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Design and Analysis of a Multi-Variable Rate Channel Access Scheme for Geostationary Mobile Satellite Network

by

Junaid A. Israr, B. Eng.

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of

Master of Engineering

Ottawa-Carleton Institute for Electrical Engineering
Faculty of Engineering
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Abstract

In this thesis, a TDMA based system for a geostationary (GEO) mobile satellite service (MSS) system for North America is designed and analyzed with the help of an original and comprehensive software module. With a large satellite antenna diameter, it is relatively easy to implement a GEO MSS system which is capable of supporting a direct link to a hand-held user terminal. The system caters to users of various data rates ranging from 8 kb/s to 64 kb/s with two distinct types of user terminals. It can provide an acceptable quality of speech service at 8 kb/s with hand-held terminals and higher data rate services to users with a more capable terminal. Furthermore, a new TDMA frame structure is developed for the system which provides capacity enhancements up to 122% (depending on the frame contents) relative to the conventional TDMA frame structures. The proposed frame structure is highly efficient when the majority of the users in the system operate at data rates higher than 8 kb/s. An exhaustive link budget analysis is performed to determine the capacity of the system. The software module produces a precise multiple spot beam layout for the continent of North America and performs interference and frequency assignment analysis. The results from the software module and the link budget analysis are used to conduct a detailed bandwidth limited and power limited capacity analysis.

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List of Symbols

$G_{\max}$	maximum antenna gain
η	antenna efficiency
λ	signal wavelength
$\alpha_{3\text{dB}}$	3-dB beamwidth of satellite antenna
D	satellite antenna diameter
α	angle of signal reception at satellite with respect to boresight
ϕ_g	latitude of ground station
Δl	difference in longitude between ground station and subsatellite point
T	nadir or tilt angle of the satellite
R_E	equatorial radius of the earth
h	satellite altitude measured from the surface of the earth
r	satellite altitude measured from the center of the earth
θ	elevation angle
γ	central angle
d	slant range distance to the satellite
D_A	extent of coverage area
L_s	path loss
ϕ_{gc}	latitude of center of spot beam
ϕ_{gB}	latitude of a grid-square
Δl_c	difference between satellite longitude value and boresight longitude value (taken positive if boresight is to the west of the satellite)
Δl_B	difference between satellite longitude and grid-square longitude value (taken positive if grid-square is to the west of the satellite)
$G_c(\theta)$	antenna gain characteristics as a function of reception angle
θ_c	angle of received desired signal with respect to boresight

θ_i	angle of received interference signal with respect to boresight
L_c	path loss experienced by the desired signal
L_i	path loss experienced by the interfering signal
X_{ij}	interference received in spot beam i from spot beam j
$\frac{E_b}{N_o}$	ratio of data bit energy to noise power density
KTB	Noise Power, where K = Boltzmann's constant = $1.38 * 10^{-23}$ J/K, T = Noise Temperature in °K and B = bandwidth in Hz.
$\left(\frac{C}{N}\right)_u$	ratio of uplink carrier power to thermal noise power
$\left(\frac{C}{N}\right)_d$	ratio of downlink carrier power to thermal noise power
$\left(\frac{C}{I}\right)$	ratio of carrier power to interference noise power
$\left(\frac{C}{N}\right)_{IM}$	ratio of carrier power to intermodulation noise power
n_8, n_{16}, n_{32}	number of users operating at 8, 16, and 32 kb/s respectively
n_{48}, n_{64}	number of users operating at 48 and 64 kb/s respectively
S_8, S_{16}, S_{32}	uplink signal share for users operating at 8, 16 and 32 kb/s respectively
S_{48}, S_{64}	uplink signal share for users operating at 48 and 64 kb/s respectively

Chapter 1

Prologue

1. Introduction

The advancements in microelectronics have allowed new applications for telecommunication satellites such as mobile and personal communications. The future wireless systems must provide services that support traditional mobile voice communications as well as a variety of voice and data services for a wide range of applications. Services supporting multimedia capabilities, Internet access, imaging and video conferencing will likely be needed in any true future wireless system. At the same time, global standards organizations are working towards the convergence of many diverse systems existing today (including paging, cordless, cellular, mobile satellite etc.) into a seamless radio infrastructure capable of offering a wide range of services.

Figure 1-1 represents the breadth of services and market segments being included in the next generation wireless system architectures. It is evident that a number of different operating environments, ranging from very-high-capacity indoor picocells to large outdoor terrestrial cells and satellite coverage, are envisioned for future wireless systems. It is largely believed that close integration between the satellite and terrestrial components will facilitate the initial deployment of services via satellite where there is little or no existing fixed infrastructure.

Figure 1-1: A flexible, multifunctional network envisioned for a future wireless system

In view of such global framework, the satellite network operators are faced with a number of technical and economic constraints. The satellite system designer must choose, among others, the constellation to use, the spot beam sizes, the most efficient deployment of ground stations and multiple access schemes. Since a satellite spot beam is large, it may straddle a number of countries and regions with dissimilar terrestrial networks which presents another complex challenge to the system designer.

The era of satellite communications opened in the form of many experiments in the late fifties and early sixties with satellites in low altitude orbits. The low altitude orbits presented several problems including but not limited to complex antenna tracking and interrupted service due to

the satellite disappearing over the horizon. By the mid-1960's, the geostationary equatorial orbit (GEO) with its unique characteristics became increasingly attractive and presented a better solution for communication systems. During the 1970's and 1980's GEO satellites became by far the most popular medium for providing commercial satellite based communication services. However, by the 1990's, competing terrestrial technologies such as cable, microwave radio and particularly fiber optic systems provided attractive and low cost alternatives for telecommunications and threatened the position of satellites. Subsequently, the identification of applications suitable for satellite communications led to the design and deployment of satellite systems for long distance *mobile communications*. Satellites offer unique service to users in rural and remote areas which are outside the range of existing telecommunication systems.

The year 1990 was a turning point for MSS, when Motorola introduced the concept of a low earth orbit (LEO) satellite system capable of directly serving hand-held terminals. At that time, the concept of providing direct links to hand-held terminals was considered infeasible even with the most advanced satellite systems. However, by 1994, several schemes had been devised to provide mobile service to hand held phones at all altitudes ranging from Iridium's 780 km to the GEO's 36,000 km. A GEO satellite based system is a strong candidate due to the long experience acquired through years of operational practice. The field of view provided by the GEO satellite is large and hence very few are required to provide global coverage. Also, since the satellite appears stationary to users on earth, the complications associated with antenna tracking, Doppler effects and loss of coverage are mitigated. Beginning in late 1998, systems supporting communication directly between hand-held

phones and satellites are expected to be in operation. These systems will also see service for fixed telephone and temporary and emergency communications, which will have significant impact in areas and times of great need.

1.1 Thesis Motivation

For satellite communication systems to be economically viable, efficient use must be made of the satellite's limited resources such as bandwidth and power. This is particularly important in MSS systems where a large number of uncoordinated and statistically bursty users are expected to share these resources in a mutually cooperative and efficient manner. Depending on the system requirements and the nature of the applications supported by the system, it is important to choose the appropriate multiple access technique in the system design step.

Recently, many authors [1], [2], [3], [4], [5], [6] have investigated issues related to future mobile satellite communication systems with the capability of providing personal services. For example, [1] addresses some of the most significant topics related to Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA) that are considered as candidates for the third generation MSS systems. However, not much research has been devoted to investigate the capacity performance of a complete future third generation MSS system with its service requirements and system characteristics.

At present, TMI¹ Communications, operate a geostationary satellite MSAT, providing voice and low data rate (9.6 kbps) services to users in North America. The system currently employs Single Channel per Carrier (SCPC) FDMA as system multiple access scheme. This research effort is undertaken in collaboration with TMI Communications to seek alternate multiple access schemes for a next generation MSS system, providing voice and higher data rate services to users in North America with a geostationary satellite.

The third generation MSS systems are expected to provide multiple data rate services to users with different types of user terminals. The data rates are expected to range from 8 kb/s for speech to 64 kb/s for applications such as internet access, file transfers, etc. The user terminals are expected to be similar to the hand-held cellular handsets for speech users. Larger transportable terminals are expected to be used for higher data rate services. The existing and the planned geostationary MSS systems provide speech services and low data rate services to users. For example, the Thuraya system planned for the Middle-East provides GSM compatible services for users with hand-held, vehicular and transportable user terminals [7]. [3] presented an analysis of a public mobile satellite system compatible with the GSM cellular network. However, most of the assumptions made in the analysis may not be valid for a truly third generation satellite system but are more representative of the existing MSAT system operating in North America. For example, the user terminal is required to transmit at a peak power of 18.6 W which is prohibitive for a hand-held terminal. Also, systems with very few spot beams are considered which restrict the ability of the system to utilize the

¹ TMI Communications, Inc., 1601 TelesatCrt, Gloucester, Ontario, Canada. Tel.: (613) 742-0000.

reciprocal relationship between the spot beam size and the satellite antenna gain. The few spot beams are also restrictive in utilizing the concept of frequency reuse to enhance the capacity of the system.

Currently, there is a lack in the existing literature of a TDMA frame structure that can support users with multi-variable data rates efficiently. An investigation is performed and a structure is developed and compared with traditional frame structure for efficiency.

For the third generation systems, a GEO satellite-based system is a strong candidate due to the long experience acquired through years of operational practice. The future geostationary mobile satellite systems being envisaged for North America consist of several spot beams (around 100 spot beams) with coverage extending to the Caribbean and Hawaii Islands and the coastal waters [8]. Also, since a regional system is sought, a LEO or a MEO based satellite system is not very practical.

1.2 Thesis Work Description

In this thesis, a geostationary mobile satellite system with multiple spot beams covering North America and supporting users with multiple data rates is considered and analysis for its capacity is presented. The system design involves a thorough investigation and analysis of several key issues which are summarized in the following:

- an understanding of earth satellite geometry to generate individual spot beams.

Using vector analysis, an original mathematical relationship is developed in this

thesis to calculate an essential parameter required for spot beam contour generation.

- an understanding of the traffic characteristics to determine appropriate spot beam sizes (contour power levels) and the overall spot beam layout for the desired coverage area.
- an understanding of all link budget parameters to establish the power requirements/constraints of the system. Since a new system design is undertaken, reasonable assumptions regarding performance requirements and communication terminal characteristics are made. The satellite channel propagation characteristics, modulation techniques, error correction schemes, satellite amplifier characteristics, ground station characteristics and the data rates constitute an integral part of the link budget and are analyzed accordingly.
- a realization of the problem of interference from co-channel spot beams when attempting frequency reuse and designing a methodology to determine and tackle the interference. As a result, several possible frequency assignments for the different spot beams are devised. The frequency assignment is followed by a bandwidth-limited capacity calculation.
- an understanding of the parameters involved in the power-limited capacity analysis. A power-limited capacity analysis for the proposed design with multiple data rate users (with different communication terminal capabilities) transmitting within the same frame is not available in existing literature. Therefore, an *original* methodology is developed to calculate the power-limited capacity for the proposed system.

A new TDMA frame structure is proposed which provides significant capacity improvements and reasonable overhead relative to traditional TDMA frame structure. A complete return link budget is presented which assists in determining the feasibility of the proposed system. Considerable effort has been devoted to the design and implementation of a complete software module during the course of the research. The software module assists in the spot beam layouts, calculation of guard times, interference analysis based on the link budget and frequency assignment. It is shown that the proposed TDMA frame structure can provide significant capacity improvement by comparison to conventional approaches.

1.3 Thesis Organization

The chapters of the thesis are organized as follows:

Chapter 2 presents background information related to mobile satellites systems. The chapter briefly discusses the different orbits and availability of satellite systems. This is followed by a short reference to the service characteristics expected for future systems and the choice/features of the available multiple access schemes to cater to these requirements. Next, a brief discussion about the link propagation characteristics is provided.

Chapter 3 presents the new TDMA frame structure developed in this thesis, which is suitable for future geostationary MSS systems. The frame contents and the defragmentation dynamics are discussed. The performance of the proposed frame structure is evaluated and compared to that of the conventional structures.

Chapter 4 is a description of the complete channel access system design. The chapter provides a brief background about the earth-satellite geometry which leads to the spot beam contour calculations. The coverage of North America with spot beams of different contour levels is presented next. The calculations involved in interference analysis and frequency assignment are presented next with details regarding the link budget.

Chapter 5 provides detailed description of the software module designed to aid in design of a complete multiple spot beam MSS operating in North America. All features incorporated in the software module are discussed. An effort is made to implement the theoretical concepts presented in Chapter 4 in an actual software system in order to derive preliminary results.

In Chapter 6, the results of the preliminary design are presented. The capacity of the system is calculated assuming both power-limited and bandwidth-limited scenarios. A comparison is made between the traditional TDMA frame structure and the proposed frame structure with realistic calculation of guard time values obtained from the design. The coverage pattern for North America is presented followed by the interference analysis results for different frequency assignment schemes.

Chapter 7 summarizes the results obtained in the coursework of this thesis. Conclusions are drawn and suggestions are presented for future research work.

Chapter 2

Background

In this chapter, background information pertaining to issues associated with Mobile Satellite Service (MSS) systems is presented. The choice of different orbits for an MSS system is discussed initially followed by the desired service characteristics, multiple access schemes and the channel propagation conditions.

2. Mobile Satellite Systems

The choice of a mobile satellite system involves finding the best solution in terms of the following factors: [9]

- a) orbits and availability,
- b) satellite,
- c) system capacity,
- d) multiple access,
- e) diversity,
- f) signal quality,
- g) system cost.

The constellation determines the number of satellites; the altitude and capacity determine the satellite's size; and the modulation/multiple access method and altitude determine its

complexity. All parameters are interdependent, for example, a good multiple access system in connection with a constellation at a reasonable altitude simplifies the satellite, provides good voice quality, and minimizes cost [10]. In this chapter, a review of some of the above parameters is presented.

2.1 Orbits and Availability

Several MSS systems offering voice and data service from three different orbits have been proposed [1][7][9][11]. Three types of satellite systems exist including the low earth orbit (LEO) satellites, medium earth orbit (MEO) satellites and geostationary earth orbit (GEO) satellites. The LEO satellite systems include the Iridium Inc.'s Iridium (at an altitude of 780 km), Constellation Communications Inc.'s Aries (1,018 km) and Loral-Qualcomm's Globalstar (1,389 km) [11]. Medium earth orbit (MEO) or Intermediate circular orbit (ICO) systems include I-CO's Project 21 (10,355 km). Ellipsat's Ellipso (7,800 km) is considered as a LEO but is closer to the MEO orbits. Geostationary earth orbit (GEO) regional mobile satellite systems at about 36,000 km include AMSC and MSAT (US and Canada respectively), Aces (South East Asia) and Thuraya (UAE).

2.1.1 Low Earth Orbits

Since the satellites are close to earth (typical altitudes vary from 500 -2,000 km), the Effective Isotropic Radiated Power (EIRP) required for a given link margin is lower. For instance, the path loss for Iridium at 20° elevation angle is 18 dB lower than that of MEO satellites . Although this allows Iridium to potentially have higher link margin yet this is counterweighed by the fact that Iridium must cope with more shadowing and more severe Ricean fading as it

is also seen at lower elevation angles [1]. Also, the lower elevation angle reduces availability especially in built up areas. Further, it is not always possible to see multiple satellites to allow diversity. Globalstar, with a higher orbit than Iridium, offers dual satellite diversity with 85% of time availability [1], but has a lower link margin than Iridium.

In a LEO system, the field of view (FOV) of each satellite is lower and therefore a large number of satellites are required. Since the FOV is small, every satellite need not be in view of a user terminal. This requires either networking in space with inter-satellite links similar to Iridium or a large number of earth stations as in Globalstar. Further, frequent handovers are required because the satellites move rapidly and the beams move with the satellites. The time delay is short for local calls and is comparable to that for an MEO for international calls since the signal is usually relayed over multiple satellites or multiple hops. The satellites move fast and therefore have higher Doppler frequencies. This may require differentially coherent communications, which implies E_b/N_0 ratio higher than that required for coherent schemes used by GEOs and MEOs.

2.1.2 Medium Earth Orbits

The MEO satellites operate normally at an altitude of 10,355 km. Due to the higher altitude, they have a larger FOV than LEOs and require 10-12 satellites to cover the earth. A constellation of 12 satellites in 3 planes provides higher average availability than LEOs for latitudes up to 65°. Furthermore, the availability is more uniform at these latitudes. A larger constellation of 18 satellites in 4 planes provides diversity for approximately 85% of the time and increases the average availability in urban areas from about 65-70% to around 90% for

latitudes up to 50° . The higher availability is achieved because satellites are seen at higher elevation angles and hence diversity is provided. The MEO satellites orbit the earth at a slower rate and can be seen for a longer time during a call which also minimizes the handover rate relative to a LEO. MEO satellites require a larger EIRP than LEOs to make up for the additional path loss. With the larger FOV, a MEO system requires fewer gateways and there is no need for intersatellite links. [1]

2.1.3 Geostationary Earth Orbits

The GEO satellites are used for regional systems. With the help of large antennas (> 10 meters) and high power output, the GEOs provide competitive link margins. Further, since the satellite is stationary, fixed terminals can be oriented towards the satellite with high gain antennas to provide a range of voice and data services. This can be accomplished by LEO and ICO systems but with greater complexity. The satellites are in an equatorial link belt and hence always south or north of the users. As well, the satellites exist at higher elevation angles (typically above 30°). This enables the users to position themselves for better communication. The GEO systems have a relatively straightforward ground station architecture that does not require multiple tracking antennas since the satellite is relatively stationary. The critical issue with GEO satellites is end-to-end time delay which can reach up to 500 ms. In a GEO satellite system, a user at the edge of the spot beam has a lower link margin, which is not the case in MEO or LEO satellite systems where the user experiences more averaging as the satellite position changes. [1]

2.2 Service Characteristics

A typical MSS network is designed based on the requirement that a large number of user terminals are able to simultaneously interconnect their respective voice, data, teletype and facsimile services through a satellite. When designing a system, it is essential first to establish the network services required and the nature of the circuits needed to carry these services.

Figure 2-1 depicts an overall typical mobile satellite communication system.

Figure 2-1: Elements of a typical mobile satellite communication system.

An MSS system may carry different types of information ranging from digital voice, of reasonable quality, to data at various speed (depending on the requirements of the supported applications) or slow scan video for facsimile transfers. With advances in technology, teleconferencing applications can also be supported even though full motion video may be contingent on the availability of large amount of inexpensive bandwidth. There are three types of services that a typical MSAT system is expected to provide to its users, namely:

1. Continuous Voice Service
2. Continuous Data Service
3. Packet Data Service

The continuous services for voice or data are similar in the sense that both of them are based on circuit switching. A circuit switched connection is one for which a specific transmission path or circuit is established for dedicated use during the duration of each call, that is, from the time a call is set up to the time it is terminated. [12]

The difference between voice and data calls is that a user terminal participating in a voice call uses a voice activity switch (to provide a time assigned speech interpolation advantage in terms of the power limited operation of the satellite), whereas no such activity switch is used for the data call (a circuit assigned to a data call is assumed to be always active). The voice activity switch turns the transmitted signal off from the mobile terminal during idle periods of voice. This reduces the power required by the satellite repeater to the level required by the active voice sources. [12]

Until recently, the packet data service was expected to carry low-rate, low-volume data for application like messaging, paging or telex-type services. The future systems are expected to provide hybrid satellite/ground-based personal communication service which would include high quality voice, variable bit-rate data (4.8kbps to 64kbps), along with image and position determination to mobile and fixed users. This would entail the need of [22]:

- extending concepts typical to cellular network to satellite systems. This is due to the need to integrate satellite systems with terrestrial networks.
- channel sharing to cope with higher variance of traffic per spot beam. This is due to the increased demand for capacity.
- decentralize the network control in order to reduce the signaling information exchanges. This is to ensure high required link availability.

2.3 Multiple Access Schemes

A key element that determines the satellite network complexity and efficiency is the selected multiple access scheme. Considering the environmental conditions, the optimal scheme should provide: [4]

1. highly efficient use of the available transponder power and bandwidth for single or multiple spot beam satellites,
2. resistance to hostile propagation conditions like multipath fading and shadowing,
3. adaptability to highly variable traffic patterns, i.e., equally efficient for high and low traffic loads and graceful performance degradation in case of non-nominal conditions,

4. flexibility to different application, i.e. digital voice, data and mixed traffic,
5. adaptability to different network configurations: star, multi-star, partially meshed, etc.,
6. compliance with power flux density (PFD) requirements for user terminal providing minimum RF interference to other services.

A review of the existing access techniques shows that none of them satisfy all these requirements. Requirement 1 implies coherent detection at the modem side in order to maximize the power efficiency together with some sort of spectral shaping to limit the bandwidth occupancy. Moreover, carrier activation has to be used to maximize the satellite power utilization. The peculiar propagation characteristics of the mobile/fixed channel call for a pilot-based synchronization system able to keep the mobile in-lock even in the absence of the communication carrier (i.e., during speech pauses or between consecutive data bursts). Requirements 3, 4 and 5 call for avoiding a rigid framing structure in handling the traffic channels. [12]

The multiple access schemes can be classified into the following three categories:

- Fixed Assignment,
- Random Access and
- Controlled Access techniques.

Fixed Assignment schemes, such as those using frequency division multiple access (FDMA), time division multiple access (TDMA), or code division multiple access (CDMA),

permanently assign a fraction of the system's resources to each user. Such schemes are best suited to routes carrying large quantities of steady traffic.

For an MSS system with a large population of bursty short traffic sources, a permanent assignment scheme might be insufficient. Random Access techniques like Pure or Slotted Aloha, may be better suited for such systems. This is despite the fact that they have to be operated at low efficiency in order to avoid problems of instability. [12]

For systems where the information generated by an active user tends to be long (for example, in voice calls or long data transactions), Controlled Access techniques, may be a better alternative. In these schemes, a fraction of the system's resources (bandwidth or time) is set aside to carry requests for (resource) assignment. Successful requests get an appropriate assignment which can then be used for the actual message transmission. Circuits may be assigned in a random access mode. The division of the system's resources may be done either over time, as in Reservation Aloha, or over frequency. For telephone speech traffic on satellite mobile systems and for other fixed thin route networks, a demand assignment multiple access (DAMA) scheme is often preferred in which a circuit-switched FDMA, TDMA or CDMA channel is assigned to the user only of the period of the call for which it is needed. [10]

2.3.1 Fixed Assignment Schemes

These schemes permanently assign a part of transmission resource to each user in a manner proportional to the user's requirements. These schemes tend to be suitable for users who generate traffic fairly regularly. The actual entity being shared could be either bandwidth,

time, or a set of mutually orthogonal codes, resulting in Frequency Division Multiple Access, Time Division Multiple Access or Code Division Multiple Access respectively. Figure 2-2 provides a graphical representation of these schemes. Each of these schemes will now be presented briefly.

Figure 2-2: Frequency Division Multiple Access, Time Division Multiple Access and Code Division Multiple Access

2.3.1.1 Frequency Division Multiple Access (FDMA)

To illustrate the concept of FDMA, let us consider a satellite system with a total satellite system bandwidth of B Hz serving N nodes. If the users generate equal amounts of traffic, access is provided by dividing the bandwidth into bands of (B / N) Hz and permanently assigning one such band to each user for transmission. If the users generate unequal amounts of traffic, bandwidth can be assigned in proportion to the traffic generated by each user. The band assigned to a user is available over all time, or at least, for extended periods. [14]

Figure 2-3: Frequency Division Multiple Access [14]

In some circumstances, FDMA schemes may be comparatively inefficient since they require guard bands between neighboring bands to prevent the transmission in one band from interfering with those in the neighboring bands. Given that the system requires guard bands of Δ Hz around each user frequency band, the bandwidth available for to each station for information transfer is:

$$B_T = [B - (N + 1) \Delta] / N$$

Another problem with FDMA systems is that they require the satellite amplifier to be linear in nature. The high power amplifier (HPA) on board the satellite is usually constructed from a travelling wave tube (TWT) device. An HPA works most efficiently when it is operated close to saturation but then non-linearities occur. Unfortunately, the linearity requirement of the FDMA system implies that the TWT has to be backed off substantially in order to operate it as a linear amplifier. This in turn, leads to inefficient usage of the available satellite power. For this reason, fixed assignment strategies have tended to increasingly shift from FDMA to TDMA as certain technical problems associated with the latter are overcome. [10]

2.3.1.2 Time-Division Multiple Access (TDMA)

Again, to illustrate the concept of TDMA, let us consider a system where the available system bandwidth is B Hz. Also, consider the total transmission time to be divided into frames of T seconds each. Let each frame be further subdivided into N slots of duration T / N seconds where each slot is permanently assigned to one of the N users for its transmissions. Unlike the FDMA scheme where a user continuously transmits in its assigned frequency channel, in a TDMA scheme each user transmits over the full system bandwidth of B Hz but only during its own time slot in each frame. This is illustrated in Figure 2-4.. [14]

Figure 2-4: Time-division multiple access

Corresponding to guard bands in FDMA scheme, TDMA requires guard times to separate one user's transmission from that of the next one in the frame. Since the transmission from each user is essentially done in the burst mode, additional preambles may also be required to enable carrier synchronization (for coherent demodulation) and clock synchronization (for bit timing in digital transmissions). These synchronization procedures are essential to allow the receiver to recover the information contained in the transmitted burst. [14]

A TDMA system also requires overall system timing so that each user can unambiguously determine the frame boundaries and the position of its own slot within the frame. Any

possibility of error in this determination will translate into a longer guard time requirement and will have a detrimental effect on the overall efficiency of the system. The receivers in a TDMA system must be capable of rapid burst synchronization, that is quickly acquiring carrier (and possible, clock) at the beginning of the bursts they are intended to receive [14].

It is evident from the above that a TDMA system requires considerably more complex timing and synchronization than an equivalent FDMA system. Another disadvantage of TDMA is that the transmissions from each mobile station are in the form of bursts of T / N seconds with the station being idle for the remaining duration of the frame. This implies that the transmitters in a TDMA system would have a high peak power requirement even though their average transmitted power is considerably lower. For MSS systems with small user terminals, this may be undesirable. Because of their hardware limitations, user terminals in such systems would prefer to transmit continuously at the average power level rather than in bursts of high power.

In a TDMA system, at any given instant only one user would be in the transmitting mode. This makes it easier to exercise power control in the system by requiring each user to adhere to pre-specified transmission power limit. Because of this the system may be operated such that the satellite transponder is close to saturation limit. [14]

2.3.1.3 Code Division Multiple Access (CDMA)

For a digital system, it is possible to have a number of users share the same bandwidth and time, while keeping them separated by ensuring that they use different codes which are orthogonal to each other. Each station is assigned a pseudo-random sequence for transmitting its message bits. The mode of transmission is to EX-OR (exclusive-or) each data bit with specified sequence and transmit the resulting sequence. Knowing the sequence used for transmission the receivers can then extract the information being sent by essentially process of correlation. It is important to note that CDMA systems are inherently more inefficient than FDMA and TDMA schemes. This is primarily because the high effective transmission rate (compared to the actual bit rate) requires considerably more bandwidth for its operations. Acquiring and maintaining clock and carrier synchronization in such a system is also reasonably complex.

The main advantage of CDMA is that it inherently provides a processing gain of M and can be used in systems which must transmit at low power. The performance of CDMA can be further improved if error detection and correction coding is used. Normally, in FDMA and TDMA systems, coding leads to undesirable increase in bandwidth. In a CDMA system, the signal is already spread over a very large spectrum and the increase in spectrum due to coding is not too significant. At the same time, coding improves the system performance enormously.

In environments with noise, this processing gain may also be used to advantage. Moreover the inherent anti-jam (AJ) and anti-interference (AI) properties of the PN sequences provide certain amount of security to data transmission in a CDMA system.

2.3.2 Random Access Schemes

Fixed assignment strategies tend to be inefficient when the user population consists of a large number of bursty users. Such low duty-factors users generate traffic in bursts with long

inactive periods between bursts; hence it will be inefficient to assign fixed transmission resources to each of them in a permanent fashion. Random schemes using contention based strategies for multiple access are more suitable for use in such an environment. In these schemes, a transmitter uses the entire transmission resource of the system only when it is needed. That is, there is no fixed (permanent) assignment of transmission resource in this fashion allows a large number of bursty users to be supported by the system.

2.3.3 Controlled Access or Reservation Based Schemes

The random access schemes presented above require channel sensing mechanism which allow transmissions to be aborted if the channel is sensed to be busy. Since such sensing would not be practical in a satellite system, it would be inappropriate to use these schemes for multiple access in a VSAT or MSS environment. For these satellite systems, random access schemes which may be applied can provide only limited values of capacity. Higher capacity requires the use of more complex collision resolution schemes. Even these protocols are only able to increase capacity to about 48% [12]. If bandwidth efficiency is a major criterion along with the ability to support a large and bursty user population, then a better option is to employ schemes with embedded reservations.

2.4 Mobile Satellite Propagation Characteristics

Satellite Communications with land mobile terminals suffer from strong variations of the received signal due to signal shadowing and multipath fading. Shadowing of the satellite signal by obstacles in the propagation path (buildings, bridges, trees, etc.) results in attenuation over the total signal bandwidth. This attenuation increases with carrier frequency, i.e., it is more marked at L-band than at UHF. For low satellite elevation, the shadowed areas are larger than for high elevation. Multipath fading occurs because the satellite signal is received not only via the direct path but also after being reflected from objects in the surroundings. Due to their different propagation distances, multipath signal can add destructively resulting in a deep fade.

Therefore, for all types of land mobile systems, the communication link between the satellite and the mobile terminal is the most critical part of the transmission path and limits the performance of the total system. The introduction of judicious fade margin in to the link margin has substantial consequences for the system cost. The link availability determines the achievable throughput, efficiency and the resulting message delay. Furthermore, the time varying behavior of the land mobile satellite link must be considered when choosing a modulation scheme as well as when designing channel access and error protection methods. Also, carrier recovery, bit timing and frame synchronization have to be adapted carefully to the channel behavior. For these reasons, it is essential to thoroughly investigate characteristics of land mobile satellite link.

Various tables and empirical expressions are available in literature giving shadowing margin versus environment, the satellite elevation angle and terrestrial coverage probability. According to [9], for a suburban or urban environment, a fade margin of 10 dB or more is required.

2.5 Summary

The thesis research work has focussed on a geostationary satellite system capable of providing multi-variable data rate services to users in North America with TDMA as multiple access scheme. As discussed in this chapter, the field of view with a geostationary satellite is large and hence one satellite is sufficient to provide service to the continent of North America. Also, since the satellite is relatively stationary, issues such as the Doppler effect, hand-over and inter-satellite links need not be examined. The data rates being considered range from 8 kb/s for speech users with hand-held terminals to 64 kb/s for data users with transportable terminals. The performance of the TDMA frame structure is evaluated in terms of bandwidth and power-limited capacity. A comparison between the proposed TDMA system and a CDMA system is suggested as future research work.

In the next chapter, the new TDMA frame structure is introduced and choice of its parameters is discussed. Also, its capacity performance is compared with the traditional TDMA frame structure.

Chapter 3

A Novel TDMA Frame Structure for MSS Systems

3. Introduction

In this chapter, a novel TDMA frame structure is proposed for a regional GEO MSS system. It accounts for multiple users' data rates (8kb/s to 64kb/s) with hand-held as well as fixed terminals and permits dynamic change in user rate during the call. The traditional frame structures provide variable rate service by assigning several time slots to higher data rate users. This is very inefficient in GEO-MSS systems since guard time and some other overhead bits for these specific systems must exist in each time slot. The basic idea of the proposed scheme is to defragment time slots frequently in a frame to minimize non-information bits which leads to higher capacity. A preliminary study is provided to evaluate the expected guard time along with the procedure for the frame defragmentation dynamics.

Initially, traditional TDMA frame structures are discussed with typical parameter values and time-slot assignment dynamics. This is followed by a presentation of the new TDMA frame structure with its choice of parameters. The time slot assignment mechanism and the required signaling procedure ensues. The chapter concludes with a brief comparison between the capacity performance of the traditional and proposed frame structure.

3.1 Traditional TDMA Frame Structures

In traditional cellular TDMA systems, each time slot in the frame is fixed in length. In GSM, for example, each time slot consists of 156.25 bits in a 4.615ms frame. Also, the time slot is at a predetermined location in the frame and has a fixed amount of overhead bits associated with it. The overhead bits may include a training sequence for the equalizer, synchronization bits, and guard time. In GSM, they are 26 bits, 8 bits and 30.47 μ sec respectively [15]. Figure 3-1 depicts the GSM-TDMA frame structure.

Figure 3-1: Physical Structure for GSM Hyperframe, Superframe, Multiframe, Frame, and Time Slot

The delay equalization process in the receiving path is required to compensate for the spread in time delays resulting from the multipath propagation. Also, the process is essential when delay spreads are significant compared to the information bit period. In GSM, the transmitted bit period is about $37\mu\text{sec}$, and delay spreads of about $5\mu\text{sec}$ are common [15]. The delay-spread problem becomes critical and difficult to solve with higher transmission bit rate.

The GSM system is specified to allow operation of mobile stations in cells when they are up to 35 km from their base station. As signals from all the mobiles in the cell must reach the base station without overlapping each other, a guard period of 68.25 bits ($252\mu\text{sec}$) is provided in the access burst. This long guard period in the access burst is needed when the mobile station attempts its first access to the base station, or after handover has occurred. To provide the same long guard period in the other bursts would be spectrally inefficient. The GSM system overcomes this problem by using adaptive frame alignment. When the base station detects a 41-bit random access synchronization sequence with a long guard period, it measures the received signal delay relative to the expected signal from a mobile station of zero range. This delay, called the timing advance, is signaled using a 6-bit number to the mobile station, which advances its time base over the range of 0 to 63 bits, i.e., in units of $3.69\mu\text{sec}$. By this process the TDMA bursts arrive at the BS in their correct timeslots and do not overlap with adjacent ones. This process allows the guard period in all other timeslots to be reduced to $8.25 \times 3.69\mu\text{sec} = 30.47\mu\text{sec}$ (8.25 bits). [25]

In a terrestrial cellular system, a user demanding high data rate services (higher than what can be accommodated in a regular time slot) can be assigned multiples of the regular time slot. The overhead associated per time slot is not significant and multiple assignments of the time slots are feasible. For example, in GSM, the overhead is $\frac{16.25 \text{ overhead bits}}{156.25 \text{ total bits}} = 10.4\%$. On the other hand, a GEO MSS system frame structure is not similar and the assignment of multiple time slots may not be practical. Despite extensive literature survey, very few details are available regarding TDMA frame structure for any of the recent GEO MSS systems being launched or planned. Nevertheless, a frame structure for the TMI's MSAT MT-ST signaling channel is presented in Figure 3-2 for comparison purposes [17]. The MT-ST is a TDMA channel used by the mobile terminal to respond to the requests made by the Earth Station. It is also very important to note that for the MSAT system, there are only five large spot beams covering the whole of North America (a sixth spot beam covers the Hawaii Islands). Therefore, the guard time value is excessively large. The future systems being planned consist of several spot beams (around 100) and the guard time value is expected to be relatively small.

Figure 3-2: The MSAT TMT-ST TDMA signaling Channel Frame Structure [17]

Although the above MT-ST signaling channel is not meant for data transmission, the figure is presented to depict the difference in the number of overhead bits. In this specific frame structure, the overhead is $\frac{63.14 \text{ ms}}{120 \text{ ms}} = 52.61\%$. Again, as before, a user demanding high data rate services (higher than what can be accommodated in a regular time slot) can be assigned multiples of the regular time slot. In this case, each time slot has an overhead of 52.61% and assignment of multiple time slots is spectrally inefficient.

In the next section, the new TDMA frame structure suitable for future MSS systems is presented and analyzed. A new time-slot assignment scheme for high data rate users is discussed and compared with the traditional multiple time slot assignment mechanism.

3.2 Proposed Frame Structure [18]

For purposes of comparison with the proposed TDMA frame structure, a 50ms traditional frame structure operating at 160 kb/s is defined. Each time slot is designed to accommodate user data and overhead bits (synchronization bits, equalizer training sequence and head and tail bits). Also, there must exist a guard time between two consecutive time slots. The duration of 50 ms is expected to incorporate an acceptable delay in addition to the normal 250 ms delay associated with the one-way GEO satellite link.

The choice of the data rate has a significant impact on the peak power requirements of the mobile terminal. If the data rate is very high, the mobile terminal must transmit with high peak power during its time slot to satisfy the carrier-to-noise (C/N) ratio. The high data rate leads to a high bandwidth value which, due to KTB^I , results in large noise power. In [9], a regional geostationary MSS system with speech users is described and a carrier data rate of 45 kb/s is assumed. The users are assumed to operate with a data rate of 4.8 kbps and each carrier has 8 users. However, this carrier rate cannot be adopted because of the requirement to support higher data rate (8kbps - 64kbps) users. If a very low carrier data rate (100 kb/s for example) is chosen, the system must have several carriers and the access schemes tends towards FDMA. A carrier data rate of **160 kbps** is chosen to strike a balance between the two conflicting requirements of low peak power dissipation and few carriers. The overhead bits including synchronization, equalizer training and head and tail bits are assumed to be 40 altogether. As will be shown later, the actual number of bits does not affect the comparison

of the performance of the traditional time-slot assignment mechanism and the proposed mechanism.

The minimum data rate to be supported is 8 kb/s which translates into 400 bits of coded user data in a 50 ms frame. The overhead for the time slot consists of the 40 bits mentioned above and a guard time. The value of the guard time depends upon the size and location of the spot beam. There is significant difference in the sizes of the spot beams in the proposed system. According to the results from Chapter 6, the guard time value can range from 0.7ms to 7.2ms. Therefore, it is proposed that multiple discrete guard time values be used in the system. For the purposes of the comparison, an average guard time value of 2.25 ms is used.

Each time slot is, therefore, $(440 \text{ bits} / 160 \text{ kb/s}) + 2.25\text{ms} = 5.0\text{ms}$ long. Hence, the 50ms frame has a capacity of ten 8kb/s time slots. If the user wishes to communicate at data rates higher than 8kb/s (16kb/s for example), the user shall be allocated multiple time slots (two 8kb/s for a 16kb/s user) in the frame. In the traditional frame structure, there always exists guard time between any two time slots even if a user has been assigned two consecutive time slots.

In the proposed frame structure, the time slots would be variable in length. Also, the overhead bits per time slot would be 40 bits (excluding the guard time) as in traditional TDMA frame structure. In addition, each time slot would have a guard time of 2.25ms

¹ Noise Power = KTB , where K = Boltzmann's constant = 1.38×10^{-23} J/K, T = Temperature in °K and B = bandwidth in Hz.

irrespective of the corresponding bit rate. The frame length is still considered to be 50ms and the transmission rate is 160kb/s. The length of the time slot assigned to each user will be determined from the data rate at which that the user wishes to operate. The time slot lengths for different data rates are listed in Table 3-1.

Data Rate	Duration of a time slot in the proposed frame
8 kb/s	5.0 ms
16 kb/s	7.5 ms
32 kb/s	12.5 ms
48 kb/s	17.5 ms
64 kb/s	22.5ms

Table 3-1: The time slot lengths (includes overhead bits and guard time) for different data rates

For example, if the user wishes to operate at 64 kb/s, his/her particular time slot would span $3200\text{bits} / 160 \text{ kb/s} = 20\text{ms}$ for user data, 0.25ms for overhead and 2.25ms as guard time. Such variable length time slot allocation is expected to improve frame efficiency considerably. *The frame efficiency is defined as the ratio of the time used for revenue-generating traffic to the time used to transmit all the bits in the frame.* For example, considering the case of 64kb/s user data rate, frame efficiency would be $20\text{ms}/(20.25 + 2.25\text{ms}) = 88.89\%$, much better than the $20\text{ms}/[20 + 8 \cdot (0.25 + 2.25)]\text{ms} = 50.0\%$ allowed by the traditional TDMA time slot allocation.

Furthermore, the *time slot allocation* for each user shall be dynamic and would be allowed to change periodically, see Figure 3-3. If a user is transmitting in the last 5.0ms of the current

frame, the user may be made to transmit in a different 5.0ms segment of the next (or future n^{th}) frame. The segment assignment for the next (or future n^{th}) frame would be done by the satellite on-board processor or alternatively at an earth gateway with additional time delay. The objective is to accumulate all the 'in use' time slots in one portion of the frame to result in a contiguous segment of 'not in use' space towards another portion of the frame. When there is no call, a segment of the frame is available to be used by a user at any data rate (subject to the length of the segment).

Figure 3-3: An illustration of the defragmentation process in the frame

The main advantage of this scheme is the increased efficiency due to reduced overhead in the transmission of users at higher data rates. Furthermore, it is very versatile and flexible. The following are a few factors that make the scheme attractive.

- A change in number of overhead bits (other than guard time) does not affect the capacity performance (efficiency) of this scheme as drastically as it does for the traditional TDMA case. The ‘defragmentation’ of the frame may be done every n frames ($n \geq 1$). If the complexity involved in performing ‘defragmentation’ every frame is too high, the frame may be ‘defragmented’ less frequently (only when a call is cleared).
- It may also be better to reassign time slots for only one user every time a call is cleared. The remaining users in the frame shall maintain their current time slot assignments. There should be no significant loss in performance because frame ‘defragmentation’ occurs only when the call is cleared. If more than one time slot needs to be relocated, it can be done sequentially as the delay in the process will not significantly affect the overall capacity performance for the expected slow traffic variations. It is also to be noted that additional signaling will be required to perform the defragmentation process. However, it is considered to be very minimal as compared to the overall capacity provided.

3.3 Signaling required for defragmentation of frames

It is observed that the ‘defragmentation’ of the frame would be required only when new calls are being admitted or cleared from the system. It is proposed that the signaling for ‘defragmentation’ shall follow ARQ protocol. Although this process might take a relatively long time, it can easily be absorbed in the long call setup and termination time. The impact of such an ARQ scheme on the overall performance of the system is suggested for future research work (see Chapter 7).

3.4 A Comparison of the Frame Structures

A brief comparison is made here to evaluate the performance of the proposed TDMA frame structure in terms of throughput. More accurate results are presented later in Chapter 6, when augmented with the completeness of other system design parameters. At 160kb/s, the 2.25ms guard time translates into 360 bits and along with 40 bits for other overheads, the total number of overhead bits is 400. With a 50ms frame operating at 160kb/s, there are 8000 total bits available. In the proposed system, if the 64 kb/s time slot is considered, the number of information bits including forward error correction (FEC) bits is 3200 and with the addition of 400 overhead bits, total bits are 3600. Therefore, the frame has the total capacity of $8000/3600 = \text{two } 64 \text{ kb/s}$ users (with 800 bits to spare which can accommodate an 8kb/s user). The traditional frame structure has a total of ten 8kb/s slots and it can accommodate one 64kb/s user and two 8kb/s users. Therefore, using the proposed frame structure, there is a 100% improvement in the capacity for 64kb/s users. However, it may be rare to find all users in the frame structure operating at a data rate of 64 kb/s. A similar analysis is carried out for other data rates and the results presented in Table 3-2.

Data Rate, kb/s	Overhead bits/ TS (with GT)	Info. bits (with FEC)	Total bits in TS (prop. structure)	Capacity (proposed structure)	Capacity (traditional structure)	Improvement
8	400	400	800	10.0	10.0	0%
16	400	800	1200	6.67	5.00	33%
32	400	1600	2000	4.00	2.50	60%
48	400	2400	2800	2.85	1.67	71%
64	400	3200	3600	2.22	1.25	78%

Table 3-2: Improvement in Capacity with the proposed frame structure over the traditional frame structure

The performance of the proposed frame structure is enhanced by the inherent long guard time requirements of GEO-MSS systems. The performance of the system depends heavily upon the choice of guard time values and is evaluated with exact guard time values in Chapter 6.

In the next chapter, a complete system design is presented with the specifications and the calculations. The calculations and the design parameters are the basis of the software module discussed in Chapter 5.

Chapter 4

System Design

4. An Introduction to the Design Procedure

In the previous chapter, the concept of the new TDMA frame structure is discussed with preliminary results. To verify the proposed capacity enhancements, a future MSS system supporting 8 kb/s - 64 kb/s data rate users is designed with multiple spot beams. In this chapter, calculations of the design parameters are presented. The steps involved in the design can best be summarized as follows:

- generation of individual spot beams,
- arriving at a spot beam layout acceptable for the desired coverage area,
- design a methodology for interference analysis in the spot beams,
- using the specifications and the link budget, compute the acceptable interference levels for possible frequency reuse,
- device frequency assignment strategy and assign frequencies to the spot beams,
- perform link budget analysis for capacity investigation purposes.

In the next section, the system specifications are presented which are then followed by calculations pertaining to the spot beam layout generation. The antenna pattern and the earth-

satellite geometry are discussed in Section 4.2 and 4.3 respectively. Section 4.4 explains the calculations performed to achieve individual spot beam contour layouts. This is followed by Interference Analysis in Section 4.5 and the chapter is concluded with a detailed description of the link budget parameters in Section 4.6.

4.1 System Specifications

The system is designed to operate in North America, including the Caribbean Islands and the Hawaii Islands. Some of the following specifications are adopted from the *MSAT* satellite system operated by TMI Communications [19]. The remaining specifications are determined during this research as part of the future system design. The following are the system design specifications:

1. The system shall operate with a total bandwidth of 29 MHz. The link between the user terminal and the satellite shall operate in the L-band (1-2 GHz) while the link between the satellite and the central earth station shall operate in the Ku-band (12.5 - 18 GHz). The L and Ku-band configuration is most popular among the current GEO MSS systems (*MSAT*, *European Mobile Satellite* [3]). The operating conditions under these frequency bands are well-known and the future MSS systems being designed are intended to replace the existing ones in the same bands.
2. The system shall operate with QPSK as the modulation scheme. QPSK is considered the most appropriate choice when ease of implementation, bandwidth and power efficiency and resistance to non-linearities are considered [17].

3. The satellite shall operate with a 14 m antenna. In order to permit reliable communications between the satellite and a hand-held mobile terminal, the satellite antenna must be large. The practical limit of the GEO mobile satellite antenna diameter is determined by the fairing height of the launch vehicle, which for the Atlas IIAS is about 12 or 13 m, corresponding to a gain at 2 GHz of 42 dB [9]. Once one has arrived at a large antenna diameter, less RF power is required to provide a large circuit capacity. The currently planned Thuraya system by the Thuraya Satellite Telecommunications Co. shall operate with a 12 m antenna [7].

4. The system shall support multiple data rates ranging from 8 kb/s to 64 kb/s. These data rates include error correction detection/coding and overhead bits which differ for different data rates. The existing *MSAT* Circuit-Switched Data currently provides 2.4 kb/s and 4.8 kb/s throughput and supports fixed and mobile applications such as e-mail, fax, LAN access and file transfer [20]. For future MSS systems, higher data rates in the neighborhood of 32 kb/s and possibly up to 64 kb/s are being envisaged.

5. The system shall provide a bit error rate of less than 10^{-2} for the 8 kb/s speech user and less than 10^{-5} for higher data rates. The existing *AMSC* system is designed with a nominal threshold of 1% (10^{-2}) error rate for the 6.4 kb/s speech channel [17]. Also, from experience, bit error rate of 10^{-2} has proved to deliver acceptable speech quality while a bit error rate of 10^{-5} is not uncommon for data users.

6. The satellite is located at 106.5°W and has an antenna capable of generating multiple spot beams covering all of North America. The current *MSAT* satellite is located at 106.5°W and it provides service to North and Central America (including coastal waters to 400 km), Mexico, Hawaii, and the Caribbean [20] with seven large beams. The coverage area for a future MSS system serving North America is expected to be identical. However, the number of spot beams shall be much larger to utilize the high gain of satellite antenna effectively. The Asian Cellular Satellite System (ACeS), currently being deployed in the Asia-Pacific region is designed to operate with 140 spot beams. The Thuraya system is expected to have 256 re-configurable spot beams providing services to the Arab states, Central Asia, India and the East Europe [7].
7. The satellite has a Ku-band amplifier capable of generating 80W of power. The Ku-band satellite amplifier power is an important factor which determines the total capacity of the network. It is useful to derive a relationship between the network capacity and the satellite amplifier power and then substitute the value of the amplifier power.
8. The system shall yield optimum performance down to an elevation angle of 15° , identical to the requirement of the current *MSAT* system [8].
9. The speech users operating at data rate of 8 kb/s shall have a voice activity factor of 40% [9].

10. Due to the variability of the traffic intensity expected from different regions of North America, the spot beam areas (due to the edge-of-beam power level) are to be manipulated. Therefore, two adjacent spot beams may represent different edge power levels with respect to their centers. Therefore, in the *forward* link, the satellite shall dedicate different power levels to the centers of the spot beams. The impact of such dynamic power assignment on the system capacity and satellite power utilization is suggested as future research work (Chapter 7).

The ability to generate spot beams and to create an acceptable layout for the desired coverage area is an integral part of the MSS system design. The generation of the spot beams is based on the antenna pattern, path loss and the earth satellite geometry. In principle, a signal transmitted from an edge of the spot beam is received at the satellite with a power level which is less (attenuated) by a certain amount with respect to a signal transmitted from the center of the spot beam. The amount of attenuation is determined by the antenna pattern and the path loss. A signal transmitted from the satellite to a user terminal at an edge of the spot beam also undergoes similar attenuation with respect to the center of the spot beam due to the transmit antenna pattern and the path loss. Figure 4-1 is a very brief illustration of the concept of attenuation in the spot beam. Also, due to the spherical shape of the earth, the shape of the spot beam is drastically different in different regions of the desired coverage area. For example, as shown in Figure 4-2, a 3 dB contour may appear as a small circle near the equator but may appear irregular in shape (resembling an ellipse) towards the high latitudes.

In the next section, the principles of antenna pattern are presented along with the actual values used in the system design.

Figure 4-1: An illustration of the spot beam attenuation

Figure 4-2: Difference in the shapes of the spot beams in different regions due to the spherical nature of earth

4.2 Antenna Pattern

For communications with handheld terminals, the link budget requires a larger gain of the satellite antenna. As discussed earlier in this chapter, a 14 m antenna is chosen. A typical antenna pattern response is depicted in Figure 4-3. An antenna has a maximum gain in the boresight (center of the antenna pattern) direction and the areas around the boresight experience less gain. The antenna pattern is identical in both transmission and reception modes.

Figure 4-3: Radiation characteristics of a rotational-symmetric directional antenna [10]

The gain of an antenna in boresight direction is given by [10]:

$$G_{\max} = \eta \left(\frac{\pi D}{\lambda} \right)^2 \cong 10 \log_{10} \eta \left(\frac{\pi D}{\lambda} \right)^2 \text{ dBi} \quad \text{Eq. 4-1}$$

where:

η = antenna efficiency; typical range: 0.550.65

D = antenna diameter = 14 m

λ = wavelength = speed of light / frequency

In the proposed system, η is chosen as 65% and $D = 14$ m. In a typical GEO-MSS system, the link between the user terminal and the satellite dictates the performance of the system due to the limited capabilities of the user terminal. Therefore, the analysis presented here is for the user terminal and the satellite link. The frequency of interest is the L-band frequency of 1.6 GHz which yields a wavelength of 0.1875 m. Hence, $G_{\max} = 45.5$ dBi.

The gain of the antenna in regions distant from the boresight is a function of the angle, α , with respect to the boresight. The value of α , at which the gain is half of that at the boresight is often referred to as 3-dB (half-power) beamwidth, α_{3dB} . The 2-sided 3 dB (half-power) beamwidth of an antenna with a diameter D and operated at a certain frequency is [10]:

$$2\alpha_{3dB} = 70^\circ \cdot \frac{\lambda}{D} \quad \text{Eq. 4-2}$$

In the proposed system, the 3-dB beamwidth, $\alpha_{3dB} = 1.09375^\circ$. A generalized antenna pattern relating the gain of the antenna, G with α and α_{3dB} is given in Eq. 4-3 below. If $\alpha = 0$ then the signal is received at boresight while if $\alpha = \alpha_{3dB}$ then the signal is received with half the maximum gain at the edge of the 3-dB spot beam.

$$\frac{G}{G_{\max}} = \left[\frac{\sin 1.39 \left(\frac{\alpha}{\alpha_{3dB}} \right)}{1.39 \left(\frac{\alpha}{\alpha_{3dB}} \right)} \right]^2 \quad \text{Eq. 4-3}$$

The background presented above regarding antenna patterns and gain/attenuation relationships is very instrumental in the generation of spot beams. As mentioned earlier, a spot beam is a contour of a certain gain, for example -3 dB, with respect to the boresight. The steps involved in generating spot beams can be itemized as follows.

1. identify the center of the spot beam (record its coordinates); it will serve as the boresight,
2. compute the path loss from the satellite to the center of the spot beam,
3. locate the locations in the vicinity of the boresight where the composite effect of the path loss and the antenna gain is of desired attenuation with respect to the boresight.

However, due to the spherical structure of the earth, step 3 is not straightforward and requires insight into the earth-satellite geometry. In the next section, a brief background regarding earth-satellite geometry is presented. This is followed by actual spot beam contour calculations in Section 4.4.1.

4.3 Earth Satellite Geometry

The basic problems regarding earth-satellite geometry involve calculating the distance to the satellite and the azimuth and the elevation angles of the user terminal antenna. The angles are required by the antenna to point at the satellite. Given the latitude, ϕ_g , of the user terminal and difference in longitude, Δl , taken relative to the sub-satellite point (a term used to refer to a position on earth which lies on the line joining the center of the earth and the satellite), the angles and the distance can be calculated. Assuming that the earth is spherical with a radius equal to its mean equatorial radius of 6378 km, these quantities can be calculated using the geometry in Figure 4-4. The basic trigonometric formulae, needed involving the laws of cosines and sines for plane and spherical triangles are listed in Appendix A.

Figure 4-5: The parameters associated with the plane triangle EOP

4.3.1 Slant Range

The slant range d is determined by the law of cosines applied to plane triangle EOP [14], redrawn in Figure 4-5.

$$\begin{aligned} d &= \sqrt{R_E^2 + r^2 - 2R_E r \cos \gamma} \\ &= \sqrt{h^2 + 2R_E(R_E + h)(1 - \cos \phi_s \cos \Delta l)} \end{aligned} \quad \text{Eq. 4-5}$$

where $r = R_E + h$.

4.3.2 Elevation

The elevation angle θ is obtained from the law of sines, which implies the following: [14]

$$\cos \theta = \frac{r}{d} \sin \gamma = \frac{r \sin \gamma}{\sqrt{R_E^2 + r^2 - 2R_E r \cos \gamma}} \quad \text{Eq. 4-6}$$

or

$$\cos \theta = (R_E + h) \sqrt{\frac{1 - \cos^2 \phi_g \cos^2 \Delta l}{h^2 + 2R_E(R_E + h)(1 - \cos \phi_g \cos \Delta l)}} \quad \text{Eq. 4-7}$$

Normally, a minimum value for θ , $\theta_{\min}$ is specified as part of the system specifications. As long as the user is at a location where $\theta \geq \theta_{\min}$, a certain quality of service is guaranteed.

4.3.3 Coverage Area (Footprint)

The coverage area of the satellite is defined as the area on the earth's surface where a satellite is seen with an elevation angle $\theta \geq \theta_{\min}$. $\theta_{\min}$ is called "minimum elevation".

Figure 4-6: Coverage area (footprint) of a satellite [10]

The coverage area of a satellite is a spherical cap on the earth's surface. The extent of the coverage area is characterized by $\theta_{\min}$, $T_{\max}$, $d_{\max}$, $\phi_{g \max}$. The extension of coverage increases with higher h and lower $\theta_{\min}$.

$$\text{With } \phi_{g \max} = \arccos \left[\frac{R_E}{r} \cos \theta_{\min} \right] - \theta_{\min}, \quad [10] \quad \text{Eq. 4-8}$$

the extent of the coverage area (length of arc) is given by:

$$D_A = \frac{2\phi_{g \max}}{360^\circ} 2\pi R_E \quad \text{Eq. 4-9}$$

with $\phi_{g \max}$ in degrees.

In the next section, the relationships presented above are used to generate a multiple spot beams layout for the desired coverage area.

4.4 Spot beams Generation/Layout

As mentioned earlier in this chapter, the system is required to perform well down to elevation angles of 15° . Using Eq. 4-8, $\theta_{\min} = 15^\circ$, $r = 42,165$ km, $R_E = 6,378$ km, the maximum latitude $\phi_{g \max}$ (assuming $\Delta l = 0$) = 66.59° . Therefore, the system should provide optimal service till the latitude of 66.59° and higher, if possible. The system is also required to provide service in the coastal regions, approximately 400 km into the either oceans. **With the above restrictions, the system is designed to provide service to users located between the latitudes of 10° and 70° and between the longitudes of 50° and 170° .** The area defined by the latitudes and longitudes is to be covered with several spot beams. As outlined in Section 4.1, the initial step in the generation of spot beam is the identification of the center of the spot beam. For example, New York city can be at the center of the spot beam (boresight). The next step is to seek the contour boundary, which is the locus of locations around the center of the spot beam where the composite effect of the antenna gain and the path loss result in an x dB loss relative to the center of the spot beam. This step is explained in detail below.

4.4.1 Spot beam Contour Calculations

A mathematical closed form for the locus of a contour of a certain attenuation is seen to be of a very complicated process. The alternative strategy adopted here in this thesis involves dividing the desired coverage area into small grid squares and computing the attenuation level for each grid-square with respect to the boresight. Although this is considered computationally inefficient, it is done only once and with a smart design of a database system, the overall performance becomes acceptable as will be seen later.

The parameters required for the calculation of the attenuation are the coordinates (latitude and longitude) of the center of the spot beam (boresight), coordinates of the grid-square and satellite (longitude only). As mentioned before, the attenuation for a specific grid-square is derived from the composite effect of the path loss and the antenna pattern gain with respect to the boresight. The path loss, L_s , is determined for both the boresight and the grid-square location using Eq. 4-10. The difference in the value of L_s for the two locations yields one source of attenuation or gain depending upon the coordinates. In Eq. 4-10, d is the slant range distance to the satellite determined by Eq. 4-5 and λ is the wavelength of the signal.

$$L_s = \left(\frac{4\pi d}{\lambda} \right)^2 \quad \text{Eq. 4-10}$$

The second source of attenuation is the antenna pattern. Given the values of the coordinates of the boresight, grid-square and the satellite, the objective is to calculate the value of α , the reception angle with respect to the boresight and then use Eq. 4-3 to calculate the relative attenuation. Using vector analysis, earth satellite geometry and the antenna pattern, an

original relationship is developed to calculate α from the given parameters. Figure 4-7 shows the parameters and the vectors required for the analysis.

Figure 4-7: The earth satellite geometry and the vectors required for the attenuation computations

In Figure 4-7, the point A represents the satellite while B and C are the grid-square and the center of the spot beam (boresight), respectively. Therefore, a signal transmitted from C shall be received at the satellite with maximum gain ($G_{\max}$) while a signal from B is received with relatively less gain. The following is a brief description of the remaining parameters in Figure 4-7.

- ϕ_{gC} = latitude of the center of spot beam (boresight)

- ϕ_{gB} = latitude of the grid-square
- Δl_C = difference between the values of the satellite longitude and the boresight longitude
(taken positive if the boresight is to the west of the satellite)
- Δl_B = difference between the values of the satellite longitude and the grid-square longitude
(taken positive if the grid square is to the west of the satellite)
- r = distance from the center of the earth to the satellite = 6,378 km + 35,787 km = 42,165 km.
- $\vec{OA}, \vec{OB}, \vec{OC}, \vec{AB}, \vec{AC}$ and $\vec{BC}$ are the vectors used in the analysis.

Since α is a solid angle, it can be calculated by considering ABC as a triangle and utilizing the cosine law. According to the cosine law:

$$|\vec{BC}|^2 = |\vec{AB}|^2 + |\vec{AC}|^2 - 2|\vec{AB}||\vec{AC}|\cos\alpha \quad \text{Eq. 4-11}$$

$$\therefore \alpha = \arccos \left[\frac{|\vec{AB}|^2 + |\vec{AC}|^2 - |\vec{BC}|^2}{2|\vec{AB}||\vec{AC}|} \right] \quad \text{Eq. 4-12}$$

The objective now is to relate each of $|\vec{AC}|$, $|\vec{AB}|$ and $|\vec{BC}|$ with ϕ_{gC} , ϕ_{gB} , Δl_C , Δl_B and r . The

following analysis relates $|\vec{AC}|$ with ϕ_{gC} , Δl_C , and r . The analysis is derived from Figure 4-7.

$$\vec{OA} + \vec{AC} = \vec{OC}$$

$$\therefore \vec{AC} = \vec{OC} - \vec{OA}$$

$$\vec{OA} = r \mathbf{i} \quad \left| \vec{OA} \right| = \sqrt{r^2} = r = 42,165 \text{ km}$$

$$\vec{OC} = r \cos \phi_{gC} \cos \Delta l_C \mathbf{i} + r \cos \phi_{gC} \sin \Delta l_C \mathbf{j} + r \sin \phi_{gC} \mathbf{k}$$

$$\left| \vec{OC} \right| = \sqrt{r^2 \cos^2 \phi_{gC} \cos^2 \Delta l_C + r^2 \cos^2 \phi_{gC} \sin^2 \Delta l_C + r^2 \sin^2 \phi_{gC}} = R_E = 6,378 \text{ km}$$

$$\therefore \vec{AC} = (r \cos \phi_{gC} \cos \Delta l_C - r) \mathbf{i} + r \cos \phi_{gC} \sin \Delta l_C \mathbf{j} + r \sin \phi_{gC} \mathbf{k}$$

$$\left| \vec{AC} \right| = \sqrt{r^2 (\cos \phi_{gC} \cos \Delta l_C - 1)^2 + r^2 \cos^2 \phi_{gC} \sin^2 \Delta l_C + r^2 \sin^2 \phi_{gC}}$$

Eq. 4-13.

The following analysis relates $\left| \vec{AB} \right|$ with ϕ_{gB} , Δl_B , and r . Again, the analysis is derived from

Figure 4-7.

$$\vec{OA} + \vec{AB} = \vec{OB}$$

$$\therefore \vec{AB} = \vec{OB} - \vec{OA}$$

$$\vec{OB} = r \cos \phi_{gB} \cos \Delta l_B \mathbf{i} + r \cos \phi_{gB} \sin \Delta l_B \mathbf{j} + r \sin \phi_{gB} \mathbf{k}$$

$$\left| \vec{OB} \right| = \sqrt{r^2 \cos^2 \phi_{gB} \cos^2 \Delta l_B + r^2 \cos^2 \phi_{gB} \sin^2 \Delta l_B + r^2 \sin^2 \phi_{gB}} = R_E = 6,378 \text{ km}$$

$$\therefore \vec{AB} = (r \cos \phi_{gB} \cos \Delta l_B - r) \mathbf{i} + r \cos \phi_{gB} \sin \Delta l_B \mathbf{j} + r \sin \phi_{gB} \mathbf{k}$$

$$\left| \vec{AB} \right| = \sqrt{r^2 (\cos \phi_{gB} \cos \Delta l_B - 1)^2 + r^2 \cos^2 \phi_{gB} \sin^2 \Delta l_B + r^2 \sin^2 \phi_{gB}}$$

Eq. 4-14

Finally, the relationship between $\left| \vec{BC} \right|$ and ϕ_{gB} , ϕ_{gC} , Δl_B , Δl_C , and r is derived.

$$\begin{aligned}
 \vec{AB} + \vec{BC} &= \vec{AC} \\
 \therefore \vec{BC} &= \vec{AC} - \vec{AB} \\
 \therefore \vec{BC} &= r(\cos \phi_{gC} \cos \Delta l_C - \cos \phi_{gB} \cos \Delta l_B) \mathbf{i} + r(\cos \phi_{gC} \sin \Delta l_C - \cos \phi_{gB} \sin \Delta l_B) \mathbf{j} \\
 &\quad + r(\sin \phi_{gC} - \sin \phi_{gB}) \mathbf{k} \\
 \left| \vec{BC} \right| &= r \sqrt{(\cos \phi_{gC} \cos \Delta l_C - \cos \phi_{gB} \cos \Delta l_B)^2 + (\cos \phi_{gC} \sin \Delta l_C - \cos \phi_{gB} \sin \Delta l_C)^2} \\
 &\quad + (\sin \phi_{gC} - \sin \phi_{gB})^2
 \end{aligned}$$

Eq. 4-15

The values of $\left| \vec{AB} \right|$, $\left| \vec{AC} \right|$ and $\left| \vec{BC} \right|$ can be substituted into Eq. 4-12 to calculate the value of

α . Once the value of α has been determined, Eq. 4-3 can be used to calculate the antenna gain relative to the boresight gain. The antenna gain value can then be combined with the path loss value to yield the composite attenuation value. To illustrate the use of the above equations and concepts, an example is presented next.

Let us assume that the spot beam is centered in the region of New York at the latitude of 40.45°N and longitude of 75°W . Also assume that the satellite is at a longitude of 106.5°W and the grid-square of interest is at a latitude of 40°N and longitude of 70°W . Therefore $\phi_{gB} = 40^\circ$, $\phi_{gC} = 40.45^\circ$, $\Delta l_B = 70 - 106.5 = -36.5^\circ$, $\Delta l_C = 75 - 106.5 = -31.5^\circ$, and $r = 42,165$ km.

The first step is to calculate the path loss from both the boresight and the grid-square locations to the satellite. To enable the calculation of the path loss, the slant range distances from these locations to the satellite must be calculated first. Using Eq. 4-5 and Eq. 4-10, the distance from the boresight to the satellite is 38,334.96 km and the corresponding path loss is 188.19 dB. Similarly, the distance from the grid-square location to the satellite is 38566.05 km and the corresponding path loss is 188.24 dB. Therefore, in terms of path loss, the grid square location receives a signal which is 0.05 dB less in power than the one received at the boresight location. Note that in a different situation, the path loss at the grid-square might be lower in magnitude than that of the boresight when the distance to the satellite is shorter.

The next step is to compute α and the corresponding antenna attenuation. The values of

$|\vec{AB}|$, $|\vec{AC}|$ and $|\vec{BC}|$ must be calculated first. Using Eq. 4-13, Eq. 4-14 and Eq. 4-15, the values of $|\vec{AC}|$, $|\vec{AB}|$ and $|\vec{BC}|$ are 38,566.05 km, 38,334.9 km and 427.7 km respectively.

Using Eq. 4-12, the value of α is 0.536° which when substituted into Eq. 4-3 yields a gain value of -4.03dB relative to the boresight gain. Therefore, the composite gain for the particular grid-square region is the sum of -4.03 dB from the antenna pattern and -0.05 dB from the path loss. The total attenuation value is therefore 4.08 dB with respect to the center of the spot beam.

The process can be repeated for several grid-square locations around the center of the spot beam and the attenuation values can be stored into a database. The database can later be queried to obtain the coordinates of the locations with any particular attenuation value. For example, if a 3 dB contour is desired, the grid-square locations with attenuation value of approximately -3 dB can be retrieved and plotted onto a map.

4.4.2 Coverage of North America

The next step in the system design is to ensure that the desired service area is fully covered with spot beams. Since a signal transmitted from the center of the spot beam (boresight) enjoys maximum gain onboard the satellite receive antenna, an attempt was made to make the centers of spot beams coincide with cities of high population and/or high expected traffic.

In order to enhance the capacity of the system and cater to the varying amounts of traffic generated from different regions of North America, four distinct edge of the spot beam attenuation levels were chosen. This is similar to the concept of macro, micro and picocells in the terrestrial cellular systems. The edge of the spot beam attenuation level along with its location determine the size of the spot beam. The variation in the size of the spot beam help in servicing specific areas more effectively than others. The four different attenuation levels are:

1. -1.0 dB (Highest Traffic Intensity, e.g. regions of New York, San Francisco, ..)
2. -1.5 dB (Moderate Traffic Intensity, e.g. regions of Ottawa, Chicago, ..)

3. -2.0 dB (Low Traffic Intensity, e.g. regions of Phoenix, Orlando, ..)
4. -3.0 dB (Lowest Traffic Intensity, e.g. regions of Oklahoma, Banff Islands, ..)

In absolute practical terms, the edge of the spot beam attenuation level is identical for all spot beams. However, the center of the spot beam receives more power from the satellite by 1.0, 1.5, 2.0 or 3.0 dB depending on the type of the spot beam. This affects the forward link (satellite to the user terminal) performance of the system. Since the forward link is generally not considered critical for a GEO MSS system, the performance analysis for this link is suggested as future work (see Chapter 7). The task of covering the desired coverage area with several spot beams is quite meticulous as it involves ensuring minimum overlap between the spot beams and providing service to all of the desired coverage area. The final configuration of spot beams covering North America with four distinct edge of spot beam attenuation levels is given in Chapter 6.

4.5 Interference Analysis

The final spot beam configuration is followed by co-channel interference and frequency assignment analysis. The co-channel interference analysis is vital to ensure an acceptable quality of service for a user in a particular spot beam. The co-channel interference is calculated by assuming a user (normally termed as the “wanted signal”) is using a frequency in a particular spot beam and that one or more other user(s) are simultaneously using the same particular frequency in other spot beam(s). A scenario illustrating such frequency reuse and potential interference is depicted in Figure 4-8.

Figure 4-8: An uplink (user terminal to the satellite) interference scenario

The analysis includes calculating the level of interference that would be acceptable in a particular spot beam under worst case scenario and the calculation of the actual interference. The worst case scenario implies that the “wanted signal” is received at the lowest possible power level. The “acceptable” level of interference is calculated using the link budget for the user in a spot beam. For example, if the user is in a 3-dB spot beam, link budget analysis can be used to calculate the maximum tolerable amount of interference for the user at the edge of the contour. Section 4.6.1 deals with the link budget and concludes with the calculation of maximum tolerable interference. The interference received from each of the interfering users (P_i) is given by:

$$\frac{P_i}{L_i} G_c(\theta_i) \quad \text{Eq. 4-16}$$

where P_i = transmit power of the interfering user, L_i = path loss for the interfering signal, $G_c(\theta_i)$ = antenna pattern gain experienced by the interfering user. The total received interference is given by:

$$\sum_i \frac{P_i}{L_i} G_c(\theta_i) \quad \text{Eq. 4-17}$$

where $i \geq 1$.

The value of i cannot be determined beforehand as in the case of terrestrial cellular system analysis. In the analysis for terrestrial cellular systems, $i = 6$ co-channel interfering users are normally assumed. Traditional co-channel interference analysis for FDMA and TDMA satellite systems have often considered the hexagonal spot beam structures (all 3 dB) [10]. The analysis is useful to provide some preliminary insight into the interference value. However, it is based on several following assumptions which are not valid for the purposes of the design under consideration.

- the coverage area is flat such that all the spot beams are of equal sizes,
- there exists no difference in the slant range of the users to the satellite,
- the spot beams are all 3 dB contours, i.e. the power received at the edge of the spot beam is 3 dB less than that received at the center of the spot beam, and
- there is no overlap between the spot beams.

Most of the above assumptions are *not* valid in the proposed system. The overall coverage area is the entire North America which cannot be considered flat due to the spherical shape and hence the curvature of the earth. The distance between two furthest points in a 3 dB spot beam at the equator may only be about 200 km in diameter while it may be about 1000 km

towards the northern areas, as explained earlier. The contours of same power level are of much different sizes in different locations of the desired coverage area. The slant ranges are significantly different from within the spot beams and they contribute to the path loss. The path loss in addition to the reception angle define the spot beam contour and therefore the slant range cannot be ignored. Also the differences in the slant range define the guard time calculations in Chapter 3.

Because of traffic variations expected from different regions of the coverage area, the spot beams are not all 3 dB contours. As explained in Section 4.3.2, the contours are preset at -1.0 dB, -1.5 dB, -2.0 dB and -3.0 dB. There are significant overlaps in the spot beams and it is quite difficult and cumbersome to rearrange the spot beams such that the overlap is minimized and simultaneously have no gaps between the spot beams. However, the task is accomplished and the final layout is depicted later in Figure 6-1.

The actual interference computations involve calculating the interference received from all the spot beams into the remaining spot beams. Assuming a system with a total of N spot beams, for every spot beam i ($i \in \text{spot beam } 1, 2, 3, \dots, N$), the interference received from j ($j \neq i, j = \text{spot beam } 1, 2, 3, \dots, N$) into i is calculated and tabulated. This can best be represented using a matrix notation as follows.

$$\begin{bmatrix} X_{11} & X_{12} & X_{13} & \dots & X_{1N} \\ X_{21} & X_{22} & X_{23} & \dots & X_{2N} \\ \vdots & & & & \\ \vdots & & & & \\ X_{N1} & X_{N2} & X_{N3} & \dots & X_{NN} \end{bmatrix} = \begin{bmatrix} 0 & X_{12} & X_{13} & \dots & X_{1N} \\ X_{21} & 0 & X_{23} & \dots & X_{2N} \\ \vdots & & 0 & & \\ \vdots & & & & \\ X_{N1} & X_{N2} & X_{N3} & \dots & 0 \end{bmatrix}$$

In the matrix above, X_{ij} represents the interference received in spot beam i from spot beam j . The diagonal elements X_{ij} ($i = j$) = 0 because there is no interfering user in the spot beam with the wanted signal. The calculations of the matrix is a lengthy procedure but it is done only once and the results are stored into a database for frequent future use. Once the matrix has been setup, the frequency assignment procedure involves a fast database lookup for interference values. The next section provides insight into the link budget analysis and the calculations of acceptable interference values.

4.6 Link Budget Analysis

For a GEO-MSS system, the return *uplink* (user terminal to the satellite) is most critical due to the limited power output capability of the user (hand-held) terminal [21] and essentially dictates the overall performance and the capacity of the system. During the course of the research, considerable time and effort have been devoted to understand the impact of different parameters on a typical GEO MSS link budget. Different authors present the same information in several different ways and it is challenging to grasp their explanation without fully understanding and practicing with the fundamentals of the link budget [3], [9], [21].

In the proposed design, only the return link budget was considered to evaluate the system performance. Some of the performance specifications of the system are not initially provided and are determined during the course of the research. The specifications such as the acceptable bit error rate (BER) and the code rate have a direct consequence on the system throughput and capacity performance and must be chosen carefully. After several design iterations, it is decided to provide an upper BER threshold of 10^{-2} for the 8 kb/s voice users and an upper BER threshold of 10^{-5} for the higher data rates at 16 kb/s, 32 kb/s and 64 kb/s. A Viterbi codec with a $2/3$ code rate is employed in with $K = 3$ constraint length . The actual information data rates are therefore 5.33 kb/s, 10.6 kb/s, 21.2 kb/s and 42.4 kb/s. An example provided in [21] assumes the voice channel to operate at a data rate of 4.8 kb/s and therefore a data rate of 5.33 kb/s for the proposed system is deemed acceptable. The performance of the codec is given in Figure 4-9 [22].

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Figure 4-9: Performance of rate $2/3$ $K = 3$ code with Viterbi decoding. Numerical bound and simulation results [22]

From Figure 4-9, an E_b/N_o of 3.0 dB is required to achieve an upper BER threshold of 10^{-2} at the ground station after the complete return (user terminal to the ground station via satellite) link. Figure 4-10 illustrates the composition of a return link budget for the proposed system with a user operating at 8kb/s. The *uplink*, *downlink* and the *overall* combined E_b/N_o are related by the following equation.

$$\left[\text{uplink} \frac{E_b}{N_o} \right]^{-1} + \left[\text{downlink} \frac{E_b}{N_o} \right]^{-1} = \left[\text{overall} \frac{E_b}{N_o} \right]^{-1}$$

As mentioned before, the return *uplink* budget is the most crucial and the *uplink* E_b/N_o is only marginally affected by the *downlink* (satellite to the ground station) E_b/N_o . Therefore, an *uplink* E_b/N_o of 3.5 dB is chosen such that the overall combined *uplink* and *downlink* E_b/N_o is 3.0 dB.

Figure 4-10: A complete return link budget for a user operating at a data rate of 8 kb/s

Some of the important parameters in the link budget are explained next. They are classified according to the user data rate. The link budget for the user operating at a data rate of 8 kb/s is presented first followed by the link budget for a user operating at 64 kb/s. The link budget for users operating at 16 kb/s, 32 kb/s and 64 kb/s is identical because identical user terminals are assumed to operate at these data rates. Therefore, in the proposed system, there are two types of terminals; one hand-held terminal suitable for 8kb/s speech communication and

another transportable terminal suitable for higher data rate communication. The following is the return link budget for a user operating at a data rate of 8 kb/s.

4.6.1 Uplink return (user terminal to satellite) budget for data rate of 8 kb/s

The template used for the link budget is similar to that in [9]. The characteristics of the 8 kb/s hand-held terminal become evident in the following link analysis.

1. The user terminal has a peak power output of 4.6 watts = 6.6 dBW. A peak power dissipation of 4.6W is of concern to a user with a hand-held terminal. However, the peak dissipation of 4.6 W is required when the user is at the edge of its 3 dB contour. The requirement can be relaxed immensely if the user is located in a more favorable region of the spot beam. If the user is located at the center of the spot beam, the hand-held terminal is required to transmit at a peak power of 2.3 W = 3.6 dBW. This power control feature is not considered in this thesis and is suggested as future research work in Chapter 7. As discussed in Chapter 3, Section 3.2, an 8kb/s user transmits 440 bits in a frame of 8,000 bits. Therefore, on average, an 8kb/s user terminal dissipates $\frac{440}{8000} \cdot 4.6 W = 230mW$.

This value is close to that of existing terrestrial systems.

2. The antenna gain for the user terminal is 3 dBi. There is a loss of approximately 0.7 dB within the terminal [9]. Therefore, the user terminal EIRP is $6 + 3 - 0.7 = 8.3dB$.
3. Free Space (Path) Loss can be determined using the following formula:

$$L_s = \left(\frac{4\pi d}{\lambda} \right)^2 \quad (\text{Eq. 4-10}),$$

where λ is the wavelength of the signal. For the L-band link (user terminal to the satellite), the frequency is assumed to be 1.6 GHz and therefore the wavelength is 18.75 cm. With a distance of 36,500 km (which is an approximate distance from the satellite to its nearest point on earth), the free space loss is 188.0 dB. For the Ku-band link (satellite to the ground station), the frequency is 12 GHz and the free space loss is 205.3 dB. Polarization and other losses account for 0.1 dB [9].

4. A fade margin of 10 dB is chosen so that the system can perform in a satisfactory manner for no line-of-sight conditions and it can also tolerate shadowing by trees and low buildings. [3], [9], [21]

5. The channel bit rate is assumed at 160 kb/s and QPSK scheme is applied with a filter roll-off factor of 25%. Therefore, the channel bandwidth is

$$\frac{160}{2} \cdot (1 + 0.25) = 100 \text{ KHz} = 50 \text{ dBHz}.$$

The satellite antenna noise temperature is 27 dBK [9]. Therefore, the noise power is:

$$KTB = -228.6 + 27 + 50 = -151.6 \text{ dBW}$$

6. The satellite antenna diameter is 14 m and is therefore capable of providing a maximum (boresight) gain of 45.5 dB (see Section 4.1). The actual gain of the antenna depends upon the reception angle as outlined before. For the purposes of calculating the “acceptable” amount of interference, the worst case scenario is assumed where the user is

at the edge of a 3 dB spot beam. Therefore, the gain provided by the satellite antenna is $45.5 - 3 = 42.5$ dB.

Therefore, the signal power received at the satellite is given by:

$$\begin{aligned} Rx'd \text{ Signal Power} &= EIRP - \text{Free Space Loss} - \text{Other Losses} + \text{Satellite Antenna Gain} - \\ &\quad \text{Fade Margin} \end{aligned}$$

$$= 8.93 - 188.0 - 0.10 + 42.5 - 10.0 = -146.6 \text{ dBW} \quad \text{Eq. 4-18}$$

The *uplink* noise power is -151.6 dBW.

Therefore, the *uplink* carrier signal power to noise power ratio,

$$(C/N)_u = -146.6 - (-151.6) = 5 \text{ dB}$$

The **required** *uplink* (E_b/N_o) is 3.5 dB with a $\left(\frac{2}{3}\right)$ code rate. Therefore, the **required**

uplink energy of coded bit to noise density ratio, $(E_c/N_o) = 3.5 + 10\log_{10}\left(\frac{2}{3}\right) = 1.739 \text{ dB}$.

Hence, **required** $(C/N)_u = \left(E_b/N_o\right) \times (\text{Data Rate}/\text{Bandwidth})$

$$= 1.739\text{dB} + 52.04 - 50.00 = 3.78 \text{ dB}$$

The available $(C/N)_u = 5 \text{ dB}$, while the required $(C/N)_u = 3.78 \text{ dB}$ and therefore an additional 1.22 dB of noise power can be allowed into the system. The current thermal noise

power is -151.6 dBW and the total allowed noise power is $(-151.6 + 1.22) = -150.38$ dBW.

In absolute terms, total allowed (thermal + interference) noise is

9.1622×10^{-16} W while the current thermal noise is 6.9183×10^{-16} W. Therefore, a total of 2.2438×10^{-16} W = -156.49 dBW is allowed as *uplink* interference noise. With a received carrier power of -146.6 dBW, the required carrier to interference ratio in the system $(C/I) = -146.6 - (-156.49) = 9.89$ dB. The calculations are summarized in Table 4-1.

Return Uplink (user terminal to sat.)	
Distance to Satellite, km	36500
Frequency, MHz	1600.0
Channel Bandwidth, kHz	100.0
Bit rate per carrier, kb/s	160.0
RF power, W	4.6
Transmitter power, dBW	6.6
Loss, dB	-0.7
Antenna Gain, dBi	3.0
Uplink EIRP, dBW	8.9
Free Space Loss, dB	-188.0
Fading Margin, dB	-10.0
Receive antenna efficiency, %	65.0
Receive antenna diameter, m	14.0
Receive antenna gain, dB	42.5
Polarization and atmosphere loss,	-0.1
Receive Carrier Power, dBW	-146.6
Bandwidth, dBHz	50.0
Noise Temperature, dBK	27.0
Noise power, dBW	-151.6
(C/N) _u , dB	5.0
(C/I), dB	9.9
(C/N) _u , total, dB	3.8

Table 4-1: Return Uplink (user terminal to the satellite) Budget for a user operating at a data rate of 8 kb/s

The *return downlink* (satellite to ground station) budget for a user operating at 8 kb/s is presented in the next section.

4.6.2 Return downlink (satellite to ground station) budget for data rate of 8 kb/s

The satellite relays or '*bent-pipes*' the *uplink* signal (from user terminal) to the ground station. The objective of this *return downlink* budget is to calculate the amount of satellite power required to bent-pipe a user operating at a data rate of 8 kb/s. The required satellite power is a function *downlink* carrier to noise ratio, $(C/N)_d$. The value of $(C/N)_d$ is determined by the required total (overall) carrier to noise ratio, $(C/N)_{total}$, the *uplink* carrier to noise ratio, $(C/N)_u$ and the carrier to inter-modulation noise ratio, $(C/N)_{IM}$. The required overall $(E_b/N_o)_{total}$ is 3.0 dB with a $2/3$ code rate. Therefore, the required total energy of

coded bit to noise density ratio, $(E_c/N_o)_{total} = 3.0 + 10\log_{10}\left(\frac{2}{3}\right) = 1.24$ dB.

Hence, the required $(C/N)_{total} = 1.24$ dB + 52.04 – 50.00 = 3.28 dB. The *uplink* carrier to noise ratio, $(C/N)_u$, *downlink* carrier to noise ratio, $(C/N)_d$ and the *total* carrier to noise ratio, $(C/N)_{total}$ are related by the following relationship [21].

$$(C/N)_{total} = \left[(C/N)_u^{-1} + (C/N)_d^{-1} + (C/N)_{IM}^{-1} \right]^{-1} \quad \text{Eq. 4-19}$$

Using Eq. 4-19, and substituting, $(C/N)_u = 3.78 \text{ dB}$, $(C/N)_d = 3.28 \text{ dB}$ and $(C/N)_{md} = 16.0 \text{ dB}$ [9], the required $(C/N)_d = 15.86 \text{ dB}$. The carrier bandwidth is $100 \text{ kHz} = 50 \text{ dBHz}$ and the antenna noise temperature is assumed to be 23 dBK [9]. With Boltzman constant $= -228.6 \text{ dB/K}$, the noise power is -155.6 dBW . The required $(C/N)_d$ value of 15.86 dB and noise power of -155.6 dBW imply that the required carrier power at the ground station must be -139.74 dBW .

To determine the amount of power required from the satellite to satisfy the above carrier power requirement at the ground station, several gain/attenuation factors need to be considered. These factors are discussed next.

1. The ground station is assumed to have a large antenna setup capable of providing a gain of 60 dB . The MSAT system operated by TMI Communications has an 11 m antenna at the ground station which provides comparable gain value [20]. Therefore, the carrier power must be at a power level of at least $-139.74 - 60 = -199.74 \text{ dBW}$ before it arrives at the ground station amplifier.
2. A fade margin of 7 dB is assumed. The return downlink is always a line of sight link between the satellite and the ground station and therefore a 7 dB fade margin will suffice [9], [21]. The unfaded carrier power level is therefore $-199.74 + 7 \text{ dB} = -192.74 \text{ dB}$.

3. The free space (path) loss is calculated to be 205.3 dB using Eq. 4-10. The carrier power level at the output of the satellite amplifier must therefore be at a power level of $-192.74 + 205.3 \text{ dB} = 12.56 \text{ dB}$. Hence, a carrier with an 8kb/s user demands an EIRP power level of $12.56 \text{ dBW} = 18.03 \text{ W}$.
4. The satellite Ku-band antenna gain is assumed to be 25.4 dBi. [9]
5. An amplifier back-off factor of 4 dB is assumed. The authors in [9] assume a back-off factor of 3 dB which is not considered sufficient [23].
6. The satellite Ku-band amplifier can provide $100 \text{ W} = 20 \text{ dBW}$ of power [9] to bent-pipe the incoming *uplink* signal. An equipment transmit loss of 1 dB reduces the available amplifier power to 80W .
7. Since a non-regenerative repeater is assumed in the system, the available power of 80W is consumed to relay the *uplink* composite useful carrier signal and the noise. Therefore, only a certain portion of the total satellite power of 80W can be considered as available for generating the *downlink* carrier signal. This portion of the total satellite power is referred to as the *Uplink Signal Share* and is calculated based on the ratio of the *uplink* useful carrier signal to the composite *uplink* signal. It is defined as follows:

$$\text{Uplink Signal Share} = \frac{C_u}{(C_u + N_u)} = \frac{\left(\frac{C}{N}\right)_u}{\left(\frac{C}{N}\right)_u + 1}$$

In the case of 8 kb/s users, the value of $(C/N)_u = 3.78$ dB and *Uplink Signal Share* = 0.705 = -1.5 dB. Therefore, if all the users in the system are assumed to operate at a data rate of 8 kb/s, only $0.705 * 80\text{W} = 56.4$ W are available to bent-pipe the useful *uplink* carrier signal.

8. The amplifier power of 80W (19 dBW) with an antenna gain of 25.4 dBi, a back-off factor of 4 dB and an *Uplink Signal Share* of -1.5 dB yields total EIRP of 38.9 dBW.
9. The calculation of the number of the carriers is considered in the power-limited capacity calculations, Section 6.5.

The calculations are summarized in Table 4-2.

Return Downlink	
Frequency, GHz	12.0
Bit rate per Carrier, kb/s	160.0
Amplifier RF power, W	80.0
Transmitter power, dBW	19.0
Uplink Signal Share, dB	-1.5
Antenna gain, dBi	25.4
Back-off, dB	-4.0
Total E.I.R.P, dBW	38.9
Number of Carriers, dB	26.3
E.I.R.P/ carrier, dBW	12.6
Free Space Loss, dB	-205.3
Fading Margin, dB	-7.0
Receive antenna gain, dB	60.0
Receive carrier power, dBW	-139.7
Bandwidth, dBHz	50.0
Noise temperature, dBK	23.0
Noise power, dBW	-155.6
$(C/N)_d$, thermal, dB	15.9
(C/I_m) , dB	16.0
$(C/N)_d$, final, dB	12.9
Total Return Link	
$(C/N)_u$, dB	3.8
$(C/N)_d$, total, dB	12.9
$(C/N)_{total}$, dB	3.3
Bandwidth to bit rate, dB	-2.0
(E_c/N_o) of carrier, dB	1.3
(E_b/N_o) of carrier, dB (2/3 code rate)	3.0

Table 4-2: Return Downlink budget for a user operating at a data rate of 8 kbls. Some of the parameter values are chosen from [9].

Since the user data terminals for higher data rate users are different than the 8kb/s users, the link budgets for the former are different from those of the latter. The following is the return link budget for a user operating at one of the high data rates.

4.6.3 Uplink return (user terminal to satellite) budget for data rate of 16, 32, 48 and 64 kb/s

The link budgets for users operating at 16 kb/s, 32 kb/s and 64 kb/s are identical because the user data terminals are assumed to be operating at the same power level. The calculations are all exactly the same as in Section 4.5.1. However, some values of the parameters change due to the different type of terminal used for high speed access. The data terminal used for rates above 8 kb/s is more capable than the hand-held terminal. From Figure 4-9, an E_b/N_o of 6 dB is required to achieve an upper BER threshold of 10^{-5} at the ground station after the complete return (user terminal to the ground station via satellite) link. An *uplink* E_b/N_o of 8.0 dB is chosen such that the overall combined *uplink* and *downlink* E_b/N_o is 6.0 dB. The following are brief descriptions of the parameters used in the link budget for high data rate users.

1. The user terminal has a peak power output of $5.7 \text{ W} = 7.5 \text{ dBW}$. Again, the requirement can be relaxed if the user is located in a more favorable region of the spot beam.
2. The antenna gain for the data terminal is 5 dBi. There is a loss of approximately 0.7 dB within the terminal [9]. Therefore, the user terminal EIRP is $7.5 + 5 - 0.7 = 11.8 \text{ dB}$.
3. As before, the path loss is 188.0 dB.

4. A fade margin of 7 dB is chosen so that the system can perform in a satisfactory manner for line-of-sight conditions as the data terminal is expected to be stationary when communicating.
5. As before, the channel bandwidth is 50 dBHz and the satellite antenna noise temperature is 27 dBK [9]. Therefore, the noise power is $KT B = -228.6 + 27 + 50 = -151.6$ dBW.
6. The satellite antenna diameter is kept at 14 m and is therefore capable of providing a maximum (boresight) gain of 45.5 dB (see Section 4.1). The actual gain of the antenna depends upon the reception angle as outlined before. For the purposes of calculating the “acceptable” amount of interference, the worst case scenario is assumed where the user is at the edge of a 3 dB spot beam. Therefore, the gain provided by the satellite antenna is $45.5 - 3 = 42.5$ dB.

Using Eq. 4-18, the signal power received at the satellite is:

$$= 11.8 - 188.0 - 0.10 + 42.5 - 7.0 = -140.8 \text{ dBW}$$

The *uplink* noise power is -151.6 dBW.

Therefore, the *uplink* carrier to noise ratio, $(C/N)_u = -140.8 - (-151.6) = 10.8$ dB

The required *uplink* $(E_b/N_o)_u$ is assumed to be 8 dB with a 2/3 code rate. Therefore, the required uplink energy of coded bit to noise density ratio,

$$(E_c/N_o)_u = 8 + 10 \log_{10} \left(\frac{2}{3} \right) = 6.239 \text{ dB}.$$

Hence, the **required** uplink carrier-to-noise ratio,

$$(C/N)_u = 6.24 \text{ dB} + 52.04 - 50.00 = 8.28 \text{ dB}.$$

The available $(C/N)_u = 10.8 \text{ dB}$, while the required $(C/N)_u = 8.28 \text{ dB}$ and therefore an additional 2.52 dB of interference noise power can be allowed into the system. The current thermal noise power is -151.6 dBW and the total allowed noise power is $(-151.6 + 2.52) = -149.08 \text{ dBW}$. In absolute terms, total allowed (thermal + interference) noise power is $1.2359 \times 10^{-15} \text{ W}$ while the current thermal noise power is $6.9183 \times 10^{-16} \text{ W}$. *Therefore, a total of $5.4406 \times 10^{-16} \text{ W} = -152.64 \text{ dBW}$ is allowed as uplink interference noise.* Hence, with a received carrier power of -140.8 dBW, the required carrier to interference ratio in the system $(C/I) = -140.8 - (-152.64) = 11.84 \text{ dB}$. The calculations are summarized in Table 4-3.

Return Uplink (user terminal to sat.)		
Distance to Satellite, km		36500
Frequency, MHz		1600.0
Channel Bandwidth, kHz		100.0
Bit rate per carrier, kb/s		160.0
RF power, W		5.7
Transmitter power, dBW		7.6
Loss, dB		-0.7
Antenna Gain, dBi		5.0
Uplink EIRP, dBW		11.9
Free Space Loss, dB		-188.0
Fading Margin, dB		-10.0
Receive antenna efficiency, %		65.0
Receive antenna diameter, m		14.0
Receive antenna gain, dB		42.5
Polarization and atmosphere loss,		-0.1
Receive Carrier Power, dBW		-140.8
Bandwidth, dBHz		50.0
Noise Temperature, dBK		27.0
Noise power, dBW		-151.6
(C/N) _u , dB		10.9
(C/I), dB		11.8
(C/N) _u , total, dB		8.3

Table 4-3: Return Uplink (user terminal to satellite) budget for high data rate users

The *return downlink* (satellite to ground station) budget for a user operating at high data rates is presented in the next section.

4.6.4 Return downlink (satellite to ground station) budget for data rate of 16, 32, 48 and 64 kb/s

As mentioned before, the number of signals which can be relayed by the satellite is a function of the available onboard satellite amplifier power and the required *downlink* carrier to noise ratio, $(C/N)_d$. The value of $(C/N)_d$ is determined by the required total (overall) carrier to

noise ratio, $(C/N)_{total}$, the *uplink* carrier to noise ratio, $(C/N)_u$ and the carrier to intermodulation noise ratio, $(C/N)_{IM}$. The calculation of the required $(C/N)_d$ is presented next.

The required overall $(E_b/N_o)_{total}$ is 6.0 dB with a $2/3$ code rate. Therefore, the required total energy of coded bit to noise density ratio, $(E_c/N_o)_{total} = 6.0 + 10\log_{10}\left(\frac{2}{3}\right) = 4.24$ dB. Hence, the required $(C/N)_{total} = 4.24 \text{ dB} + 52.04 - 50.00 = 6.28 \text{ dB}$.

Substituting 6.28 dB, 8.3dB and 16.0dB for $(C/N)_{total}$, $(C/N)_u$, and carrier-to-intermodulation noise ratio $(C/N)_{IM}$ [9] respectively, the required $(C/N)_d = 12.1 \text{ dB}$. With the addition of the gain/attenuation factors discussed in Section 4.6.2, a carrier with a high data user demands an EIRP power level of $8.8 \text{ dBW} = 7.58 \text{ W}$.

As per specifications (Section 4.6.2), the satellite Ku-band amplifier can provide net power of 80W. The calculations of the remaining parameters of the *downlink* budget are similar to those used in the budget of 8 kb/s users. In the case of all users in the system operating at data rates higher than 8 kb/s, the value of $(C/N)_u = 8.3 \text{ dB}$ and *Uplink Signal Share* = -0.6 dB. Therefore, only $0.87 * 80 \text{ W} = 69.6 \text{ W}$ are available to bent-pipe the useful *uplink* carrier signal. Table 4-4 is a typical *downlink* budget assuming identical frame structures in each carrier with 64 kb/s users.

Return Downlink	
Frequency, GHz	12.0
Bit rate per Carrier, kb/s	160.0
Amplifier RF power, W	80.0
Transmitter power, dBW	19.0
Antenna gain, dBi	25.4
Back-off, dB	-4.0
Total E.I.R.P, dBW	40.4
Signal share due to uplink noise, dB	-0.6
Number of Carriers, dB	-31.0
E.I.R.P/ carrier, dBW	8.8
Free Space Loss, dB	-205.3
Fading Margin, dB	-7.0
Receive antenna gain, dB	60.0
Receive carrier power, dBW	-144.1
Bandwidth, dBHz	50.0
Noise temperature, dBK	23.0
Noise power, dBW	-155.6
$(C/N)_d$, thermal, dB	11.5
$(C/N)_{IM}$, dB	16.0
$(C/N)_d$, final, dB	10.2
Total Return Link	
$(C/N)_{ur}$, dB	8.3
$(C/N)_d$, total, dB	10.2
$(C/N)_{total}$, dB	6.1
Bandwidth to bit rate, dB	-2.0
(E_c/N_o) of carrier, dB	4.1
(E_b/N_o) of carrier, dB (2/3 code rate)	5.9

Table 4-4: Return Downlink (Satellite to Ground Station) budget for high data rate users

As in the case of 8 kb/s users, the calculations of the number of the carriers is explained in Chapter 6, Section 6.5.

4.6.5 Summary

In this chapter, the calculations pertaining to the system design are presented. The earth-satellite geometry and the antenna pattern is used to calculate the spot beam contours layout

for North America. The interference analysis and link budget analysis is conducted in detail. In the next chapter, the software module designed to use the calculations and perform capacity analysis is presented. The objective and functionality of each of the software components is discussed in detail.

Chapter 5

Software Module for the Design and Analysis of a Multi-Variable rate Geostationary Mobile Satellite Network

5. Purpose of the software module

A significant portion of the research conducted in this thesis is to provide a software module for the design of a multi-variable rate geostationary mobile satellite network. The software module is developed in Microsoft® Visual Basic 5.0 and Microsoft® Access 97. The module is designed with an easy-to-use Graphical User Interface (GUI) and is intended to perform complex exhaustive calculations in reasonable time. The development of the software is initially undertaken to provide some insight into the spot beam shapes in the desired coverage area (North America, including the Caribbean and the Hawaii Islands) and hence facilitate the calculations of guard times. It is enhanced to perform interference analysis and frequency assignment. The software design involves illuminating North America with multiple spot beams from a satellite in the geostationary orbit. The concept of spot beams and antenna and distance attenuation in the vicinity of the center of spot beam is presented in the preceding chapter.

5.1 Objectives of the Software

The objectives of the software are as follows:

1. Calculate and tabulate the gain values (relative to the center of the spot beam) due to the path loss and the satellite antenna pattern satellite in the vicinity of the centers of the spot beam.
2. Using the tabulated relative gain values, generate spot beam contours of any desirable threshold value for the differential power gain.
3. Modify the choice of the coordinates of the centers of spot beams and repeat steps 1 and 2 to obtain an acceptable spot beam configuration.
4. Retrieve and provide attenuation values for any particular location (grid square) in North America.
5. Calculate guard time values for each of the spot beams.
6. Calculate co-channel interference received from each of the spot beams to the remaining spot beams.
7. Calculate (from link budget) the acceptable interference power level in each of the spot beam.
8. Perform Frequency Assignment in the spot beams.
9. Find the overall system capacity (explained in detail in Chapter 6).

The software module is carefully designed to be flexible enough to account for several different parameters (for example, antenna pattern, satellite location, traffic intensity in a particular location, link budget parameters, etc.). The graphical user interface allows the user

to experiment with different parameters and spot beam layouts. In the next section, an overview of the software module design is presented.

5.2 An Overview of the Software Module

The software module can easily be decomposed into the following three major components which are depicted in Figure 5-1.

- The graphical user interface,
- The software managing the interaction between the user interface and the database and the necessary calculations required to produce results,
- The database which stores all the calculations for easy and quick retrieval.

Figure 5-1: An overall diagram of the software system components

The main strategy adopted to accomplish all of the above stated objectives involves dividing North America into a square grid of 0.022458° (equivalent to 2.5 km if measured at the

equator) between the latitudes of 10° N and 70° N and between the longitudes of 40° W and 170° W . The concept is illustrated in Figure 5-2.

Figure 5-2: An illustration of the grid-squares covering entire North America.

The information about each of the grid-squares (region enclosed within the 0.022458° square grid) is stored in the database. The grid-square is designed to be a *record* capable of storing the attenuation with respect to the boresight (of any spot beam), experienced by a signal transmitted from the coordinates. Upon initialization, the database contains only the coordinates of each of the grid-squares and the centers of the spot beam. Since the area of coverage extends from latitude of 10°N to 70°N and a longitude of 40°W to 170°W, there

exist a total of $\left(\frac{70^\circ - 10^\circ}{0.022458^\circ} \right) \times \left(\frac{170^\circ - 40^\circ}{0.022458^\circ} \right) = 15,465,089$ grid-squares. To manage such a

huge number of records, the database is organized into several files, each pertaining to a certain region in North America.

5.3 Organization of the Database

The database consists of several files, each of which is related to the different features implemented in the software package. Figure 5-3 is an overall diagram of the database files.

The dotted rectangles represent a repetition of the enclosed rectangle(s). As presented in Chapter 6, there are altogether 102 centers with their spot beams providing service to all of North America. Therefore, each of the dotted rectangle represents 102 instances of a file.

The name 'Centre X' is generic and denotes one of the 102 centres.

The purpose of each of the files in Figure 5-3 is explained next.

Figure 5-3: A breakdown of the database files. The dotted squares represent a repetition of the enclosed files. Centre X is a generic name and can denote any one of the 102 centres chosen to cover North America.

5.3.1 Filenames 10lat, 20lat, 30lat, 40lat, 50lat and 60lat

These files store the grid-square coordinates along with the attenuation values with respect to the center. File *10lat* stores information pertaining to grid-squares located between the latitudes of 10°N and 20°N and between the longitudes of 50°W and 170°W. Similarly, the file *20lat* stores information pertaining to grid-squares located between the latitudes of 20°N and 30°N and between the longitudes of 50°W and 170°W and so on. The total coverage area between the latitudes of 10°N and 70°N and longitudes of 50°W and 170°W is divided into such files to expedite information retrieval from the database and to ease database management. A sample of a table from the file *40lat* is shown in Table 5-1.

Longitude	Latitude	Detroit	Memphis	Knoxville	StLouis Missouri	Pittsburgh
80.00	40	-4.06	-22.10	-4.22	-43.31	-5.52E-02
80.02	40	-4.02	-22.28	-4.20	-46.82	-5.57E-02
80.04	40	-3.98	-22.46	-4.18	-52.85	-5.64E-02
80.06	40	-3.95	-22.65	-4.16	-94.58	-5.72E-02
80.08	40	-3.91	-22.84	-4.14	-52.67	-5.82E-02
80.11	40	-3.87	-23.04	-4.13	-46.66	-5.93E-02
80.13	40	-3.84	-23.25	-4.11	-43.13	-6.06E-02
80.15	40	-3.80	-23.46	-4.09	-40.62	-6.21E-02
80.17	40	-3.76	-23.67	-4.07	-38.66	-6.37E-02

Table 5-1: Some of the records stored in the 40lat database file. Each row contains the coordinates of a grid-square and the attenuation experienced by a signal transmitted from these coordinates with respect to the boresight of each of the spot beams. Please note that only a few selected columns are shown here for illustration purposes.

Each record in the file contains the coordinates of the grid-square and the attenuation, in dB, experienced by a signal transmitted from these coordinates with respect to the boresight of each of the spot beams. For example, a signal transmitted from a grid-square at 40°N and 80°W would experience an attenuation of 4.06 dB with respect to the boresight of the spot beam in the Detroit region. The same signal would experience an attenuation of 22.10 dB with respect to the boresight of the spot beam in the Memphis region.

5.3.2 Filename 'Centres'

This file contains information pertaining to the actual centers of the spot beams. Each record in the file represents one center, see Table 5-2.

Name	X° (Lat.)	Y° (Long.)	Intensity (Traffic)	Guard Time (s)	Threshold (dB)	User Rate (kb/s)
ColumbiaSC	81.00	34.00	2	1.89E-03	-148.80	8
Dallas	96.50	32.50	1	1.11E-03	-149.42	8
Houston	95.20	29.50	1	1.00E-03	-148.57	8
Detroit	83.22	42.13	1	1.92E-03	-147.68	8
Phoenix	112.10	33.30	2	1.36E-03	-150.94	8
SanDiego	117.10	32.43	2	1.37E-03	-151.10	8
Memphis	90.00	35.07	2	1.65E-03	-148.33	8
Miami	80.15	25.52	3	1.81E-03	-150.63	8
Boiseldaho	116.15	43.71	3	2.60E-03	-156.58	8
Knoxville	83.95	35.96	2	1.89E-03	-153.43	8
SanAntonio	98.50	29.50	2	1.18E-03	-148.97	8
YellowStone	108.93	45.50	3	2.71E-03	-156.58	8

Table 5-2: A sample of records stored in the 'Centres' database file. Again, only a few selected columns are presented in the table here

The record contains the *center's* name, its coordinates (latitude and longitude), the spot beam traffic intensity expected, the guard time for the spot beam, the user data rate in the spot beam and the interference threshold value for the user in the spot beam. The spot beam traffic intensity dictates the edge-of-spot beam attenuation level. The values are as follow:

- '0' means that high traffic intensity is expected and the spot beam contour power level = 0.5 dB below the boresight.
- '1' means that moderate traffic intensity is expected and the spot beam contour power level = 1.3 dB below the boresight.
- '2' means that low traffic intensity is expected and the spot beam contour power level = 2.0 dB below the boresight.
- '3' means that lowest traffic intensity is expected and the spot beam contour power level = 3.0 dB below the boresight.

The 'Guard Time' field represents the value of the time calculated for the spot beam and it depends upon the size and more importantly on the location of the spot beam. As mentioned in Section 4.1, due to the spherical shape of the earth, the shape of the spot beam is drastically different in different regions of the desired coverage area. For example, a 3 dB contour may appear as a small circle near the equator but may appear irregular in shape (resembling an ellipse) towards the high latitudes. Therefore, the guard time values are vary significantly in different spot beams. The calculations of the guard times are presented in Section 5.5. The 'threshold' field represents the amount of interference which can be tolerated by a user in the spot beam. The amount of interference depends upon the user data rate and the calculations are presented in Section 4.6.1.

5.3.3 Filename '*Centre X with High, Moderate, Low & Lowest Intensity*'

This database file is created to aid in the plotting of the spot beam contours. The 'X' is generic and can be replaced by the actual center name. For example, the actual database file may be '*New York High Intensity*', '*New York Moderate Intensity*', '*New York Low Intensity*' or '*New York Lowest Intensity*'. The file is a collection of the coordinates of grid-squares that exhibit a desirable attenuation value. For example, the file named '*New York High Intensity*' contains the coordinates of those grid-square which have an attenuation value of -0.5 ± 0.04 dB with respect to the boresight of the New York spot beam. To illustrate the file contents, a sample is provided from '*New York High Intensity*' in Table 5-3. These files are generated by scanning the *10lat*, *20lat*, *30lat*, *40lat*, *50lat* and *60lat* files for the grid-squares with the appropriate attenuation values for a particular *center*.

Longit. (°)	Latit (°)	Attenuat. (dB)
77.09	40.04	0.47
77.11	40.04	0.49
77.14	40.04	0.50
77.16	40.04	0.51
77.18	40.04	0.52
77.20	40.04	0.54
73.34	40.06	0.53

Table 5-3: A sample of the contents of the file called 'New York High Intensity'.

5.3.4 Filename 'Centre X Interference'

This file is very instrumental for frequency assignment as it contains the maximum amount of attenuation experienced by a signal in any co-channel spot beam with respect to boresight gain of *center X*. As before, a separate file is created for each of the different centers.

Interfering Center Name	Min Signal (dB)	Max Intf. (dB)	Latitude (°)	Longitude (°)
ColumbiaSC	-2.00	-22.80	30.38	114.96
Dallas	-2.00	-17.80	31.54	114.40
Houston	-2.00	-20.39	31.93	114.35
Detroit	-1.99	-22.70	29.85	117.79
Phoenix	-2.00	-1.616	32.87	114.46
Memphis	-1.99	-20.66	29.94	115.47
Miami	-1.99	-24.67	30.53	118.80
Boiseldaho	-1.98	-13.04	31.41	114.44
Knoxville	-2.00	-22.81	29.79	117.63
SanAntonio	-1.99	-17.83	29.76	115.86
YellowStone	-2.00	-13.54	34.64	115.68
RapidCity	-2.00	-17.59	29.65	116.24
LasVegas	-2.00	-0.34	35.14	116.58

Table 5-4: A sample of maximum interference values for the spot beam of San Diego.

An example is presented in Table 5-4 for the spot beam centered around San Diego. The table contains the name of the interfering spot beams, the attenuation experienced by a user in

the San Diego spot beam, the strength of the interfering signal and the coordinates of the calculation of the interfering signal strength. For example, let us consider two users who operate simultaneously at the same frequency and time slot in the San Diego and Miami spot beams. In the worst case, the signal from the user in the San Diego spot beam shall be received with an attenuation of -1.99 dB with respect to the maximum antenna gain (at the boresight). At the same time, the user in the Miami spot beam shall be received with an attenuation of -24.67 dB with respect to the boresight gain of the San Diego spot beam. Following similar logic, if a user in San Diego is operating simultaneously with a user in Las Vegas, the signal from the latter would appear -0.3416 dB with respect to the boresight gain of the San Diego antenna element. The interfering signal would be stronger than the actual desired signal which would appear as -2.00dB with respect to the boresight gain of the San Diego antenna element. It is to be noted that the information provided in this file is made prior to frequency assignment. During the process of frequency assignment, the data in the file can be retrieved to calculate the actual amount of interference received. The data in the file can be accessed repeatedly for several iterations for different assignment trials and configurations. This feature provides a great deal of system versatility and eases up the computational burden.

5.3.5 Filename 'Centre X Neighbours'

This file contains a list of the names of the neighboring spot beams for the Centre X. For example, Table 5-5 is a sample list of the neighbors of Ottawa along with the distance to each spot beam's center. The records can be retrieved in an increasing order of distance. This file is specially useful for the purposes of frequency assignment. A separate list is maintained for

all centers. The name ‘Centre X Neighbours’ may be a misnomer as it may imply the immediate neighbors of Centre X. In the database file, all the centers (except X) in the system are neighbors of Center X. Some of the ‘neighbors’ may be very far away and that is why a list of neighbors is maintained in increasing order of distance from the center X.

Neighbour Name	Distance (Km)
PortlandMaine	376.68
Sudbury	443.51
NewYork	512.86
Pittsburgh	535.81
Detroit	623.31
NewBrunswick	737.24
NewYorkSea	838.27
RichmondVirginia	854.78
Labrador	886.61
BelcherIslands	913.96
Thunderbay	934.30
PEI	975.09

Table 5-5: A sample of the neighbour spot beams of the Ottawa spot beam along with the distances from the center of Ottawa spot beam to the centers of the remaining spot beam

5.3.6 Filename ‘Centre X AllLowInt’

This file is an output of the frequency assignment algorithm. The procedure of frequency assignment can start from any *center* X. The file has multiple tables; each table contains a list of *centers* assigned to a particular frequency. Depending on the algorithm and the assumptions regarding the user data rates, the system network may require as few as 12 and as many as 14 frequencies (see Chapter 6 for more details). Therefore, the number of tables

in the database file may vary from 12 to 14. The 'AllLowInt' label in the filename implies that the frequency assignment is done based on the assumption that all co-channel interfering users are operating at a data rate of 8 kb/s. For example, if the frequency assignment algorithm is initiated from Columbia South Carolina (ColumbiaSC), the table for ColumbiaSC Frequency 1 may appear as in Table 5-6. According to Table 5-6(a), the spot beams centered around ColumbiaSC, Memphis, Ottawa, San Antonio etc. spot beams are assigned Frequency 1.

CoChannelCentre	CoChannelCentre
FortWorthWestTexas	ColumbiaSC
MonterreySea	Memphis
SanSalvador	Ottawa
SableIsland	SanAntonio
NormanWells	Haiti
Hebron	MexicoCity
	PortNelson
	Phoenix
	Banff

(a)

(b)

Table 5-6: The two tables (a) and (b) list the co-channel centers assigned to Frequency 1 and 12. The frequency assignment algorithm is initiated from Columbia South Carolina

5.3.7 Filename 'Centre X MixedInt'

The purposes of these files are exactly as described in Section 5.3.6. However, the name 'MixedInt' implies that the frequency assignment is based on the assumption that the co-channel interfering users are a mix of 8, 16, 32 or 64 kb/s users. A particular type of user type (8 kb/s, 16 kb/s, 32 kb/s, 48 kb/s and 64 kb/s) is assigned to each spot beam prior to frequency assignment. The assignment is done on a random basis. Since no expected traffic models are available for the proposed system, it is assumed that on average, half of the

interfering users are 8 kb/s speech users with hand-held terminals and the rest are higher data rate users. Since all the higher data rate users have the same data terminal power transmission characteristics, no distinction need be made between them for interference analysis.

5.4 Features Implemented in the Software Module

Upon startup, the user is presented with an interface similar to the one shown in Figure 5-4. Each of the command buttons can be related to one of the tasks outlined in the objectives section. A brief description of the individual features is given below.

Figure 5-4: The initial software startup display

5.4.1 Add Center to the Database

This feature allows the user to introduce a new *center* into the database. The user is allowed to enter the name and the coordinates of the new *center* into the system. The user may directly proceed to allow the software to compute attenuation values for grid-squares located till 10° north, 10° south, 10° east and 10° west of the new *center* coordinates. The translation of 10° into decibels for a power level depends entirely upon the geographical location of the center of the spot beam. If the center of the spot beam is near the equator, 10° may translate to approximately 20dB of attenuation with respect to the power level of the center. Alternatively, if the center is far north towards the polar regions, 10° may result in only 4dB (approximately) of attenuation.

Alternatively, the user may also specify a specific range (depicted as 'x' and 'y' in Figure 5-5) in all directions. Based on the coordinates of the new *center* and the range, the software accesses the appropriate database files (*10lat*, *20lat*, *30lat*, etc.) and calculates the attenuation values with respect to the new *center* coordinates. The calculations are performed for all the grid-squares that exist in the specified/default range.

Figure 5-5: The extent of attenuation calculations performed by the software.

5.4.2 Get Details about a Specific Location

This feature provides the user with the attenuation values stored in the database for any particular grid-square. The user is asked to input the coordinates of the grid-square and the software produces a result similar to Figure 5-6.

Latitude	Longitude	Detroit	Knoxville	Pittsburgh	New York	Richmond	Ottawa	Portland	Sudbury
40.22	75.89	18.45	12.63	2.51	0.063	1.57	5.98	1.60	17.69

Figure 5-6: The amount of attenuation experienced by a user in the grid-square at a latitude of 40.22° and longitude of 75.89° . A 18.45 dB value for the Detroit region represents the attenuation with respect to the boresight attenuation of the Detroit region spot beam.

In Figure 5-6, a specific grid-square with latitude = 40.22°N and longitude = 75.89°W is chosen. According to the results, this grid-square receives a signal which is 18.45 dB

attenuated with respect to the boresight of the spot beam centered in the Detroit region. Similarly, the grid-square receives a signal which is 0.063 dB attenuated with respect to the boresight of the spot beam around the New York region.

5.4.3 *Add Table to the Database*

This feature allows the user to add a certain region of North America into the database. For example, if the region enclosed between latitudes of 50°N and 60°N and longitudes of 130°W and 140°W is to be included into the database, the user can specify these coordinates. The software then generates grid-squares pertaining to the specified region and updates the appropriate file (*10lat*, *20lat*, etc.). The user may then wish to add a *center* (located in the vicinity of newly generated grid-squares) to the database by specifying its coordinates (see Section 5.3.1 for details of this feature).

5.4.4 *Load Map*

This feature loads the map of North America in a separate window and allows the user to scroll to different regions of the map and view the spot beams. The user is presented with a pull down menu to select the centers. The user can then select the contour level and actually plot the spot beam corresponding to the *center*. As mentioned in Chapter 4 and earlier in this chapter, four distinct power levels are chosen for the system design. The user can choose from (i) high intensity (ii) moderate intensity (iii) low intensity and (iv) lowest intensity. The user can also delete any spot beam. Depending upon the intensity input from the user, the

software selects the corresponding database file Centre X with High, Moderate, Low or Lowest Intensity to plot the spot beam.

The imposition of the contours on the North America map is not an easy undertaking. The mapping of the coordinates onto the map is not linear unless the scanned map projection has the latitudes and longitudes equally spaced. Unfortunately, because such a projection introduces severe distortions, a map projection with equally spaced latitudes and longitudes does not exist and the software had to be adapted to the 'Mercator' projection [24]. In the 'Mercator' projection, the longitudes are equally spaced but the space between latitudes increases in a non-linear fashion. Using interpolation techniques, a polynomial was generated to aid in the plot.

5.4.5 Get Contour for a Power Level

The software allows the user to generate contours of one of four power levels for a *center*. The user can choose a *center* that exists in the database and specify the intensity (high, moderate, low and lowest) level for the contour. The software surveys the database for grid-squares with attenuation values associated with the *center*. If, at a particular square-grid, the difference between the attenuation value and specified power level is less than a certain threshold, the coordinates of the square-grid are stored into a database file. This is also explained in Section 5.3.3. The user can then plot the coordinates as they would define the spot beam pertaining to the specified *center* and of the specified power level.

5.4.6 Change Name

This feature permits the user to change the name of any *center* that exists in the database. The software alters the *center* name in the ‘Centers’ file and the files pertaining to grid-squares (*10lat*, *20lat*, etc). This feature is sought when the user rearranges the spot beams.

5.4.7 Interference

This feature allows the user to determine the interference received from one specific spot beam into another assuming that there exist a co-channel user in that spot beam. It is assumed that both users use the same time slot and the same frequency. A more detailed analysis regarding the Interference and Tier Analysis is presented in Section 5.7.

5.4.8 Delete Center

The user can delete the *center* from the database. All the information regarding the *center* is purged from the database.

The following section deals with in-depth description of the procedure involved in the calculations of the results. More specifically, the calculation of attenuation, interference analysis and frequency assignment are discussed.

5.5 Attenuation Calculation

As explained in Chapter 4, the calculation of attenuation involves determining both (i) the path loss and (ii) the angle of reception at the satellite with respect to the boresight. The analysis commences with the specification of the center of the spot beam; the user must input the coordinates of the center. A completely separate database file is maintained for the

centers. Each center is a separate record with fields such as its coordinates, spot beam contour power level, and guard time value.

The coordinates of the center are used to determine the square-grids that shall be used to calculate the antenna gain and the path loss. If X° and Y° denote the longitude and latitude of the center respectively, the software calculates the received attenuation values in a vicinity of $X^\circ + a^\circ$, $X^\circ - b^\circ$, $Y^\circ + c^\circ$, $Y^\circ - d^\circ$ around the *center*. The value of a , b , c , d is 10° by default but can also specified by the user. The software calculates the gain values for all grid-squares located between $X^\circ + a^\circ$, $X^\circ - b^\circ$, $Y^\circ + c^\circ$ and $Y^\circ - d^\circ$.

As explained in Chapter 4, *center* coordinates serve as a reference for the path loss and boresight. All the remaining attenuation values are calculated relative to the *center* calculations. An example is presented next to aid in understanding the above details.

Let's assume that a *center* is chosen in the Miami region with coordinates of longitude = $X = 80.15^\circ$ W and latitude = $Y = 25.52^\circ$ N. As per specifications, the satellite is assumed to be at 106.5° W. Using Eq. 4-5, the distance between the satellite and the center of the spot beam is 37,196.98 km. Using Eq. 4-10, the path loss at the Miami center is -187.93 dB. For this example, the grid square with latitude = 30° N and longitude = 90° W is selected to demonstrate the attenuation calculations. The path loss from this grid-square to the satellite is -187.89 dB. The angle, α , is calculated as 1.663° and the corresponding antenna attenuation is -14.07 dB. Therefore, the total attenuation is:

$$-187.89 + (-14.07) = -201.96 \text{ dB.}$$

Hence, a signal transmitted from this grid-square is received at least

$$-201.96 - (-187.93) = -14.03 \text{ dB}$$

below in power level as compared to the signal transmitted from the center of the spot beam.

5.6 Calculation of Guard Time

In a TDMA frame structure for GEO-MSS systems, the guard time is a very significant component of the overhead associated with each time slot and therefore must be determined accurately to help evaluate the performance of TDMA schemes (also discussed in Chapter 3). The calculation of the guard time involves calculating the minimum and maximum distances from within one spot beam to the satellite. To accomplish this task, the distance to the satellite has to be calculated from all the grid-squares contained within the spot beam. The maximum and the minimum distances can then be stored and their difference dictates the value of guard time. This is depicted in Figure 5-7. The equation relating the difference in distances to the Guard Time is given in Eq. 5-1.

$$\text{Guard Time} = \frac{\text{Difference between Max. and Min. Distances to the Satellite}}{\text{Speed of Light}} \quad \text{Eq. 5-1}$$

As an example, a *center* is chosen in the Miami region with coordinates of longitude = 80.15° W and latitude = 25.52°N. Again, the satellite is assumed to be located at a longitude of 106.5° W. Also, the center is assumed to have a 3 dB contour spot beam. According to the

software calculations, the minimum distance to the satellite is 36,942.31 km and it occurs at a latitude of 23.27°N and a longitude of 83.21°W. The maximum distance to the satellite is 37,488.28 km and it occurs at a latitude of 27.92°N and a longitude of 76.89°W. Using Eq. 5-1, the guard time is:

$$\frac{(37,488.28 - 36,942.31) \times 1000}{(3 \times 10^8) \text{ m/s}} = 1.82 \text{ ms.}$$

The guard time value is stored in the 'Centers' file.

Figure 5-7: An arbitrary spot beam is shown to illustrate the concept of guard time calculations. The spot beam is big enough to cause significant difference in the propagation times to the satellite

5.7 Interference Analysis

The software has provision for two kinds of interference analysis, termed as “Interference Analysis” and “Tier Interference Analysis”. Interference Analysis is useful for determining the amount of interference emanating from one spot beam to another. To illustrate this, let us assume an example involving two users operating at the same time slot on the same frequency. Also assume that one user is operating in the Miami spot beam while the other user is operating in the Chicago spot beam. To perform worst-case interference analysis, the user in the Miami spot beam is assumed to be at the edge of his/her spot beam. For example, if the Chicago spot beam is a 3.0 dB contour, the user is assumed to be 3.0 dB below the boresight gain. This ensures that the desirable signal is received with weakest strength. To calculate the maximum possible interference that can be received by the user in Miami, all the square grids within the Chicago spot beam should be scanned to determine the grid square which provides maximum interference to the user in the Miami spot beam. At first, the obvious solution may be to seek the grid square in Chicago spot beam that is nearest in distance to the Miami spot beam. However, due to the *sinc* function antenna pattern (existence of side lobes), the grid-square physically nearest to the Miami spot beam may not produce the maximum interference. This is shown in Figure 5-8.

Figure 5-8: A superimposition of the antenna pattern on the spot beam contours illustrating the non-linear relationship between the distance from the boresight and the attenuation

Therefore, it is imperative to scan and calculate the interference received from all grid-squares in the Chicago spot beam. The software calculates the maximum interference received from the spot beam and also assists in locating the exact square grid which is emanating the maximum interference.

Tier interference Analysis allows the user to calculate the amount of interference being received from several spot beams simultaneously. The user can specify the number and names

of the interfering spot beams. The user can also specify the type of user terminal being employed in each of the interfering spot beams. The software then computes the total received interference power from various spot beams. This is very useful as it helps in determining the frequency reuse distance.

5.8 Frequency Assignment Analysis

Frequency Assignment is the next major task in the system design. The system bandwidth is 29 MHz and effort has to be made to assign frequencies efficiently. Due to the nature of the sizes and irregular shapes of the spot beams, conventional frequency assignment techniques based upon the hexagonal analysis (as in terrestrial case) are not suitable for GEO-MSS systems [10].

Two or more spot beams can be assigned the same frequency if the maximum interference received from one spot beam to the remaining spot beams is below a specified threshold. The process can be expedited if the interference received from all the spot beams to all the remaining spot beams can be calculated offline and stored into a separate database file. The software can execute once and generate the matrix presented in Section 4.5. The frequency assignment can then be carried out relatively quickly by querying the database for interference values. The frequency assignment is performed assuming one of the following two distinct interference scenarios at a time:

1. All interfering co-channel users are 8 kb/s users with terminals identical to the terminal of the desirable user

2. The interfering co-channel users are a randomly assigned mix of 8 kb/s and higher data rate users. As explained before, on average, half of the interfering users are assumed to be 8 kb/s users and the rest are high data users. The terminals for all the higher data rate users are identical and are more capable than the terminal of the desirable user.

The analysis for each of the three scenarios is expected to yield the maximum number of frequency bands, N , required to provide service to all spot beams in North America with tolerable interference. The system bandwidth of 29 MHz can then be divided by N to determine the capacity of each spot beam. The steps involved in frequency assignment follow:

1. Assign different data rate users randomly to the spot beams
2. Calculate the threshold interference that can be tolerated by the user in each spot beam and store it into the '*Centres*' file database file.
3. Assign a particular frequency to a maximum number of spot beams. A frequency, f_x , can be assigned to another spot beam, S , if and only if the mutual interference between S and the spot beams which have already been assigned f_x is tolerable.
4. To facilitate the calculations, a list of spot beams that can simultaneously use f_x is maintained (Section 5.3.6). Also, the interference received from each spot beam into the remaining spot beams is already tabulated (Section 5.3.4).
5. The basic algorithm is given below; most of the details regarding the updating of the thresholds after the frequency assignment are omitted.

```

start from a center X and mark it assigned
Add it to ' $f_x$  list'
while unassigned centres left
    traverse through the neighbors of X with no frequency assigned yet
    for each neighbor Y
        retrieve interference received from ALL centres in ' $f_x$  list' to Y
        TOTALINT = add the total interference
        if TOTALINT > threshold of Y then
            success = false
            exit
        else
            for every center Z in ' $f_x$  list'
                retrieve interference received from Y to Z
                if interference from Y > threshold of Z then
                    success = false
                else
                    success = true
                end if
            end for
        end if
        if success = true then assign Y to ' $f_x$  list'
        update the thresholds for the centres in the ' $f_x$  list'
    end for
    increment the frequency counter, now try the procedure with  $f_x = f_x + 1$ 
    ( $f_x$  list is empty)
end while

```

This algorithm is successfully implemented for the two scenarios and the results are presented in the next chapter. The direct search algorithm for frequency assignment explained above yields a preliminary set of results for cluster size (number of frequency bands). There exists potential for using more than one frequency band in one spot beam to ensure maximum reuse and bandwidth utilization. This algorithm is extended and bandwidth-limited capacity analysis is made more accurate. In the next section, the extension to the algorithm is discussed. The resulting frequency assignment configuration and bandwidth-limited capacity analysis is presented in the next chapter.

5.8.1 An Extension to the Frequency Assignment Algorithm

The existing algorithm allows one frequency band to be assigned per spot beam. Every time a frequency band is assigned to a spot beam, the spot beam is marked as “already assigned” and is not reconsidered for another frequency band. Due to the fewer number of spot beams available later in the process of frequency assignment, an unequal number of spot beams per frequency band result. The algorithm is extended to repeat frequency assignment and allow more than one frequency band to be assigned to each spot beam. This results in a significant enhancement of bandwidth-limited capacity of the spot beam with more than one frequency band. The centres and their corresponding frequency band(s) assignments are presented in the next chapter.

Chapter 6

Results and Capacity Analysis

6. Results

In this chapter, results obtained from the software module are presented. They are used later to evaluate the system capacity. As explained in Chapter 5, the software module has been instrumental in providing a complete system design. The development of the module produces results which are incrementally incorporated into the system design and capacity calculations. The capacity calculations are carried out for the proposed system assuming two distinct approaches. The two approaches are as follows:

- **bandwidth-limited** case (from frequency assignment)
- **power-limited** case (from the link-budget)

In the case of bandwidth-limited capacity calculation, the frequency assignment performed by the software module is utilized. As explained in Chapter 5, identification of the spot beam centers, the spot beam (coverage of North America) layout and the interference analysis culminate in a particular frequency assignment. The frequency assignment provides an insight into the frequency reuse. Based on bandwidth of each carrier, number of carriers is calculated. The number of users in the system depends on the number of users

per carrier which in turn depends on the traffic mix (number of 8kb/s, 16kb/s, 32kb/s, 48kb/s and 64kb/s users) and the choice of guard time in the frame. The calculation of the capacity in the power-limited case stems from the link budget. The satellite amplifier is capable of providing a limited amount of power which is shared between the carriers in the system. The share of power dedicated to each carrier depends on the frame contents; specifically on the received signal power levels in each time slot in the frame.

In the bandwidth limited case, the capacity calculations are conducted for both the traditional and the proposed frame structures and the results are compared. The power-limited capacity calculations are almost indifferent for the two frame structures. This is because there is no satellite power consumed during the guard time (majority) portion of the overhead. In the next section, results pertaining to the spot beam centers, the spot beam (coverage of North America) layout, interference analysis and guard time calculations are presented.

6.1 List of Centres

The choice of the coordinates of the centres is a meticulous undertaking as it involved ensuring that the entire North America is covered completely with spot beams. The objective is to try and cover all grid-square locations in North America with several spot beams (of different edge-of-spot beam power levels) with minimum overlap taking into consideration variability of traffic intensity from a spot beam to another. Since a mathematical optimization solution (if one exists) is beyond the scope of the thesis, an ad-hoc approach is adopted to yield an acceptable spot beam configuration. The list of the centres and their coordinates are presented in Table 6-1 and Table 6-2.

Spot Beam Centre	TI	Lat.	Long.	Spot Beam Centre	TI	Lat.	Long.
ColumbiaSC (S. Carolina)	2	81.00	34.00	Tuxtla (Mexico)	3	94.20	16.80
Dallas (Texas)	1	96.50	32.50	Campeche (Mexico)	3	89.00	19.00
Houston (Texas)	1	95.20	29.50	Hawaii (Hawaii)	3	155.0	20.00
Detroit (Michigan)	1	83.22	42.13	Guadalajara (Mexico)	3	102.5	19.50
Phoenix (Arizona)	2	112.1	33.30	GulfofCalifornia	3	113.1	28.53
SanDiego (California)	2	117.1	32.43	Tehuantepec (Mexico)	3	98.00	16.80
Memphis (Tennessee)	2	90.00	35.07	LaPaz (Mexico)	3	109.5	24.00
Miami (Florida)	3	80.15	25.52	PEI (Prince Edward Islands)	1	64.13	46.20
Boiseldaho (Idaho)	3	116.15	43.71	NewBrunswick	1	68.00	48.00
Knoxville (Tennessee)	2	83.95	35.96	Sudbury (Ontario)	2	81.70	46.60
SanAntonio (Texas)	2	98.50	29.50	Saskatoon (Saskatchewan)	2	104.3	52.10
YellowStone (Wyoming)	3	108.93	45.50	LynnLake (NW Terr.)	2	96.50	57.50
RapidCity (S. Dakota)	3	103.32	44.32	Calgary (Alberta)	2	111.1	53.00
Winnipeg (Manitoba)	2	98.23	49.58	CarolHarbor (NW Terr.)	3	83.50	67.00
LasVegas (California)	3	116.43	36.40	Hopedale (Newfoundland)	3	56.00	57.00
GrandJunction (Utah)	3	110.98	39.35	GulfMexicoSea (Mexico)	3	89.00	27.50
ColoradoSprings (Colorado)	3	105.7	38.25	YellowKnife (NW Terr.)	2	112.0	61.00
EIPaso (New Mexico)	3	107.8	33.10	Thunderbay (Ontario)	2	88.30	46.70
ArkansasCity (Kansas)	3	99.50	38.35	DesMoines (Iowa)	2	93.30	41.00
MobileAlabama (Alabama)	2	86.63	31.81	Longlac (Ontario)	2	86.00	52.80
FortWorthWestTexas	3	101.8	33.20	PortNelson (Manitoba)	1	90.00	55.00
GuaymasMexico	3	109.1	28.03	Duluth (Minnesota)	2	93.80	47.00
Chihuahua (Mexico)	3	103.8	28.90	Banff (Alberta)	2	115.5	50.00
NewOrleans (Louisiana)	2	91.90	31.40	UraniumCity (Saskatchewan)	1	104.0	59.00
OklahomaCity	3	95.50	35.65	PeaceRiver (Alberta)	1	118.0	58.20
StLouisMissouri (Missouri)	1	89.50	38.46	PrinceRubert (British Columbia)	1	128.5	55.00
Pittsburgh (Pennsylvania)	1	79.55	40.65	HolyCross (Alaska)	3	158.0	62.00
Chicago (Illinois)	1	88.40	42.53	MonterreySea (Mexico)	3	95.00	25.00
Cincinatti (Ohio)	1	85.53	39.17	QueenCharlotte- Islands (BC)	3	133.7	51.80
NewYork (New York)	0	75.00	40.45	PortlandSea (Oregon)	3	127.5	44.00
RichmondVirginia (Virginia)	1	78.07	37.33	SanJoseSea (California)	3	126.0	36.50

Table 6-1: The names, expected traffic intensities (TI) and the coordinates of some of the centers of the spot beams

Spot Beam Centre	TI	Latit.	Longit.
Guadalupelsland (Mexico)	3	121.5	31.00
Labrador (Newfoundland)	2	71.00	52.00
GreatBearLake (North West Terr.)	2	122.0	70.50
Ottawa (Ontario)	1	76.52	44.92
SanFrancisco (California)	0	122.2	37.20
JacksonVille (Florida)	2	83.23	29.15
PortlandMaine (Maine)	1	72.35	43.34
ReddingCalifornia (California)	3	121.5	40.30
PortlandOregon (Oregon)	1	122.3	45.50
Omaha (Nebraska)	3	97.00	42.50
Monterrey (Mexico)	3	100.5	24.66
MexicoCity (Mexico)	2	98.60	19.80
Durango (Mexico)	3	105.0	23.50
GjaoHaven (North West Terr.)	2	94.00	70.00
Frobisher (North West Terr.)	3	73.70	63.00
Newfoundland	3	53.00	52.00
SableIsland (Nova Scotia)	3	58.00	44.50
Haiti	3	73.00	19.00
JacksonVilleSea (Florida)	3	76.50	32.00
BelcherIslands (North West Terr.)	3	78.75	53.00
SanPedroSula (Mexico)	3	89.00	14.50
Fairbanks (Alaska)	2	146.0	64.50
BathurstInlet (North West Terr.)	2	107.5	70.00
Habana (Cuba)	3	84.00	23.00
Jamaica (Caribbean)	3	78.00	17.00
Hebron (Newfoundland)	3	60.00	63.00
NewYorkSea (New York)	3	70.25	39.00
ManzanillaSea (Mexico)	3	107.5	19.00
BermudaIsland	3	65.00	32.50
BelizeCitySea (Mexico)	3	82.50	17.00
DawsonCreek (British Columbia)	1	122.5	56.00
StKitts (Caribbean)	3	67.00	17.20
Dominica (Caribbean)	3	60.00	15.00
SanSalvador (Bahamas)	3	73.00	24.00
DominicanRepublic (Caribbean)	3	66.00	22.50
Cuba	3	79.00	21.00
Vancouver (British Columbia)	2	122.5	50.10
WatsonLake (Yukon Territory)	2	134.3	64.50
LosAngeles (California)	0	119.9	35.00
NormanWells (North West Terr.)	2	131.0	69.00

Table 6-2: The names, expected traffic intensities (TI) and the coordinates of remaining centers of the spot beams

6.2 Spot beam coverage of North America

As shown in Figure 6-1, there are altogether 102 spot beams chosen in the design of the system. The edge-of-spot beam power level is one of four values with respect to the center of the spot beam. Figure 6-1 depicts the spot beam coverage layout produced with the aid of the software module developed. This layout is also the basis for the interference analysis, frequency assignment and the calculation of the guard time values. In Figure 6-1, different colours are used to differentiate between the spot beams with different edge-of-spot beam power levels according to traffic intensity expected. The edge-of-spot beam power levels and their respective colour codes are as follows:

- -0.5dB (High Traffic Intensity) *Red*
- -1.3dB (Moderate Traffic Intensity) *Blue*
- -2.0dB (Low Traffic Intensity) *Magenta*
- -3.0dB (Lowest Traffic Intensity) *White*

As can be seen in Figure 6-1, the coverage extends to all parts of North America including the Caribbean and the Hawaii Islands, coastal regions and areas situated at a latitude of more than 70°N. The choice of the edge-of spot beam power level is dependent on the traffic intensity expected from the users in a particular region. Since no formal traffic characteristics/models are available to the author, the expected traffic intensity has largely been based upon the population in a particular area. However, it is also known [8] that the current TMI's operated MSAT system is experiencing its highest traffic concentration in the

West beam (specifically the British Columbia region in Canada). Therefore, spot beams with moderate traffic intensity power levels have been assigned to the region in spite of the relatively low regional population. It should also be noted that the spot beam coverage includes areas in both the Pacific and the Atlantic oceans to serve ships and cruises where the terrestrial cellular services are unavailable.

Figure 6-1: A particular spot beam layout to provide MSS service to North America

6.3 Guard Time Values

The minimum guard time calculations are performed for all spot beams in Figure 6-1. As explained in Chapter 5, the guard time values are calculated by computing the maximum difference between the propagation delays from locations within a spot beam to the satellite. The guard time values associated with each spot beam are presented in Table 6-3 and Table 6-4. They range from 0.76080 ms to 7.1869 ms. It is obvious that the range of the guard time values is quite large and the choice of only one value will result into a great deal of waste in the overall system capacity. For ease of implementation, the guard time is assigned one of the following four values; 1.40, 2.25, 3.5 and 7.2ms, with the number of corresponding spot beams; 24, 29, 26 and 23, respectively.

Spot Beam Centre	Guard Time (ms)	Spot Beam Centre	Guard Time (ms)
MexicoCity	0.7608	Cuba	1.6792
LosAngeles	0.7966	Guadalupelsland	1.6804
Tehuantepec	0.7995	Chicago	1.8076
ManzanillaSea	0.8110	RichmondVirginia	1.8144
Guadalajara	0.8534	Miami	1.8198
Tuxtla	0.8938	ColumbiaSC	1.8920
SanFrancisco	0.8939	Knoxville	1.8963
SanPedroSula	0.9880	OklahomaCity	1.9042
Houston	1.0013	Detroit	1.9295
Durango	1.0381	LasVegas	1.9401
LaPaz	1.0715	Pittsburgh	1.9614
Dallas	1.1108	Haiti	1.9737
Monterrey	1.1341	PortlandOregon	1.9740
Campeche	1.1494	DesMoines	1.9840
SanAntonio	1.1856	ColoradoSprings	1.9926
MonterreySea	1.2480	ArkansasCity	2.0517
GuaymasMexico	1.2938	GrandJunction	2.1108
NewYork	1.3396	SanSalvador	2.1833
Chihuahua	1.3458	SanJoseSea	2.2148
BelizeCitySea	1.3524	StKitts	2.3867
GulfofCalifornia	1.3595	ReddingCalifornia	2.3908
Phoenix	1.3644	JacksonVilleSea	2.4078
SanDiego	1.3775	Ottawa	2.4231
NewOrleans	1.3992	Omaha	2.4729
Habana	1.5150	Duluth	2.5184
StLouisMissouri	1.5277	PortlandMaine	2.5186
JacksonVille	1.5428	RapidCity	2.5856
GulfMexicoSea	1.5502	Boiseldaho	2.6017
MobileAlabama	1.5620	Thunderbay	2.6382
Jamaica	1.5896	DominicanRepublic	2.6934
ElPaso	1.6103	YellowStone	2.7147
FortWorthWestTexas	1.6369	Longlac	2.7450
Memphis	1.6529	Banff	2.7919
Cincinatti	1.6672	Sudbury	2.8995

Table 6-3: The minimum guard time values associated with some of the spot beams

Spot Beam Centre	Guard Time (ms)
Saskatoon	2.9971
PortlandSea	2.9971
Dominica	3.0653
Calgary	3.1478
DawsonCreek	3.1567
PrinceRubert	3.2240
Winnipeg	3.3202
NewBrunswick	3.3231
PeaceRiver	3.4183
BermudaIsland	3.4358
PEI	3.4830
NewYorkSea	3.4932
Hawaii	3.5459
Vancouver	3.6217
PortNelson	3.7639
YellowKnife	3.9140
Labrador	3.9915
BelcherIslands	4.0210
LynnLake	4.0751
UraniumCity	4.3196
NormanWells	4.3283
QueenCharlotte Islands	4.6282
Newfoundland	4.7503
SableIsland	5.0869
CarolHarbor	5.3697
Hopedale	5.6238
WatsonLake	5.6856
Fairbanks	6.1751
Frobisher	6.4883
Hebron	6.6685
BathurstInlet	6.9323
GreatBearLake	7.0771
HolyCross	7.1139
GjaoHaven	7.1869

Table 6-4: The minimum guard time values associated with remaining spot beams

As discussed in Chapter 3, the time slot duration in a frame depends on the user data rate and the overhead bits. In the MSS system proposed in this thesis, the guard time has a drastic

impact on the frame capacity. Table 6-5 shows the duration of the time slot for different data rate users with the four distinct guard time values mentioned earlier. Note that the time slot duration are only applicable for the proposed frame structure; explained in Chapter 3.

Data Rate	Duration of Time Slot in the Proposed Frame with Different Guard Time values				
	0 ms	1.4 ms	2.25 ms	3.5 ms	7.2 ms
8 kb/s	2.75 ms	4.15 ms	5.0 ms	6.25 ms	9.95 ms
16 kb/s	5.25 ms	6.65 ms	7.5 ms	8.75 ms	12.45 ms
32 kb/s	10.25 ms	11.65 ms	12.5 ms	13.75 ms	17.45 ms
48 kb/s	15.25 ms	16.65 ms	17.5 ms	18.75 ms	22.45 ms
64 kb/s	20.25 ms	21.65 ms	22.5ms	23.75 ms	27.45 ms

Table 6-5: The duration of the time slots for different data rate users and with different guard time values

According to Table 6-5, duration of an 8 kb/s user time slot can be 4.15, 5.0, 6.25 or 9.95 ms, depending upon the spot beam. This large difference in the duration of the time slots has a significant impact on the capacity of the system. In traditional frame structure, a user demanding high data rate services is assigned multiple time slots with the above guard time values existing between each time slot. In the next section, a comparison of the proposed and the traditional frame structure is given, with regard to the capacity of the frame structures.

6.3.1 Comparison of the Proposed and the Traditional Frame Structures

At a frame rate of 160kb/s, the 1.40ms guard time translates into 224 bits. Along with 40 bits for other overheads, the total number of overhead bits is 264. With a 50ms frame operating

at 160kb/s, there are 8,000 total bits available. In the proposed system, if the 64 kb/s time slot is considered, the number of information bits including forward error correction (FEC) bits is 3,200 and with the addition of 264 overhead bits, total bits are 3,464. Therefore, the frame has the total capacity of $8000/3464 = \text{two } 64 \text{ kb/s users}$ (with 1,072 bits to spare which can accommodate a 16kb/s or an 8kb/s user). With a guard time of 1.4 ms, the traditional frame structure has a total of twelve 8kb/s time slots and it can accommodate one 64kb/s user and four 8kb/s users. Therefore, using the proposed frame structure, there is a 100% improvement in the capacity for 64kb/s users.

In Table 6-6, a 53% capacity improvement is shown with a data rate of 64 kb/s and a guard time value of 1.4ms. The capacity improvement of 53% is calculated using the following formula:

$$\begin{aligned} \text{Capacity Improvement} &= \frac{\text{Total Capacity (prop.struct.)} - \text{Total Capacity (trad.structure)}}{\text{Total Capacity (trad.structure)}} \\ &= \frac{2.3 - 1.5}{1.5} \times 100 = 53\% \end{aligned}$$

A similar analysis is carried out for other data rates and the results presented in Table 6-6.

Data Rate, kb/s	Guard Time (ms)	Overhead bits/ time slot (incl. guard time)	Info. bits with FEC	Total bits in time slot (prop. struct.)	Total Capacity (prop. struct.)	Total Capacity (trad. struct.)	Capacity Improvement
8	1.40	264	400	664	12.0	12.0	0%
	2.25	400		800	10.0	10.0	
	3.50	600		1000	8.0	8.0	
	7.20	1192		1592	5.0	5.0	
16	1.40	264	800	1064	7.5	6.0	25%
	2.25	400		1200	6.6	5.0	32%
	3.50	600		1400	5.7	4.0	42%
	7.20	1192		1992	4.0	2.5	60%
32	1.40	264	1600	1864	4.2	3.0	40%
	2.25	400		2000	4.0	2.5	60%
	3.50	600		2200	3.6	2.0	80%
	7.20	1192		2792	2.8	1.2	133%
48	1.40	264	2400	2664	3.0	2.0	50%
	2.25	400		2800	2.8	1.6	75%
	3.50	600		3000	2.6	1.3	100%
	7.20	1192		3592	2.2	0.8	175%
64	1.40	264	3200	3464	2.3	1.5	53%
	2.25	400		3600	2.2	1.2	83%
	3.50	600		3800	2.1	1.0	110%
	7.20	1192		4392	1.8	0.0	-

Table 6-6: Improvement in Capacity with the proposed frame structure over the traditional frame structure

The proposed TDMA frame structure promises a capacity improvement of 175% in some particular scenarios (for data rates of 48 kb/s with a guard time of 7.2 ms, see Table 6-6). In some cases with large guard time values, the traditional frame cannot support any 64 kb/s user at all and therefore the proposed frame structure is the only option. The capacity improvement varies from 0% to 175% depending upon the user data rate and the spot beam guard time value. If all users operate at 8kb/s, there is no difference between the proposed

and the traditional frame structures. The difference in the time slot assignment mechanism for higher data rate users results in significant capacity improvement, as shown in Table 6-6. It should be noted that several other combinations of mixed data rates (ranging from 8 to 64 kb/s) are possible and again the efficiency enhancement will be in the range of 0 to 175%.

6.4 Frequency Assignment and the Bandwidth-limited Capacity

As mentioned in Chapter 4, the total system bandwidth is chosen typically to be 29 MHz which is divided among a number of distinct frequency bands. The frequency bands can then be re-used leading to increased network capacity. The frequency assignment yields the number of distinct frequency bands required in the network. The process of assigning frequency bands to different spot beams in one cluster depends heavily upon the mutual interference between the spot beams in various neighboring clusters sharing the same frequency bands. For the proposed system, the frequency assignment algorithm is implemented for two assumptions (mentioned shortly) regarding the interfering user terminals (explained in Chapter 5). The algorithm is implemented separately for both the assumptions and two distinct sets of results are obtained. Briefly, the two assumptions are as follows:

- all interfering users are 8kb/s users (terminal peak power = 4.6 W, antenna gain = 3 dBi), or
- the interfering users are a random mix of 8kb/s, 16 kb/s, 32 kb/s and 64kb/s users.

The data terminals for the 16, 32, 48 and 64 kb/s users have a peak power dissipation of 5.7 W and an antenna gain of 5 dBi).

The analysis is conducted for each of the assumptions separately and the results are provided in the next section.

6.4.1 All interfering users operate at a data rate of 8 kb/s:

The frequency assignment algorithm (explained in Chapter 5) is executed 102 times; *a different spot beam is assumed as the initial center every time*. Each execution of the software module yields a particular frequency assignment configuration. A typical result from one execution is summarized in Table 6-7. In this particular example, 14 frequency bands are required and therefore the bandwidth available per spot beam is $29\text{MHz} / 14 = 2.07 \text{ MHz}$. The list of spot beams which can use a particular frequency (Frequency 1, for example) without causing unacceptable interference to the co-channel spot beams is also provided by the software module.

Total Frequencies Required = 14						
<i>Frequency 1</i>	<i>Frequency 2</i>	<i>Frequency 3</i>				<i>Frequency 14</i>
ColumbiaSC	Dallas	Houston				Gulf of California
Memphis	GulfMexicoSea	Mobile Alabama		.	.	Newfoundland
Ottawa	Cincinnati	Des Moines				
San Antonio	Grand Junction	La Paz				
Haiti	San Diego	Pittsburgh				
Mexico City	New York	Las Vegas				
Port Nelson	Jamaica	Saskatoon				
Phoenix	Calgary	Dominican Rep.				
Banff	Prince Rupert	PEI				

Table 6-7: A typical example of the results obtained from the frequency assignment algorithm.

The results in Table 6-7 are obtained when the frequency assignment algorithm is executed assuming *Columbia, South Carolina* as the initial starting point. However, to achieve maximum capacity per spot beam, the number of frequency bands (frequency reuse factor or the cluster size) is desired to be low.

When all interfering users are assumed to be operating at a data rate of 8 kb/s, the lowest value for the number of frequency bands is 13 and is obtained when the frequency assignment algorithm is initiated from Hebron (Newfoundland), Boise (Idaho) or New York Sea (the coastal region near New York). Therefore, the bandwidth allowed per spot beam is $29\text{MHz} / 13 = 2.23 \text{ MHz}$. Since each carrier occupies a bandwidth of 100KHz, there exist $2.23\text{MHz} /$

$100\text{KHz} = 22$ carriers per spot beam. There exists a total number of 102 spot beams and therefore the system bandwidth-limited capacity is $22 * 102 = 2,244$ carriers. The frequency assignment is depicted in Figure 6-2. All the spot beams sharing the same frequency band are represented with the same color in the figure.

If the bandwidth-limited capacity of the system is desired in terms of the number of 8, 16, 32, 48 and 64 kb/s users, the frame structure for each carrier must be established first. For example, if all users in the system are assumed to operate at a data rate of 8 kb/s and guard time values of 1.4, 2.25, 3.5 and 7.2ms are distributed among 24, 29, 26 and 23 carriers respectively out of a total of 102 carriers.

Guard Time Value	No. of carriers with Guard Time value	No. of 8 kb/s users in the 50 ms frame	Total No. of 8 kb/s users
1.40	$(24/102) * 2244 = 528$	12	6336
2.25	$(29/102) * 2244 = 638$	10	6380
3.50	$(26/102) * 2244 = 572$	8	4576
7.20	$(23/102) * 2244 = 506$	5	2530
<i>Bandwidth-Limited System Capacity for 8 kb/s users with traditional & proposed frame structure</i>			19,822

Table 6-8: The bandwidth-limited system capacity with all users operating at 8 kb/s.

There is no difference between the traditional and the proposed frame structures in the bandwidth-limited capacity for the 8 kb/s users. This is because the number of 8 kb/s users in the 50ms frame is identical in both cases.

In this case, since all interfering users are assumed to operate at a data rate of 8 kb/s, the overall system capacity can be calculated only with 8 kb/s users. In the next section, the

analysis is repeated assuming that the interfering users are a mix of 8, 16, 32, 48 and 64 kb/s users.

Figure 6-2: Frequency Assignment assuming all interfering users operate at 8kb/s

6.4.2 *The interfering users are a mix of 8, 16, 32, 48 and 64 kb/s users*

Following the other assumption where the interfering users are assumed to be a mix of users operating at different data rates (a more realistic assumption), the lowest value for the number of frequency bands is 12 and is obtained when the frequency assignment algorithm is initiated from Lynn Lake (North West Manitoba), Carol Harbor (North West Territories) or Dawson Creek (British Columbia). The procedure used to obtain the value of 12 is identical to that presented in Section 6.4.1. Therefore, the bandwidth allowed per spot beam is $29\text{MHz} / 12 = 2.41\text{MHz}$. *Since each carrier occupies a bandwidth of 100KHz, there exist $2.41\text{MHz} / 100\text{KHz} = 24$ carriers per spot beam.* *There exists a total number of 102 spot beams and therefore the system bandwidth-limited capacity is $24 * 102 = 2,448$ carriers.* The frequency assignment is depicted in Figure 6-3. The result is unexpectedly better than the case with all interfering users operating at 8 kb/s. This is because in this case, although some of the co-channel interfering users use a more capable terminal, they can simultaneously tolerate more interference.

If the bandwidth-limited capacity of the system is desired in terms of the number of 8, 16, 32, 48 and 64 kb/s users, the frame structure for each carrier must be established first. Table 6-9 illustrates the overall system capacity achieved when all users in the system operate at a data rate of 8 kb/s.

Guard Time Value	No. of carriers with Guard Time value	No. of 8 kb/s users in the 50 ms frame	Total No. of 8 kb/s users
1.40	$(24/102) * 2448 = 576$	12	6912
2.25	$(29/102) * 2448 = 696$	10	6960
3.50	$(26/102) * 2448 = 624$	8	4992
7.20	$(23/102) * 2448 = 552$	5	2760
<i>Bandwidth-Limited System Capacity for 8 kb/s users with traditional & proposed frame structure</i>			21,624

Table 6-9: The bandwidth-limited system capacity with all users operating at 8 kb/s.

The increase in the number of available carriers leads to a direct increase in the number of the users that can be supported in the system. From Table 6-9, the capacity of the system increases from 19,822 users (Table 6-8) to 21,624 users. Table 6-10 illustrates the overall system capacity achieved when all users in the system operate at a data rate of 16 kb/s.

Guard Time (GT) value	No. carriers with GT	No. 16 kb/s users in prop. frame	Total No. of 16 kb/s users	No. 16 kb/s users in trad. frame	Total No. of 16 kb/s users
1.40	576	7.5	4320	6	3456
2.25	696	6.6	4593	5	3480
3.50	624	5.7	3556	4	2496
7.20	552	4.0	2208	2.5	1380
<i>Bandwidth-Limited System Capacity for 16 kb/s users with:</i>		<i>prop. frame</i> 14,677	<i>trad. frame</i> 10,812		
		Improvement = 35.74%			

Table 6-10: A comparison of the system bandwidth-limited capacity for users operating at a data rate of 16 kb/s with proposed and traditional frame structures

The proposed frame structure is very efficient as compared to the traditional frame structure when higher data rates are used in the system. As shown in Table 6-10, the system capacity is significantly better with the proposed frame structure. With the proposed frame structure, the capacity increases from 10,812 16kb/s users to 14,677 users, a marked improvement of

35.74%. The capacity enhancements for data rates higher than 16kb/s are illustrated in Table 6-11.

Guard Time (GT) value	No. carriers with GT	No. 32 kb/s users in prop. frame	Total No. of 32 kb/s users	No. 32 kb/s users in trad. frame	Total No. of 32 kb/s users
1.40	576	4.2	2419	3.0	1728
2.25	696	4.0	2784	2.5	1740
3.50	624	3.6	2246	2.0	1248
7.20	552	2.8	1545	1.2	662
<i>Bandwidth-Limited System Capacity for 32 kb/s users with:</i>		<i>prop. frame</i>	8,994	<i>trad. frame</i>	5,378
Improvement = 67.23%					
<i>Similarly,</i>					
<i>Bandwidth-Limited System Capacity for 48 kb/s users with:</i>		<i>prop. frame</i>	6,446	<i>trad. frame</i>	3,517
Improvement = 83.28%					
<i>Bandwidth-Limited System Capacity for 64 kb/s users with:</i>		<i>prop. frame</i>	5,158	<i>trad. frame</i>	2,323
Improvement = 122.04%					

Table 6-11: A comparison of the system bandwidth-limited capacity for users operating at a data rate of 32, 48 and 64kb/s with proposed and traditional frame structures.

Table 6-11 presents an abridged comparison of the improvements offered by the proposed frame structure when the users in the system operate at data rates of 32, 48 and 64 kb/s. As expected, the capacity improvement offered by the proposed frame structure as compared to the traditional frame structure is more pronounced at high data rates. The performance of the traditional frame structure is not admirable at high data rates due to allocation of the guard time and overhead bits in each time slot. With the proposed frame structure, the capacity

improves to up to 122.04% when all users in the system are assumed to operate at a data rate of 64 kb/s.

Figure 6-2: Frequency Assignment assuming all interfering users operate at 8kb/s

6.4.3 Bandwidth-Limited Capacity with the extended algorithm

As discussed in Section 5.8 and 5.8.1, the frequency assignment algorithm is modified to allow more than one frequency band to be assigned to a spot beam. The algorithm is executed assuming the interfering users operate at mixed data rates. The resulting frequency band assignment is given in Table 6-12 and Table 6-13. In Table 6-12, spot beam center ‘San Diego’ is assigned frequency bands 3, 10, 11 and 12 which results in a bandwidth capacity improvement of 300% as compared to single frequency assignment per spot beam for ‘San Diego’ alone. Similarly, ‘Hawaii’ can reuse the entire frequency band of 29 MHz as the interference from co-channel interfering spot beams is minimal.

As discussed in Section 6.4.2, when the interfering users are a mix of users operating at different data rates, the lowest value for the number of frequency bands is 12 . Since the total system bandwidth is 29 MHz, the bandwidth per frequency band is $29\text{MHz} / 12 = 2.41\text{MHz}$. *Since each carrier occupies a bandwidth of 100KHz, there exist $2.41\text{MHz} / 100\text{ KHz} = 24$ carriers per spot beam.* With only one frequency band per spot beam, the system bandwidth-limited capacity is $24 * 102 = 2,448$ carriers. The extended algorithm allows for more than one frequency band to be assigned to each spot beam, interference permitting. *From Table 6-12 and Table 6-13 , there exist a total of 145 frequency bands which translate into a bandwidth-limited capacity of $24 * 145 = 3,480$ carriers.* The extension to the algorithm results in a capacity improvement of 42.1% as calculated below.

$$\frac{3480 - 2448}{2448} \times 100 = 42.1\%$$

In most cases, MSS systems are ²⁴⁴⁸power limited. However, due to large coverage area and different time zones; while the system may not reach its power-limited capacity, the demand

for bandwidth in one particular region may exceed the available bandwidth. Hence, it is desirable to maximize bandwidth-limited capacity.

Spot Beam Centre	FB No.	Spot Beam Centre	FB No.
ColumbiaSC (South Carolina)	2	Tuxtla (Mexico)	12
Dallas (Texas)	1 12	Campeche (Mexico)	10
Houston (Texas)	3	Hawaii (Hawaii)	1 to 12
Detroit (Michigan)	4	Guadalajara (Mexico)	5
Phoenix (Arizona)	1	GulfofCalifornia (Carolina)	2
SanDiego (California)	3 10 11 12	Tehuantepec (Mexico)	6
Memphis (Tennessee)	2	LaPaz (Mexico)	3
Miami (Florida)	5	PEI (Prince Edward Islands)	1 7
Boiseldaho (Idaho)	6	NewBrunswick	4
Knoxville (Tennessee)	7 12	Sudbury (Ontario)	8
SanAntonio (Texas)	2	Saskatoon (Saskatchewan)	1 12
YellowStone (Wyoming)	7	LynnLake (North West Terr.)	9
RapidCity (S. Dakota)	5	Calgary (Alberta)	2 11
Winnipeg (Manitoba)	8	CarolHarbor (North West Terr.)	11
LasVegas (California)	8	Hopedale (Newfoundland)	11
GrandJunction (Utah)	4	GulfMexicoSea (Mexico)	5
ColoradoSprings (Colorado)	6	YellowKnife (North West Terr.)	4 9 10
ElPaso (New Mexico)	9	Thunderbay (Ontario)	7
ArkansasCity (Kansas)	10	DesMoines (Iowa)	6
MobileAlabama (Alabama)	3	Longlac (Ontario)	1
FortWorthWestTexas	11	PortNelson (Manitoba)	2
GuaymasMexico (Mexico)	12	Duluth (Minnesota)	4
Chihuahua (Mexico)	10	Banff (Alberta)	3
NewOrleans (Louisiana)	6	UraniumCity (Saskatchewan)	6
OklahomaCity (Oklahoma)	7	PeaceRiver (Alberta)	1 12
StLouisMissouri (Missouri)	9 11	PrinceRubert (British Columbia)	2
Pittsburgh (Pennsylvania)	3	HolyCross (Alaska)	6
Chicago (Illinois)	3	MonterreySea (Mexico)	8
Cincinatti (Ohio)	5	QueenCharlottelands (BC)	10
NewYork (New York)	5	PortlandSea (Oregon)	9
RichmondVirginia (Virginia)	1 10 11	SanJoseSea (California)	6
Ottawa (Ontario)	2	Guadalupeland (Mexico)	5
SanFrancisco (California)	2	Labrador (Newfoundland)	1

Table 6-12: Frequency assignment with the extended algorithm assuming the interfering users are a mix of 8kb/s, 16 kb/s, 32kb/s, 48 kb/s and 64 kb/s users, FB No. = Frequency Band No

Spot Beam Centre	FB No.
Jacksonville (Florida)	4
GreatBearLake (North West Terr.)	5
PortlandMaine (Maine)	6 8
ReddingCalifornia (California)	7
PortlandOregon (Oregon)	1 11 12
Omaha (Nebraska)	9
Monterrey (Mexico)	9
MexicoCity (Mexico)	3 7
Durango (Mexico)	4
GiaoHaven (North West Terr.)	3
Frobisher (North West Terr.)	10
Newfoundland	12
SableIsland (Nova Scotia)	10
Haiti	6
JacksonvilleSea (Florida)	8
BelcherIslands (North West Terr.)	6
SanPedroSula (Mexico)	9
Fairbanks (Alaska)	4
BathurstInlet (North West Terr.)	8
Habana (Cuba)	7
Jamaica (Caribbean)	12
Hebron (Newfoundland)	12
NewYorkSea (New York)	9
ManzanillaSea (Mexico)	11
BermudaIsland	3 7
BelizeCitySea (Mexico)	11
DawsonCreek (British Columbia)	7
StKitts (Caribbean)	2 3 5 7 11
Dominica (Caribbean)	1 4 6 8 10 12
SanSalvador (Bahamas)	1
DominicanRepublic (Caribbean)	4 8 9 10
Cuba	2
Vancouver (British Columbia)	5
WatsonLake (Yukon Territory)	3
LosAngeles (California)	1 4
NormanWells (North West Terr.)	8

Table 6-13: Frequency assignment with the extended algorithm assuming the interfering users are a mix of 8kb/s, 16 kb/s, 32kb/s, 48 kb/s and 64 kb/s users, FB No. = Frequency Band No

6.5 Power-Limited Capacity Calculations

The power limited capacity of the proposed system is dictated by the available satellite amplifier Ku-band *return downlink* (*return* = satellite to earth station) RF power and the frame duration. Since the user terminal to earth station link is most critical, it is used to derive the system capacity. The underlying concept is to allocate the RF power available onboard the satellite among several carriers judiciously until no power remains to support further carriers. In the *return uplink* (mobile user terminal to the satellite), several users (in their respective frames) access the satellite and are then 'bent-pipe' for the *return downlink*. The amount of power consumed at the satellite for the 'bent-pipe' operation varies for each carrier according to the power levels of each user in the frame.

The task is to calculate the total number of different rate users who can be sustained in several carriers within one frame duration. The concept of frame duration is introduced here to provide a mechanism for assigning a certain amount of weight to each type of user. For example, if a 8 kb/s user requires p W of power during the frame to 'bent-pipe' and his/her time slot duration is z ms, then the energy consumed by that user in a 50 ms frame is $p * z$. At the same time, if a 32 kb/s user requires $(2.5^1 * p)$ W of power during the frame and his/her time slot duration is $(3.2^1 * z)$ ms, then the energy consumed by that user in a 50 ms frame is $(8 * p * z)$. Therefore, in this specific example, a 32 kb/s user uses eight times as much energy as an 8 kb/s user. This comparative mechanism can be instrumental in determining the sensitivity of the system power consumption to each of the user data rates.

¹ Arbitrarily chosen to serve as an example

The total useful satellite energy available within one frame duration of 50 ms is determined by the total *return* satellite RF amplifier power available and the signal share value for each user in the frame. In this thesis (chapter 4), a value of 80 W was used as the total available power. As in chapter 4, if an antenna gain of 25.4dB and a back-off of 4dB is assumed, the total EIRP available to ‘bent-pipe’ all carriers is 40.43 dBW. However, the EIRP available to ‘bent-pipe’ the useful carrier part of the composite (carrier + noise) *uplink* signal depends upon the uplink signal share value for each user in the frame.

As discussed in Section 4.6.2, a non-regenerative repeater is assumed in the system, the available power of 80W is consumed to relay the *uplink* composite useful carrier signal and the noise. Therefore, only a certain portion of the total satellite power of 80W can be considered as available for generating the *downlink* carrier signal. This portion of the total satellite power is referred to as the *Uplink Signal Share* and is calculated based on the ratio of the *uplink* useful carrier signal to the composite *uplink* signal.

If the power required by each data rate user (Section 4.6.2) and his/her time slot duration in the frame (Section 3.2) is known, the energy required for each data rate user can be calculated.

Let P_i denote the power required to bent-pipe a user operating at a data rate of i kb/s ($i = 8, 16, 32, 48$ or 64) and let T_i denote his/her time slot duration within a T_{Fr} (50 ms) frame. Also, let n_i represent the number of users operating at a data rate of i kb/s and let S_i represent the *uplink* signal share for each user operating at a data rate of i kb/s.

As calculated in Section 4.6.2, $S_8 = 0.70$ (*uplink* signal share for an 8 kb/s user) and $S_{16} = S_{32} = S_{48} = S_{64} = 0.87$. Therefore, the total power available to bent-pipe multiple carriers, P_{sat} with multiple data rate users is determined using the following relationship:

$$P_{sat} = \frac{(n_8 * S_8) + S_h (n_{16} + n_{32} + n_{48} + n_{64})}{\sum_{i=8,16,32,48,64} n_i} * EIRP_{(after\ backoff)} \quad \text{Eq. 6-1}$$

where $S_h = S_{16} = S_{32} = S_{48} = S_{64} = 0.87$.

Therefore, the total available energy, E_{sat} is,

$$E_{sat} = P_{sat} * T_{Fr}$$

Let E_i denote the energy required for a user operating at a data rate of i kb/s and let E_{Ti} represent the total energy required for all users operating at i kb/s.

Then,

$$E_{Ti} = n_i * P_i * T_i$$

Let the total energy required for all users operating at all data rates be denoted by E_t .

Accordingly,

$$E_i = \sum_i n_i * P_i * T_i \quad , \quad i = 8, 16, 32, 48, 64$$

The power-limited capacity of the system is calculated by selecting a combination of different values of n_i such that the following condition is satisfied.

$$E_{sat} \geq E_r \quad \text{Eq. 6-2}$$

$$\text{or} \quad E_{sat} \geq \sum_i n_i * P_i * T_i \quad , i = 8, 16, 32, 48 \text{ and } 64 \text{ kb/s}$$

The power required by each data rate user, P_i (Sections 4.6.2 and 4.6.4) and the time slot duration, T_i (Section 3.2) is given as follows:

i (kb/s)	P_i (dBW)	T_i (ms)
8	18.03	2.75
16	7.58	5.25
32	7.58	10.25
48	7.58	15.25
64	7.58	20.25

Table 6-14: The power required by a satellite to bent-pipe a user operating at i kbl/s and the corresponding time slot duration in the 50 ms frame.

Using the values in Table 6-14 and substituting the values of $EIRP_{(after \text{ back-off})}$ (40.43dBW or 11,041 W), T_{Fr} (50 ms), $S_g = 0.70$ and $S_h = 0.87$, Eq. 6-2 can be re-written as follows:

$$\left[\frac{0.70n_8 + 0.87(n_{16} + n_{32} + n_{48} + n_{64})}{\sum_{i=8,16,32,48,64} n_i} * 11041 * 50 \right] \geq$$

$$(n_8 * 18.03 * 2.75) + (n_{16} * 7.58 * 5.25) + (n_{32} * 7.58 * 10.25) +$$

$$(n_{48} * 7.58 * 15.25) + (n_{64} * 7.58 * 20.25) \quad \text{Eq. 6-3}$$

Any combination of values of n_8 , n_{16} , n_{32} , n_{48} and n_{64} that satisfies the above inequality and also minimizes the difference between the two sides of the equation determines the capacity of the system. There also exist an upper bound to the values of n_8 , n_{16} , n_{32} , n_{48} and n_{64} which can be individually determined using Eq. 6-1 and setting the remaining n_i values to 0. For example, the maximum value of n_8 can be determined by setting n_{16} , n_{32} , n_{48} and n_{64} equal to 0 and evaluating Eq. 6-1. The range of values for each of n_8 , n_{16} , n_{32} , n_{48} and n_{64} are given in Table 6-15.

Range of values	Max. No. of users per 50 ms frame	Max. No. of carriers in the system
$0 \leq n_8 \leq 7,794$	18	433
$0 \leq n_{16} \leq 12,068$	9	1,340
$0 \leq n_{32} \leq 6,181$	4	1,545
$0 \leq n_{48} \leq 4,154$	3	1,384
$0 \leq n_{64} \leq 3,128$	2	1,564

Table 6-15: The range of possible values for n_8 , n_{16} , n_{32} , n_{48} and n_{64} .

From Table 6-15, the power-constrained system capacity is limited to 7,794 8 kb/s users simultaneously accessing the system. Similarly, 12,068 16 kb/s, 6,181 32 kb/s, 4,154 48 kb/s and 3,128 64 kb/s users can simultaneously access the system. To aid in determining various candidate combinations, a Matlab[®] program was executed. The Matlab[®] code is presented in Appendix B. It is assumed that the satellite power is not consumed during the guard times and therefore the above analysis is applicable with different guard time and voice activity values. Table 6-16 lists some of several values of n_8 , n_{16} , n_{32} , n_{48} and n_{64} that satisfy Eq. 6-3.

n_8	n_{16}	n_{32}	n_{48}	n_{64}
0	0	0	69	3077
0	0	0	73	3074
0	0	0	235	2955
0	0	0	316	2894
0	0	0	397	2830
30	200	300	1010	2150
200	200	300	1200	1925
1000	200	3000	973	393
1000	3000	0	0	1925
1000	3000	0	16	1913
2000	1000	0	19	1964
4000	4000	0	29	491
4000	200	300	58	1162
6000	0	0	10	631
6000	0	100	7	587
6500	200	20	557	2
7580	0	12	50	33

Table 6-16: The values of n_8 , n_{16} , n_{32} , n_{48} and n_{64} that satisfy Eq. 6-1.

6.6 Summary of Results

As in the case of any GEO-MSS system, it is evident from power-limited and bandwidth-limited analysis that the proposed geostationary MSS system is power limited. The maximum capacity achievable in terms of the number of users operating at a data rate of 8 kb/s is 21,624 when the system is bandwidth-limited (only one frequency band per spot beam) and 7,794 when the system is power-limited. However, upon comparison with the traditional frame structure, the proposed frame structure promises a capacity enhancement as high as 122%. In the proposed system, there are 102 spot beams required to provide service to the desired area of coverage. The total bandwidth needs to be divided into 12 bands each of which can be

reused many times (Section 6.4.2). If a spot beam is allowed to use more than one frequency band (Section 6.4.3), the bandwidth-limited capacity is improved by 42.1%.

In the next chapter, the research is concluded and the main contributions and findings are highlighted. Also, avenues for possible extensions of this research effort and related topics are identified and discussed.

Chapter 7

Conclusions and Recommendations for Future Research

7. Conclusions

In this thesis, a complete TDMA based system for a geostationary (GEO) mobile satellite service (MSS) system for North America is designed and analyzed with the help of an original and comprehensive software module. With a large satellite antenna diameter, it becomes possible to implement a GEO MSS system which is capable of supporting a direct link to a hand-held user terminal. The system caters to users of various data rates ranging from 8 kb/s to 64 kb/s with two distinct types of user terminals. It can provide an acceptable quality of speech service at 8 kb/s with hand-held terminals and higher data rate services to users with a more capable terminal. Furthermore, a *new* TDMA frame structure is proposed for the system which provides capacity enhancements ranging from 0% to 122% (depending on the frame contents) relative to the conventional TDMA frame structures. An exhaustive link budget analysis is performed to determine the capacity of the system. The major conclusions are presented in the following sections.

7.1 New TDMA Frame Structure

A comparative performance analysis of the proposed TDMA frame structure with the traditional TDMA frame structure yields results which heavily depend upon the choice of the user data rate and guard time values. The higher data rate users employ a larger user terminal and therefore in a frame with different rate users, the signal is received at the satellite with varying power levels and different voice activities within the time slots. The performance of the proposed frame structure is enhanced by the inherent long guard time requirements of GEO-MSS systems. The guard time values in the system range from 0.76 ms to 7.18 ms. For the purposes of analysis, four distinct guard time values of 1.4 ms, 2.25 ms, 3.5 ms and 7.2 ms are considered. The capacity enhancements promised by the proposed TDMA frame structure vary from 0% to 122 % depending upon the data rates of the users in the frame and the guard time values. When all the users in the frame operate at a data rate of 8 kb/s, there is no difference between the traditional frame structure and the proposed frame structure. However, in the case of higher data rate users, the dynamic rearrangement of variable-size time slots in the proposed frame as opposed to static fixed-size multiple time slot assignment results in much better utilization of the frame and hence the increased capacity.

7.2 Spot Beam Design and Layout

The multiple spot beam MSS system designed during the course of the research provides a graphical visual illustration of the spot beam layout for the entire continent of North America. Using vector analysis, an *original* relationship is developed to associate the coordinates of particular location on earth (assuming the earth is a sphere) and the angle of signal reception

at the satellite antenna with respect to the boresight of the spot beam. The difference in the shapes and sizes of the spot beams in different regions of North America is clearly evident with the final spot beam layout (see Figure 6-1). This yields in different guard time values for the spot beams and the values are calculated separately for each spot beam. The software module also performed interference analysis for the spot beam layout based on user defined required E_b/N_0 , user terminal's peak power capabilities, channel fading characteristics, channel bandwidth, satellite antenna noise temperature, etc. Using the results from the interference analysis, frequency assignment algorithm is implemented assuming different types of traffic mixtures in the system. The results from the frequency assignment algorithm yield the bandwidth-limited capacity of the system in terms of the number of carriers. This capacity can be translated into the number of users by assuming certain traffic characteristics.

There are two traffic configurations assumed for the frequency assignment and bandwidth-limited capacity calculations. In the first configuration, all interfering users are assumed to be 8 kb/s speech users with hand-held terminals. Based on the interference analysis and frequency assignment, 13 distinct frequency bands are required in the system when all the interfering users are 8 kb/s speech users. Since the total system bandwidth is 29 MHz, the bandwidth allowed per spot beam is $29 \text{ MHz} / 13 = 2.23 \text{ MHz}$. Since each carrier occupies a bandwidth of 100 kHz, there exist $2.23 \text{ MHz} / 100 \text{ kHz} = 22$ carriers per spot beam. There exist a total of 102 spot beams and therefore the system bandwidth-limited capacity is $22 \cdot 102 = 2,244$ carriers, assuming one frequency band is assigned per spot beam. When all users in the system are assumed to operate at a specific data rate, the capacity can be calculated in terms of the number of users and a comparison between the proposed and traditional frame

structure can be done. The proposed frame structure promises a capacity enhancement of 0%, 35.7%, 66.8%, 85.23% and 122.0% when all users in the system operate at data rates of 8, 16, 32, 48 or 64 kb/s respectively.

In the second configuration, the interfering users are assumed to be operating at data rates of 8 kb/s, 16 kb/s, 32 kb/s, 48 kb/s and 64 kb/s with user terminals of different capabilities. Again, based on the interference analysis and frequency assignment, 12 distinct frequency bands are required in the system. The bandwidth allowed per spot beam is $29 \text{ MHz} / 12 = 2.41 \text{ MHz}$. Since each carrier occupies a bandwidth of 100 kHz, there exist $2.41 \text{ MHz} / 100 \text{ kHz} = 24$ carriers per spot beam. There exist a total of 102 spot beams and therefore the system bandwidth-limited capacity is $24 \cdot 102 = 2,448$ carriers, assuming one frequency band is assigned per spot beam. If multiple frequency bands are assigned to each spot beam (interference permitting), the system bandwidth capacity is improved by 42.1%. With multiple frequency bands assigned per spot beam, the system can support 3480 carriers. The results are better than the case with all interfering users operating at 8 kb/s. The reason is that while some of the co-channel interfering users employ a more capable terminal, they can simultaneously tolerate more interference.

7.3 Power Limited System Capacity

The total amount of satellite amplifier power dictates the total capacity of the system in terms of the number of carriers. The amount of power allocated to each carrier depends upon the data rate of users operating in the frame. The situation in this system is unique because in a frame with different rate users, the signal is received at the satellite with varying power levels

for different time duration within the time slots. To help investigate the power-limited capacity of the system in terms of the number of users, the concept of energy is used instead of power. Given the total power available at the satellite and the fixed frame duration, the total available energy is calculated. Also, given the fixed time slot duration of each user in the frame and the power required by each user for signal relay, the energy required by each user can be calculated. The task is to determine the total number of different rate users which can be accommodated in a frame across several carriers with the given total satellite energy. Since there are five data rate users, there exist no unique solution and therefore a range of solutions is presented in this thesis (Section 6.5). The maximum number of 8, 16, 32, 48 and 64 kb/s users that can be supported in the system are 7,794, 12,068, 6,181, 4,154 and 3,128 respectively.

7.4 Recommendations for Future Research

Since several aspects of the system channel access scheme were analyzed in this thesis, many issues can be identified for future research work. The assumptions made regarding several parameters can be thoroughly investigated and the capacity performance calculations can be refined. The issues requiring further investigation can be broadly classified as one of the following:

- Multiple Access Techniques
- Signaling required for the proposed frame structure
- Link Budget Analysis
- Frequency Assignment Analysis and Layout

In the next sections, each of the above is discussed briefly.

7.4.1 Multiple Access Techniques

The design of the software module and the spot beam layout obtained from it are not limited to evaluate the performance of a TDMA based system only. The layout can easily be extended to assess the performance and capacity of an FDMA based system or a CDMA based system. Several authors [1], [2], [4], [6], [25], [26] have compared the capacity performance of different multiple access schemes for a GEO MSS system. However, a complete system design with multiple spot beams for North America has not been explored. The proposed TDMA system can be compared with a counterpart CDMA system in terms of capacity and throughput performance and complexity.

7.4.2 Proposed Frame Structure

The improved performance with the proposed frame structure is achieved at an expense of additional signaling. The impact of the additional signaling in terms of delays involved and the additional power requirements from the satellite for the signaling channel is to be investigated. Typically, the long delay associated with a GEO-MSS system is the foremost reason of concern. Since it is proposed that the signaling be carried out during call setup or termination, the delay can be absorbed in the long call setup and termination times. However, an exact analysis is preferred to justify the performance improvements promised by the new proposed frame structure.

Also, the proposed frame structure can be compared with the currently planned and soon to be launched ACeS and Thuraya systems. Both these systems have adopted TDMA as their

multiple access scheme. However, very little details are available at present, regarding the frame structures used in these systems. With more details readily available shortly, a comparative analysis of the assumptions and the capacity performance can be undertaken.

7.4.3 Link Budget Analysis

In the analysis of the proposed system, a non-generative satellite system is considered with no on board processing capabilities. The performance of the system is expected to improve dramatically with the inclusion of an onboard processor in the system. The link budget analysis changes as the *uplink* (user terminal to the satellite) and the *downlink* (satellite to the ground station) become independent. Also, in the current analysis, the modulation schemes are assumed identical for both the *uplink* and *downlink*. The modulation schemes can be different depending upon the operating environments in both the links. In the thesis, a dual-hop link is assumed for communication between two user terminals of the system. If two user terminals wish to communicate with each other, the information from one user is relayed to the ground station via the satellite first (one complete return link) and then forwarded to the other user terminal again via the satellite (one complete forward link). This causes additional delay in the system. The analysis in the thesis can be repeated assuming a single-hop approach where the ground station is not required and a direct satellite link is established between two user terminals wishing to communicate with each other.

Also, in this thesis, only the return link is analyzed as it is most critical. However, the forward link needs to be investigated as well. Since the spot beam contours can represent different power levels at their respective edges, this affects the power transmitted by the satellite to the

center of each spot beam. The power utilization onboard the satellite for the forward link is an important issue to be investigated. Also, the effect of adjacent channel interference should be incorporated in the link budget analysis.

7.4.4 Frequency Assignment Analysis and Spot Beam Layout

In this thesis, the process of frequency assignment is based on a direct search method. However, if more precise information regarding traffic characteristics, frequency plan and interference characteristics is available, the spot beam layout and frequency assignment may be improved. Any criteria required to enhance capacity with alternate frequency assignment can be easily included into the existing Microsoft® Visual Basic algorithm. If precise traffic characteristics are available, the spot beam layout can be made accurate and the spot beam overlap can be reduced.

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Appendix A

The following are the reference formulae for plane and spherical geometry. [14]

For any spherical triangle ABC whose side lengths a , b , and c are measured by the great circle arcs subtended at the center of the sphere:

$$\frac{\sin A}{\sin a} = \frac{\sin B}{\sin b} = \frac{\sin C}{\sin c} \quad (\text{sine law})$$

$$\cos a = \cos b \cos c + \sin b \sin c \cos A \quad (\text{cosine law for sides})$$

$$\cos A = -\cos B \cos C + \sin B \sin C \cos a \quad (\text{cosine law for angles})$$

For any plane triangle ABC

$$c^2 = a^2 + b^2 - 2ab \cos C \quad (\text{law of cosines})$$

$$\frac{\sin A}{a} = \frac{\sin B}{b} = \frac{\sin C}{c} \quad (\text{law of sines})$$

Appendix B

The Matlab code used to determine the different combinations of n8, n16, n32, n48 and n64 that satisfy Eq. 6-1 is given below. Some of the results obtained from this algorithm are presented in Table 6-16.

```
*****
```

```
maxn8 = 7794;
maxn16 = 12068;
maxn32 = 6181
maxn48 = 4154
maxn64 = 3128
energyfactor = 11041 * 50;

result = [0 0 0 0 0 0 0];

i = 0;
a = 0;
b = 0;
sumval = 0;

for a = 0: maxn8
    for b = 0: maxn16
        for c = 0: maxn32
            for d = 0: maxn48
                for f = 0: maxn64
                    sumval = a + b + c + d + f;
                    if (sumval ~= 0 )
                        leftsum = ((0.7*a) + 0.87 * (b + c + d + f)) *
                            energyfactor / sumval;
                        rightsum = (49.58 * a) + 7.58 * ((5.25 * b) + (10.25 *
                            c) + (15.25 * d) + (20.25 * f));
                        difference = leftsum - rightsum;
                    end

                    if (difference > 0) & (difference < 5)
                        result = [result; a b c d f leftsum rightsum]
                    end;
                end;
            end;
        end;
    end;
end;
```

```
*****
```


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