain conditions is the most significant factor. The only two-way interaction effect is between type of brigade and weather and terrain conditions. As the number of units in the same area increase, the network will be more connected because of the multi-hop capability of units. The distance between units is an important factor for this performance measure.

When we evaluate the system, the system performs well for all performance measures. It seems that the system does not have a serious problem. The multi-hop capability of units extends the connectivity of the network. The effect of the higher usage of multimedia files is negative on the system performance. Units should send this type of data, when the network is less congested.

7.2. Different Scenarios

To see the performance of the system in different types of operations, we model different types of operations and conduct simulation runs. To investigate the effects of different types of operations on performance measures, we model a defense scenario, a delay scenario and a movement scenario. All these types of operations have a different effect on performance measure, since each has different characteristics in terms of mobility patterns, distances to other units, and message traffic rates.

The highest value of ROBC is in attack scenario. In offensive operations, most of the message traffic is achieved by wireless communications systems. Hence, message traffic rate is the highest in this scenario. Since the message traffic rate is a significant factor as we evaluate in experimental design, the value of ROBC is higher than other scenarios.

The highest value of ROUD is in delay operation scenario. In delay operation scenario, the distance between units is higher than all other scenarios. As the distance between units get larger, the value of ROUD increases. The defense and delay operations give similar results in terms of performance measures.

Consequently, the system is capable of supporting the brigade under different types of operations.

7.3. Future Research Topics

In this study we evaluate messaging system of a mechanized infantry brigade. The system can be studied in higher echelons such as Corps operations or lower echelons such as battalion operations. Also, the Armored Brigade, Infantry Brigade can be studied.

We model and analyze the mobile subsystem of a communications network on the battlefield. The studies that include the wide area subsystem and local area subsystem can be conducted.

In our study, the mobile users use TDMA technique to access the channel. The tactical communications systems that use different routing and channel access protocols and comparisons of these protocols can be studied.

The tactical internet will provide the infrastructure that supports a wide variety of battlefield management systems in near future. Different systems including evolving tactical communications systems, such as tactical internet on the battlefield can be studied.

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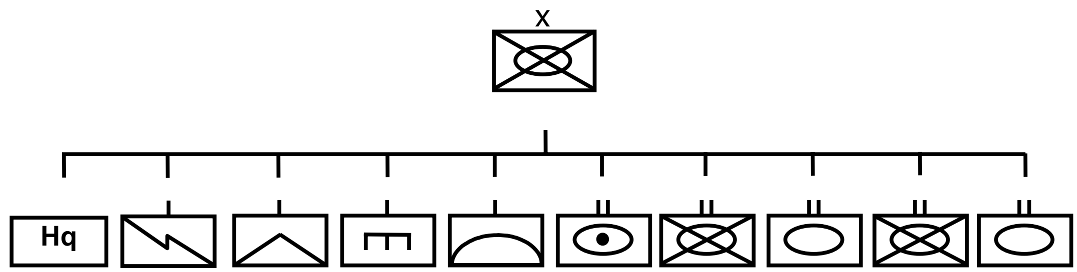
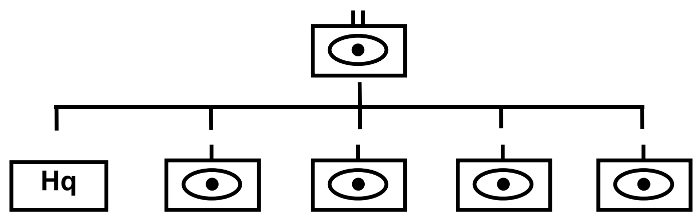
APPENDIX-A

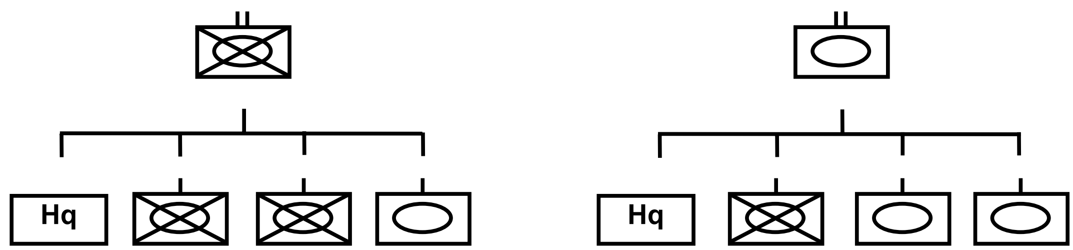
Hq



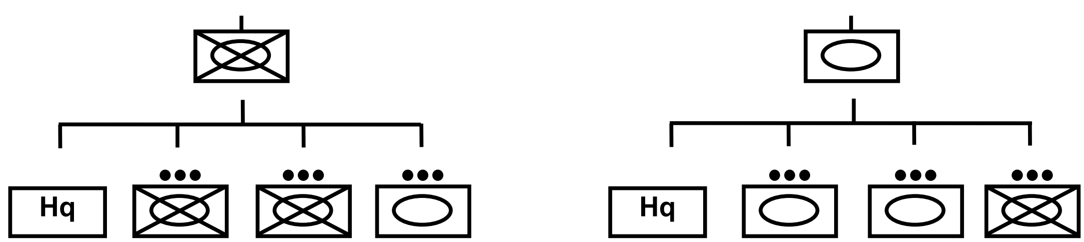
a) The organizational chart of a Mechanized Infantry Brigade



b) The organizational chart of a Mechanized Artillery Battalion



c) The organizational charts of Mechanized Infantry and Armored Battalions



d) The organizational charts of Mechanized Infantry and Armored Companies

Figure A.1. The organizational chart of a Mechanized Infantry Brigade and its units

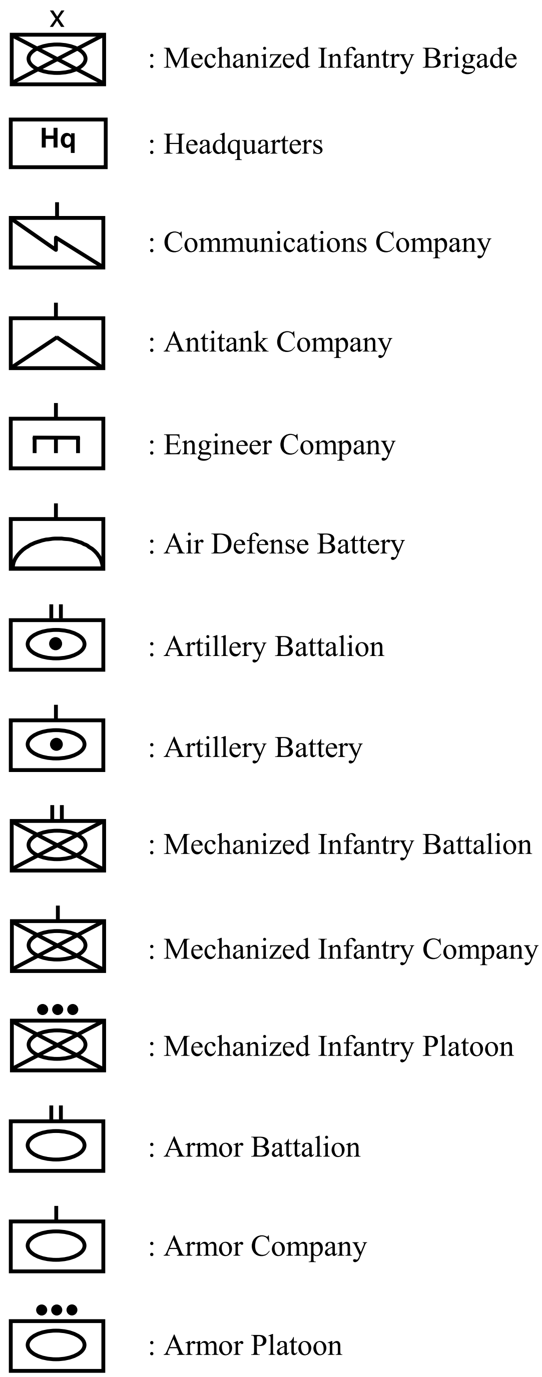


Figure A.2. Explanation of Unit Symbols

APPENDIX B

```
145$ BRANCH,1:
        If,rap1mem,146$,Yes:
        If,rap2mem,147$,Yes:
        Else,148$,Yes;
146$ ASSIGN: rap=1:NEXT(149$);
147$ ASSIGN: rap=2:NEXT(149$);
148$ ASSIGN: rap=3:NEXT(149$);
149$ BRANCH,1:
        If,destrap1mem,150$,Yes:
        If,destrap2mem,151$,Yes:
        Else,152$,Yes;
150$ ASSIGN: destrap=1:NEXT(157$);
151$ ASSIGN: destrap=2:NEXT(157$);
152$ ASSIGN: destrap=3:NEXT(157$);
157$ BRANCH,1:
        If,type==2,161$,Yes:
        If,type==3,160$,Yes:
        Else,163$,Yes;
161$ ASSIGN: maxhop=3:NEXT(169$);
160$ ASSIGN: maxhop=1:NEXT(169$);
163$ ASSIGN: maxhop=5:NEXT(169$);
169$ ASSIGN: call duration=uniform(calldur(type,1),calldur(type,2)):
        timein=tnow:NEXT(174$);
190$ ASSIGN: i=0:NEXT(183$);
183$ WHILE:  i<13:NEXT(181$);
181$ ASSIGN: i=i+1:
        n=i:NEXT(184$);
184$ WHILE:  n<13:NEXT(182$);
182$ ASSIGN: n=n+1:
        Dist(i,n)= Sqrt((Coor(i,1)-Coor(n,1))*(Coor(i,1)-
              Coor(n,1))+(Coor(i,2)-Coor(n,2))*(Coor(i,2)
               - Coor(n,2))):
        Dist(n,i)=Dist(i,n):
        Adj(i,n)=0:
        Adj(n,i)=0:NEXT(188$);
188$ IF:    dist(i,n)<=transrange(i).and.dist(i,n)<=
             transrange(n).and.i<>n:NEXT(189$);
189$ ASSIGN: Adj(i,n)=1:
        Adj(n,i)=1:NEXT(187$);
187$ ENDIF;
185$ ENDWHILE;
186$ ENDWHILE:NEXT(191$);
206$ ASSIGN: i=13:
        n=13:NEXT(199$);

199$ WHILE:  i<56:NEXT(198$);
198$ ASSIGN: i=i+1:
        n=i:NEXT(200$);
200$ WHILE:  n<56:NEXT(214$);
214$ ASSIGN: n=n+1:
        Dist(i,n)=Sqrt((Coor(i,1)-Coor(n,1))*(Coor(i,1)-
             Coor(n,1))+(Coor(i,2)-Coor(n,2))*(Coor(i,2)
             - Coor(n,2))):
        Dist(n,i)=Dist(i,n):
```

```
          Adj(i,n)=0:
          Adj(n,i)=0:NEXT(204$);
204$ IF:    dist(i,n)<=transrange(i).and.dist(i,n)
          <=transrange(n).and.i<>n:NEXT(205$);
205$ ASSIGN: Adj(i,n)=1:
          Adj(n,i)=1:NEXT(203$);
203$ ENDIF;
201$ ENDWHILE;
202$ ENDWHILE:NEXT(207$);
223$ ASSIGN: i=56:
          n=56:NEXT(216$);
216$ WHILE:  i<99:NEXT(215$);
215$ ASSIGN: i=i+1:
          n=i:NEXT(217$);
217$ WHILE:  n<99:NEXT(231$);
231$ ASSIGN: n=n+1:
          Dist(i,n)=Sqrt((Coor(i,1)-Coor(n,1))*(Coor(i,1)-
                Coor(n,1))+(Coor(i,2)-Coor(n,2))*(Coor(i,2)
                - Coor(n,2))):
          Dist(n,i)=Dist(i,n):
          Adj(i,n)=0:
          Adj(n,i)=0:NEXT(221$);
221$ IF:    dist(i,n)<=transrange(i).and.dist(i,n)
          <=transrange(n).and.i<>n:NEXT(222$);
222$ ASSIGN: Adj(i,n)=1:
          Adj(n,i)=1:NEXT(220$);
220$ ENDIF;
218$ ENDWHILE;
219$ ENDWHILE:NEXT(224$);
298$ ASSIGN: ch=0:
          ABRestTot=0:
          BARestTot=0:
          BothFree=0:NEXT(299$);
299$ WHILE:       ch<28:NEXT(300$);
300$ ASSIGN:      ch=ch+1:NEXT(301$);
301$ IF:    ABRest(Hop(y),ch)==0.and.
          BARest(Hop(y),ch)==0:NEXT(302$);
302$ ASSIGN: BothFree=BothFree+1:NEXT(303$);
303$ ENDIF;
304$ IF:    ABRest(Hop(y),ch)==1:NEXT(305$);
305$ ASSIGN: ABRestTot=ABRestTot+1:NEXT(306$);
306$ ENDIF;
307$ IF:    BARest(Hop(y),ch)==1:NEXT(308$);
308$ ASSIGN: BARestTot=BARestTot+1:NEXT(309$);
309$ ENDIF;
325$ ENDWHILE:NEXT(310$);
310$ ASSIGN: ch=0:
          k=0:
          ToA=AINT(min(BothFree,max(0,BothFree/2-
          (ABRestTot-BARestTot)/2))):NEXT(311$);
311$ WHILE:  ch<28:NEXT(312$);
312$ ASSIGN: ch=ch+1:NEXT(313$);
313$ IF:    ABRest(Hop(y),ch)==0.and.
          BARest(Hop(y),ch)==0:NEXT(314$);
314$ BRANCH,1:
          If,ToA<=k,435$,Yes:
          Else,436$,Yes;
```

```
435$ ASSIGN: Decide 202.NumberOut True=Decide 202
         .NumberOut True + 1:NEXT(315$);
436$ ASSIGN: Decide 202.NumberOut False=Decide 202.
         NumberOut False + 1:NEXT(316$);
315$ ASSIGN: k=k+1:
         BARest(Hop(y),ch)=1:NEXT(317$);
317$ ENDIF;
318$ ENDWHILE:NEXT(319$);
319$ ASSIGN: ch=0:
         ABRestTot=0:
         BARestTot=0:NEXT(320$);
320$ WHILE:  ch<28:NEXT(321$);
321$ ASSIGN: ch=ch+1:NEXT(322$);
322$ IF:    ABRest(Hop(y),ch)==1:NEXT(323$);
323$ ASSIGN: ABRestTot=ABRestTot+1:NEXT(324$);
324$ ENDIF;
326$ IF:    BARest(Hop(y),ch)==1:NEXT(327$);
327$ ASSIGN: BARestTot=BARestTot+1:NEXT(328$);
328$ ENDIF;
329$ ENDWHILE:NEXT(165$);
165$ BRANCH,1:
         If,slot/2<(29-ABRestTot).and.slot/2<
         (29-BARestTot),437$,Yes:
                  Else,438$,Yes;
437$ ASSIGN: Decide 183.NumberOut True=Decide 183.
         NumberOut True + 1:NEXT(344$);
438$ ASSIGN: Decide 183.NumberOut False=Decide 183.
         NumberOut False + 1:NEXT(335$);
344$ ASSIGN: ch=0:
         k=0:NEXT(345$);
345$ WHILE:  k<slot/2:NEXT(346$);
346$ ASSIGN: ch=ch+1:NEXT(347$);
347$ IF:    ABRest(Hop(y),ch)==0:NEXT(348$);
348$ ASSIGN: k=k+1:
         SelectCh(Hop(y),k)=ch:
         Channels(Hop(y),ch)=2:
         Channels(Hop(y+1),ch)=1:NEXT(349$);
349$ ENDIF;
350$ ENDWHILE:NEXT(351$);
351$ ASSIGN:      ch=0:NEXT(352$);
352$ WHILE:  k<slot:NEXT(353$);
353$ ASSIGN: ch=ch+1:NEXT(354$);
354$ IF:    BARest(Hop(y),ch)==0:NEXT(355$);
355$ ASSIGN: k=k+1:
         SelectCh(Hop(y),k)=ch:
         Channels(Hop(y),ch)=1:
         Channels(Hop(y+1),ch)=2:NEXT(356$);
356$ ENDIF;
357$ ENDWHILE:NEXT(371$);
```

APPENDIX-C

Table C.1. The number of calls in a day at an offensive operation

Unit	Minimum	Average	Maximum
Brigade Headquarters	42.8	67.83	92.86
Air Defense Battery	16	36.5	57
Antitank Company	19.5	39	58.5
Communications Company	26	47	68
Engineer Company	20	33	46
Artillery Battalion Hq.	23	57	91
Artillery Battery	19	35	51
Mech.Inf/Armor Bat.Hq.	44	70.25	96.5
Recon. Platoon	6	17	28
Radar Section	7	14	21
Recon Squad	5	12	19
Mortar Platoon	18.5	28.5	38.5
Comm. Platoon	12	22	32
Antitank Platoon	17	28	39
Mech.Inf/Armor Company	14	35	56
Mech.Inf/Armor Platoon	10.5	18.5	26.5

Table C.2. Call duration times (seconds)

	Minimum	Average	Maximum
Messages	1.7	5.1	8.5
Voice Calls	15	82.5	150
Live Video	20	70	120
Other Data	5	47.5	90

APPENDIX-D

Table D.1. Factors and Design Points

	DESIGN POINTS	A	B	C	D	E
1	00000	-1	-1	-1	-1	-1
2	10000	+1	-1	-1	-1	-1
3	01000	-1	+1	-1	-1	-1
4	00100	-1	-1	+1	-1	-1
5	00010	-1	-1	-1	+1	-1
6	00001	-1	-1	-1	-1	+1
7	11000	+1	+1	-1	-1	-1
8	10100	+1	-1	+1	-1	-1
9	10010	+1	-1	-1	+1	-1
10	10001	+1	-1	-1	-1	+1
11	01100	-1	+1	+1	-1	-1
12	01010	-1	+1	-1	+1	-1
13	01001	-1	+1	-1	-1	+1
14	00110	-1	-1	+1	+1	-1
15	00101	-1	-1	+1	-1	+1
16	00011	-1	-1	-1	+1	+1
17	11100	+1	+1	+1	-1	-1
18	11010	+1	+1	-1	+1	-1
19	11001	+1	+1	-1	-1	+1
20	10110	+1	-1	+1	+1	-1
21	10101	+1	-1	+1	-1	+1
22	10011	+1	-1	-1	+1	+1
23	01110	-1	+1	+1	+1	-1
24	01101	-1	+1	+1	-1	+1
25	01011	-1	+1	-1	+1	+1
26	00111	-1	-1	+1	+1	+1
27	11110	+1	+1	+1	+1	-1
28	11101	+1	+1	+1	-1	+1
29	11011	+1	+1	-1	+1	+1
30	10111	+1	-1	+1	+1	+1
31	01111	-1	+1	+1	+1	+1
32	11111	+1	+1	+1	+1	+1

Table D.2. Results of 15 replications for ROBC

	00000	**10000**	**01000**	**00100**	**00010**	**00001**	**11000**	**10100**
1	0.0026	0.0101	0.0089	0.0065	0.0038	0.0037	0.025	0.0094
2	0.0037	0.0066	0.0089	0.0044	0.0041	0.0081	0.0239	0.0095
3	0.005	0.0068	0.0134	0.0025	0.0032	0.0069	0.0287	0.0093
4	0.0054	0.0068	0.0106	0.0044	0.0054	0.0073	0.0241	0.0115
5	0.0029	0.0063	0.0114	0.0067	0.005	0.0093	0.0254	0.0101
6	0.0045	0.0129	0.0087	0.0027	0.0058	0.0105	0.0221	0.0101
7	0.006	0.0141	0.0102	0.0062	0.0029	0.0049	0.0225	0.0092
8	0.0031	0.0107	0.0111	0.0064	0.004	0.0058	0.0225	0.0119
9	0.0024	0.0088	0.0109	0.0047	0.0044	0.0059	0.0216	0.0144
10	0.0031	0.0102	0.0082	0.0046	0.0029	0.0025	0.023	0.0087
11	0.0046	0.0068	0.0078	0.0024	0.004	0.0032	0.0242	0.0079
12	0.0016	0.0129	0.0128	0.0055	0.0054	0.0086	0.0219	0.0098
13	0.0037	0.0101	0.0115	0.0073	0.0025	0.007	0.0223	0.0152
14	0.0067	0.0095	0.0127	0.0044	0.0063	0.0049	0.0261	0.0061
15	0.0037	0.0088	0.0103	0.0026	0.0024	0.0062	0.0171	0.0099
AVG	0.0039	0.0094	0.0105	0.0048	0.0041	0.0063	0.0234	0.0102
VAR	2E-06	6E-06	3E-06	3E-06	2E-06	5E-06	7E-06	5E-06
	10010	**10001**	**01100**	**01010**	**01001**	**00110**	**00101**	**00011**
1	0.0148	0.0065	0.0082	0.0111	0.0086	0.003	0.0053	0.0039
2	0.0082	0.0076	0.0083	0.0149	0.0082	0.0021	0.0073	0.0035
3	0.0066	0.0047	0.0127	0.0134	0.0067	0.0015	0.0063	0.0054
4	0.0109	0.007	0.0092	0.0114	0.0064	0.0058	0.0092	0.006
5	0.0099	0.0048	0.0098	0.011	0.0048	0.0042	0.0089	0.004
6	0.0102	0.0054	0.0078	0.0118	0.0045	0.0048	0.0051	0.004
7	0.0123	0.0084	0.0137	0.0108	0.0038	0.005	0.0053	0.0085
8	0.0113	0.0045	0.0137	0.014	0.0076	0.0044	0.003	0.0106
9	0.0072	0.0067	0.0093	0.0083	0.0079	0.0049	0.0046	0.0044
10	0.0094	0.0069	0.0116	0.0135	0.0093	0.0024	0.0047	0.0047
11	0.0086	0.0072	0.0083	0.0129	0.0069	0.0015	0.004	0.0036
12	0.011	0.008	0.0135	0.011	0.0055	0.0065	0.0048	0.0075
13	0.011	0.005	0.0086	0.0128	0.0063	0.0025	0.0059	0.005
14	0.0066	0.0052	0.0116	0.0109	0.0039	0.0035	0.0037	0.0055
15	0.0116	0.0073	0.0116	0.0109	0.0041	0.004	0.0079	0.0036
AVG	0.01	0.0063	0.0105	0.0119	0.0063	0.0037	0.0057	0.0053
VAR	5E-06	2E-06	5E-06	3E-06	3E-06	2E-06	3E-06	4E-06

Table D.2. Results of 15 replications for ROBC (cont'd)

	11100	11010	11001	10110	10101	10011	01110	01101
1	0.0257	0.0208	0.0116	0.0071	0.0077	0.0061	0.0096	0.003
2	0.0243	0.0224	0.0098	0.0057	0.0076	0.0062	0.0105	0.0109
3	0.022	0.0246	0.0083	0.0119	0.0066	0.0075	0.008	0.0041
4	0.0216	0.0211	0.0104	0.0119	0.0072	0.0087	0.0129	0.0047
5	0.023	0.0245	0.0086	0.0096	0.0064	0.0047	0.0117	0.0069
6	0.0224	0.0266	0.01	0.0114	0.0089	0.0075	0.0097	0.0065
7	0.0238	0.0288	0.0084	0.0131	0.0039	0.0038	0.0114	0.0043
8	0.0213	0.021	0.0091	0.012	0.0083	0.0071	0.0084	0.0068
9	0.0179	0.0249	0.0078	0.0081	0.0059	0.0045	0.0137	0.0046
10	0.0201	0.0241	0.0065	0.0065	0.0055	0.008	0.0097	0.0045
11	0.0226	0.0267	0.0104	0.0077	0.0054	0.0066	0.0088	0.0055
12	0.0245	0.0246	0.0082	0.0117	0.0057	0.0077	0.012	0.0093
13	0.0272	0.0251	0.0081	0.0098	0.006	0.0085	0.0076	0.0036
14	0.0246	0.0221	0.0099	0.0081	0.0079	0.0076	0.0113	0.0047
15	0.0225	0.0252	0.0113	0.0107	0.0083	0.0098	0.0135	0.0083
AVG	0.0229	0.0242	0.0092	0.0097	0.0068	0.007	0.0106	0.0058
VAR	5E-06	5E-06	2E-06	5E-06	2E-06	3E-06	4E-06	5E-06
	01011	**00111**	**11110**	**11101**	**11011**	**10111**	**01111**	**11111**
1	0.0057	0.0079	0.0214	0.0118	0.0107	0.0039	0.0072	0.0094
2	0.0059	0.0053	0.0235	0.0109	0.0103	0.0085	0.0064	0.0097
3	0.006	0.0081	0.0213	0.0077	0.0076	0.0068	0.006	0.0077
4	0.006	0.0055	0.0252	0.0072	0.0086	0.007	0.0068	0.0075
5	0.0063	0.0038	0.0184	0.012	0.0083	0.0062	0.0057	0.0093
6	0.0066	0.0039	0.0212	0.0068	0.009	0.0056	0.006	0.0076
7	0.0046	0.0069	0.0259	0.0079	0.012	0.0053	0.004	0.0076
8	0.0052	0.0054	0.0235	0.0083	0.0082	0.0054	0.0074	0.0084
9	0.0114	0.0077	0.028	0.0102	0.0098	0.0084	0.0038	0.0083
10	0.0035	0.0054	0.0232	0.0082	0.0096	0.0043	0.0047	0.0113
11	0.0044	0.0058	0.0234	0.0111	0.0082	0.0046	0.0039	0.0091
12	0.0068	0.007	0.0204	0.0066	0.0116	0.0082	0.003	0.0087
13	0.0068	0.0103	0.0254	0.0081	0.0095	0.0042	0.0055	0.0105
14	0.0095	0.005	0.0239	0.0106	0.0113	0.0068	0.0052	0.0076
15	0.008	0.0048	0.0229	0.0093	0.0084	0.0053	0.0049	0.0096
AVG	0.0064	0.0062	0.0232	0.0091	0.0095	0.006	0.0054	0.0088
VAR	4E-06	3E-06	6E-06	3E-06	2E-06	2E-06	2E-06	1E-06

Table D.3. Results of 15 replications for ROUD

	00000	**10000**	**01000**	**00100**	**00010**	**00001**	**11000**	**10100**
1	0.0061	0.0052	0.0091	0.0095	0.0055	0.0084	0.0066	0.0098
2	0.0095	0.0056	0.0081	0.0107	0.0093	0.0101	0.0077	0.0111
3	0.0055	0.0083	0.0096	0.0084	0.0049	0.0079	0.0076	0.0078
4	0.0074	0.0087	0.0082	0.0084	0.0079	0.0098	0.0079	0.009
5	0.0084	0.0066	0.0079	0.0066	0.006	0.004	0.0068	0.0084
6	0.0125	0.008	0.0099	0.0052	0.009	0.0111	0.0065	0.0063
7	0.01	0.0077	0.0081	0.0092	0.0077	0.0079	0.0064	0.0051
8	0.0083	0.0083	0.0084	0.0094	0.0047	0.0106	0.0074	0.006
9	0.0077	0.0054	0.0088	0.0092	0.0045	0.0064	0.0059	0.0103
10	0.0077	0.0102	0.0067	0.0133	0.0073	0.005	0.0081	0.0073
11	0.0102	0.0078	0.0093	0.0091	0.0049	0.0104	0.0092	0.0053
12	0.011	0.0075	0.009	0.0068	0.0076	0.0071	0.0077	0.0093
13	0.0052	0.0077	0.0094	0.0088	0.005	0.0085	0.006	0.008
14	0.0068	0.0038	0.0086	0.0124	0.006	0.0084	0.0063	0.0104
15	0.0088	0.0088	0.0066	0.0096	0.0081	0.0067	0.0084	0.0053
AVG	0.0083	0.0073	0.0085	0.0091	0.0066	0.0082	0.0072	0.008
VAR	4E-06	3E-06	9E-07	4E-06	3E-06	4E-06	9E-07	4E-06
	10010	**10001**	**01100**	**01010**	**01001**	**00110**	**00101**	**00011**
1	0.0074	0.0122	0.0122	0.0078	0.0094	0.012	0.0079	0.0117
2	0.0067	0.0053	0.0096	0.0085	0.0092	0.0103	0.0059	0.005
3	0.0076	0.0081	0.0077	0.0075	0.0076	0.006	0.0073	0.0055
4	0.0053	0.0077	0.009	0.006	0.0086	0.0058	0.0075	0.0038
5	0.0053	0.0042	0.0094	0.007	0.0085	0.0066	0.005	0.007
6	0.0062	0.0086	0.006	0.0054	0.0105	0.0073	0.0066	0.0065
7	0.0078	0.0058	0.0089	0.009	0.009	0.0074	0.0072	0.0045
8	0.0038	0.0064	0.0086	0.005	0.0096	0.0054	0.009	0.0096
9	0.0078	0.0086	0.0091	0.007	0.0063	0.0083	0.0041	0.0063
10	0.0084	0.0094	0.0122	0.0079	0.0107	0.0088	0.0124	0.0057
11	0.0091	0.007	0.0089	0.0077	0.0057	0.0088	0.01	0.0071
12	0.0104	0.0062	0.0075	0.0048	0.0083	0.005	0.0078	0.0045
13	0.0069	0.0066	0.0127	0.0063	0.0077	0.008	0.0133	0.0065
14	0.0038	0.005	0.0109	0.0076	0.0067	0.0045	0.0078	0.008
15	0.0056	0.0077	0.0065	0.0045	0.0108	0.004	0.0108	0.0041
AVG	0.0068	0.0073	0.0093	0.0068	0.0086	0.0072	0.0082	0.0064
VAR	3E-06	4E-06	4E-06	2E-06	2E-06	5E-06	7E-06	5E-06

Table D.3. Results of 15 replications for ROUD (cont'd)

	11100	**11010**	**11001**	**10110**	**10101**	**10011**	**01110**	**01101**
1	0.0079	0.0054	0.0063	0.0066	0.0086	0.007	0.0116	0.008
2	0.0074	0.0087	0.0079	0.0052	0.0082	0.008	0.0093	0.0077
3	0.0093	0.0071	0.0055	0.0053	0.009	0.0075	0.0067	0.0068
4	0.0071	0.0058	0.0043	0.0067	0.0083	0.0071	0.0074	0.0064
5	0.0092	0.005	0.0068	0.0088	0.0111	0.0066	0.0062	0.0111
6	0.0084	0.0068	0.0072	0.0081	0.0054	0.0072	0.0065	0.0098
7	0.0061	0.0068	0.0103	0.0052	0.0102	0.0043	0.0081	0.0092
8	0.0123	0.0071	0.0093	0.007	0.0086	0.0073	0.0077	0.006
9	0.0062	0.0085	0.0103	0.0082	0.0053	0.0063	0.0048	0.0091
10	0.011	0.007	0.0081	0.0045	0.0101	0.0038	0.0067	0.0047
11	0.0078	0.0058	0.0058	0.0063	0.006	0.0063	0.0075	0.0087
12	0.0049	0.0057	0.0082	0.0092	0.009	0.0094	0.0067	0.0101
13	0.0094	0.0039	0.0064	0.0072	0.0045	0.0056	0.0081	0.0101
14	0.0063	0.0064	0.0075	0.011	0.0079	0.0064	0.0092	0.0101
15	0.0089	0.0061	0.008	0.0073	0.0059	0.0122	0.0046	0.0087
AVG	0.0081	0.0064	0.0075	0.0071	0.0079	0.007	0.0074	0.0084
VAR	4E-06	2E-06	3E-06	3E-06	4E-06	4E-06	3E-06	3E-06
	01011	**00111**	**11110**	**11101**	**11011**	**10111**	**01111**	**11111**
1	0.0072	0.0095	0.0075	0.0076	0.0054	0.006	0.0129	0.0077
2	0.0042	0.0058	0.0071	0.0084	0.0073	0.007	0.0055	0.006
3	0.0038	0.0071	0.0052	0.009	0.0081	0.0068	0.0091	0.0086
4	0.0065	0.0095	0.0041	0.0097	0.0052	0.0045	0.0076	0.0049
5	0.0068	0.0087	0.0081	0.0101	0.0062	0.0092	0.0069	0.0072
6	0.0061	0.0094	0.0057	0.0105	0.0052	0.0069	0.0067	0.0076
7	0.0044	0.0094	0.0063	0.0072	0.0082	0.0069	0.0065	0.0075
8	0.0099	0.0069	0.0093	0.0088	0.0065	0.0057	0.0065	0.0062
9	0.0063	0.0058	0.0061	0.0081	0.0077	0.0099	0.0091	0.0049
10	0.0071	0.0064	0.0096	0.0086	0.0062	0.0086	0.0098	0.004
11	0.0114	0.0034	0.0061	0.0074	0.0092	0.0088	0.0051	0.0063
12	0.0066	0.0055	0.007	0.006	0.005	0.0057	0.0073	0.0074
13	0.0088	0.0095	0.0083	0.0065	0.0074	0.0061	0.0078	0.0058
14	0.0037	0.005	0.0065	0.0085	0.0046	0.0083	0.0092	0.0062
15	0.005	0.0053	0.0069	0.0075	0.0059	0.0053	0.0079	0.0075
AVG	0.0065	0.0071	0.0069	0.0083	0.0065	0.007	0.0079	0.0065
VAR	5E-06	4E-06	2E-06	2E-06	2E-06	3E-06	4E-06	2E-06

APPENDIX-E

Table E.1. ANOVA results for ROBC

Tests of Between-Subjects Effects

Dependent Variable: ROBC

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squa.	Nonc. Para.	Obs. Power[a]
Corrected Model	1.557E-02	31	5.023E-04	138.9	.000	.906	4305	1.000
Intercept	4.312E-02	1	4.312E-02	11921	.000	.964	11921	1.000
A	3.633E-03	1	3.633E-03	1004	.000	.692	1004	1.000
B	3.989E-03	1	3.989E-03	1103	.000	.711	1103	1.000
C	9.352E-06	1	9.352E-06	2.585	.109	.006	2.585	.165
D	3.307E-07	1	3.307E-07	.091	.762	.000	.091	.013
E	3.201E-03	1	3.201E-03	885.0	.000	.664	885.0	1.000
A * B	6.627E-04	1	6.627E-04	183.2	.000	.290	183.2	1.000
A * C	1.200E-08	1	1.200E-08	.003	.954	.000	.003	.010
B * C	1.555E-05	1	1.555E-05	4.299	.039	.010	4.299	.305
A * B * C	7.208E-07	1	7.208E-07	.199	.656	.000	.199	.018
A * D	6.750E-07	1	6.750E-07	.187	.666	.000	.187	.017
B * D	6.256E-06	1	6.256E-06	1.730	.189	.004	1.730	.103
A * B * D	7.841E-07	1	7.841E-07	.217	.642	.000	.217	.019
C * D	1.320E-05	1	1.320E-05	3.649	.057	.008	3.649	.251
A * C * D	1.430E-06	1	1.430E-06	.395	.530	.001	.395	.026
B * C * D	4.201E-07	1	4.201E-07	.116	.733	.000	.116	.014
A * B * C * D	5.547E-06	1	5.547E-06	1.533	.216	.003	1.533	.090
A * E	1.553E-03	1	1.553E-03	429.3	.000	.489	429.3	1.000
B * E	2.315E-03	1	2.315E-03	640.1	.000	.588	640.1	1.000
A * B * E	1.374E-04	1	1.374E-04	37.981	.000	.078	37.981	1.000
C * E	2.901E-07	1	2.901E-07	.080	.777	.000	.080	.013
A * C * E	.000	1	.000	.000	1.000	.000	.000	.010
B * C * E	1.121E-06	1	1.121E-06	.310	.578	.001	.310	.023
A * B * C * E	1.344E-06	1	1.344E-06	.372	.542	.001	.372	.025
D * E	3.502E-06	1	3.502E-06	.968	.326	.002	.968	.055
A * D * E	4.800E-08	1	4.800E-08	.013	.908	.000	.013	.010
B * D * E	4.256E-06	1	4.256E-06	1.177	.279	.003	1.177	.068
A * B * D * E	6.601E-07	1	6.601E-07	.182	.669	.000	.182	.017
C * D * E	4.332E-06	1	4.332E-06	1.198	.274	.003	1.198	.069
A * C * D * E	6.487E-06	1	6.487E-06	1.793	.181	.004	1.793	.107
B * C * D * E	1.387E-06	1	1.387E-06	.383	.536	.001	.383	.026
A * B * C * D * E	2.080E-06	1	2.080E-06	.575	.449	.001	.575	.035
Error	1.621E-03	448	3.617E-06					
Total	6.032E-02	480						
Corrected Total	1.719E-02	479						

a. Computed using alpha = .01

Table E.2. ANOVA results for ROUD

Tests of Between-Subjects Effects

Dependent Variable: ROUD

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squa.	Nonc. Para.	Obs. Power[a]
Corrected Model	3.049E-04	31	9.834E-06	3.005	.000	.172	93.159	1.000
Intercept	2.707E-02	1	2.707E-02	8272	.000	.949	8272	1.000
A	3.488E-05	1	3.488E-05	10.660	.001	.023	10.660	.751
B	9.720E-07	1	9.720E-07	.297	.586	.001	.297	.022
C	3.467E-05	1	3.467E-05	10.594	.001	.023	10.594	.748
D	1.843E-04	1	1.843E-04	56.308	.000	.112	56.308	1.000
E	1.704E-06	1	1.704E-06	.521	.471	.001	.521	.032
A * B	4.720E-06	1	4.720E-06	1.442	.230	.003	1.442	.084
A * C	4.201E-07	1	4.201E-07	.128	.720	.000	.128	.015
B * C	4.320E-07	1	4.320E-07	.132	.717	.000	.132	.015
A * B * C	2.133E-08	1	2.133E-08	.007	.936	.000	.007	.010
A * D	1.435E-05	1	1.435E-05	4.386	.037	.010	4.386	.312
B * D	1.925E-06	1	1.925E-06	.588	.443	.001	.588	.035
A * B * D	3.008E-06	1	3.008E-06	.919	.338	.002	.919	.053
C * D	1.875E-08	1	1.875E-08	.006	.940	.000	.006	.010
A * C * D	7.854E-06	1	7.854E-06	2.400	.122	.005	2.400	.151
B * C * D	7.500E-08	1	7.500E-08	.023	.880	.000	.023	.011
A * B * C * D	4.563E-07	1	4.563E-07	.139	.709	.000	.139	.015
A * E	1.951E-06	1	1.951E-06	.596	.440	.001	.596	.036
B * E	3.203E-07	1	3.203E-07	.098	.755	.000	.098	.014
A * B * E	2.083E-07	1	2.083E-07	.064	.801	.000	.064	.012
C * E	1.430E-06	1	1.430E-06	.437	.509	.001	.437	.028
A * C * E	6.750E-09	1	6.750E-09	.002	.964	.000	.002	.010
B * C * E	5.333E-09	1	5.333E-09	.002	.968	.000	.002	.010
A * B * C * E	3.203E-07	1	3.203E-07	.098	.755	.000	.098	.014
D * E	1.064E-06	1	1.064E-06	.325	.569	.001	.325	.023
A * D * E	2.214E-06	1	2.214E-06	.677	.411	.002	.677	.040
B * D * E	3.000E-07	1	3.000E-07	.092	.762	.000	.092	.013
A * B * D * E	4.320E-07	1	4.320E-07	.132	.717	.000	.132	.015
C * D * E	1.610E-06	1	1.610E-06	.492	.483	.001	.492	.031
A * C * D * E	4.602E-06	1	4.602E-06	1.406	.236	.003	1.406	.082
B * C * D * E	1.613E-07	1	1.613E-07	.049	.824	.000	.049	.012
A * B * C * D * E	4.563E-07	1	4.563E-07	.139	.709	.000	.139	.015
Error	1.466E-03	448	3.272E-06					
Total	2.884E-02	480						
Corrected Total	1.771E-03	479						

a. Computed using alpha = .01

APPENDIX-F

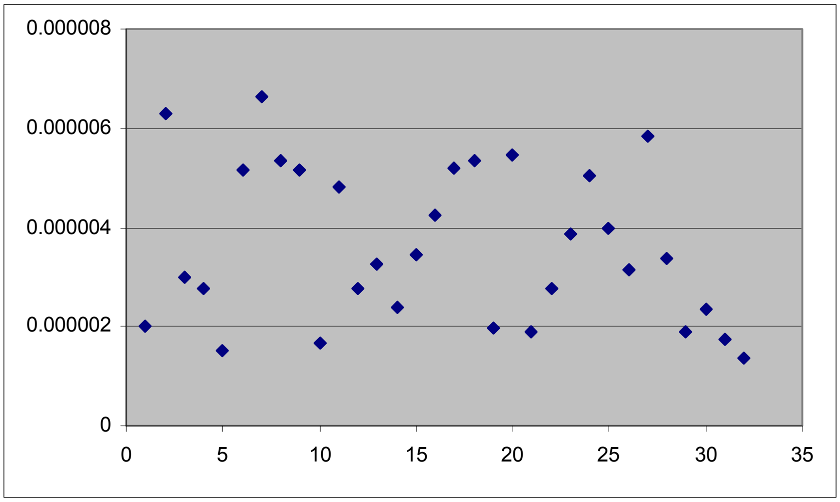


Figure F.1. Scatter plot of variances of ROBC

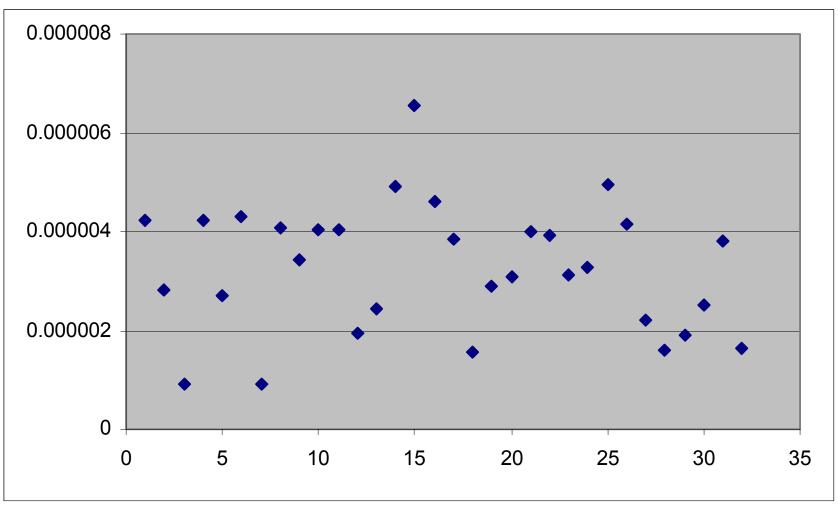
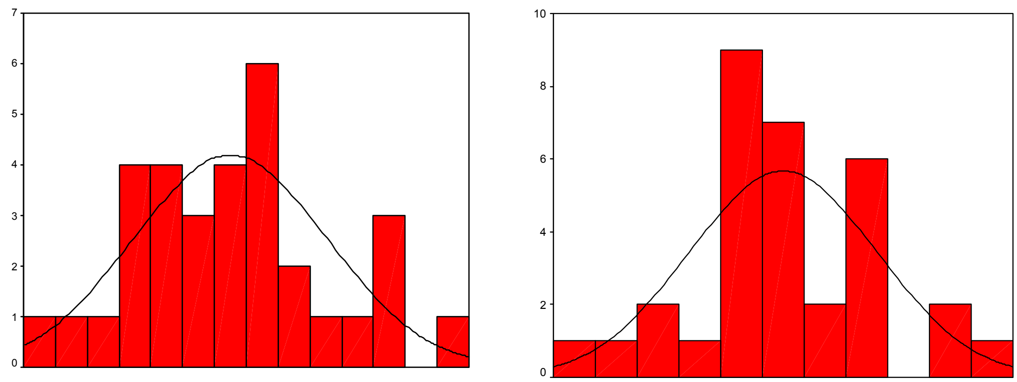


Figure F.2. Scatter plot of variances of ROUD

APPENDIX-G

Table G.1. Residual analysis for performance measures

	ROBC			ROUD		
	y	y^	e=y-y^	y	y^	e=y-y^
00000	0.0039406	0.0039	-4.062E-05	0.0083029	0.00834	3.708E-05
00010	0.0096406	0.0094	-0.0002406	0.0074179	0.0073067	-0.0001113
00100	0.0110594	0.0105	-0.0005594	0.0083029	0.0085133	0.0002104
00110	0.0043094	0.0048	0.0004906	0.0088404	0.0091067	0.0002662
00001	0.0039406	0.0041	0.0001594	0.0067179	0.00656	-0.0001579
00011	0.0056906	0.0063	0.0006094	0.0083029	0.0081533	-0.0001496
01101	0.0236094	0.0234	-0.0002094	0.0074179	0.0072333	-0.0001846
01111	0.0100094	0.0102	0.0001906	0.0079554	0.00796	4.583E-06
00101	0.0096406	0.01	0.0003594	0.0065246	0.0068067	0.0002821
00111	0.0063406	0.0063	-4.062E-05	0.0074179	0.0072533	-0.0001646
01001	0.0106906	0.0105	-0.0001906	0.0088404	0.00928	0.0004396
01011	0.0110594	0.0119	0.0008406	0.0067179	0.0068	8.208E-05
10001	0.0061594	0.0063	0.0001406	0.0083029	0.0085733	0.0002704
10011	0.0043094	0.0037	-0.0006094	0.0072554	0.0072133	-4.208E-05
10101	0.0060594	0.0057	-0.0003594	0.0088404	0.0081733	-0.0006671
10111	0.0056906	0.0053	-0.0003906	0.0067179	0.0063867	-0.0003313
11101	0.0232406	0.0229	-0.0003406	0.0079554	0.0081467	0.0001912
11111	0.0236094	0.0242	0.0005906	0.0065246	0.0064067	-0.0001179
11001	0.0093344	0.0092	-0.0001344	0.0074179	0.00746	4.208E-05
11011	0.0100094	0.0097	-0.0003094	0.0070621	0.0071067	4.458E-05
10000	0.0067094	0.0068	9.062E-05	0.0079554	0.0078733	-8.208E-05
10010	0.0063406	0.007	0.0006594	0.0065246	0.007	0.0004754
10100	0.0106906	0.0106	-9.062E-05	0.0072554	0.0074067	0.0001512
10110	0.0057906	0.0058	9.375E-06	0.0088404	0.0084333	-0.0004071
01100	0.0061594	0.0064	0.0002406	0.0067179	0.00652	-0.0001979
01110	0.0060594	0.0062	0.0001406	0.0072554	0.0071467	-0.0001088
01000	0.0232406	0.0232	-4.062E-05	0.0070621	0.00692	-0.0001421
01010	0.0089656	0.0091	0.0001344	0.0079554	0.00826	0.0003046
11100	0.0093344	0.0095	0.0001656	0.0065246	0.00654	1.542E-05
11110	0.0067094	0.006	-0.0007094	0.0070621	0.0070467	-1.542E-05
11000	0.0057906	0.0054	-0.0003906	0.0072554	0.00786	0.0006046
11010	0.0089656	0.0088	-0.0001656	0.0070621	0.00652	-0.0005421



a) Histogram of residuals of ROBC b) Histogram of residuals of ROUD

Figure G.1. Histograms of Residuals

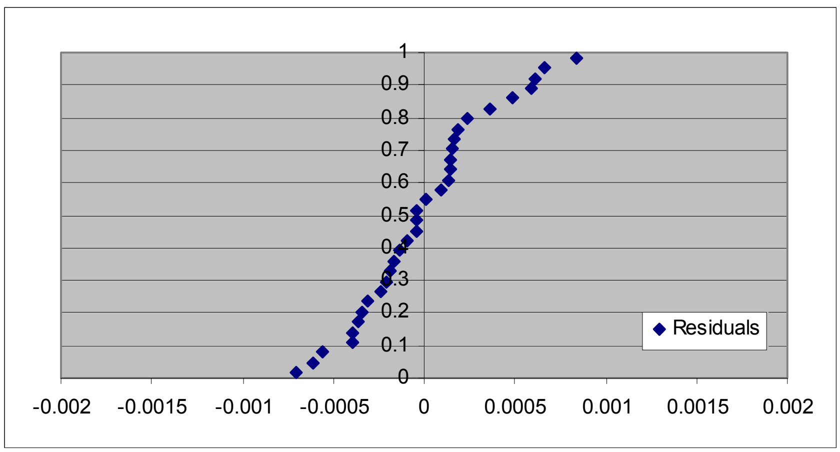


Figure G.2. Normal probability plot of ROBC

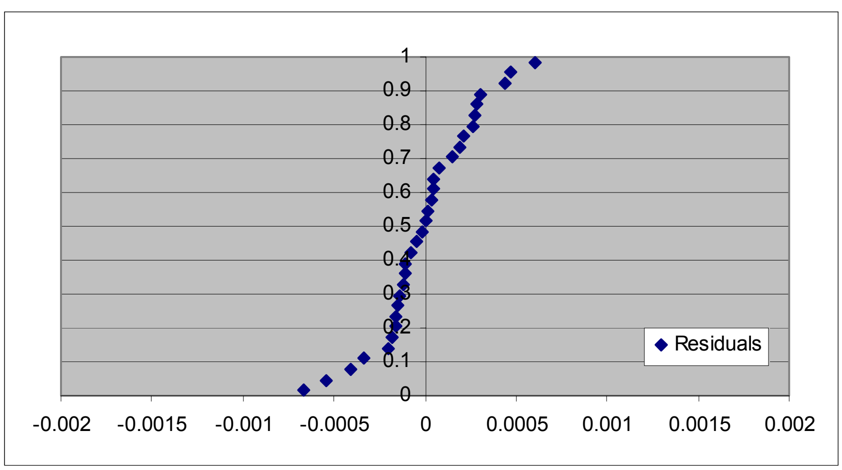


Figure G.3. Normal probability plot of ROUD

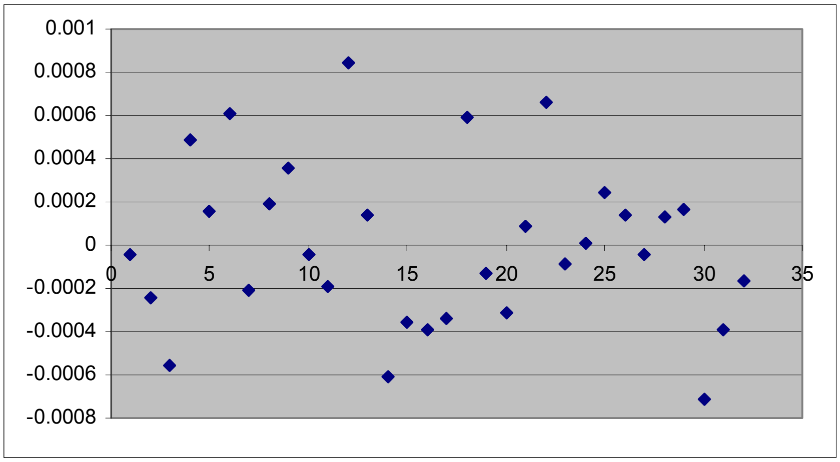


Figure G.4. Scatter plot of residuals of ROBC

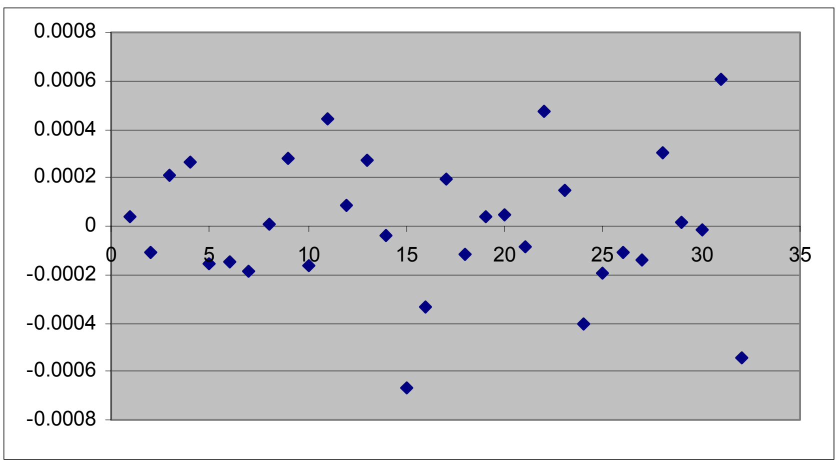


Figure G.5. Scatter plot of residuals of ROUD