3-2000

A Performance Analysis of a Joint LMDS/ Satellite Communication Network

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THESIS

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THESIS

Presented to the Faculty

Department of Electrical and Computer Engineering

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the

Degree of Master of Science in Engineering and Environmental Management

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March 2000

AFIT/GE/ENG/00M-20

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Acknowledgements

There are several people that I would like to thank for their support throughout the months of hard work involved in the thesis. First, I would like to thank my advisor Major Richard Raines and my committee members Dr. Temple and Major Baldwin. Second, I would like to thank Captain Stephen Conklin, Captain Bret Neville, Captain Alex Muller, and Lt David Banker. Without their guidance and support developing the OPNET simulation model, I would have been lost. Last, and most importantly, I would like to thank the most important person in my life, Lori Janssen, for her continual love and support through all the long hours.

Ronald J. Zwickel

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Abstract

The goal of this research is to provide a performance analysis of a joint terrestrial/ satellite communication network. The systems of interest are the Local Multipoint Distribution Service (LMDS) terrestrial system and the proposed Teledesic satellite network. This analysis is performed using the OPNET network simulation tool. Simulations are run for twelve separate scenarios involving three factors which include: number of users, modulation type, and Quality of Service (QoS). The key metrics for characterizing simulation scenarios are the end-to-end delay, bit error rate, and average system throughput. The results obtained display the benefit of improved throughput, approximately 20 Mbps for the low user load and approximately 8 to 11 Mbps for the high user load, when the modulation schemes where changed. This improvement comes at the expense the bit error rate. For example, the bit error rate increased by a factor of 5 for the low user load when changing from BPSK to QPSK and by a factor of 1.5 for the QPSK to 8-PSK change. The peak end-to-end delay results, ranging from .053 seconds to .446 seconds, proved to support real-time voice communication for all but one scenario (BPSK/ high user load). The QoS proved to be a benefit for scenarios with a high user load (150 users) increasing the average throughput by 2 to 4 Mbps. The QoS also reduced the peak end-to-end delay, narrowing the range from .04 to .104 seconds. The analysis of these three main operational characteristics gives a fundamental look at the joint network's performance capabilities.

Chapter 1

Introduction

1.1 Research Goal

The goal of this research was to analyze the throughput, bit error, and packet delay performance capabilities of a combined LMDS/ Satellite system under different user loads, Quality of Service requirements, and in the presence of a varying urban attenuation.

1.2 Research Motivation

By combining a satellite network with a terrestrial network a person gains advantages of both systems. The terrestrial system is capable of very high data rates with the capability of increased communications security. The satellite network provides increased mobility through the unlimited range not found with the terrestrial system, but does not have the dedicated bandwidth of the terrestrial network. If the systems are combined they can work together to provide the tactical capabilities (terrestrial) and the global capabilities (satellites) required by the warfighters.

The United States Air Force has recently shown great interest in simulating all possible military communication systems. The J-6 (Joint Staff) is sponsoring research into modeling all DoD communications systems in order to analyze the communication capabilities of the armed forces as a whole. This project has been named the NETWARS (Networks and Warfare Simulation) model. The analysis of the integrated terrestrial/satellite network and the simulation model created for the analysis is a valuable addition to the NETWARS model.

This research analyzes major performance characteristics of an integrated terrestrial/ satellite network using a network simulation tool called OPNET. For a communication network to be useful in a military environment, it must be designed to consider security, mobility, and availability. Computer simulations are a cost-effective method for analyzing a communication network since the hardware and setup costs are minimal.

The goal of the research is to produce a simulation that models how the network performs with multiple users in a mobile environment. The simulation should be capable of providing key communication specifications such as end-to-end delay, data error rates, and throughput. Since the network includes two heterogeneous networks, the transition of a user from one system to the other is tracked while noting all connection delays and data loss.

The terrestrial system modeled is an LMDS (Local Multipoint Distribution System) which operates like typical cellular phone networks. The satellite network modeled is a LEO (Low Earth Orbit) system similar to the proposed Teledesic system.

1.3 Scope

This thesis presents research of a performance analysis of a combined terrestrial/ satellite network. To analyze the performance of the network, three separate areas were considered: end-to-end delay, bit error rate, and throughput. The network was tested by varying three basic factors: number of users, modulation type, and Quality of Service (QoS). The simulation model is developed using the OPNET modeling tool.

1.4 Approach

The first step of this research was to complete a thorough literature review to gather all specifications and previous research concerning various LEO satellite networks and current LMDS networks.

In order to test the dynamics of the integrated terrestrial/satellite network of interest in this thesis, a model was developed that included the satellite and a typical cellular cluster of

LMDS cells. It was not necessary to implement the full satellite constellation since the simulation only required a portion of the satellite system for the duration of the simulation runs.

The next stage of the research required creating a model of the partial satellite network (Teledesic) that was used for simulation. This task was accomplished using the Satellite Tool Kit produced by Analytical Graphics. This model provided the fundamental orbital information that will be used in the OPNET model.

The OPNET model was then developed. The satellite orbital information was transferred in this model in order to control the satellite nodes. The LMDS and satellite nodes were then modified to mimic the theoretical, real-world integrated communication system. The mobile users depicted within the model were equipped to handle both communication formats (satellite or LMDS) and to negotiate a transfer in systems with minimal data loss. The simulation modeled the mobile users traveling from one LMDS cell to another as well as from an LMDS cell to satellite coverage areas. The key output of the simulation were overall delay, error-rates, and throughput evident from one mobile user to another mobile user.

After the model was developed and the simulations had been executed, the data was analyzed and documented in the thesis. The thesis and OPNET models were the final product as a result of this research.

Chapter 2

Literature Review

2.1 Introduction

A hybrid network consisting of a terrestrial line-of-site (LOS) communication system and an advanced satellites network is the focus of this literature review. This system combines the high data rate advantages of the terrestrial system with the unrestricted mobility of a satellite communication system. The advanced satellite networks discussed within this literature review are the IRIDIUM network developed by Motorola and the proposed Teledesic network being developed by Boeing and Microsoft. The IRIDIUM network is a Low Earth Orbit (LEO) satellite system developed for voice, data and fax communication applications. The Teledesic network is a high-capacity broadband network also using LEO satellites. The wireless terrestrial system considered is a Local Multipoint Distribution System (LMDS). This system is fundamentally the same as the network used for cellular telephone communication since the system consists of *cells*. Users within the cell communicate through a base station. The new capability of the LMDS is near gigabit data rate. By combining the satellite network with the terrestrial system, users are given great flexibility to move while maintaining a reliable communication link.

Several previous AFIT theses have been accomplished for analyzing the IRIDIUM satellite system. An analysis of algorithms used for routing within the IRIDIUM system was researched by Pratt [Pra99]. This research followed Fossa's [Fos98] work concerning the performance and survivability of the IRIDIUM system as well as Janoso's [Jan96] analysis of routing protocols in a LEO satellite network. The transmission path for the IRIDIUM system was recently researched and analyzed by Crowe [Cro99]. These theses have given extensive insight into this satellite system's capabilities to communicate voice, data, and fax information to users world wide. There is very little open research on the Teledesic system since it is in the developmental stage and does not have a set design. The most current information can be found at the Teledesic web site [Tel99].

The LMDS has not previously been researched by AFIT. The main research done throughout the world emphasizes the need to supplement the current multimedia distribution which includes: real time video, data and computing, database consulting, games, and internet browsing [SaB98]. The other main emphasis for research of LMDS involves studying signal attenuation (power loss) due to the urban environment.

This literature review discusses the specifications for the IRIDIUM and Teledesic satellite networks including power, bandwidth, frequency, routing and orbital parameters as well as an analysis of LEO satellite networks. This literature review presents information concerning the capability of combining these satellite networks (IRIDIUM and Teledesic) with a terrestrial LMDS. The LMDS research provides basic characteristics for operating the line-of-sight (LOS) system such as frequency, bandwidth, and attenuation. The system specifications detailed in the literature review are used in a simulation to examine the performance/ survivability of the combined system. The frequency, bandwidth, and attenuation for the LMDS are considered within the simulation.

2.2 Low Earth Orbit (LEO) Satellites

A LEO satellite is characterized as such if its orbit ranges between 500 and 1500 km. This low altitude provides one of the major benefits of the LEO system over higher orbit satellite systems. Due to the low altitude the propagation time for a signal to reach the satellite from an earth-based user is relatively low, typically between 1.67 and 6.67 ms

[Pra99]. The low altitude also allows the satellites to operate with reduced power requirements. The last major benefit of the LEO systems stems from their use in polar orbits enabling them to provide true worldwide coverage.

LEO satellite networks also have negative characteristics. One being the large number of satellites required to establish whole-earth coverage. The number varies depending on the constellation design [Pra99]. LEO systems may also required more complex processing/networking capabilities on the satellites in order to provide dynamic routing since the satellites have small coverage areas and have to route through several satellites to establish a connection.

2.3 Multiple Access Environment

There are three main multiple access environments. These include Time Division Multiple Access (TDMA), Frequency Division Multiple Access (FDMA) and Code Division Multiple Access (CDMA). These forms of multiple access are designed to provide methods to efficiently use a specific frequency band for several users without conflict. The are two additional techniques that involve the design of the antenna used to transmit the signal. These are Space Division (SD) and Polarization Division (PD).

TDMA allows multiple users within a certain bandwidth by establishing time slots for transmission. Each user transmits on the same frequencies but at different times. This method has the benefit of allowing the users to utilize the entire bandwidth, but for only a portion of the time. This method requires all of the users to have detailed synchronization information to ensure that they stay within the designated time slot. The full system capacity is also limited due to the guard time bands that are required to eliminate interference between time slots as seen in Figure 1.

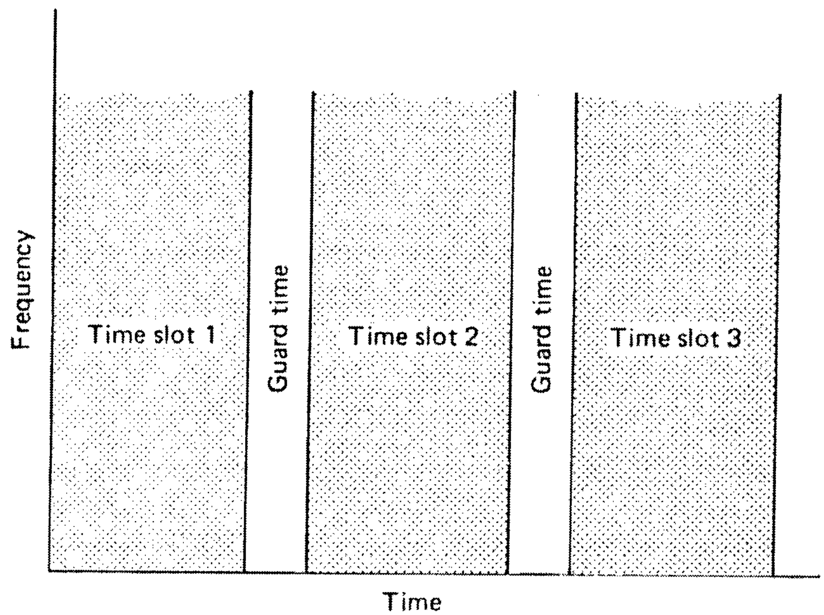

Figure 1: TDMA Plot [Ska88]

FDMA, on the other hand, allows for multiple users by splitting the available bandwidth into separate frequency bands for each user. This method allows the users to constantly transmit. But because of the reduced band for each user, the transmit rate is reduced in direct proportion to the number of allowed users. FDMA has approximately the same utilization of bandwidth as the TDMA method. FDMA also uses guard bands to avoid interference as seen in Figure 2. A combination of TDMA and FDMA can also be used by dividing the available frequency into separate bands as well as splitting each band into time slots.

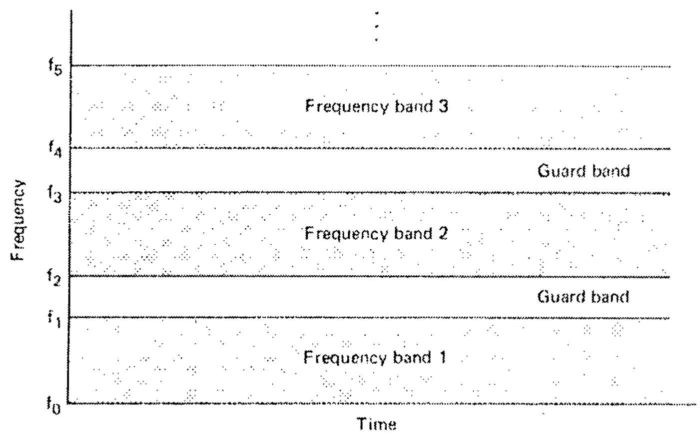

Figure 2: FDMA Spectrum [Ska88]

CDMA is the final method that will be discussed. This type of multiple access is much different. It assigns a specified pseudo random code to each user which uniquely identifies each user's signal. This unique code is applied to the data stream or waveform of the user's signal creating a resulting waveform that is a combination of the user's data waveform and the pseudo random code as shown in Figure 3. A receiver can only retrieve this modified data by applying the exact pseudo code used at the transmitter. CDMA allows all users to transmit simultaneously. The main limitation is the rate of the pseudo code which in return limits the data rate if the desired data rate/ pseudo rate ratio is to be maintained.

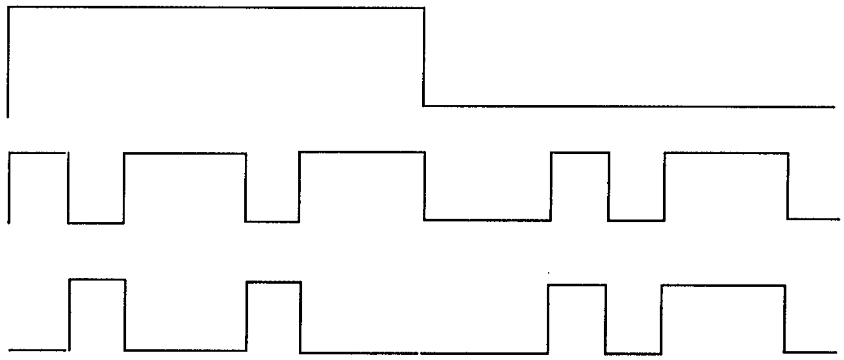

Figure 3: CDMA Waveform

2.4 Modulation Techniques and Bit Error Rate

In order to efficiently transmit a digital signal on a radio channel, it is necessary to modulate the digital waveform. There are several modulation techniques, but the technique of interest for this thesis is Phase Shift Keying (PSK) modulation. PSK uses a sinusoidal waveform with a unique phase to represent a bit or group of bits. The general analytical expression for this type of modulation can be seen in Equation 1 [Ska88]. This equation

$$s_i = \sqrt{\frac{2E}{T}} \cos(\omega_0 t + \phi_i(t)) \qquad 0 \leq t \leq T$$

$$i = 1, \ldots\ldots, M \qquad \textbf{(1)}$$

$$\phi_i(t) = \frac{2\pi i}{M}$$

gives the expression for each symbol for a M-ary PSK modulation scheme. The parameters in the equation are symbol period (T), symbol energy (E), carrier frequency (ω_0), and phase $\phi_i(t)$. For a binary PSK system, each symbol represents a single bit, where as for an M-ary PSK system each symbol represents $\log_2(M)$ bits.

When considering the calculation of the Bit Error Rate (BER) or Probability of bit error (P_b) of a digital signal, the key assumption is the existence of Additive White Gaussian Noise (AWGN). All fundamental calculations for signal detection are made assuming AWGN which has a normal distribution. The key parameter used for the calculation of the BER for a signal is the bit energy per noise density (E_b/N_o) for the signal. In order to calculate the E_b/N_o, the signal to noise ratio (S/N), Bandwidth (W) and data rate (R) must be obtained for the signal. Equation 2 details the relationship.

$$\frac{E_b}{N_0} = \frac{S}{N}\left(\frac{W}{R}\right) \tag{2}$$

For M-ary PSK, the error calculation is often done first in reference to the symbol error for the signal and then converted to bit error. Equation 3 displays the basic symbol error

$$P_E(M) = 2Q\left(\sqrt{\frac{2E_s}{N_0}}\sin\frac{\pi}{M}\right) \tag{3}$$

equation for a coherently detected M-ary PSK signal. Equation 4 displays the conversion from symbol error to bit error for orthogonal signal sets. In equation 3 E_s represents symbol energy and Q is the error function. In equation 4, k represents bits/symbol.

$$P_B = P_E\frac{2^{k-1}}{2^k - 1} \tag{4}$$

A common method of referencing the BER is done through E_b/N_0 versus P_E or P_B curves as shown in Figure 4. This graph displays the requirement for much more signal energy in M-ary systems with a large M.

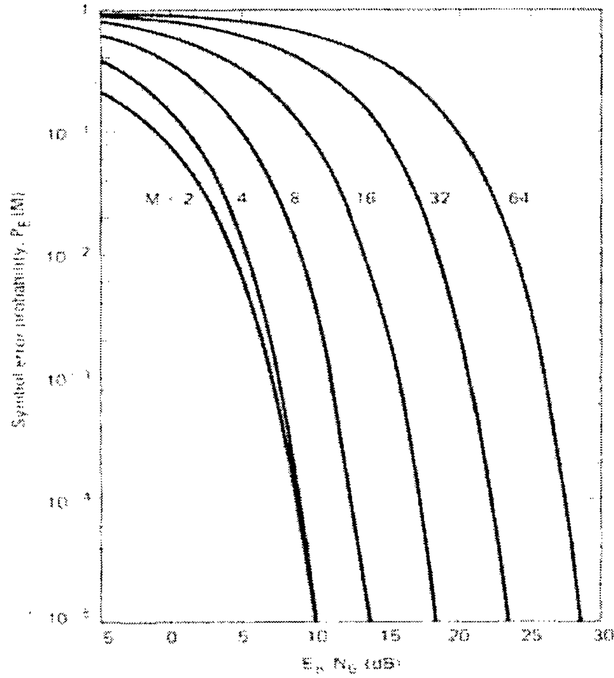

Figure 4 : M-ary PSK Symbol Error Plot [Ska88]

2.5 IRIDIUM Satellite Network

The Iridium satellite network consists of 66 satellites in 6 orbital planes following a near polar orbit with an inclination of 86.4° and an altitude of 780 km. Each orbital plane has 11 active satellites, evenly spaced throughout the orbit, each weighing 1516 lbs. The orbital planes are spaced 31.6° apart except the for 6th and 1st planes which have 22° of separation. All of the orbits have an eccentricity of approximately zero resulting in circular orbits. The period for one revolution for each satellite (100.44 min) can be calculated using (5) where R is the radius of the earth, h is the altitude of the satellite and μ is the gravitational

$$P = \sqrt{\frac{4\pi^2(R+h)}{\mu}} \tag{3}$$

constant (3.986005 x 10^{14} m^3/s^2). The in-view time for a satellite traveling directly overhead can be calculated by relating the period of the satellite to the central angle (γ) for the satellite. Equations 6 and 7 display the method for calculating the time in view. The minimum elevation for each satellite in reference to an earth station (Control station or user) is

$$\gamma = \cos^{-1}(\cos(L_e)\cos(L_s)\cos(l_s - l_e) + \sin(L_e)\sin(L_s)) \quad \textbf{(6)}$$

$$\text{In View Time} = \frac{2\gamma}{360}P \quad \textbf{(7)}$$

approximately 8.2°. Given this minimum elevation angle, the maximum in view time for any satellite can be calculated using (7) assuming direct overhead path of the satellite. The average in view time for all satellites (not just overhead) considering the 8.2° elevation angle in approximately 10 minutes [Com93].

2.5.1 IRIDIUM Communications Specifications

The communication link between the IRIDIUM satellites and ground users is maintained in the L-Band (1616-1625.5 MHz). The Ka band is used for the earth station (gateway) to satellite links (19.4-19.6 GHz for downlinks; 29.1-29.3 GHz for uplinks) and for the Inter-satellite links (23.18-23.38 GHz) [Cro99]. The bandwidth for the user link is sufficient to handle 3,840 carrier channels per satellite using frequency reuse of the 10.5 MHz maximum bandwidth available. The ground station uplink and downlink both use 100 MHz and the ISLs (Inter Satellite Links) use 200 MHz [MaD95],[Cro99]. The user links use a combination of Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA) to provide services to the full number of channels. The user voice signal is modulated using Quadrature Phase Shift Key (QPSK) modulation.

The total bandwidth available to the IRIDIUM network for user communication is 10.5 MHz which is separated into 240 different 41.67 kHz channels. The system utilizes a frequency reuse factor of 12, which splits each satellites coverage area into four 12 cell clusters. Each cell is then allocated 20 of the 240 channels. The satellites 48 cells are arranged into four clusters which are distributed so adjacent satellite cells do not use the same 20 channels. An example of the cluster arrangement can be seen in Figure 5.

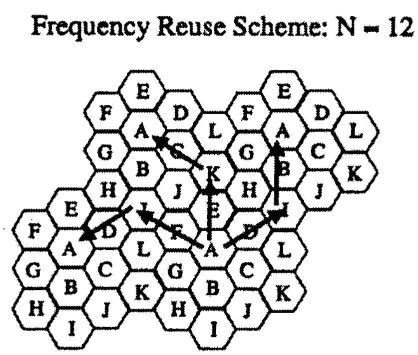

Figure 5: IRIDIUM Frequency Reuse [Fos98]

Each of the 20 channels is set up to contain four TDMA users, which results in 80 users per cell. Since each satellite operates 48 cells the resulting number of users for the satellite is 3840.

Unlike most communication satellite systems, IRIDIUM is designed to use ISLs (Inter-Satellite Links) to aid in efficient communication and routing while a majority of the other satellite links use a "bent-pipe" approach which involves no dynamic routing. The ISLs enable the IRIDIUM system to dynamically route data between adjacent satellites in the same plane or adjacent planes.

The power specifications for the IRIDIUM system are different for each type of communication (User, ISL, and gateway) link. Table 1 displays the average power per satellite for each communication type.

Table 1 : IRIDIUM Power Specifications [Wer95]

Communication Type	Average Power
User Link (~1.6 GHz)	13 W
ISL (~23 GHz)	7 W
Gateway Link	3.9 W

2.5.2 IRIDIUM Processing

The method for call processing used by the system is similar to that used by the Advanced Mobile Phone System cellular phone system [Hub97],[Fos98]. This system is based on home gateways and visiting gateways. Each gateway maintains a Home Location Register (HLR) which contains information for all local subscribers as well as a Visited Location Register (VLR) which contains information for all subscribers visiting the gateway's area. When a user powers a handset, a signal is sent to the satellite overhead which establishes the user as "ready to receive". The signal is routed through ISLs until it is directly over the nearest gateway. When the gateway receives the signal, it determines whether the user is a local subscriber. If the user is local, the gateway updates the user information in the HLR. If the user is a visitor the gateway sends a request to the user's home gateway requesting permission to set up calls for the visitor. The home gateway then sends clearance to the visited gateway and updates the HLR with the user's current location. [Fos98]

The call setup for the network is performed by the gateways. When a call is made to a mobile user, the call is routed to the mobile user's home gateway. The home gateway then sends a ring signal to the satellite directly over the mobile user. When the mobile user responds to the ring signal, an *off hook* signal is routed back to the gateway which then routes the voice packets to the mobile user. If the link is a mobile-to-mobile link, the gateway is not required to route the packets. The gateway can set up the communication and drop out. When the mobile user is in a visited gateway, the home gateway sends a signal to the visited gateway to ring the subscriber. The mobile user then sends the off hook signal to the visited gateway which forwards the signal to the home gateway. The home gateway is then responsible for sending the packets to the mobile user [Fos98].

2.6 Teledesic Satellite Network

The Teledesic satellite network [Tel99] is being designed to be a broadband network capable of global coverage. The network will use LEO satellites for the benefit of the low latency of the constellation. The network consists of three segments: terminals (users), gateways, and satellite constellation. The system is being designed to achieve 64 Mbps data rates for the downlink and 2 Mbps data rates for the uplink. The Teledesic network will be compatible with IP, ISDN, and ATM protocols. This allows for easier system adaptation to current terrestrial internet architectures.

The Teledesic Network will use fast packet switching. This will be accomplished through the use of short fixed-length packets that contain a header that includes the destination address, sequence information, and header error-control as well as a payload section containing the data [Tel99]. Since this is a dynamic network, there will be buffering at the terminal destinations to account for the variation in delay for all packets.

2.6.1 Teledesic Satellite Constellation

The current proposed satellite constellation will consist of 288 operation satellites in 12 orbital planes at approximately 1400 km [Gav97][Tel99]. All planes have an inclination of 89.2° and contain 24 satellites.

The communication to the satellites is proposed to use the Ka band (18.8 – 19.3 GHz for downlink, 28.6 – 29.1 GHz for uplink). The minimum elevation angle for the entire service area is maintained at 40° with the ability to achieve 99.9 percent availability [Tel99]. Since this elevation angle is very high, the attenuation effects of the atmosphere are minimized. The overlapping coverage areas for the satellites allow the system to be easily maintained without any down time for the users. Each satellite divides its available spectrum into several cells and uses a frequency reuse scheme similar to that used by IRIDIUM. Multiple users are able to simultaneously use the resources within a single satellite cell through the use of TDMA.

2.7 Local Multipoint Distribution Service (LMDS) Communication System

A LMDS is a communication system designed to operate under LOS conditions within the Ka band (27.5 – 31 GHz). The available bandwidth is shared with satellite uplink frequencies at 28.35-28.6 GHz and 29.5-30 GHz. The purpose of LMDS networks is to provide a large bandwidth for communicating large quantities of data at high data rates. The main application driving the pursuit of LMDS is to provide advanced Internet and the new High Definition Digital Television (HDTV).

Most of the research currently being performed either involves characterizing the attenuation effects of the urban terrain on the LMDS signals or defining possible communication protocols that could be used. Some typical ranges for a LMDS network would be from 100 yds to 5 km for one cell [Iza99]. For example, the smaller radius would be for a network that would be contained within a single office building. The larger cell size would allow communication within a city where several cells could be joined throughout to form a network similar to the cellular telephone system.

One study performed by Papazian [PaH97] considering the propagation attenuation in an urban environment gave a breakdown of the attenuation versus distance. These results are shown in Figure 6. These results give a basic loss analysis for the different distances. The power requirements for transmitters/ receivers used in simulation are designed to overcome the documented attenuation.

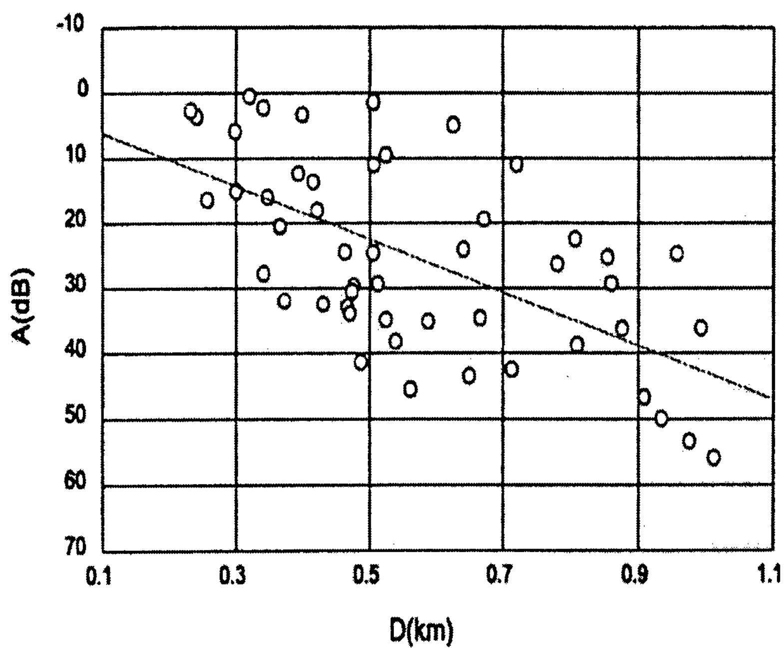

Figure 6: LMDS Urban Attenuation [PaH97]

A possible communication technique that could be used for a LMDS network considers using a CDMA technique. This technique uses a spread spectrum type signal to code each user with a unique spreading code allowing several users to use the same frequency band for communication. This technique yields better privacy of communication since the pseudo-random code used for spreading can be private information and thereby not allowing anyone to decode the transmitted signal. This type of communication is used by the cellular phone network.

Another possible protocol for communication is called Contention-TDMA (Time Division Multiple Access) [TrV98]. This allows users to communicate ,depending on availability, during specific time slots which are determined and controlled by the LMDS base station. The communication link uses ATM (Asynchronous Transfer Mode) cells within a specific packet to accomplish data communication.

A large portion of the documentation concerning LMDS networks deals with the frequency band itself that has been allocated by the FCC. As stated previously this band lies primarily in the Ka band. The following exact specifications have been set by the FCC at 27.5-28.35 GHz, 29.1-29.125 GHz and 31-31.3 GHz ranges [Gar98].

2.8 Summary

In order to accomplish the integration of a LMDS system with a LEO satellite network (IRIDIUM or Teledesic), consideration must be made for all parameters including power, bandwidth, frequency, routing algorithms and orbital parameters. Much information has been gathered considering these items. The challenge of this thesis is to combine all aspects of both systems and produce a viable simulation that actually accounts for the key parameters.

Chapter 3

Methodology

3.1 Introduction

This chapter discusses the methodology used to analyze a joint LMDS/ Satellite communication network and the design and testing of the simulation model created. Section 3.2 gives a basic overview of the problem, covers the scope of the problem, and discusses the methodology used for analysis. Section 3.3 lays out all of the operational assumptions made in modeling the network. The computer modeling tools and the models created with each tool are discussed in Section 3.4. All of the parameters used within the computer models are covered in Section 3.5. The desired metrics are specified in Section 3.6 and the validation and verification of the models is discussed in Section 3.7. Section 3.8 summarizes the information in this chapter.

3.2 Problem Overview

As stated in Chapter 2, the existing literature on an LMDS system is very minimal and is centered around the urban attenuation and the frequency band allocation. The use of LEO satellite systems for communication has had considerable coverage concerning the IRIDIUM. With the exception of the Teledesic homepage [Tel00], very little open-literature research results exist for the Teledesic system.

The purpose of this thesis is to analyze the performance characteristics of the combined LMDS/ Teledesic-like-LEO satellite network concerning achievable average throughput, bit error rates, and end-to-end delays. It is not possible to address all performance characteristics due to the time and resources available; therefore the scope of the thesis is limited as discussed in the following section.

3.2.1 Scope Definition

The scope of this problem is limited because of time constraints and available resources. The LMDS system is limited to a single seven-cell, standard frequency reuse configuration. The network is also considered fully connected wherein each cell is connected to each other cell by a fiber optic line (~155 Mbps) which will limit the routing necessary. The control channel used within the LMDS network is also modified to allow easy connection setup and user tracking through a management node.

The satellite network is based on a Teledesic-like constellation. The implementation of the satellite network is limited concerning the routing protocol, connection setup (call setup), signal powers, and constellation.

In general, there are some limitations to the scope of the problem concerning the number of users, system failure and traffic distribution. These limitations are described below.

3.2.1.1 Cell cluster

A single seven-cell cluster is used to apply frequency reuse of the LMDS frequency band. This is a standard cluster configuration used for analysis. It allows a convenient geometric configuration of the cells as shown in Figure 7.

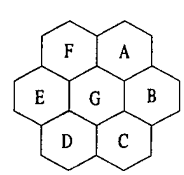

Figure 7: Seven-Cell Cluster

3.2.1.2 LMDS Network

The LMDS Network of seven cells is fully connected using fiber optic landline connections. These landline connections provide 155 Mbps data rates from cell to cell. By using this connection scheme, there is no need for a routing protocol since there will be sufficient bandwidth to route all calls from one cell to any adjacent cell. This puts the resource bottleneck in the cell bandwidth, which is the throughput of concern for the thesis.

3.2.1.3 Control Function and Management Node

The LMDS model also simulates the user tracking and connection setup through the user of a management cell that is connected to each of the cells. This management node tracks all users, tracks cell resources, and sets up all routing. This node retrieves all this information from each cell.

The model uses a band of the LMDS frequency band as a control channel for passing information from user to cell. The communication technique used is a form of TDMA, but since the data communication is the point of interest of this thesis the control channel specifics are not considered in detail.

3.2.1.4 Teledesic-like Constellation

The LEO constellation used for the purpose of the analysis in this thesis is a Teledesic-like constellation. The functionality of the system has been scoped for the thesis in the areas of routing, establishing connection, power requirements, and constellation size. The routing is set during the simulation, assuming the most direct path. The connections are established to supplement the LMDS or communicate with a few select global users. These connections are established purely based on resources available within the nearest satellite.

The power requirement is not considered, since the satellite network is only being analyzed for its ability to supplement system throughput and effective end-to-end delay. The constellation size is limited to only the number of satellites required to reach each site of interest.

3.2.1.5 General Limitations

The number of users within the system is one of the factors for the analysis. By increasing the number of users, the available throughput is directly affected. The number of users that are allowed to use the system is controlled by the Quality of Service (QoS) specified. Without a quality of service, the number users would be limitless, but the throughput may be unacceptable if too many users are in a single cell. For the purpose of the simulation, a maximum of one hundred users are allowed to use a cell's resources at one time.

Equipment failures are not considered within the scope of this thesis. The failures possible within the system can definitely affect the throughput. The goal of this thesis is to analyze the effect of the number of users, QoS, and basic processing delays on the throughput and system delay.

Because of the data rates possible for the LMDS/ Satellite system, the traffic considered for the analysis is data traffic although the rates and delays should prove to support any kind of traffic (real-time or data). The distribution of the data traffic is considered uniform for any user to any other user within the system. The generation of traffic from each user is considered constant since the queuing delay within the system is not going to be considered.

3.2.2 Methodology Used

There are three basic methods of evaluation that can be used to evaluate a systems performance: analytical modeling, simulation, and measurement. Simulation is the most appropriate for the LMDS/ Satellite network. Since analytically representing the probabilistic nature of the traffic is very difficult, the analytical method would be unrealistic and would require excessive simplifications. It is unrealistic to consider the measurement technique for two reasons. The first is that the only LEO satellite network capable of supplementing the LMDS data rates is the Teledesic Network, which is not yet operational. The second is that the financial resources, as well as time required to construct and test an adequate system, are not within the scope of this thesis. The simulation technique is obviously the best method, since the use of sophisticated computer simulation tools (OPNET, STK) allows an accurate representation of a typical system. The network simulation tool OPNET can model the packet generation, delays, communication specifications, and error analysis, while the STK satellite modeling tool can precisely create the LEO satellite models for use in the simulation.

3.3 Operation Assumptions

The simulation of the LMDS/ Satellite network was accomplished using the OPNET network simulation tool by MIL3. The Teledesic-like satellite orbits were created using the STK satellite tool kit by Analytical Graphics. Many assumptions were necessary in order to simulate this network since neither system is currently operational and little information was available concerning the technical specifications for either the satellite or LMDS system. The details that were available were incorporated into the model. Additional assumptions were also made in order to make the simulation run within the time constraints of this thesis.

3.3.1 LMDS Cell Size

As discussed in the scope limitation section, the LMDS system was limited to seven cells for the simulation. The standard cell sizes for the LMDS networks are planned to be from two to five miles [Iza99]. The attenuation research [PaH97] studied LMDS signals extending out to 2 km. The cells for the simulation were set at 2 km radii to correlate to the attenuation research. Figure 6 on page 17 displays a scatter diagram of the attenuation data gathered by Papazian et al [PaH97]. The least squares linear fit for this data can be seen in Table 2.

Table 2 : LMDS Attenuation [PaH97]

Site (Antenna Height)	Slope(dB/km)	Intercept (dB)
Northglenn (40-ft)	42.4	7.3
San Jose (40-ft)	40.9	2.1
San Jose (80-ft)	6.7	9.4

From the information in Table 2, the approximate attenuation for the site can be estimated for the 2 km radius cells used in the simulation. Comparing the data in Figure 5 with the slope in Table 2, one can see that there is large range above and below the linear fit for the attenuation. Therefore, the attenuation for the simulation was allowed to uniformly vary between the values as shown in Table 3. These values were obtained from the visible linear fit error shown at approximately 1km.

Table 3: Simulation Attenuation

	High Estimate	Linear Fit Estimate	Low Estimate
Attenuation (dB/km)	52.4	42.4	27.4

3.3.2 LMDS Multiple Access

The access technique used for an LMDS network could be any of the three described in Chapter 2 (TDMA, FDMA, or CDMA). The FDMA technique was chosen for the simulation for ease of application within OPNET concerning the Quality of Service that can be established for all users within the network. The FDMA technique simply splits the available frequency into a separate band for each channel within a cell. The breakdown of the frequencies for each cell will be discussed within the model design section. The LMDS network simulation model assumed equal bandwidth for uplink and downlink, since this network is assumed to be used for two-way communication. This differs from most literature because the existing literature is based on a LMDS network designed to support a broadcast type service such as the new High Definition Television (HDTV).

3.3.3 Packet Format and Size

No open-source literature exists on the packet structures for an LMDS network. The main goal of the simulated network is to chose a packet size that will have small enough end-to-end delay to be able to accommodate any kind of traffic (data, voice, or video). The other main factor for choosing the packet size is the simulation time that will result, since within OPNET the simulation time is directly related too how many packets are created.

Within the LMDS network, there is not a problem with delay due to the propagation time (maximum 1.3333×10^{-5} s), but if the packet size is too large the transmission delay may be too large to support video or voice applications. Also, when supporting, video or voice applications, care must be taken to include the longer propagation times associated with satellite links. This factor, used in conjunction with packet transmission times, tend to limit the range of useful packet sizes.

Considering the worst case scenario for the Teledesic-like orbit which is a link traveling all the way around the world before reaching its destination, the propagation delay is calculated below:

$$\text{Orbit Altitude} = 1400 \text{ km}$$
$$\text{Around World} = 2 \bullet \pi \cdot \bullet (1400 + 6378) = 48870 \text{ km}$$
$$\text{Worst Case Prop Distance} = \text{User - to - Sat} + \text{Around World} + \text{Sat - to - user}$$
$$\text{Worst Case Prop Distance} = 1400 + 48870 + 1400 = 51670 \text{ km}$$
$$\text{Worst Case Prop Delay} = \text{Worst Case Prop Distance} / \text{Speed of Light}$$
$$\text{Worst Case Prop Delay} = 51670 \text{ km} / 300000 \text{ km/s} = .172 \text{ secs}$$

The common standard for voice communication maximum delay is known to be 400 millisecs. With this standard the LMDS/ satellite network would be allowed .228 secs for transmission and processing delays. Assuming 14 μsecs of processing delay per processor and a maximum of eleven satellites to circle the globe, this would leave .2278 secs for transmission of a packet. At two Mbps, this would allow for a maximum packet length of 455,600 bits. The worst case satellite scenario would not allow for real-time video unless a low refresh rate is chosen for the video stream. Real-time video may be possible within the LMDS network since the propagation delays within the network are in the range microseconds. For the purpose of this thesis, a packet length of 100,000 bits was chosen primarily to lessen the number of events per simulation run. This packet length is not typical for voice communication, but the end-to-end delay is one of the products of the thesis, therefore the support of voice communication will be proven/disproven through simulation.

Since the analysis being performed is a link layer analysis, the packet format used within the simulation does not include details considering the network layer manipulation of the packet.

3.3.4 Processing Delay

There is not a documented processing delay for either the LMDS or Teledesic systems, therefore one must be assumed. For the IRIDIUM system, the processing delay is assumed to be 14 μsecs [Fos98]. Since IRIDIUM is an established system that uses ISLs, like Teledesic, it seems reasonable to use this processing delay throughout the LMDS/ Satellite system. This is a logically assumption since both the LMDS/ Satellite system and the IRIDIUM system operate using a dynamic packet routing scheme.

3.3.5 Traffic Distribution

The traffic for the LMDS/Satellite network was setup to be random in three areas: Traffic Destination, Traffic Start, and Traffic duration. The traffic destination was chosen from any mobile user or from three fixed sites (Wyoming, Washington, DC, and Germany). The traffic start time for each mobile user was randomly set for any time during the simulation. The traffic duration was set to be for any length of data from 100k bits to 500 M bits.

The traffic destination was set to be a uniformly distributed where any user could select any other user or fixed site. In order to ensure the full capacity of the system was tested, each destination could only be selected by one user, since the system was set to allow the users to accept data from only one user at a time.

The traffic start time for each user was normally distributed in order to represent a peak traffic time in the simulation. This was chosen to cause a majority of calls to be within one specified standard deviation. Table 4 displays the mean and standard deviation chosen for the simulation.

Table 4: Traffic Start Statistics

Simulation Start (min)	Mean Traffic Start(min)	Standard Deviation(min)	Variance
0.0	5	2	4

The traffic duration was also normally distributed. This was done in order to ensure that a majority of calls were relatively long. This would make sure that the network capacity and throughput was tested at a worse case type of scenario. Table 5 displays the statistics for the traffic duration.

Table 5: Traffic Duration Statistics

Mean Duration	Standard Deviation	Variance
500 Mbits	200 Mbits	$4x10^4$

3.3.6 Satellite Constellation

The constellation used for the simulation was assumed to be a Teledesic-like constellation with 288 satellites in 12 orbital planes. To maximize efficiency of simulation resources, the constellation was not fully constructed within the model. The reduced constellation size did not reduce the accuracy of the model. The constellation was constructed using the STK software. The shortest path was then configured for each of the remote sites. This shortest path configuration was used throughout the simulation assuming a best-case scenario for satellite communication. The worst-case scenario was then implemented through inspection of the STK orbits for the constellation. This scenario was designed to require communication to the remote sites by traveling around the world before reaching the remote site. The maximum number of hops to travel this distance was also assumed. The delay for this worst-case scenario was then calculated and added to the best-case scenario model to simulate the worst-case satellite communication delay. The simulation, thereby, gives the worst-case or best-case delay time. This allows the use of a very limited number of fixed satellites to represent the constellation.

3.3.7 Satellite Multiple Access

As previously mentioned, the satellite network used for the simulation was modeled after the Teledesic system. The documented multiple access scheme used for this system is a FDMA/ TDMA combination for the user uplink and an asynchronous TDMA scheme for the downlink. The uplink was also limited to approximately 2 Mbps, and the downlink was limited to 64 Mbps, but since any satellite uplink is limited to approximately 2 Mbps the associated downlinks will also be at 2 Mbps. The simulation split the uplink frequency into 10 channels with 7 time slots. The intersatellite links also used a TDMA scheme for packet routing. The downlink was simply split into appropriate time slots. For the purpose of the simulation, the appropriate frequency/ time slots were assigned during connection for the user and destination.

3.4 Model Designs and Operation

The network model was modeled using OPNET 6.0 network simulation tool developed by MIL3. This simulation tool executes an interrupt driven program that is a combination of a graphically user interface and C++ programs. The satellite orbit characteristic were derived by analyzing a satellite constellation developed using the STK 4.0.6 (Satellite Tool Kit) by Analytical Graphics.

3.4.1 OPNET Model

The OPNET model consists of seven separate nodes consisting of seven processes and numerous transmitters, receivers and antennas. The nodes used within the model include a user node, LMDS cell node, remote site node, management node, and three satellite nodes. All nodes except the user node are fixed nodes. Figure 8 displays the overall model used for the simulation.

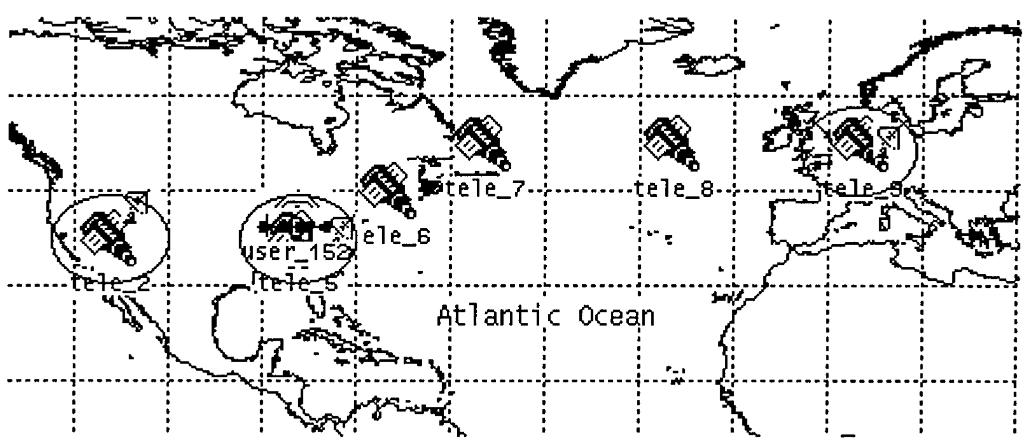

Figure 8: Overall OPNET Model

3.4.1.1 User Node

The user node contains a transmitter, receiver, and antenna for the LMDS system as well as a transmitter, receiver, and antenna for the satellite system. These transmitters and receivers are connected to three separate processes. The processes are also connected to each other. All connections within the node are made using packet streams.

3.4.1.1.1 User Node LMDS Transmitter

The transmitter within each user was set to have three channels, which use the uplink frequencies within the LMDS band plan. The first channel is used as a control channel for the LMDS network location update. The user sends responses back to a cell concerning whether the user correctly received a page from that cell. The second channel is used to send a resource request to the current cell and receive the resource information returned by the cell. The third channel is used to send the data from the user to the current cell. The channel specifications for the third channel are set with the information returned from the current cell. The frequency band plan for the LMDS simulation model can be seen in Figure 9. The power specification for the transmitter was set to accommodate the worst-case mean urban attenuation and other losses in order to achieve an E_b/N_0 of at least 4 dB at the cell limit of 2 km. The 4 dB E_b/N_0 was selected to represent a received signal that could be demodulated at 10 dB (achieves P_b of 10^{-5} for BPSK and QPSK systems) with a coding gain of 6 dB. A 6 dB coding gain can be achieved through the use of a typical six state convolutional encoder/decoder. The resulting power was set at 150 Watts.

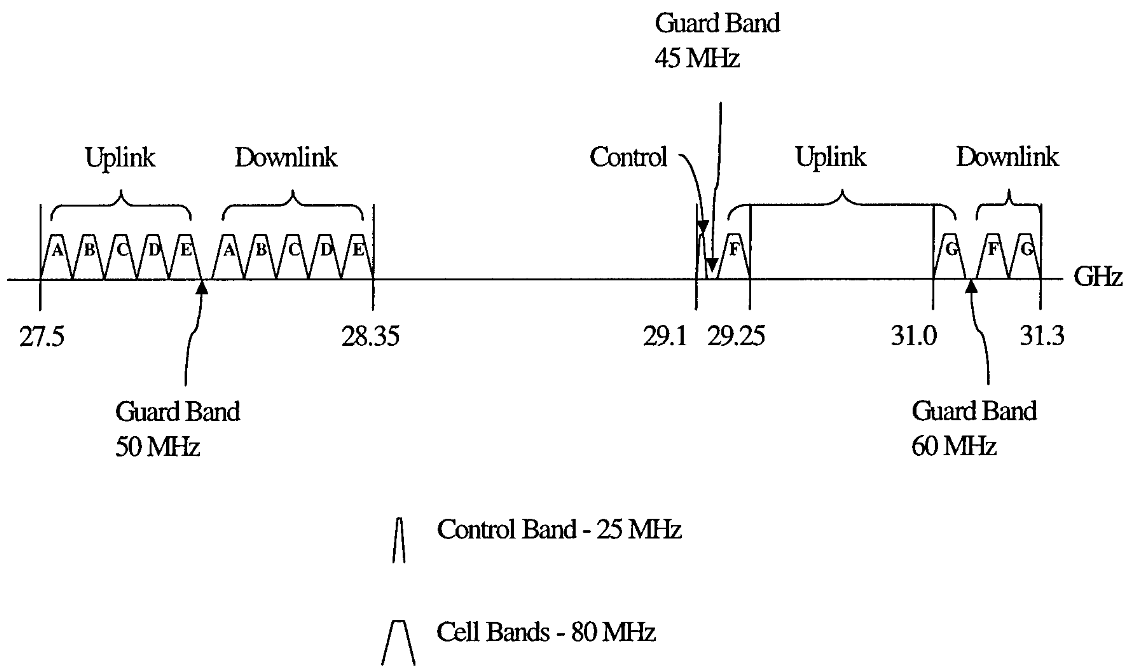

Figure 9: LMDS Frequency Band Plan [Gar98]

3.4.1.1.2 User Node LMDS Receiver

The LMDS receiver within the user node also has three channels. These channels have the same functions as the corresponding channels within the transmitter. The receiver uses the downlink frequencies specified in the LMDS band plan.

3.4.1.1.3 User Node Satellite Receiver/ Transmitter

The satellite transmitter used within the user node has two channels. The first channel is used for control information for satellite communication. This channel is used to request resources from the satellite network. The control channel is located in the first time slot of each second within each of ten uplink frequency bands. The second channel is used for data transmission and has a capacity of 2 Mbps. The data channel consists of the remaining 22 time slots. Figure 10 displays the basic frequency band plan for the satellite network.

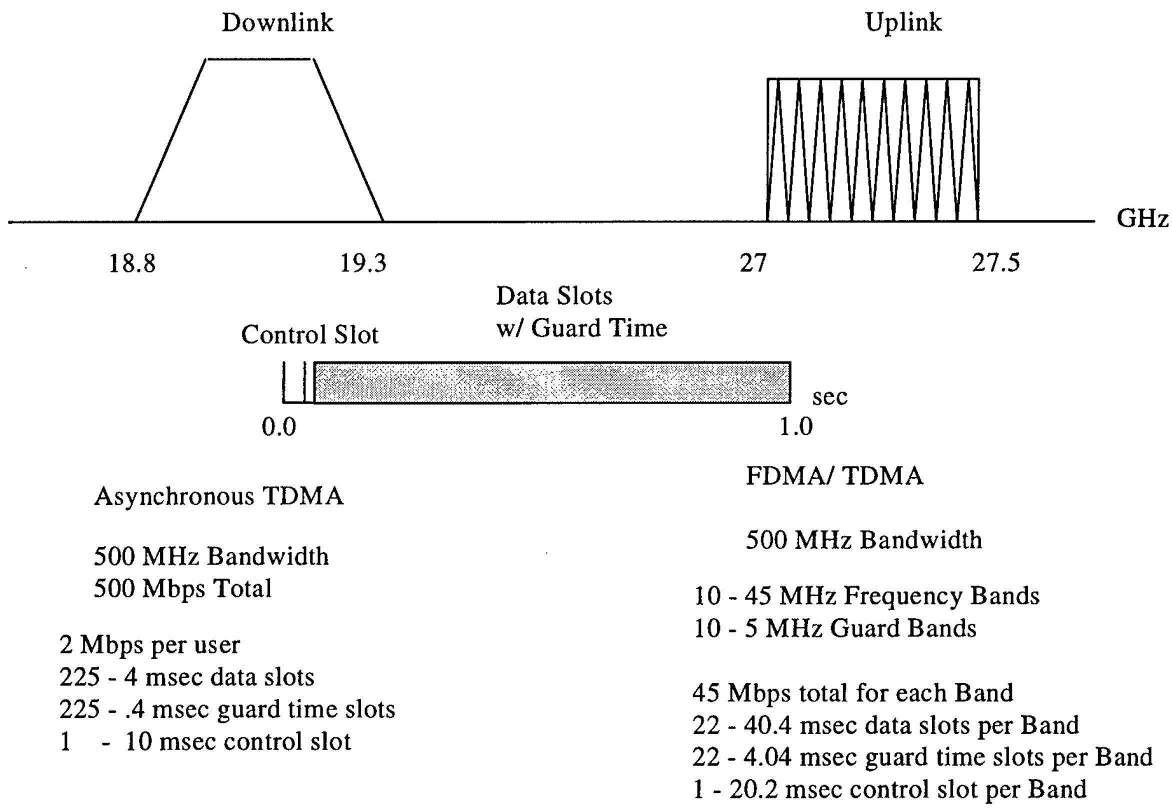

Figure 10: Satellite Frequency Band Plan [Tel00]

3.4.1.1.4 LMDS/ Satellite Antenna

All antennas used within the user node as well as all nodes throughout the simulation are set as omni-directional for simulation purposes. This is sufficient for the simulation since the gain of the antenna can be adjusted to represent a directional type antenna.

The LMDS Antenna gain within the user node was adjusted to simulate a dish type antenna with a .5 m radius. The cell antenna gain was adjusted to represent the cellular type antenna used in the experiments done by Papazian et al [PaH97].

3.4.1.1.5 User Node Processor Process

The main processor within the user node is connected to the second and third channel of the LMDS transmitter/ receiver and the second channel of the satellite transmitter/ receiver. This processor is responsible for receiving packets and creating resource requests, setting transmitter/ receiver attributes, and data generation and reception. All end-to-end, bit-error rate, and throughput data are gathered within this processor process.

The process consists of eight states. The first state (Init) executes all initialization for the process. The second state (Idle) is the holding state for the process. The third state (pkt_in) is responsible for retrieving all data from the receiver and determining the origin and purpose of the data. The fourth state (Traffic) generates all data packets for the LMDS network. The fifth state (setup) generates a resource request that is sent either to the current LMDS cell or to the current satellite. The sixth state (end_sim) executes some commands necessary to end the simulation. The final two states (stop and no_match) are used to ensure source and destination are using a common frequency. Figure 11 displays this process as seen in OPNET.

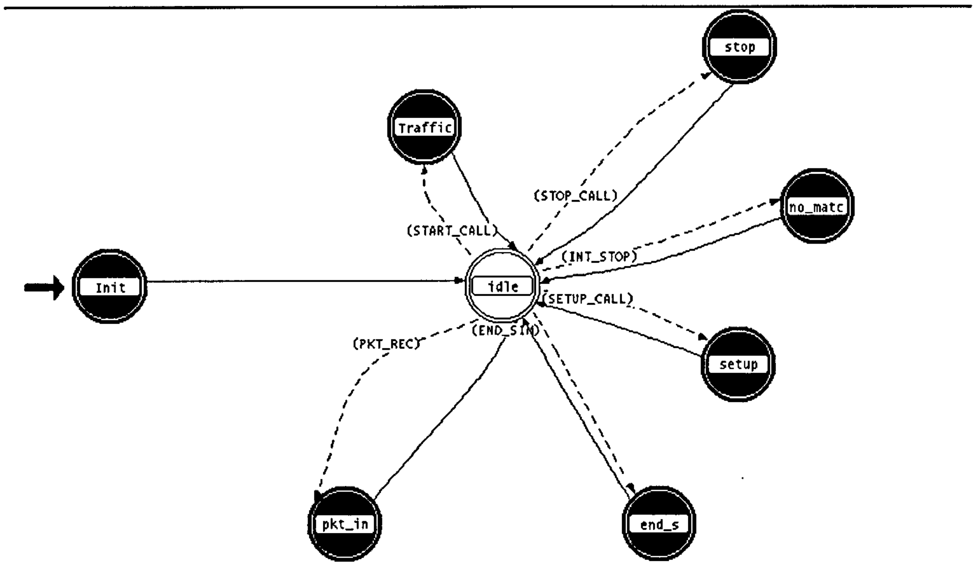

Figure 11: User Traffic Process Model

3.4.1.1.6 User Node Location Update Process

This process is responsible for tracking the users' positions throughout the LMDS network. This process is connected to the first channel of the LMDS transmitter/ receiver. It receives location update pages from the cells and determines if the page is from the closest cell. It sends a response to the cell if the propagation and processing time of the paging packet is within a specified time limit.

This process consists of four states. The first state (Init) sets all initializations for the process and the beginning of the simulation. The second state (Idle) is the holding state within the process. The third state (locate) receives the paging packets from the cells and does a time check from the packets time-sent information and determines whether the cell is the closest. The final state (st_5) executes end of simulation calculations. Figure 12 displays the OPNET process model.

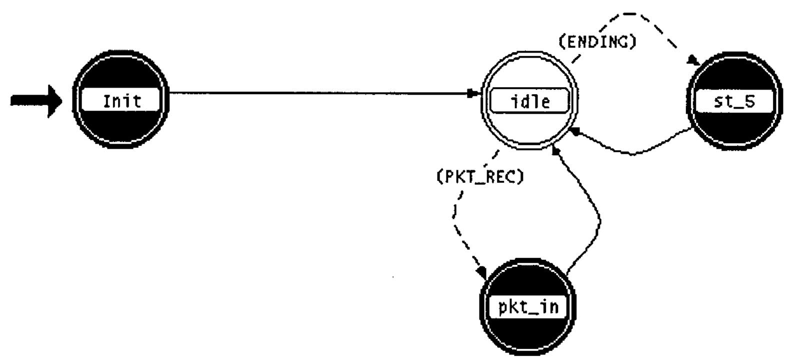

Figure 12: User Location Update Process

3.4.1.1.7 User Satellite Traffic Node

This process is responsible for receiving requests for satellite communication and relaying these requests to the nearest satellite. It receives the requests from the user traffic node. The process is also responsible for ending satellite communication at the end of a call or when the user transitions into a new LMDS cell with open resources.

The process consists of five states. The first state is the (init) state which is responsible for the initial setup of the node. The second state is the holding state (idle). The third state is the (sat_con) state, which is responsible for receiving the requests from the user traffic process and requesting resources from the nearest satellite. This state also receives all satellite traffic for the node and collects the statistics. The sat_traf state creates all the packets for transmission to the satellite. The end_sim state executes final calculations at the end of the simulation. Figure 13 displays this process.

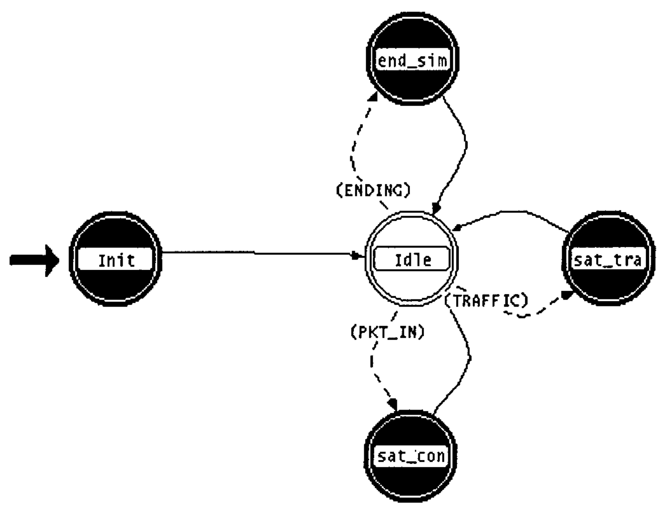

Figure 13: User Satellite Traffic Process

3.4.1.2 LMDS Cell Node

The LMDS cell node is responsible for sending location update pages and resource request responses to the user node. It is also responsible receiving and relaying location update information, resource requests, and resource terminations to the management cell. The resource information sent to the users is obtained from the management cell. The LMDS cell node contains two radio receivers, two radio transmitters, seven point-to-point transmitters, seven point-to-point receivers, an antenna and two processes (dat_xfer and res).

3.4.1.2.1 LMDS Cell Radio Transmitter and Receiver

The LMDS cell radio transmitter and receiver contain 102 separate channels. The first 100 channels are set for user data reception and transmission. These channels are dynamically set each time a user successfully requests resources from the cell. Each time a user successfully requests resources from the cell, the bandwidth for each user that is transmitting data is reduced to equally divide all available bandwidth among all users. For example, if there are currently two users, each uses 40 MHz of bandwidth. But if another user requests resources, all users will be reduced to 26.66 MHz. The 101st channel is designated as the location update channel where all paging packets are sent and all user responses are received. All cells use the same frequency for this channel, therefore they use a TDMA type of scheme where each cell transmits every 3.5 seconds. The 3.5 second paging interval was selected primarily to reduced the simulation time resulting from the large number of packets created through this location update function. The 102nd channel is used for resource requests and resource responses. All cells also use the same frequency for this channel. Therefore, a TDMA scheme is also used for this channel. Each request response is delayed by an amount specified by the user number. For the simulation, this delay was set at .0002 second multiplied by the user number. This allows enough time for the 1024 bit packet to be transmitted with approximately ten percent guard time.

3.4.1.2.2 LMDS Cell Point-to-Point Transmitters and Receivers

There are total of several pairs of point-to-point transmitters/ receivers. The first pair is used to communicate to the management node. The remaining six pairs are used to link the cells to each other. The pair that links the management node is used to relay the location update information an resource information that is received from the users. The links between the cells are purely used to route data packets from cell to cell, when users are communicating from one cell to another. These links are set up as fiber optic links having a capacity of 155 Mbps.

3.4.1.2.3 LMDS Cell Data Transfer Process

The data transfer process is used for three main purposes. The first includes routing all data received from the users. The second involves receiving and tracking resource request information from the management cell and setting the first open channel to the appropriate specifications. The third function includes tracking the number of data packets received and forwarded for each user for reference during handoff.

There are four states within this process. The first state (Init) sets all the initialization parameters for the process. The second process (Idle) is the holding state for the process. The third state (dat_xfer) is responsible for the main function of the process. This state receives all packets sent to the process and either routes the packet to the appropriate channel, sets channels specifications, returns packet count information, or clears a channel. The final state (chan_ch) periodically checks the user lists to ensure no user is registered incorrectly. Figure 14 displays this process.

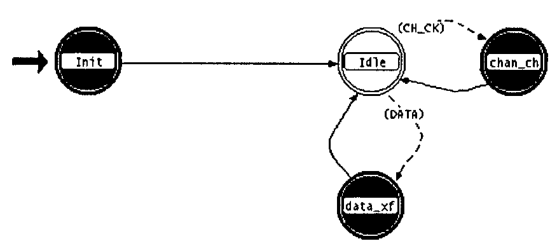

Figure 14: Cell Data Transfer Process

3.4.1.2.4 LMDS Cell Resource/ Location Update Process

This process handles the location updates and resource requests from the users. It sends the location update pages every 3.5 seconds and receives the location update responses and routes them to the management node. The process receives all resource requests from the users within its coverage area and routes the requests to the management node. It then forwards the resource information to the user and the LMDS data transfer process.

This process contains six states. The first state (Init) initializes the process. The second state (Idle) is the holding state for the process. The third state (loc_upd) sends the paging packet to all users every 3.5 seconds. The fourth state (loc_reg) receives all location update responses from the users and forwards the update to the management cell. The fifth state receives all resource request and response information and forwards the information to the user, the LMDS data transfer process, and the management node. Figure 15 displays the process model.

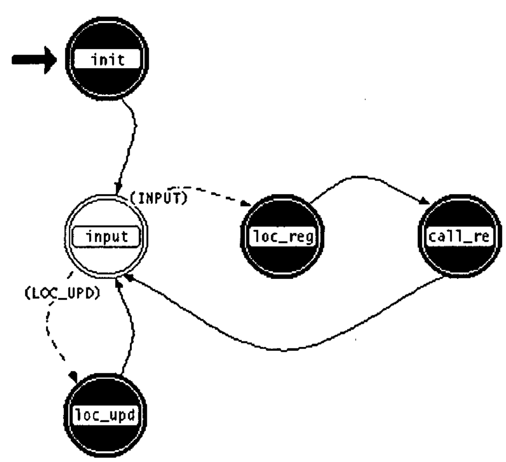

Figure 15: Cell User Register Process

3.4.1.3 Remote Site Node

The remote site node is used simply as a remote fixed destination for the users within the LMDS network. By including these remote sites into the simulation, the simulation can calculate the end-to-end delay for the satellite network where the packets must travel around the world. This node contains a receiver, an antenna and a single processor.

3.4.1.3.1 Remote Site Node Receiver

The receiver within this node has a single channel that is matched with the satellite that is directly overhead. It is not necessary to consider the TDMA aspect of this downlink because for the purpose of the simulation, there will only be one remote user at each remote location.

3.4.1.3.2 Remote Site Processor

This simply retrieves the packets received by the node and tracks the end-to-end delay for each packet. The processor contains four states. The first is the (Init) state which initializes the process. The second is the (Idle) state which is the holding state for the process. The third is the (sat_con) state which retrieves the packets and records pertinent statistics. The final state (end) is responsible for collecting the end-to-end data for the remote sites. Figure 16 displays the process.

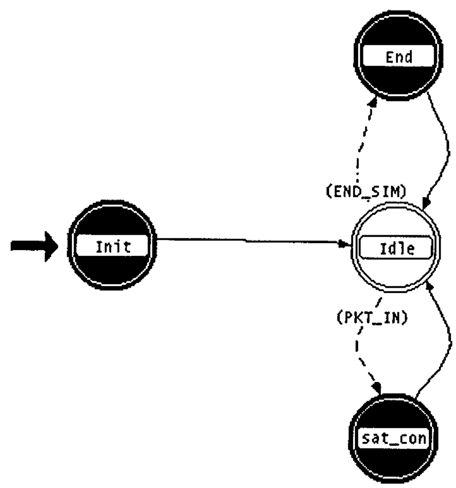

Figure 16: Remote Site Processor

3.4.1.4 Management Node

The management node is responsible for receiving location update information and resource request information, storing necessary data, and sending the appropriate information to the cells concerning location updates and resources available. This node is an abstraction of a function that would be held within one of the cells, but for the purpose of simplifying the simulation, the function was placed in this node. The node contains six point-to-point receivers, six point-to-point transmitters, and a processor.

3.4.1.4.1 Management Node Receivers/ Transmitters

Each pair of transmitters/ receivers within the management node is connected to one of the cells by a 6 Mbps connection. If the management function was not abstracted from only the cells, the function would only require six MHz of the 155 Mbps fiber connection between cells. All information from the processor within the management node is passed through one of the six receivers/transmitters to the appropriate cell.

3.4.1.4.2 Management Node Processor

The management node processor receives all location update and resource requests from the cell and sends the appropriate location or resource information back to the cell for distribution to the appropriate users. When a user moves from one cell to another while transmitting data, the management cell accomplishes the handoff function by reallocating resources for all necessary cells and sending resource information for all affected users through the appropriate cells.

The processor contains eleven states. The first state (Init) initializes the process. The second state (Idle) is the holding state for the process. The third through ninth states are for a specific cell. These states check whether a location update is for its particular cell, updates the user location information, and starts the handoff procedure when necessary. The tenth state is responsible for allocating resources for all new resource requests and for reallocation resources for all handoffs. All resource information is sent to the appropriate cells from this state. The last state is the holding state (Idle). Figure 17 displays this process.

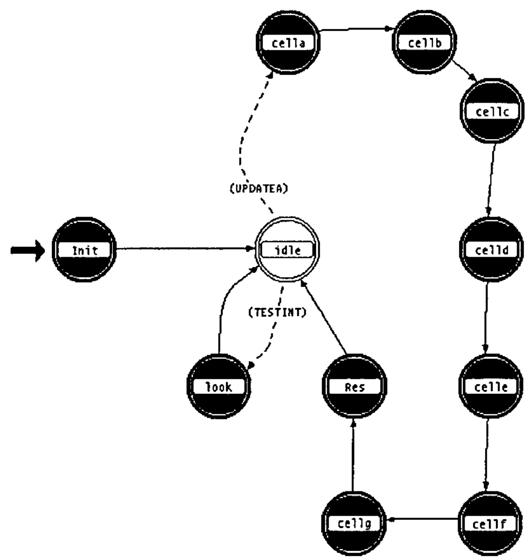

Figure 17: Management Process

3.4.1.5 Satellite Nodes

The satellite nodes in this simulation are based on a Teledesic-like orbit with stationary satellites representing the satellite that would be constantly overhead as the network revolved around the earth. The real world delays that would actually be encountered are calculated into the transmission of the packets as discussed in Section 3.3.6. The satellite nodes have two functions. The first is to allocate resources, if available, to a user upon request. The second function is to route packets to the appropriate user or remote site. The satellite node contains two antennas: one for uplink/ downlink and one for intersatellite links. The satellite node also has a receiver/ transmitter pair for uplink/ downlink, a receiver/ transmitter pair for intersatellite links, and a single processor.

3.4.1.5.1 Satellite Node Receivers/ Transmitters

The receiver for the uplink has ten channels to represent the FDMA/ TDMA format. Each of the channels is connected to the processor. The frequency band plan for the satellite uplink/ downlink was shown in Figure 9. The first time slot in each of the channels is set aside for control information. The receiver for the intersatellite link has a single channel is set to Ka band (20 GHz) for simulation purposes and uses a TDMA scheme for all data. The actual frequency is unspecified for the Teledesic system. The transmitter for the downlink has a single channel to represent the TDMA format. The first time slot with in the channel is set for control information. The transmitter for the intersatellite link is set similar to the corresponding receiver.

3.4.1.5.2 Satellite Node Processor

The satellite node processor is responsible for receiving all resource request packets and assigning resources when available. This node is also responsible for routing all data to the appropriate user or satellite. All information received or sent by the node follows a TDMA scheme for multiple access. The node is responsible for tracking all time slots for all channels. This process contains four states. The first initializes the state. The second is the holding state. The third receives all incoming packets and determines whether the packets are resource information or data and either sends a resource reply or routes the data. The final state tracks satellites users with a specific channel. Figure 18 displays this processor.

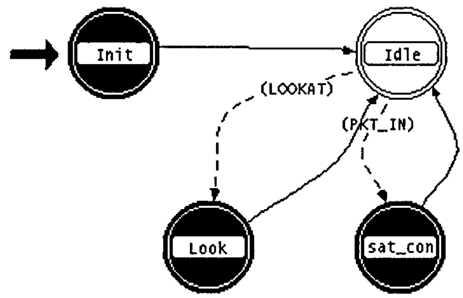

Figure 18: Satellite Main Processor

3.4.1.5.3 Other Satellite Processors

The satellite main processor was simplified for the satellites that were only to be used for downlink and inter-satellite links. These processors simply received and routed packets to the appropriate node or satellite.

3.4.2 STK Satellite Constellation Model

The satellite constellation for the simulation was based on a Teledesic-like network. The STK (Satellite Tool Kit) by Analytical graphics was used to create a full network of 288 satellites. From a visual inspection of the network, the number of satellites required for coverage was identified for the simulation. As stated in Section 3.3.6, the full constellation was not used for the simulation to allow for reasonable execution time for the simulation. In order to create the satellite orbit using STK, the software required the input of the data shown in Table 6. The table contains data for the first satellites for each orbital plane.

Table 6: Satellite Orbit Setup Parameters

Orbit Type	Inclination(°)	Altitude(km)	RAAN(°)	Start Time(sec)	Stop Time(sec)
Circular	89.2	1400	0	0	6826.73
"	"	"	0	284.45	"
"	"	"	15	142.23	"
"	"	"	15	426.67	"
"	"	"	30	284.45	"
"	"	"	30	568.9	"
"	"	"	45	426.68	"
"	"	"	45	711.12	"
"	"	"	60	568.9	"
"	"	"	60	853.35	"
"	"	"	75	711.13	"
"	"	"	75	995.57	"
"	"	"	90	853.35	"
"	"	"	90	1137.8	"
"	"	"	105	995.58	"
"	"	"	105	1280.02	"
"	"	"	120	1137.8	"
"	"	"	120	1422.25	"
"	"	"	135	1280.03	"
"	"	"	135	1564.47	"
"	"	"	150	1422.25	"
"	"	"	150	1706.7	"
"	"	"	165	1564.48	"
"	"	"	165	1848.92	"

After creating the satellites with this data, the start time for each satellite was adjusted back to zero. But since the longitude of the ascending node was set from the start time entered in the beginning, the orbits were staggered appropriately for each satellite. The RAAN specified in the table is the Right Ascension of the Ascending Node which is the longitude of the satellite when it crosses the equator.

3.5 Model Input Parameters

This section covers the input parameters used in OPNET and STK to create and model the LMDS/ Satellite network. Justification for all the parameters is discussed.

3.5.1 OPNET Parameters

Many of the details for the OPNET input parameters have been covered in Section 3.4.1. The LMDS frequency band plan for the receivers and transmitters was discussed in Section 3.4.1.1.1. This band plan was chosen to allow for equal uplink and downlink bandwidth and to accommodate the 7-cell frequency reuse scheme. The cell size of 2 km was discussed in Section 3.3.1. It was chosen to coordinate with the previous research. The data connection start and length for each user was discussed in Section 3.3.5. The path that each mobile user follows during the simulation is set to model ground vehicles moving through the LMDS network. The paths are deterministic and were designed to force each user to traverse multiple cells. This requires the network to execute handoffs. The packet size and arrival rate were discussed in Section 3.3.3. The transmitter power was set at 150 W for the cells and the users as discussed in Section 3.4.1.1.1. The antenna gain was adjusted to the attenuation results achieved in previous research [PaH97] as discussed in Section 3.1.1.1.4. The antenna height for the LMDS cells was set for 40 ft to correspond to the previous research discussed in Section 2.6. The processing delay was set to 14 μsec as discussed in Section 3.3.4. Table 7 outlines the key parameters and their values for the simulation.

The satellite network has fewer pertinent parameters since the simulation uses a truncated network. The frequency band plan was discussed in Section 3.4.1.1.3. This band plan was derived from Teledesic information [Tel00]. It did have to be modified because the Teledesic plan proposes using a band of the LMDS frequency band, which has already been allocated for LMDS purposes by the FCC.

Table 7: Simulation Parameters

Simulation Parameter	Value
Cell size	2 km
Data Transmission Start	Normal Distribution Mean- 5 min Std Deviation- 2 min
Data Transmission Length	Normal Distribution Mean- 500 Mbits Std Deviation- 200 Mbits
Packet Size	100,000 bits
Transmitter Power	150 W
User Antenna Gain	46.75 dB
Cell Antenna Gain	14 dB
Cell Antenna Height	40 ft
Urban Attenuation	Uniform Distribution From 27.2 dB to 54.2 dB
Processing Delay	14 microsecs
Arrival Rate	Constant (Relative to data rate)

3.5.2 Simulation Factors

The factors affecting the simulation for the LMDS system include the modulation type of the transmitter/ receiver (BPSK, QPSK, etc.), urban attenuation, number of users, and the specified quality of service (QoS, guaranteed bandwidth). The modulation types used for simulation runs included BPSK, QPSK, and 8-PSK. The urban attenuation was discussed in Section 3.3.1 and the breakdown for the test parameters shown in Table 3. The number of users was adjusted from 50 to 150. The QoS was adjusted from 0 to 10 Mbps.

The only factor affecting the satellite network in the scope of this simulation is the delay. This data represents best case and worst case scenarios as discussed in Section 3.3.6.

3.6 Performance Metrics

The simulation metrics that are of interest include bit-error rate within the LMDS network, end-to-end delay, and throughput. The metrics are designed to analyze the performance of the network under a varying urban environment, using a variety of modulation types and QoS values.

3.6.1 Bit-Error Rate

OPNET calculates the bit errors for each packet in the receiver of each node. This metric identifies how many bits are in error within a single packet and overall for a specified receiver. The larger number of bit errors detected results in the need for either a very powerful error correcting device or higher transmission powers. The metric is calculated within OPNET by comparing the received E_b/N_o (Energy per bit/ Noise Energy per Hz) to a graph which is a plot of the BER versus the E_b/N_o for a specific modulation type.

3.6.2 End-to-End Delay

This metric is the total delay for a packet to go from the source's traffic generator to the destination's processor. This delay includes all transmission, propagation, and processing delay that a packet encountered. This metric is dependent on the change in transmission rates, packet size, adjusted satellite delay, and number of processors encountered. The key of this metric is to identify whether the delay exceeds the voice and video delay thresholds.

3.6.3 Throughput

This metric is the average throughput for the entire user transmission. This throughput is affected by the transmission rate and any delays caused by handoffs or switching to satellite communications. This metric displays the expected user throughput under the different total user loads considering the QoS specification.

3.7 Model Verification and Validation

This section covers the verification tests that were accomplished to ensure that the simulation's logic was correct throughout the network. The validation of the simulation consisted of tests to determine how accurately the model represents an LMDS/ Satellite network.

3.7.1 Verification

There were verification tests accomplished to prove the logic of the simulation model in three main areas. The first area was the accurate assignment of resources within the LMDS network and within the satellite network. The LMDS system was shown to properly assign resources through a test which observed the receivers and transmitters of several users which started communication at known times. Through analysis of the corresponding receiver/ transmitter data it was observed that LMDS system properly divided the available resources among the users. Each cell correctly increased and decreased resources when new users began transmission as well when users ended transmission. The resources were also seen to be reallocated when the handoff occurred. The satellite network was tested by observing corresponding user transmitter/receivers as they began and terminated transmission.

The second area concerned the delays evident within the entire LMDS/ Satellite network. This was tested by establishing a user at a fixed location with a fixed system and comparing the model output to the analytical calculation which includes propagation delay, transmission delay, and processing delay.

The third area of interest was the switch from LMDS resources to satellite resources. This was tested by moving a user from a LMDS cell to outside the range of the cell. All relevant receivers and transmitters were then tracked to determine the routing of the packets produced by the transmitting user.

3.7.2 Validation

The validation of the model consisted of comparing the simulation results with calculated worst-case limits for each of the metrics. The bit-error rate was compared to the calculated worse possible bit-error rate considering the transmission power, overall attenuation, antenna gain, and modulation type. The delay was also compared to the worst case and best case scenarios which included a maximum satellite hop scenario and same cell scenario, respectively. The throughput was correlated to the number of users transmitting simultaneously to ensure that the correct total resources were being used.

3.8 Summary

The methodology used to create a simulation model that tests basic performance characteristics of an LMDS/ Satellite network was covered in this chapter. Several simplifying assumptions and model limits were also discussed. The model details were covered concerning the OPNET and STK portions of the simulation. The results of the simulation and an analysis of these results is presented in Chapter 4.

Chapter 4

Analysis

4.1 Introduction

This chapter presents the analysis of the simulation results obtained from the OPNET model. Section 4.2 covers the statistical accuracy of the data. The analysis of the LMDS/ Satellite network was performed concerning three operational characteristics of the network. The first area of concern was the packet delay experienced throughout the network. This is covered in Section 4.3. The second point of interest was the bit error experienced by the user received data. This is analyzed in Section 4.4. The final part of the analysis in Section 4.5 concerned the average throughput achieved throughout the network. Finally an overall assessment of the LMDS/ Satellite network is discussed in Section 4.6.

4.2 Statistical Accuracy

The combined LMDS/ Satellite network was tested under multiple scenarios concerning modulation type, Quality of Service, and number of users. The modulation types used were BPSK, QPSK, and 8-PSK. The Quality of Service was set at either 0 (no service guarantee) or 10 Mbps. Each scenario was set to include 50 or 150 mobile users with 3 fixed remote sites. Four different seeds were used for each scenario to ensure statistically sound results for all three areas of interest. The scenarios used throughout can be seen in Table 8.

The packet delay, bit error rate, and throughput are calculated for each user transmission within the network. All user results are combined to calculate an overall mean for each point of interest for each scenario and seed.

A 90% confidence interval is calculated for each of the metrics by calculating a mean and standard deviation for each of the four seeds. The confidence interval is calculated using the *student's t-distribution* shown in Equation 8. The confidence interval is denoted by the

$$100\ (1-\alpha)\%\ CI\ =\ \overline{X} \pm t_{\alpha/2}\frac{s}{\sqrt{n}} \qquad \textbf{(8)}$$

100(1-α) term. The mean is represented by the X-bar in the equation. The s represents the sample standard deviation and the n is the number of samples. The $t_{\alpha/2}$ term is the t-distribution value for α/2 with (n-1) degrees of freedom.

Table 8: OPNET Test Scenarios

Scenario	Modulation Type	Number of Users	Quality of Service (Mbps)
1	BPSK	50	0
2	"	150	0
3	"	50	10
4	"	150	10
5	QPSK	50	0
6	"	150	0
7	"	50	10
8	"	150	10
9	8-PSK	50	0
10	"	150	0
11	"	50	10
12	"	150	10

Applying the confidence interval to two scenarios for the packet delay for the BPSK modulation and the QPSK modulation yields the results in Tables 9 and 10. Because of the dynamic nature of the LMDS/ Satellite network, the standard deviation of the results proves to be relatively high peaking at 40 percent of the mean as in the case of the average throughput of the 8-PSK,150 user,10 Mbps QoS scenario. Therefore, a 90% confidence interval was chosen to illustrate the statistical accuracy of the data. The 90% confidence interval for the BPSK packet delay data displays the dynamic nature of the simulation. The four seeds used for each scenario resulted in a range of .94 msec to 11.7 msec. This range achieved a sufficient level of confidence with the use of four seeds. The confidence interval for the QPSK data proves that this data is also statistically sound with the use of four seeds since the range is between 2.3 and 7.9 msecs.

A t-test was also conducted when comparing data points with overlapping confidence intervals. Equation 9 was used to calculated the pooled estimate of the standard deviation [Tal92]. Equation 10 was used to calculate the t value for the two data points [Tal92].

$$s^2 = \frac{(n_1 - 1)s_1^{\;2} + (n_2 - 1)s_2^{\;2}}{n_1 + n_2 - 2} \tag{9}$$

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\frac{s^2}{n_1} + \frac{s^2}{n_2}}} \tag{10}$$

The n1 and n2 in both equations represents the number of samples which is four throughout this analysis. The s1 and s2 in (9) are the corresponding standard deviations for the two data points. The $\overline{X}_1$ and $\overline{X}_2$ represent the corresponding data points. By calculating the t value for two means it is possible to determine whether they are statistically equal.

Table 9: Average Packet Delay for BPSK Modulation

				90% Confidence Interval		
QOS (Mbps)	Users	Mean (secs)	Std Dev (secs)	Min (secs)	Max (secs)	Range (secs)
0	50	0.03129	0.00268	0.02813	0.03445	0.00631
0	150	0.10460	0.00497	0.09875	0.11045	0.01170
10	50	0.01375	0.00040	0.01328	0.01422	0.00094
10	150	0.01496	0.00045	0.01442	0.01549	0.00106

Table 10: Average Packet Delay for QPSK Modulation

				90% Confidence Interval		
QOS (Mbps)	Users	Mean (secs)	Std Dev (secs)	Min (secs)	Max (secs)	Range (secs)
0	50	0.01302	0.00336	0.00907	0.01697	0.00790
0	150	0.04675	0.00156	0.04492	0.04858	0.00367
10	50	0.01286	0.00300	0.00933	0.01638	0.00706
10	150	0.01304	0.00096	0.01192	0.01417	0.00225

4.3 Packet End-to-End Delay Analysis

The end-to-end packet delay was analyzed on two different levels. The first level provides a comparison of the scenarios within one modulation scheme, while the second, a comparison of the modulation schemes. The test scenarios for the simulation included four simulations for each modulation. Each scenario was executed with four different seeds.

4.3.1 Average Delay

A key parameter for the analysis of a communication network concerns the end-to-end delay that any packet experiences. The extent of this delay dictates whether the system is capable of handling certain applications. If the delay exceeds certain thresholds, the network may not be capable of supporting real-time applications such as voice or video. The standard limitation for real-time voice is 400 msec.

The mean packet delay as well as the peak delay was calculated for all scenarios performed for the network. A comparison of the delay for the BPSK scenarios can be seen in Figure 19. This figure displays the delay for four scenarios: 50 users and a QoS of 0; 150 users and a QoS of 0; 50 users and a QoS of 10 Mbps; and 150 users and a QoS of 10 Mbps. From the graph it can be determined that the delay is the greatest when the largest numbers of users are operating with no quality of service threshold. This is as expected since the available bandwidth within a single cell could be divided into 100 separate and equal frequency blocks (800 KHz each) if 100 users establish a call at the same time. As in the case of the BPSK scenarios, each user would only have 400 Kbps available. The final two scenarios are approximately equal (.0137 and .0149 milliseconds), but when comparing the data the final scenario has a slightly larger delay.

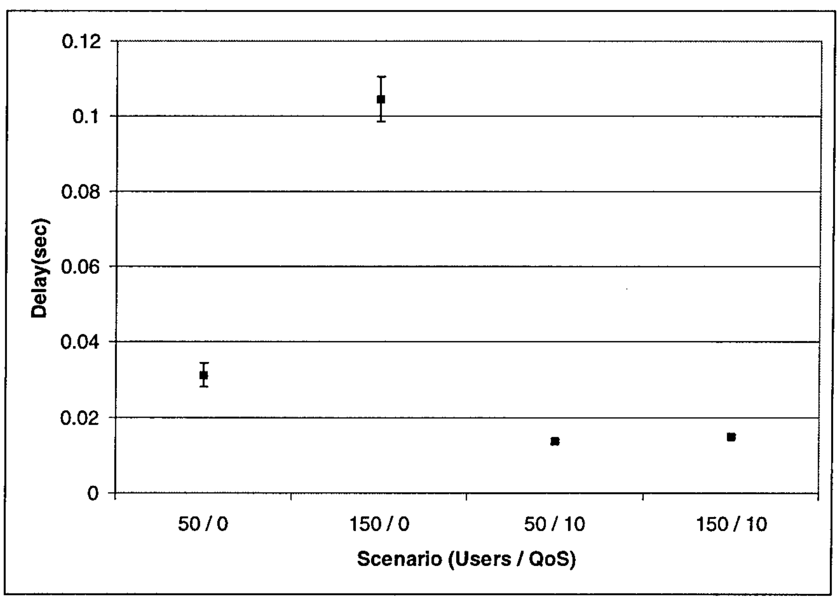

Figure 19: BPSK Average Packet Delay

Figure 20 displays the QPSK delay statistics shown in Table 10. The corresponding scenarios for the QPSK simulations displayed the same relationship as the BPSK tests. The only exception is the first scenario which displayed approximately the same delay (.01302 sec) as the third and fourth scenarios (.01286 and .01304). This can be explained by the fact that in the QPSK system the available bandwidth is twice as high as in the BPSK system allowing the QPSK system to handle the 50 user load with or without the 10 Mbps QoS. The data rate comparison will be discussed further in later sections. After comparing the 8-PSK scenarios it was noted that the relationship between the scenarios was the same as for the QPSK modulation. The second scenario (150 users/ QoS 0) displayed a statistically higher delay (.027 seconds) than the other 8-PSK scenarios (.009, .009, and .012 seconds).

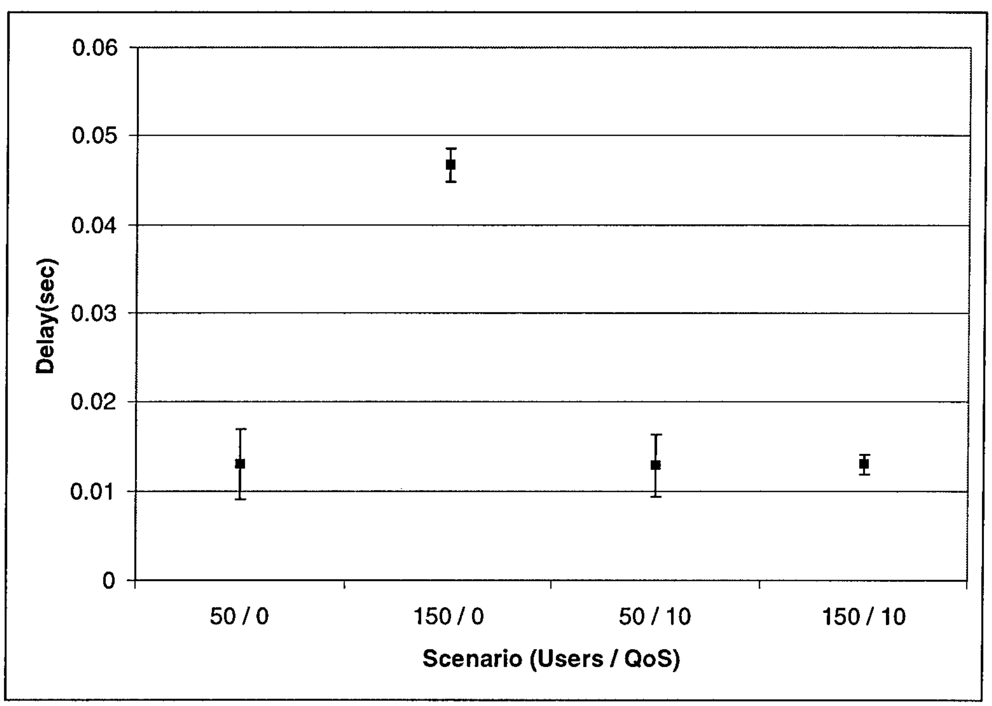

Figure 20: QPSK Average Packet Delay

Comparing the delays for the different modulations, it would be expected to see lower delays with the higher data rate modulation schemes. Figure 21 displays a comparison of the modulation schemes with 50 users and zero QoS. From this data, it is shown that with a low user load, the BPSK scenario has approximately .02 sec longer average delay than the QPSK scenario which is .004 seconds longer than the 8-PSK scenario. By using a t-test it was determined that there is statistically insignificant difference between the QPSK and 8-PSK modulation schemes since with a load of only 50 users each scheme is able to maintain a relatively high data rate which will be discussed in Section 4.5. On the other hand when the user load is increased to 150 the delay for the QPSK system does become .02 seconds longer than the 8-PSK system as shown in Figure 22.

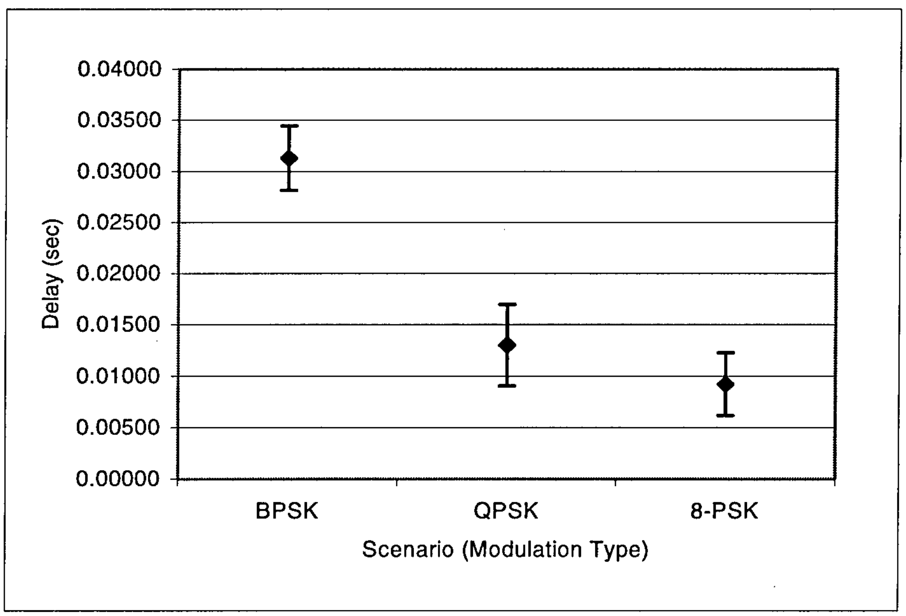

Figure 21: Ave Packet Delay with Low User Load

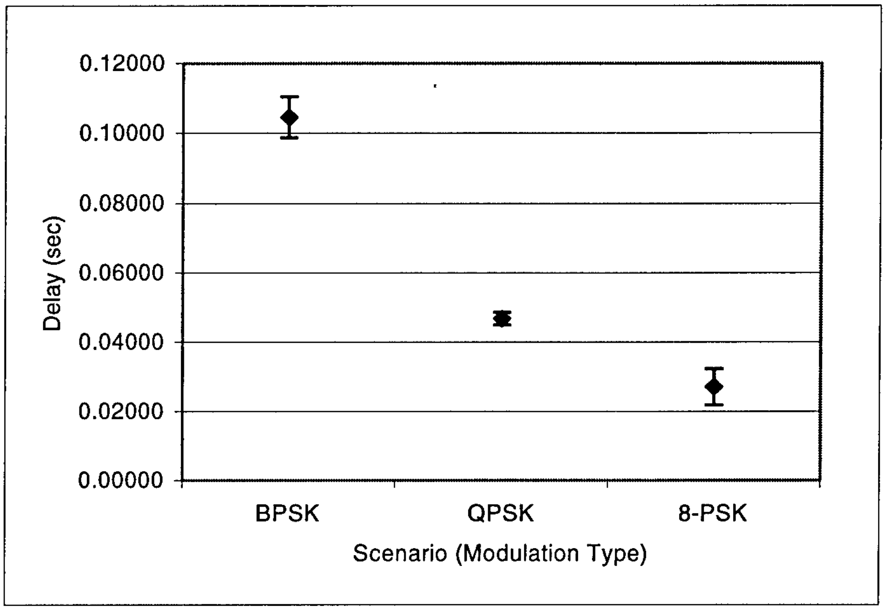

Figure 22: Ave Packet Delay with High User Load

When including the QoS in the runs, the average delay for each of the modulation types tends to have only a slight difference (.001 to .002 seconds) as shown in Figure 23. This is as expected since the QoS forces each of the systems to maintain the same minimum throughput within the cells. The delay does decrease slightly (.001 to .002 seconds) since the higher rate modulation schemes will not redirect the mobile users to the lower data rate/higher delay satellite communication link. The difference for between the QPSK and 8-PSK modulation schemes is shown to be statistically equal. There is not a statistical difference between the QPSK and 8-PSK as there is between the BPSK and QPSK because the increase in data rate for the QPSK to 8-PSK modulation schemes is 1.5. Whereas, the increase between QPSK and BPSK is a factor of two.

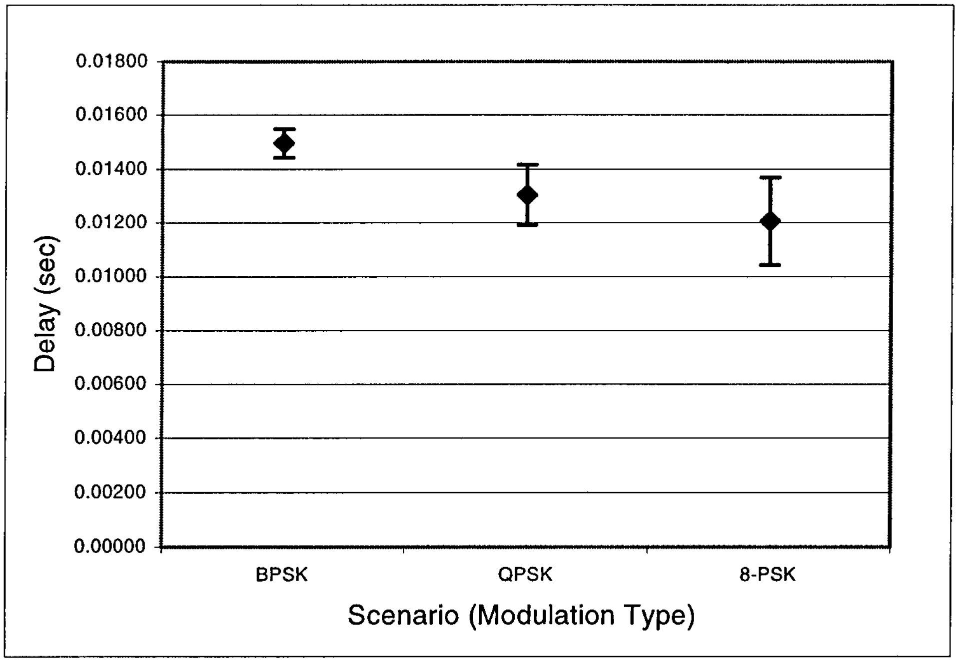

Figure 23: Ave Packet Delay with QoS and High User Load

4.3.2 Peak Packet Delay

The area of most concern for the packet delay analysis is the peak delay. As discussed earlier, this is important because it determines the capability of the system to support real-time applications.

After analyzing the average delay, it is shown that the scenario that could cause a large peak delay is the high user load (150) and zero QoS. Figure 24 displays a comparison of the three modulation schemes for this user load and QoS. From this plot of the peak delay data, it can be seen that the BPSK scenario produced a peak delay of approximately .45 sec with a confidence interval that exceeded .5 sec. This delay exceeds the limit for real-time voice communications. This proves that a packet size of 100 Kbits would not be appropriate for a BPSK system operating under in conditions similar to this scenario. The remaining scenarios all were well under the specification. Tables 19 through 21 of Appendix A display the data for the peak delay.

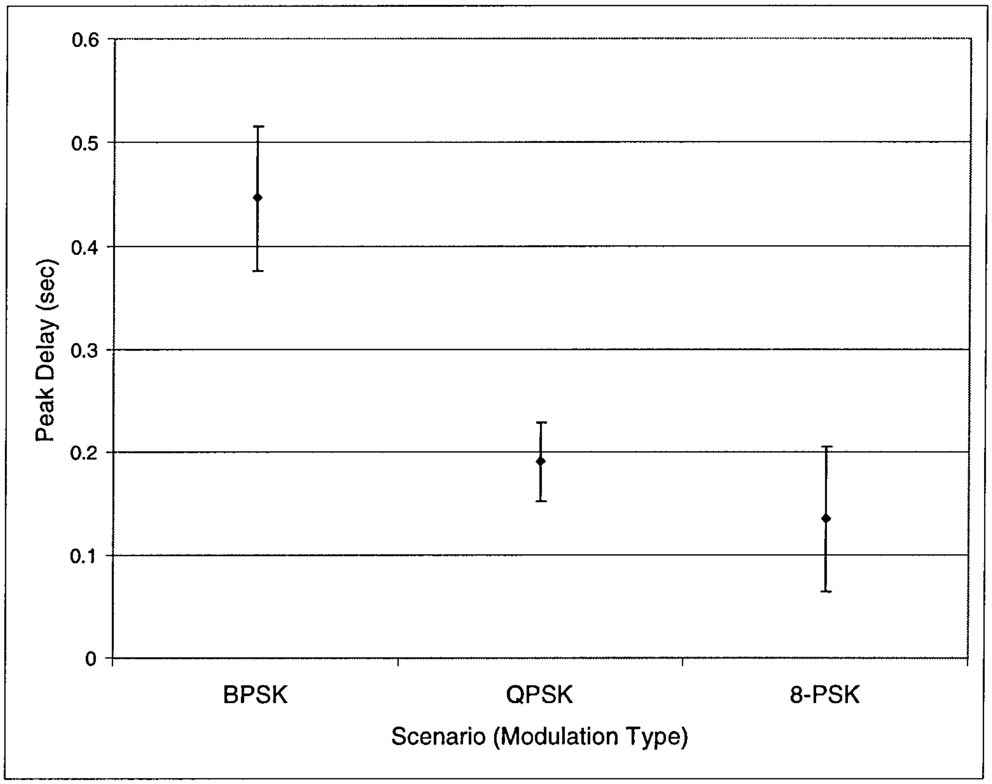

Figure 24: Peak Delay for High User Load and No QoS

4.3.3 Satellite Packet Delays

A goal of this thesis was to establish the capability of the joint LMDS/ Satellite network to support a real-time application such as voice. The major concern was the satellite portion of the network. The simulation was set to test the satellite communication to remote locations under best case and worst-case scenarios. This data was collected in conjunction with all the LMDS scenarios. Table 11 displays the results of this simulation.

Table 11: Satellite Peak Packet Delays (Seconds)

			90% Confidence Interval	
	Mean Delay	Std Dev	Min	Max
Best Case	0.040843	7.08E-07	0.040842	0.04084312
Worst Case	0.145593	1.19E-05	0.145584	0.14560155

The best-case delay was a result of shortest distance for satellite communication to a remote site located in Germany. The worst case was a result of a path from the LMDS site in Ohio, around the world, to a remote site in Wyoming resulting in 20 satellite hops. From the data, it can be seen that the delays meet the specifications for real-time voice. The reason that the worst-case delay was not excessive for voice communication is that the instantaneous data rate for the satellite network is very high resulting in short transmission delays. Therefore, the only delay evident is the propagation time, which as discussed in Section 3.3.3 will remain within voice communication limits.

4.4 Bit Error Rate (P_b)

The bit error rate of a system is a crucial measurement. It determines the transmitter power and error correction techniques that may be necessary for the system. All twelve scenarios within the model were setup to collect data for the bit error rate. In order to make a direct comparison, the transmitted power was kept constant regardless of the modulation type. This power selection is described in Section 3.4.1.1.1.

4.4.1 Average Bit Error

The average bit error rate for each of scenarios was calculated and recorded. Tables 15 through 17 display the data with the 90% confidence intervals. The data proved to have a large standard deviation, which averaged 30 percent of the mean for all scenarios. This can be expected since the data was collected for all users independent of encountering errors. The average error gives an overall picture of the performance comparison between the modulation schemes. Figure 25 displays the data for the 50-user scenario without the QoS. From this plot the BPSK scenario is seen to have the lowest average bit error. By referencing the bit error data in Figure 25 to the bit error plots, it is possible to figure how much gain in Eb/No would be required to bring the systems

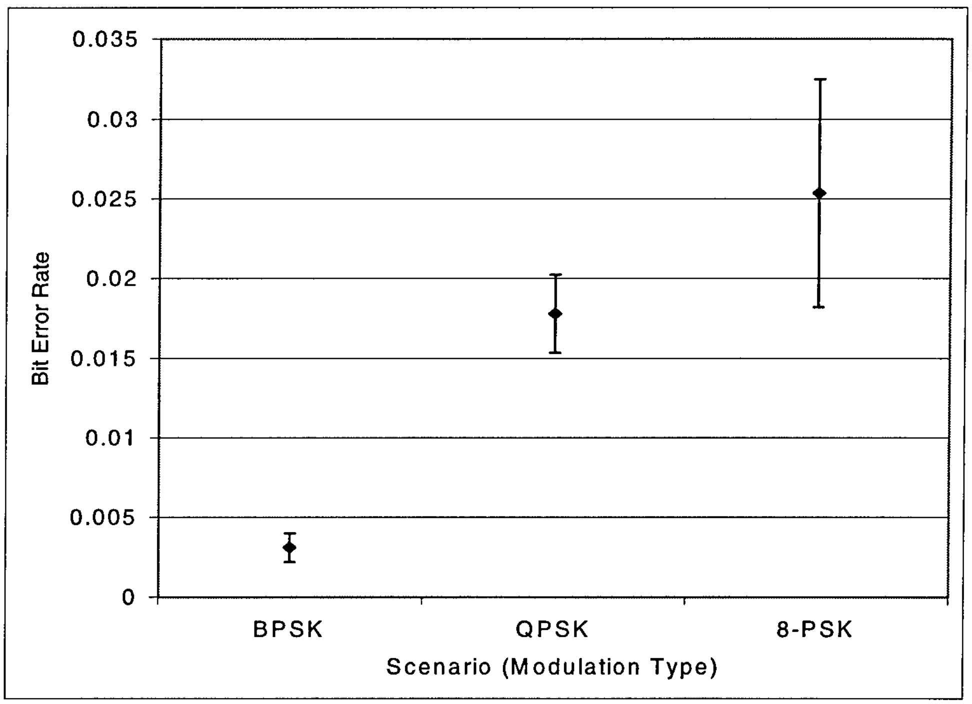

Figure 25: Bit Error Rate for Low User Load and No QoS

average bit error within an acceptable range of 1×10^{-5}. By referencing Figure 4 the following gains were established as presented in Table 12.

Table 12: Required Eb/No Gains

Modulation Type	Eb/No Gain
BPSK	4 dB
QPSK	5 dB
8-PSK	7 dB

The gain in E_b/N_o could be achieved in the following ways: increased antenna gain of the transmitter, increased transmitted power, increased receiver antenna gain, or through error correction techniques. The system was designed to require a 6 dB coding gain for a worst case BPSK signal.

4.5 System Throughput Analysis

The main initiative for designing an LMDS/ Satellite network would be to provide users, in some cases mobile, with the capability to achieve very high data rates without the need for installation of landlines for each user in the system. The throughput analysis for the simulation was the key for the number and type of scenarios that were developed. Table 8 gives a breakdown of all scenarios that were used for the throughput analysis as well as the delay and bit error analyses.

4.5.1 Average Throughput

The first part of the throughput analysis deals with the affect of the number of users and QoS for a given modulation type. One would expect to see a decrease in throughput with an increase in users and possibly stabilization with the addition of the QoS factor. Figure 26 displays a comparison for the BPSK scenarios.

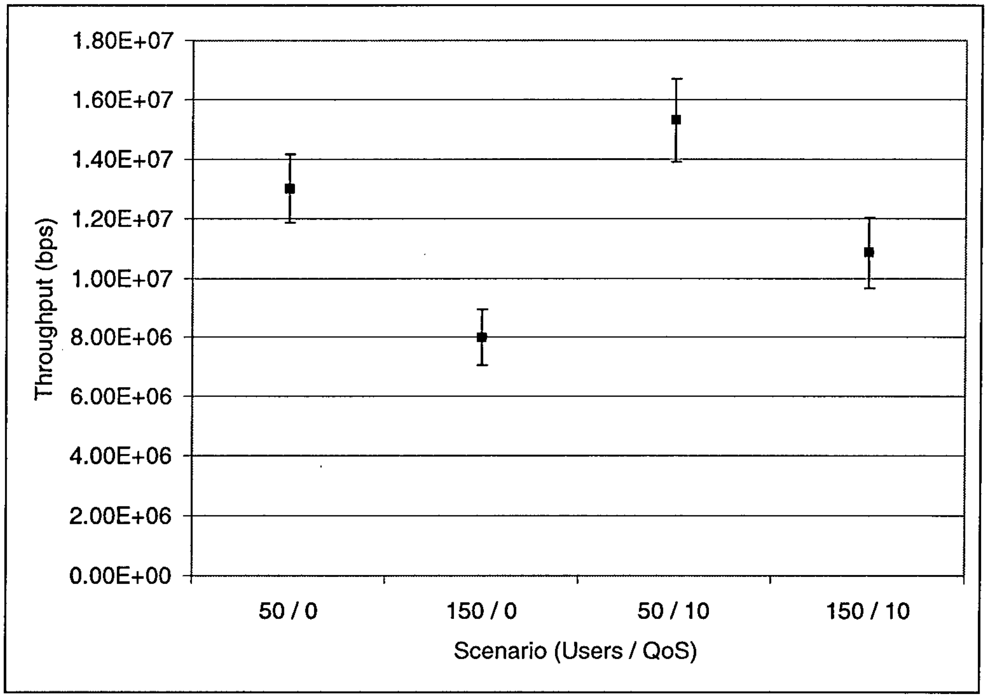

Figure 26: BPSK Average Throughput

This figure displays the expected results. The throughput decreases from the 50-user scenarios to the 150-user scenarios. There is also an increase from the scenarios without QoS to the scenarios with QoS. A t-test was used to prove a statistical difference between the 50-user scenarios. The average throughput also increased by 2.5 Mbps for the 150 user scenarios. The 50 user scenarios did show a statistically substantial increase, with the mean increasing by approximately 2 Mbps.

The QPSK throughput had similar characteristics as the BPSK for the 150 user scenarios. As shown in Figure 27, the throughput increased for the 150 user scenario with the addition of the QoS, while the throughput remained the same for the 50 user scenario. This is expected since the network did not have to use satellite communication for the 50 user scenario without QoS. The throughput ranged from 15 Mbps to 20 Mbps for the 150-user scenario, but remained the statistically constant at 35 Mbps for the 50-user scenario.

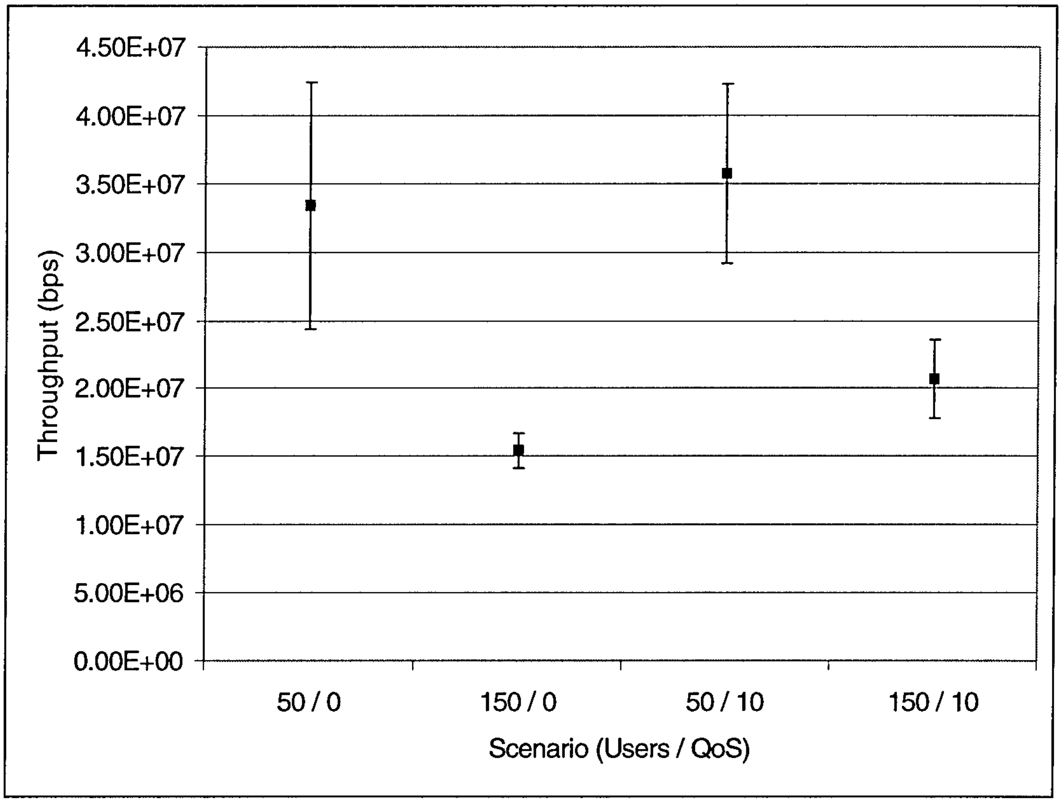

Figure 27: Average Throughput for QPSK Modulation

For the 8-PSK scenarios detailed in Table 8, there appeared to be no significant increase in throughput due to the QoS. Figure 28 displays the comparison for the 8-PSK scenarios. The increase did not occur for this modulation, since the 150-user load is not as high a load for this scenario. The 8-PSK system has a much larger available throughput. The 50-user group displayed a mean throughput of 58 Mbps and the 150-user group achieved a throughput of between 27 and 30 Mbps.

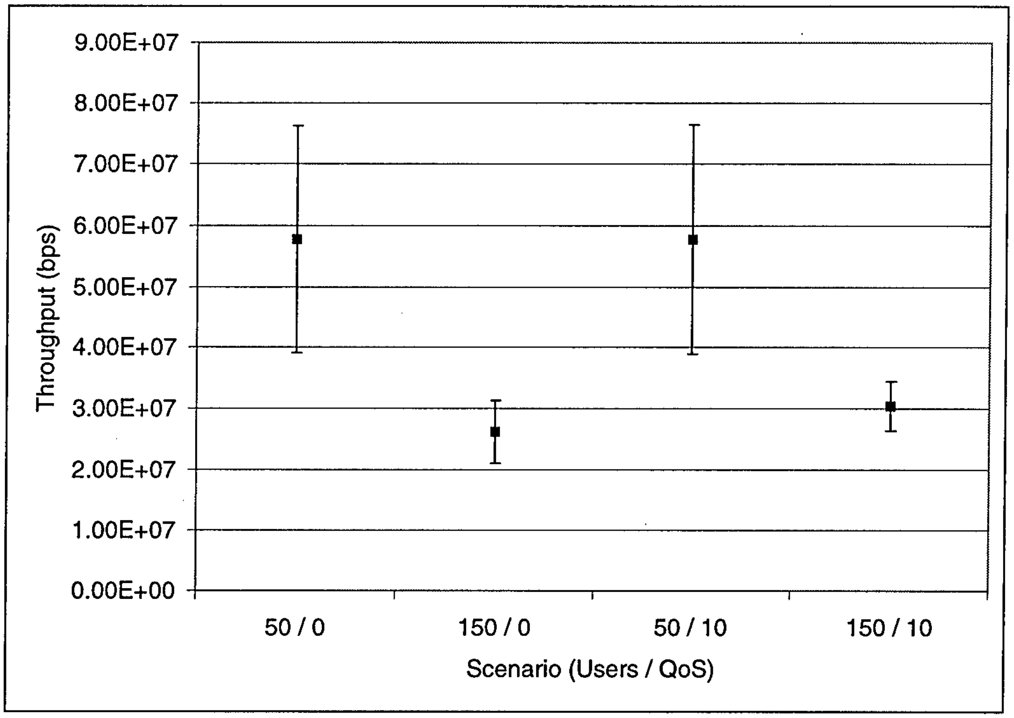

Figure 28: 8-PSK Average Throughput

A comparison of the modulation types, concerning throughput, gives the expected conclusion. As the modulation type changes from BPSK to QPSK the throughput increases for all scenarios. For the change from QPSK to 8-PSK, the throughput mean does change, but because of the high dynamic nature of the throughput during one scenario the difference is not statistically significant. The range of the throughput of a simulation is illustrated in Figure 29. This figure displays the wide range of throughput values throughout a single simulation which leads to the large confidence intervals. All throughput data can be seen in Appendix A in Tables 19 through 21.

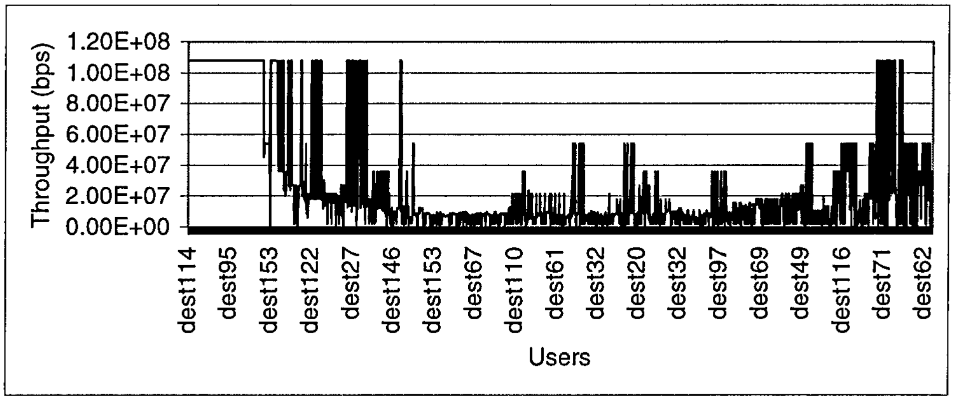

Figure 29: Throughput vs. Time for 8-PSK/ 150 Users

4.6 Summary of Analysis

The delay analysis provided proof that the LMDS/ Satellite network will be capable of real-time voice applications for the QPSK and 8-PSK modulation schemes. The delay within the LMDS cells was primarily a function of the data rate, therefore if a smaller packet size is chosen or a QoS is selected any modulation technique will be sufficient.

The bit error analysis displayed the increase in bit error as the modulation types were stepped through. Data collected gave evidence that an increase in Eb/No would be needed to achieve the desired P_b. This was set into the simulation at the beginning when the transmitted power was set assuming a 6 dB coding gain.

The throughput analysis displayed increases of 20 Mbps for the 50 user scenario and 7 to 8 Mbps for the 150 user scenario when comparing the BPSK and QPSK modulation schemes. The analysis also showed an increase of 37 Mbps for the 50 user scenario and 18 to 20 Mbps for the 150 Mbps scenario when comparing the BPSK and 8-PSK modulation shcemes.

Chapter 5

Conclusions and Recommendations

5.1 Restatement of Research Goal

The goal of this research was to analyze the throughput, bit error, and packet delay performance capabilities of a combined LMDS/ Satellite system. This analysis was achieved by varying user loads, modulation techniques, and Quality of Service requirements in the presence of varying urban attenuation.

5.2 Conclusions

The LMDS/ Satellite network is a very flexible network concept consisting of a terrestrial network, that is designed around a block of the Ka frequency band, and a high capacity satellite network such as the proposed Teledesic system. The usefulness of this network depends primarily on the throughput capability and application support. The network achieved a throughput for all scenarios ranging from 7 to 57 Mbps depending on user load, modulation, and QoS. The application support depends on several factors. The two addressed in this thesis were the packet delays and bit errors. The system proved capable of achieving exceptable bit error rates with the aid of simple encoding. The packet delay also proved to support real-time voice applications as long as a QoS was chosen to ensure a data rate that would minimize the transmission delay.

5.3 Significant Results of Research

Very little openly published literature exists concerning either the LMDS type networks or high capacity LEO satellite networks (Teledesic). One of key contributions of this research was the analysis of a wireless high capacity network under a mobile urban environment. The analysis provided an example of throughput characteristics, delay, and bit error that can be expected when operating within a urban environment. The research gave an analysis of a very dynamic environment where users would be entering and leaving LMDS cell resources. The results of the research yeild insight into some physical design characteristics that may be needed for such a system.

5.4 Recommendation for Future Work

The main area for further research concerning an LMDS/ Satellite network would be in the area of the satellite network. This research used a simplified satellite network to provide a basic best case/ worst case analysis of packet delay. This eliminated the dynamic nature of the network. Further work could analyze the complete satellite network to incorporate the dynamic routing that would be used. This expanded model could also incorporate a more complex model of the resource allocation of the satellite network.

Another area that could be pursued is in the area of optimizing the LMDS cell sizes to provide the best throughput to a varying number of users. This research was set to test the LMDS system at two loads to develop a comparison. The user load could be increased and made more dynamic in order to test optimum cell sizes.

Appendix A

Table 13: Average Packet Delay (Seconds) for 8-PSK Modulation

				90% Confidence Interval		
QOS (Mbps)	Users	Mean	Std Dev	Min	Max	Range
0	50	0.00923	0.00259	0.00618	0.01228	0.00610
0	150	0.02706	0.00443	0.02184	0.03228	0.01043
10	50	0.00900	0.00234	0.00625	0.01176	0.00551
10	150	0.01206	0.00138	0.01043	0.01368	0.00325

Table 14: Average Bit Error Rate for BPSK Modulation

				90% Confidence Interval		
QOS (Mbps)	Users	Mean	Std Dev	Min	Max	Range
0	50	0.00310	0.00077	0.00220	0.00400	0.00180
0	150	0.00096	0.00101	-0.00022	0.00215	0.00237
10	50	0.00463	0.00175	0.00258	0.00669	0.00411
10	150	0.00193	0.00113	0.00059	0.00326	0.00267

Table 15: Average Bit Error Rate for QPSK Modulation

				90% Confidence Interval		
QOS (Mbps)	Users	Mean	Std Dev	Min	Max	Range
0	50	0.01779	0.00208	0.01534	0.02024	0.00489
0	150	0.00783	0.00204	0.00543	0.01023	0.00479
10	50	0.01639	0.00063	0.01565	0.01713	0.00148
10	150	0.01262	0.00165	0.01068	0.01456	0.00388

Table 16: Average Bit Error Rate for 8-PSK Modulation

				90% Confidence Interval		
QOS (Mbps)	Users	Mean	Std Dev	Min	Max	Range
0	50	0.02536	0.00609	0.01820	0.03252	0.01432
0	150	0.01125	0.00289	0.00785	0.01464	0.00680
10	50	0.02629	0.00509	0.02030	0.03228	0.01197
10	150	0.01524	0.00228	0.01256	0.01792	0.00536

Table 17: Average Throughput (bps) for BPSK Modulation

				90% Confidence Interval		
QOS (Mbps)	Users	Mean	Std Dev	Min	Max	Range
0	50	13019177	989378	11855174	14183181	2328007
0	150	8023455	808962	7071711	8975199	1903488
10	50	15306287	1201957	13892185	16720390	2828205
10	150	10854921	1005405	9672062	12037780	2365718

Table 18: Average Throughput (bps) for QPSK Modulation

				90% Confidence Interval		
QOS (Mbps)	Users	Mean	Std Dev	Min	Max	Range
0	50	33414123	7654985	24408033	42420213	18012180
0	150	15446177	1082423	14172706	16719647	2546941
10	50	35768022	5596349	29183918	42352126	13168208
10	150	20734906	2456556	17844768	23625044	5780276

Table 19: Average Throughput (bps) for 8-PSK Modulation

				90% Confidence Interval		
QOS (Mbps)	Users	Mean	Std Dev	Min	Max	Range
0	50	57763364	15695476	39297636	76229092	36931456
0	150	26346383	4354044	21223851	31468915	10245064
10	50	57800528	15911451	39080706	76520349	37439643
10	150	30469193	3428484	26435582	34502803	8067222

Table 20: Peak Packet Delay (Seconds) for BPSK Modulation

				90% Confidence Interval		
QOS (Mbps)	Users	Mean	Std Dev	Min	Max	Range
0	50	0.11161	0.04617	0.05728	0.16593	0.10865
0	150	0.44649	0.05951	0.37647	0.51650	0.14003
10	50	0.04330	0.00491	0.03752	0.04907	0.01154
10	150	0.12737	0.11750	-0.01087	0.26560	0.27647

Table 21: Peak Packet Delay (Seconds) for QPSK Modulation

				90% Confidence Interval		
QOS (Mbps)	Users	Mean	Std Dev	Min	Max	Range
0	50	0.05357	0.02271	0.02685	0.08029	0.05344
0	150	0.19112	0.03283	0.15250	0.22974	0.07724
10	50	0.10489	0.05073	0.04521	0.16457	0.11936
10	150	0.09383	0.03519	0.05243	0.13523	0.08280

Table 22: Peak Packet Delay (Seconds) for 8-PSK Modulation

				90% Confidence Interval		
QOS (Mbps)	Users	Mean	Std Dev	Min	Max	Range
0	50	0.08412	0.05062	0.02456	0.14367	0.11910
0	150	0.13492	0.06028	0.06400	0.20584	0.14184
10	50	0.07835	0.04965	0.01993	0.13677	0.11684
10	150	0.07481	0.05229	0.01329	0.13632	0.12303

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
15-03-2000	Master's Thesis	Mar 1999 - Mar 2000

4. TITLE AND SUBTITLE
A Performance Analysis of a Joint LMDS/ Satellite Communication Network

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Zwickel, Ronald J., Capt., USAF

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/EN)
2950 P Street, Building 640
WPAFB OH 45433-7765

8. PERFORMING ORGANIZATION REPORT NUMBER
AFIT/GE/ENG/OOM-20

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFCA/ITAI
ATTN: Mr. Kenneth Fore
Rm 1065
203 W Losey St
Scott AFB, IL 62225-5222

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

13. SUPPLEMENTARY NOTES
Advisor: Maj. R.A. Raines, ENG, DSN: 785-3636, ext. 4715

14. ABSTRACT
The goal of this research is to provide a performance analysis of a joint terrestrial/ satellite communication network. The systems of interest are the Local Multipoint Distribution Service (LMDS) terrestrial system and the proposed Teledesic satellite network. This analysis is performed using the OPNET network simulation tool. The key metrics for characterizing simulation scenarios are the end-to-end delay, bit error rate, and average system throughput. The results obtained display the benefit of improved throughput for different modulation types, approximately 20 Mbps for the low user load and approximately 8 to 11 Mbps for the high user load. This improvement comes at the expense of the bit error rate. For example, the bit error rate increased by a factor of 5 for the low user load when changing from BPSK to QPSK and by a factor of 1.5 for the QPSK to 8-PSK change. The peak end-to-end delay results, ranging from .053 seconds to .446 seconds, proved to support real-time voice communication for all but one scenario (BPSK/ High user load). The QoS proved to be a benefit for scenarios with a high user load (150 users) increasing the average throughput by 2 to 4 Mbps. The QoS also reduced the peak end-to-end delay, narrowing the range from .04 to .104 seconds. The analysis of these operational characteristics gives a fundamental look at the system.

15. SUBJECT TERMS
LMDS Network, Teledesic, Throughput, Delay, Quality of Service

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Maj. Richard A. Raines
U	U	U	UL	91	19b. TELEPHONE NUMBER *(Include area code)* (937) 255-2024