A Performance Analysis of a

Low Earth Orbit Satellite System

THESIS

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Presented to the faculty of the Graduate School of Engineering

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science (Computer Engineering)

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ABSTRACT

This thesis provides a performance analysis of the TELEDESIC® Low Earth Orbit Satellite System. It analyzes the system's performance to meet the real-time communications constraints with a full satellite constellation. Computer simulation results are the sources to evaluate delays associated with packets transmitted from source to destination earth stations. The simulation is run at low, medium and high loading levels with two different, uniform and non-uniform, traffic distributions. The evaluated results are end-to-end packet delays and packet rejection rate. The results show that the TELEDESIC® satellite system network is capable of meeting the real-time communication requirements with delay values much smaller than 400 ms.

CHAPTER 1

INTRODUCTION

1.1 Research Goal

The goal of this research is to analyze a Low Earth Orbit (LEO) satellite network's capability to provide real-time communications with two different traffic distributions using a full satellite constellation. This research specifically targets a system that possesses architectural similarities of the proposed TELEDESIC® system.

1.2 Research Motivation

This thesis covers the delay performance analysis of the TELEDESIC® satellite system. Because LEO satellite communications is a new area, interesting research opportunities are available. Commercial organizations are still working on significant projects in the communications area including enormous satellite systems like the IRIDIUM®, GLOBALSTAR®, TELEDESIC®, and ELLIPSO®. The IRIDIUM® satellite system is the first commercial system designed to use inter-satellite communication links. The TELEDESIC® system will be the first satellite system designed to use eight inter-satellite links. It will also gain a reputation of being the first system with 288 satellites to cover all the areas of the world. The system will provide fiber-like quality telecommunication services that span the globe. Those services include broadband Internet access, high-quality voice, and video-conferencing [Tel98a].

There are two trends in military communications today. The first one is the ability to use advanced mobile communications systems. This is especially advantageous for wireless remote communications in field, in naval and air operations. Mobile communications has proved itself to provide accurate, on-demand information to tactical military users. The second trend in military communications is that the military communication systems are getting a part of commercially equipped systems. Not long ago, the military communications systems were application specific stand-alone systems. But today, these systems are being designed to cooperate with commercial systems and with other military systems. The TELEDESIC® satellite system, a new LEO satellite technology currently under development, aims to provide global information communications to all parts of the world. In military aspects, this system seems to have good potential for future integration into military communications systems. A delay performance analysis of the TELEDESIC® satellite system will provide information about packet delay from one source earth station to a destination earth station. The feasibility of integrating commercial LEO satellite systems into military communications systems depends on the critical time it takes for an information packet to reach its destination with accurate data and just in time before it is really needed.

1.3 Overview of Results

This research uses an approach similar to the one taken by Major Carl Fossa [Fos98] in his study of the IRIDIUM® system. Fossa's research focused on the delay performance analysis of the IRIDIUM® satellite system in which the system traffic loading level was increased while simultaneously modeling satellite failures. Fossa's thesis showed that the IRIDIUM® satellite was capable of having acceptable end-to-end packet delays (less than 400 ms) for different loading levels and different traffic distributions. Fossa's thesis also showed that the IRIDIUM® satellite system was highly survivable.

This research extends Fossa's work by modeling a complex satellite data network over four times larger than Fossa's model. But this research did not include the satellite removal algorithm to analyze the delay performance with non-operational satellites. This research covered a delay performance analysis of the TELEDESIC® satellite system with a full system configuration. The system is at low, medium, and high traffic loading levels of 50%, 83% and 100% respectively. This research uses seven earth stations which transmit packets from source to destination earth stations and models both uniform and non-uniform traffic distributions. The system end-to-end delay performance is shown to be below 400 ms for all cases considered. This result proves that the system performs under the real-time communication requirement of 400 ms with a packet rejection rate of zero for all loading levels and traffic distributions.

This research improves upon Fossa's work by analyzing the ability to route packets from source earth stations to destination earth stations by having an inter-connectivity between eight satellites, unlike the IRIDIUM® satellite having four inter-connected satellites to route a packet from a specific source to destinations.

1.4 Summary

The goal of this research has been defined in this chapter. A summary of the motivation to design such a LEO satellite network has also been defined in this chapter. Chapter 2 presents a description about the satellite systems, their advantages and disadvantages, essentially focusing on the LEO Satellite Systems since the TELEDESIC® satellite is a LEO type satellite system. Chapter 3 describes the methodology used to analyze the delay performance of the TELEDESIC® satellite system and explains the design of the simulation model. In Chapter 4, the simulation results are provided and analyzed. The statistical accuracy of the simulation is also explained. Chapter 5 contains conclusions and recommendations for future research in the area of LEO satellite networks.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter describes the satellite systems, their advantages and disadvantages, focusing on the Low Earth Orbit (LEO) satellite system since the TELEDESIC® satellite is a LEO type satellite system.

Section 2.2 presents a view of contemporary satellite systems along with their advantages and disadvantages. Section 2.2.3 covers some types of LEO satellites and explains their primary specifications. In Section 2.3, a comparison between differing LEO type satellites is made. In Section 2.4, The LEO satellite system network configuration and constellation is presented. Section 2.5 discusses the network survivability aspects associated with LEO satellite systems. Finally, the summary takes place in Section 2.6.

2.2 SATELLITE SYSTEMS

2.2.1 The Geostationary Earth Orbit (GEO) Satellite

A GEO satellite appears to be stationary to an observer on the ground and has an altitude of 35,800 kilometers (km) above the surface of the Earth [Fos98]. The inclination and the eccentricity of the GEO orbit are almost 0° relative to the Earth.

The advantages of the GEO satellite systems make the system orbit a communications requisite. GEO satellites are stationary to the ground stations within a coverage area and that property makes the tracking and operational needs on each terminal stay at minimum levels. Also, the Doppler-shift to and from other radio systems are minimal because the satellite appears stationary to all the ground stations.

GEO satellite systems also have disadvantages that make the LEO satellite system more advantageous to use than the GEO. Since the satellites are far from the earth compared to the LEO satellites, the propagation delays are naturally greater. A typical one-way propagation time (uplink or downlink) for a GEO satellite is approximately 120 ms while one-way propagation time for LEO satellite is less than 10 ms. Another disadvantage is that the GEO satellites do not have an adequate coverage to the locations beyond 75° latitude. So service inconsistencies will be inevitable beyond this latitude. Finally, because of the great distance between GEO satellites and Earth, a higher transmitter power is needed to overcome the transmission energy losses [RiM95a].

2.2.2 Highly Elliptical Orbit (HEO) Satellite

HEO satellite systems have disadvantages as well. Because of the large movement of a HEO type satellite with respect to an observer on the earth, satellite systems using this type of orbit must overcome the Doppler-shift effects to receive correct and valid ranging and communication data. Switching over to another satellite in the same orbit can be performed to avoid loss of communications.

2.2.3 Low Earth Orbit (LEO) Satellite

LEO satellites have been proposed to meet the requirements needed for growing global mobile communications. LEO satellites have either elliptical or circular orbits. A LEO satellite has an altitude less than 2,000 kilometers (km) above the surface of the Earth [Stu96]. A global communications system which has a LEO type orbit uses more satellites in different orbits.

A few years ago, the use of LEO satellites was considered unfeasible because of the great number of satellites required and the complexity of the network that was needed to support that type of orbit. However, as satellite communications technology matured, research has shown that the use of LEO satellites is feasible and provides some advantages over GEO and HEO satellite systems.

The lower altitude of the LEO satellite system makes the propagation delays comparably smaller than GEO and HEO satellite systems. Also, since the system consists of many satellites, failure of a satellite does not dramatically affect the overall satellite system as the adjacent orbital satellites can be directed to perform the activities of the defective satellite. The LEO satellite is lighter than the individual satellites used for GEO and HEO satellite systems. With this property, smaller and lighter LEO satellites are easily carried by launch vehicles such as the Space Shuttle or Pegasus rockets. This reduces the cost paid for satellite transportation by these expensive vehicles. Finally, because of the lower altitude between a LEO satellite and the Earth, a lower transmitter power is needed to overcome the transmission energy losses compared to GEO and LEO satellite systems.

The LEO satellite system has disadvantages as well. Many LEO type satellites are required to cover the same area that is covered by one GEO satellite. Also, the dynamic movement of a LEO type satellite creates a Doppler effect on the transmitted signal. Satellites in LEO systems are also effected by atmospheric drag that reduces the ellipticity of an elliptical orbit and causes an altitude loss of a circular orbit [RiM95b]. At low altitudes, friction causes excessive heat that results in burning the satellite.

IRIDIUM®, GLOBALSTAR®, and TELEDESIC® satellite systems are all LEO satellite systems.

2.2.3.1 The Globalstar Satellite System

GLOBALSTAR® was designed to provide worldwide voice, data, fax, paging, short message, and position location services. Each satellite has a 1414-km orbit above the Earth. It relays communications between the user and a Gateway instead of connecting one user directly to another. The party being called is connected with the Gateway through the Public Switch Telephone Network. This maximizes the use of existing, low cost communications services. GLOBALSTAR® will contain 56 satellites that will be operating in low earth orbit. Each orbit has 1,414-km circular orbit with an inclination angle at 52 degrees. It is scheduled to be operational in 1999 [Glo98].

2.2.3.2 The Iridium Satellite System

The IRIDIUM® system is designed to provide wireless telephone service. The constellation consists of 66 satellites in a LEO type orbit. The altitude of the system is 780 km. This provides better propagation delay values compared to GEO type satellites. The system provides transmissions of type voice, data, fax and paging to reach its destination from one place to another at anytime. The satellite antenna has fixed, moving cells. System cost will be higher than GLOBALSTAR® satellite system.

2.2.3.3 The Teledesic Satellite System

The TELEDESIC® satellite system will provide fiber-like quality telecommunication services covering all the areas in the world. Those services include broadband Internet access, digital voice, video-conferencing, data, and interactive multimedia activities. The TELEDESIC® network will consist of 12 orbits, each one having 24 satellites. So, the total number of operational satellites in the system will be 288 [Tel98b]. To avoid collisions, the orbital planes will not cross directly over the poles, but will be inclined at 98° [Woo98a].

The network has both the advantages of circuit-switched networks which is low delay digital pipes, and packet-switched networks which is effective handling burst data [Tel98c]. The system will solve terrestrial problems and reach to all the parts of the world which were not serviceable due to economical and technological reasons. The system will be fully operational in 2003 [Tel98b].

2.3 Comparison of the Globalstar, Iridium, and Teledesic Satellite Systems

Geostationary satellite systems have higher propagation delays. In order to have smaller rates of delay, those types of satellites need to have some changes in their current network structures. The TELEDESIC® satellite system will use fiber-optic characteristics to support low latency, low error rates, flexibility, and higher rates of service availability.

The TELEDESIC® satellite system must have the flexibility to meet the requirements needed for multiple channel rates, protocols, and priority. IRIDIUM® and GLOBALSTAR® are considered to be big LEO type satellites. These systems have higher bandwidth and power values, as well as providing data transmission, and paging at higher bit rates. TELEDESIC® satellite is considered to be a broadband LEO type satellite system. Its terrestrial counterpart is fiber. On the other hand, the IRIDIUM® and GLOBALSTAR® have cellular type terrestrial counterparts [Koh97].

TELEDESIC® will have 16 Kbps voice transmission, which is comparably the better value between those three satellite systems. Data transmission will be 7.2 Kbps for the GLOBALSTAR® satellite, 2.4 Kbps for the IRIDIUM satellite, and 16-2048 Kbps for the TELEDESIC® satellite. TELEDESIC® uses Ka-Band frequency interval (18 to 31 GHz). TELEDESIC® also uses earth-fixed cells with steering ability while IRIDIUM® and GLOBALSTAR® use fixed moving cells [Woo98a].

A big disadvantage, relative to all the advantages that the TELEDESIC® satellite system offers, is the overall system cost. Design, construction and positioning the satellites has an estimate value of $ 9 billion [Tel98b], three times more expensive than the IRIDIUM® satellite.

The TELEDESIC® network models the most famous network, the Internet. It also has some more valuable services like real-time connections, location-insensitive access and broadband-on-demand capability. Their low altitude satellites will offer small values of propagation delays and this is a nice benefit against the traditional satellite systems.

2.4 The Teledesic Satellite System Network Configuration and Constellation

2.4.1 The Teledesic Network Configuration

IRIDIUM® and TELEDESIC® are two proposed satellite constellations that use Intersatellite Links (ISL). ISLs provide inter-connectivity between the satellites. The ground-based segment of the system will consist of terminals, gateways, and control systems. The terminals will provide the interface between satellite network and terrestrial end-users. They will perform the translation between the TELEDESIC® network's internal protocols and the standard protocols of the terrestrial world, thus isolating the satellite-based core network from complexity and change. The terminals will accept a wide range of standard network protocols, including IP, ISDN, ATM and others [Tel98c]. GigaLink terminals provide gateway connections to public networks and to TELEDESIC® support and data base systems [Koh97].

The only feasible frequency band internationally allocated to fixed satellite service that meets TELEDESIC®'s requirements is the Ka band (18-31 GHz). High rain attenuation, terrain blocking, and other terrestrial systems operating in this band make it difficult for earth terminals to communicate reliably with a satellite at low elevation angles. The TELEDESIC® constellation assures a minimum elevation angle of 40° within its entire service area [Koh97]. The low orbit and high frequency (30 GHz uplink/20 GHz downlink) allow the use of small, low-power terminals and antennas, with a size and cost comparable to a notebook computer.

TELEDESIC® uses small, "Earth-fixed" cells both for efficient spectrum utilization and to respect countries' territorial boundaries [Koh97]. The Earth's surface is mapped into a fixed grid of approximately 20,000 "super-cells," each consisting of nine cells (each cell being 53 km^2). Each super-cell is a square (160x160 km). Super-cells are arranged in bands parallel to the Equator. There are approximately 250 super-cells in the band at the Equator, and the number per band decreases with increasing latitude [Tel98c].

A satellite footprint encompasses a maximum of 64 super-cells, or 576 cells. The actual number of cells for which a satellite is responsible varies with satellite orbital position and distance from adjacent satellites. In general, the satellite closest to the center of a super-cell has coverage responsibility. As a satellite passes over, it steers its antenna beams to the fixed cell locations within its footprint. This beam steering compensates for the satellite's motion as well as the Earth's rotation. An analogy is the tread of a bulldozer that remains in contact with the same point while the bulldozer passes over [Tel98c].

2.4.2 The Teledesic Satellite Constellation

Studies performed by C. J. Wang, and J. G. WALKER have shown that the successful satellite configuration can be constructed either by the star network or the delta network [Wan93, Wal77]. According to Walker, a successful satellite constellation can be constructed by the delta network if the system contains more than one satellite for the global communication needs. Since LEO type orbits have more than one satellite per orbital plane, a delta network could be a suitable constellation approach for the success of the system.

The TELEDESIC® network will consist of 288 operational satellites, as well as some in-orbit spares. The satellites will circle the Earth in twelve separate north-south orbital planes. Each plane will be having 24 satellites evenly spaced [Tel98b]. Adjacent orbital planes will be evenly spaced, except for the contra-rotating planes where the distance will be closer. There will be no Inter-Satellite Links (ISL) between the two contra-rotating satellites because the high opposing satellite velocities make it difficult to maintain communications [Woo98b].

2.5 Network Performance

The TELEDESIC® satellite system is a new project for future expectations on satellite communications. In this thesis, the performance analysis of the TELEDESIC® satellite system is analyzed. Due to the rapidly growing need for voice, data, and video transfers inside communication networks, the existence for reliable communication service is an important issue. The network must be capable of sending and receiving information reliably for all circumstances. Information delay is a disadvantage and always needs to be at smaller values for a network to furnish fast access to information for end-users.

The TELEDESIC® network uses adaptive routing algorithms to move information. Each decision in each one of the individual satellites is done in a swift way using these types of algorithms. The algorithm uses the information, which travels through each node, in order to know the current status of the network. This allows the network to select the best route through the network to minimize end-to-end delay. As a result, the traffic will increase up to a desired level and the performance of the network will also increase.

Each satellite in the constellation is a node in the fast packet switch network and has inter-satellite communication links with eight adjacent satellites. Each satellite is normally linked with four satellites within the same plane (two in front and two in the back) and with one in each of the two adjacent planes on either side. This interconnection arrangement forms a non-hierarchical mesh network and provides a robust network configuration that is tolerant to faults and local congestion.

A database contained in each satellite defines the type of service allowed within each earth-fixed cell. Channel resources (frequencies and time slots) are associated with each cell and are managed by the current satellite. As long as a terminal remains within the same earth-fixed cell, it maintains the same channel assignment for the duration of a call, regardless of how many satellites and beams are involved.

Since the topology of a LEO-based network, as well as traffic flows through the network and queue sizes, are dynamic, TELEDESIC® uses a distributed adaptive routing algorithm. This algorithm uses information, which is transmitted throughout the network by each satellite to get the current status of the network in order to select the path of least delay to a packet's destination. The algorithm also controls the connection and disconnection when intersatellite links communicate [Koh97].

The network has the advantages of both circuit-switched networks which provides delay for digital pipes, and packet-switched networks which is effective in handling burst data and multiple number of rates [Tel98c]. The space-based network will use fast-packet switching. All of the TELEDESIC® communications links transport data and voice as fixed-length packets. Each packet contains a header that includes a destination address, sequence information, and an error-control section used to verify the integrity of the header, and a payload section that carries the user data, which is digitally encoded. Since the terminals interface with a wide range of standard network protocols, including IP, ISDN, ATM and others, a protocol conversion to and from the TELEDESIC® packet format must take place in the terminals at the edge of the network [Tel98c].

The TELEDESIC® system will use Multi-Frequency Time Division Multiple Access (MF-TDMA) on the uplink and Asynchronous Time Division Multiplexing Access (ATDMA) on the downlink. These two methods will help overcome the problems of basic TDMA, namely the large antenna size required to handle the entire bandwidth and the difficulty of time slot synchronization.

Since environmental factors such as Sun noise and rain attenuation can degrade the transmitted signal, TELEDESIC® will use forward error control (FEC) to provide a bit error rate (BER) of less than 10^{-10}, making it an essentially noise-free Channel.

The latency guarantees of the large Internet Service Providers (ISP) such as AT&T and Sprint are the driving force behind TELEDESIC®'s latency requirements. These ISPs guarantees their customer latencies, from 140 ms down to 100 ms. Therefore, TELEDESIC® is aiming for an end-to-end delay as low as 20 ms and less than 75 ms on all links of distance less than 5,000 km, and a round-trip latency of less than 100 ms on most connections [Tel98d].

2.6 Summary

In this chapter, the literature review covered the essential information concerning satellite systems. In section 2.2, the Geostationary Satellites (GEO), Highly Elliptical Satellites (HEO), and Low Earth Orbit Satellites (LEO) have been briefly described along with the performance advantages and disadvantages of each type system. In Section 2.2.3, the GLOBALSTAR®, IRIDIUM®, and TELEDESIC® satellite systems were explained. Those systems use LEO type satellites. A brief comparison of the GLOBALSTAR®, IRIDIUM®, and TELEDESIC® systems were covered in Section 2.3. The TELEDESIC® Satellite System networks configuration and constellation has been described in Section 2.4. In Section 2.5, the network survivability has been explained and the summary takes place in Section 2.6. The next chapter gives us the methodology for the performance analysis of the TELEDESIC® Satellite Networks System.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter describes the methodology used to analyze the performance of the TELEDESIC® satellite system and explains the design of the simulation model developed to analyze the system. Section 3.2 mentions three different methods of analysis and recommends the best method used to analyze the TELEDESIC® satellite system. Section 3.3 explains the scope of the problem. Section 3.4 explains the assumptions used in the simulation model. The design and operation of the simulation model are explained in Section 3.5. Section 3.6 discusses the approach taken to simulate the model with high loading values for lower simulation run times. Section 3.7 presents a discussion of the verification and validation of the simulation model. Section 3.8 describes the input parameters needed to run the simulation model. Finally, performance metrics, beneficial to the analysis of the simulation model, are explained in Section 3.9.

3.2 Method of Analysis

Performance analysis of a communications network requires definite measurement approaches, such as analytical modeling of a system being analyzed, measurement of collected data for the model, and simulation of the system using presumed data values [Fos98]. Each one of these approaches has advantages to reach to an accurate estimation for the overall system design.

Analytical modeling for the TELEDESIC® system is not the best method since route selection in this research uses a complex but accurate approach to send packets from source to destination. It is not practical to use analytical modeling because it is not so easy to predict the route of a packet directed from one earth station to another one since the routing algorithm is dynamic. Therefore, we can not easily measure end-to-end packet delays in this model by analytical modeling method. Also, the size of the satellite system makes analytical modeling an impractical method since we can not measure end-to-end packet delays easily which are formed in network queues, using an analytical approach.

Measurement of collected data is a very precise approach since the data used in the analysis are the results of tested values. Since the TELEDESIC® system is not yet operational, we can not use real time values that the system uses in order to analyze the packet delay and survivability of the TELEDESIC® satellite system. So, we can easily eliminate this method for this research.

The simulation method used in this research is an appropriate approach because of the number of satellites and that the computations done to route packets from one earth station to another are dynamic. Making the simulation run faster with high loading values is one of the objectives in this research. Simulation makes it easier and faster to obtain system delay performance with both low and high loading values.

3.3 Scope of Problem

The purpose of this research is to analyze the delay performance of the TELEDESIC® satellite system with a full system configuration. The results must be accurate and the end-to-end delays must be within reasonable values. The scope of the problem is limited to call setup procedures, handoff procedures, numbers and types of users, and types of equipment failures. These limitations do not affect end-to-end delay results.

3.3.1 Call Setup Procedures

Call setup procedures increase the overall delay. Implementing the simulation model with call setup procedure increases the complexity of the model. Because of having separate channels, the end-to-end delays are not affected by the call setup procedures. Since it was assumed that the call setup procedures have different channel allocations, and that they do not affect the end-to-end delay analysis, the call setup procedures will not be modeled in this research.

3.3.2 Handoff Procedures

The satellite-to-satellite handoff of a packet coming from an earth station link increases the end-to-end-packet delay. Satellite processing delay is affected by the handoff between one satellite to another one through the link directed from one earth station to another earth station. If the handoff time from one satellite to another one is considerably long, then the satellite processing delay will increase relatively. As a result of this increment, the shortest path that the packet takes to the receiving earth station will also be affected with higher number of nodes. For this reason, satellite-to-satellite handoffs are modeled in this research.

Beam-to-beam handoffs do not have significant effects on either satellite propagation delays or the shortest paths that packets take to the destination. Beam-to-beam handoffs require more queuing, affecting the simulation run times. TELEDESIC® satellites require 288 queues for satellite-to-satellite handoffs and take shorter time to simulate the model. Beam-to-beam handoffs will not be modeled in this research since they have negligible delay characteristics compared to satellite-to-satellite handoff delays.

3.3.3 Equipment Failures

Equipment failures considerably affect end-to-end delays for the TELEDESIC® satellite system. There are 288 satellites and the number of equipment failures that will occur in time for the overall system must always be kept in mind because they have significant effects on either satellite propagation delays or on the shortest paths that packets take to the destinations.

In the event of complete failure of one satellite, a packet is directed to another satellite in the inter-satellite link coverage area. Since the inter-connectivity for the TELEDESIC® satellite system is eight, a packet can be directed to a satellite which is closest to the defective satellite, in order to keep the cost of losing one useful satellite at minimum levels. This cost directly increases the end-to-end delay of packets from a source to a destination. Complete failure of a satellite has greater impact on the delay performance of the TELEDESIC® satellite system than the equipment failure itself. If the system maintains acceptable end-to-end delays under complete failure of satellites, then the system will also be capable of handling equipment failures within reasonable delay benchmarks.

3.3.4 Number and Types of Users

The TELEDESIC® users in this study are modeled as seven stationary earth stations and no mobile users are modeled for this study. The reason is that the velocity of a mobile user in a fast vehicle like an airplane is much slower than the velocity of a LEO satellite. So, the mobile TELEDESIC® users are considered as stationary earth stations.

A mobile user, while leaving the coverage area for the next coverage area of another satellite, will cause a handoff and thus increases the end-to-end delay. Considering how faster the satellites are moving, the handoff problem will be much bigger than the individual mobile user. So, the traffic generated by the mobile users is only for the related satellite and the handoff will be smaller than the handoff problems of the satellites. In this study, the locations of the seven earth stations are selected so that they were distributed between 149 degrees east and 149 degrees west longitudes as well as between 61 degrees north and 35 degrees south latitudes. The locations of the earth stations are summarized in Table 1.

Table 1 - Earth Station Data

CITY	LONGITUDE	LATITUDE	ALTITUDE
Capetown	18.37	33.93	-0.001
Tokyo	139.75	35.75	0.009
Rio de Janeiro	-43.22	-22.90	0.009
Anchorage	-149.98	61.17	0.036
Washington D.C.	-77.00	38.89	0.008
Canberra ACT.	149.12	-35.24	-0.001
Ankara	29.30	39.40	0.091

3.4 Assumptions

The software packages SATLAB® and DESIGNER® are used to simulate the delay performance analysis of the TELEDESIC® satellite system. The actual published TELEDESIC® values are used in the simulation. However in some parts, it was necessary to make assumptions for the specific values that were not published before in books and articles related with the TELEDESIC® satellite system. The rationale for the assumptions is explained in this section, together with the effects on the simulation progress.

3.4.1 Packet Size

In the simulation, the TELEDESIC® voice packets are modeled as packet voice traffic. Data structures represent the voice traffic of the system. The multiple access methods used in the system are Time Division Multiple Access (TDMA), Space Division Multiple Access (SDMA)/Frequency Division Multiple Access (FDMA), and Asynchronous Time Division Multiple Access (ATDMA).

Between cells in a super-cell, TDMA is used. Between cells, which are scanned simultaneously in adjacent super-cells, SDMA is used. Within each cell's time slot, FDMA is used for uplink. Within each cell's time slot, ATDMA is used for downlink [Woo98a]. The voice transmission has been assumed and shown by TDMA slots. The exact frame structure is not published in open literature.

TELEDESIC® communication links transport data and voice as 512-bit fixed-length packets. The basic unit of channel capacity is the "basic channel". It supports a payload data rate of 16 Kbps and an associated "D-channel" of 2 Kbps for signaling and control functions. Ninety-seven channels can be aggregated to support an equivalent T-1 (1.544 Mbps) connection. A TELEDESIC® terminal can support multiple simultaneous network connections. In addition, the two directions of a network connection can operate at different rates [Koh97].

TELEDESIC® uses terminals with a wide variety of data rates. Standard terminals operate at basic channel payload rate of 16 Kbps up to 2.048 Mbps, which makes the combination of 128 basic channels. These terminals use antennas with different diameters determined by the terminal's maximum transmit channel rate, climatic region, and availability requirements. The burst data rate for uplink/downlink time slot is 2.048 Mbps and, the sustained data rate for uplink/downlink time slot is 16 Kbps.

Using the equation TDMA Frame Length = $\frac{NumberOfBitsPerPacket}{SustainedDataRate}$, (1)

We can calculate and assume the value of TDMA Frame Length, which is unpublished.

$$\text{TDMA Frame Length} = \frac{512 bits}{16{,}000 bps} = 32 \text{ ms.} \quad (2)$$

User uplink or downlink time slot with a burst data rate will be equal to 0.25 ms.

$$\text{User uplink/downlink time} = \frac{512 bits}{2{,}048{,}000 bps} = 0.25 \text{ ms.} \quad (3)$$

The 100 user time slots take up a total of 25 ms, which leaves 7 ms of the TDMA frame for framing bits and guard time slots. A possible frame structure is to use a framing time slot twice as long as an individual user time slot. This would result in 1024 framing bits taking up 0.5 ms. Subtracting this value from the 7 ms remaining in the TDMA frame leaves 2 ms for guard time slots. This can be divided into 100, 16 μs guard time slots between time slots in the frame and 25, 16 μs guard time slots at each end of the frame.

Although the exact frame structure is not published in open literature, this approach is rational. It uses 6.35% of the 32 ms frame for guard time, and utilizes 78.125% of the frame for the actual data bits.

3.4.2 Packet Arrival Rate

Voice communications can be modeled with M/M/1 queue structures. The voice packets were assumed to be arriving in a Poisson manner. Each satellite has a maximum capacity of supporting 100,000 16-Kbps channels for the system [Woo98a]. Because of the full-duplex nature of the channels, it was assumed that each satellite has a maximum of 50,000 simultaneous users. Each user's uplink time slot frame for transmission is 32 ms. Assuming each voice packet is one uplink time slot, the maximum packet arrival rate will be equal to 1,562,500 packets-per-second.

$$\frac{50{,}000\,packets}{32ms} = 1{,}562{,}500 \text{ packets-per-second} \quad (4)$$

So, the minimum time required to transmit one packet will be 0.64 μsec.

3.4.3 Loading Levels

The simulation model was executed at different loading levels and earth station arrival rates were different for each simulation with different loading levels. Each earth station has a percent utilization of the satellite uplink that is represented by the simulation loading level. In this research, the uplink utilization values are 50%, 83%, and 100% respectively. The uplink utilization, earth station arrival rate, network arrival rate, and processor utilization values are as shown in Table 2.

Table 2 – Earth Station Loading Level Values

Uplink Utilization	**Earth Station Arrival Rate(packets-per-second)**	**Network Arrival Rate (packets-per-second)**	**Processor Utilization**
50 %	781,250	5,468,750	30 %
83 %	1,296,875	9,078,125	50 %
100 %	1,562,500	10,937,500	60 %

Since there are seven earth stations, the network arrival rate for uplink utilization will be equal to seven times the earth station arrival rate value for every uplink. The processor utilization is calculated using the equation $\rho = \frac{\lambda}{\mu}$, where ρ represents the utilization, λ is the earth station packet arrival rate, and μ is the packet service rate. The mean packet processing delay is the inverse of the packet service rate and is assumed to be 0.384 μsec. Using pilot tests, different packet service rates have shown that the maximum uplink traffic was not more than 60 % of the processor utilization. Assuming ρ equals to 0.6, the service rate will be equal to λ/μ, where λ is 1,562,500 packets-per-second. The service rate is calculated to be 2,604,167 packets-per-second. The inverse of the service rate will give us the mean satellite process delay, which is 0.384 μsec.

3.4.4 Satellite Processing Delay

Voice communications can be modeled with M/M/1 queue structures. Since each voice packet has the same size, it is expected that the service time for each packet to be approximately equal to each other. Since each voice packet is assumed to have the equal packet size, the use of Gaussian random variable will assure that each packet will have similar delays for the satellite processing delay time. The mean used for the Gaussian random variable is 0.384 μsec. The calculation used to find this value is explained in Section 3.4.3.

3.4.5 Traffic Distribution

There are two traffic distributions that are used in the simulation. First, the simulation was run with uniform traffic distribution, where there is an equal probability of experiencing each possible outcome. In this case, the source and the destination of each generated packet were in random process with equal probabilities for all of the seven earth stations.

So, the transmit probability for each earth station equals one divided by the total number of earth stations, which equals to 0.143. Since each earth station can send packets to other earth stations except itself, the destination probability for each earth station will be equal to $\frac{1}{6}$, which is 0.167. The uniform traffic distribution is shown in Table 3.

Table 3 – Uniform Traffic Distribution

Location	**Transmit Probability**	**Destination Probability for Each Earth Station**						
		Capetown	Tokyo	Rio	Anchorage	Washington	Canberra	Ankara
Capetown	0.143	0	0.167	0.167	0.167	0.167	0.167	0.167
Tokyo	0.143	0.167	0	0.167	0.167	0.167	0.167	0.167
Rio	0.143	0.167	0.167	0	0.167	0.167	0.167	0.167
Anchorage	0.143	0.167	0.167	0.167	0	0.167	0.167	0.167
Washington	0.143	0.167	0.167	0.167	0.167	0	0.167	0.167
Canberra	0.143	0.167	0.167	0.167	0.167	0.167	0	0.167
Ankara	0.143	0.167	0.167	0.167	0.167	0.167	0.167	0

A uniform traffic distribution is not the only representation for a real communications network system. In a real communications system, we should expect to see non-uniform traffic distributions, as well. For this reason, the simulation was also run with both low and medium overall network loads for the non-uniform traffic distribution. The reason for this approach is to simulate a high traffic load between two locations in the world, using non-uniform distributions.

Since the TELEDESIC® satellite system is not operational yet, we can not represent the real traffic distribution values. Only the assumed values for uniform and non-uniform traffic distributions will give us a chance to compare them in order to see their effect on a communications network.

As mentioned above, the purpose of using a non-uniform traffic distribution is to simulate a high traffic load between two locations in the world. It was assumed that these two desired locations transmit more often than the other earth stations and that they are more likely to transmit with each other than to the other earth stations in the world. As a result, their individual transmit probabilities will be greater than the probabilities of the other earth stations. Except for these two desired locations, the other earth stations will have destination probabilities of $\frac{1}{6}$, which is 0.167 transmitting to each other earth station. Since the desired earth stations transmit with each other more often than the other earth stations, their individual destination probabilities to each other will be 0.667. The other earth stations will have destination probabilities of (1-0.667) / 5, which is 0.067. The two high-traffic locations were selected to be Washington D.C. and Ankara. The non-uniform traffic distribution is as shown in Table 4.

The simulation was run with a network arrival rate of 5,468,750 packets-per-second, which is the rate for the 50% uplink loading level. Having a different transmit probability, the uplink utilization, earth station arrival rate, and the processor utilization values will be different than the 50% uplink loading level values. For a transmit probability of 0.25, the uplink utilization will be:

$$\frac{5{,}468{,}750\, packets\_per\_second X\, 0.25}{1{,}562{,}500\, packets\_per\_second} \text{X } 100 = 87.5\ \% \qquad (5)$$

The earth station arrival rate will be:

$$1{,}562{,}500\,packets\_per\_second\,X\,0.875 = 1{,}367{,}187 \textit{ packets-per-second.}$$

And the processor utilization will be:

$$\frac{1{,}367{,}187\,packets\_per\_second}{2{,}604{,}167\,packets\_per\_second}\,X\,100 = 52.5\% \qquad (6)$$

For a transmit probability of 0.10, the uplink utilization will be 35%, the earth station arrival rate will be 546,875 *packets-per-second,* and the processor utilization will be 21%.

Table 4 - Non-Uniform Traffic Distribution 50 % Load

Location	**Transmit Probability**	**Destination Probability for Each Earth Station**						
		Capetown	Tokyo	Rio	Anchorage	Washington	Canberra	Ankara
Capetown	0.100	0	0.167	0.167	0.167	0.167	0.167	0.167
Tokyo	0.100	0.167	0	0.167	0.167	0.167	0.167	0.167
Rio	0.100	0.167	0.167	0	0.167	0.167	0.167	0.167
Anchorage	0.100	0.167	0.167	0.167	0	0.167	0.167	0.167
Washington	0.250	0.067	0.067	0.067	0.067	0	0.067	0.667
Canberra	0.100	0.167	0.167	0.167	0.167	0.167	0	0.167
Ankara	0.250	0.067	0.067	0.067	0.067	0.667	0.067	0

Finally, the simulation was run with a network arrival rate of 9,078,125 packets-per-second. This is the assumed medium overall network load for the simulation with uplink loading percentage of 83%. Transmit probabilities for Washington D.C. and Ankara were assumed to be 0.161 and the other earth stations will have the transmit probabilities of (1– 0.161) / 5, which is 0.136. So, the uplink utilization, earth station arrival rate, and the processor utilization values will be different for the medium overall network loading. The non-uniform traffic distribution is as shown in Table 5.

For the transmit probability 0.161, the uplink utilization will be:

$$\frac{9{,}078{,}125 \, packets\_per\_second X 0.161}{1{,}562{,}500 \, packets\_per\_second} \text{X } 100 \approx 94 \% \tag{7}$$

The earth station arrival rate will be:

$$1{,}562{,}500 \, packets\_per\_second X 0.94 = 1{,}468{,}750 \, packets\text{-}per\text{-}second.$$

And the processor utilization will be:

$$\frac{1{,}468{,}750 \, packets\_per\_second}{2{,}604{,}167 \, packets\_per\_second} \text{X } 100 \approx 56 \% \tag{8}$$

Table 5 - Non-Uniform Traffic Distribution 83 % Load

Location	**Transmit Probability**	**Destination Probability for Each Earth Station**						
		Capetown	Tokyo	Rio	Anchorage	Washington	Canberra	Ankara
Capetown	0.136	0	0.167	0.167	0.167	0.167	0.167	0.167
Tokyo	0.136	0.167	0	0.167	0.167	0.167	0.167	0.167
Rio	0.136	0.167	0.167	0	0.167	0.167	0.167	0.167
Anchorage	0.136	0.167	0.167	0.167	0	0.167	0.167	0.167
Washington	0.161	0.067	0.067	0.067	0.067	0	0.067	0.667
Canberra	0.136	0.167	0.167	0.167	0.167	0.167	0	0.167
Ankara	0.161	0.067	0.067	0.067	0.067	0.667	0.067	0

3.4.6 Routing Algorithm

Routing algorithms can be classified as non-adaptive and adaptive. If a network is stable in its topology and if traffic flows a non-adaptive algorithm, then in this case all routes are computed initially and never change. This relieves the nodes from having to monitor changes and compute new routes. Alternately, adaptive algorithms attempt to make routing decisions based on current traffic and topology. These algorithms can be divided into three sub-classes as centralized routing, isolated routing, and distributed routing.

The simulation uses the Dijkstra routing algorithm. The shortest path from a source to all the destinations is calculated by the connectivity of each satellite to one another. The shortest path to the destination is calculated each time when the connectivity between the source and the destination gets a different value. The connectivity change depends on either the movement of the satellites in the constellation or the removal of some of the satellites from the constellation. The actual routing algorithm used in TELEDESIC® is not published. The actual algorithm should balance the load for the satellites that have heavy network load shared, by routing that network load to the other satellites around them. The overhead which result from updating the satellite routing tables should be kept in mind for the actual satellite system. The Dijkstra algorithm used in this simulation does not contain the overhead caused by updating routing tables. This is an error. But it makes the design of the simulation simple. For the overall simulation, making the design simple has more gains than the overhead caused by updating the satellite routing tables.

3.4.7 Packet Delays

The delay components associated with the end-to-end delay for a packet are the access time delays, the processing and queue time delays, and the propagation delays. Access time delay results from the multiple access method used for a packet received by all the other earth stations. The processing and queue time delays result from the fact that a packet will have delays at every node it encounters. The propagation delays are related to the uplink, crosslink, and downlink packet transmissions. As a result, the end-to-end packet delay will be equal to the combinations of these individual delay components.

The equation used to calculate the end-to-end packet delay for a packet is as follows:

$$T_{Packet} = T_{access} + T_{uplink} + (N-1)\cdot T_{cross} + N \cdot T_{sat} + T_{downlink} \qquad (8)$$

In this equation, N is the total number of nodes a packet encounters in the path. The effects of perturbations such as the gravitational effect of earth, atmospheric drag due to the friction caused by collision with atoms and ions, and the Doppler shift effect are ignored for the end-to-end packet delay calculation. Since it was assumed that TELEDESIC® voice and data packets use TDMA access method, the access delay time is assumed to be a TDMA access delay. The *TDMA* access delay used in this research is 16.25 ms. TELEDESIC® voice and data packets are assumed to have sustained data rates of 16,000 bps and burst data rates of 2,048,000 bps. The number of bits per packet is equal to the product of sustained data rate and TDMA frame length. It is published that TELEDESIC® voice and data packets have 512 bits per packet. So, the TDMA frame length will be equal to:

$$TDMA\ frame\ length = \frac{512 bits}{16{,}000 bps} = 32 \text{ ms.} \qquad (9)$$

Denoting *Tf* as the TDMA frame length and *Tslot* as the TDMA slot time, the TDMA access delay time (T_{TDMA}) can be calculated using the formula below.

$$T_{TDMA} = \frac{Tf}{2} + Tslot \qquad (10)$$

$$Tslot = \frac{512bits}{2{,}048{,}000bps} = 0.25\ ms. \quad (11)$$

Then, TDMA access delay will be equal to:

$$T_{TDMA} = \frac{32ms}{2} + 0.25ms = 16.25\text{ ms.} \quad (12)$$

The altitude of a TELEDESIC® satellite is published to be 700 km above the surface of the Earth [Koh96]. Since, we know the altitude of the satellites, the propagation delay can be found using the formula below.

$$Propagation\ Delay = \frac{Distance\ to\ Satellite}{Speed\ of\ Light} \quad (13)$$

Propagation delay will then be equal to $\frac{700km}{3x10^8 m/\sec} \approx 2.33$ ms.

Uplink and downlink time delays, *Tuplink* and *Tdownlink* respectively, can be within altitude of 700 km which is the altitude of satellites above the surface of the Earth when the satellite is directly overhead, and 2346.65 km which is the maximum propagation distance. The maximum propagation distance can be calculated using the formula below [Fos98].

$$Propagation\ Distance = (R_e + \text{h})\sqrt{1 + \frac{R_e}{R_e + h} - 2\frac{R_e}{R_e + h}Cos(\theta)} \quad (14)$$

In this formula, R_e is the radius of Earth, which is assumed to be 6,378 km., and h is the altitude of satellites above the surface of the Earth, which is 700 km. Angle θ is the earth central angle and can be calculated using the formula below where E is the minimum elevation angle [Fos98].

$$\theta = \left[\cos^{-1}\left(\frac{R_e \cos E}{R_e + h}\right)\right] - E \qquad (15)$$

Minimum elevation angle for the TELEDESIC® satellite system is published to be 40° degrees. Using the equation above, earth central angle will be equal to 6.34° degrees. And the maximum propagation distance, which was shown by the formula above, will be 2346.65 km. Crosslink time delay ($Tcross$) is the propagation delay a packet will have when it travels from one node to another, while going from source to destination. The crosslink time delay for every earth station is calculated using the number of nodes for the packet and using the average distances a packet will have to travel from one node to another on its way to its destination point. The average distance that the packet had is assumed to be the average crosslink distance. So, using the formula below, the crosslink time delay for each earth station is calculated. The delay equation verified that both the computed delay values and the simulated values were consistent with each other.

3.4.8 ISL Connectivity

The connectivity for each TELEDESIC® satellite can be established by having up to eight inter-satellite links (ISL) with adjacent satellites. Each satellite can receive and send packets to and from the two forward and aft satellites in the same orbital plane. A satellite can also receive and send packet to and from a satellite in the adjacent orbital planes. One improvement made for the satellite connectivity between satellites is that a satellite can see another one, which it is two orbital planes away from itself. The connectivity between the satellite and the other satellite in the adjacent two orbits located on the left and right of the satellite can be established if the horizontal pointing angle between these satellites is within the steering range of the satellite antenna. Satellites can establish connectivity when the horizontal pointing angle is assumed to be smaller than 50 degrees with a steering range of 32.5 degrees with respect to zero degrees parallel to the equator. It is shown in Figure 1 [Woo98b].

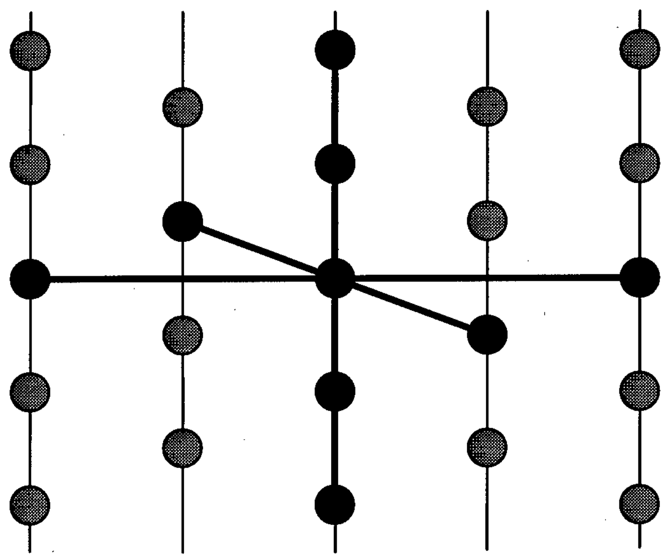


Figure 1: ISL Connectivity for the TELEDESIC® Satellite System

3.4.9 Queue Capacity

The maximum capacity that a network queue can hold is calculated using the formula below [Fos98].

$$T_{Max} = T_{access} + T_{uplink} + (N-1)\cdot T_{cross} + N\cdot T_{sat} + T_{downlink} + N\cdot(Q-1)\cdot T_{sat} \qquad (16)$$

Here T_{Max} is the maximum amount of time acceptable for communication in this model and it was assumed to be 400 ms. If the maximum amount of end-to-end delay exceeds 400 ms, then the packets will be rejected because of the limited queue size.

According to the equation 16 above, the maximum queue capacity that a network queue can hold for one satellite is calculated to be 70,000 packets. *N* is the total number of nodes a packet encounters in the path. From pilot studies operating at a low loading value, it was seen that the total number of nodes a packet encounters in the path does not exceed 14. The *TDMA access delay* used in this research is calculated and assumed to be 16.25 ms. *Crosslink time delay* is the propagation delay a packet encounters when it travels from one node to another while going from source to destination.

The crosslink time delay for every earth station is calculated and explained in Section 3.4.6, using the number of nodes for the packet and using the average distances a packet will have from one node to another on its way to its destination point. The minimum distance for an uplink or downlink is the satellite altitude of 700 km. This is the altitude of satellites above the surface of the Earth when the satellite is directly overhead. The maximum distance for an uplink or downlink is 2346.65 km. Maximum end-to-end delay for different queue sizes is shown in Figure 2.

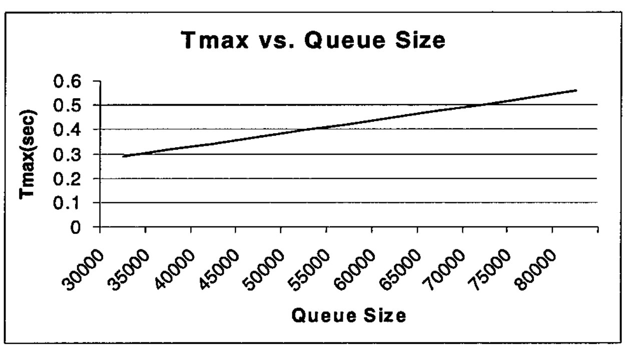


Figure 2: Maximum End-to-End Delay for Different Queue Sizes

It was verified that for queue sizes having the capacity of more than 70,000 packets, the end-to-end delay exceeds 400 ms. Figure 2 above shows that the maximum end-to-end delay is over 0.5 seconds for a queue size of 70,000 packets.

3.4.10 Network Access

The earth stations defined in the simulation have the ability to see a satellite with a minimum elevation angle of 40°. The earth central angle, which is the angle between nadir and earth station, will be equal to 6.34° degrees. The elevation angle and the earth central angle are as shown in Figure 3.

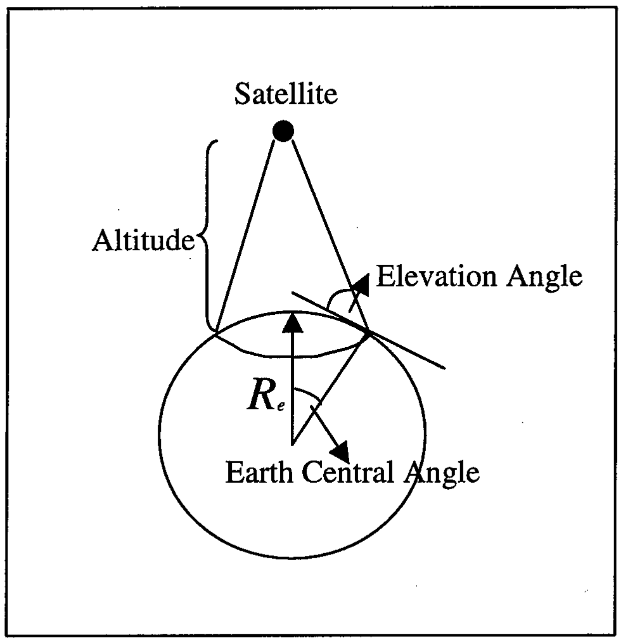


Figure 3: Earth Central Angle and Minimum elevation Angle

The terrain that surrounds an earth station has effect on a satellite's network access. In this research, the effect of the terrain surrounding an earth station was not modeled. The maximum traffic load generated by an earth station will not exceed the uplink capacity that a satellite has for the network access.

3.5 Simulation Model

SATLAB® and DESIGNER® are the two simulation packages used in this research. SATLAB® sends the essential satellite orbital parameters to the DESIGNER®

simulation package. DESIGNER® models and analyzes the simulation model according to the values obtained from SATLAB® over fixed intervals of time.

Each satellite's position over a specified period of time is calculated using the orbital parameters of each satellite that were defined in the SATLAB® simulation packet. The position information calculated for each satellite is then stored in three matrices. These matrices are the visibility matrix, the elevation matrix, and the distance matrix. DESIGNER® uses the matrices in analyzing the model. At specified time periods, DESIGNER® receives the current visibility, elevation, and distance matrices from SATLAB®. The Bones-SATLAB® Interface Module (BSIM) provides the communication connection between DESIGNER® and SATLAB® simulation packets.

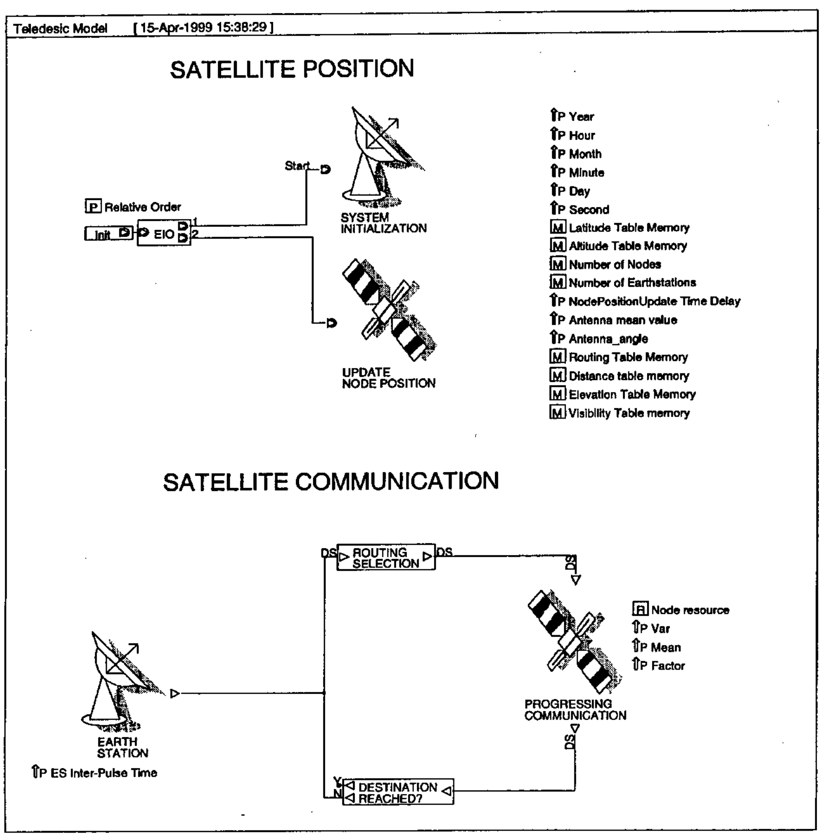


Figure 4: The Simulation Highest Level Representation

The matrix information received from SATLAB® is essential since the values in these three matrices are the snapshot information of each and every satellite of the TELEDESIC® satellite system. DESIGNER® calculates the shortest path and delay based on the information it receives from SATLAB®. The matrices are updated in specified time intervals so that DESIGNER® uses the dynamic satellite position matrices to model the dynamic manner of the TELEDESIC® satellite system. The highest level representation of the simulation is as shown in Figure 4 above. In Figure 4, two main modules are shown, the *Satellite Position* module and the *Satellite Communication* module. The *Satellite Position* module is the interface module with SATLAB®. It keeps track of the routing table values. The values inside the routing table are periodically updated so that the simulation runs in a dynamic TELEDESIC® system environment.

The *Satellite Communication* module generates packets, routes the packets to their destination locations by calculating the shortest path from each source to destination, and collect information for analyzing the delay performance of the simulation model. The main data generated for each packet is end-to-end packet delay. Earth-to-satellite, satellite-to-satellite, and satellite-to-earth links in this module generates end-to-end packet delays from the source to the destination. The path that a packet encounters, while being transmitted from one earth station to another one, can also be traced. The *Satellite Position* module consists of two blocks. The *System Initialization* block acquires the number of earth stations from the SATLAB® simulation tool and initializes SATLAB® to the simulation epoch. The *Update Node Position* block uses the visibility, elevation, and distance matrices to update node positions periodically from the SATLAB® simulation tool. The *Node Position Update Time Delay* parameter is used to update the matrices periodically from SATLAB®. Each time the parameter is used to update the matrices, the routing table is recalculated based on the new values for each satellite position. The values in these matrices are used to find the shortest path that a packet takes. The shortest path is calculated in the *Satellite Communication* module.

The *Satellite Communication* module consists of four blocks. The *Earth Station* block generates packets with a Poisson arrival rate. Each packet is represented as a data structure and the contents of this data structure is as shown in Table 6.

Table 6: The Data Structure for Packets Generated

Field Name	**Type**	**Description**
Sequence Number	Integer	Sequentially number packets
Source	Integer	Node sending packet
Destination	Integer	Destination of packet
Current Node	Integer	Current location of packet
Next Node	Integer	Next node in path to destination
TNOW	Real	Simulation run time
Delay	Real	Cumulative end to end delay
Hop Count	Integer	Cumulative number of nodes in path

The Sequence Number labels each generated packet with a sequence number. The Source, Destination, Current Node, and Next Node fields are used to route a packet from the source to the destination. These fields are also used to check to see if the packet reaches to its destination. If the packet is not at its destination, then the Current Node and the Next Node fields are used each time until the Next Node field becomes equal to the Destination field. In order to find the path that a packet follows, the Current Node and Next Node fields are used together with the Hop Count field to determine the path. The TNOW field in the data structure represents the elapsed time since epoch. The Delay field measures the end-to-end packet delay as packet moves along the network. Finally, the Hop Count field counts the number of nodes a packet encounters as it moves from source to destination. Each time a new node is encountered, the Hop Count field is incremented by one.

The next block that the packet is directed to is the *Routing Selection* block. In this block, the Current Node and Destination fields are read. The next node in the path is read from the routing table. Once the next node is read from the routing table, the *Routing Selection* block updates the Next Node field and increments the Hop Count field. The next block is the *Progressing Communication* block. In this block, there are three different links, one of which the packet is directed. They are earth-to-satellite, satellite-to-satellite, or satellite-to-earth links. The main data generated for each packet is the end-to-end packet delay. The delay is calculated in a different block for each link. The delay components for a satellite-to-satellite link, or a satellite-to-earth link are propagation delay, the satellite processing delay, and the queuing delay. The delay components for an earth-to-satellite link are earth station processing delay, TDMA access delay, and propagation delay. Once the delay is calculated in a different block, the *Progressing Communication* block updates the Delay field in the database for the packet. The *Destination Reached* block is the next block to which the packet will arrive. In this block, the Next Node and Destination fields are compared to see whether the packet has reached to its destination. If they are equal, then the packet has arrived to its destination. If they are not the same, then the Next Node field will be the Current Node field and the packet will be directed to the *Routing Selection* block and it will follow the blocks respectively until Destination and Current Node fields are equal to each other.

3.6 Scaling

One of the goals of this research is to evaluate the TELEDESIC® satellite system at high loading levels. The scaling method used in this research follows the same method used by Maj Fossa for the analysis of the IRIDIUM® satellite system. Using the scaling method, the TELEDESIC® satellite system can run in considerably short simulation run times and the actual traffic load that the TELEDESIC® satellite system has can be modeled with high loading values for accurate end-to-end packet delays.

The node-position-update-time-delay parameter is used while the simulation passes data from SATLAB® to DESIGNER®. So, the first factor is to check to see the effect of the node-position-update-time-delay parameter on the simulation run time. The simulation was performed with a low loading level and different node-position-update-time-delay values between one second to 150 seconds. It was clearly seen that the simulation with node-position-update-time-delay values greater than 60 seconds ran at approximately the same speed. The node-position-update-time-delay significantly affected the simulation run-time. The simulation was then executed with different loading levels and a fixed node-position-update-time-delay value of 90 seconds. Each time the network traffic was increased, it was easily seen that the simulation run time was increasing also significantly higher than the previous loading levels. Since the simulation models the TELEDESIC® satellite system with three different loading values, low, medium, and high, it was the best approach to scale the simulation. The reason for scaling was to obtain accurate end-to-end packet delays in short simulation run times with higher traffic loads. It was always kept in mind that the scaling should have never changed the end-to-end packet delays.

The traffic load is obtained by dividing the arrival rate λ by a factor F. When the packet arrival rate is scaled by a factor F, the inverse of the packet arrival rate, which is the packet inter-arrival time, will be multiplied by the scaling factor F. The main output data generated for each packet is the end-to-end packet delay. The contributors to the end-to-end packet delay are processing delay, propagation delay, and queuing delay. The processing delay is the inverse of the service rate μ. It is easy to factor the processing delay by the factor *F* since it is an input parameter for the simulation. The propagation delay is calculated for each of the three different links and is multiplied by the scaling factor *F* in the block where it is calculated. The queuing delay, which is calculated in each node by the simulation, is a contributor to the average service time T_{av}. The average service time can be calculated using the equation below.

$$T_{av} = \frac{1}{\mu - \lambda} \tag{17}$$

The average queuing delay is the difference between the T_{av} and the average processing delay, which is shown in the equation below [Fos98].

$$W = \frac{1}{\mu - \lambda} - \frac{1}{\mu} \tag{18}$$

Since the packet arrival rate and the service rate are scaled by the factor as described above, the average queuing delay will be multiplied by the factor *F*. The cumulative end-to-end delay for a packet will be the actual delay. Since the end-to-end packet delay is multiplied by a scaling factor *F*, the cumulative end-to-end delay for a packet will also be multiplied by the scaling factor *F*. Dividing the cumulative end-to-end delay by the scaling factor *F* again, it will be the real-time delay value for the simulation model.

To determine the effect of scaling on the simulation, the simulation was run both with a scaling factor of 10,000 and non-scaled. The reason to run the simulation at two different ways was to compare the end-to-end packet delays so that it can be easy to see that the scaling does not affect the output of the simulation. First, the simulation was run having earth stations with a node-position-update-time-delay value of 60 seconds. The simulation run time took nearly four hours to simulate 37 minutes of real time. The average end-to-end delay for all the packets in the scaled simulation was 83.438 ms. For the non-scaled simulation, the average end-to-end delay for all the packets was 83.439 ms. Then, the simulation was run with different scaling factors. With the scaling factor of 100,000, it was seen that the average end-to-end delay for all the packets was 83.438 ms. In order to decrease the simulation run time, the simulation was run with a scaling factor of 100,000. After scaling by a factor of 1,000,000, it was seen that the end-to-end packet delays were not as accurate as the previous delay values with different the scaling factors.

3.7 Verification and Validation

In all phases of the simulation, the model was tested to see that the overall simulation model was working with accurate values. The simulation model contained several tests, and all of these tests were important in order for the simulation to model the TELEDESIC® network accurately. The verification part contained tests to verify that the model was designed to work the way it should. The validation part contained tests to prove that the output of the simulation was accurate with the computed and expected outcomes of the model designed for the TELEDESIC® satellite system.

3.7.1 Verification of the Model

The model used in this research follows the same structure constructed by Maj. Fossa in his research area for the IRIDIUM® satellite system. However, having a different constellation and different parameters unique to the TELEDESIC® satellite system, changes to portions of Fossa's simulation model were in order to model the TELEDESIC® constellation in accordance with both the published and assumed data inputs. The actual published TELEDESIC® values were used in the simulation. However in some cases, it was necessary to make assumptions for the specific values that were not published before in books and articles related with the TELEDESIC® satellite system.

DESIGNER® simulation tool has a nice property for the verification of the simulations. Before saving the block constructed by the user, it verifies that the block components do not have dependency problems and that the connections from input ports all the way to the output ports are completed and the values are assigned correct variable types inside the blocks. So, each time a block was saved, it was verified that the complete model inside the block was functioning correctly.

The path a packet takes from source to destination is examined. At the beginning, the simulation model followed an IRIDIUM®-like pattern in order to send packets from the source to the destinations. The path was examined and it was seen that the inter-connectivity was four. So, the source code used in *Cost Matrix* block inside the *Satellite Position* module needed to be changed. The inter-connectivity between satellites was fashioned to be eight so that the simulation model was following a TELEDESIC®-like pattern in order to send packets from the source to the destinations. The path was reexamined. The tests made to analyze the path showed that the logic of the source code was sound and that the *Progressing Communication* block was receiving the correct data from the *Routing Selection* block. It was verified that the packets were going to destination earth stations with accurate path and with minimum cost.

The packet arrival rate was tested. The test of packet arrival rate showed that the generated packets were accurate in accordance with the calculations made to verify that. This test verified that the traffic generator was generating packets correctly and that the *Route Selection* block was receiving the generated packets correctly. The average end-to-end delay was examined and it was seen that the delay was greater as the loading level was higher. The packets received at each earth station were examined. The traffic distribution test revealed that for non-uniform traffic distribution, the selected earth stations generated and transmitted more packets with each other than with other earth stations. So, it was verified that the logic was correct and that the transmitted and received packets at each earth station for each traffic distribution were correctly transmitted.

3.7.2 Validation of the Model

For the validation of the TELEDESIC® simulation model, the end-to-end delays that each packet generated in the simulation were compared with the computed delay expectations by the general delay formula which was explained in Section 3.4.6. The simulation was run for one packet generated between earth stations and the high loading was used for the traffic loading. The end-to-end delay from Washington D.C. to other earth station was measured and the delays were calculated by hand to see that they were matching. It proved that both the simulated and computed delay values were almost equal to each other. The simulated and calculated delay values for each earth station from Washington D.C. are as shown in Table 7.

The simulation uses the actual calculated distances to calculate the end-to-end packet delays. Since the information provided for the TELEDESIC® satellite system is limited, it is impossible to compare the simulation results with the real-time delay expectancies. However, the end-to-end delay was compared to the real-time communication requirement of 400 ms. The path was also examined. Testing of the code written for the inter-connectivity of eight satellites proved that packets were directed to the correct satellite node based on the inter-connectivity pattern designed for the TELEDESIC® satellite system.

Table 7: The Simulated and Calculated Delay Comparison

Earth Stations	The Simulated End-to-End Delays	The Calculated End-to-End Delays
Capetown	between 0.1155-0.125-sec.	0.119965-sec.
Tokyo	between 0.0705-0.075-sec.	0.07409-sec.
Rio de Janeiro	between 0.0525-0.058-sec.	0.05702-sec.
Anchorage	between 0.045-0.061-sec.	0.05969-sec.
Canberra	between 0.105-0.112-sec.	0.10933-sec.
Ankara	between 0.085-0.095-sec.	0.093743-sec.

3.8 Input Parameters

The input parameters in this research are used to simulate different cases. The parameters were explained in the previous sections in this chapter. Here, the ranges of these parameters are defined.

3.8.1 Loading Level

The simulation was run at different loading levels and earth station arrival rates were different for each simulation with different loading levels. Each earth station has a percent utilization of the satellite uplink that was represented by the simulation loading level. In this research, the uplink utilization values are 50%, 83%, and 100% respectively.

3.8.2 Traffic Distribution

There are two traffic distributions that are used in the simulation. First, simulations were performed with low, medium, and high overall network loads using a uniform traffic distribution, where there is an equal probability of experiencing each possible outcome. Second, simulations were performed with both low and medium overall network loads using non-uniform traffic distribution.

3.9 Performance Metrics

3.9.1 End-to-End Delay

The end-to-end packet delay is the average packet delay transmissions from Washington D.C. to other earth stations. The benchmark for maximum end-to-end packet delay is 400 ms. This benchmark value is the real-time voice communication requirement. A delay value which is higher than this amount represents an undesirable operation.

3.9.2 Packet Rejection Rate

The packet rejection rate is the ratio of rejected packets to transmitted packets. Rejected packets are those packets that are not allowed to reach the receiving earth station because of overflow of the queues in the network model. The benchmark for packet rejection rate is 1%, and a rejection value, which is higher than this amount will represent an undesirable performance.

3.10 Summary

In this chapter, the methodology was defined and explained with the limitations and the assumed simulation input parameters. These input parameters were explained in the previous sections and together with the published TELEDESIC® satellite system parameters, they form the skeleton of this research to analyze the delay performance of the TELEDESIC® satellite system. The scaling method uses the same approach Maj Fossa used for his research on the IRIDIUM® satellite system. The source code for route selection was developed. The correct operation of the simulation model was verified and validated by changing the input parameters and comparing the simulated results with the computed results. The simulation model uses a source code, which calculates the shortest path by looking at two satellites in the closest two orbits and two satellites in the same orbit, making the inter-connectivity eight for the TELEDESIC® satellite system.

CHAPTER 4

ANALYSIS

4.1 Introduction

In this chapter, the simulation results are analyzed. The statistical accuracy of the simulation is explained in Section 4.2. The analysis of end-to-end delay and packet rejection rate is conducted using five different test scenarios. These different test scenarios are explained and presented in Sections 4.3 through 4.5. The mean end-to-end packet delay and the packet rejection rate are the two main measurements analyzed for real-time communication of the TELEDESIC® satellite system. Section 4.3 explains the five different test scenarios that are used in the simulation. In Section 4.4, the analysis of the end-to-end delay and packet rejection for all test scenarios is explained. Section 4.5 presents the analysis for each test scenario. Ultimately, the summary of the analysis of the TELEDESIC® satellite system is explained in Section 4.6.

4.2 Statistical Accuracy

The simulation was executed with two different global seed values. The reason for using two different global seed values was to get accurate delay results which are independent from the Poisson traffic arrival rate values. These global seeds were used for the input parameters in the simulations for three different loading levels with both uniform and non-uniform traffic patterns. So, the end-to-end packet delays from Washington D.C. to other earth stations contained three sample mean delays. The confidence intervals of the end-to-end packet delays were calculated using the *student's t-distribution*, which is shown in the equation below:

$$100(1-\alpha)\% CI = \bar{x} \pm t\,[1-\alpha; n-1]\, s/\sqrt{n} \qquad (19)$$

The sample mean is donated by $\bar{x}$, and s is the standard deviation of the sample means. The number of sample means is shown by n, and t is the *student's t-distribution.* The confidence intervals used are 95% and 90%. A 95% confidence interval shows that the variance in end-to-end delay is within a range that is orders of magnitude less than the mean end-to-end delay value. As the packet is directed to another satellite in the path, the path changes dynamically. As a result of changes in the path, the propagation distance also changes. So, because of the variance resulted from this change, the confidence interval of 95% was selected to measure the interval where the data was statistically accurate. The 95% confidence interval for the end-to-end delay from Washington D.C. to other earth stations with a uniform traffic distribution and low loading level is shown in Table 8. The confidence intervals for all the earth stations are less than ± 0.96-ms. This interval is actually very small.

Table 8: 95% CI for Uniform-Low-Load Full Satellite Constellation

Destination	Average Mean	Standard Deviation	95% Confidence Interval	
			Minimum	Maximum
Capetown	0.1211546	0.00016466	0.1206536	0.1216557
Tokyo	0.0739923	0.00002703	0.0739101	0.0740746
Rio	0.0537057	0.00003354	0.0536037	0.0538078
Anchorage	0.0554382	0.00031661	0.0544749	0.0564015
Canberra	0.1107995	0.00000363	0.1107885	0.1108106
Ankara	0.0911825	0.00000285	0.0911738	0.0911911

4.3 Delay Test Scenarios

The loading levels used for the simulation of the TELEDESIC® satellite system are low, medium and high loading levels. Each of the three different loading levels was used to simulate both uniform and non-uniform traffic distributions. So, the delay test scenarios contain five different test scenarios for the real-time communication simulation analysis of the TELEDESIC® satellite system. The low, medium, and high loading levels were explained in Section 3.9.1. The uniform and non-uniform traffic distributions were described in Section 3.9.3. The delay test scenarios were executed with a full satellite constellation. The simulation results have shown that none of the delay test scenarios exceed the 400 ms real-time communication requirement criteria.

4.3.1 Uniform Distribution Low Load

Each earth station has a percent utilization of the satellite uplink that was represented by the simulation loading level. In this research, the uplink utilization value for the uniform distribution with a low loading rate is 50% for each earth station. The seven earth stations generate packages with a network arrival rate of 5,468,750 packets-per-second. Every earth station generates 781,250 packages-per-second. The end-to-end packet delays are expected to be smaller than the medium and high loading levels for the model with both the full constellation and removed satellites because of a lesser amount of queuing delays. The loading levels are described in Section 3.4.3.

4.3.2 Uniform Distribution Medium Load

The medium loading level of the uniform distribution has earth stations that generate more packets than the low loading level. Every earth station generates 1,296,875 packages-per-second, with network arrival rates of 9,078,125 packets-per-second. Because of more packets generated into the system, it is expected that more queuing delays will be encountered. As a result, the end-to-end packet delay results should be greater for the medium loading level than the packet delays that will be received in low loading level. The uplink utilization for the medium loading level is 83% for each of the seven earth stations as presented in Section 3.4.3.

4.3.3 Uniform Distribution High Load

Every earth station generates 1,562,500 packets-per-second, with network arrival rates of 10,937,500 packets-per-second. Because more packets are generated into the system than the low and medium loading level simulations, it is expected that the queuing delays will be also higher in this type of loading than the low and medium loading types. Therefore, the end-to-end packet delay results should be greater for the high loading level than the packet delays that will be received in low and medium loading levels. The uplink utilization for the high loading level is 100% for each of the seven earth stations as presented in Section 3.4.3.

4.3.4 Non-uniform Distribution Low Load

The purpose of using a non-uniform traffic distribution is to simulate a high traffic load between two locations in the world. In this scenario, two earth stations transmit and receive most of the traffic with a low network offered load. The simulation was executed with a network arrival rate of 5,468,750 packets-per-second, which is the rate for the 50% uplink loading level. Having a different transmit probability, the uplink utilization, earth station arrival rate, and the processor utilization values will be different than the 50% uplink loading level values. Because the traffic between source and destination earth stations is not uniformly distributed, Washington D.C. and Ankara transmit at 87.5% uplink utilization. The other earth stations transmit at 35% uplink utilization. The non-uniform distribution with low loading and the calculation used to find uplink utilization are explained in Section 3.4.5.

4.3.5 Non-Uniform Distribution Medium Load

In this scenario, two earth stations transmit and receive most of the traffic with a medium network offered load. The simulation was executed with a network arrival rate of 9,078,125 packets-per-second, which is the rate for the 83% uplink loading level. Having a different transmit probability, the uplink utilization, earth station arrival rate, and the processor utilization values will be different from the 83% uplink loading level values. Because the traffic between source and destination earth stations is not uniformly distributed, Washington D.C. and Ankara transmit at 94% uplink utilization. The other earth stations transmit at 79% uplink utilization. The non-uniform distribution with medium loading and the calculation used to find uplink utilization are explained in Section 3.4.5.

4.4 Analysis of Delay Performance Metrics

The mean end-to-end packet delay and the packet rejection rate are the two primary measurements to estimate the TELEDESIC® satellite system's network ability for a real-time communications. The mean end-to-end packet delay and the packet rejection rate are explained in Sections 3.4.7 and 3.9.2. The simulation was designed to execute with an end-to-end packet delay less than 400 ms. The benchmark for the packet rejection rate is 1%. A rejection value which is higher than this amount represents an undesirable performance. The mean end-to-end packet delay and the packet rejection rate are closely related with the maximum queue size, which is defined in Section 3.4.9. If the queue size is increased, the packet rejection rate decreases but the end-to-end delay packet delay increases. Similarly, a decrease in the queue size increases the packet rejection rate but decreases the end-to-end packet delay.

4.4.1 Delay Analysis

The mean end-to-end packet delay measured from Washington D.C. to other six earth stations was lower than 400 ms for all the test scenarios tested. It was the result of selecting the queue size with a definite amount that any packet having an end-to-end delay greater than 400 ms would be rejected from the system. However, the simulation results have also shown that the processor utilization was not 100%. As a result of this, the obtained delay values were close to each other. But the main thought in the simulation-model design phase was that any packet with an end-to-end packet delay greater than 400 ms would be rejected from the network. The minimum mean end-to-end delay was 53.706 ms between Washington D.C. and Rio de Janeiro in the uniform low load scenario. The maximum mean end-to-end delay was 122.087 ms between Washington D.C. and Capetown in the uniform high load scenario.

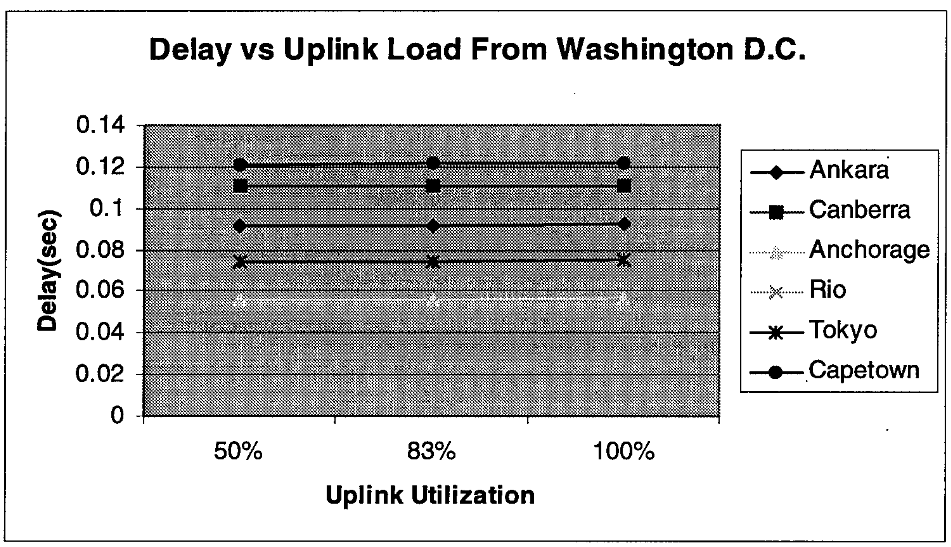


Figure 5: Delays for Uniform Distribution

As the input parameters given to the system have been changed, several trends have been notified. First, it was clearly seen that increasing the loading level for a given traffic distribution did not have a significant impact on queuing delay because of the processor usage not being able to execute simulations with 100% performance. The delay and uplink load comparison between Washington D.C. and the other earth stations are as shown in Figure 5 above.

The increase for all of the earth stations was significantly smaller when the uplink utilization was increased from 50% to 83% and then to 100%. This indicates that the processor was not fully executing the simulations with 100% utilization.

The second trend was that non-uniform loading did not have a significant impact on queuing delay either. Because of the processor usage not executing the simulations by 100% performance, the end-to-end packet delays were not at significantly greater values. The delay and uplink load comparison between Washington D.C. and the other earth stations for non-uniform traffic distribution are as shown in Figure 6 below.

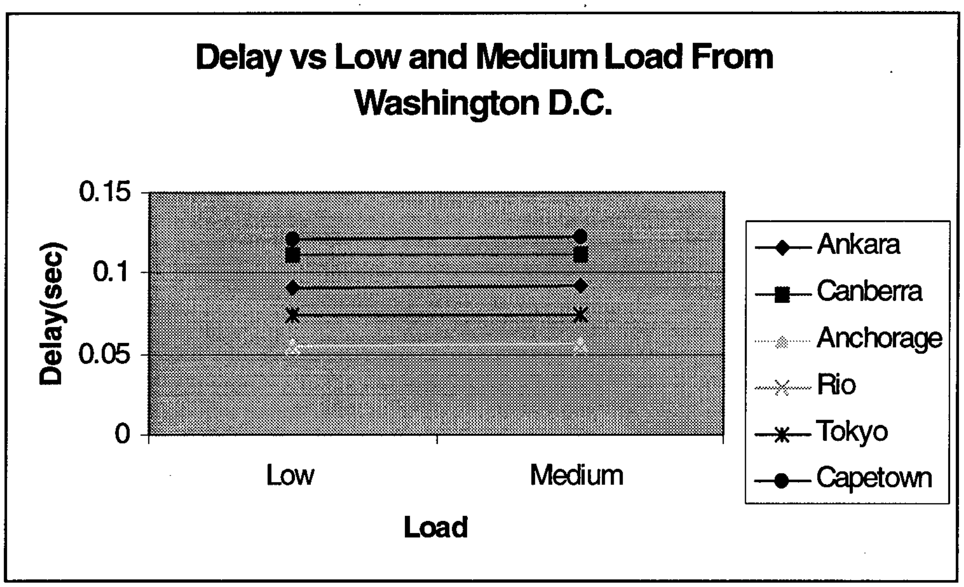


Figure 6: Delays for Non-Uniform Distribution

The increase for all of the earth stations was significantly smaller when the loading was increased from low to medium load level. This result also indicated that the processor was not fully utilized with the uplink loading set to 100%.

Finally, it was seen that the non-uniform traffic scenarios had higher end-to-end delay than the uniform traffic scenarios with the same network arrival rate. The packets generated and received between Washington D.C. and Ankara were comparably greater in amount than the packets generated and received by the other earth stations from Washington D.C. The network arrival rates were the same for the non-uniform low load and uniform low load scenarios as explained in Section 3.4.5. Likewise, the network arrival rates for the non-uniform low load and uniform low load scenarios were the same. The end-to-end delay between Washington D.C. and Ankara for each of the test scenarios is as shown in Figure 7.

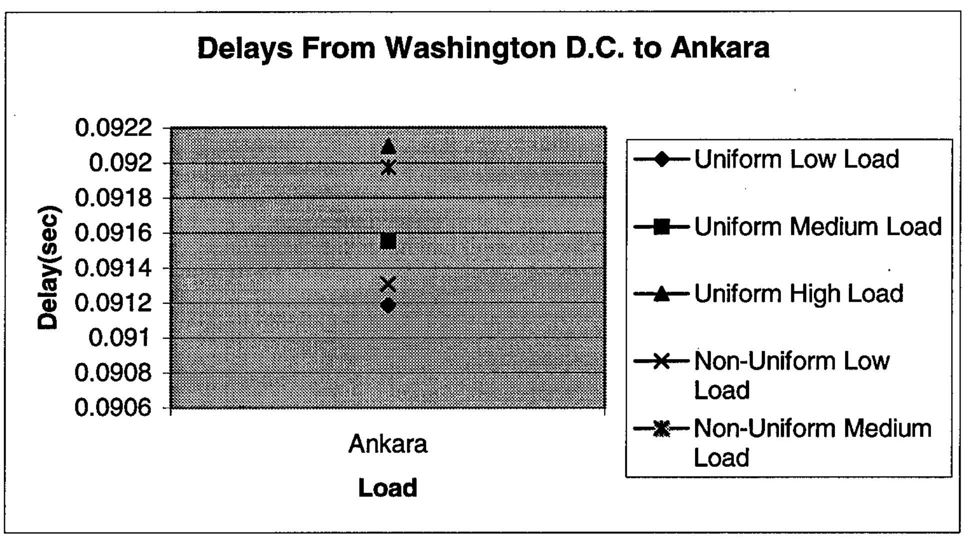


Figure 7: Delays from Washington D.C. to Ankara

The non-uniform low load scenario had a higher end-to-end delay than the uniform low load scenario. Also, it was noticed that the non-uniform medium load scenario had a higher end-to-end delay than the uniform medium load scenario. These two results were not only true for the high traffic link between Washington D.C. and Ankara, but also for all the packets directed from Washington D.C. to the other earth stations. An example of this conclusion is as shown in Figure 8 below for the traffic link between Washington D.C. and Capetown, which had the highest delays of all the scenarios.

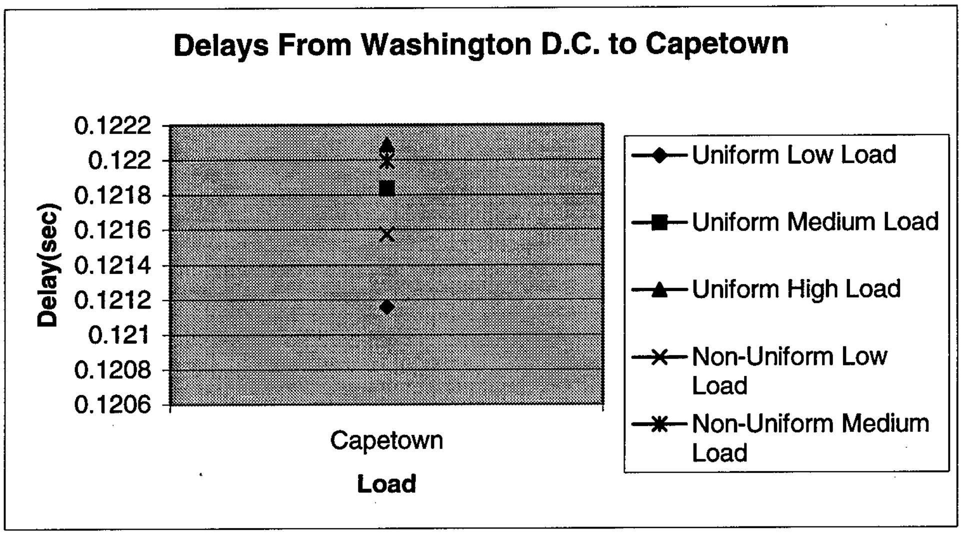


Figure 8: Delays from Washington D.C. to Capetown

4.4.2 Packet Rejection Analysis

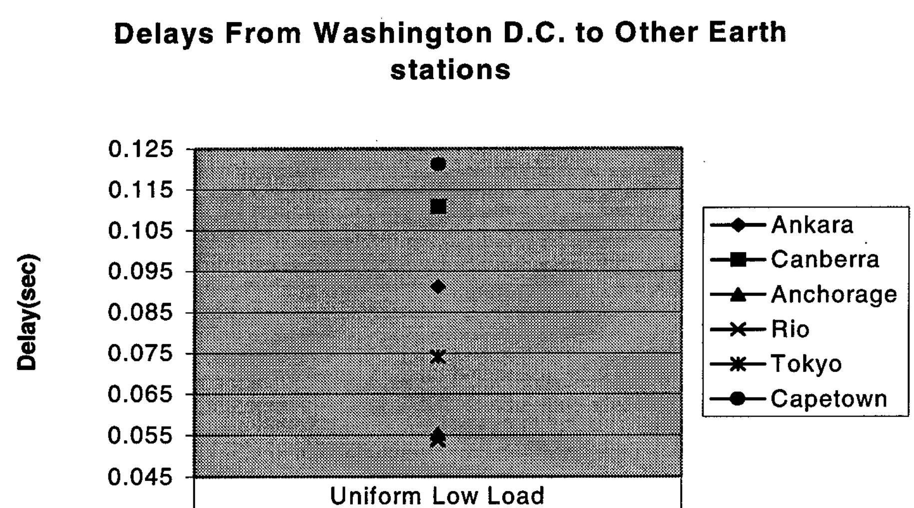
The packet rejection rate was 0% for all of the test scenarios. Since none of the packets had end-to-end delay performances greater than 400 ms, the packets were not rejected. The highest delay obtained was 122.087 ms between Washington D.C. and Capetown.

4.5 Analysis of Delay Test Scenarios

The individual analysis of each scenario is explained below. The end-to-end packet delays and the packet rejection rates are examined for each of the earth stations.

4.5.1 Uniform Distribution Low Load

The end-to-end packet delays for the uniform low load scenario were less than 400 ms, which was set as the benchmark for all the scenarios for this research. The packets were not rejected because of the uplink processor usage being less than 100%. The end-to-end delay from Washington D.C. to other earth stations changed from 53.706 ms to 121.155 ms. The end-to-end delay is shown against the different earth stations for the uniform low load in Figure 9.



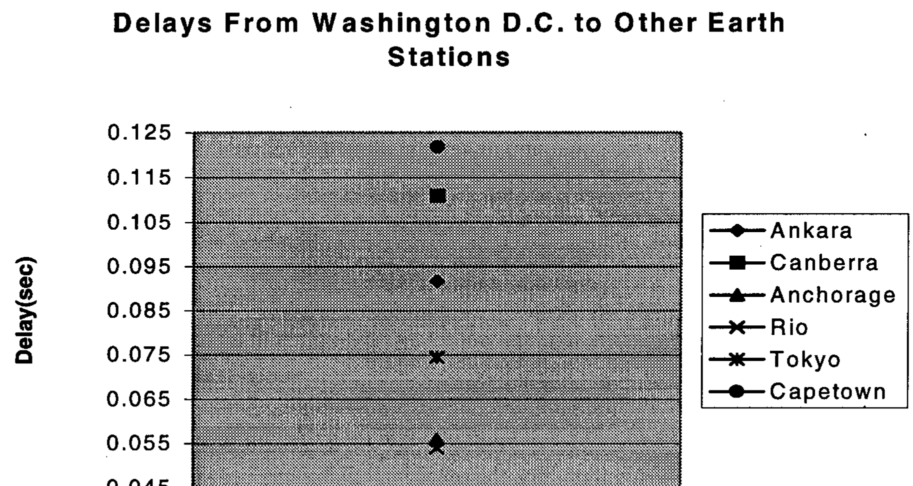
	Uniform Low Load
Ankara	0.091182454
Canberra	0.110799535
Anchorage	0.055438202
Rio	0.053705732
Tokyo	0.073992317
Capetown	0.121154645

Figure 9: Delays from Washington D.C. to Other Earth Stations Uniform Low Load

Queuing delay did not have a significant impact at this loading level. In this scenario the TELEDESIC® satellite system was able to provide real-time communications. The performance in this scenario is compared with the other scenarios to determine the effect of increasing the traffic load or changing the traffic distribution.

4.5.2 Uniform Distribution Medium Load

The end-to-end packet delays for the uniform medium load scenario were also less than 400 ms. The packets were not rejected because of the uplink processor usage being less than 100%. The end-to-end delay from Washington D.C. to other earth stations changed from 53.913 ms to 121.838 ms. The end-to-end delay is shown against the different earth stations for the uniform medium load in Figure 10.



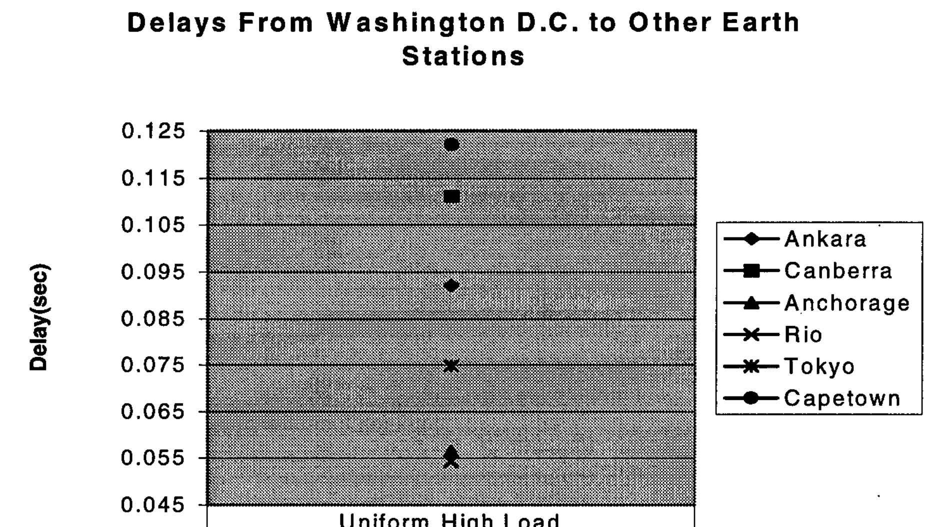
	Uniform Medium Load
Ankara	0.091553572
Canberra	0.110947659
Anchorage	0.055863613
Rio	0.05391271
Tokyo	0.074465812
Capetown	0.121838432

Figure 10: Delays from Washington D.C. to Other Earth Stations Uniform Medium Load

Queuing delay did not have a significant impact at this loading level as well. In this scenario the TELEDESIC® satellite system was able to provide real-time communications.

4.5.3 Uniform Distribution High Load

The end-to-end packet delays for the uniform high load scenario were also less than 400 ms. The packets were not rejected because of the uplink processor usage being less than 100%. The end-to-end delay from Washington D.C. to other earth stations changed from 54.314 ms to 122.087 ms. The end-to-end delay is shown against the different earth stations for the uniform high load in Figure 11. Queuing delay did not have a significant impact at this loading level as well. In this scenario the TELEDESIC® satellite system was able to provide real-time communications.

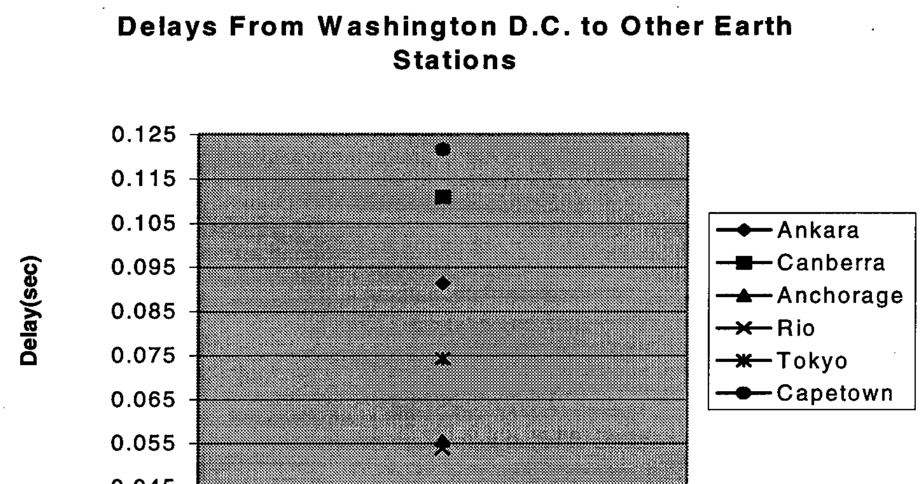


	Uniform High Load
Ankara	0.09209551
Canberra	0.111048816
Anchorage	0.056501878
Rio	0.05431414
Tokyo	0.074831238
Capetown	0.122086533

Figure 11: Delays from Washington D.C. to Other Earth Stations Uniform High Load

4.5.4 Non-uniform Distribution Low Load

The end-to-end packet delays for the non-uniform low load scenario had delay values less than 400 ms as the uniform load scenarios. The packets were not rejected because of the uplink processor usage being less than 100%. The end-to-end delay from Washington D.C. to other earth stations changed from 53.888 ms to 121.574 ms. The end-to-end packet delays for this type of scenario was higher than the end-to-end delay values for the uniform low load scenario. The traffic rate between Washington D.C. and Ankara was comparably higher than the packets generated and transmitted in uniform load scenarios. The end-to-end delay is shown against the different earth stations for the non-uniform low load in Figure 12.



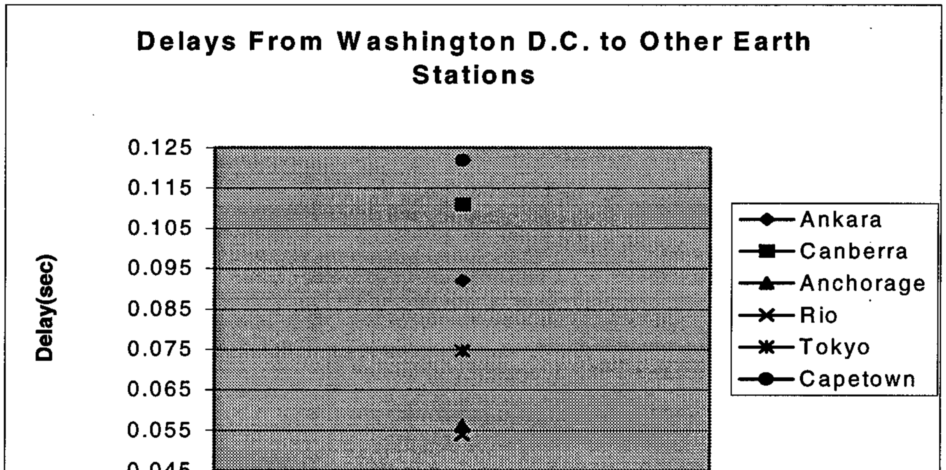
	Non-Uniform Low Load
Ankara	0.09130839
Canberra	0.110912527
Anchorage	0.055602887
Rio	0.0538878
Tokyo	0.074200614
Capetown	0.12157399

Figure 12: Delays from Washington D.C. to Other Earth Stations Non-Uniform Low Load

The end-to-end packet delay was 91.182 ms for the uniform low load scenario. The delay difference is 0.126 ms, which is small. Queuing delay did not have a significant impact at this loading level as well. In this scenario the TELEDESIC® satellite system was able to provide real-time communications below 400 ms.

4.5.5 Non-Uniform Distribution Medium Load

The end-to-end packet delays for the non-uniform medium load scenario had delay values less than 400 ms as all the other load scenarios. The packets were not rejected because of the uplink processor usage being less than 100%. The end-to-end delay from Washington D.C. to other earth stations changed from 53.934 ms to 121.993 ms. The end-to-end packet delays for this type of scenario was higher than the end-to-end delay values for the uniform medium load scenario. The traffic rate between Washington D.C. and Ankara was comparably higher than the packets generated and transmitted in uniform load scenarios. The end-to-end delay is shown against the different earth stations for the non-uniform medium load in Figure 13.



	Non-Uniform Medium Load
Ankara	0.09197677
Canberra	0.11102047
Anchorage	0.056076196
Rio	0.05393384
Tokyo	0.074639305
Capetown	0.121993421

Figure 13: Delays from Washington D.C. to Other Earth Stations

4.6 Summary of Analysis

The delay analysis presented in Sections 4.3 to 4.5 showed that the TELEDESIC® satellite system is capable of meeting real-time communications constraints. In the delay analysis, the non-uniform low load scenario had greater mean end-to-end packet delays than the uniform low load scenario. Likewise, the non-uniform medium load scenario had greater mean end-to-end packet delays than the uniform medium load scenario. The uniform high load scenario had the greatest mean end-to-end packet delays from Washington D.C. to other earth stations. Meanwhile, the packet rejection rate was obtained to be 0% for all of the test scenarios because of the uplink processor usage being less than 100%. The packets between Washington D.C. and Ankara were transmitted in higher traffic rates in the non-uniform load scenarios. The minimum mean end-to-end delay was 53.706 ms between Washington D.C. and Rio de Janeiro by the uniform low load scenario. The maximum mean end-to-end delay was 122.087 ms between Washington D.C. and Capetown by the uniform high load scenario. The delay analysis demonstrated the importance of analyzing the TELEDESIC® satellite system at high loading levels and non-uniform traffic distributions. Future research in this area could perform a delay analysis with other traffic distributions since only one non-uniform traffic distribution was used in this research.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of the Research Goal

The purpose of this research was to analyze the delay performance of the TELEDESIC® satellite system with two different traffic distributions and with a full system configuration. Uniform and non-uniform traffic distributions were used to analyze the performance of the system. The system consisted of 288 satellites and seven ground stations.

5.2 Conclusions

The TELEDESIC® satellite system is a new project for future expectations on satellite communications. With 288 satellites at lower altitudes, the TELEDESIC® satellite system is designed to have smaller packet delays from one location to another on the earth. The TELEDESIC® satellite system's robust design offers a network structure that is capable of small packet delay values. This property makes the system dominant compared to other LEO type satellite systems.

In this research, the proposed TELEDESIC® system model met the real-time voice communications requirement of 400 ms with end-to-end packet delays. The analysis revealed that delay times were always less than 122.1 ms. Compared to the IRIDIUM® satellite system, the TELEDESIC® satellite system had better end-to-end packet delays. Because of small end-to-end packet delays, the packet rejection rate stayed fixed at zero level. Both the uniform and non-uniform load scenarios met both benchmarks with packet delays comparably smaller than the IRIDIUM® satellite system.

5.3 Significant Results of the Research

Considering the research done before by Stenger [Ste96] and Fossa [Fos98], this research revealed the delay performance for a satellite network that uses eight interconnected links for each satellite. The previous two works performed on the IRIDIUM® satellite system contained an ISL structure of four satellites.

The routing algorithm used in the TELEDESIC® system is proprietary and not available in the open literature. Because the TELEDESIC® Company has not announced the routing algorithm that the actual TELEDESIC® satellites use, it was necessary to create a simulation model that would execute in a TELEDESIC®-like manner. The interconnectivity between satellites was fashioned to be eight so that the simulation model would follow a TELEDESIC®-like pattern in order to send packets from the source to the destinations. The path was reexamined and the path a packet took contained two adjacent satellites in two adjacent orbits and two adjacent satellites in the same orbit, making the connectivity eight. The tests made to analyze the path showed that the logic of the source code was sound.

There is still a lack of openly published literature in the area of LEO satellite network performance. Previous research analyzed only the IRIDIUM® satellite system. Another contribution of this research was that the research subject added another LEO-type satellite system into the satellite communications area in which the future researchers can compare two delay performances to have a better understanding of LEO-type satellite system constellation and network structure.

5.4 Recommendations

There are three primary areas for future research. The first area for research extension is to use additional traffic patterns and distributions. A second area for future research is to have satellite failures and investigate the delay performance as the number of failures increase. The third area for future research deals with routing algorithms. Different routing algorithm can be implemented to observe overhead and delay performance.

APPENDIX

This Appendix contains the tabulated end-to-end delay results and 95% confidence intervals for each test scenario. The results for the uniform low load scenario with a full satellite constellation is presented in Section 4.2

Table 9: 95% CI for Uniform-Medium-Load Full Satellite Constellation

Destination	Average Mean	Standard Deviation	95% Confidence Interval	
			Minimum	Maximum
Capetown	0.1218384	0.00002106	0.1217744	0.1219025
Tokyo	0.0744658	0.00011398	0.0741190	0.0748126
Rio	0.0539127	0.00000829	0.0538875	0.0539379
Anchorage	0.0558636	0.00009847	0.0555640	0.0561632
Canberra	0.1109477	0.00003732	0.1108341	0.1110612
Ankara	0.0915536	0.00003259	0.0914544	0.0916527

Table 10: 95% CI for Uniform-High-Load Full Satellite Constellation

Destination	Average Mean	Standard Deviation	95% Confidence Interval	
			Minimum	Maximum
Capetown	0.1220865	0.00000266	0.1220784	0.1220946
Tokyo	0.0748312	0.00003889	0.0747129	0.0749496
Rio	0.0543141	0.00000660	0.0542941	0.0543342
Anchorage	0.0565019	0.00005217	0.0563431	0.0566606
Canberra	0.1110488	0.00004724	0.1109051	0.1111925
Ankara	0.0920955	0.00005999	0.0919130	0.0922780

Table 11: 95% CI for Non-Uniform-Low-Load Full Satellite Constellation

Destination	Average Mean	Standard Deviation	95% Confidence Interval	
			Minimum	Maximum
Capetown	0.1215740	0.00000106	0.1215708	0.1215772
Tokyo	0.0742006	0.00000179	0.0741952	0.0742060
Rio	0.0538878	0.00003316	0.0537869	0.0539887
Anchorage	0.0556029	0.00013201	0.0552012	0.0560046
Canberra	0.1109125	0.00000283	0.1100391	0.1109211
Ankara	0.0913084	0.00000526	0.0912924	0.0913244

Table 11: 95% CI for Non-Uniform-Low-Load Full Satellite Constellation

Destination	Average Mean	Standard Deviation	95% Confidence Interval	
			Minimum	Maximum
Capetown	0.1219934	0.00000518	0.1219777	0.1220092
Tokyo	0.0746393	0.00021654	0.0739805	0.0752982
Rio	0.0539338	0.00000113	0.0539304	0.0539373
Anchorage	0.0560762	0.00004970	0.0559250	0.0562274
Canberra	0.1110205	0.00000263	0.1110125	0.1110285
Ankara	0.0919768	0.00000817	0.0919519	0.0920016

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13. ABSTRACT *(Maximum 200 words)*

This thesis provides a performance analysis of the TELEDESIC Low Earth Orbit Satellite System. It analyzes the system's performance to meet the real-time communications constraints with a full satellite constellation. Computer simulation results are the sources to evaluate delays associated with packets transmitted from source to destination earth stations. The simulation is run at low, medium and high loading levels with two different, uniform and non-uniform, traffic distributions. The evaluated results are end-to-end packet delays and packet rejection rate. The results show that the TELEDESIC satellite system network is capable of meeting the real-time communication requirements with delay values much smaller than 400 ms.

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