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Comparative Analysis of Mobility Management Schemes in a Low Earth Orbit Satellite Network

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THESIS

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A COMPARATIVE ANALYSIS OF MOBILITY MANAGEMENT SCHEMES IN A LOW EARTH ORBIT SATELLITE NETWORK

THESIS

Presented to the faculty of the Graduate School of Engineering and Management

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In Partial Fulfillment of the

Requirements for the Degree of

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List of Abbreviations

AC	Authentication Center
ACM	Address Complete Message
A-key	Authentication key
AMPS	Advanced Mobile Phone System
ANI	Automatic Number Identification
ANSI	American National Standard Institute
ASE	Application Service Element
ASI	Application Service Interface
ASR	Authorization Status Report
BER	Bit Error Rate
BISDN	Broadband ISDN
BS	Base Station
BSC	Base Station Controller
BSS	Base Station Subsystem
BTS	Base Transceiver Station
CAVE	Cellular Authentication and Voice Encryption
CC	Control Channel
CCIS	Common Channel Interoffice Signaling
CCITT	International Telegraph and Telephone Consultative Committee
CCS	Common Channel signaling
CDMA	Code-Division Multiple Access
CLIP	Calling Line Identity Presentation
CLIR	Calling Line Identity Restriction
CRC	Cyclic Redundancy Check
CTIA	Cellular Telecommunications Industry Association
CUG	Closed User Group
D-AMPS	Digital Advanced Mobile Phone System
DCN	Data Communication Network
DoD	Department of Defense
DPC	Destination Point Code
DSSN1	Digital Subscriber Signaling System no. 1
DUP	Data User Part

EIA	Electronic Industry Association
EIR	Equipment Identification Register
EML	Element Management Layer
ESN	Electronic Serial Number
ET	Earth Terminal
ETC	Earth Terminal Controller
FC	Forward Channel
FDD	Frequency Division Duplexing
FEC	Forward Error Correction
FDS	Full Duplex Systems
FISU	Fill-In Signal Unit
FM	Frequency Modulation
GEO	Geosynchronous Satellite
GMS	Gateway-Management System, or Global System for Mobile
GOS	Grade Of Service
GTT	Global Title Translation
HDLC	Higher-level Data Link Control
HDS	Half Duplex Systems
HLR	Home Location Register
IAM	Initial Address Message
ID	Identification
IMSI	International Mobile Station Identification
IP	Internet Protocol
IS	Interim Standard
IS-41	Interim Standard 41 (Mobility Management)
ISCP	ISDN Signaling Control Part
ISDN-UP	Integrated Services Digital Network User Part
ISL	Inter-Satellite Link
ISND	Integrated Service Digital Network
ISUP	Integrated Service Digital Network User Part
ITU-T	International Telecommunication Union - Telecommunications Standardization Sector
LA	Location Area
LAP-B	Link Access Procedure Balanced

LEO	Low Earth Orbit
LMI	Layer Management Interfaces
LSSU	Link Status Signal Units
LU	Location Update
MAP	Mobile Application Part
MC	Message Center
MF	Multi-Frequency
MIB	Management information Base
MOC	Message Origination Controller
MRVT	MTP Routing Verification Test
MS	Mobile Station or Mobile Subscriber
MSC	Mobile Switching Center
MSRN	Mobile Station Roaming Number
MSU	Message Signal Unit
MTP-2	Message Transfer Part-Level 2
MTP-3	Message Transfer Part-Level 3
MTTF	Mean Time To failure
MTTR	Mean Time To repair
NE	Network Element
NML	Network Management Layer
NSDU	Network Service Data Unit
NSP	Network Services Part
OA&M	Operation, Administration and Maintenance
OAM&P	Operation, Administration, Maintenance, and Provisioning
OMAP	Operation, Maintenance, and Administration Part
OPC	Origination Point Code
OPNET	Optimized Network Engineering Tools
OS	Operation Systems
OSI	Open System Interconnection
PCN	Personal Communications Network
PCM	Pulse Code Modulation
PCR	Preventive Cyclic Retransmission
PCS	Personal Communications Services
PDU	Protocol Data Unit

PSTN	Public Switched Telephone Network
RC	Reverse Channel
REL	Release
RLC	Release Complete
RM	Reference Model
ROSE	Remote Operation Service Element
SABM	Set Asynchronous Balanced Mode
SCCP	Signaling Connection Control Part
SDLC	Synchronous Data Link Control
SF	Single Frequency
SIM	Subscriber Identity Module
SIF	Signaling Information Field
SIO	Service Information Octet
SIPO	Signaling Indication Process Outage
SLS	Signaling Link Selection
SMAP	Systems Management Application Process
SMS	Short Message Service
SP	Signaling Point
SS7	Signaling System Number 7
SSD	Shared Secret Data
STK	Software Took Kit
STP	Signaling Transfer Point
SU	Signaling Units
TC	Transactions Capabilities
TCAP	Transactions Capabilities Application Part
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TIA	Telecommunication Industry Association
TLA	Two Location Areas
TLC	Temporary Location Cache
TLDN	Temporary Local Directory Number
TMN	Telecommunication Management Network
TMSI	Temporary Mobile Station Identity
Um	Air Interface

UP	User Part
UUI	User to User Information
VLR	Visitor Location Register
VPN	Virtual Private Network
WIN	Wireless Intelligent Network

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Abstract

In the 60's the United Status and the Union of Soviet Socialist Republics engaged in a "space race" to be the first to put a man on the moon. Today, the space race is between large multinational telecommunication corporations with the winner receiving the financial rewards by providing communication services to the billions without even a simple telephone. Many entrants are using Low Earth Orbit (LEO) satellites to provide the communications infrastructure, but the number of customers a satellite can support is limited by bandwidth available. This resource must be used efficiently, and this involves reducing the management overhead. This thesis investigates one aspect of management overhead, the bandwidth cost associated with mobility management.

This thesis provides a performance analysis of three different mobility management topologies and their associated protocols when used in a LEO satellite constellation. Simulations were developed to compare two aspects of mobility management protocols. The first aspect was to determine which is the better location for the Visitor Location Register (VLR) and Authentication Center, collocated with the Home Location Register in the terrestrial gateways or placed on the communications satellites. The second aspect compared three methods of updating the VLR, if the VLR is onboard the satellite. Three different update schemes were examined: using the standard IS-41-C protocol, transferring the database from one satellite to another, or discarding the database and rebuilding it from scratch.

The thesis results concluded that simply moving the VLR from the gateway to the satellite did not decrease the traffic overhead associated with mobility management. In fact, the amount of traffic increased about 33 percent. Moving the AC and VLR together to the satellite however decreased the traffic load by average of 10 percent over the standard model. With the AC and VLR onboard the satellite, it is determined that discarding the database and rebuilding it from scratch is the best update method. This scheme reduced the mobility management traffic by taking advantage of the properties of the satellite constellation. These properties reduced total mobility traffic overhead by 30 percent.

A COMPARATIVE ANALYSIS OF MOBILITY MANAGEMENT SCHEMES IN A LOW EARTH ORBIT SATELLITE NETWORK

Chapter 1: Introduction

"The beginning of knowledge is the discovery of something we do not understand."
- *Frank Herbert (1920-1986)*

1.1. Background

As the twenty-first century begins, there is a push to provide universal telephone service. Currently, the industrialized nations have approximately 500 telephones for every thousand people, while developing nations lag far behind with only about 60 telephones for every thousand people (Figure 1) [CIA99]. Trying to build a conventional public switched telephone network (PSTN) infrastructure to give the rest of the world the same communications availability as the industrial nations will be too costly and labor intensive. Instead, the lofty goal of universal telecommunications service throughout the world can only be achieved through to use of cellular and satellite networks [Meg97].

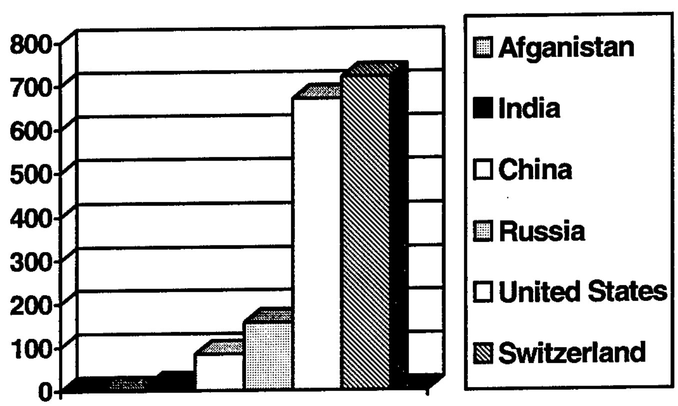

Figure 1. Number of Telephones per 1000 people [CIA99]

there were more than 45 million cellular subscribers worldwide. By the year 2005, it is predicted that there will be more than 100 million subscribers (Figure 2) [GSM96]. PCN has the potential to provide low cost connections in areas with dense populations, but for many rural areas, PCN may not be economically feasible. Although cellular telephone networks are wireless for the subscriber, they rely on a terrestrial backbone to support communications between the other components of the network, and to connect the subscriber. This infrastructure is not cost-effective if it supports a limited number of customers. In addition, PCNs with their fixed antennas and terrestrial base stations cannot adequately cover the oceans, mountainous regions, remote islands and other inaccessible areas.

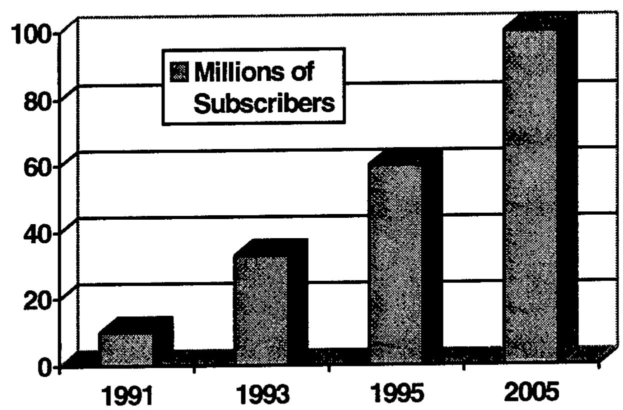

Figure 2. Cellular Subscriber Growth Worldwide [GSM96]

In contrast, Low Earth Orbiting (LEO) satellites can provide connectivity anywhere in world, without the need of any terrestrial components in remote areas. Satellite networks, like Iridium® [Iri00] and Globalstar® [Glo00], have recently begun operations and are designed to give mobile subscribers (MS) the ability to place and receive calls anytime from anyplace. Providing this capability to the mobile user requires the satellites to support the five basic functions of a mobile network: mobility management, radio system management, call processing management, terrestrial transmission facilities management, and operations, administration and maintenance [GaS97].

To explain each one briefly, mobility management comprises the functions needed to enable the users to be mobile. Radio management handles the radio resources, connections and transmission paths between the mobile users and the network. Call processing management establishes, maintains, and releases calls to and from the subscriber. Terrestrial transmission facilities management works with the physical means of providing voice and data communication interactions between the PSTN and the satellite network. Finally, operations, administration and maintenance allow the satellite network provider the means to monitor and control the network [GaS97].

Satellite and cellular networks share the same five functions of a mobile network, and so when the satellite systems were being developed, the protocols for each of these management functions were transferred from the terrestrial cellular environment into the satellite arena, without any major modifications. However, satellite systems have different limitations and strengths than a PCN, thus the best protocol for a PCN may be inappropriate for a satellite system. This research examines one aspect of network management, mobility management, and determines if protocols based on satellite properties are advantageous, when compared to those developed for a PCN.

1.2. Research Goal

This research has two goals:

- to compare the overhead associated with different mobility management schemes

- to determine if a topology taking in account the strengths and weaknesses of LEO satellites has less overhead than a standard terrestrial-based topology.

1.3. Research Motivation

This thesis provides a performance analysis of three different mobility management topologies and their associated protocols when used in a LEO satellite constellation. The subject of LEO satellite-based communication networks is a relatively new field receiving much attention. This interest is generating a wealth of fresh topics for research, since certain aspects of satellite operations are not specified in literature. Specifically, the protocols used by the satellites for the five basic mobile network functions are not readily available, thus creating the opportunity for researchers to speculate on which ones are being used today, and develop new protocols for the satellites of tomorrow. The most intriguing aspect is the homogenous nature of the current generation of satellite networks, allowing new protocols to be tested without the need to worry about compatibility issues.

This thesis concentrates the area of mobility management. Mobility management involves four major functions: intersystem handoff, automatic roaming, authentication, and call processing. The interactions between these four areas create a complex web that defies finding an easy way to derive an optimal solution, i.e., optimization in one area usually leads to degradation in another. Reviewing research in terrestrial cellular networks show many possible options for mobility management. This variety of approaches, coupled with the scarcity of information about specific satellite implementations of mobility management, make an intriguing combination.

1.4. Approach

This research used [Lee97] as a point of departure. In [Lee97], two user location-tracking algorithms were investigated in the LEO environment: the *gateway approach* and the *satellite approach*. In the *gateway approach*, the user information database is located in the terrestrial gateways. In the *satellite approach*, the information is maintained on board the satellites. His conclusions indicate that the *satellite approach* performs better than the *gateway approach* in call setup delay and number of hops required to establish initial call requests.

This thesis first examines a standard mobility management protocol, Interim Standard-41 (IS-41), currently used in most of North America. The protocol is changed in four incremental steps to determine if the protocol can be modified to take advantage of the LEO satellite network's unique characteristics without losing compatibility with the PSTN and other external networks. The first step moves the Visitor Location Register (VLR) from the terrestrial gateways to the satellites. This is followed by moving the Authentication Center (AC) from the gateways to the satellites. The third step determines the overhead associated with moving the VLR database from one satellite to the next. Finally, with the VLR and AC in each of the satellites, a new time-based location updating scheme is introduced where the world is divided into fixed cells, and intersatellite communications eliminate the need for transferring the VLR database. Each of these changes is compared with the standard protocol model in use today. The key performance measure is the amount of traffic generated by each protocol. However, the number of messages sent, average number of hops, and peak loading are also examined.

1.5. Overview of Results

This thesis shows that simply moving the VLR from the gateway to the satellite does not decrease traffic overhead associated with mobility management. In fact, the amount of traffic increases about 33 percent. Moving both the AC and VLR to the satellite does decrease the traffic load by an average of 10 percent.

With the AC and VLR residing in the satellite, this thesis shows that with certain changes to the protocol, completely discarding the database and rebuilding it from scratch is the best method examined to update the VLR database on a satellite. This scheme reduced the mobility management traffic by taking advantage of the satellite constellation's properties. These properties allowed the total mobility traffic overhead to be reduced by 30 percent.

1.6. Summary

This chapter introduced the goals of the research, and provided some of the motivation behind pursuing this line of study. The chapter continued with a brief synopsis of the foundation this thesis builds on. Section 1.5 concluded this chapter by presenting an overview of the results from this study. The following chapters will provide more depth on the facts, models and results used to support this thesis.

Chapter 2 presents a review of the current literature for mobility management and low earth orbiting satellites. First, the many proposed and actual versions of mobility management protocols used in a terrestrial cellular network environment are examined. This is followed by an overview of LEO satellites, their strengths and weaknesses, and why they are being used for mobile communications. The chapter concludes with an explanation of the use of mobility management in low earth orbiting satellites.

Chapter 3 describes the methodology used to compare the overhead associated with different mobility management schemes. This includes the presentation of models developed to support the thesis. Chapter 4 presents results obtained through network simulation and analyzes it. Chapter 5 concludes the thesis with a discussion of conclusions and recommendations for areas of future research in mobility management in a LEO environment.

Chapter 2: Literature Survey

2.1. Introduction

This chapter examines the area of mobility management in Low Earth Orbiting (LEO) Satellite systems. This specific field is not well represented in literature, and a Literature Survey cannot address it as a unified topic. Instead, it is better to explain the topic as three separate areas, and then combine them into a coherent subject.

Section 2.2 provides a brief overview of cellular networks. This section goes into detail about how a typical Personal Communication Network (PCN) is configured, and explains its major components. Section 2.3 provides an in-depth discussion of the mobility management schemes used in a PCN, concentrating on IS-41-C. Section 2.4 gives an overview of satellite communications with special emphasis on LEO satellites. Finally, Section 2.5 concludes the chapter by explaining mobility management in a satellite network.

2.2. Wireless Communications

> "You see, wire telegraph is a kind of a very, very long cat. You pull his tail in New York and his head is meowing in Los Angeles. Do you understand this? And wireless telegraph operates exactly the same way: you send signals here, they receive them there. The only difference is that there is no cat."
>
> -- *Albert Einstein (1875-1955)*

2.2.1. Introduction

Communications have advanced rapidly since 1837 when Samuel Morse first demonstrated the wire telegraph in the United States. Over the next 150 years, the telegraph, telephone, radio, and television have become commonplace. Wireless communications, both cellular and satellite, will soon be just as ubiquitous.

With each communication advance, new challenges must be faced and overcome. Moving from a fixed communications system to a mobile system is no different. Many of the basic assumptions used to build the public switched telephone network (PSTN) do not hold in a wireless network. First, the subscribers in a wireless network are not in a fixed location. They are usually mobile and may not be located near where their cellular phone is registered. So, the network must have the ability to locate and route calls to the mobile subscriber (MS) quickly and efficiently. Second, the network must compensate for limited processing and power capabilities of the small handheld radios used to communicate with the network [LaS96]. Another concern is that the reliability and bandwidth capacity of the channels used in wireless system are less than in the PSTN. The network protocols must conserve bandwidth and robustly handle errors. Finally, the user's equipment is low powered and not physically attached to network, and the network doesn't offer complete coverage. So, connectivity between the network and the user may possibly be sporadic. The network must be able to tolerate intermittent disconnects.

2.2.2. Network configuration

To overcome these obstacles and provide service to the maximum number of subscribers possible, most wireless systems have adopted a standard configuration based on a cell architecture [RoM99]. Figure 3 shows an idealized version of a cell.

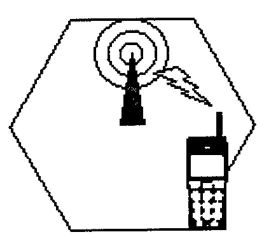

Figure 3. Idealized Cell

Typically, it is viewed as a hexagon with a base transmitter located in the center. Any cellular telephone that is within the hexagon can communicate with the base transceiver. A wireless system, like PCN, consists of a large number of these cells. Figure 4 provides an illustration of a small PCN network. This PCN consists of fifteen cells, each with a base transceiver to communicate with mobile users. The base transceiver is connected to the other base transceivers through a fixed landline network (dark and light connecting lines). Tracing a communication path on Figure 4, a subscriber (lower left corner) sets up an air link with the base transmitter controlling the cell it is located in. The signal is then passed through the landlines to the nearest base transmitter to receiver (light connecting lines. The signal is then converted back to an air link, and is received by the mobile user's handset (upper right corner).

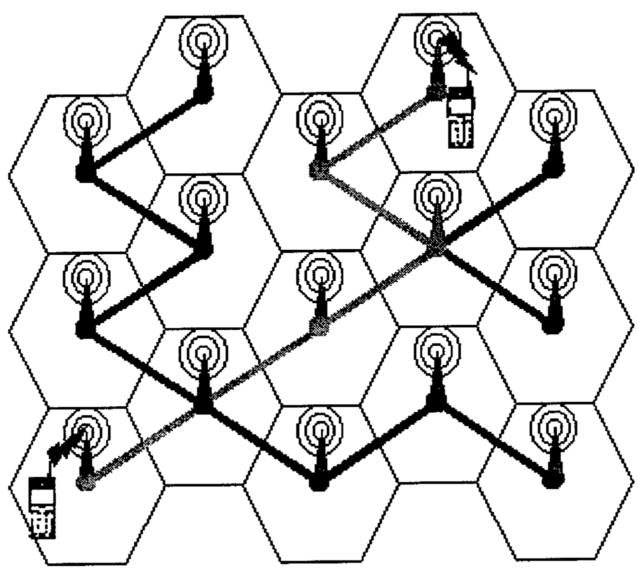

Figure 4. Small PCN

To support the mobile subscribers, the network has to interface with the MS's equipment, and be able to connect users on the PCN or the standard telephone system. To perform all these tasks and various bookkeeping details, the PCN is composed of three major components: the mobile terminal equipment, the base station subsystem, and network subsystem.

2.2.2.1 Mobile Terminal Equipment

The mobile terminal equipment is the equipment the subscriber uses to communicate with the rest of the network. This equipment may be a telephone, laptop, fax, or other communication device. It must be small and lightweight, require little power to transmit, and receive signals clearly using a small omni-directional antenna [Lut98]. The equipment must also support the protocols of the network to allow for handoffs, to update its location, to acknowledge terminal paging, and to send and receive calls.

2.2.2.2 Base Station Subsystem

As discussed earlier, current PCNs are designed using a cellular architecture. This means a coverage area is divided into a large number of smaller areas called cells [AkH95a]. Because each base transceiver controls only one cell, and transmits its signal out a limited distance, the same frequency is available for use in others cell, located at least one cell away. A typical seven cell pattern is shown in Figure 5. The cells with the same letter are using the same frequency. This frequency reuse allows the cellular network to support more users with a limited bandwidth.

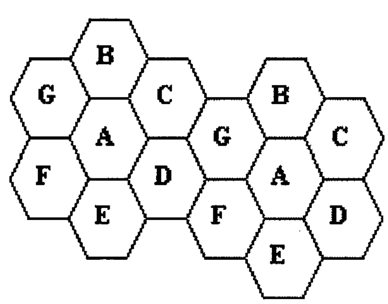

Figure 5. Seven Cell Frequency Reuse

Inside each of these cells is a base station subsystem consisting of a Base Transceiver Station (BTS) and a Base Station Controller (BSC). The BTS communicates with all the mobile subscribers within its coverage area [AkH95b]. In a large urban area, the potential exists for a large number of BTSs to be deployed. The BSC manages the radio resources for one or more BTSs. It handles radio channel setup, frequency hopping, and handovers. The BSC also translates the voice channel used over the radio link to the standard 64 kbps channel used by the PSTN. In addition the BSC is the connection between the MS and the Network Subsystem.

2.2.2.3 Network Subsystem

The network subsystem is the interface to the fixed landline network, and performs all the functions of a standard network node. Standard network nodes can forward data packets using a standard protocol like Internet Protocol (IP), maintain a routing table, and communicate with other nodes. In addition, the network subsystem node can verify the service class information of the subscriber, obtain location information and interpret the routing information and route the call. In a PCN, the mobile switching center (MSC), home location register (HLR), and the visiting location register (VLR) handle these processes [JaC95].

The MSC is the central component of the Network Subsystem. It acts like a normal switching node of the public telephone network. The MSC also provides all the functionality needed to handle a mobile subscriber, such as registration, authentication, location updating, handovers, and call routing to a roaming subscriber. The information needed to handle this additional functionality is located in two types of databases: the HLR and the VLR.

The HLR is the database maintained by the mobile subscriber's service provider. It is normally located in the coverage area where the mobile subscriber spends a majority of his time. This register maintains all the basic information about the subscriber. It usually contains the telephone number of the cellular phone, the subscriber's billing information, his authentication and profile information [HaL98], and the last known location of the subscriber [Lin97a].

The VLR contains selected administrative information from the HLR, necessary for call control and provision of the subscribed services for each user currently located in the geographical area controlled by the VLR. The MSC center uses the information in the HLR and VLR to efficiently route calls to and from the mobile subscriber [HaL98].

2.2.3. Challenges

"Welcome every problem as an opportunity. Each moment is the great challenge, the best thing that ever happened to you. The more difficult the problem, the greater the challenge in working it out."

-- *Grace Speare*

2.2.3.1 Medium

Creating a seamless wireless communication network is fraught with challenges. To start with wireless communication is limited by the medium. Unlike wired networks, wireless networks operate in a limited bandwidth. This bandwidth must support all the customer and management traffic. This limitation can be mitigated by dividing the service area into cells and reusing the frequencies in nonadjacent cells as described in

Section 9. This requires the base station and terminal to limit their transmission power to prevent bleeding over into other cells.

Limited power is beneficial because it conserves battery power, but it also leads to increased shadowing. Shadowing is caused by obstacles between the base station and the terminal that block the radio transmissions, which leads to fading and lost calls [Lut98]. Another difficulty of wireless communication is multipath fading. As signals travel through the air, there are obstacles that cause the signal to reflect. These reflections can create interference with the original signal and cause this signal to arrive at the receiver at different time. The effect the channel rates of the wireless link [AbL97].

2.2.3.2 Mobility

The system must handle the mobility of the users. Users will change their network attachment point over time. Therefore, the capability to gracefully pass the communication connection from one network attachment to another is needed. In a packet switched network, new packets will have to be routed to the new cell, and packets in transit during handoff will have to switch destinations. Ideally, this is done without delaying or losing any packets. If the system is part of an ATM network, then packets must also be kept in the correct order. For a circuit-switched network, the entire circuit will have to be rerouted, again without losing information. If losses do occur, then the network must be able to recover gracefully. The TCP/IP protocol handles all packet losses as if they are caused by network congestion, which triggers recovery procedures, that reduces throughput needlessly [LaS96].

Another challenge is having the channel capacity to accept handovers. During times of heavy use, the cell may not have the capacity to accept the call, which will result in a forced termination [Lin97a]. But reserving too many channels for the possibility of call transfers results in preventing new calls from being established (new call blocking) while channels are idle. This reduces revenue and results in unsatisfied customers.

2.2.3.3 Location Management

Even if the terminal is not communicating during the transition from one network attachment to another, information still needs to be passed between the handset and the base station. Unlike the standard telephone system, the telephone number of a wireless terminal does not signify the location of the terminal. Instead the terminal must be tracked. Therefore, as a terminal travels from one spot to another, it needs to inform the network of its new location so that it can receive incoming calls. The base station in turn needs to inform the handset of the new frequencies that are used in cell it is entering.

Keeping track of highly mobile user tends to waste bandwidth and power by sending unnecessary location updates [AkH95b]. This problem is compounded by the tremendous growth of wireless networks. With only a limited number of frequencies available, the networks are forced to shrink the size of the cells to increase capacity and coverage [ScK99]. As the number of cells increase, so does the signaling requirement for location management. This increase in signaling reduces the bandwidth available for customers. It also increases the number of handoffs and the problems associated with it.

In addition, overall location management traffic generated between base stations, mobile users, and management nodes imposes a significant burden on the wireline network. Inter-switch networking traffic can account for up to 30 percent of the load on the switches [DaS97].

Another limitation to wireless communications is the additional time required to set up calls. In most location management schemes at least two database lookups are required, and then at least one paging cycle must be done before a call can be established [AbL97].

2.3. Wireless Location Management

"If you don't find it in the index, look very carefully through the entire catalogue."

Sears, Roebuck, and Co.,
Consumer's Guide, 1897:

2.3.1. Introduction

Providing the subscriber with the ability to place or receive calls from anywhere in the world requires the PCN to carry out specific processes. The first process, location management, gives subscribers the ability to roam from one coverage area to another. Location management provides the network the means to locate the subscriber as soon as an incoming call is made [Lin97a]. The second process, handoff, allows the network to smoothly transfer a call when a user moves from one cell to another. Other important processes supported by the network include managing the radio spectrum, providing uniform coverage, and reducing interference problems [JaC95]. This Section concentrates on the investigation of Mobility Management schemes, which includes location management, paging, call setup, and call teardown.

Mobility Management is defined as tracking all the mobile subscribers all the time. So when an incoming call arrives, using Location Management, a mobile subscriber can be located and paged in a cellular network within a certain amount time [DaS97]. Without a mobility management facility, wireless communications would be one-way. Mobile users could call out but never receive calls. Currently, most PCNs use two basic activities to handle Mobility Management: location management and terminal paging [DaS97].

2.3.2. Location Management

If a call is made to the mobile user before the network is aware the user exists, the call is lost because the network cannot route the call. Location update is how a mobile user registers with the network and lets the network know its location. How and when the mobile user should send out location update messages has been the subject of much research [AkH95a, AkH95b, GuR98, HaL98].

With the first wireless systems, the mobile user had to manually register with the local wireless service to receive incoming calls. If the user entered a new service area without registering, the service provider had no record of his existence [NgN98].

This evolved into automatic registration. Automatic registration allows the mobile terminal equipment to communicate with the base station without manual intervention. Interim Standard IS-41 is the basis of most automated location management systems used in the United States. But location update is only half of the equation; the other half is terminal paging.

2.3.3. Terminal Paging.

When an incoming call comes in, the network needs to contact the mobile subscriber. This process is called terminal paging. The process works as described below.

A call enters the PCN at one of the switches. This originating switch looks at the number requested, determines the mobile subscriber's Home Location Register, and queries the HLR for the MS's current location. The HLR, in turn, queries the visitor location register of the cell in which the MS last registered. The VLR then queries the mobile switching center to determine if the mobile subscriber is able to receive the call. The mobile switching center sends out a paging message to its service area. Ideally, the mobile terminal equipment hears and acknowledges the page. The MSC then assigns a temporary local directory number (TLDN) to the terminal and gives this routable address to the VLR. The VLR passes the TLDN to the HLR, which informs the originating switch. The originating switch can now connect the call [Lin97a].

2.3.4. Location Update and Terminal Paging Interaction

If bandwidth and power were not limiting factors, then every time a mobile user entered a new cell, it could register with the base station. This would allow the network to know exactly where the user is at all times, and reduce the paging area to just the one cell [WaJ99]. Under this scenario, the number of registration updates is high and the traffic load on the wired network between MSC and HLRs increases. On the other hand, paging is minimal and performed very quickly [GuR98].

At the other extreme, the mobile user could conserve power by never registering with the network [NgN98]. Then when an incoming call arrived, the network would send out a paging message to every cell in the network. If the mobile user is on, it is found and receives the call [DaS97]. The system requires no databases, but the paging flood has a high cost [WaJ99].

But since bandwidth and power are limiting factors, cellular networks currently try to minimize the average cost of paging and registration. The modular nature of a cellular network allows the system to group adjacent cells together to share the registration and paging tasks. This group of cells is called a location area (LA)[AkH95b].

In a static location area, all the cells within the LA broadcast the same LA signature. When a mobile user crosses an LA boundary, it detects the new signature and sends a location update message [RoM99]. The user's location information is then added to the VLR, which then forwards the information to the HLR [GuR98]. Then, as long as the user remains in the same LA, it is not required to send any additionally location update messages. When an incoming call arrives, the network consults the HLR, determines the mobile user's LA, and sends a paging signal to each cell of the location area [AkH95b].

A simple relationship exists between registration/paging costs and the size of the Location Area. As the size of the LA increases, the cost of registering is lowered, but the cost to page all the cells goes up. If the size of the LA decreases, then mobile users have to register more often, increasing their cost, but the cost of paging goes down.

2.4. Location Update Schemes

A person travels the world over in search of what he needs and returns home to find it.
George Moore (1852-1933)

2.4.1. Introduction

An optimal solution attempts to minimize the total cost for location management without requiring excessive computation or communications costs. As mentioned earlier, the total cost can be viewed as a tradeoff between the cost of registering mobile users and the cost to page the users when there is an incoming call [AbL97]. A good mobile terminal tracking policy balances location update with paging so that the total cost is minimized [AkH95b]. This goal of reaching an optimal cost has lead to research in developing new location update algorithms, reducing paging costs, and reducing database accesses [AkH95a, AkH95b, GuR98, HaL98]. Some of these schemes will be presented in the following sections.

2.4.2. Location Update Algorithms

2.4.2.1 Introduction

A majority of the research in location management has been concentrated on developing better location update algorithms [Abl97, AkH95a, GuR98, HaL98, Lin97a]. This area of research is critical, since power and computation limitations of mobile terminals have been of paramount concern. The standard approaches to location update can be divided into two types: static and dynamic updates.

In static updates, the configuration of the network is determined during the construction of the net. The network's location areas are established, and are not altered while the network is running. If any changes are needed, they are determined off-line, and are hard-wired into the system. In the United States, IS-41 is a common static location update algorithm, but other proposed algorithms include: reporting cell, time-based, movement-based, and distance-based algorithms.

Unlike static location update, dynamic location update is not predetermined. Instead, the mobility pattern of the mobile subscriber and how often it receives incoming calls determine when it registers [AbL97]. This scheme, when implemented correctly, can provide significant savings over static methods, but at higher computational and implementation costs.

2.4.2.2 IS-41

The North American Standard IS-41 provides a good benchmark for all location management schemes. It is the most extensively used scheme in the United States. A trace diagram of the IS-41's location update message passing is presented in Figure 6. In IS-41, cellular networks are divided in location areas. Each location area broadcasts a unique signature on a special frequency for mobile terminal receivers. When the mobile terminal enters a new location area, it reads the new location area's signature, determines it is in a new location area, and broadcasts a location update message. This message is received by the base station, which then passes the information to the VLR of the location area. The VLR looks up the address for the HLR, and requests verification of the user as a valid user. The HLR returns a Secret Shared Data (SSD) field, which is used to authenticate the mobile user. Upon authentication, the VLR sends the HLR a registration message informing it that the mobile user is now in the VLR's area. The HLR sends a deregistration message to the old VLR and then acknowledges the message. The mobile terminal is then acknowledged [Lin97a].

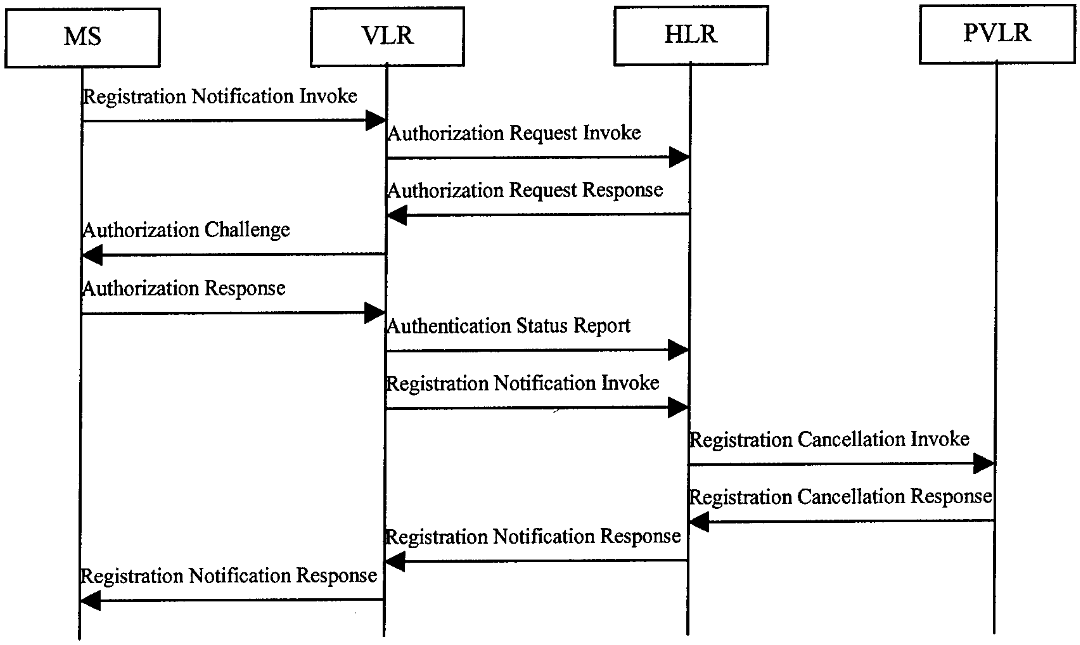

Figure 6. IS-41 Location Update Trace Diagram

Paging under IS-41 is just as straightforward. The entire process to setup a call from the PSTN to a mobile user is traced in Figure 7. A call enters the PCN at one of the switches. This originating switch looks at the number requested, determines the mobile subscriber's HLR, and queries the HLR for the MS's current location. The HLR then queries the visitor location register of the cell in which the MS last registered. The VLR then queries the mobile switching center to determine if the mobile subscriber is able to receive the call. The mobile switching center sends out a paging message to its service area. Ideally, the mobile terminal equipment hears and acknowledges the page. The MSC then assigns a temporary local directory number (TLDN) to the terminal and gives this the routable address to the VLR. The VLR passes the TLDN to the HLR, which informs the originating switch. The originating switch can then connects the call [Lin97a].

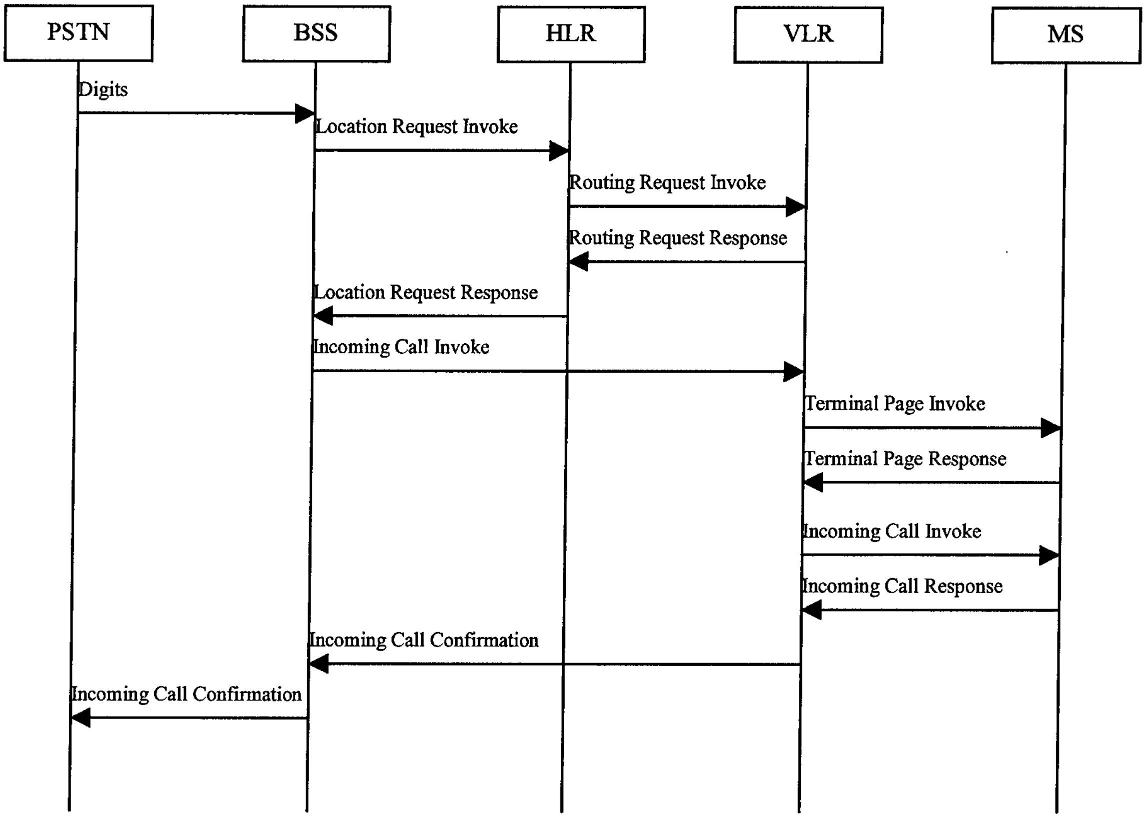

Figure 7. IS-41 PSTN to MS Call Setup

2.4.2.3 Time-Based Location Update

Time-based location update is one of the simplest location update schemes. After waiting a specific amount of time, the mobile terminal sends out a location update message [DaS97]. The virtue of this scheme is that it requires no external stimulus, needing only an internal clock or countdown timer for updating. Time-based updating also provides predictable updates, which are advantageous, when either the HLR or VLR are not reliable [HaL98]. The downside is that many location update messages are sent even when the mobile user is stationary. This wastes both communication bandwidth and terminal power. Another problem associated with time-based update is the size of the paging area. A fast moving user can be many miles from its last updated location and can be difficult to find.

The newer time-based variations are dynamic and allow the time interval to be adjusted according to the expected frequency of incoming calls. Optimally, this allows the terminal equipment to predict when the next call will be received and send out a location update message just before the HLR needs it. In [HaL98], it is shown that the reliability of the home location register is also a factor in determining how often a mobile terminal should update. If the HLR is unreliable, then updates should be done more often than the average time between incoming calls. Otherwise the updates should occur approximately once between calls.

2.4.2.4 Movement-Based Locatio n Update

Another simple location update algorithm is movement-based location update. In this scheme, the terminal monitors the broadcast signature of the cell's base station. Every time a different signature becomes the strongest, the user knows that it has entered a new cell, and updates in cell number. After the terminal crossed a predetermined number of cells (n), it sends out a location update message [AhK95]. The paging area is easy to calculate since the MS can only be up to n cells away. As Figure 8 shows, if n is 4 and the cellular network is hexagonal, then the paging area contains 61 cells. This number can be calculated from Equation 1.

$$Cell_{total} = 1 + \sum_{x=0}^{n} 6x \qquad (1)$$

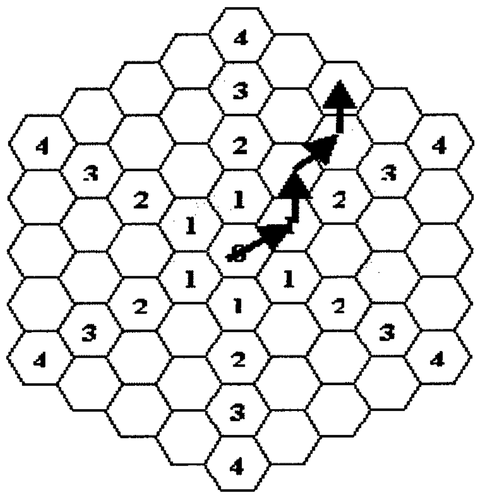

Figure 8. MS Movement (n=4)

This scheme is effective since it reduces the number of update messages sent by a stationary or slow-moving terminal. It is also widely used since it requires only limited computation resources and is easy to implement.

The chief disadvantage of movement-based location update include an excessive number of update messages are sent if the terminal is moving quickly and the number of incoming calls is low [AkH96]. Another disadvantage is a higher paging cost. Since the terminal does not update every time it enters a location area, its location is not precisely known. When the network receives an incoming call, it must search for the terminal by sending polling signals to all the cells in the vicinity of the last known location [AkH96]. Another concern is that if the terminal is on the boundary between two cells, that it would often bounce between the two signatures. This causes many messages to be generate when in turns wastes significant bandwidth, processing power and power output [AhK95].

2.4.2.5 Distributed HLR with Two Location Areas

Distributed HLR with Two Location Areas (HLR/TLA) is designed to address some of the concerns with movement-based location update. The mobile subscriber has a small built-in memory to store addresses for the two most recently visited location areas. The HLR also has an extra field. The HLR also store the two most recently reported location areas [Lin97a].

The advantage of HLR/TLA is that the MS does not register if it moves back to a previously visited location area. If a user is bouncing between two location areas, no registration is needed. When there is an incoming call, the HLR pages the last reported location area. If the user is found then the cost is the same as IS-41. If the user is not found, the second location area is then paged. The scheme outperforms IS-41 when call-to-mobility ratio is low (i.e. when the user moves more often than receives calls) or when registration costs are high.

The disadvantage of HLR/TLA is that its performance degrades when the users are highly mobile, and do not remain in a two LA region. Also, the scheme is not appropriate in wireless communication systems that have high paging cost and low registration costs [Lin97a].

2.4.2.6 Reporting Cells

Another proposed scheme is to establish two different types of cells: Passive cells and reporting cells [BaK93]. Passive cells, do not send out a signature signal, and do not accept registrations except for initial registrations. All registration is done when entering a reporting cell. When the reporting cells are chosen correctly, the number of registrations can be less than other schemes. It has an advantage over movement-based since there can never exist the Ping-Pong scenario between two cells. It has an advantage over time-based schemes, if the mobile user does not move. In this scenario, no updates are needed.

The disadvantages of reporting cells are many. The biggest is that there is a possibility that a mobile subscriber can move across the network without ever hitting a reporting cell. If this happens, the user cannot be found. This defeats the purpose of location management [BaK93].

2.4.2.7 Distance-Based Location Update

The fourth basic location update algorithm is based on the distance a mobile user travels. The terminal equipment, using its knowledge of the topology of the cells [AkH95], sends a location update message only after the exceeding a threshold distance (d) between the current cell and the cell where it sent the last location update message [AbL97]. This guarantees that the user is never farther than distance *d* from the last reporting cell. The paging area is again easily calculated by paging all the cells within *d* of the reporting cell.

Distance-Based location update algorithm's chief advantage is that generates 2.5 times less update messages than either time or movement-based systems. So theoretically, it provides the best location update and paging costs [AbL97]. Unfortunately, this algorithm has the highest overhead, and requires both the network and the terminal to know how to calculate the distance. This is performed either by knowing the topology of the network or having a way to know the distance traveled by the terminal.

2.4.2.8 Distance-Based Dynamic Location Tracking

All the location update algorithms discussed so far have been static. Newer algorithms provide a dynamic component, which allows it to change the frequency of the update messages based on the characteristics of the individual terminal. The key idea is to optimize the algorithm to allow the terminal update its location just before the update cost is greater than the cost to page to terminal [AkH95a].

The first dynamic location scheme discussed is the distance-based dynamic location tracking. This method uses the cost for terminal paging, cost for location updating and the distribution of incoming calls to calculate the distance (*d*) the mobile subscriber can travel before it needs to send a location update message [AkH95b]. This process is computationally intense, but mitigates this by calculating a new distance (*d*) only when one of the three system parameters changes. Otherwise, the distance remains constant.

This offers the advantage of optimizing the cost for location management. It also makes the complexity of the algorithm is independent of the system parameter values [AkH95b]. But, this method has disadvantages. Even though the computational overhead is reduced due to infrequent distance recalculation, it is still computational intensive when the calculation is done. The method also requires additional bandwidth to inform the network of the distance being used. Finally, the mobile subscriber's equipment must be able to determine the distance traveled.

2.4.2.9 Dynamic Predictive Location Management

Another dynamic scheme that has been proposed is based on the fact the mobile movement has regularity [GuR98]. If the class of transportation (foot, car, plane) of the mobile user is known, then there is knowledge of user movement constraints. Using this information and the incoming call arrival rate, the shape of the location area can be dynamically tailored to match each individual's movement pattern.

This leads a hierarchical cellular structure, with the each user given a different shape and size of LA. This is done by creating a transition probability matrix. The matrix considers layout of the streets and highways, the incoming traffic patterns and the user's mobility.

From the probability matrix, an optimal location area is created, and stored in the HLR. This information is then communicated to the mobile user as a list of cell identifications (IDs) that are in the current LA. The user maintains this list of cell IDs, and monitors the strongest broadcast channel. When the cell ID on the broadcast channel is not in the user's list, then it is time to send a location update message. The message not only provides the network with the user current location, but also the dwell time the user spent in each cell of the previous LA. In return, the HLR calculates a new LA and sends a new list of cell ids in the new location area [GuR98].

This system works well if the movements of the user are predictable. The location updating and paging cost is kept low, since the LA includes only the cells that are most likely to be visited. Another advantage of the scheme is the computational complexity is removed from the mobile terminal and placed in the computationally unrestricted HLR.

Unfortunately, if the user's movements are more random, the scheme breaks down and does not provided a noticeable improvement.

2.4.3. Terminal Paging Schemes

2.4.3.1 Introduction

So far emphasis has been placed on the various methods of improving the registration of the mobile user. The second task required for mobile communications is terminal paging. Terminal paging is finding the mobile user when there is an incoming call.

The simplest type of paging is network flooding. When an incoming call is received, every cell in the network is paged for the mobile user. This method generates an unacceptably high traffic load on the wireless network. Imagine the Teledesic system, with over 20,000 cells, paging each of them for one user. Instead, most current systems, like IS-41, page only in the last reported LA of the mobile user [GuR98]. But, a typical LA has 60 cells, so there is still room for improvement.

2.4.3.2 Multi-step paging

Researchers have concentrated on investigating the maximum paging delay [AkH95a, AkH95b, and GuR98]. This research examines how much delay can be tolerated by the customer when finding terminal. By increasing the maximum paging delay to allow two or three paging calls, the paging area can be decreased. This is the basic premise behind multi-step paging.

There are two major types of multi-step paging: static location and shortest-distance-first. In static location, the location area is subdivided into equal sized subregions. The number of subregions is determined by the number of paging cycles allowed. When an incoming call is received, the subregion where the MS registered is paged first, then the rest of the subregions in the location area are paged in any order. The scheme is best used with any location update scheme that uses LAs as a basis.

The shortest-distance-first does not divide the area in specific subregions. The area is split into rings surrounding the cell where the user is registered. The number of rings is based on the number of paging cycles that can be made within the maximum paging delay. The ring closest to the center cell is paged first, then the page is propagated outward until the MS is found or time expires [AkH95a]. This paging scheme works well with distance-based or movement-based location updates.

By allowing multiple paging cycles, the average total costs are reduced significantly. Even increasing the paging cycle from one to two cycles makes a big difference [AkH95a]. Multi-step paging increases in use, as networks struggle to reduce management bandwidth.

2.4.4. Database Architectures

2.4.4.1 Introduction

Another way to reduce the cost of location management is to reduce the cost of updating or finding the mobile user in the database. As mentioned earlier, most location schemes use two types of databases: the HLR and the VLR. The architecture used to deploy these databases can either be centralized or distributed.

2.4.4.2 Centralized Database

Centralized databases were established first. They use simple algorithms and are easy to implement. The chief disadvantage to a centralized database is that it is hard to store all the mobile subscriber information in one database. As the network grows to support more subscribers, the load on the database increases as multiple users try to access the database simultaneously. Finally, if the database is inaccessible, the entire network goes down [WaJ99].

2.4.4.3 Decentralized Database

Recognizing these disadvantages, decentralized databases have become more prevalent. The most common configuration consists of a HLR and VLR in each location area. This does not reduce the amount of network traffic, but distributes it, and reduces the likelihood of a database being a bottleneck. To connect a call to a mobile subscriber, the wireless network switch uses the mobile subscriber's number to find the HLR. The HLR then retrieves the subscriber's location, and passes the information to the switch. The switch can then put through the call [WaJ99].

2.4.4.4 Distributed HLR/TLC

A variation to a distributed database that tries to limit the number of database accesses is the Distributed Home Location Register and Temporary Location Cache (HLR/TLC). In this scheme, there is no VLR. Instead, all the information is kept in the HLR, and so only one lookup is required. This can lead to a 20 to 40 percent reduction in wired network traffic [LaS96]. The downside is that whenever the MS moves, the HLR must be updated. One way to decrease the network traffic is to keep a TLC at each of the signal transfer points (STP). Once information about a user is retrieved from the HLR, the information is kept in a cache. Therefore, when the information is needed for another call, the information is retrieved from the TLC instead of querying the HLR [LaS96]. This system is further improved by allowing any STP in the path between the switch and the destination to also store this information in its cache. This eliminates the need to query the HLR if it receives an incoming call to the same mobile subscriber.

The disadvantage to this scheme is the possibility of stale data. Since the HLR is not queried every time, there is a chance that the MS has moved and the information in the cache is incorrect. This leads to the switch being unable to find the user, and then must query the HLR. The signal load and connection time increases. If the local call to mobility ratio is greater than 5, then the signal load and connection time is reduced when compared to the standard model [LaS96].

2.5. Introduction to Satellites

"Satellites are invisible to the naked eye and therefore can have no influence on the Earth and therefore would be useless and therefore do not exist."

Francesco Sizi, quoted by T. Cox

2.5.1. Introduction

Wireless communications based on cellular technology has made great in-roads in the developed nations with over 200 million subscribers worldwide [Evo97]. The biggest deterrent to cellular technology becoming more prevalent in developing countries is the need for a wired backbone. Satellites can eliminate this need. Other advantages for satellites include their global coverage, and that they can act as an extension to cell, mobile, and terrestrial public switched telephone networks [ChG98].

2.5.2. Geosynchronous Satellites

The science fiction writer Arthur C. Clark first suggested the concept of using geosynchronous satellites (GEOs) for communications purposes in 1945. Satellites of this type are positioned over the equator at an altitude of 35,786 kilometers and match the speed on the Earth's rotation. This allows the satellite to appear motionless to an earth observer. GEOs offer several advantages over land-based communications systems. Rapid two-way communications can be established over wide areas with only a single relay in space [Evo97]. With three satellites spaced 120 degrees apart, worldwide coverage from 70 degrees north latitude to 70 degrees south latitude can be provided [GaK98]. Earth stations can be set up and moved quickly. Furthermore, satellite systems are virtually immune to impairments such as multipath fading [Evo97]. The disadvantages of GEOs are the relatively long propagation delay of 560ms [GaK98], high transmitter-power requirements, and poor coverage at the far northern and southern latitudes. Moreover, GEOs are expensive to launch and because only a handful of satellites are typically used to achieve global coverage, they are vulnerable to single point of failure.

2.5.3. Low Earth Orbiting Satellites

The GEO disadvantages have led to interest in non-geosynchronous satellites. Recent research has examined the use of low earth orbiting satellites (LEOs) [GaK98, Gav97, Lee97]. LEOs orbit the earth at between 700 and 2000 kilometers and offer several advantages over GEOs. First, they are smaller, lighter and cheaper to launch [Lut98]. Being in a lower orbit, they have reduced propagation delay and lower transmit-power requirements. This allows users to communicate with small handheld terminals having omni-directional antennas. However, at LEO altitudes, a communications system requires more satellites to achieve global coverage (see Table 1). In addition, satellite movement relative to the ground terminal introduces Doppler shift in the received signal, and each satellite is visible from a ground terminal for only about 8 to 10 minutes at a time so that handoffs between satellites are frequent [Evo97].

Table 1. Number of Satellites for Coverage [GaK98]

Satellite Altitude (kilometers)	Number of Satellites for global coverage (10° min elevation)
500	135
700	88
1,000	60
2,000	28
4,000	15
35,786	3

Nevertheless, the majority of the new satellite systems coming on line in the next 10 years will be LEOs. Not all LEOs are the same, and can be categorized into as big, little and broadband.

The big LEOs support voice and data communications with large satellites, typically weighing between 400 to 2,000 kilograms and operating at frequencies about 1 GHz. Examples of these are Iridium® and Globalstar®. Iridium® consists of 66 satellites arranged in six planes, all in a nearly polar orbit. Each satellite has four intersatellite links and can route voice and data traffic through other satellites in the constellation, reducing the number of gateways needed.

Globalstar is a digital telecommunications system that offers wireless telephone, data, paging, fax and position location services worldwide. The 48-satellite constellation is not as sophisticated as Iridium® as it offers only "bent-pipe" relays to the local ground-based infrastructure.

The little LEOs use much smaller satellites, weighing between 40 and 100 kilograms, and operate in the UHF and VHF bands. Using the lower bands, the transmission equipment on the satellite and ground stations is cheaper. Orbcomm, STARNET, and VITASET are examples of little LEO systems [GaK98, Lee99].

The final category of LEOs is broadband. Teledesic is the sole example of this type of system. It is intended to provide broadband wireless data communications with stationary terminals at ISDN rates (1.544 Mbps). Like Iridium, it has inter-satellite links, but it has eight rather than four inter-satellite links.

This thesis uses the Iridium constellation for the simulation model. Section 2.6 will explain the constellation more thoroughly.

2.6. Iridium

2.6.1. Overview

Iridium, named after the atom with 77 orbiting electrons, was developed by an international consortium of telecommunications companies, including Motorola, Raytheon, Siemens, Telesat and Bechtel [Fos98b]. The system began in 1987, when research began on developing a low earth orbit (LEO) satellite constellation that could communicate directly with telephones. The constellation was based on a study by William S. Adams and Leonard Rider of the Aerospace Corporation, who published a paper in *The Journal of the Astronautical Sciences* in 1987 on the configurations of circular, polar satellite constellations at various altitudes providing continuous, full-earth coverage with a minimum number of satellites. However, by 1992 several modifications had been made to the system, including a reduction in the number of satellites from 77 to 66 by the elimination of one orbital plane [Nel98]. The satellites are coordinated by a network of terrestrial gateways connecting the satellite system to the existing public switched telephone network. Starting on May 5, 1997, the entire constellation was deployed within twelve months on launch vehicles from three nations: the U.S. Delta II, the Russian Proton, and the Chinese Long March. The final complement of five satellites was launched aboard a Delta II rocket on May 17, 1998. Commercial service officially began November 1, 1998.

2.6.2. Technology

The Iridium constellation consists of 66 satellites in near-polar circular orbits inclined at 86.4°. The 66 satellites are arranged in six planes, each plane containing 11 satellites. The co-rotating planes spaced 31.6 degrees apart and counter-rotating planes spaced 22 degrees apart, at an altitude of 780 km [PrR99]. The altitude range considered for the satellite system ranged for 370 km and 1100km. The lower limit marks where the atmosphere becomes substantial enough to require onboard propulsion, and extensive stationkeeping to keep the satellites from leaving orbit. The upper limit marks the beginning of the Van Allen radiation belts. Extensive shielding is required on the satellite if they fly above the radiation protection blanket provided by the belts. The final altitude was reached by cost considerations, which limited the constellation to 66 satellites. [Nel98]

With the satellites at 780 kilometers above the Earth, a satellite completes an orbit every 100 minutes and 28 seconds [BrR96]. With the circumference of the Earth being approximately 40,161 km, the ground speed of the satellite is approximately 24,000 km per hour. This speed limits the in-view time of a stationary customer to about 9 minutes and 6 seconds.

Each satellite covers a circular area roughly the size of the United States with a diameter of about 4400 km, having an elevation angle of 8.2° at the perimeter and subtending an angle of 39.8° with respect to the center of the earth. A more precise measurement was calculated by Fossa [Fos98b] as 15,299,900 km^2, which equates to a footprint radius of 2209 km (diameter 4418km). This coverage area is divided into 48 cells. The satellite has three main beam phased array antennas, each of which serves 16 cells [Woo00]. The same antenna doesn't service the same cell for the entire in-view time. Instead, the antennas walk from one cell to another as the satellite moves. Each antenna illuminates are specific cell for approximately one minute. Complex protocols are required to provide continuity of communication seamlessly as handover is passed from cell to cell and from satellite to satellite. The communications link requires 3.5 million lines of software, while an additional 14 million lines of code are required for navigation and switching. As satellites converge near the poles, redundant beams are shut off. There are approximately 2150 active beams over the globe.

The Iridium system is not just satellite constellation; it is a complete network consisting of satellites, gateways, and user handsets.

2.6.3. Satellites

The Iridium network uses a more sophisticated satellite than has been deployed up to this point (Figure 9). Instead of the typical "bent pipe" configuration, similar to Globalstar and other competitors, Motorola went with a satellite that has the capability to communicate with other satellites in the constellation. The communication is accomplished using intersatellite links (ISLs). This capability allows the network to route calls from one subscriber to another without every using a terrestrial links. Unfortunately, this capability increases the weight, cost and complexity of each of the satellites. A satellite weighs approximately 680 kg, is 13 meters in length and 4 meters in width. A total of 125 satellites have been ordered from Lockheed Martin for more than $700,000,000 [JPL00]. The total cost of this endeavor is estimated at $3.45 billion.

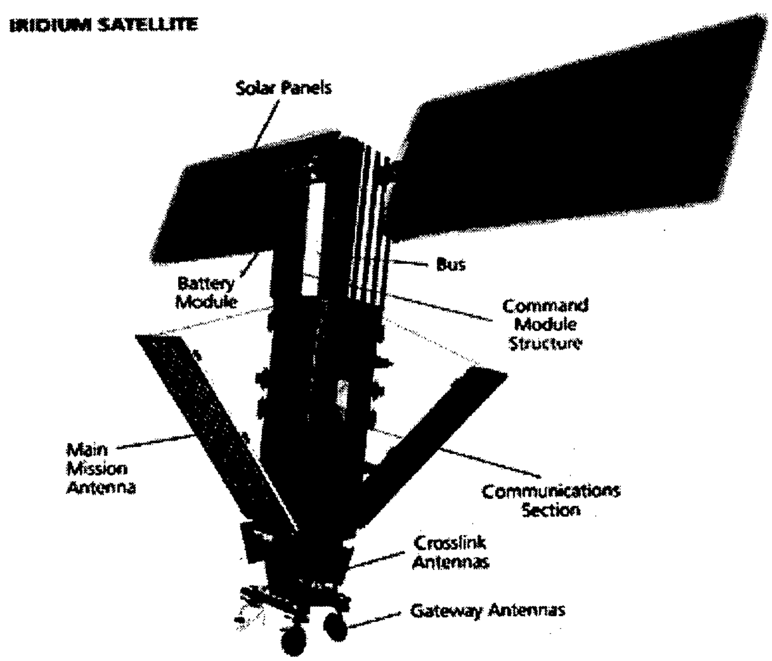

Figure 9. Iridium Satellite

The satellite's internal guidance is controlled by gyroscopes in a 3-axis stabilized configuration. This is supplemented by a hydrazine propulsion system. Power to the satellite is provided by two solar panels on a 1 axis articulation. Designed to last 8 years, the expected life span is five years.

Each satellite has a capacity of about 1100 channels. However, the actual number of users within a satellite coverage area will vary and the distribution of traffic among cells is not symmetrical.

Gateways

The connection between the Iridium system and land-based public-switched telephone networks (PSTNs) is achieved by Iridium gateways. The Iridium constellation is connected to the gateway using high-gain, 3.048-m-diameter parabolic tracking antennas operating at Ka-band frequencies with the uplink operating at 29.1 to 29.3 GHz and the downlink at 19.4 to 19.6 GHz. The antennas are housed in radomes approximately 5 m in diameter. These co-located antennas will provide the necessary geographic diversity to overcome weather as well as atmospheric signal fading and blocking.

At the heart of an Iridium gateway is the mobile switching center (MSC), a Siemens GSM-D900 switch. The MSC has two "sides:" a land side, which connects to the local telephone network, and a mobile side, which connects to an earth terminal controller (ETC). The ETC is analogous to the base-station system of a terrestrial GSM system and it controls a set of earth terminals (ETs) which communicates with the constellation using K-band radio links. Information for physical subscriber equipment is kept in the equipment identification register (EIR).

The gateway message origination controller (MOC) supports a variety of messaging services, such as direct messaging to Iridium pagers. The gateway-management system (GMS) provides operational, administration and maintenance support for each of the gateway subsystems. [Bro96]

User Handsets

The Iridium handsets are built by Motorola and Kyocera, a leading manufacturer of cellular telephones in Japan. Handsets will permit both satellite access and terrestrial cellular roaming capability within the same unit. The unit also includes a Subscriber Identity Module (SIM) card. Major regional cellular standards, like IS-41 and GSM, are interchanged by inserting a different Cellular Cassette. Paging options are available, as well as separate compact Iridium pagers [Flo93]. Current pricing is $1399 for the handset, $199 to activate the service and then a $19 service charge each month. In addition the cost of a call ranges from $1.79 to $4.79 [Tel00]. Most Iridium handset will be designed to be dual-mode. This means that not only with the user be able to communicate with the Iridium satellite, but also, with the local cellular network, if available.

The handsets, when communicating with the satellites, operate in the L-band, specifically 1621.35 to 1626.5 MHz. This 5.15 MHz bandwidth is divided into 120 FDMA channels, each with a bandwidth of 31.5 kHz and a guardband of 10.17 kHz to minimize intermodulation effects and two guardbands of 37.5 kHz to allow for Doppler frequency shifts. Within each FDMA channel, there are four TDMA slots in each direction (uplink and downlink). The coded data burst rate with QPSK modulation and raised cosine filtering is 50 kbps. Each TDMA slot has length 8.29 ms in a 90 ms frame.

The supported vocoder information bit rate is 2,400 bps for digital voice, fax, and data. The total information bit rate, with rate 3/4 forward error correction (FEC) coding, is 3,450 bps. The bit error ratio (BER) at threshold is nominally 0.01 but is much better 99 percent of the time [Bro96].

The vocoder used by the Iridium system converts the analog (voice) signal to digital one using pulse code modulation (PCM) with a nominal data rate of 64 kbps. The vocoder transmits a set of parameters that emulate speech patterns, vowel sounds, and acoustic level. The resulting bit rate of 2.4 kbps is thus capable of transmitting clear, intelligible speech comparable to the performance of high quality terrestrial cellular telephones, but not quite the quality of standard telephones [Nel98].

Communications

All these components combine together to give the user the ability to receive and sender personal communications worldwide using a single telephone number. It is designed to augment the existing terrestrial and cellular telephone networks, not to replace them. In areas where Iridium has agreements with the local cellular telephone provider, and the user has a dual-mode handset, communications will be through the terrestrial cellular network instead of Iridium.

The user dials a telephone number with the handset using an international 13 digit number. The user presses the "send" button to access the nearest satellite. The system identifies the user's position and authenticates the handset at the nearest gateway with the home location register (HLR). Once the user is validated, the call is sent to the satellite. The call is routed through the constellation and drops to the gateway closest to the destination. There it is completed over standard terrestrial circuits. For a call from the

PSTN to a mobile user, the process is reversed. After the call is placed, the system identifies the recipient's location and the handset rings, no matter where the user is on the earth. It is projected that about 95 percent of the traffic will be between a mobile handset and a telephone at a fixed location. The remaining 5 percent of the traffic represents calls placed from one handset to another handset anywhere in the world.

Communications between a satellite and the mobile user occurs once a minimum elevation angle of 8.2 degrees is reached. This angle is a compromise between cost and reception quality. The higher the satellite is in the sky, (i.e. the higher the elevation angle) the less atmosphere the signal must travel through, and better the quality. The lower the elevation angle the larger the satellite's coverage area, and the fewer satellites required to provide worldwide coverage.

According to the literature, the signal strength has a nominal 16 dB link margin. This margin is robust enough for users in exterior urban environments, but is not sufficient to penetrate buildings. Mobile users have to stand near windows or go outside to place a call. Handover from cell to cell within the field of view of an orbiting satellite is imperceptible. Handover from satellite to satellite every nine minutes may occasionally be detectable by a quarter-second gap.

Inter-Satellite Links

Iridium maintains up to 4 ISLs on each satellite. The ISL are links established between satellites in the plane (intra-planar) and between satellites in adjacent planes (inter-planar). In the intra-planar links are maintained permanently, with each satellite having forward and aft connectivity with the satellites directly in front and behind. Inter-planar links are dynamically established and terminated as the satellite transcends its orbital path. Except for the satellites in counter-rotating planes one and six, each satellite has four ISLs. The satellites located within planes one and six maintain only three ISLs each, two of which are intra-planar. Satellites in these planes are not allowed to establish ISL between each other doe to the rapid angular change that occurs between satellites in counter-rotating planes

The ISLs operate in the frequency range of 23.18 to 23.38 GHz at 25Mbps. The horizontal pointing angle between two satellites in adjacent orbital planes, using a reference of zero degrees parallel to the equator, varies between approximately ±65 degrees over one orbital period. This angle varies most slowly over the equator where satellites in adjacent orbits are the most separated, and it varies most rapidly over the poles where the orbits cross over the poles. The variation in horizontal azimuth between satellites makes steerable antennae necessary to maintain inter-orbital links. Even with steerable antennas, it would be very difficult to maintain inter-orbital links between orbital planes one and six at the higher latitudes where the azimuth varies rapidly. An approach used to maintain inter-orbital links is to select a nominal horizontal azimuth close to that between satellites over the equator. Then the antenna is designed to be steerable over a range that allows inter-orbital links at lower latitudes where the horizontal azimuth changes more slowly. Nominal horizontal azimuth of ±45 to 50 degrees with an antenna steerable over a 30 to 45 degree range is sufficient to maintain inter-orbital links between latitudes of 50 to 60 degrees north and south.

2.7. Summary

The location management strategies used in current and future satellite systems are not discussed in open literature sources, so comparison of the strategies is impossible. But satellite systems have the same type of location management needs that are present in cellular phone networks. Information on these location management systems are available and can be adapted for use in a satellite environment. Knowledge of cell networks and satellite constellations can be used to make a good working model of the typical satellite location management system. By doing so, strategies for optimizing location update and paging costs can be investigated.

Chapter 3: ANALYSIS AND MODELING METHODOLOGIES

"Do not believe in anything simply because you have heard it. Do not believe in anything simply because it is spoken and rumored by many. Do not believe in anything simply because it is found written in your religious books. Do not believe in anything merely on the authority of your teachers and elders. Do not believe in traditions because they have been handed down for many generations. But after observation and analysis, when you find that anything agrees with reason and is conducive to the good and benefit of one and all, then accept it and live up to it."

Buddha (c.563-c.483 B.C)

3.1. Introduction

This chapter explains the methodology used to analyze the overhead associated with modified mobility management protocols in three different mobile management topologies using three different traffic patterns. Section 3.2 starts by reintroducing the problem being analyzed. Section 3.3 continues with a discussion of the possible methods that can be used to analyze the problem, and explains why simulation as the best choice for this problem. Section 3.4 presents the software and hardware environment used to develop the simulation models.

With the general methodology explained, Section 3.5 addresses the scope of the problem and how the complexity of the model can be reduced without affecting the accuracy. Section 3.6 extends the discussion by adding simplifications to the model with a slight loss of accuracy. With the problem clearly defined and scoped, the input factors are introduced in Section 3.7, and foster a better understanding of how modifications to the initial environment produces the expected results. Simulation scaling, or reducing the computational intensity of the problem, is introduced in Section 3.9 to provide a way to produce accurate data in minimal time. Section 3.8 takes the scoped and simplified problem and explains the working models developed to produce the data. Section 3.10

categorizes the performance metrics produced by the models and how they are used to analyze the results produced by the simulation. Finally, Section 3.11 closes out the chapter with a short explanation of how the model are validated and verified.

3.2. The Problem

Before discussing the methodology involved in analyzing the problem and deriving potential results, it would be wise to restate the problem being examined.

3.2.1. Problem Domain

A review of currently published and on-line literature reveals a dearth of specific information on present generation of Low Earth Orbiting (LEO) satellite communication systems. Most of the information available is either outdated facts from the satellite system's public affairs office, or derived conclusions from academic papers. One case in point is the complete absence of published works on mobility management protocols used in a LEO satellite network. Only one mention of call setup was found, and it compared Iridium® to AMPS [Hub97]. All research has concentrated on terrestrial cellular telephone and personal communication networks.

3.2.2. Problem Statement

This effort determines if a standard mobility management protocol, ANSI's Interim Standard for mobility management (IS-41-C) or Global System for Mobile communications' (GSM) Mobile Application Part (MAP), is adequate for a LEO satellite system, or whether a satellite specific protocol should be developed. A variety of changes to the standard topology are examined, and a change to the IS-41-C protocol using time-based updating is introduced and compared against the standard protocol.

3.2.3. Expected Results

Standard mobility management protocols were designed for terrestrial cellular network systems. These protocols should not be as efficient as a protocol specifically designed for a satellite communications network. This is because a satellite system has to address a different set of problems than a terrestrial network. These problems include:

1. LEOs move very quickly with respect to the mobile users they support. Handoffs due to the satellite moving out of range are much more frequent than handoffs due to the mobile user leaving the satellite's footprint.

2. Satellites do not have a high speed SONET backbone for handling mobility management traffic. Instead satellites support all control traffic using organic resources.

3. LEOs have large areas of coverage. A single spot beam on a satellite generates a cell, which encompasses an area larger than hundreds of normal cells. In Iridium, a single cell covers 318,750 kilometers. This "macro-cell" needs to handle greater number of mobile users generating more mobility management messages than in a typical terrestrial cell.

4. In all operational satellite communication networks, the traffic management databases are located at the terrestrial gateways. So, to access any routing, authentication, or location information, the satellite must first establish

communications with a ground station. This station may be located thousands of miles away, and require several satellite hops to reach.

3.3. Method of Analysis

According to [Jai91], there are three possible ways to analyze a problem. An actual system can be created and directly measured; a theoretical model can be proposed and analyzed mathematically; or a computer model can be built and the problem simulated.

Direct measurement is not practical since access to and the ability to change the mobility management protocols of an operational satellite communications network is not available. In addition, the actual mobility management protocol used may be proprietary and not in open literature.

Analytical modeling is used to help validate the findings of this research but cannot be used to thoroughly analyze the problem. The research involves a LEO satellite system with a dynamic architecture containing a large number of nodes and queues. While analyzing a single node is practical given certain simplifying assumptions, scaling that analysis to a large network of nodes requires including additional assumptions. These new assumptions negatively impact the accuracy of the results. Through analysis, results acquired are only accurate within an order of magnitude, and this may not be specific enough to convincingly validate the thesis proposal.

Therefore, for this research, simulation is most appropriate tool to use. Current computer simulation software and hardware can handle both the large number of nodes involved and the dynamic nature of the architecture. Also, simulations provide a good check on the proposed hypothesis by limiting the researcher's bias in constructing the problem. The researcher determines the inputs and develops the algorithms; but the results are automatically generated. Unfortunately, detailed simulations still demand high levels of performance from the hardware platform and software tools. The current generation of computers cannot handle a completely accurate model within a reasonable amount of time, so models must be created with certain assumptions and simplifications. These simplifications are usually minor enough that they don't significantly alter the output and the simulation still generates better results than an analytical model. The assumptions and simplifications made are discussed in Sections 3.5 and 3.6.

3.4. Operating Environment

The simulation is developed in two stages on two different computer platforms. In the first stage, a LEO constellation is developed using Analytical Graphics' Satellite Tool Kit® (STK®) [STK00] version 4.01 on a Micron® ClientPro 200 with 64 MB of memory. STK® was chosen because it provided an analytical engine to calculate telemetry and display multiple 2D maps to visualize various time-dependent information for satellites. Using the up-to-date satellite database provided with the tool, it is easy to generate the position, altitude, acquisition times, and communication coverage for the satellites in any operational constellation. This information is then exported into a file format that could be read into Mil 3®'s Optimized Network Engineering Tools (OPNET®) [Mil00].

In the second stage, the satellite orbit information is imported into the OPNET® environment running on a Sun® Microsystems's Ultra 2 workstation. OPNET® was selected to develop and run the simulation for four main reasons:

1. It provides seamless integration of satellite ephemeris data from STK®. After importing the data from STK®, OPNET® can perform simulation runs without additional interaction with STK®. This advantage leads to the second factor: the ability to run OPNET® without interfacing with another package.

2. Previous network theses at AFIT used the combination of Cadence SATLAB® and Designer®. This required training in developing a simulation using two separate software applications. After development, the simulation required links between the two packages to run and generate results. The interdependence required at least one researcher to develop pilot studies to determine how the passing of data from SATLAB® to Designer® affected the run-time performance of the simulation [Fos98a]. Using OPNET® eliminates this concern.

3. OPNET® is the standard simulation tool used by the Department of Defense (DoD) for creating network simulations. This made the software available for research on this thesis. It also allows the models developed at AFIT to be incorporated in an overarching DoD Network simulation system called NETWARS. Therefore, thesis work can be applied to real-world problems, and produce results that are immediately available to DoD units.

4. OPNET® is a sophisticated workstation-based environment for the modeling and simulation of communication systems, protocols, and networks [Opn97]. Using a state-transition paradigm, models of communication systems, protocols and networks can be constructed, executed and analyzed. With currently available workstations, a fairly sophisticated model can be run within a reasonable amount of time.

3.5. Scope of Problem

When developing the scope of a problem, two major concerns had to be considered: accuracy and tractability. First and foremost, the simulation must accurately model the communications system under study. The simulation must accurately model the behavior under review and generate meaningful results. Usually, the finer the detail and greater the complexity of the model, the closer it represents the real world system being modeled.

On the other hand, time and computing resources are limited, and the model must be developed and run within these limited resources. To this end, simplifications need to be made. The scope of this problem is limited to represent the Iridium® system within time and computing resources available. The selection of the Iridium® constellation is discussed in Section 3.6.1. This constraint has led to evaluating all facets of Iridium® and eliminating the factors that do not impact the key areas of concern.

Since the main emphasis of this effort is examining the overhead caused by the various mobility management topologies, specifically interactions between the home location register (HLR), visitor location register (VLR), authentication center (AC) and the mobile switching center (MSC). With this in mind, equipment failures, error correction and detection, SS7 routing, intersystem handoffs, subscriber mobility, and beam modeling were judged to not significantly affect mobility management and were not modeled. The reasons for eliminating these areas are discussed in the following subsections.

3.5.1. Equipment Failures

All networks experience equipment failures, and a robust communication protocol needs to handle unexpected outages. These physical failures only affect the data link and network layer protocols in the standard OSI Reference Model. All higher layer protocols are not impacted by equipment failures, unless the failures are so catastrophic that the network layer cannot provide connectivity [Tan96]. Mobility management protocols are generally located on the seventh layer of the reference model, and so are not affected by equipment failures [GaS97, Hei99]. For this reason, equipment failures are not modeled.

3.5.2. Error Detection and Correction

Error detection and correction is another integral part of any communication management scheme, but for this simulation model all communication paths, both wired and wireless, are assumed to be error-free. While this is not realistic especially on radio links, it does not affect our simulation results. In most communication protocols, error detection and correction is handled by the second layer of the OSI Reference Model, the Data Link Layer [Tan96]. The data link layer is responsible for the reliable delivery of communication packets or frames between two points. Since this function is handled at a layer below the mobility management protocol, so it can safely be abstracted out.

3.5.3. SS7 Routing

Iridium® and all LEO constellations with inter-satellite links (ISLs) require the ability to dynamically route packets from one destination to another. The requirement is driven by the constantly varying topology of the constellation. Satellites are constantly sweeping the earth surface; changing their position relative to other satellites; and severing and reestablishing ISLs. All network functions are normally performed by the System Signaling number Seven protocol (SS7). This is a very complex protocol, which provides excellent performance objectives with respect to availability, dependability, and delay. For example, any SS7 route set are not down for more than 10 minutes per year, nor does it allow more than one undetected signaling error in ten billion [MoS90]. This capability comes at a high cost in complexity. Previous simplifications to the model have already eliminated equipment failures and errors, so the required performance objectives of the satellite can be met without the complex SS7 protocol. Instead, a simple dynamic routing algorithm is used. This algorithm is discussed in Section 3.6.6.

3.5.4. Intersystem Handoffs

Mobility management is commonly dividing into four major functions: intersystem handoff, automatic roaming, authentication, and call processing. Gallagher defines the basic intersystem handoff as "a handoff between two radio channels that are controlled by two different mobile switching centers" [GaS97]. In the case of the Iridium® system, this involves transferring a call in progress from one satellite to another without a communications interruption.

This aspect of mobility management is not addressed by this thesis because it is fundamentally different from the other aspects of mobility management. With intersystem handoffs, a dialog is established between the mobile subscriber (MS), the current satellite supporting the call, and one or more satellites that are candidates to take over support for the call. The conversation involves setting up an inter-satellite communication link to facilitate the handoff, having the gaining satellite provide an open channel for the MS to use, and after a successful handoff, releasing the MS channel on the losing satellite [GaS97]. This entire process is localized and does not involve interaction between the HLR, VLR, AC, or MSC.

Our research involves determining the optimal location of the visitor location register, and bandwidth utilization due to communications between the HLR, VLR, AC, and MSC. Intersystem handoffs do not utilize these assets, and so can be ignored in this simulation.

3.5.5. Subscriber Mobility

Subscriber mobility is the primary reason that cellular and personal communication systems have mobility management systems. Mobility management systems are also required in satellite communication systems, but due less to the subscriber being mobile, and more to the speed that the satellites are orbiting.

In the Iridium® system, every satellite completes one orbit of the earth every 100 minutes and 28 seconds [BrR96]. With the circumference of the Earth being approximately 24,900 miles, the ground speed of the satellite is approximately 14,871 miles per hour (Equation 2).

$$V_{ground} = \frac{D_{CircumferenceOfEarth}}{T_{CompleteOneOrbit}} \qquad (2)$$

The fastest plane, the SR-71 Blackbird, can only reach a speed of 2,194 miles per hour. That is only one seventh of the speed of the satellite. In practical terms, a stationary subscriber averages a satellite handoff every nine minutes and 6 seconds (Equation 3).

$$T_{StationaryHandoff} = \frac{T_{CompleteOneOrbit}}{N_{Satellites}} \tag{3}$$

The SR-71 can only reduce or extend the time between handoffs by a maximum of 1 minute and 21 seconds (Equation 4). Thus, the mobility of the subscriber is usually insignificant in comparison to the mobility of the satellite, so mobile subscribers are considered stationary for the simulation.

$$T_{SR71Handoff} = T_{StationaryHandoff} \pm \frac{V_{SR71} D_{SatelliteCoverage}}{(V_{Satellite})^2} \tag{4}$$

3.5.6. Beam modeling

The final simplification is to not model the 48 spot beams present on each of the Iridium® satellites. The spot beams are the "cells" of the Iridium® system. Iridium® uses 3168 spot beams cover the Earth, and in a perfect simulation, each of these beams would be represented. Unfortunately, when spot beams are included, the number of queues and processors modeled jumps from 66 to 3168, causing simulation times to lengthen, and memory requirements to increase. This increase in computational complexity does not provide any added benefit for the standard mobility management models.

Spot beams represent the link between the mobile subscriber and the satellite, and allow frequencies to be reused and permit more subscribers access to the network. If sufficient bandwidth is available to handle the specified capacity of the satellite without frequency reuse, then spot beams become unnecessary. Once again, this facet of the Iridium® system can be abstracted way because it does not directly affect the primary focus of the research.

The one flaw to this reasoning is the issue of terminal paging. Currently, both IS-41-C and GSM MAP do terminal paging over an entire location area (LA). This area typically contains 60 cells. For this simulation, each satellite and its spot beams comprise a single location area. With LA paging, the spot beams are unnecessary. If further research is done in this area, and multi-step paging as described in [AkH95a, AkH95b, GuR98] is used, then spot beams will need to be modeled.

3.6. Assumptions

After simplifying the model by eliminating unneeded functionality, the model is then re-evaluated against satellite specifications and the tradeoffs needed to actually simulate the model within time and resource constraints. To produce the highest fidelity model, actual satellite specifications are used whenever the information is available. Unfortunately, in many cases, specific data can not found in the available literature. To overcome this, assumptions on the constellation characteristics had to be derived, and were based on [Fos98, Ste96, PrR99]. In addition to deriving system characteristics, some simplifications are made to allow the model to be created. The simplifications and assumptions made are discussed in the following subsections. The subsections address the reasons in choosing the LEO constellation used, the constellation's configuration, the traffic properties, the simulation's time scale, the routing algorithm and finally how mobile-to-mobile traffic is handled.

3.6.1. Choosing Iridium®

The primary emphasis of the research is to evaluate the overhead generated by mobility management in a global satellite communication constellation. Standard geostationary satellites (GEO) like Milstar are ruled out because by their characteristics. Orbiting 36,000 kilometers above the earth, a single satellite can cover one third of the earth's surface [Lut98]. Only three satellites are required to cover the Earth, and the inter-satellite routing consists of passing messages either to the satellite on the left or right. This severely limits the need to have a mobility management protocol. In addition, the antenna needed to communicate with a GEO is too large to be easily transportable. So candidate satellite constellations are limited to LEOs.

Currently, there are many LEO systems either operational or in the advanced planning stages. The front runners for this study are Iridium®, Globalstar®, and Teledesic®.

Globalstar® is the simplest system of the three using a standard "bent pipe" communications architecture. It employs no inter-satellite communication links and communicates only with ground stations within its coverage area [Cro99]. This type of system is just an extension of the terrestrial system and does not use mobility management protocols on the satellite. The satellite simply routes all communications it receives from the mobile users to the MSC within its coverage area. These factors eliminated it from consideration.

Teledesic® and Iridium® both have inter-satellite links and have the ability to route calls from one side of the globe to the other. The difference is the type of user they are designed to handle. Teledesic® is designed to create an *Internet in the Sky*, and will provide high-speed communications to service providers at fixed ground stations connected to the public switched telephone network (PSTN). With few mobile subscribers, and most at known locations, the system has little need for a robust mobile management system and is eliminated from consideration.

Therefore, the Iridium® constellation was chosen to represent the constellation in this research. It has ISLs and is designed to support thousands of mobile users. It is also one of the best-documented satellite constellations currently available.

3.6.2. Traffic Properties

All data within an OPNET simulation are passed as packets. The size, structure, and distribution of the packets can be quickly and easily configured.

3.6.2.1 Packet size and structure

Fossa [Fos98a] calculated the size for a packet passing from a mobile subscriber to an Iridium® satellite as 432 bits since a voice packet fills one uplink TDMA slot. Since then, the TDMA frame length is published as 90 ms and the sustained data rate has been reduced to 2,400 bps [Nel98], so the number of bits is 216 (Equation 5).

$$2{,}400bps\left(\frac{90ms}{1000ms/s}\right) = 216bits \tag{5}$$

3.6.2.2 Distribution of Incoming Calls

This model assumes that only voice traffic is being transmitted. Call interarrivals are modeled using an M/M/1 queue. Calls are assumed to arrive according to a Poisson distribution [All90]. With the bandwidth available for user communications reduced to 5.15 MHz, the number of users supported by a satellite is now 1,920 (Equation 6).

$$\frac{120channels(4users/channel)48cells/satellite}{12cells} = 1920users/satellite \tag{6}$$

Each user can send a packet every 90 ms, so the maximum packet arrival rate within a satellite footprint is 21,333 packets per second (Equation 7). The packet arrival rate includes the traffic generated by the users and the network management operations.

$$\frac{1920 users (1 packet/user)}{90 ms}\left(\frac{1000 ms}{1 \sec}\right) = 21{,}333 packets/\sec \qquad (7)$$

3.6.3. Constellation Configuration

The Iridium® constellation system is shown in Figure 10. It consists of 66 satellites and 12 terrestrial gateways. The specifications for system components are described in the following subsections.

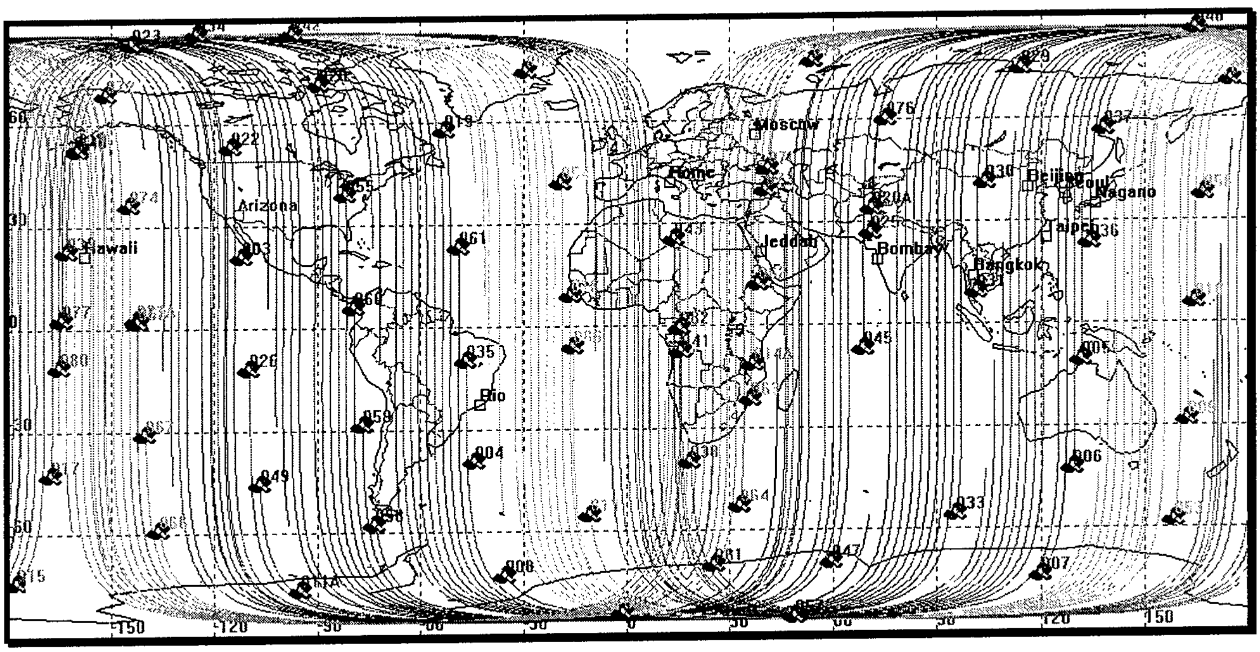

Figure 10. Iridium® Constellation with Gateways

3.6.3.1 Satellites

The satellites are arranged in six orbits with 11 satellites plus spares in each orbit. For the simulation, only the 66 primary satellites are modeled. The spare satellites are not needed since equipment failures are not a consideration. Each Iridium® satellite can have up to four ISLs. The ISLs are established with the adjacent satellites and creates a Walker Delta Network [Ste96]. Figure 11 shows the two different types of links that can be established: intra-planar links (light) and inter-planar links (black).

Satellites always maintain their two intra-planar links. These links are with the satellites immediately forward and aft within the same orbital plane. These links are always available because the relative position between the three satellites never changes. Approximately 4,000 miles separate these satellites.

Two additional links can be established with the satellites in the two adjacent planes (inter-planar links). For this to happen, two conditions must hold before these links can be established:

1. The satellites must be flying between 60 degrees North latitude and 60 degrees South latitude. Once a satellite leaves this region and travels into the polar regions, the relative position between the inter-planar satellites changes too quickly for the ISL antennas to maintain a good connection [Fos98a]. The links are automatically severed.
2. No inter-planar ISL can be established between satellites in the first and sixth orbits. Due to the nature of the orbits, the first and sixth orbits are always moving in opposite directions. This is known as counter rotating orbits and once again, the rate

of change between the satellites is too great to have a link established [PrR99]. This creates a seam, which can only be crossed by using intra-planar links over the poles.

Communications over the ISLs has a data rate of 25 Mbps. No information is available on if the inter-satellite links are partitioned into separate channels. It seems that they are divided for two reasons. First, Iridium® uses a GMS type protocol that supports out of channel signaling [Hub97]. Out of channel signaling requires dedicated channels for sending handoff, connection, and automatic roaming messages. Secondly, the ISLs must route packets generated from the mobile subscribers. The communication links between the mobile subscriber and a satellite consist of a combination of time division multiple access and frequency division multiple access. These links generate a stream of 216 bits long packets. The best way to handle these packet streams is to establish channels to handle same type of packets within the ISLs. For the purposes of the simulation, the ISLs have been simplified to being a single 25 Mbps channel.

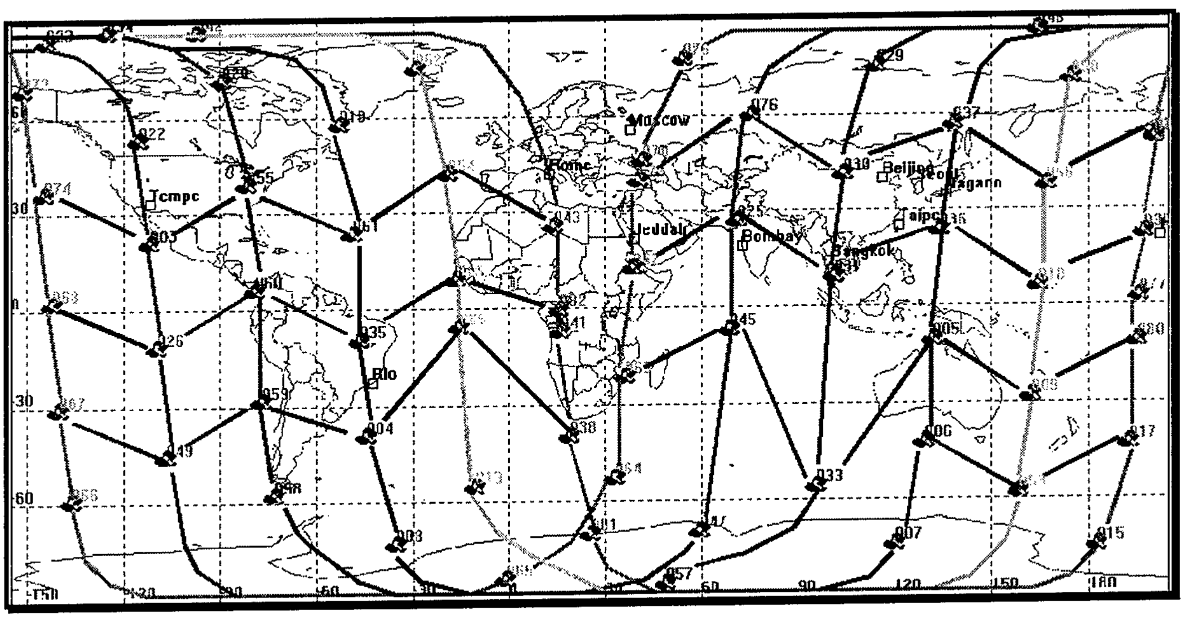

Figure 11. Iridium® Inter-Satellite Links

3.6.3.2 Gateways

Currently, the Iridium® system uses 12 Gateways to connect with the PSTN. The gateway locations are listed in Table 2. The gateways can access a satellite once the satellite has risen 8.2 degrees above the horizon. This connection is maintained until the satellite has fallen below 8.2 degrees above the horizon. To simplify the establishment of communications, it is assumed there is no obstacles, such as trees or buildings, to prevent contact from being established at the lowest possible point.

The communication data rate between the gateways and any overhead satellite is 25 Mbps. This communication bandwidth is divided into 3,840 channels. For this thesis, the channels are ignored, and the entire bandwidth is used as a single channel.

Table 2. Location of Iridium® Gateways

City	Latitude	Longitude	Used in Simulation
Beijing, China	39:55N	116.23E	No
Moscow, Russia	55:45N	37:37E	Yes
Rome, Italy	41:52N	12:37E	Yes
Bombay, India	18:58N	72:50E	Yes
Nagano, Japan	35:00N	135:46E	Yes
Seoul, Korea	37:35N	127:03E	No
Jeddah, Saudi Arabia	21:30N	39:12E	No
Tempe, Arizona	33:23N	111:55W	Yes
Honolulu, HI	21:19N	157:48W	Yes
Rio de Janeiro, Argentina	22:27S	42:43W	No
Taipei, Taiwan	25:02N	121:38E	No
Bangkok, Thailand	13:50N	100:24E	NO

3.6.4. Mobile Subscribers

Mobile subscribers are stationary, as explained in Section 3.5.5. They are placed together in a group containing between 216 to 28,800 members.

The Iridium® system supports up to 86,000 active users worldwide and 1,920 users within the footprint of one satellite. To test the system, a worst case scenario is assumed. The following three criteria are satisfied when placing the mobile subscribers into the model:

1. A large number of the mobile subscribers are located together in the footprint of a single satellite and all have their phones on. To test mobility management, it is not required for the subscribers to be placing calls, just have the phone on standby to generate the mobility management traffic needed.

2. The mobile subscribers have different HLRs and those HLRs are located the maximum distance from the subscribers. This is normally six or seven satellite hops away and may require crossing the seam between the first and sixth orbit.

3. Finally, the nearest gateway to the subscribers is at least one satellite hop away.

The communication data rate between the mobile subscribers and the supporting satellite is 2,400 bps. There a maximum of 1,920 active users in any satellite footprint, so the maximum supported rate needed in 4 Mbps (Equation 8).

$$1{,}920 user (2{,}400 bps / user) = 4{,}608{,}000 bps \tag{8}$$

For perfect fidelity, the bandwidth would be divided into 48 spot beams, with each beam supporting 40 users. Each user would have a sustained data rate of 2,400 bps. Instead, for this simulation, the model is simplified by providing only one 4.6 Mbps ground to satellite channel, and allowing a maximum transmission rate of 21,333 packets per second (Equation 9).

$$1{,}920 users \frac{1 packet}{90 ms}\left(\frac{1000 ms}{1 \sec}\right) = 21{,}333 packet / \sec \tag{9}$$

The bandwidth used by the users is in the L-band and is not the same frequency used by the terrestrial gateways. In this simulation, the two frequencies are modeled separately.

3.6.5. Simulation Run Time

The simulation needs to run long enough to exercise all the time factors in the various scenarios. This ensures accurate portrayal of the fitness for the different test cases. The time sensitive variables in the simulation are mobile subscriber handoffs due to satellite movement, time-based location update requirements, and maximum allowable delay of voice communications.

3.6.5.1 Satellite handoff

A satellite in the Iridium® constellation completes one orbit in 100 minutes and 28 seconds. This means that any fixed point on the globe falls into a new satellite's footprint every 9 minutes and 8 seconds. If the VLRs are located within the satellites, they need to transfer their databases to another satellite every 9 minutes. To adequately simulate this event, the simulation should run long enough to have each mobile group's information transferred at least three times. This will give 9 sample points. Therefore, the simulation runs for at least 27 minutes and 24 seconds.

3.6.5.2 Time-based location update

IS-41-C has a time-based periodic location update to ensure that a mobile subscriber is still on and residing within the satellite footprint. The MSC defines the length of the time interval for location updating. The typical range is between ten minutes and one hour [GaS97]. For this simulation, two different times are used. In the first and second test cases in each scenario, the periodic location update occurs ten minutes after the last location update. A periodic location update is generated after waiting a specified amount of time since the subscriber experienced a hand-over, finishes a call, or sent the last update. In the third test case, 20 minutes passes between periodic updates.

For the time-based protocol being introduced in this thesis, the interval is exactly the same as the time it takes for a satellite to pass overhead: 9 minutes and 8 seconds. The minimum time of 27 minutes and 24 seconds is required to test if a time-based location update protocol can maintain the satellite's VLR database.

3.6.5.3 Voice communication delay

Another time constraint is the delay experienced connecting or disconnecting a mobile call. This simulation is not designed to accurately calculate the end-to-end delay experienced when setting up a call. This precludes the need to consider voice communication delay.

3.6.6. Routing

3.6.6.1 Routing Algorithm - Bellman-Ford

As mentioned in Section 3.5.3, this simulation does not use the standard (but complex) SS7 for routing data packets. Instead, a simple dynamic routing is needed to provide the routing of data packets. Two routing algorithms have been shown to work well in a LEO environment. These are extended Bellman-Ford and Darting [Pra99].

Stenger demonstrated that at low traffic loading, an extended Bellman-Ford routing algorithm provided good results, if it converges [Ste96]. The other candidate is Darting, which Pratt showed provided better results in a fully loaded system [Pra99].

For this research, an extended Bellman-Ford algorithm was chosen because it is easier of the two to implement, and without equipment or link failures, routing does not need to be as robust as SS7. Extended Bellman-Ford is an extension to the standard distributed Bellman-Ford. The purpose of the enhancement is to eliminate the original algorithm's susceptibility to looping and failure to converge when the network becomes disconnected. When a change occurs, all the nodes in the network do not immediately know of the change. To inform others of the change, the affected nodes pass network update packets to their neighbor, which update their routing table based on the new information, and then pass it on to other nodes that may be affected by the change.

This flood of packets is a weakness in the algorithm because it restricts the network capacity available for data packets. This is not a concern since overhead involved in routing is not measured in this thesis.

3.6.6.2 Routing Delay

Fossa determined the most probable satellite delay when processing a packet. He calculated the minimum time between packets is 23.44 μs, so the switching must be less than this (Equation 10).

$$\frac{1}{42{,}667\,packets/\sec} = 23.44\mu s \tag{10}$$

Using a switching delay of 14 μs allows the satellite to process the packets without causing a backup or lost packets [Fos98a].

3.6.7. Mobile Subscriber to Mobile Subscriber Communications

Even though the Iridium® system is a fully independent worldwide network, it is usually used as an extension of the PSTN. The one exception happens when an Iridium® mobile subscriber is outside the range of a cellular network calls another Iridium® mobile subscriber.

In this case, the mobile subscriber's request goes to the satellite and is forwarded to the nearest gateway with a VLR, which contacts the subscriber's HLR. The HLR then determines if the subscriber is authorized to make the call. If approved, the gateway then contacts the receiver's HLR, which then request a destination number from the VLR servicing the receiver. The HLR returns the destination number to the caller's VLR. The VLR then places the call through the receiver's VLR. The receiver's VLR then pages the receiver. If found, the receiver is connected with caller.

For purposes of the thesis, the assumption is made that 5 percent of the calls placed are between mobile subscriber on the Iridium® system. The rest of the time, a MS calls someone within the PSTN. These values are based [Nel98].

3.7. Input Factors

After narrowing the scope of the problem and stating the assumptions governing the simulation, it is time to discuss the input factors needed to generate the scenarios. In this thesis, changing the location of various components involved in mobility management are compared. Specifically, the visitor location register (VLR), and authentication center (AC) are moved from the terrestrial gateways into the satellites. With the VLR located in satellite, three different VLR updating schemes are tested: the Home Location Register providing the updates, the VLR database being passed from one satellite to another, and finally the VLR database rebuilt each time during periodic MS location updates. These different topologies and updating schemes are then simulated using three loading factors. The first test case is on a fully loaded system. The second test case is run a moderately loaded system, and the third tests a fully loaded system using a different timing interval for updating locations and generating calls.

Table 3 shows the combination of factors that are tested during the 15 simulation runs used in this research. That is followed by seven subsections, which explain how each factor is determined.

Table 3. Input Factors Combination Table

	Total Users	Calls per Hour	VLR Location	AC Location	VLR Update
1	12,336	24,672	Gateway	Gateway	HLR
2	12,336	24,672	Satellite	Gateway	HLR
3	12,336	24,672	Satellite	Satellite	HLR
4	12,336	24,672	Satellite	Satellite	DB Transfer
5	12,336	24,672	Satellite	Satellite	DB Discard
6	6,168	24,672	Gateway	Gateway	HLR
7	6,168	24,672	Satellite	Gateway	HLR
8	6,168	24,672	Satellite	Satellite	HLR
9	6,168	24,672	Satellite	Satellite	DB Transfer
10	6,168	24,672	Satellite	Satellite	DB Discard
11	12,336	49,344	Gateway	Gateway	HLR
12	12,336	49,344	Satellite	Gateway	HLR
13	12,336	49,344	Satellite	Satellite	HLR
14	12,336	49,344	Satellite	Satellite	DB Transfer
15	12,336	49,344	Satellite	Satellite	DB Discard

3.7.1. Traffic Loading

The first factor to consider, is the number of subscribers needed in the scenarios to simulate full and moderate loading. The Iridium® system is designed to support mobile subscribers, much like a cellular telephone system. Assuming that Iridium® strives for the same "grade of service" (GOS) as AMPS, it is designed for a GOS of 2 percent blocking [Rap96]. This implies that during the busiest time of day, only 2 out of 100 calls are blocked because no channel is available.

Based on typical cellular use, a typical user generates calls averaging about three minutes in length, and does not send or receive more than two calls in an hour. This means each user generates a traffic intensity of 0.1 using Equation 11, where μ is the average number of call requests per hours, and H is the average duration of a call, giving the user 's traffic intensity A_{μ}. .

$$\begin{aligned} A_u &= \mu H \\ A_u &= (2 calls / hr) 3 \min / call = 0.1 \end{aligned} \tag{11}$$

A Iridium® satellite has 48 spot beams with each beam supporting 40 channels. The number of subscribers that a single beam can support can be found using the Erlang B (blocked calls cleared) formula (Equation 12), where A represents the user's traffic intensity and C is the number of channels available. The results indicate that a beam can support 257 subscribers. Therefore one Iridium® satellite can support 12,336 users.

$$\Pr[blocking] = GOS = \frac{\frac{A^c}{C!}}{\sum_{k=0}^{C} \frac{A^k}{k!}} \tag{12}$$

For the simulations in this thesis, a fully loaded satellite has 13,104 active subscribers in its footprint. A moderately loaded satellite has 6,552 users. The final traffic loading configuration changes the ratio of location updates to call placed. In the first two series, periodic location updates happen every 10 minutes, and calls are placed once every half hour. In the third test case, periodic location updates occur less frequently, once every 20 minutes, while call generation increases to one every 15 minutes.

3.7.2. PSTN Call Generation

With the number of mobile subscriber determined for each of the scenarios, it is a simple matter to calculate the number of calls that are generated by the PSTN. The GOS is based on two calls every hour for each of the subscribers. According the 1999 Hart survey, *Dynamics and Trends in the Wireless Marketplace*, fifty percent of cellular phone usage is for outgoing calls; the other fifty is for incoming calls. Based on these assumptions, every mobile subscriber is likely to place one call and receive one call per hour.

During the high load scenario, this requires the PSTN to generate 1,920 calls per hour to each of the mobile subscriber groups. Since there are three groups in each scenario, and there are six PSTN gateways, the total number of calls each PSTN gateway needs to make is 16 calls per minute (Equation 13).

$$\frac{1{,}920 calls/group/hr(3 MSGroups)}{6 PSTNStations(60\min/hr)} = 16 calls/\min \qquad (13)$$

During the low load scenario, the number is reduced to 8 calls per minute.

3.7.3. Location of the VLR

Iridium® has only 12 gateways throughout the world. These gateways control all mobility management aspects for the Iridium® system. This presents a potential bottleneck during heavy usage. The problem is aggravated by the location of the gateways near major population centers. This could lead to limited bandwidth for handling both control signals and calls. Two different locations for the VLR are tested: terrestrial and satellite.

3.7.3.1 Terrestrial

Presently, the VLRs are located at the 12 gateways. This means that on average each VLR must service six satellites, and could present a potential bottleneck. Metrics on the number of bits sent and received by the gateways are collected to see if this is the case.

3.7.3.2 Satellite

Placing the VLR in the satellite should localize some of the mobility management traffic to the satellites supporting the mobile subscribers. Specifically, periodic location updates, VLR lookup, and call setup between two subscribers on the same satellite are reduced to one hop. A possible disadvantage is the need to transfer the entire contents of the VLR database to next satellite during satellite handoff.

3.7.4. Location of the Authentication Center

The Authentication Center (AC) is almost always collocated with the HLR because it must be a very secure system. It is used to prevent fraudulent access to the cellular network. This security is provided by maintaining a set of A-keys for all legitimate mobile equipment. This key is known only by the AC and the equipment itself, and is never divulged over the air. If the keys are compromised then the network would be without security.

Like the VLR, the AC is located within the terrestrial gateways. This presents a potential bottleneck during heavy usage. In the thesis scenarios, two different locations for the AC are tested: terrestrial and satellite.

3.7.4.1 Terrestrial

A conventional cellular telephone network interacts with and shares authentication data within a heterogeneous environment. The requestors for authentication of its mobile subscribers are not necessarily trustworthy, and so the A-key is never given. Instead, the temporary key, the Secret Shared Data (SSD), is given. All authentication is performed by the AC collocated with the HLR. This is secure, but uses extra bandwidth.

3.7.4.2 Satellite

The Iridium® system is not constrained by the problems of a heterogeneous environment. It is a homogeneous system that controls all communication pathways between the system components. Since the satellites remain under control of the network at all times, they are trustworthy and can be given access to the A-keys of the mobile equipment. By placing the responsibility of authentication in the satellite, bandwidth can be saved.

3.7.5. Transfer of the VLR Database

Research in [Lee97] indicates that moving the VLR to the satellite would reduce the bandwidth needed to support mobility management. An area that is not addressed in his thesis is how to transfer the information contained in the VLR from one satellite to another. This effort compares three different methods: HLR update, VLR database transfer, and discarding the VLR database and rebuilding it using MS location update messages.

3.7.5.1 HLR Update

The first method of VLR database update is simply the standard VLR update provided by the IS-41-C protocol. When a mobile subscriber enters a new location area (LA), it registers with the VLR supporting the LA, which in turn communicates with the subscriber's HLR. Subscribers are deregistered when the HLR sends a deregistration message.

3.7.5.2 Database Transfer

The second method examined has the satellite transfer the content of its VLR database to the next satellite every 9 minutes and 8 seconds. To prevent a loss of a subscriber during the transfer, the satellites maintain a copy of the database after the transfer. The subscribers are deregistered after the specific time interval has expired since that last location update by the subscriber.

3.7.5.3 Database Discard

The final method examined uses the regularity of the satellite orbits, and the ability of the satellites to steer their spot beams. Since the satellite only support an area for a maximum of 9 minutes and 8 seconds, the periodic location updates are exactly that length of time.

To limit the number of messages passed between the VLR and HLR during location update, the Iridium®'s steerable spot beams are used. The world is divided into 2150 specific cells. Each cell is given a unique identifier. This number remains with the geographic area it is assigned to. The satellite directs its spotbeam to cover one of these cells, and the beam maintains coverage of the cell until the next satellite is in position to take over responsibility. While a spot beam is covering a cell, it broadcasts the cell unique identifier. When a subscriber does a location update, it sends the standard location update information plus the unique identifier of the cell it was in at the last update. If the identifier sent is for the cell the subscriber is currently in, then the VLR handles authentication locally without passing messages to the HLR. If the number is different, then the VLR registers the subscriber as required in the standard protocol.

3.8. Model Design

With the scope of the problem down to a manageable size, all the assumptions defined, and the inputs known, it is time to specify the model. As mentioned in Section 3.4, this simulation is created in two stages. The first stage defined the ephemeris data needed to plot the orbits of the 66 satellites in the Iridium® constellation. This task is accomplished using STK®, and the satellite database that came with the package. First, the 66 satellites are constructed in the six near-polar orbits. The satellites chosen provided the most uniform coverage of the globe. The ephemeris is then generated to include one full orbit (100 minutes 28 seconds) for each satellite. The time simulation runs from 0001Z to 0142Z on 1 October 1999.

This time period was chosen for three reasons: First, the full Iridium® constellation is in orbit. Second, the six orbital planes are clearly delineated, and the satellites within the planes are evenly spaced, and finally the beginning of the new year seemed appropriate. These orbits are then loaded into OPNET®.

The bulk of the simulation design is completed using OPNET®. OPNET® is a network simulation tool that can generate nodes, paths and packets. The first task is to generate the five separate scenarios needed to represent the areas of interest in the thesis. The top level for each of the scenarios looks identical, it contains one application attribute definition, six terrestrial gateways, three groups of mobile subscribers and the 66 satellites in the Iridium® constellation. A picture of the standard Iridium® network developed in OPNET is shown in Figure 12. The four different nodes are explained in the following subsections.

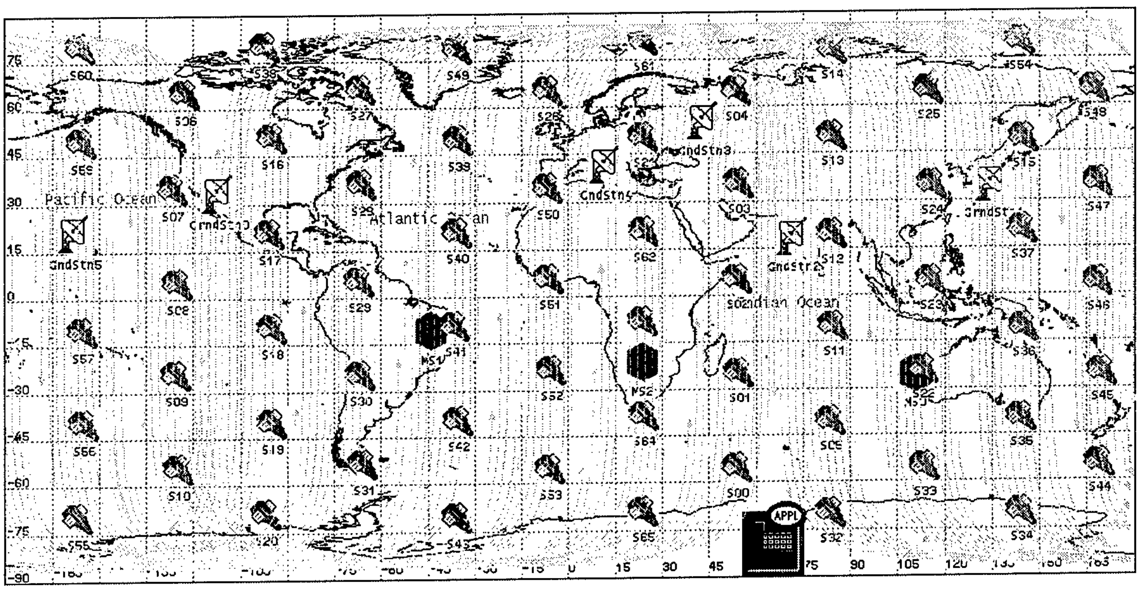

Figure 12. OPNET Model for Standard Iridium® Network

3.8.1. Application Attribute Definition

The application attribute definition is a common OPNET device for storing globally available information. This node is developed to serve two purposes: to provide the bookkeeping tasks needed to run the scenario in a dynamic environment, and second to store a global database for HLR lookup.

The application node contains only one node, and is run only during initialization and shutdown. At initialization, it identifies all the types of nodes present in the system, and determines the unique identifiers assigned to the nodes by the simulation kernel. These identifiers are needed to establish the routing tables and HLR database. The HLR database is then populated with all the subscribers and assigns them to a mobile group and HLR.

3.8.2. Terrestrial Gateway

In the Iridium® network, there are 12 terrestrial gateways, which connect to the PSTN. These are located in the areas specified in Table 2. For the scenarios run during this thesis, only 6 of the gateways are used. The number is limited to guarantee at least one satellite hop between the mobile subscribers and the nearest terrestrial gateway. The model developed to represent the gateway consists of two layers of the OSI model, layer three and seven. The layer three functions of routing packets are performed by the receiver, transmitter and router nodes. The mobility management functions of layer seven are performed by the director (split), HLR, VLR and PSTN (Figure 13).

The receiver and transmitter processes are standard OPNET-provided nodes. The frequencies are set to communicate on the gateway channel of the satellites. The input and output streams are designated as the first channel of the router. No special adaptation is required to incorporate the nodes into the model.

The router is created specifically for this theses and controls two sets of input and output streams. Stream 0 carries packets to and from layer seven processes. Stream 1 sends packet to and receives packets from the rest of the network. The router is very simple. All incoming packets from the network have their destination checked, if the destination is this node, then the packet is passed to the transport layer. If not, the packet is destroyed. To route packets from the transport layer to network, the router doesn't use a routing table. Instead it determines which satellite is the closest and send the packet to that satellite.

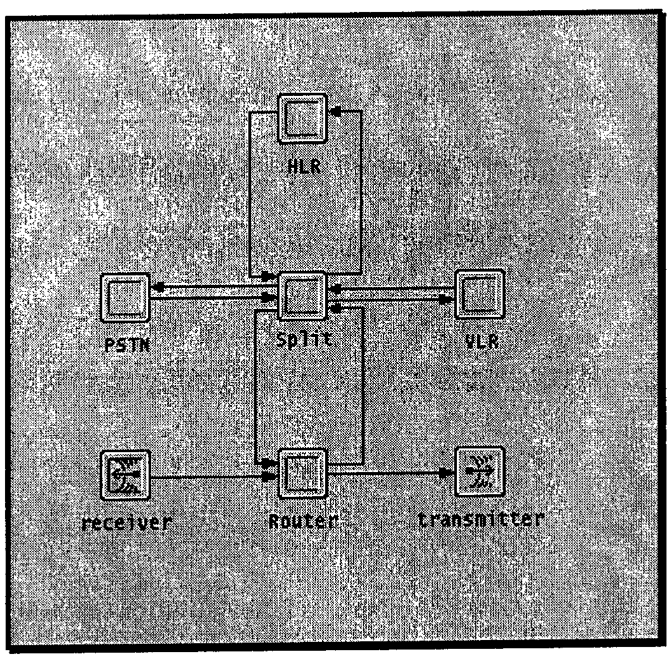

Figure 13. Terrestrial Gateway Model

Once a packet is passed up from the layer three processes, the director (called split in the diagram) opens the packet and determines which of the three processes needs to process the packet.

The PSTN process handles the tasks associated with connecting calls with the terrestrial telephone network. In the model, it performs four tasks: it generates calls according to a Poisson distribution to connect with the mobile subscribers in the network. Second, it terminates calls when requested by a mobile subscriber. Third, using a exponential distribution to determine the length of the call (3 minute mean) , it terminates calls placed with Iridium® network. Finally, the PSTN process accepts connections from the mobile subscribers.

The HLR in each gateway is assigned a specific number of mobile subscribers at the beginning of the scenario. This number of subscribers does not change during the scenario. It manages all the HLR and AC responsibilities for its assigned subscribers. The tasks handled include authentication, MS lookup for the call connection, and registration and deregistration of users.

The VLR handles the VLR responsibilities for the mobile subscribers that are located in its area of responsibility. The VLR does all mobility management communications with the mobile subscriber. It authenticates the user, pages the user when there are incoming calls, requests a communication line for establishing calls, and handles registration and deregistration. Details on the responsibilities of the HLR and VLR are located in Section 2.10.

The terrestrial gateway configuration isn't altered when generating the various scenarios. Instead, the HLR and VLR processes are modified to accommodate the changes in protocols. In the second scenario, moving the VLR to the satellite, the VLR in the gateway no longer supports mobile subscribers and acts only as an MSC for the PSTN. In the third scenario, the authentication functions of the HLR are disabled, and those functions are handled by the VLR in the satellite. There are no additional changes to the gateway for the fourth and fifth scenario.

3.8.3. Mobile Subscriber Node

The mobile subscriber node represents a large number of mobile subscribers located within the footprint of one satellite. The mobile subscriber is stationary, but it is able to originate calls, provide location update, authentication, and respond to terminal paging using IS-41-C protocol standards. The internal processes of the mobile subscriber node are shown in Figure 14. Like the terrestrial gateway, the mobile subscriber group model supports functionality at two levels of the OSI model. Layer three is handled by the receiver, transmitter, and router processes. The receiver and transmitter processes are standard OPNET-provided nodes. The frequencies are set to communicate on the MS channel of the satellites. The input and output streams are designated as the first channel of the router. No special adaptation is required to incorporate the processes into the model.

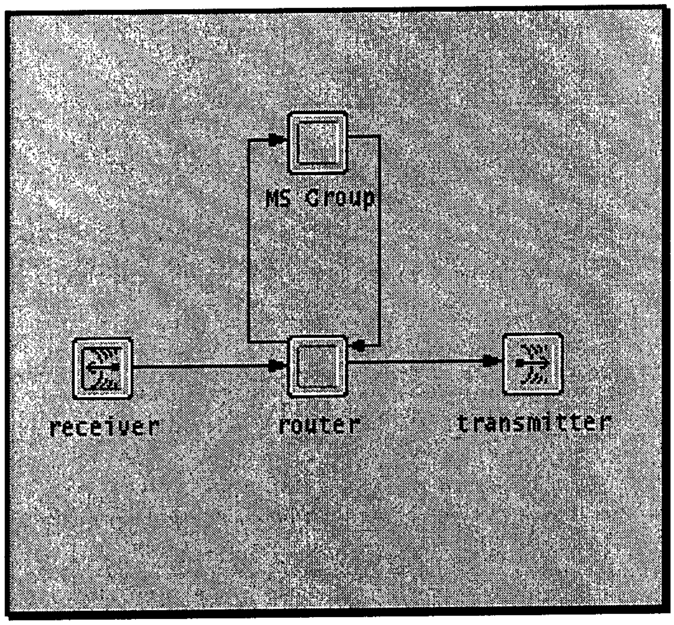

Figure 14. Mobile Subscriber Group Model

The router is created specifically for this thesis and controls two sets of input and output streams. Stream 0 carries packets to and from layer seven processes. Stream 1 sends packet to and receives packets from the rest of the network. The router is very simple. All incoming packets from the network have their destination checked, if the destination is this node, then the packet is passed to the transport layer. If not, the packet is destroyed. To route packets from the transport layer to network, the router does not use a routing table. Instead, it determines which satellite is the closest and sends the packet to that satellite.

The mobility management traffic is generated by and received by the MS Group process. The process mimics hundreds to thousands of individual mobile subscribers. Each subscriber is independent and performs the tasks associated with a Iridium® user. The subscriber can place a call, hang up after completing a call, send out a required location update message, or turn on and off the phone. A database is used to maintain the current state of the subscriber, and ensure that the next activity is possible.

Two MS Group processes are developed for the thesis. The standard MS Group uses standard IS-41-C type communications. In the fifth scenario, the location update message used by the MS Group is modified to include the cell identification number.

3.8.4. Satellite Nodes

In each scenario there are 66 satellite nodes. A satellite node is used to model the routing, orbits and mobility management functions for a satellite in the Iridium® constellation. Two distinct process models are developed to model the satellite in the five scenarios: the standard and the enhanced model.

3.8.4.1 Standard Satellite Model

The standard satellite model replicates the current Iridium® satellite currently in orbit. The satellite supports six communication channels. It has 4 ISLs with each supporting a 25 Mbps channel. It also has a terrestrial gateway to satellite, and MS to satellite link supporting a 12.5 Mbps channel. An illustration of the internal processes of a standard satellite model is shown in Figure 15.

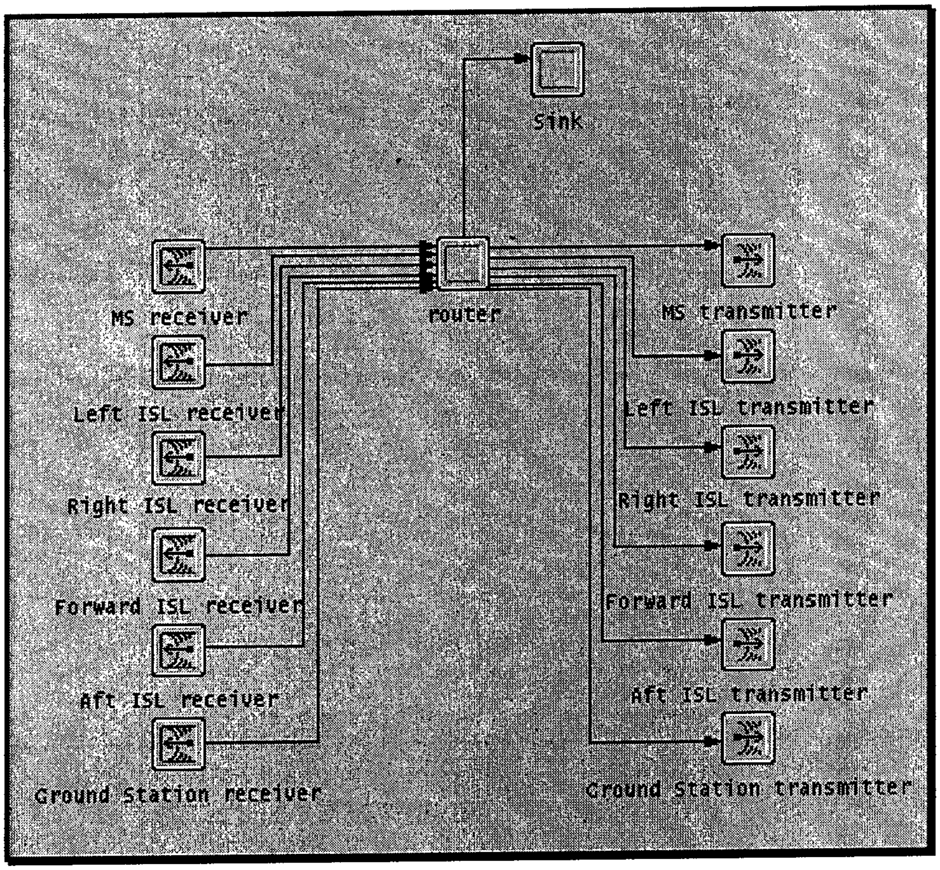

Figure 15. The Standard Iridium® Satellite Model

Similar in structure to the other two node models, the satellite support mobility management at two layers of the OSI model: level three and seven. The layer three functions of routing packets are performed by the receiver, transmitter and router nodes. The mobility management functions of layer seven are performed by the sink.

The receiver and transmitter processes are standard OPNET-provided nodes. One receiver and transmitter pair has been assigned to each of the radio links established by the satellite. Any receiver-transmitter pair that cannot be used because of the satellite's location or position is disabled. The inter-planar ISLs links are disabled when the satellite enters the polar regions, and is not re-enabled until it crosses the 60 degree North or 60 degree South line. The inter-planar link between the first and sixth orbit is permanently disabled.

The router created for this research uses an extended Bellman-Ford routing algorithm to handle all dynamic routing. The model monitors the topology of the constellation and the location of the terrestrial gateways and mobile subscribers by sending out echo packet periodically. When a node receives an echo packet, it immediately sends one in return. The sending node, after receiving the returning echo, can determine how far the echo destination is away, and compute a cost associated with that destination. It examines the routing table it keeps internally and makes modifications to the table to reflect the new cost derived from the echo. If the cost difference is greater than a specified threshold, the node generates and sends out a packet to all of its neighbors containing a complete copy of its routing table. The algorithm is modified slightly to reduce the number of routing packets sent. Instead of immediately sending out routing packets every time a change occurs to the routing table, the node waits a short time, and collates all the changes received in the interim and then sends all the changes are once. The reduction in traffic is close to two orders of magnitude. The disadvantage to waiting is the algorithm takes longer to converge to a best solution.

The layer seven is very simple in the standard satellite model, since the satellite does not support any mobility management functionality. All mobility management is handled by routing control signals to the nearest terrestrial gateway, which contains the VLR and HLR, and handles automated roaming, authentication, and call processing. The only process in layer seven is a sink, which destroys any misrouted packets.

3.8.4.2 Enhanced Satellite Model

The enhanced satellite model has all the features of the standard satellite model, plus a varying amount of mobility management responsibilities. The mobility management functions assigned to the satellite are handled by the satellite's VLR. Again, layer three and seven are represented by the process internal to the satellite. This process is shown in Figure 16. Since no modification is made to layer three, no discussion is necessary. Please, refer to Section 3.8.4.1 for that information.

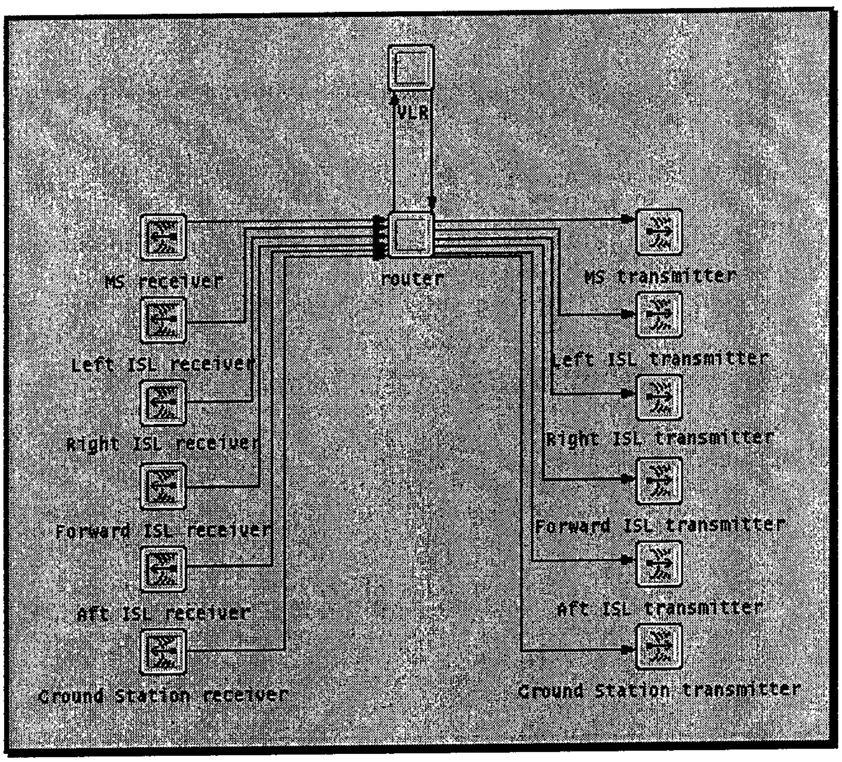

Figure 16. The Enhanced Iridium® Satellite Model

The responsibilities of the mobility management are handled by the VLR. The VLR needs to have sufficient memory and speed to handle all typical mobility management traffic. The biggest memory requirement is for the VLR database used to store the information about the mobile subscribers being supported. The amount of memory needed for database is simply the maximum number of subscribers supported by the VLR multiplied about the size of a VLR entry. The Iridium® system is based on having approximately 10 million user worldwide [Gav97]. In a mobility management scheme based on AMPS, the typical VLR entry contains the MS identification (IMSI-15 bits, TMSI-15 bits), the HLR identifier (14 bits), the local area identifier (14 bits), information about the services allowed for the subscriber (15 bits), and the Mobile Station Roaming Number (15 bits) for a total of 88 bits.

To determine the amount of memory required to support the VLR database, a maximum number of subscribers a satellite can support needs to be determined. Assuming the minimum acceptable grade of service for the network is 10% (one in every 10 calls is blocked), the maximum users within a spot beam is 390. Therefore, 18,720 users can be supported on one satellite. The VLR database needs 205,920 bytes of memory to support the maximum number of subscribers (Equation 14). The speed of the processor should be adequate to parse through the typical sized database in less than a second.

$$\frac{18{,}720 subscribers(88 bits/subscriber)}{8 bits/byte} = 205{,}920 bytes \tag{14}$$

In the second scenario, the VLR is exactly like the VLR developed for the terrestrial ground station in the first scenario. The only difference is that the VLR is now located in the satellite. In the third scenario, the VLR is modified to allow it to authenticate mobile subscribers without retrieving an SSD from the HLR. The VLR is still required to report the results to the HLR. The fourth scenario supports the transfer of the contents of the VLR database from one satellite to another. When the VLR recognizes that is supporting a new location area, it automatically transfers its VLR database contents to the satellite following it in the same orbit. The transfer is accomplished every 9 minutes and 8 seconds.

The fifth scenario drops the requirement for transferring the VLR database. The database is maintained by updating the MS entry on a time basis. If an MS does not make a check in, it is automatically dropped from the VLR database, but the HLR is not notified. The only time a deregistration message is sent is when the MS initiates the conversation with a deregistration message. The mobile subscriber sends a location update message every 9 minutes and 8 seconds. Part of the location update message is the location identifier of the LA during the last update. If the identifier is the same as the current LA, then the VLR authenticates the MS but does not send an Authorization Status Report (ASR) to the HLR. The ASR is only sent when the location identifiers do not match. If a call connection is passed to the VLR before the first update by the MS, the VLR assumes the MS is present and page the LA. If no response is given, the message to passed to previous VLR, if that is still unsuccessful, the HLR is informed that the subscriber could not be found.

3.9. Simulation Scaling

To this point in describing the model development, packet generation or how it effects the running of a simulation has not be addressed. Fossa reported that "modeling the actual traffic load of the Iridium® will run very slowly" [Fos98a]. As an example, he pointed out that when running a 15 minute simulation between only two earth stations at 11 percent capacity, the resulting execution cycle took two to three weeks to complete.

Using pilot studies and proper scaling, Fossa demonstrated that accurate results can be obtained without the time penalty incurred with using an actual traffic load. This is confirmed using a pilot study on model of the Iridium® system as it is currently configured.

In an OPNET® simulation, networks are modeled as interconnection of finite state machines, with all communication between processes done through message passing. This is true, whether the message is a data packet, interface control information, remote process activation, interrupt, or other methods. The transfer of a single message is accomplished by an event. The number of events generated directly effects the speed of the simulation.

Since, this research examines the generation and passing of mobility management packets,. the number of packets created and passed is the biggest factor in the determining the length of each simulation run. To find a reasonable time period for each simulation run, a pilot study is developed to test the effect of scaling the number of packet generated.

The pilot used a model with the full Iridium® constellation, six earth stations, and three groups of mobile subscribers. The six earth stations from Table 1 were chosen and included Honolulu, Tempe, Moscow, Rome, Bombay and Nagano. Three groups of mobile subscribers are placed in South America, Africa, and Australia. Four pilot simulations are run. The first simulation exercised the full capacity of the Iridium® constellation. It placed 29,000 mobile subscribers in each of the three groups. Each of the earth stations generated 4 calls per second. The simulation is run for 548 seconds and generated 356,798,602 octets of control information. The second simulation reduced the number of subscribers by a factor of 10 and also reduced the number of calls by the same factor. This produced 35,380,728 octets of information. The third simulation again reduced the number of subscribers and calls by a factor of 10. This simulation generated a total of 3,635,926 octets. Finally, the last simulation ran with 29 subscribers in each group, and each earth station only generating one call every 250 seconds. This run sent 358,016 octets of information. The variance between the runs is less than 2 percent (See Table 4). Balancing the need for the most accurate results with a reasonable length for each run, a scaling factor of 200 is chosen. The simulation runs reduced the number . With a scaling factor of 200, the simulation ran for approximately 76 minutes on a Sun Ultra 10, instead of over 8 hours for the unscaled or baseline system.

Table 4. Pilot Results

Simulation	Users	Octets Generated	Octets Generated (Scaled)	Difference from baseline (%)
Baseline	29,000	356,798,602	356,798,602	0.0%
one tenth	2,900	35,380,728	353,807,280	0.8%
one-hundredth	290	3,635,926	363,592,600	1.8%
one-thousandth	29	358,016	358,016,000	0.3%

3.10. Performance Metrics

This section discusses the five performance metrics investigated in this study: total mobility management bytes, total mobility management packets, total conversations, calls not completed, and packets lost.

3.10.1. Total Mobility Management Bytes

The first metric is the number of mobility management bytes needed to be support all the mobility management functionality for the scenarios tested. The count is generated through two operations. First, the size of each control packet is multiplied by the number of hops the packet transversed. This value is then added to the accumulated total for the entire system, and the total for the gateway generating the signal. The number derived is compared to maximum number of packets in the system to determine the percentage of bandwidth devoted to control. The number is also used to determine the relative efficiency between the different protocols.

3.10.2. Total Mobility Management Packets

The next metric is the number of mobility management packets needed to be support the mobility management functionality. The count is simply the number of packets created to support mobility management. This value is accumulated over of the entire simulation run. The number is used to determine how many messages are required to be passed to handle mobility management functionality.

3.10.3. Total Conversations

A conversation is defined as a series of messages required to complete a single management task. Management tasks include updating the location of a mobile subscriber or establishing a call between two customers. The number of conversations made during a simulation run is the combination of three factors: a random seed generating the calls, a random seed determining the next action of a mobile subscriber, and the number of mandatory location updates. The lower the number of conversations, the less traffic that needs to be generated. The number is also used to determine relative efficiency between the different protocols.

3.10.4. Calls Not Completed

Another metric is the number of incoming calls that could not be completed because the receiver could not be found. Not counted are calls that could not be completed because the receive is either off the air, or busy with another call. The value is used to determine if the protocol is performing the job it is designed for. The most efficient algorithm is useless if the algorithm only works half of the time.

Ideally, every call goes through the first time and with a minimal amount of delay. This metric reflects the interaction between frequency of mobile subscriber updates, size of the paging area, and the frequency of incoming calls.

3.10.5. Packets Lost

The final metric is the number of packets lost. Mobility management packets have to compete with short message signaling, operation and maintenance packets for space on signaling channel. Overloading the system results in lost packets due to buffer overflows. With the queue in each of the satellite supporting 4000 packets, the chances of packet loss should be minimal.

3.11. Model Verification and Validation

3.11.1. Verification

Verification is testing the model to ensure that it performs as intended. Model verification is completed at two levels: unit level and system level

3.11.1.1 Unit Level Testing

At the unit level, the simulation model is viewed as a composite of three different types of nodes: satellites, gateways, and mobile subscribers. During the first round of testing, each of the nodes went through a complete syntactical check using OPNET's built-in verification tools. This verified that there are no grammatical errors in the code, all variable are declared and properly sized and formatted.

The second round involved white box testing. The internal algorithms used by the nodes are tested. The testing involved verifying the entrance, exit, and loop transition for each state transition. This verified that all states are defined, and no undefined transitions are present.

The third round concentrated on black box testing. The nodes are tested in isolation to verify the inputs and outputs. Each input is examined before entering the node, and the output variables are compared with expected results.

3.11.1.2 System Level Testing

After the individual nodes are verified, then the interactions between the nodes are tested. The interactions are limited to two nodes, first satellite to gateway, then satellite to mobile subscriber. The interactions examined the message passing between the nodes. After two node interactions are verified, a three way interaction is tested. Once again, the messages passed are examined.

A routing test is then executed, where a network of ten stationary satellites is given 500 msec to find the shortest paths. The routing tables of each of the satellites are then examined for loops and other anomalies.

The final test is a step-by-step trace of both the location update and terminal page involving one mobile subscriber, three satellite nodes and two gateways. The mobile subscriber is attached to one of the gateways as a visiting node, while the other gateway generated traffic for the MS. The satellites provided connectivity between the two gateways.

3.11.2. Validation

Formal validation of a computation simulation is usually divided into validating three aspects of the model: the operating assumptions, the input values, and the results. These areas are subjected to validity tests based on real system measurements, theoretical solutions or expert evaluation.

3.11.2.1 Validation of Operating Assumptions

When developing the model, Iridium® specifications are used whenever the information is available. When the information is not available, the model relied on the assumptions made in previous theses referenced in [Ste96, Fos98, Pra99].

3.11.2.2 Validation of Input Values

All input values are compared with values specified in the literature about Iridium, and available information about the two standard protocols.

3.11.2.3 Validation of Results

For this simulation, real system measurements are not available for comparison, so validation is based on theoretical results from highly simplified models. The three output results for this research are total number of control packets, calls lost, and number of packets lost.

3.11.2.3.1 Control Packet Validation

A simulation is set up similar to the system trace used in system verification. A system of two gateways, three satellites and one mobile subscriber is constructed. A location update sequence is recorded for each of the mobility management protocols. These traces are compared with the traces found in current literature. After the traces are validated, the counts reported by the simulation are compared to the theoretical results derived through analysis.

3.11.2.3.2 Calls Lost

The system is set to request connections with six imaginary and four active mobile subscribers. The simulation is executed, and the results are compared with the expected results. The expected results are that at the initial start of the system, calls are lost until the subscribers register with the HLR. After registration, no calls should be lost.

3.11.2.3.3 Number of Packets Lost

There are two conditions that lead to packets being lost in the system. The first condition is buffer overflow. This is tested by reducing the queue size in each of the satellite to zero, and setting the satellite processing time to 20ms. Packets are then sent in a uniform rate of 1 packet every 10 ms. The system outputs are then compared with the expected loss of half of the packets sent.

The second condition that leads to packet loss is excessive delay on data packets. If a data packets takes more then 400ms to reach its destination, it is dropped from the system. A test is setup where packets are routed from the originating gateway through three satellite to the destination gateway. The packet generator is altered to put a creation time on the packets that would cause them to expire while in transit. The times are predetermined and caused one fourth of the packets to expire while processing through the first satellite, a one fourth to expire in the second satellite, etc.

3.12. Summary

This chapter focused on the methodology used to develop a computer simulation to evaluate the mobility management overhead using various protocols and topologies. The problem is first defined and scoped to include only the most important aspects of mobility management. The model is then simplified to reduce complexity and allow the system to run within the time and computing constraints of the environment. The input factors to the problem are then discussed. The performance metrics are then presented and discussed. This is followed by a discussion of the simulation model, with a breakdown of the different types of nodes, and packets used. The chapter ended with a discussion of the verification and validation used to ensure the correctness of the model.

Chapter 4: Analysis

"[Analysis] is where the answer is right and everything is nice and you can look out of the window and see the blue sky -- or the answer is wrong and you have to start over and try again and see how it comes out this time."

-Carl Sandburg (1878-1967)

4.1. Introduction

The purpose of this chapter is to present an analysis of the data generated from the five test scenarios described in Chapter 3. The chapter begins with a discussion of the statistical accuracy of the data in Section 4.2. The expected variances in each of the metrics are also discussed. The analysis of the mobility management metrics is then presented in four parts.

In Section 4.3, the first scenario, the standard IS-41-C protocol, is discussed, and the three test cases (low, high, and modified load) developed are discussed. Section 4.4 presents the second scenario. It explains the changes in topology made. Section 4.5 continues with the third scenario and the topological changes made to create the scenario. With the final topology in place, Sections 4.6 and 4.7 explain the fourth and fifth scenarios. The last two scenarios introduce two different methods to update the contents of the VLR database located in the satellite.

With the scenarios explained, the analysis of the data begins in Section 4.8. The analysis of average hop count, number of conversations, total number of hops, total number of message sent, and total number of bytes sent are explained in the subsections. The chapter concludes with a summary of the all the analysis presented.

4.2. Statistical Accuracy

Five different topology-protocol test cases are presented in this thesis. Each of the test cases is investigated under three different traffic loads. In addition, all scenarios are run five times using a different random number generator seed each time to guarantee that the metrics are not causally effected by the Poisson traffic generator. A data set is collected for each of the runs. The data set includes the number of mobility management conversations, the number of hops, the number of mobility management bytes, and the number of mobility management packets

Once all the data set are collected, the results of the runs using the different seeds are combined and an average mean and standard deviation for the metric is calculated. A 95 percent confidence interval is calculated for each metric using the student's t-distribution (Equation 15), where the $100(1\text{-}\alpha)$ is the confidence interval, $\bar{x}$ is the average of the five samples, s is the average of the five sample means, n is the number of sample means, and t is the student's t-distribution [Jai91].

$$100(1-\alpha)\%CI = \bar{x} \pm t[1-\alpha; n-1]s/\sqrt{n} \qquad (15)$$

To determine if the five random runs is sufficient to gain a 90 percent confidence interval on the data collected, the average hop count is chosen to compare between two scenarios. The average is collected in two scenarios, the low load and the high load. If the number of runs is sufficient then the average hop count for the two scenarios should be equivalent.

Table 5 shows the standard deviations for the hop count are low, with the highest deviation be 0.1096298. Table 6 also shows a low standard deviation for all the scenarios run, with the highest deviation of 0.1333 shown by the database transfer scenario. A comparison the average hop count ranges for each of the five scenarios shows that in each case the ranges overlap. From a purely statistically point of view, the ranges for the low load and the high load are equivalent. This shows that five runs of the simulation with different seed values are sufficient to produce a small confidence interval using the given input test parameters. All the charts presented in the rest of this chapter represent the average of five simulation runs, very similar to the information presented in Table 5 and Table 6.

Table 5. Average Hop Count, Low Load

Average Hop Count	Mean	Standard Deviation	95% Confidence Interval		
			Range	Minimum	Maximum
IC-41-C	7.075	0.0698493	0.061224	7.0142053	7.1366540
VLR on Satellite	4.018	0.1096298	0.096093	3.9219975	4.1141833
AC on Satellite	2.984	0.0773963	0.067840	2.9157593	3.0514383
Database Transfer	2.754	0.0838670	0.073511	2.6808711	2.8278936
Location Update	2.936	0.0675176	0.059181	2.8765673	2.9949284

Table 6. Average Hop Count, High Load

Average Hop Count	Mean	Standard Deviation	95% Confidence Interval		
			Range	Minimum	Maximum
IC-41-C	7.073	0.0485987	0.042598	7.0306546	7.1158502
VLR on Satellite	4.057	0.0636733	0.055811	4.0013453	4.1129674
AC on Satellite	2.965	0.0786411	0.068931	2.8960432	3.0339044
Database Transfer	2.777	0.1333093	0.116848	2.6601258	2.8938228
Location Update	2.917	0.0448915	0.039348	2.8776844	2.9563810

4.3. Iridium® Standard Topology

This section briefly explains the test scenarios used to establish a baseline using the topology currently fielded by the Iridium® network. In this topology, all mobility management databases and functions are located in the terrestrial gateways. The scenario is referred to as either the standard scenario or the IS-41-C scenario. As stated previously, each of the test scenarios is run using five different seeds Three test cases are run: low load, high load and modified high load.

4.3.1. Low Load

In this test case, the number of subscribers and amount of traffic generated by the PSTN is low (50 percent of the maximum). The scenario simulates a network operating under minimal load. Each of the six terrestrial gateways attempts to place 2 calls per second to the mobile subscriber. Each of the mobile subscriber groups places 2 calls per second, with 90 percent of the calls going to the PSTN, and the other 10 percent to other mobile subscribers.

The number of subscriber in each MS Group is half the maximum number that can be supported by a satellite with a GOS of 2 percent. In this scenario, each group contained 14,400 subscribers.

This test case is designed to reflect an unstressed network, and should establish a typical load generated by the standard IS-41-C protocol. This is used as a basis to judge the fitness of the proposed changes.

4.3.2. High Load

The next test case increases the number of subscribers and the amount of traffic generated by the PSTN to reflect a full load with a GOS of 2 percent. In this scenario, the number of subscribers increases to 86,400. The number of calls from each of the terrestrial gateways increases to 4 calls per second, and each MS Group also generates 4 calls per second.

This scenario is designed to reflected the network during the busiest hour of the week. This could be during the evening rush hour on a Thursday or Friday. The number of blocked calls should increase and should the number of mobility management messages sent. Overall, the mobility management should increase, but not double.

4.3.3. High Load, Modify Call and Update Frequency

The final test case maintains the number of subscribers at a high level but the traffic load is again doubled. The number of calls from the terrestrial gateways and from the MS groups is now 8 calls per second. In addition, the frequency of periodic updates is decreased from once every 10 minutes to once every 20 minutes.

This scenario determines the sensitivity of each of the topologies to traffic generation and location updates. The topologies, which handle calls in the shortest number of hops, are favored over the topologies that do better with location updates.

4.4. Satellite VLR Topology

This is the first modified topology tested. It is also the simplest. The VLR and its associated database are moved from the terrestrial ground station and placed into the orbiting satellites. The method of updating remains the same as specified in the IS-41-C standard. The mobile subscribers transmits a location update message when any one of the following occurs:

1. The subscriber first becomes active.

2. The subscriber moves into a new location area. For this scenario, that is when a different satellite supports the subscriber.
3. A sufficient amount of time has passed since the last update. For the first two test cases, the periodic update occurs every ten minutes, and in third test case the update occurs every 20 minutes.

There are two expected results from moving the VLR database to the satellite. First the number of hops between the mobile user and the VLR is reduced to one, and this reduces the number of hops required to complete any mobility management conversation. Second, the number of location updates increases. This should be very evident in the third run. When the VLR is located in the terrestrial gateway, the mobile subscriber most likely never leaves the location area, since the location area covers almost a tenth of the Earth's surface. But when the VLR database is moved to the satellite, the subscriber changes VLR database every time a new satellite comes into view.

The three test cases run with the Satellite VLR topology are the same as described in Section 4.3. The expected results are a reduction in the number of hops during conversations, but additional conversations, especially in test case three.

4.5. Satellite AC Topology

The next scenario retains topological changes made in scenario two, and adds to it. The authentication center (AC) is moved from the terrestrial gateway and added to the VLR in the satellite. Without modifying the protocols, the addition of the AC to the satellite causes a slight decrease in the number of hops required to place calls in the system and during initial registration with the system.

The three test cases performed with the Satellite AC topology are the same as described in Section 4.3. The expected results are very similar message and location update pattern are the Satellite VLR topology with only a slight decrease in hop counts.

4.6. Satellite VLR Database Transfer

The fourth scenario makes the first major change to the protocol provided by IS-41-C, database transfer. This area is not addressed in the standard, and is not a likely scenario in terrestrial cellular network. It is a distinct possibility in a satellite environment. In this scenario, every 9 minutes and 8 seconds, the satellites transfer their VLR databases to the next satellite. The AC is relatively static and remains with the satellite.

The transfer of the VLR database has advantages and disadvantages. The first advantage is that an up-to-date database limits the number of times the HLR needs to be accessed. All authentication and location update is done locally with only one registration message needed sent to the HLR every 9 minutes. The disadvantage is the amount of information needed to be transferred between satellites.

The three test cases weigh the advantages and disadvantages of database transfer. During a light load, when there are few subscribers on the air, the database transfer should be an advantage. During a heavy load, the database becomes much larger and the advantage of an up-to-date database may be overcome by the cost of transferring large amounts of the data.

4.7. Satellite VLR Periodic Updates

The fifth and final scenario makes the most changes to the protocol provided by IS-41-C. Once again the VLR and AC are located in the satellite, but now the VLR database is not transferred from one satellite to another. Instead the database is rebuilt every time a new satellite comes into view. The difference between this scenario and the second one, is that the HLR is not informed about the changes, unless the MS indicates it has traveled into a new location area.

By eliminating constant location updating of the HLR database, when the only change is the satellite supporting the MS, the number of messages should finally be reduced to an equivalent amount as the first scenario. The chief advantage of this scenario is the localization of the VLR without the penalty of database transfer.

The expected results is a reduction in both the number of hops required to complete a mobility management conversation and a reduction in the number of conversation needed to maintain the location of the mobile subscribers.

4.8. Analysis of Performance Metrics

The primary measurements used to assess the overhead involved in performing the mobility management functions in the Iridium® are the average number of hops per message, total number of conversations, total number of hops, and total number of bytes passed in support of mobility management. These metrics are defined in Section 3.10.

Each of the measurements is collected as described in Section 4.3, with every scenario executed five times, with each run having a different seed. The particular performance metric data is then averaged and a standard deviation is calculated. From this, a 95 percent confidence level is derived. All the charts in this chapter have been designed to clearly show the confidence levels. Using a floating bar chart, the values from each of the five scenarios are stacked. The value is displayed as a bar, with the length of the bar show the confidence level of the data. Any overlapping bars indicate that the values in question are not statistically different and should be considered as equivalent.

4.8.1. Analysis of the Average Number of Hops

The first metric collected and analyzed is the average number of hops a message takes from one mobility management entity to another. The lower the number of hops, the quicker the message arrives at its destination, and the lower the bandwidth utilization required for the message.

According to Lee, the number of hops required for a *Gateway Approach* algorithm is expected to require at least two more hops than using a *Satellite Approach* [Lee97]. The research in this thesis verifies his conclusion. When the VLR resided in the terrestrial gateway, it took 7.07 hops (low load scenario) to send a message from one mobility management function to another. Once the VLR is moved to satellite, the hop count dropped to 4.01 (low load scenario). Figures 14 -16 show that moving the VLR closer to the mobile subscriber eliminated one uplink and downlink required to access the earthbound VLR. The other hop eliminated occurred due to the internal structure of the terrestrial gateway. In the standard model, the VLR, AC, and HLR are all located together in the terrestrial gateway, and have internal connections to pass messages to each other. So certain mobility management messages are sent internally and are not reflected in the average hop count. This eliminates many single hop messages, increasing the hop count average for the messages that are sent over the network.

The average number of hops also decreased by one when the Authentication Center is placed in the satellites. In the low load scenario, the hop count is reduced from 4.01 to

2.98. Again, moving a mobility management function closer to the user decreased the number of hops needed to communicate with that entity.

The other important inference derived from this metric is that the method to update the VLR had very little effect on the average number of hops. The database transfer scenario showed a slightly lower hop count, because of the addition of the single hop database transfer conversation.

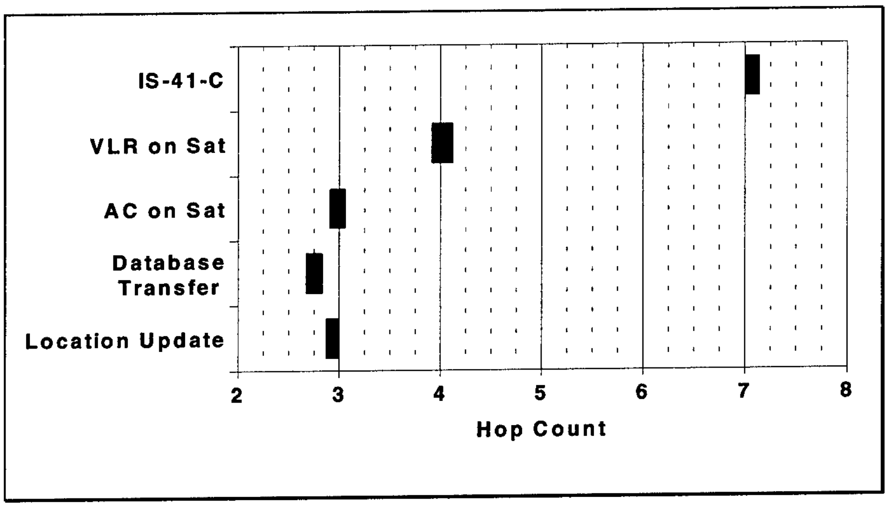

Figure 17. Average Number of Hops (Low Load)

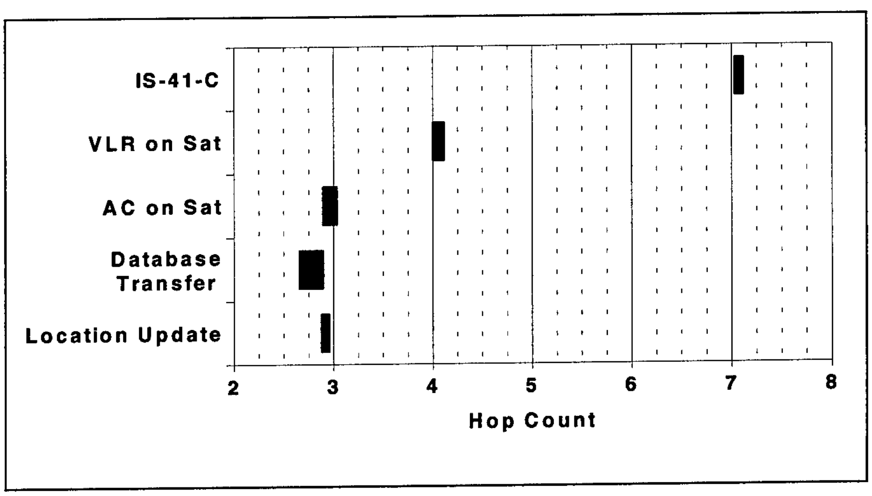

Figure 18. Average Number of Hops (High Load)

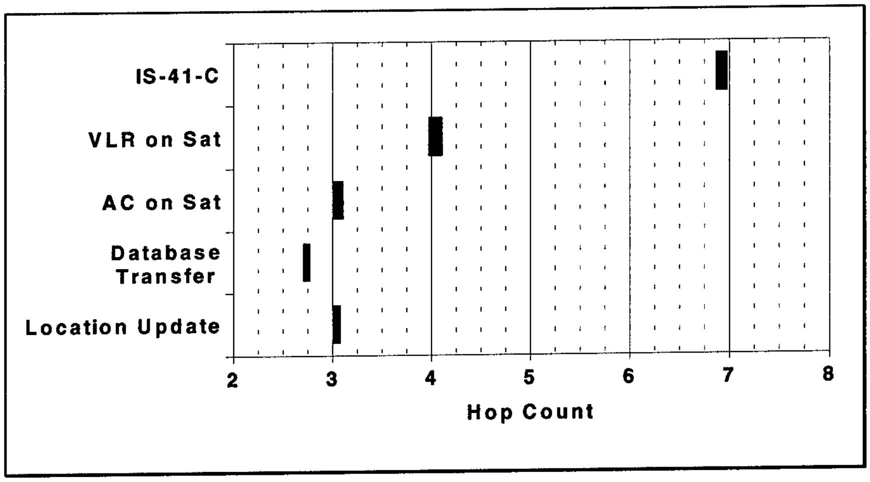

Figure 19. Average Number of Hops (Modified Load)

4.8.2. Analysis of Number of Conversations

A conversation is defined as a series of messages required to complete a single management task. Management tasks include updating the location of a mobile subscriber or establishing a call between two customers. The number of conversations made during a simulation run is the combination of three factors: a random seed generating the calls, a random seed determining the next action of a mobile subscriber, and the number of mandatory location update. The lower number of conversations, the less traffic that needs to be generated.

At a low load, the number of conversations is generally low, and all the algorithms generated approximately the same amount of traffic. Figure 20 shows that the difference between the high value of 2223.8 and the low value of 1662 is only about 25.3 percent. Statistically, the topologies fell into two groups: the standard IS-41-C and the VLR location update in one, and the other three topologies in the other. The first group generated approximately 1675 conversations, while the other three topologies generated about 2200 conversations. The key difference is the number of location update messages generated independent of the load. A more in-depth look at location update conversations is discussed in the next subsection.

The two groupings seen in the low load test case, were also seen in the high load test, as shown in Figure 21. The groupings are even more pronounced in the modified load test case (Figure 22). Overall the number of conversations generated favored the topologies that limited the number of location update messages required to be sent.

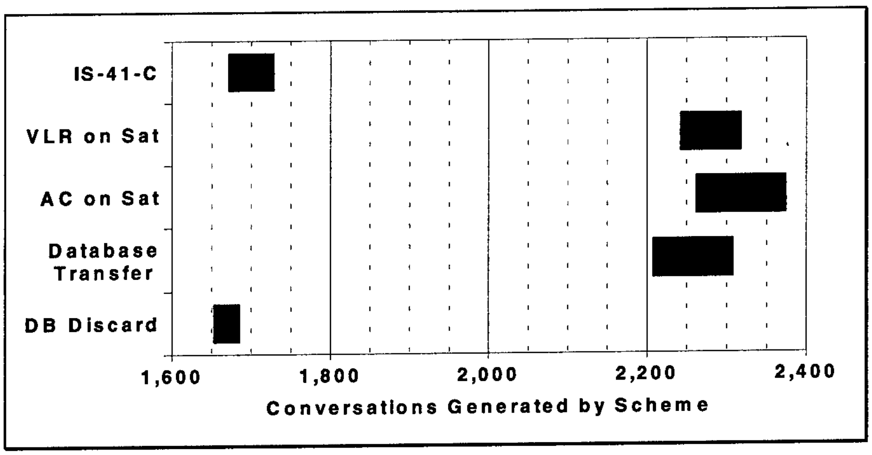

Figure 20. Number of Conversations (Low Load)

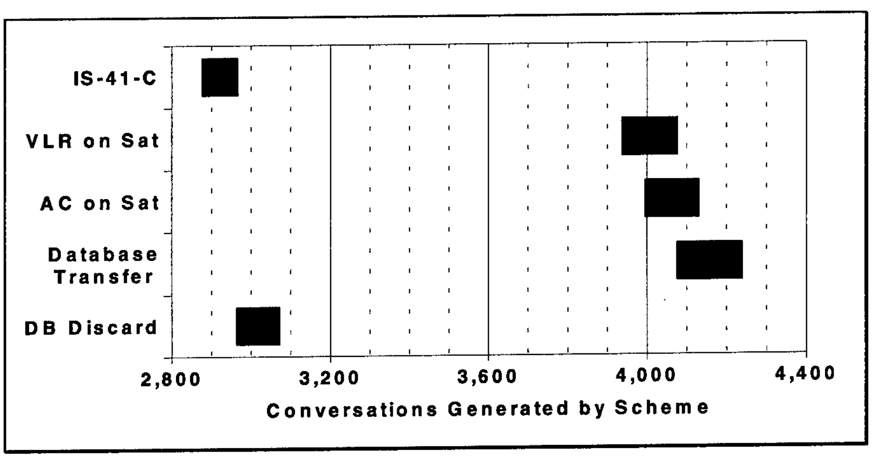

Figure 21. Number of Conversations (High Load)

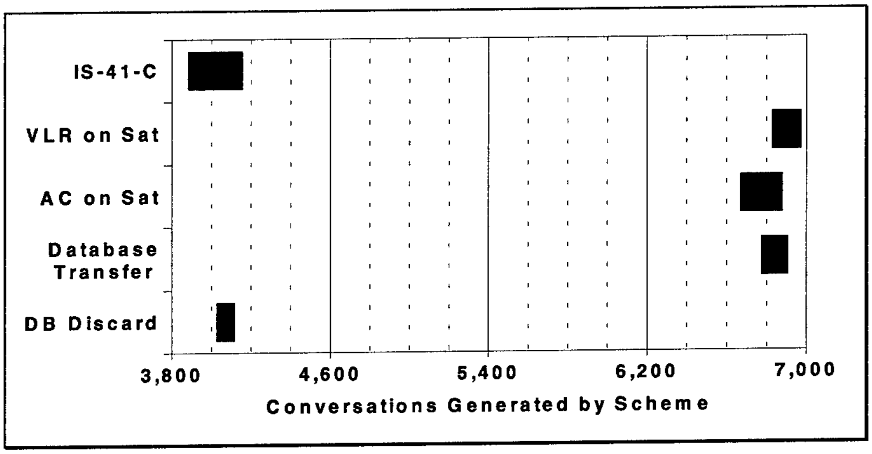

Figure 22. Number of Conversations (Modified Load)

4.8.2.1 Analysis of Location Update Conversations

A preliminary analysis of the number of conversations generated by each of the topologies seemed to favor the protocols with the fewest location updates. To verify this hypothesis, the number of location update messages is examined more closely. In Figure 23, the low load test case supports the conclusion that number of location updates directly affected the total number of conversations by each of the scenarios. A quick check shows that the difference in total conversations between the IS-41-C and the VLR on the satellite scenarios, in the low load test case, is 561.8. The difference in location update conversations between the same two scenarios is 452.4. So 80.5 percent of the difference is due to location update message.

An analysis of the high load (Figure 24) and the modified load (Figure 25) revealed the same pattern evident in the low load test case. The gap between the two groups increased in the modified load test cases to 3111.4, from the standard protocol's 3788.2 conversation to VLR in the Satellites' 6899.6. The increase is due to the modified load's change in the periodic update to once every 20 minutes, if not done earlier. The standard and discard VLR database scenarios are able to take advantage of the longer update interval and reduced number of updates. The other three scenarios could not, because they updated location of the mobile subscribers during every handover.

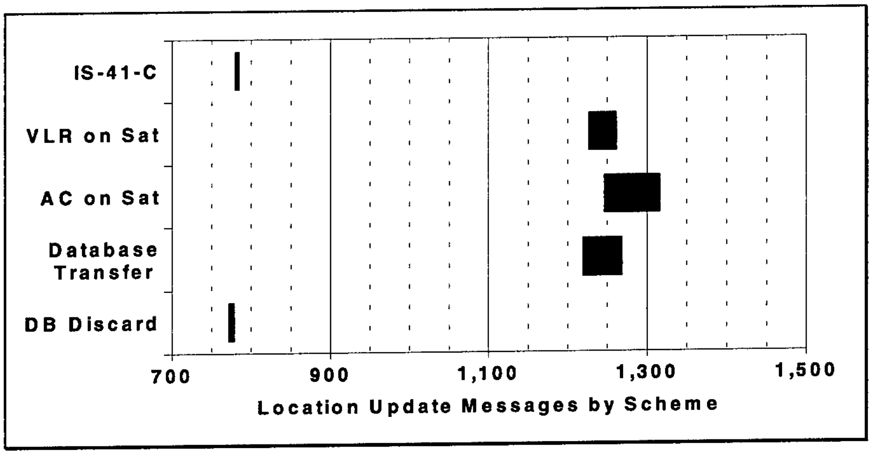

Figure 23. Location Updates (Low Load)

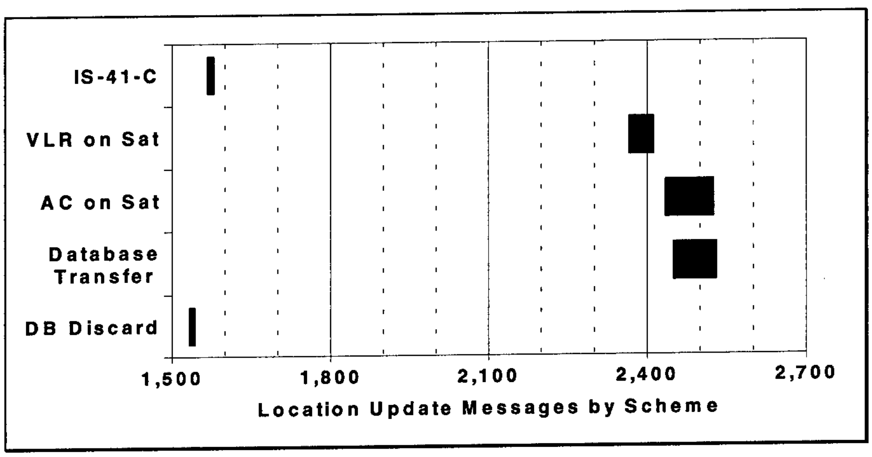

Figure 24. Location Updates (High Load)

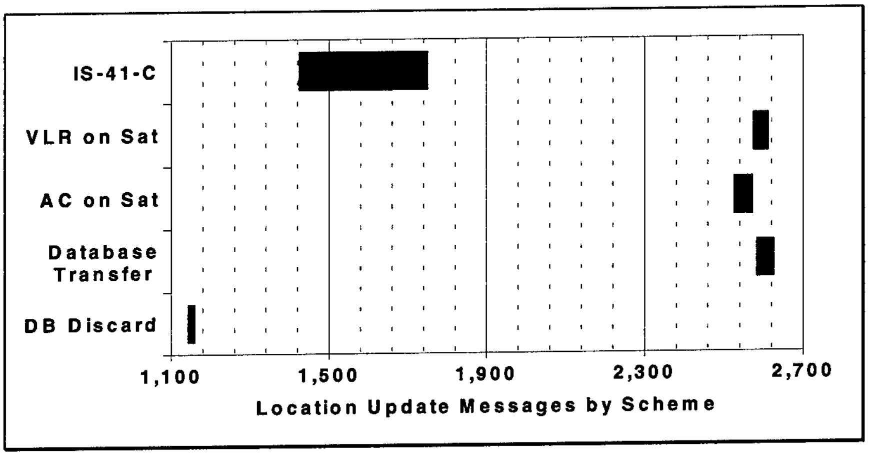

Figure 25. Location Updates (Modified Load)

4.8.3. Analysis of Calls Lost

Calls are considered lost when one of three conditions exists. First, the MS has never reported in and the HLR has the user marked as unknown. The second condition occurs when the MSC pages the last known location of the MS and the MS is not found. Finally, the HLR routes a message request to a VLR that doesn't have knowledge of the MS addressed in the message. Lost messages signify the inability to reach the user due to a problem in the mobility management scheme.

With the mobile subscriber group being stationary, the number of lost calls should be zero. Unfortunately, that goal is not met. Analysis of the individual records reveal the majority of the lost calls occur because some mobile subscribers never check-in. This explains why the number of lost calls is roughly equivalent in the low load (Figure 26) and high load (Figure 27) test cases. Once a majority of the subscribers register, the number of lost calls decreases dramatically. The modified load (Figure 28), and the low load scenarios show a clear separation between the standard and VLR location update scenarios. The possible reason for this separation is the method of location update for two is different. With the standard protocol, each registration is reported to the HLR, while in the location update scenario, only selected updates are reported. The database discard scenario in all cases is more than any of the other scenarios. This is due to the limited interaction between the VLR and HLR.

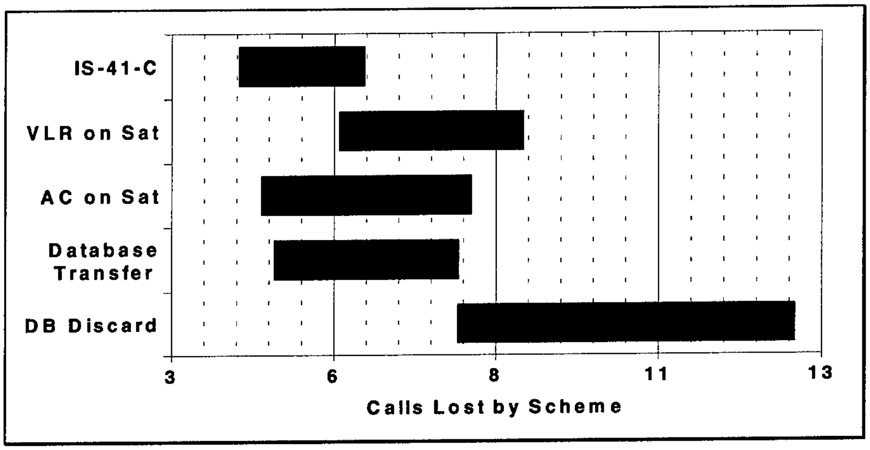

Figure 26. Number of Calls Lost (Low Load)

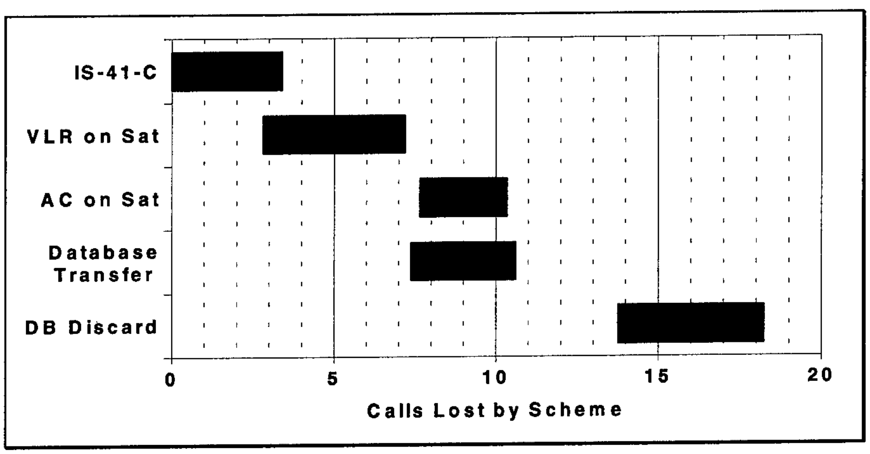

Figure 27. Number of Call Lost (High Load)

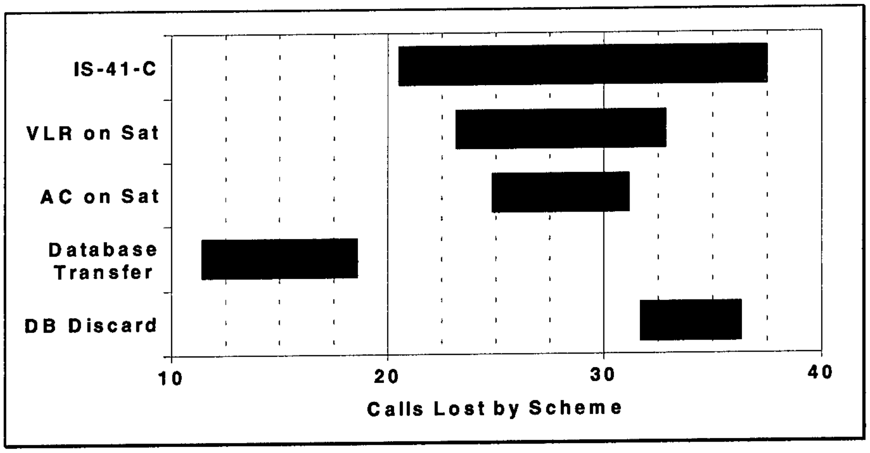

Figure 28. Number of Lost Calls (Modified Load)

4.8.4. Analysis of Total Hop Count

The total number of hops is the combination of messages sent and the number of hops each message took to reach the destination. This shows one measure of the efficiency of the protocol examined. The fewer the number of hops taken, the less time and bandwidth is needed by the mobility management to perform its task.

Examining the charts for the low load (Figure 29), high load (Figure 30) and modified load (Figure 31) test cases, a clear delineation occurs once the Authentication Center is moved. Authentication makes a difference, because each mobility management activity requires authentication at some point in the process. With at least a two hop distance between the MS Group and the nearest terrestrial gateway, having to get the Secret Shared Data adds at least four hops to each conversation.

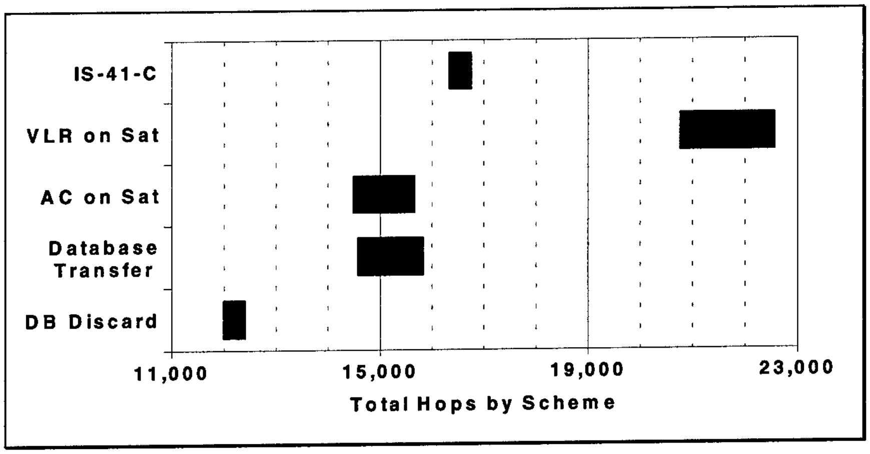

Figure 29. Total Hops (Low Load)

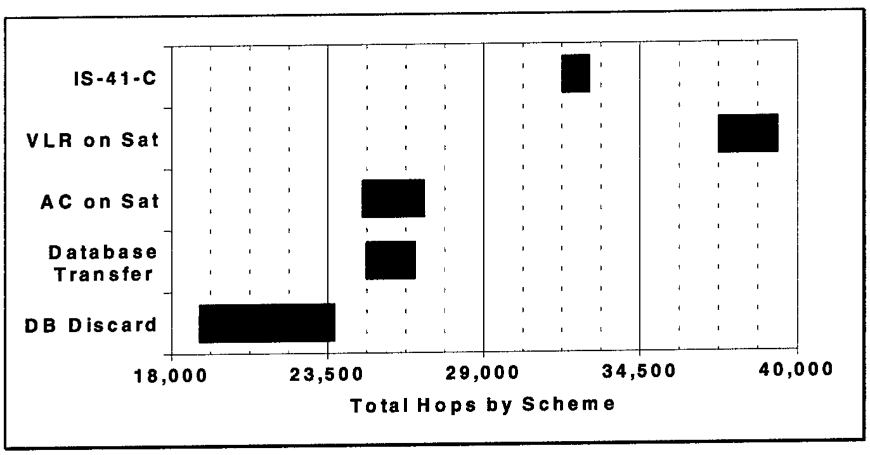

Figure 30. Total Hops (High Load)

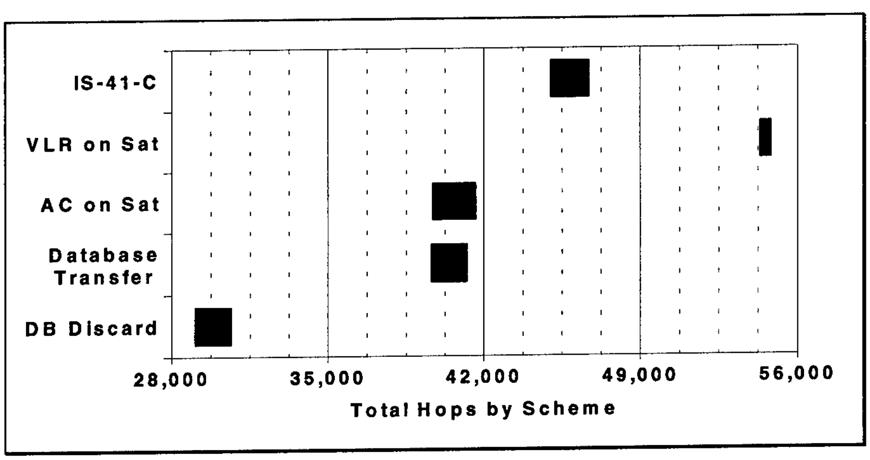

Figure 31. Total Hops (Modified Load)

4.8.5. Analysis of Total Management Messages Sent

Another measurement of the efficiency of a mobility management scheme is the number of messages that need to be sent to perform its required tasks. The number of messages includes only those messages that must be passed from one node, gateway, MS group, or satellite, to another. Internal node traffic is not considered because it doesn't use satellite bandwidth. The fewer number of messages needed to complete a task the better.

In this measurement, the standard IS-41-C sends the fewest number of messages over the airwaves. In the high load test case (Figure 33), the standard protocol only sent 7261 messages, while the next best scheme, the VLR database discard protocol sent 9,982 messages, an increase of 2721. The low count on the standard protocol can be attributed to the collocation of all the major mobility management components. Since only six gateways are modeled, and the assignment of mobile subscribers to HLRs is evenly distributed, in one out of every six conversations the mobile subscriber's VLR and HLR are located in the same gateway. This increased the number of messages kept in the gateway, and reduced network traffic. The VLR location update scenario did well because the algorithm is specifically designed to reduced the number of messages sent over the ISLs. Only one message is sent out during the first location update of a subscriber, and none after that. The other scenarios partition the mobility management functions into two geographically separated locations and this requires additional messages to be passed to complete a mobility management task. This pattern was repeated in the low load (Figure 32) and model load (Figure 34) scenarios.

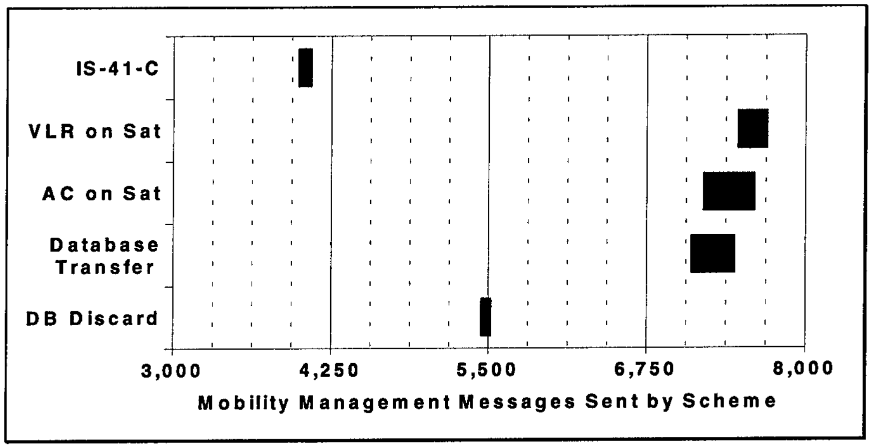

Figure 32. Total Management Messages Sent (Low Load)

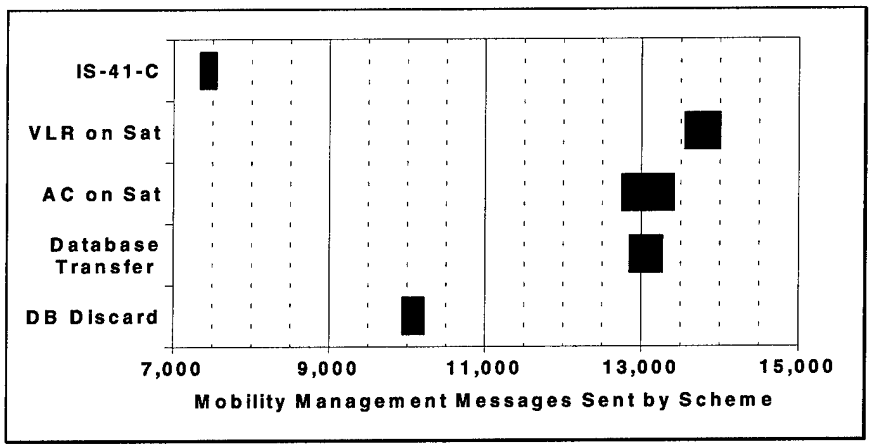

Figure 33. Total Management Messages Sent (High Load)

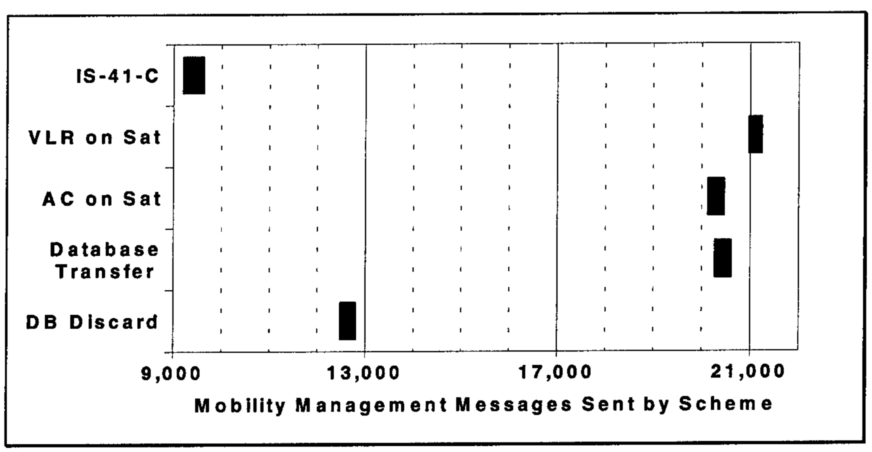

Figure 34. Total Management Messages Sent (Modified Load)

4.8.6. Analysis of Total Management Bytes Sent

The final metric examined is the total number of management bytes that are sent by each scenario during the 1,704 second simulation execution. The number is generated by summing the network load for every message that is passed. The network load is defined as the size of a management message multiplied by the number of hops required for the message to get from the source to destination. The total number of bytes shows the load offered to the network to perform mobility management tasks. This reflects to overhead associated with the protocol and must be subtracted from the total bandwidth to get the bandwidth available to the user.

The first conclusion derived from the metric is that by moving the VLR from the gateway and into the satellite, the traffic load on the network is increased. The largest differential occurred in the modified load test case (Figure 37). The standard protocol generated 2,277,900 bytes of traffic, while after moving the VLR, mobility management traffic increased to 3,390,300 bytes. This corresponds to an 33 percent increase in the load. The large difference can be explained by two factors. First, the messages that formerly are sent internally between the HLR and VLR are now required to be sent over the network. Second, when a mobile subscriber contacts a new satellite, the VLR on-board has no prior knowledge of the subscriber and must complete the initial registration, instead of the abbreviated conversation used for subsequent location updates.

Another conclusion is that transferring the database between the satellites doesn't measurably decrease that traffic load. In the high load test case (Figure 36), the AC in the satellite scenario produced 2,516,400 bytes while the database transfer scenario produced 2,525,300 bytes. The difference is statistically insignificant. In the data transfer scheme, the advantage of a reduction in location management costs is offset by the cost of moving the database from one satellite to another. Once again, the low load scenario (Figure 35) displayed the same pattern.

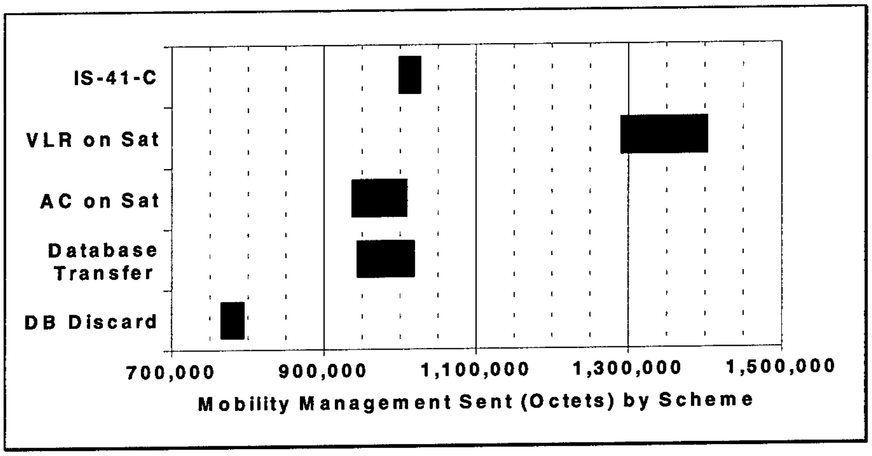

Figure 35. Total Management Bytes Sent (Low Load)

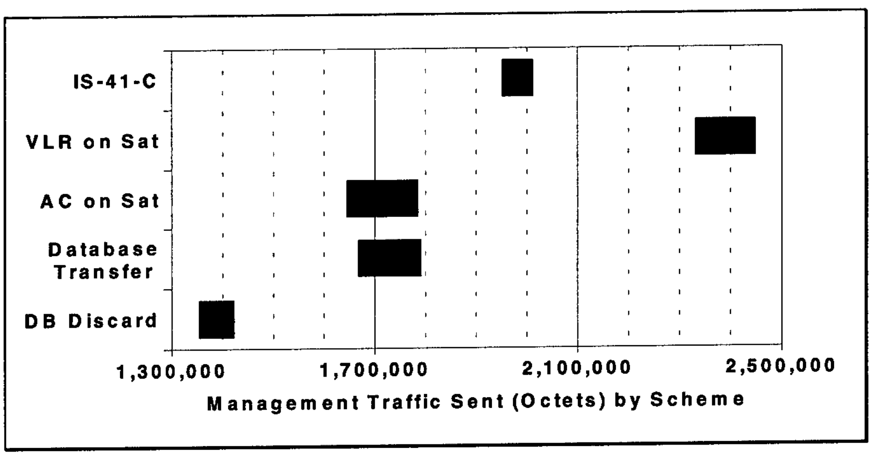

Figure 36. Total Management Bytes Sent (High Load)

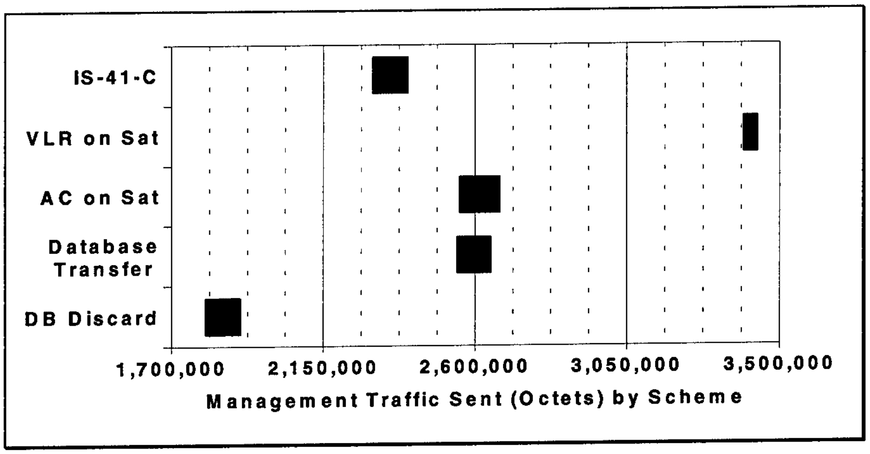

Figure 37. Total Management Bytes Sent (Modified Load)

4.9. Analysis of the Mobility Management Overhead

To this point, the analysis has been a comparison of mobility management traffic characteristics of the five scenarios tested. This section relates the mobility management overhead on the network. Overhead is the total number of packets introduced into the network to complete the required mobility management tasks. Overhead is calculated by dividing the total network traffic into the total number of mobility management packets generated in each scenario. In general, lower overhead indicates better performance.

As mentioned earlier, the maximum packet arrival rate for a satellite is 21,333 packets per second. With 66 satellites in the Iridium® system, the network can support a maximum of 1,407,978 packets per second. Each packets is 216 bits or 27 bytes in size. Mobility management messages range in size from 12 to 105 bytes, so only between one and four data packets are required to send a message. Re-examining the high load scenarios, the number of packets is determined. The results are presented in Table 7.

Table 7. Total Number of Packets Sent (Low Load)

Scenario	Total Packets (scaled)	Total Packets	Overhead
IC-41-C	88,346.84	447.82	2.32%
VLR on Satellite	106,506.10	520.86	2.44%
AC on Satellite	77,005.05	376.59	1.77%
Database Transfer	77,115.88	377.13	1.77%
Location Update	63,852.56	312.27	1.46%

The numbers are for the scaled model of the true system, so the true number of packets introduced into the system is 25 times greater. Column three in Table 7 represents the actual traffic load per satellite per second. Recalling Fossa work, a satellite can handle 21,333 packets per second. Overhead is calculated by dividing the total network traffic into the total number of mobility management packets generated in each scenario. These number reflect that even at a low load between 1.46 and 2.44 percent of the bandwidth is used by mobility management traffic.

4.10. Summary of Analysis

In this chapter, an analysis of the mobility management traffic characteristics for five different Iridium® scenarios are presented. The overall analysis shows that moving the VLR to the satellite without making modifications to the mobility management protocol causes the communication overhead to increase approximately 33 percent. If modifications are made to the protocol, then a bandwidth savings can be achieved.

The overhead associated the mobility management is found to be approximately 1.46 to 2.44 percent. When this overhead is added to the overhead created by a routing algorithm, for example, Darting (3.3 percent to 3.8 percent) [Pra99], then up to 4.04 percent of the total available bandwidth is occupied. This translates to Iridium® having to drop support to 3,474 active customers, or only support 82,525 mobile users instead of 86,000 advertised. By improving the efficiency of mobility management algorithm, enough bandwidth can be saved to support an additional 860 users.

Chapter 5: Conclusions and Recommendations

For every complex problem, there is a solution that is simple, neat, and wrong.
-- H. L. Mencken (1880 - 1956)

5.1. Restatement of Research Goal

This research had two goals:

- to compare the overhead associated with different mobility management schemes
- to determine if a topology, taking in account the strengths and weaknesses of LEO satellites, has less overhead than a standard terrestrial-based topology.

5.2. Conclusions

5.2.1. Results Synopsis

Five scenarios were developed to compare two aspects of mobility management protocols. The first aspect is the location of mobility management function. Specifically, this thesis examined the change in overhead associated with mobility management by changing the placement of the Visitor Location Register (VLR) and Authentication Center (AC) from the terrestrial gateways to the satellite As a follow on, it compared three methods of updating the VLR, when the VLR is located in the satellite. Three different update schemes were examined including the standard IS-41-C protocol, transferring the database from one satellite to another, or discarding the database and rebuilding it from scratch.

The thesis results show that simply moving the VLR from the gateway to the satellite did not decrease the traffic overhead associated with mobility management. In fact, the amount of traffic increased about 33 percent. Moving both the AC and VLR together to the satellite did decrease the traffic load by an average of 10 percent.

With the AC and VLR moved to the satellite, it is determined that with certain changes to the protocol, completely discarding the database and rebuilding it from scratch is the best. The standard protocol requires the VLR to update the subscriber's VLR entry in the HLR database after each satellite hand-over, regardless of whether the subscriber moved or not. The HLR is then required to deregister the subscriber from the satellite last handling the subscriber. Both actions added needless messages to the network. The second update scheme transferred the VLR database from satellite currently handling the mobile subscribers to the satellite handling the subscribers next. This did not decrease the traffic overhead because the savings in traffic load were offset by the amount of data moved from one satellite to the next.

The final update scheme discarded the database and rebuilt it from scratch. This scheme reduced the mobility management traffic by 30 percent by taking advantage of the properties of the satellite constellation. The first property used is that satellites cannot cover the same geographic location longer than 9 minutes and 8 seconds. If a subscriber has not updated its location within that time, it is no longer in the satellite's footprint, and it's VLR entry is purged. This means that the HLR never needs to send a deregistration message. The LEO satellites have steerable antennas and so the Earth can be divided into 2150 cells. The location of each cell is associated with a fixed geographic location and is given a unique identifier. While a cell is in-view of a satellite, the satellite maintains the same beam on the cell and broadcasts the cell's identifier. This identifier is the VLR location address stored in the HLR. This scheme reduces the number of registration messages sent to HLR. Only when the subscriber enters a new cell is the HLR updated. With the AC and VLR collocated on the satellite, the satellite can interrogate suspect mobile subscribers without HLR intervention. This reduces authentication traffic. Finally, the HLR has knowledge of what satellite is covering a particular cell at a particular time, so it can send messages without prior knowledge by the VLR. If the VLR receives a connection request before it has established the subscriber's presence, it will try to process the request anyway. These properties allowed the total mobility traffic overhead to be reduced by 30 percent.

5.2.2. Recommendations

If the conservation of Inter-Satellite Link (ISL) bandwidth is important, then moving the VLR and AC to the satellite is recommended, provided the proper changes to the mobility management protocol are made. The changes recommended are outlined in the preceding paragraph. The most significant benefit of the proposed changes is that they are internal to the Iridium® system and does not effect the Iridium®'s interoperability with any terrestrial system using IS-41-C.

The satellite hardware needs to be upgraded. The satellite needs approximately 205,920 bytes of memory to store the VLR database, and an additional 120 MB of memory for the AC database. The on board processor needs to handle all VLR and AC functions, especially VLR table lookups and authentication generation quickly, in less than 1 second.

5.3. Significant Results of Research

This work is the first to examine traffic overhead in a Low Earth Orbiting (LEO) satellite at the protocol level. All previous research concentrated on comparison studies at the data-link and network routing layer. This work, by combining the aspects of mobility management protocols with the dynamic nature of a LEO constellation, is able to obtain results that are overlooked when the factors are considered separately.

5.4. Future Research

This research can be expanded in three major areas. First, the only protocol tested was IS-41-C. This is the standard protocol for North America, and the Iridium® satellite, but other protocols are in use throughout the world. The most significant is Global System for Mobile Communication (GSM), and its corresponding over-the-air protocol called Mobile Application Part (MAP). This is a more complex protocol and requires a different message passing sequence to complete mobility management tasks. So results using GSM MAP would likely lead to conclusions different from those presented in this thesis. Testing GSM MAP is important, since the next generation of communication satellites will probably use a version of GSM, instead of IS-41-C.

The second area of research is modeling the spot-beams of the Iridium® satellite. By simplifying the model to exclude spot-beams, it was not possible to test some of the newer paging schemes suggested in various publications [AkH95a, AkH95b, GuR98]. Chapter 2 discusses of the paging schemes that have been recommended in the available literature. Reducing the amount of paging traffic can increase the available bandwidth for the mobile subscribers.

Another area of research is moving the Home Location Register into the satellite, or into geostationary satellites, which communicate with the LEOs. This area was not pursued because of it seemed unlikely to reduce the overhead involved. But, as this thesis has shown, with proper modifications to the protocol, it may result in a reduction in overhead.

The final area of research would involve modifying the protocol at a message level. Most mobility management protocols are designed to work in a heterogeneous environment. This requires an additional layer of complexity, and causes additional fields to be added to the messages. This aspect would not be required in a homogenous environment such as the Iridium® network.

Appendix

This appendix contains the tabulated results from a selected number of statistics gathered during the 75 simulation runs and the 90% confidence intervals for each test scenario.

Table 8. Number of Conversations Generated (Low Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	1696	1700	1637	1666	1611	1662	38.21649	1633.89	1690.11
VLR on Sat	2274	2280	2214	2176	2175	2223.8	51.09012	2186.22	2261.38
AC on Sat	2136	2318	2183	2149	2250	2207.2	76.07693	2151.24	2263.16
DB Transfer	2211	2258	2204	2077	2167	2183.4	67.71484	2133.60	2233.21
DB Discard	1722	1669	1704	1682	1709	1697.2	21.37054	1681.48	1712.92

Table 9. Number of Conversations Generated (High Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	2889	2921	2816	2777	2810	2842.6	59.944	2798.50	2886.70
VLR on Sat	4026	4007	3980	3801	4016	3966.0	93.8110	3896.99	4035.00
AC on Sat	4071	4063	3868	3912	3950	3972.8	90.8003	3906.00	4039.59
DB Transfer	4012	4157	3938	3947	3867	3984.2	109.4153	3903.71	4064.68
DB Discard	3032	3018	3008	2885	2892	2967.0	72.2080	2913.88	3020.11

Table 10. Number of Conversations Generated (Modified Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	3947	4019	3682	3612	3681	3788.2	181.867	3654.42	3921.98
VLR on Sat	6781	6900	6976	6834	7007	6899.6	94.527	6830.07	6969.13
AC on Sat	6795	6774	6708	6851	7070	6839.6	138.588	6737.66	6941.55
DB Transfer	6860	6840	6908	6712	6724	6808.8	86.598	6745.10	6872.50
DB Discard	3994	4071	3943	3926	3965	3979.8	56.980	3937.89	4021.71

Table 11. Number of Location Update Conversations (Low Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	780	782	778	782	777	779.8	2.280	778.12	781.48
VLR on Sat	1262	1244	1201	1233	1221	1232.2	23.059	1215.24	1249.16
AC on Sat	1181	1281	1205	1173	1251	1218.2	46.424	1184.05	1252.35
DB Transfer	1217	1244	1190	1166	1171	1197.6	32.761	1173.50	1221.70
DB Discard	776	775	769	775	768	772.6	3.782	769.82	775.38

Table 12. Number of Location Update Conversations (High Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	1557	1573	1556	1560	1568	1562.8	7.396	1557.36	1568.24
VLR on Sat	2431	2389	2416	2360	2431	2405.4	30.632	2382.87	2427.93
AC on Sat	2491	2480	2348	2389	2411	2423.8	60.817	2379.06	2468.54
DB Transfer	2430	2490	2365	2456	2368	2421.8	54.792	2381.50	2462.11
DB Discard	1550	1538	1545	1555	1543	1546.2	6.535	1541.40	1551.01

Table 13. Number of Location Update Conversations (Modified Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	1603	1587	1185	1200	1191	1353.2	220.869	1190.73	1515.67
VLR on Sat	2593	2593	2607	2568	2633	2598.8	23.732	2581.34	2616.26
AC on Sat	2590	2549	2552	2589	2622	2580.4	30.369	2558.06	2602.74
DB Transfer	2628	2604	2571	2561	2576	2588.0	27.468	2567.79	2608.21
DB Discard	1125	1151	1134	1141	1142	1138.6	9.711	1131.46	1145.74

Table 14. Number of Deregistration Conversations (Low Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	68	68	62	64	66	65.6	2.608	63068	67.52
VLR on Sat	94	88	83	103	78	89.2	9.731	82.04	96.36
AC on Sat	85	96	71	85	92	85.8	9.524	78.79	92.81
DB Transfer	97	83	86	92	79	87.4	7.162	82.13	92.67
DB Discard	51	46	54	56	49	51.2	3.962	48.29	54.11

Table 15. Number of Deregistration Conversations (High Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	124	146	124	123	140	131.4	10.807	123.45	139.35
VLR on Sat	164	176	170	160	180	170.0	8.246	163.93	176.07
AC on Sat	154	165	160	161	186	165.2	12.276	156.17	174.23
DB Transfer	168	176	157	183	166	170.0	9.925	162.70	177.30
DB Discard	105	91	93	111	93	98.6	8.877	92.07	105.13

Table 16. Number of Deregistration Conversations (Modified Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	732	721	247	261	250	442.2	259.611	251.23	633.17
VLR on Sat	509	529	546	515	523	524.4	14.276	513.90	534.90
AC on Sat	557	510	525	530	565	537.4	22.941	520.52	554.28
DB Transfer	604	550	537	502	531	544.8	37.466	517.24	572.36
DB Discard	165	206	179	189	190	185.8	15.123	174.68	196.92

Table 17. Number of Calls Attempted (Low Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	583	570	546	568	523	558.0	23.654	540.60	575.40
VLR on Sat	667	660	663	606	621	643.4	27.916	622.87	663.94
AC on Sat	638	685	645	629	659	651.2	21.845	635.13	667.27
DB Transfer	651	653	667	582	640	638.6	33.065	614.28	662.92
DB Discard	484	450	472	450	473	465.8	15.172	454.64	476.96

Table 18. Number of Calls Attempted (High Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	907	863	856	821	838	857.0	32.381	833.18	880.82
VLR on Sat	1079	1073	1078	973	1080	1056.6	46.811	1022.17	1091.03
AC on Sat	1104	1095	1048	1056	1056	1071.8	25.694	1052.90	1090.70
DB Transfer	1075	1151	1081	1019	1029	1071.0	52.402	1032.45	1109.55
DB Discard	727	738	739	669	694	713.4	30.794	690.75	736.05

Table 19. Number of Calls Attempted (Modified Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	1150	1202	1662	1639	1681	1466.8	266.514	1270.75	1662.85
VLR on Sat	3046	3121	3169	3135	3182	3130.6	53.351	3091.36	3169.85
AC on Sat	3050	3151	3060	3132	3256	3129.8	83.098	3068.67	3190.93
DB Transfer	3052	3102	3216	3099	3006	3095.0	78.224	3037.46	3152.54
DB Discard	1384	1384	1353	1343	1344	1361.6	20.816	1346.29	1376.91

Table 20. Number of Lost Calls (Low Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	5	5	2	3	4	3.8	1.304	2.84	4.76
VLR on Sat	8	7	4	9	6	6.8	1.924	5.39	8.21
AC on Sat	6	6	2	6	2	4.4	2.191	2.79	6.01
DB Transfer	3	6	8	5	4	5.2	1.924	3.79	6.61
DB Discard	7	10	14	11	5	9.4	3.507	6.82	11.98

Table 21. Number of Lost Calls (High Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	5	1	7	6	4	4.6	2.302	2.906	6.29
VLR on Sat	10	5	10	6	12	8.6	2.966	6.42	10.78
AC on Sat	8	9	6	5	5	6.6	1.817	5.26	7.94
DB Transfer	6	9	3	7	7	6.4	2.191	4.79	8.01
DB Discard	12	16	20	17	14	15.8	3.033	13.57	18.03

Table 22. Number of Lost Calls (Modified Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	34	29	10	14	9	19.2	11.520	10.73	27.67
VLR on Sat	32	28	23	34	18	27.0	6.557	22.18	31.82
AC on Sat	21	28	19	17	19	20.8	4.266	17.66	23.94
DB Transfer	15	15	26	20	15	18.2	4.868	14.62	21.78
DB Discard	29	34	27	28	33	30.2	3.114	27.91	32.49

Table 23. Number of Hops Taken (Low Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	16451	16542	15980	16383	16749	16421.0	282.42	16213.2	16628.8
VLR on Sat	19555	21664	19428	18621	20837	20021.8	1213.89	19128.1	20913.9
AC on Sat	13473	15076	14569	13162	13714	13998.8	797.39	13412.2	14585.4
DB Transfer	13319	15199	14019	13019	14177	13946.6	848.70	13322.3	14570.9
DB Discard	11798	12204	12239	11632	12190	12012.6	278.51	11807.7	12217.5

Table 24. Number of Hops Taken (High Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	31466	32241	31614	30789	30708	31363.6	633.05	30897.9	31829.3
VLR on Sat	38423	38281	37415	35060	36625	37160.8	1379.59	36146.0	38175.6
AC on Sat	25008	25805	23937	21980	23503	24046.6	1465.83	22968.3	25124.9
DB Transfer	24561	25708	24599	23125	22912	24181.0	1159.35	23328.2	25033.8
DB Discard	21302	21357	21180	13869	19890	19519.6	3216.22	17153.7	21885.5

Table 25. Number of Hops Taken (Modified Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	36183	38297	38261	36131	36248	37024.0	1146.47	36180.7	37867.4
VLR on Sat	54360	54567	54755	54016	54099	54359.4	310.37	54131.1	54587.7
AC on Sat	39899	40660	39034	37303	38493	39077.8	1291.47	38127.8	40027.8
DB Transfer	38079	40435	39813	39063	38053	39088.6	1052.37	38314.5	39862.7
DB Discard	28506	29841	28351	26787	28174	28331.8	1086.24	27532.8	29130.8

Table 26. Millions of Mobility Management Octets Sent (Low Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	1.008	1.013	.985	1.007	1.037	1.0099	0.0183	0.9965	1.0234
VLR on Sat	1.221	1.347	1.213	1.151	1.295	1.2453	0.0764	1.1891	1.3015
AC on Sat	0.873	0.973	0.927	0.850	0.891	0.9029	0.0482	0.8674	0.9383
DB Transfer	0.871	0.981	0.905	0.849	0.913	0.9037	0.0503	0.8667	0.9407
DB Discard	0.751	0.780	0.778	0.738	0.777	0.7648	0.0192	0.7507	0.7790

Table 27. Millions of Mobility Management Octets (High Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	1.935	1.982	1.953	1.896	1.889	1.9310	0.0389	1.9023	1.9560
VLR on Sat	2.390	2.390	2.338	2.205	2.291	2.3226	0.0775	2.2656	2.3797
AC on Sat	1.655	1.715	1.602	1.471	1.550	1.5984	0.0938	1.5294	1.6674
DB Transfer	1.629	1.729	1.638	1.538	1.528	1.6124	0.0825	1.5517	1.6730
DB Discard	1.389	1.388	1.380	1.305	1.303	1.3533	0.0450	1.3202	1.3864

Table 28. Millions of Mobility Management Octets (Modified Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	2.211	2.348	2.358	2.230	2.242	2.2779	0.0699	2.2265	2.3293
VLR on Sat	3.383	3.414	3.423	3.373	3.359	3.3903	0.0274	3.3702	3.4105
AC on Sat	2.567	2.614	2.503	2.406	2.492	2.5164	0.0792	2.4581	2.5747
DB Transfer	2.478	2.597	2.587	2.520	2.444	2.5253	0.0668	2.4761	2.5744
DB Discard	1.772	1.852	1.765	1.659	1.743	1.7583	0.0690	1.7076	1.8090

Table 29. Number of Mobility Management Packets Sent (Low Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	3993	4040	3865	3947	3938	3956.6	65.401	3908.49	4004.71
VLR on Sat	7392	7583	7259	7181	7404	7363.8	153.996	7250.52	7477.08
AC on Sat	6807	7399	7127	6714	7000	7009.4	271.078	6810.00	7208.81
DB Transfer	6831	7273	6966	6646	6899	6923.0	229.193	6754.41	7091.60
DB Discard	5517	5482	5599	5475	5520	5518.6	49.268	5482.36	5554.84

Table 30. Number of Mobility Management Packets Sent (High Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	7348	7444	7250	7113	7151	7261.2	137.097	7140.3	7362.0
VLR on Sat	13936	13775	13626	13126	13661	13624.8	303.940	13401.2	13848.4
AC on Sat	13052	13082	12304	12066	12657	12632.2	449.295	12301.7	12962.7
DB Transfer	12820	13059	12668	12597	12291	12687.0	283.439	12478.5	12895.5
DB Discard	10185	10078	10084	9768	9795	9982.0	188.145	9843.6	10120.4

Table 31. Number of Mobility Management Packets Sent (Modified Load)

Scheme	seed 128	seed 222	seed 007	seed 397	seed 428	Mean	Standard Deviation	90% Confidence	
								Min	Max
IC-41-C	9049	9414	8995	8673	8786	8983.4	285.118	8773.7	9193.1
VLR on Sat	21058	21107	21358	21239	21482	21248.8	175.296	21119.9	21377.8
AC on Sat	20121	20295	20145	19770	20344	20135.0	225.168	19969.4	20300.6
DB Transfer	20006	20442	20161	20220	19850	20135.8	223.614	19971.3	20300.3
DB Discard	12388	12640	12225	12085	12375	12342.6	207.211	12190.2	12495.0

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13. ABSTRACT *(Maximum 200 words)*
This thesis provides a performance analysis of three different mobility management topologies and their associated protocols when used in a LEO satellite constellation. Simulations were developed to compare two aspects of mobility management protocols. The first aspect was to determine which is the better location for the Visitor Location Register (VLR) and Authentication Center, collocated with the Home Location Register in the terrestrial gateways or placed on the communications satellites. The second aspect compared three methods of updating the VLR, if the VLR is onboard the satellite. Three different update schemes were examined: using the standard IS-41-C protocol, transferring the database from one satellite to another, or discarding the database and rebuilding it from scratch.
The thesis results concluded that simply moving the VLR from the gateway to the satellite did not decrease the traffic overhead associated with mobility management. In fact, the amount of traffic increased about 33 percent. Moving the AC and VLR together to the satellite however decreased the traffic load by average of 10 percent over the standard model. With the AC and VLR onboard the satellite, it is determined that discarding the database and rebuilding it from scratch is the best update method. This scheme reduced the mobility management traffic by taking advantage of the properties of the satellite constellation. These properties reduced total mobility traffic overhead by 30 percent.

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