Performance Characteristics

of a Multiple Use

Ku-band Satellite Network

by

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Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Master of Science

in

Electrical Engineering

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May 1989

Blacksburg, Virginia

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(ABSTRACT)

Construction of a Ku-band earth station was completed in August 1989 at the teleport in the Corporate Research Center of Virginia Polytechnic Institute and State University. At that time specific applications for the terminal were being determined. Several satellite networks which can use the Ku-band earth station are explored in this thesis. System level designs are presented for each network. The anticipated performance of the network during clear sky conditions and during periods of rain fade conditions are calculated. To aid in these calculations the software package LAMP was developed.

A detailed system design of a VSAT network is given in later chapters. The development of VSAT networks considers multiple access and data traffic control protocols. VSAT network performance under various traffic conditions also is determined.

Acknowledgements

I would like to thank my advisors, Dr. Timothy Pratt and Dr. Warren Stutzman, for the helpful suggestions and criticism they provided throughout the progress of this work. I also would like to thank Dr. Rappaport for his time and input in helping me complete this thesis.

In addition, I would like to thank Dr. Bostian for giving me the opportunity to work in the Satellite Communications Group where I have learned many new things and have met some really great people.

Finally, I would like to thank my parents for their interest, encouragement, and understanding.

Table of Contents

Performance Characteristics of a Multiple Use Ku-band Satellite Network

Chapter 1: Introduction

An attractive feature of satellite communications is the ability to provide point-to-multipoint communications over wide geographical region. An example of this service is a satellite television broadcast service that transmits television signals from a single earth station to a geosynchronous satellite which then retransmits the television signals over a region spanning as much area as an entire continent. Just as point-to-multipoint television transmissions can cover geographic regions, any multiple station satellite network can cover wide areas. These networks can range from point-to-point transmission services to multiple station satellite wide area data networks. This document reports on an investigation into the system design and performance of point-to-point, point-to-multipoint, and multipoint-to-multipoint satellite networks.

Chapter 2 proposes development of several networks that can link widely separated stations located throughout the state of Virginia. Communication requirements for several different customers are considered in determining the proposed networks. The networks proposed can use a Ku-band (12/14 GHz) earth station recently constructed at the Corporate Research center on the campus of Virginia Polytechnic Institute and State University. Chapter 3 briefly describes the operation of this station.

Chapter 4 describes eight satellite networks that could use the Ku-band earth station. The earth station provides the following services in these networks: transmission of compressed digital video, transmission of digital images, participation in a token ring network, operation as a hub station in a VSAT (Very Small Aperture Terminal) network, investigation of Ku-band land mobile/satellite propagation effects, and experimentation with satellite spread spectrum communications.

Chapter 5 presents technical and cost considerations involved in configuring the networks presented in the previous chapter. Technical considerations include link budget and rain fade performance analyses. Cost considerations consider the estimated expenses required to implement the networks. Recommendations for network implementation and additional development are also presented in Chapter 5.

Chapters 6 and 7 investigate the performance of a VSAT network. The first chapter describes multiple access techniques and packet-switching protocols used to admit and regulate the flow of data in the network. The latter chapter calculates the anticipated throughput and retransmission delay characteristics for the operating VSAT network.

Chapter 2: Network Requirements

2.1 Introduction

In this chapter the development for several satellite networks which can use a Ku-band earth station located on the Virginia Tech campus is proposed. In June 1988, the FCC granted an operating license to Virginia Tech for a 14 GHz (Ku-band) earth station. Construction of the earth station was completed in August 1988. Currently, the station is not being operated.

The intent of this chapter is to present several current needs that can be satisfied with an operational Ku-band satellite network.

2.2 Satellite Television Transmissions

The Northern Virginia Graduate Center in the Telestar building at Falls Church, Virginia, provides continuing education to residents in the Virginia suburbs of Washington D.C. Sometimes these classes are taught by faculty members from the Blacksburg campus of Virginia Tech. Consequently, the university pays travel expenses for professors teaching in both Blacksburg and Northern Virginia. The amount of instruction time versus the travel time and expense makes live classroom instruction by these professors undesirable. Television transmissions of classes taught from a studio in Blacksburg, however, is a more efficient means of providing classroom instruction to residents of Northern Virginia.

Another desirable aspect of television transmissions is that any broadcast class may be received by all of the Virginia Tech Extension locations throughout the state. One professor in a studio can lecture to dozens of locations at the same time, assuming each location has appropriate receiving equipment. Using a second audio channel in the television transmission, a voice link from each receiving location to the television studio can provide the instructor with audience feedback during the course of a lecture. Audio links are currently used with Virginia Tech's C-band satellite television system which transmits graduate level classes to business and academic locations throughout Virginia and Maryland.

The demand for televised classes at the Northern Virginia Graduate Center is increasing, and the C-band television transmissions which use only one satellite transponder can no longer fulfill this demand. Television transmissions received from another satellite or transponder can supply the Graduate Center with additional instruction.

One proposed means of receiving television transmissions at the Northern Virginia Graduate Center is to place a transmitting and receiving earth station at the Equine Medical Center (EMC) in nearby Leesburg, Virginia. This university center is an extension of the Virginia/Maryland Regional College of Veterinary Medicine. Television transmissions can be received by the station at the EMC and then routed via a terrestrial microwave link to the Telestar building in Falls Church. At this location the signal can be demodulated and routed to various viewing rooms.

A station operating at the EMC can also provide a facility for point-to-point image transmissions as described in the following section. Although a dual purpose station at the EMC can provide the Northern Virginia Graduate Center with televised classes, the proposal is no longer under consideration. A system design and performance analysis of television transmissions to this station, however, is provided in Chapters 4 and 5.

2.3 *Regional Data Networks*

2.3.1 Point-to-Point Medical Image Transmissions

This subsection presents several reasons for configuring a point-to-point data network between Virginia Tech and the Equine Medical Center (EMC) in Leesburg, Virginia. In particular, a link can be configured to transmit high resolution digital images from the EMC to the Virginia/Maryland Regional College of Veterinary Medicine.

In this network the EMC can be equipped with scanners for transmission of X-rays and other high resolution medical images. All transmitted images can then be reproduced at the College of Veterinary Medicine at Virginia Tech.

A point-to-point high resolution image transmission network serves the following purposes:

- It allows veterinary doctors at Virginia Tech to make expedient medical decisions based on the content of the received medical images.

- It eliminates time and cost spent in having a courier deliver X-rays and related materials to Blacksburg.

- It provides the College of Veterinary medicine at Virginia Tech with access to medical materials appropriate for instructional purposes.

The network configuration and equipment necessary to implement the point-to-point data transmissions described above are discussed further in Chapters 4 and 5.

2.3.2 Multiple Remote Station-to-Station Communications

There are many offices and remote locations in the state of Virginia that collect and assimilate various types of data which must be sent or delivered to other locations in the state. A few examples of these stations are given below:

- Currently, fifty-four Virginia Tech Extension offices are located throughout Virginia. Each station collects and distrubutes academic news and information relevant to the region of Virginia which each office serves. Much of this information is of interest to other extension offices as well as to the main campus in Blacksburg.

- Remote monitoring stations throughout the state can be configured to collect and record environmental conditions such as temperature, precipitation, and wind velocity. The information would be particularly relevant to current research in determining environmental effects on crop growth. In order to obtain a complete data base as well as be able to detect monitoring equipment failure, all data must be collected on a daily basis.

- Other remote stations can be placed in the catchment areas of flood plains of river valleys to sense river levels and flow rates. These stations can be used as part of an early warning system during periods in which flooding and widespread water damage may occur.

- Particle physicists at Virginia Tech require information obtained from particle accelerators as part of their research. The nearest particle accelerator, however, is located at CEBAF (Continuous Electron Beam Accelerator Facility) in Newport News, Virginia. For these scientists to analyze information obtained from the accelerator, large amounts of data must be transferred from CEBAF to Virginia Tech.

- Additional state offices throughout Virginia also may require network communications. These message transactions can carry data ranging from the coordination of state road maintenance crews to the assimilation of accounting information passed from state offices to the capitol in Richmond. Road maintenance crews provide a particular network challange in that they cover a wide geographic area and do not stay at a fixed location.

Each station described above can be equipped to route data to other stations as part of one or more networks. Networks devised to transfer information from place to place can save the state and university expenses associated with printed materials and the time spent in handling all these materials.

A satellite network can provide station-to-station transmission service at a low user cost when the transmissions described in the previous examples occur as many short bursts of information. Data transmissions from each location can be arranged in the form of small blocks of data. Transmitting information over telephone lines eliminates paper and printing costs as well as the delivery time incurred by hiring a courier to carry all printed material, but the cost for maintaining a dedicated telephone line is prohibitive for stations requiring only a few transmissions per day. A dedicated telephone line is more cost effective for low data rate transactions (2400 baud or less) that occur on a continual basis. Chapters 4 and 5 discuss how satellite networks can be configured to accomodate the communications demand for multiple station-to-station transmissions.

2.4 *Mobile Station Communications*

Considerable research is currently being performed in this country to develop feasible, cost effective mobile station/satellite communications systems. This form of communications differs from cellular radio in that mobile station/satellite communications covers regions extending accross an entire antenna beam pattern of a satellite. A mobile radio network covering the entire continental United States is feasible. This wide area coverage has attracted several commercial trucking companies to request the implementation of such a communications network for monitoring their fleets of trucks [37]. A related application for mobile station communications is the configuration of a positioning system used in aiding the navigation of airplanes, ships, and road vehicles. With the aid of two or three satellites, a mobile station quickly can calculate its latitude, longitude, and elevation [42].

Studies which use the earth station at Virginia Tech can investigate the feasibility of mobile station/satellite communications at Ku-band frequencies. Experiments can be devised to determine multipath propagation effects at 12 GHz. Propagation effects can be quantified by measuring received signal energies and received bit error rates in a variety of settings and over a range of rain rates. The results of these experiments can help determine the anticipated performance of mobile station communications networks at Ku-band.

Chapter 3: The Ku-band Earth Station

3.1 RF Terminal Overview

The network requirements outlined in the previous chapter can be implemented by using a Ku-band (12/14 GHz) RF terminal installed near the Virginia Tech Corporate Research Center in Blacksburg, Virginia. The terminal consists of a 5.5 meter diameter antenna and appropriate frequency conversion and power amplification equipment. The proposed operation for this station is transmission of QPSK modulated digital information in a single-channel-per-carrier (SCPC) mode. QPSK and SCPC are explained in Chapter 4. Descriptions of the station components and their operation are provided in subsequent subsections of this chapter. All figures and information pertaining to the RF terminal operation were taken from the *Operation and Maintenance Handbook* for the Ku-band facility prepared by Nippon Electric Co., Ltd.

The equipment for the terminal was manufactured by Nippon Electric Co., Ltd. for Satellite Business Systems (which became part of MCI in 1985). In 1987 MCI donated a complete terminal to Virginia Tech. This terminal is now installed at the teleport in the Corporate Research Center of Virginia Tech. A second RF terminal, exactly like the one in Blacksburg, was purchased by Virginia Tech at a later date. The installation site for this second terminal has not yet been determined. Although this chapter describes only one particular earth station manufactured for Satellite Business Systems (SBS), the general configuration of components and procedure of frequency conversion and amplification apply to all earth stations described in this text.

3.2 Mechanical Description

3.2.1 Antenna Components

The earth station uses a a 5.5 meter Cassegrain reflector antenna for signal transmission and reception. A Cassegrain antenna consists of a feed, subreflector, and main reflector.

The feed assembly consists of an ortho-mode transducer (OMT), π-polarizer, feed horn, rejection filter, and horn feed blower. The arrangement of these components is shown in Figure 3-1. The OMT routes transmitted signals from the 12 inch straight waveguide to the π-polarizer and directs received signals from the π-polarizer to the low noise amplifier (LNA). The π-polarizer maintains orthogonal polarization between the transmitted and received signals. It also allows manual adjustment of the horizontal and vertical polarizations of these signals over a range of 180° (π radians). The corrugated feed horn radiates transmitted signals and collects received signals propagating toward and away from the antenna subreflector. This horn is covered with a glass-reinforced teflon window for protection from dust and rain. The feed blower keeps water away from the feed horn and prevents ice from forming on the feed dome. The rejection filter keeps the 14 GHz transmitted signal from interfering with the 12 GHz received signal.

The subreflector is designed to distribute uniform amplitude and phase illumination over the main reflector aperture. It is constructed of fiberglass reinforced epoxy resin with a flame sprayed aluminized surface. The subreflector also contains heater elements and a temperature sensor to prevent ice build-up on the reflecting surface.

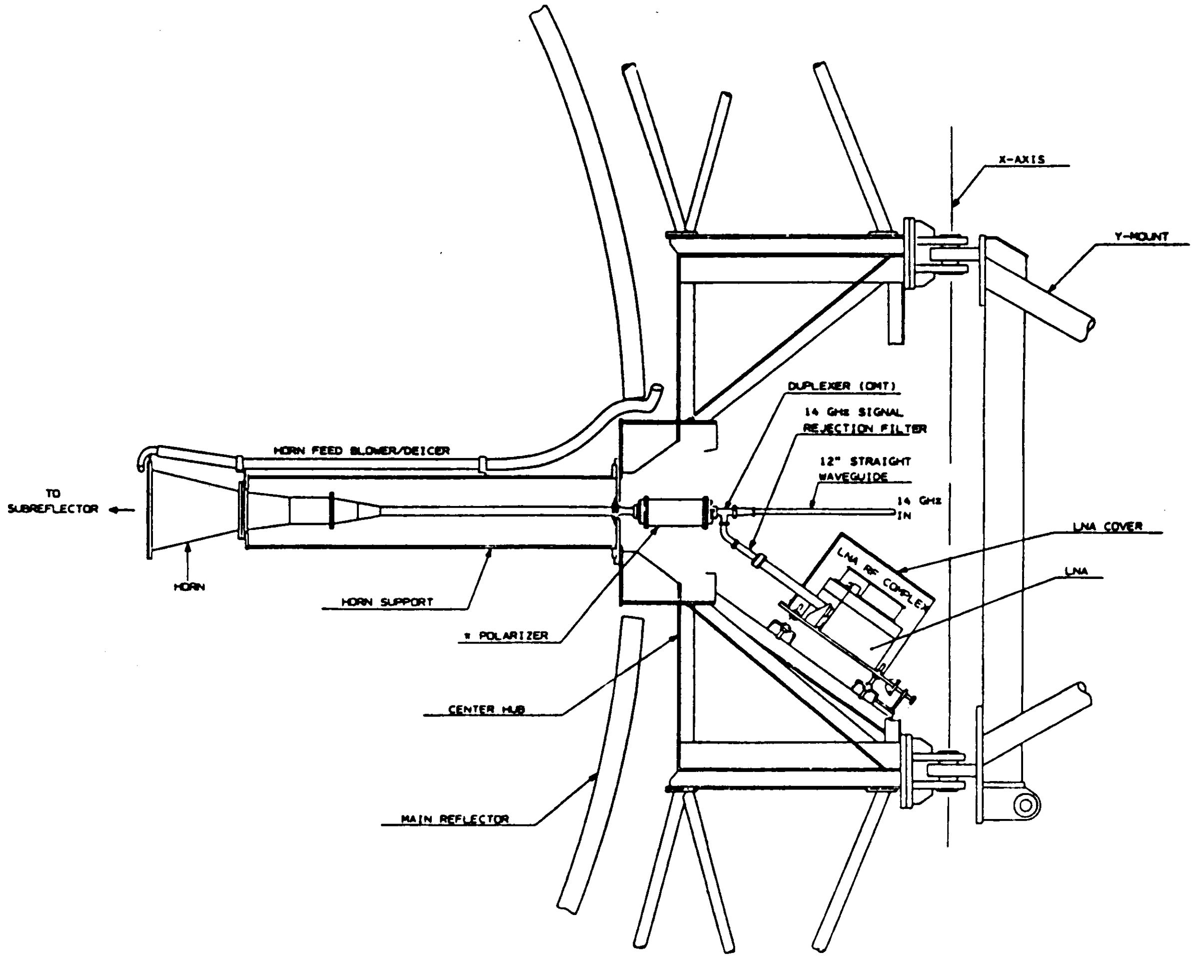


Figure 3 - 1. **5.5 Meter Antenna Feed Assembly:** (Obtained from Nippon Electric Co., Ltd., *Operation and Maintenance Handbook for the 12 and 14 GHz RF Terminal*, vol. I, prepared for Satellite Business Systems, McLean, Virginia.)

The main reflector consists of eight outer panels and one central panel. Each panel is constructed in a laminar fashion with fiberglass reinforced plastic and balsa. This sandwich is coated with a reflecting layer of aluminum and then covered with gelcoat resin for protection from weather and corrosion. Each panel also contains heating elements to prevent ice from forming on the reflector surface. Three outer panels have temperature sensors to control the operation of the heating elements.

3.2.2 Mount Structure

The mount structure provides structural stability and pointing capabilities for the antenna. The structure consists of the reflector mount, the X-mount, the Y-mount, and the drive mechanisms. Components of the structural assembly are shown in Figure 3-2.

The reflector mount joins the antenna main reflector to the Y-mount and drive mechanisms. The LNA RF complex and the deicing power distrubution board are attached to the bottom side of the reflector mount.

The X-mount and Y-mount are tubular steel space frames. The X-mount is anchored to the foundation pad. The Y-mount is attached to the top of the X-mount with swivel joints that allow rotation about the X-axis (horizontal axis along the top of the X-mount).

Two drive mechanisms are attached between each mount. Each drive mechanism is a screw jack powered by an AC synchronous stepping motor. The X-jack provides an approproximate elevation range (angle above the horizon) from 10° to 65° and the Y-jack provides an approximate azimuth range (angle from true north) of ± 20° from the pedestal azimuthal angle. When properly installed, the antenna mount structure provides coverage of the arc of geosynchronous satellites from 88° to 130° west longitude.

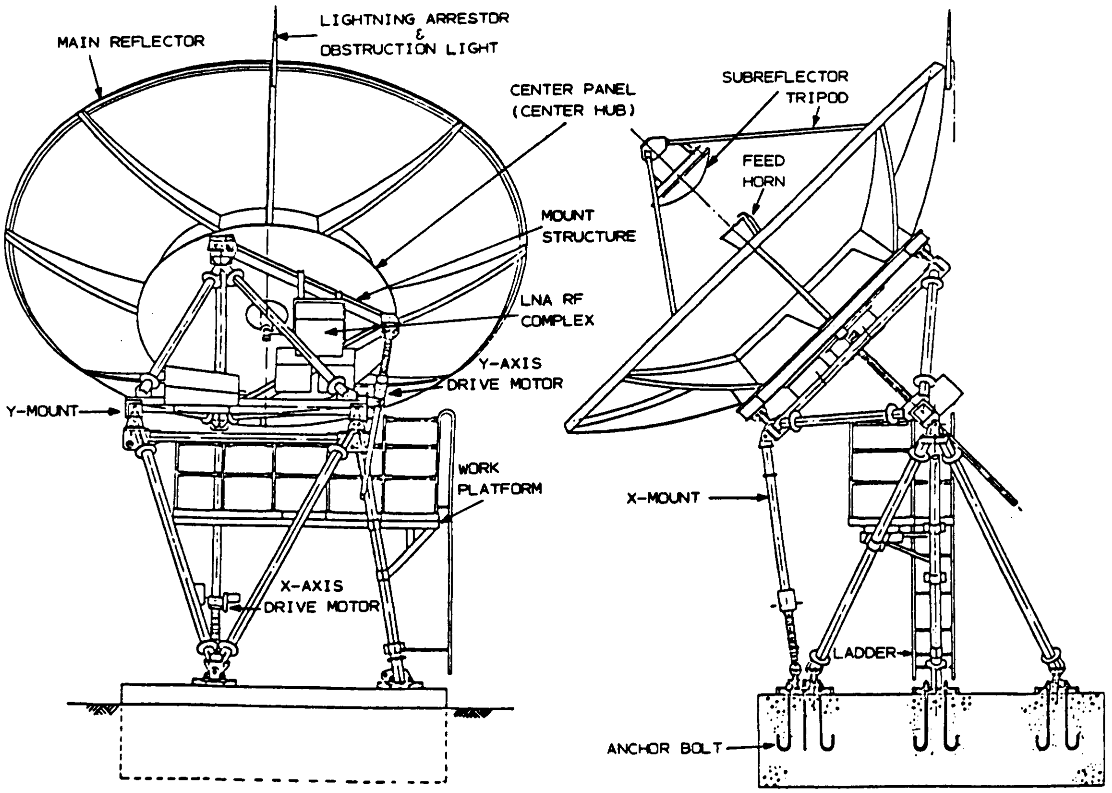


Figure 3 - 2. 5.5 Meter Antenna and Structural Assembly: (Obtained from Nippon Electric Co., Ltd., *Operation and Maintenance Handbook for the 12 and 14 GHz RF Terminal*, vol. I, prepared for Satellite Business Systems, McLean, Virginia.)

3.2.3 RF Terminal Shelter

The RF terminal shelter houses electronic equipment for the following six subsystems:

- Monitor and control subsystem
- Antenna subsystem
- Power and support equipment subsystem
- Low noise amplifier subsystem
- High power amplifier subsystem
- Up/down converter subsystem

The interior is environmentally controlled to insure proper operation of the housed electronic equipment. The various subsystems shown above are described in the remaining subsections of this chapter.

3.3 Control Subsystem Descriptions

The monitor and control (M & C) subsystem uses sensors and internal logic circuits to maintain proper operation of the electronic equipment in the RF terminal shelter. In the event of equipment failure the M & C subsystem controls the automatic switchover of any redundant equipment. The M & C subsystem also provides an interface between the equipment in the RF terminal shelter and a separate controller, or computer. Equipment operation in the shelter can be automatically controlled from a remote managerial location. The proposed remote controller will be an IBM PS/2 operating with appropriate software to direct the station equipment.

The command pointing unit in the antenna subsystem controls the position of the antenna. The antenna is moved by activating the motors on the drive mechanisms. A counter box on each drive mechanism relays the screw jack position back to the command pointing unit.

3.4 Power System Description

Power is supplied to the terminal by a 3 phase, 5 wire, 208 volt feed line wich is split into two power busses. The critical bus provides power to the redundant subsystem equipment and to two DC power supplies. The utility bus provides AC power to all remaining equipment such the air conditioner units, fans, and alarms.

Under normal operating conditions the critical power bus supplies approximately 1200 watts to the communications equipment. The redundant DC power supplies output 1072 watts of this power.

The utility bus carries most of the power used by the earth station. Most of this power is consumed by two 2400 watt air conditioners and a 300 watt vent fan.

3.5 Transmitting and Receiving Equipment

3.5.1 RF Transmit Signal Path

Baseband signals, whether originating from a television studio or sent from a computer terminal, modulate a carrier at a specified intermediate frequency (IF). The IF for the facility described in this chapter is 70 MHz. At the Virginia Tech facility this modulation is performed by the single-channel-per-carrier (SCPC) modem at the modem site. A description of the operation of this device is discussed in Chapter 4. Information is exchanged between the modem and the RF terminal via the interfacility link (IFL). The IFL can be implemented by using coaxial cable, terrestrial microwave, or even optical fiber. The Virginia Tech facility will use twisted pair cable to carry transmitted signals.

Regardless of the interfacility link medium, electrical signals at a 70 MHz IF enter the junction panel of the equipment rack found in the RF terminal shelter. The junction panel connects to equipment allowing signal transmission and reception to and from a satellite. An overall block diagram of the signal paths that pass through the junction panel is shown in Figure 3-3.

When a signal arrives at the earth station for transmission to a satellite, it must undergo frequency upconversion and amplification before being radiated from the antenna.

As shown in of Figure 3-4, the arriving 70 MHz IF signal enters a 14 GHz upconverter at a nominal -19 dBm power level. Typically this signal is somewhat distorted and must be equalized before it enters the mixing stages of the upconverter. First, the cable equalizer compensates for amplitude distortion caused by the signal passing through the transmit IFL cable. This equalizer consists of two fixed gain amplifiers, one fixed attenuator, and one variable attenuator. The nominal output signal level from the cable equalizer is -1 dBm. The delay equalizer then corrects the signal for group delay distortions caused by the electonics of the transmit signal path. This equalizer provides group delay equalization over the band of 70 MHz $\pm$ 23.8 MHz. The amplitude equalizer compensates for amplitude distortion caused by the transmit signal equipment. This third equalizer consists of two amplifier sections, a fixed attenuator, and two voltage controlled pin diode attenuators. The nominal output signal power from this stage is 6 dBm.

The equalized signal is mixed with the output of a 1 GHz phase locked oscillator and then with a 13 GHz local oscillator. The output from the mixing stages is a -5 dBm modulated carrier in the frequency range from 14.0 GHz to 14.5 GHz. The specific frequency of the 13 GHz local oscillator determines the frequency of the transmitted signal. Nominal power levels between each stage of frequency upconversion are designated in Figure 3-4.

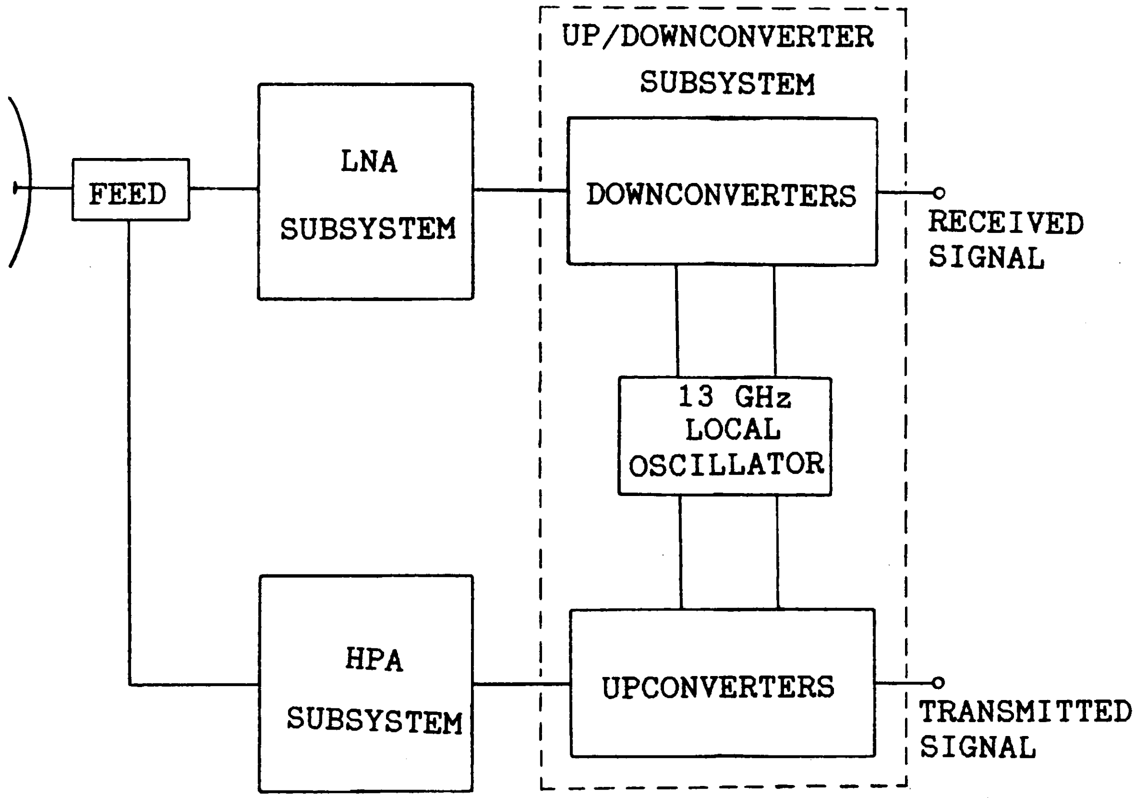


Figure 3 - 3. RF System Simplified Block Diagram: [31]

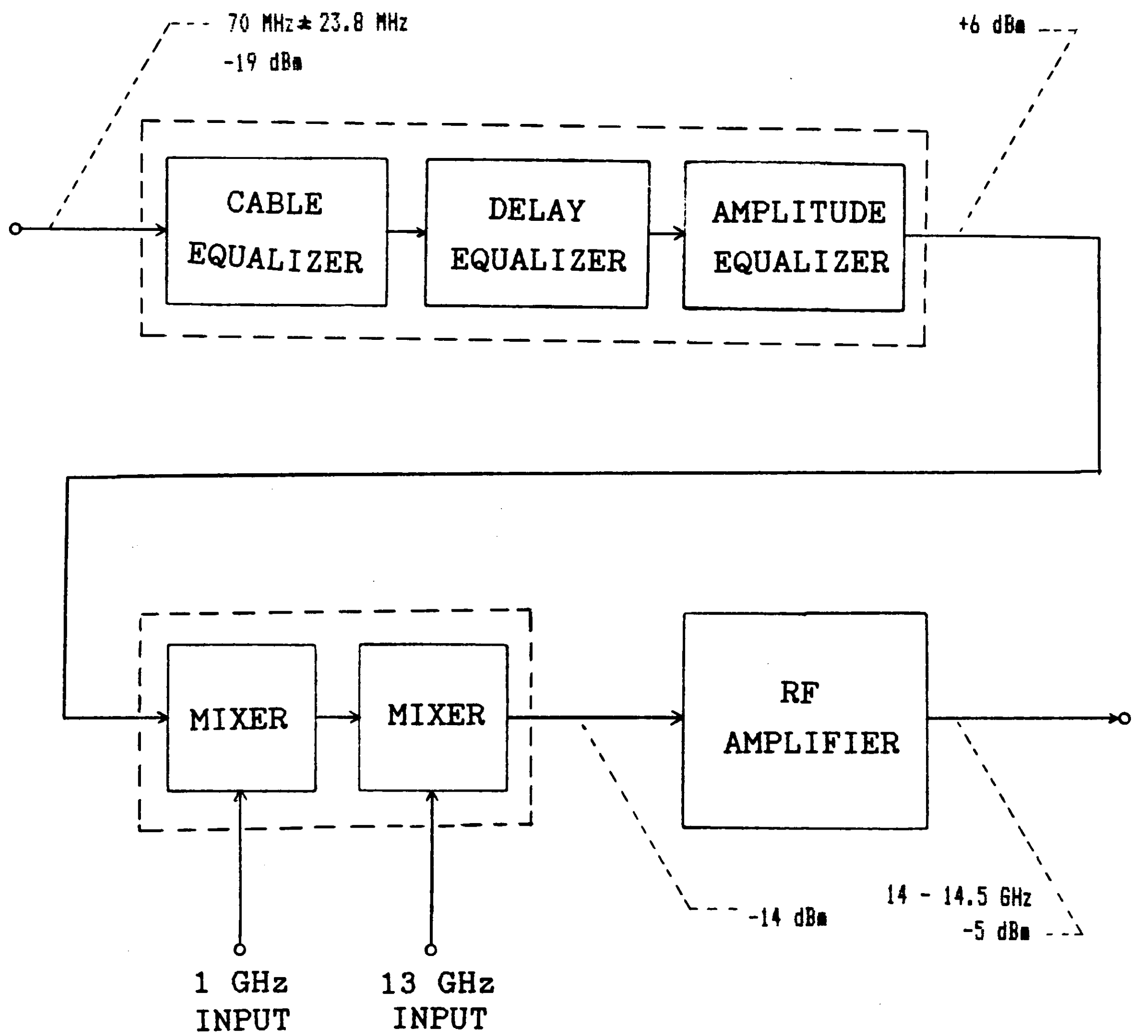


Figure 3 - 4. 14 GHz Upconverter Simplified Block Diagram: [31]

During normal transmission, two upconverters are operational at the same time. One upconverter is on-line allowing the signal to pass through to the high power amplifiers while the other remains on standby. If a component failure occurs, the failed upconverter is switched off-line automatically while the other upconverter is switched on-line.

Signals arriving from the on-line upconverter are routed to the high power amplifier (HPA) subsystem. As with the upconverters, two identical signal paths exist in the HPA subsystem; however, both HPA paths are on-line. As shown in Figure 3-5, signals arriving from the upconverter set are band pass filtered and split with a 3 dB hybrid power level divider. The resulting signals are phase-shifted 180° with respect to each other and attenuated until the two signal levels are equal. The 180° phase shift is necessary so that the power combiner at the end of the HPA path can produce an output signal equal to the sum of the two phase-shifted input signals. Each phase-shifted signal is routed to an intermediate power amplifier, providing 26 dB gain, and then through a travelling wave tube, providing another 45 dB gain. After low pass filtering, the two signals from the HPA's enter the power combiner to produce an output signal at twice the amplitude of the previous two signals. The output signal from the HPA subsystem is routed via waveguide to the antenna for transmission.

If a failure occurs in one of the HPA paths, the failed HPA is automatically switched off-line. In the event of failure, the output power from the HPA subsystem is reduced by 3 dB.

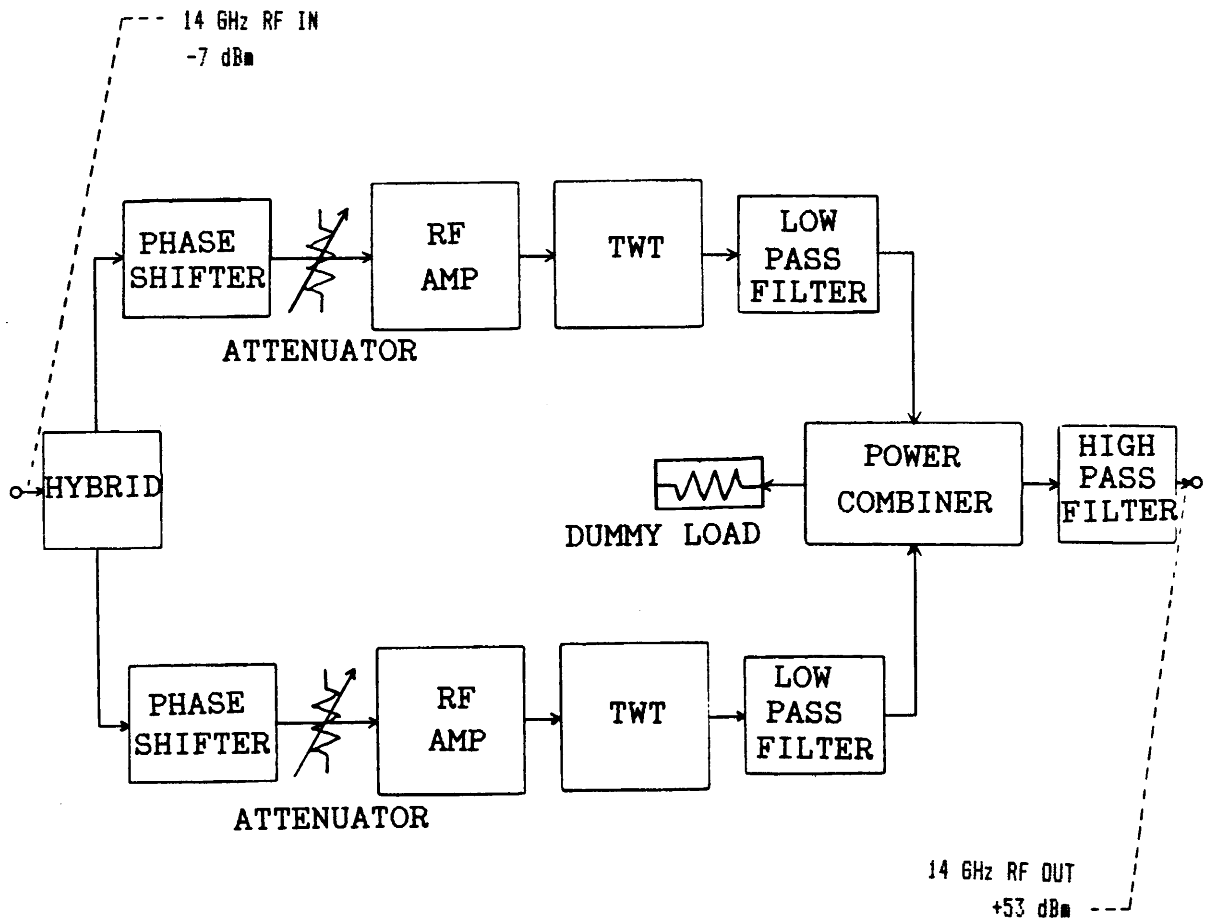


Figure 3 - 5. HPA Subsystem Simplified Block Diagram: [31]

3.5.2 RF Receive Signal Path

Signals received by an earth station from a satellite must undergo amplification and frequency conversion. The receive signal path is similar to the transmit signal path except that amplification and frequency conversion occur in reverse order.

Signals arriving from the antenna are routed through the ortho-mode transducer (OMT) to the low noise amplifier (LNA) subsystem. The LNA subsystem is designed to amplify an RF signal with minimal noise contribution. The overall noise temperature of the amplifier stages is nominally 188.6 K. As with the upconverters, the LNA subsystem consists of two amplifiers: one on-line and the other in hot standby. As shown in Figure 3-6, received signals enter an LNA unit and pass through two thermoelectrically cooled multistage FET amplifiers. The two amplifiers provide an overall gain of approximately 55 dB. If a fault is detected in one of the LNA units, it is switch off-line automatically and the other is switched on-line.

The amplified signal then is routed to the 12 GHz downconverters. Up to four downconverters can operate simultaneously, two on-line and the others in standby. The incoming signal is split into four signals of equal magnitude, each routed to a downconverter. The RF terminal at Virginia Tech, however, uses only two downconverters. An additional downconverter set would be used for a second receiver.

As shown in Figure 3-7, a downconverter accepts the 12 GHz signal, band pass filters it, and mixes it with the output of a 13 GHz local oscillator. This oscillator is the same 13 GHz oscillator used in the corresponding upconverter. (See Figure 3-3.) The specific frequency of this 13 GHz local oscillator determines the specific carrier frequency received between 11.7 GHz and 12.2 GHz. The resulting set of uplink/downlink carrier frequencies corresponds to a specified channel used in SBS satellites. After the first mixing in the downconverter, the received signal is filtered and mixed with the output of a 1.3 GHz phase locked oscillator. At this point the signal carrier frequency is 70 MHz at a nominal -11.5 dBm power level.

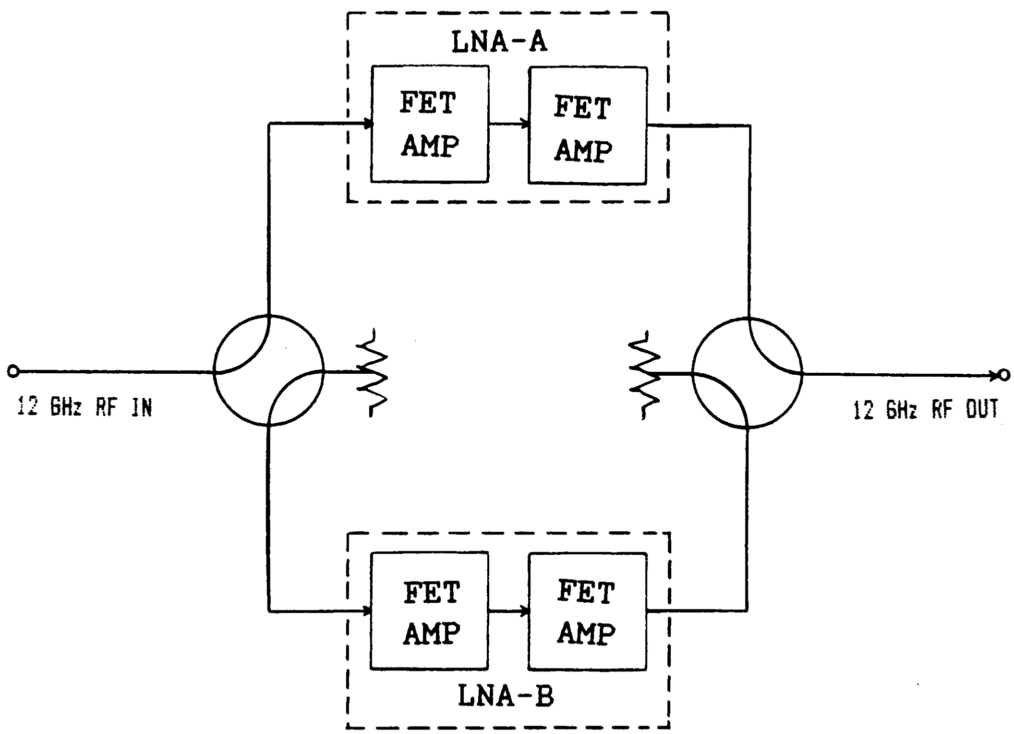


Figure 3 - 6. LNA Subsystem Simplified Block Diagram: [31]

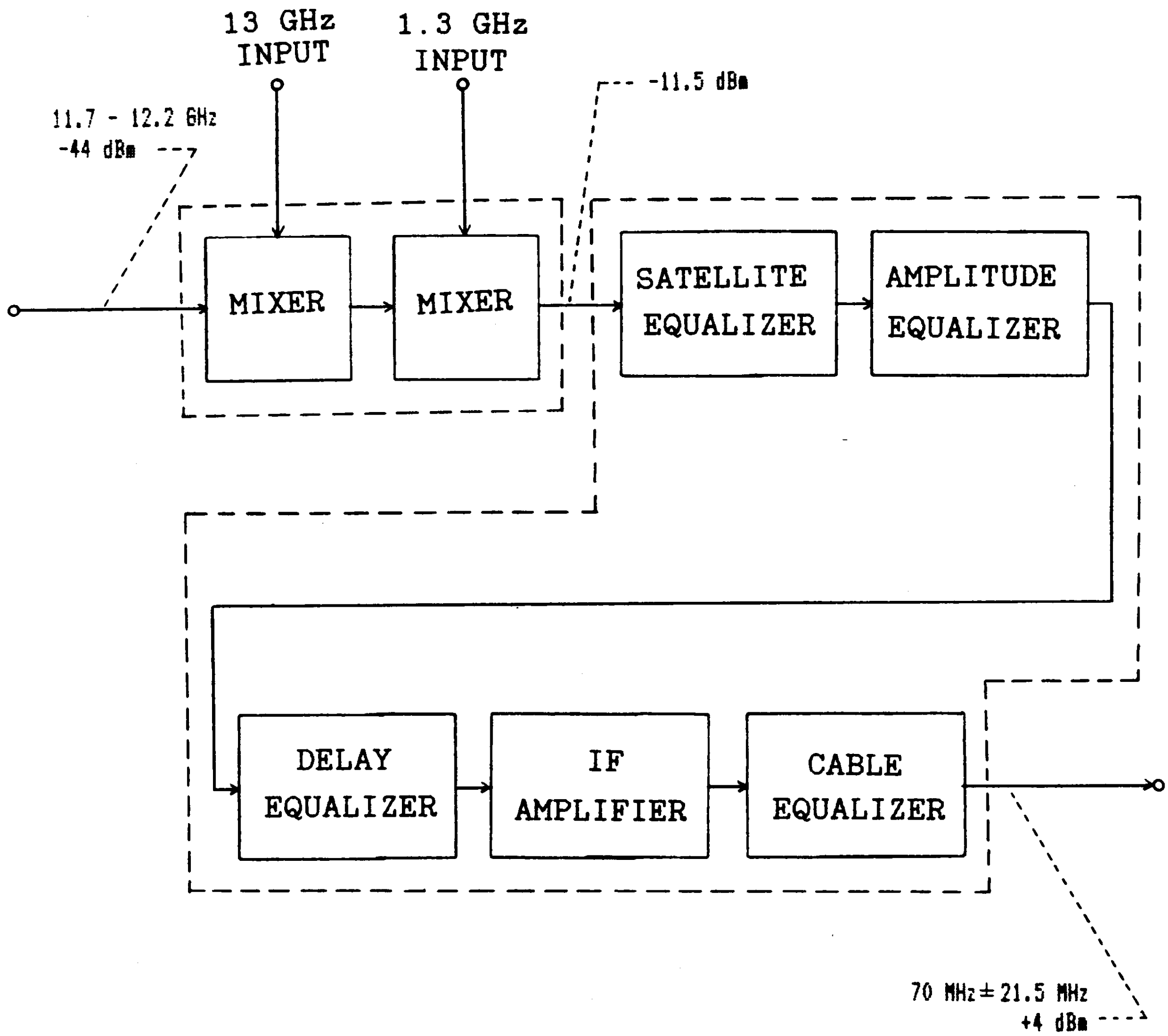


Figure 3 - 7. 12 GHz Downconverter Simplified Block Diagram: [31]

The signal then passes through four equalizers as shown in Figure 3-7. The satellite equalizer compensates for parabolic and linear group delay introduced in the satellite transponder. The amplitude equalizer compensates for amplitude distortion caused by the signal receiving equipment. This second equalizer consists of an amplifier section, a fixed attenuator, and two voltage controlled pin diode attenuators. The nominal output signal power from this stage is -9 dBm. The delay equalizer then corrects the signal for group delay distortions caused by the receiving equipment in the signal path. This third equalizer provides group delay equalization over the band of 70 MHz $\pm$ 21.5 MHz. Lastly, the cable equalizer compensates for amplitude distortion caused by the signal passing through the received signal IFL cable. This equalizer consists of two fixed gain amplifiers, one fixed attenuator, and one variable attenuator. The nominal output signal power from the cable equalizer is 4 dBm.

Signals arriving from the downconverter set pass through the junction panel shown in Figure 3-3 and are routed to the IFL. At the Virginia Tech facility the IFL carries the received signal via twisted pair cable to the SCPC modem at the modem site. This modem demodulates the signal, and land lines carry the baseband information to a user terminal.

Chapter 4: Applications

4.1 Overview

Possible applications for the Ku-band earth station at the Virginia Tech teleport are discussed in this chapter. This chapter appeared originally in the *IBM/Virginia Tech Joint Development Project Final Report on the Ku-Band Earth Station Facility* and was written by this author for that report.

The basic function of the proposed earth station facility is to accept signal information (whether it is digital data or analog video), convert the incoming signal to a form suitable for transmission, and transmit the converted signal to a specified geosynchronous satellite. The earth station must also be capable of performing the aforementioned process in reverse order: accept a signal from a satellite, convert it, and route the signal to a desired user.

Consider the conversions made to a signal for suitable transmission. Converting a signal for transmission occurs in three stages: modulation, frequency conversion, and amplification. For compressed digital video transmissions an additional stage for analog-to-digital conversion may be included. In digital communications systems modulation converts a bipolar data stream to a signal in which bit streams are represented by shifts in the phase (or possibly frequency) of a 70 MHz carrier. In analog video communications the incoming television signal frequency modulates a 70 MHz carrier to produce an FM television signal. Frequency conversion translates the signal carrier frequency from its baseband frequency (70 MHz) to a specific transponder channel frequency (~ 14 GHz for Ku-band). Amplification increases the signal power before transmission to a satellite.

Once in operation, the proposed facility will transmit single-channel-per-carrier (SCPC) digital information to designated receiving earth stations at a rate of 1.544 Mbps, a T1 bit rate. As implied by its name, each SCPC channel modulates a separate carrier within a transponder for transmission. A system employing multichannel-per-carrier transmissions frequency division stacks several channels at baseband frequencies before modulating a specific carrier. A single-channel-per-carrier system has been selected because of the small number of channels anticipated in the proposed communications system. This anticipated usage does not require the use of multichannel-per-carrier equipment, and the resulting system simplicity results in a lower overall system cost. Wideband transmissions, such as full transponder or half transponder analog video, also require SCPC modulation; however, the operating costs for these transmissions are much higher than those for narrowband SCPC transmission. Presently, use of full transponder or half transponder transmissions is not anticipated with the proposed facility. A brief operating cost comparison between wideband and narrowband SCPC transmissions is provided in Section 5.2.1.

Several applications are currently under consideration for the proposed communication system. These were briefly discussed in Chapter 2 and include broadcasting compressed digital video, transmitting high resolution medical images, participating in a token ring network, and acting as a VSAT hub for a statewide communications network. Each application is described in more detail in the following sections.

4.2 *Digital Video*

4.2.1 Introduction

Digital video is one possible means of broadcasting Virginia Tech classes to its various extension locations. This system application employs pulse-code modulation (PCM), a digital modulation scheme that samples a video signal, quantizes each sample, and assigns this quantized level to a binary code group. Strict implementation of PCM television, however, requires very high bit rates. For instance, if the maximum video frequency of a television signal were 4.1 MHz and the sampling rate were twice that frequency, the required bit rate is 65.6 Mbps for eight bit quantized values.

However, this high bit rate requirement is not necessary if the televised classes do not contain much fast movement. In these broadcasts the digital information is highly redundant. With current signal processing techniques this digital information can be compressed to the point of enabling T1 television broadcasts [43]. At a T1 bit rate, though, some reduction in the temporal resolution occurs. This reduction becomes evident when a subject appears to traverse a screen with many discrete jumps rather than with one smooth motion. Current compression techniques, however, allow television broadcasts on T1 transmissions without many distracting jumps in motion of the received video [43]. Further compression down to 56 kbps is possible; however, this amount of compression produces more tiling in the video image and jumps in the picture motion [43] .

The existing equipment in the on-campus television studios produces analog video signals. Suitable coder/decoder devices (codecs) must be procured for the transmitting station and each receiving station.

4.2.2 Implementation

On the transmitting end of the link, full bandwidth video signals produced at a television studio are directed via land lines to a video codec for sampling and digital quantization. The digital signal must then be routed to a digital modem which implements QPSK modulation at an intermediate frequency (nominally 70 MHz). Lastly, twisted pair cable carries the outgoing signal to the earth station for frequency upconversion and transmission.

At the receiving end of the link, the process described in the previous paragraph occurs in reverse order. The received signal is downconverted at the earth station, carried via land lines to the digital demodulator, and converted with the video codec to an analog signal for a television viewing. At the Leesburg facility the received signal is downconverted to an intermediate frequency (70 MHz) and then upconverted to 4 GHz for transmission through a microwave link to the Telestar building in Falls Church.

In order to receive compressed digital video, each receiving station must have the following equipment:

- An antenna with a feed capable of receiving Ku-band transmissions
- Equipment for frequency downconversion from Ku-band
- A demodulator compatible with the modulator operating at Virginia Tech
- A video codec compatible with the codec operating at Virginia Tech

The initial cost for setting up a receiving station in Leesburg is approximately $90,700. A brief cost analysis is provided in Section 5.2.2.

4.2.3 Data Transmission in an Audio Channel

Most satellite transmission equipment for television has the capacity to carry one video channel and two audio channels in a given broadcast channel. One audio channel can be used in a normal fashion while the second audio channel can be used for data communications related to the televised program material [16]. This would enable relevant printed materials and images to be transmitted to remote locations while the televised program is in progress. For this capability, the data output of a standard asynchronous modem drives a second audio modulator used in the television broadcast. The output of the modulator, in turn, is connected to appropriate land lines leading to the uplink. At the receiving end the desired data is first demodulated with an audio demodulator/amplifier and then directed to a modem for input to a personal computer.

The major problem with this configuration is manipulating the hardware configuration at the receiving end so that it appears to be receiving all of the necessary handshaking signals for inter-terminal communication. The software program TekTERM has many features well suited for unidirectional data transmission while also allowing for the necessary manipulation of the remote computer. TekTERM is a terminal emulation program that enables an IBM PC or compatible computer to connect and operate with a mainframe operating system [41]. When used for data transmissions via satellite, this program can operate in a unidirectional mode for transfer of text files [16] . The data transmission system can be quickly installed with some minor modifications to the modem cables. The cost for installing this system includes the prices for a personal computer, a modem with cables, and the TekTERM software for both ends of the satellite link.

Use of TekTERM in this manner only allows the transmitting station to initiate an ASCII file dump over the satellite link. Because all handshaking signals have been eliminated, no error checking at the receiving station is available with this hardware/software configuration. Error correction coding associated with the operating digital modems, however, will maintain the receiving station's bit error rate to levels less than 10^{-6}, the bit error rate desired for acceptable reception of a digital video signal.

4.2.4 Options Other than T1 Television Transmission

FM Television

Analog FM television may also be transmitted with an SCPC system. Although FM television is not under consideration currently, it is included in this report as an alternative means of transmitting video information.

The implementation of FM television tranmissions is analagous to that of compressed digital video. Signals produced at the television studio are routed to an FM video modulator. The output of the video modulator (nominally at a 70 MHz carrier frequency) is carried via land lines to the operation earth station for frequency upconversion and transmission. At the receiving station the signal is frequency downconverted to 70 MHz and demodulated with a compatible video demodulator. Each receiving station, in turn, must be supplied with a compatible video demodulator.

A few notes should be mentioned about the video modulator at the transmitting station. This device frequency modulates a carrier at the intermediate frequency with the AM video signal and audio subcarriers produced at the television studio. The FM video modulator also controls the bandwidth of the outgoing signal. Normally the user has a choice between full transponder analog video ($\sim$ 43 MHz at Ku-band) or half transponder video ($\sim$ 24 MHz at Ku-band). Although full transponder video compared to half tranponder video can provide receiving stations with a 2.5 dB improvement in the signal-to-noise ratio, the operating cost for full transponder video is much higher than that of half transponder video. Additional information on the performance and cost of FM television is provided in Section 5.

Other Versions of Compressed Video

Recent developments in signal processing have led to the development of high quality 512 kbps compressed video [11]. Claims have been made that it approaches the quality of full motion video. Some codecs available on the market provide reduction of video information enabling bit rates as low as 56 kbps [11]. If implemented, it would allow for transmissions at much smaller bandwidths than allowed by a T1 bit rate. Aside from the bit rate and signal bandwidth produced by the video codec, transmitting compressed video at lower bit rates is no different than transmitting at T1. However, all video codecs at the receiving stations must also be compatible with the codec selected for the transmitting station.

4.3 Medical Imagery

4.3.1 Introduction

Since the proposed earth station will link Virginia Tech with the Equine Medical Center (EMC) in Leesburg, Virginia, it could be used to transmit high resolution medical images between these two places. This link would enable radiologists at the College of Veterinary Medicine at Virginia Tech to review X-rays or other medical images produced at the Equine Medical Center. The problem presented by this endeavor is maintaining a very high degree of spatial resolution in the transmitted image. Details as small as 0.25 mm square in the original X-ray must be observable at the receiving terminal [28]. This resolution for a digitized image corresponds to the number and size of pixels used in creating a single image. For greater spatial resolution, more pixels are necessary. Gray scale resolution in monochrome images must also be maintained; however, because the human eye cannot distinguish more than 16 different levels [21], this does not remain as critical a parameter as spatial resolution.

Both analog and digital techniques may be used to transmit medical imagery. The possible analog techniques are real time slow-scan, medium-scan, or fast-scan television [23]. The digital techniques use an image capture device that scans, digitizes, and stores an image before transmission.

Slow and medium scan television are implemented using scanners and monitors normally associated with amateur television (ATV) setups, equipment developed and employed by amateur radio operators. Slow-scan television allows video transmissions within bandwidths as small as 1.1 kHz. Each video frame is renewed every eight seconds [23]. This technique has been used to provide video for teleconferencing through available voice-grade channels [3]. Medium-scan television has been developed to improve the spatial and temporal resolution offered by slow-scan television. This method allows for video transmissions within a 35 kHz bandwidth [23]. A new video frame is received 4 times a second. Fast-scan television is similar to commercial television in both performance and bandwidth characteristics. Transmissions require a 6 MHz bandwidth, and video frames are renewed 30 times a second [23]. Unfortunately, neither slow-scan nor medium-scan equipment maintains fine details such as small cracks, or fissure lines, in the received image necessary for detection by radiologists. Fast-scan equipment requires a large amount of bandwidth once the video signal modulates a carrier. After undergoing frequency modulation, the performance of fast-scan television signals is no different than the performance of FM television tranmissions discussed in Section 5.1.3. However, any analog technique requires that all radiologists wishing to view an image transmission be present at a display monitor during each image transmission. Broadcasts would have to last as long as it takes for the radiologists to obtain appropriate medical information. Furthermore, recording an analog image for subsequent observation results in some degradation of the picture quality. This degradation may inhibit detection of very small details (less than 1 or 2 mm) in a recorded image.

Digital techniques are better suited to image storage and retrieval. Transmissions need only last as long as required to send a complete digital image. Once an image is properly received and stored, digital copies can be made with little or no degradation in the picture information. Digital transmission also allows for error correction coding and image processing techniques such as filtering, image editing, gray-scale measurement, and false color substitution.

4.3.2 Implementation

Several companies offer digital image capture add-on boards that break down a photographic image into a predetermined number of pixels. These boards are designed to fit into one I/O slot of a personal computer, and their operation is supported by appropriate software for processing of the captured image. The add on boards can also be specified to accept NTSC/RS-170, NTSC/RS-343, or PAL/SECAM composite video formats [14], [10]. Standard video cameras in the United States provide an NTSC/RS-170 format.

The selected add on board must meet specifications concerning video formats, spatial resolution, gray scale quantization, and color capabilities. The video format required by the board must match the output format of the camera. Spatial resolution must be *at least* 640 lines by 480 columns to preserve any fine details shown in the image. Resolution on the order of 1024 by 1024 is preferable. Maintaining detectable gray scale resolution in monochrome images requires four bits quantization. Additional gray scale quantization is normally available, but it is usually undetectable by the human eye. Color images and false color substitution, however, does require additional quantization of each pixel. Color images of equine subjects have not normally been used in the past. If made available, their possible use can be investigated. False color substitution may be used to differentiate between two or more gray levels that are difficult to discriminate with the human eye. This differentiation may aid in the detection of small nodules or tumors that do not create images that contrast with the background in the original X-ray.

Generating a digital image begins with a video camera scanning a mounted X-ray and delivering a video signal to the image capture board. This board digitizes the image and stores the digital information on a diskette until transmission is appropriate. If immediate transmission is necessary, the image data is directly routed to the digital modem and the SCPC modulator at a T1 bit rate. Otherwise, the image data is retrieved, routed, modulated, and transmitted at times when little communications traffic is expected. At the receiving end of the link, land lines carry the recovered data to a personal computer where it is stored on a diskette. An add-on board at this station then retrieves the image data and displays it on a television monitor according to the desired composite video format.

A hardcopy of the transmitted image also can be obtained through the operation of some of these add-on boards. Processor boards from Chorus Data Systems, for example, can send image data to a graphics printer upon request [10]. The image is reconstructed in a manner similar to the half-tone process used to create newspaper photographs. Many black dots in close proximity represent dark areas while very few dots in another region represent light areas. Unfortunately, an image created in this manner would not be useful for any medical scrutiny. These half-tone photographs may only be useful for record keeping purposes.

4.3.3 Other Methods for Image Transmission

Other methods of image transmission are available; however, they are not under consideration at this time. They are presented briefly in this report as a comparison to the use of image add-on boards. In turn, they emphasize the relative ease and low cost of transmitting medical images using image capture boards.

There exists a device known as a *microdensitometer* that slowly scans and digitizes the image in an X-ray to achieve extremely high spatial and gray scale resolution. In fifteen to twenty minutes it generates enough information to resolve details approximately 10 microns wide. This machine costs approximately $90,000. These devices are primarily used as medical research tools [30].

Vortech Data in Reston, Virginia, offers broadcast service as a VSAT hub for transmitting medical images. The VSAT hub is in Dallas, Texas, and it uplinks to SBS-4 on Ku-band. Vortech also sells all of the necessary video scanners as part of its transmission service. Their digitizing unit is called the medical-imaging gateway (MIG). Currently, the University of Pennsylvania is using this service to transmit medical images from remote areas of the state to a location where radiologists are available.

4.4 The Token Ring

4.4.1 Introduction

Participation in a token ring can allow Virginia Tech to send and receive blocks of digital data in a large packet network. In particular, the Department of Physics at Virginia Tech can have access to information from the linear accelerator at the CEBAF (Continuous Electron Beam Accelerator Facility) in Newport News, Virginia.

A token ring system implies that all participating stations are interconnected in such a fashion as to create a loop, or ring. Each participating station, in turn, transmits large blocks, or packets, of data to the next adjacent station in the ring. These packets are then passed from station to station until they reach the desired receiver. Three methods currently exist for adding data to the network [4]. The first method is *register insertion* where the data packet is temporarily buffered as it arrives at a transmitting station and new data are inserted ahead of it before re-transmitting. The *token passing* method employs a special code that follows the most recent addition to the data package. A station transmitting new data must first detect the special code, or token, before adding new data to the data package. After the data are added, the token is placed immediately after the new information. The *empty slot* method divides the passed data package into separate time slots. This method uses a specified code to determine whether a given data slot is occupied or empty. An empty slot must then be detected by a station before adding new data.

4.4.2 Implementation

Currently CEBAF is not associated with any wide area network involving satellite communications. Interest in developing a satellite token ring network including CEBAF and Virginia Tech, however, has received a very favorable response from both parties.

Token rings, however, have been developed for use in local area networks varying in size up to a few kilometers. Implementation in a satellite network poses certain problems [20], [26], [46]. For instance, the time elapsed between sending and receiving a data packet on a local area network is on the order of a few milliseconds. This same data packet would spend about a quarter of a second traveling between two adjacent stations in a satellite network. This delay increases the complexity of protocols allowing for retransmission of corrupted packets. Furthermore, thermal noise incurred through satellite transmission increases the probability for bit errors in the received data. Subsequent transmissions of corrupted data may further increase received bit error rates.

Several advantages in using a satellite network are evident [20] , [26], [46]. Entire geographic regions can be covered with a satellite network. With a single satellite, for instance, this coverage can extend over the whole range of a transponder beam pattern. Satellite networks also are capable of transmitting with bandwidths large enough to handle very high bit rates. These bit rates can offer a vast improvement over the several kilobit per second rates available on telephone lines. Optical fiber can also carry much higher bit rates than telephone lines, but dedicated lines must either be leased or newly installed. Lastly, error correction coding employed by existing digital modems greatly reduce the occurrence of bit errors in received data transmissions. Coding techniques virtually eliminate significant degradation of retransmitted data. Once the data is received it can be routed both to a suitable location on campus for analysis and to the earth station upconverters for re-transmission.

Additional investigation into the dynamic behavior of a satellite token ring network is necessary before implemention. This investigation should study the bandwidth requirements, number of stations that can be supported, and the costs for maintaining each station.

4.5 *The Statewide VSAT Network*

4.5.1 Introduction

By operating as a hub for a VSAT network, Virginia Tech can transmit information to Extension locations throughout Virginia. The hub in Blacksburg would transmit large blocks of digital text to all locations equipped with a suitable small aperture antenna. For most applications a very small antenna terminal (VSAT) employs antennas with diameters equal to or less than 2.4 meters. Received information is then demodulated and directed to a personal computer for storage. This system requires each receiving station to have either a graphics printer or a facsimile machine connected to a personal computer equipped with a facsimile board. Each station, in turn, can easily generate hard copies of the stored text. These copies can then be circulated to the various offices at each location. If desired, this system can use facsimile boards capable of reproducing photographs. A video scanner can digitize the data necessary for photographic transmission.

If necessary, the proposed system may operate at night. Data transmissions, in turn, would take place at a time when little communications traffic occurs from other sources. This implies that each participating station must also be capable of operating while unattended. Personal computers for each site must be procured, and appropriate software must be developed to control the operation of each station. Successful implementation will allow current academic news to be retrieved throughout the state at the beginning of every business day.

4.5.2 Implementation

The preferred configuration of a VSAT system is that of a star network. One large antenna used at the hub is used to provide service to many smaller antennas. In comparison to the hub antenna, the VSAT antennas are relatively inexpensive to install. The cost of configuring and operating the hub antenna, in turn, is shared by the operating VSAT stations. Furthermore, in a star network the hub station controls the flow of data and any protocol conversions. Since the network control is not distributed among all the participating stations, as in a ring network, the controlling software required at each station being serviced is much simpler. A personal computer at the hub station and each VSAT station can provide all the necessary control for the network.

VSAT stations must be equipped with an antenna large enough to provide adequate performance under rain fade conditions. The discussion in Section 5.1.5 suggests that a 1.8 meter diameter antenna is most desirable for a VSAT station. Extension offices equipped with 2.7 meter (9 foot) diameter antennas may use their existing antennas provided they install an additional feed for Ku-band into each antenna. In addition to the earth station equipment, each VSAT location must also be equipped with the following items:

- Digital modem compatible with that of the hub station.
- Personal computer for control of the earth station, and storage and retrieval of information.
- Buffer to hold data to and from the modem while it is being processed by the personal computer.
- Software to control the VSAT.
- Graphics printer to produce hardcopies of the received text.
- Facsimile machine to reproduce photos.

Before any network can operate, however, protocols allowing station-to-station communications must be established. The choice of protocol depends on the amount of anticipated traffic between the remote stations and the proposed hub. For instance, if little communication is expected from the extension locations, random transmission, or a pure-Aloha protocol, is sufficient. Any packet collisions detected at the hub station cause the remote stations to retransmit after some random time interval. Because the system is intended to operate unattended, all functions for packet collision detection, information storage, and retransmission must be fully automatic [7], [35]. These automatic capabilities may be attainable with some facsimile boards.

If a large amount of communications traffic is anticipated, it becomes desirable to implement a dynamic assignment of slotted-Aloha and Aloha with capacity reservation [7]. At start up this system is in the slotted-Aloha state: stations sending small packets of information begin transmitting data at specific intervals in time. If a station then desires to begin a bulk data transaction, it transmits a reservation request which allows further transmission of a specified number of data packets that are large in comparison to the slotted-Aloha packets. Employing a dynamic protocol assignment significantly increases the overall channel efficiency. A dynamic protocol, however, does increase the complexity, and hence, the total development cost of the system.

An investigation of the performance characteristics of an operating VSAT network is presented in Chapters 6 and 7. Once in operation the behavior and throughput of the network should be observed and compared to theoretical network models. Experiments in data acquisition and network loading should be devised in order to test and predict the throughput characteristics of this network.

4.6 Land Mobile Earth Station Experiments

4.6.1 Introduction

The Ku-band terminal at Virginia Tech could be used in experiments for studying land mobile/satellite communications. These experiments would investigate low power multipath propagation effects at 12 GHz and would determine shadowing losses caused by roadside obstacles. The 5.5 meter Ku-band terminal will act as a hub station transmitting digital signals to one or more land mobile stations. These stations may be parked in an open field, stopped beside a busy highway, or even driven along a straight road while maintaining a fixed elevation angle for the receiving antenna. Measurements in the received signal energy and received bit error rates can be obtained for each of these settings. Data obtained from measurements at various mobile earth stations can determine the feasibility of Ku-band hub station-to-land mobile earth station communications. Further experimentation may determine the feasibility of mobile station-to-hub station communications at Ku-band. Eventually, experiments may be devised as a means of configuring a land mobile earth station communications network allowing mobile station to mobile station communications. Currently, mobile station to mobile station communications is being developed by Omninet, a telecommunications company in Los Angeles. Omninet intends to provide two-way data transmissions and position reporting to road vehicles. Once in full operation, a working communications network has the potential to serve a large number of costumers within the coverage of a satellite beam pattern.

Further experimentation with land mobile/satellite communications can emphasize development of a positioning system for mobile stations. Termed by the FCC as *Radiodetermination Satellite Service* (RDSS) this positioning system can aid in the navigation of airplanes, ships, and road vehicles [37]. Land vehicles can be used in the development of this system. RDSS is being developed currently at L-band and S-band frequencies (2491.75 MHz and

1618.25 MHz) by Geostar Corporation located in Princeton, New Jersey [42]. The positioning system works by having the mobile station transmit time stamped messages to at least two satellites which relay the messages to a hub station. Position calculations are made at the hub station based on the arrival times of the received time stamped messages. Once calculated, the position is transmitted back to the user. With the proposed facility at Virginia Tech, the Department of Electrical Engineering can run experiments with this technology at Ku-band (12 and 14 GHz).

4.6.2 Implementation

In an experiment the earth station at Virginia Tech would broadcast digital information at 48 kbps to one or more mobile stations. Each mobile station must be equipped with a 1.2 meter diameter antenna, frequency downconversion equipment for Ku-band signals, and a digital modem capable of handling 48 kbps transmissions. A discussion on antenna sizes and performance characteristics is provided in Section 5.1.6.

The received bit error rate can be measured by transmitting a known bit stream and comparing this stream to the received data at each mobile station. Data comparisons and recording of the dynamic bit error rates can be performed by a personal computer at the mobile earth station. To assure assimilation of the incoming data, a buffer must be connected between the digital modem and the personal computer to temporarily hold the data as it is received.

A little more is involved in implementing a radiodetermination satellite service. A mobile station must be able to transmit messages to two or three satellites simultaneously. Geostar corporation employs an omnidirectional antenna and direct sequence spread spectrum communications (described in Section 4.8) to enable operation of an RDSS network [42]. Additional investigation is necessary in order to configure such a network at Virginia Tech.

4.7 *Environmental Monitoring*

4.7.1 Introduction

The proposed earth station may also be used to obtain data concerning environmental conditions throughout the region by working with the Research Division in the Department of Agronomy at Virginia Tech. This environmental data may arrive from several different types of remote stations. Some stations may gather and transmit data describing weather conditions affecting crop growth. These stations collect hourly data on air and soil temperatures, wind speeds and directions, water vapor, precipitation, and solar radiation. Other remote stations may be placed in the catchment areas of flood plains and populated river valleys to sense river levels and flow rates. These latter stations can be used as part of a safety warning system during periods in which flooding and widespread water damage may occur.

4.7.2 Implementation

For appropriate data acquisition each remote station should transmit its collected data at least once every twenty-four hours. Daily transmissions would provide researchers with both data on current environmental conditions and frequent indications pertaining to remote station equipment reliability. These transmissions would occur at night when the anticipated amount of communications traffic is low. Transmission protocols would also be employed in the same manner as with the VSAT networks. Once environmental data is received by the facility at Virginia Tech, it can be routed by land lines to the Research Division at the Department of Agronomy.

Each transmitting station in this network must be equipped with appropriate modulation equipment and a 1.8 meter diameter antenna. The cost to configure each station is approximately

$30,000. Appropriate software controlling the operation of each station would also need to be developed. This software would be very similar to the software developed for the control of the VSAT stations mentioned in Section 4.5. System performance is discussed in Section 5.1.7.

4.8 Spread Spectrum Experiments

4.8.1 Introduction

Spread spectrum can make a communications link tolerant of intentionally generated interference, or jamming, and has served primarily military communications. As implied by its name, spread spectrum communications greatly expands the width of the frequency spectrum used to carry a signal. The effectiveness of jamming is reduced because it requires transmission of a large amount of energy over a very wide bandwidth to achieve the same effect as jamming the signal when it is sent using conventional modulation.

Spread spectrum communications also has been used to lower the power density of transmitted signal and reduce the degree of interference with adjacent satellites. The total power of a transmitted signal can be high enough to maintain a satellite communications link while its spectral density is low in comparison to a non-spread spectrum signal. Spread spectrum has allowed communications under conditions of relatively high background noise [37].

A current study in spread spectrum is investigating its use for transmitting earth stations with very small antennas (1 meter diameter and smaller) [42]. Research on this topic is directly applicable to the implementation of a radiodetermination satellite service [42]. The facility at Virginia Tech can perform experiments on the use of spread spectrum for small transmitting antennas at Ku-band frequencies.

Several modulating techniques have been developed [13], [22] . *Direct sequence* spread spectrum multiplies the message data by a *pseudorandom* bit sequence running much faster than the original data sequence. The resulting signal spectrum is increased significantly. *Frequency hopping* transmits data on carrier frequencies which appear to change randomly. In this manner the signal appears to occupy a very large bandwidth although the instantaneous bandwidth is small. *Time hopping* transmits its data at a very fast rate within nearly randomly selected time slots. Many time slots create a frame, and only one time slot within a frame is selected for transmission. *Hybrid* techniques combine some of the attributes of the previously mentioned modulations. *Chirp* spread spectrum uses short bursts of time linear frequency modulated data. This is similar to techniques used in chirp radar systems. Each of the previously mentioned techniques has varying attributes and hindrances. Many of these characteristics could be investigated with the proposed communications system at Virginia Tech.

4.8.2 Implementation

Implementing spread sprectrum communications is similar to transmitting other digital data. In addition to a digital modem, however, special coding equipment must be procured. This will add to the initial cost for this system.

The cost to operate a spread spectrum communications system would be higher than that for T1 television transmissions. Because more bandwidth is required for spread spectrum communications, the cost for transponder time on a satellite will be closer to that of analog video.

Chapter 5: Network Configuration

The following chapter appeared originally in the *IBM/Virginia Tech Joint Development Project Final Report on the Ku-Band Earth Station Facility* and was written by this author for that report.

5.1 Technical Considerations

5.1.1 Introduction

This section describes the anticipated performance of the applications discussed in Chapter 4. The performance for each application is described in terms of a clear sky link budget and a rain fade performance analysis. A discussion on the methods used to calculate link budgets and performance analyses is presented in Appendices A and B.

5.1.2 FM Television Transmissions

The most widely used method for television transmission via satellite is through frequency modulation of a single carrier. With appropriate modulating equipment the facility described in Chapter 3 can transmit analog FM television. Although FM television is not currently under consideration, it is included in this document as an alternative means of transmitting video information.

The maximum transmitted power allowed to avoid interference with adjacent satellites is calculated by using a model developed by George Sharp [40]. The procedure for calculating the maximum transmitted power is described for compressed digital T1 television transmissions in Section 5.1.3. The maximum power allowed for FM television transmissions is estimated by maintaining the same average power density used for T1 television broadcasts. The difference in transmitted power between the two television systems corresponds to the difference in the signal bandwidths. The average power density calculated for a transmitted T1 channel is -54.62 dBW/Hz. As shown in Table 5-1, using a 24 MHz bandwidth and transmitting at an output power of 19.18 dBW, the system linking Virginia Tech to the EMC can obtain an overall C/N of 19.57 dB under clear sky conditions. The EIRP from the satellite is 43.48 dBW, down from a saturation EIRP of 45 dBW. Interference with adjacent satellite systems should not be a problem because this system would transmit with the same average power density determined to be acceptable for the T1 television broadcasts. At the receiving station acceptable reception occurs while the video signal-to-noise (S/N) ratio is greater than 45 dB. This S/N ratio corresponds to an overall C/N of approximately 9.0 dB as determined by equation 5-1. As seen in Table 5-2, such a television system is feasible for uplink only and downlink only rain fades up to 9 dB and for simultaneous rain fades of 4 dB for both the uplink and downlink.

The video S/N ratio corresponding to a received C/N ratio has been found by the following relation [32]:

Table 5 - 1. **Power Budget Analysis for FM Television Transmission to the EMC in Leesburg**

Antenna/Station	
Uplink Antenna:	SBS 5.5 meter
Downlink Antenna:	SBS 5.5 meter
Transmitting Earth Station:	Virginia Tech - Blacksburg, VA
Receiving Earth Station:	Equine Medical Center - Leesburg, VA
Uplink	
Earth Station Transmitted Power	19.18 dBW
Waveguide Loss	0.17 dB
Earth Station Antenna Gain	56.72 dB
Antenna Pointing and Polarization Loss	0.50 dB
Atmospheric Attenuation	0.50 dB
Free Space Loss	207.08 dB
Transponder Antenna Gain	31.99 dB
Transponder Carrier Level	-100.36 dBW
Transponder Noise Power	-123.31 dBW
Transponder C/N	22.95 dB
Downlink	
Satellite EIRP With Backoff	43.48 dBW
Free Space Loss	205.62 dB
Atmospheric Attenuation	0.50 dB
Antenna Pointing and Polarization Loss	0.50 dB
Earth Station Antenna Gain	55.25 dB
Waveguide Loss	0.17 dB
Earth Station Carrier Level	-108.06 dB
Earth Station Noise Power	-130.31 dB
Earth Station C/N	22.25 dB
Overall C/N	19.57 dB

Table 5 - 2. Rain Fade Performance Analysis for FM Television Tranmission to the EMC in Leesburg

Uplink Fade	Overall C/N	Final S/N	Downlink Fade	Overall C/N	Final S/N
0.0	19.57	54.29	0.0	19.57	54.29
1.0	18.78	53.49	1.0	18.46	53.17
2.0	17.93	52.65	2.0	17.37	52.08
3.0	17.03	51.74	3.0	16.30	51.01
4.0	16.10	50.81	4.0	15.25	49.96
5.0	15.12	49.83	5.0	14.21	48.92
6.0	14.12	48.83	6.0	13.17	47.89
7.0	13.12	47.83	7.0	12.15	46.86
8.0	12.12	46.83	8.0	11.13	45.84
9.0	11.12	45.83	9.0	10.11	44.82
10.0	10.12	44.83	10.0	9.10	42.91

Uplink Fade	Downlink Fade	Overall C/N	Final S/N
0.0	0.0	19.57	54.29
0.0	1.0	18.46	53.17
0.0	2.0	17.37	52.08
0.0	3.0	16.30	51.01
0.0	4.0	15.25	49.96
1.0	0.0	18.78	53.29
1.0	1.0	17.71	52.42
1.0	2.0	16.65	51.36
1.0	3.0	15.61	50.32
1.0	4.0	14.57	49.28
2.0	0.0	17.93	52.15
2.0	1.0	16.89	51.61
2.0	2.0	15.86	50.57
2.0	3.0	14.84	49.55
2.0	4.0	13.82	48.53
3.0	0.0	17.03	51.74
3.0	1.0	16.00	50.72
3.0	2.0	14.99	49.70
3.0	3.0	13.98	48.69
3.0	4.0	12.97	47.68
4.0	0.0	16.10	50.81
4.0	1.0	15.09	49.81
4.0	2.0	14.09	48.80
4.0	3.0	13.09	47.80
4.0	4.0	12.08	46.80

All values are in dB.

$B = 24\text{MHz} \quad f_v = 4.2\text{MHz} \quad \Delta f_p = 7.8\text{MHz}$

$$\frac{S}{N} = \frac{C}{N} + 1.76 + 10\log_{10}\left(\frac{B}{f_v}\right) + 20\log_{10}\left(\frac{\Delta f_p}{f_v}\right) + P + Q \qquad (5-1)$$

where B is the FM television signal bandwidth, f_v is the maximum video modulating frequency (4.2 MHz in the U. S.), Δf_p is the peak deviation frequency, P is the preemphasis factor, and Q is the psophometric weighting factor. For 24 MHz television transmissions the peak deviation frequency is 7.8 MHz. Both the S/N ratio and the C/N ratio are expressed in dB. For the values appearing in Table 5-2, $P + Q$ is 20 dB [32].

It is also possible to transmit two of these analog television signals within the same 43 MHz transponder. Some overlap in the signal spectrums, will occur, though. Fortunately, the spectral density of the FM television signal is not uniform, and any overlap occurs at frequencies where the spectral density is relatively low. Specifically, this overlap occurs in the upper 5 MHz of the lower frequency signal and the lower 5 MHz of the upper frequency signal. In other words, this overlap begins 7 MHz from the center frequencies of the two signals. At 7 MHz from the center frequency, the spectral density of a typical television signal is less than -76 dB/Hz in relation to the total carrier power [22]. The adjacent channel interference created by the overlap in bandwidths can be neglected.

To transmit two analog television signals without any overlap, the bandwidths must be 21.5 MHz wide. This reduction in bandwidth, though, degrades the overall performance of the system because the bandwidth compression occurring from FM demodulation is lessened. Calculated S/N ratios, however, differ only slightly from those shown in Table 5-2.

5.1.3 T1 Compressed Video Transmissions

This subsection discusses the performance of T1 compressed video transmissions from the proposed facility at Virginia Tech. Transmission performance to existing Virginia Tech Extension locations and to the proposed facility at the Equine Medical Center in Leesburg, Virginia, is discussed.

Fifty-four Extension locations presently exist throughout Virginia. These locations operate as a service to the community providing informative programming on many different topics aimed at a variety of audiences. Topics may range from crop rotation techniques for farmers to child nutrition information for new parents. A typical location provides seating for about 25 people. Each location receives broadcasts with a 9 foot diameter antenna manufacured for C-band (4 and 6 GHz) transmissions.

The proposed facility at the Equine Medical Center is virtually identical to the one at the Virginia Tech teleport. A microwave link carrying the video transmissions will connect the facility in Leesburg to the Northern Virginia Center at the Telestar building in Falls Church.

Consider the performance of a single T1 carrier. With the proposed facilities at Virginia Tech, signal transmission is power limited to avoid interference with adjacent satellites. Through a worst case interference analysis, interference levels are acceptable if the overall single entry carrier-to-interference ratio (C/I) for an adjacent satellite system is 28 dB. The calculations for obtaining this C/I ratio are described in the communications system model developed by George Sharp [40]. The uplink carrier-to-interference ratio can be approximated by assuming that the proposed earth station interferes with a similar system operating near threshold (i.e. an overall carrier-to-noise ratio around 8.5 dB). This uplink C/I ratio corresponds to the ratio between the desired signal flux density at the adjacent satellite and the interfering signal flux density produced by the proposed earth station. The downlink carrier-to-interference ratio can be approximated by the difference between the downlink antenna boresight gain and off-axis gain for the receiving earth station. As part of the worst case interference analysis, suppose the proposed satellite system uses a transponder on SBS-3, located at 95° West longitude, the off-axis gain aimed at the nearest satellite, SBS-2 at 97° West longitude is 20.59 dBi. This value for the antenna off-axis gain is found by applying the FCC antenna pattern envelope specifications in effect during production of the SBS antenna:

$$G(\theta) = 32 - 25\log(\theta) \text{ dB} \qquad (5-2)$$

where G is the antenna gain, and θ is the off-axis angle in degrees. The difference in the look angles between SBS-3 and SBS-2 as seen from Virginia Tech is 2.86°.

With an off-axis gain of 20.59 dBi in the direction of the adjacent satellite, a single QPSK T1 transmission can be broadcast at a power level of 5.06 dBW entering the antenna terminals without exceeding the single entry C/I ratio for an adjacent satellite system. A power budget analysis for a single T1 transmission at this power level is shown in Table 5-3. For purposes of analysis, assume that the receiving station uses a 9 foot diameter antenna. Existing equipment at the Extension locations use such antennas. They have a 60 percent aperture efficiency and a nominal gain of 39.5 dBi at 3.95 GHz. These antennas can be used to receive Ku-band signals, and their receive gain will be 47.28 dBi at 12 GHz assuming their aperture efficiency drops to 45 percent. As further shown in Table 5-3, the resulting overall carrier-to-noise ratio for the described link becomes 15.70 dB, an acceptable level for a digital television system.

All values shown in Table 5-3 were calculated by *LAMP* (*L*ink *A*nalysis *M*achine *P*rogram), a software package developed as part of the IBM/Virginia Tech Joint Development Project. *LAMP* calculates and displays power budgets for geosynchronous satellite links. A description of the theory of *LAMP* operation for power budget analyses is given in Appendix A.

The power budget analysis shown in Table 5-3 is for clear sky conditions. Uplink and downlink fades due to rain are included in Table 5-4, which provides theoretical bit error rates for the QPSK system. Acceptable video reception occurs as long as the bit error rate remains below 10^{-6} [32]. During clear sky conditions, the system operates with approximately a 2 dB implementation margin. However, under the heavy rain fade conditions shown in Table 5-4, theoretical system performance becomes poor. Notice that a received bit energy-to-noise density (E_b/N_o) ratio lower than 10.6 dB produces bit error rates greater than 10^{-6}. Forward error correction available with the operating digital modem can significantly lower this system's bit error rate. Although the received E_b/N_o ratio is unchanged, error correction techniques generate a coding gain that reduces the frequency of error. With a 1/2 convolutional coding technique, for instance, a

Table 5 - 3. Power Budget Analysis for Single T1 Television Transmission to Extension Locations

Antenna/Station	
Uplink Antenna:	SBS 5.5 meter
Downlink Antenna:	9 foot
Transmitting Earth Station:	Virginia Tech - Blacksburg, VA
Receiving Earth Station:	Extension Office
Uplink	
Earth Station Transmitted Power	5.06 dBW
Waveguide Loss	0.17 dB
Earth Station Antenna Gain	56.72 dB
Antenna Pointing and Polarization Loss	0.50 dB
Atmospheric Attenuation	0.50 dB
Free Space Loss	207.08 dB
Transponder Antenna Gain	31.99 dB
Transponder Carrier Level	-114.48 dBW
Transponder Noise Power	-137.43 dBW
Transponder C/N	22.94 dB
Downlink	
Satellite EIRP With Backoff	30.43 dBW
Free Space Loss	205.62 dB
Atmospheric Attenuation	0.50 dB
Antenna Pointing and Polarization Loss	0.50 dB
Earth Station Antenna Gain	47.33 dB
Waveguide Loss	0.20 dB
Earth Station Carrier Level	-129.06 dB
Earth Station Noise Power	-144.42 dB
Earth Station C/N	15.36 dB
Overall C/N	14.66 dB

Table 5 - 4. Rain Fade Performance Analysis for Single T1 Television Transmission to Extension Locations

Uplink Fade	Overall E_b/N_o	Final BER	Downlink Fade	Overall E_b/N_o	Final BER
0.0	12.46	1.44×10^{-9}	0.0	12.46	1.44×10^{-9}
1.0	11.46	5.58×10^{-8}	1.0	10.81	4.37×10^{-7}
2.0	10.46	1.10×10^{-6}	2.0	9.36	1.53×10^{-5}
3.0	9.46	1.23×10^{-5}	3.0	8.03	1.61×10^{-4}
4.0	8.46	8.28×10^{-5}	4.0	6.79	9.62×10^{-4}
5.0	7.46	3.82×10^{-4}	5.0	5.61	3.18×10^{-3}
6.0	6.46	1.45×10^{-3}	6.0	4.46	8.14×10^{-3}
7.0	5.46	3.63×10^{-3}	7.0	3.36	1.81×10^{-2}
8.0	4.46	8.19×10^{-3}	8.0	2.27	3.13×10^{-2}
9.0	3.46	1.69×10^{-2}	9.0	1.20	4.72×10^{-2}
10.0	2.46	2.90×10^{-2}	10.0	0.15	6.77×10^{-2}

Uplink Fade	Downlink Fade	Overall E_b/N_o	Final BER
0.0	0.0	12.46	1.44×10^{-9}
0.0	1.0	10.81	4.37×10^{-7}
0.0	2.0	9.36	1.53×10^{-5}
0.0	3.0	8.03	1.61×10^{-4}
0.0	4.0	6.79	9.62×10^{-4}
1.0	0.0	11.46	5.58×10^{-8}
1.0	1.0	9.81	5.39×10^{-6}
1.0	2.0	8.36	9.65×10^{-5}
1.0	3.0	7.03	6.92×10^{-4}
1.0	4.0	5.79	2.70×10^{-3}
2.0	0.0	10.46	1.10×10^{-6}
2.0	1.0	8.81	4.60×10^{-5}
2.0	2.0	7.36	4.37×10^{-4}
2.0	3.0	6.03	2.17×10^{-3}
2.0	4.0	4.79	6.31×10^{-3}
3.0	0.0	9.46	1.23×10^{-5}
3.0	1.0	7.81	2.26×10^{-4}
3.0	2.0	6.36	1.59×10^{-3}
3.0	3.0	5.03	5.18×10^{-3}
3.0	4.0	3.79	1.34×10^{-2}
4.0	0.0	8.46	8.28×10^{-5}
4.0	1.0	6.81	9.33×10^{-4}
4.0	2.0	5.36	3.93×10^{-3}
4.0	3.0	4.03	1.12×10^{-2}
4.0	4.0	2.79	2.51×10^{-2}

All values except bit error rate are in dB.

coding gain up to 5.2 dB can be obtained [19]. However, employing 1/2 rate convolutional coding requires two times the number of transmitted bits compared to the number of information bits. The resulting broadcast becomes 3.088 Mbps for reception of T1 video with 1/2 rate convolutional coding. The bandwidth and power requirements also must double to provide the necessary E_b/N_o for adequate reception of 3.088 Mbps transmissions. The increase in bandwidth and power requirements can be alleviated by employing 7/8 rate or 15/16 rate convolutional coding, but the coding gain obtained at the receiver would only be on the order of 1 or 2 dB [19].

All values in Table 5-4 were calculated by *LAMP*. Upon request *LAMP* generates rain fade performance analyses for a specified satellite communications link. A description of *LAMP's* theory of operation is presented in Appendix B.

Transmission of digital video between Virginia Tech and the Equine Medical Center (EMC) in Leesburg offers better reception than that described for the stations using 9 foot diameter antennas. As shown in Table 5-5, transmitting at a power level of 5.06 dBW (the maximum transmitted power allowed in the previous link analysis) results in an overall carrier-to-noise ratio of 20.11 dB, a very acceptable level for digital television. Table 5-6 gives the performance analysis during uplink and downlink rain fades. As shown in this latter table, transmission of a single T1 television channel at this power level provides bit error rates less than 10^{-6} for either uplink only or downlink only rain fades up to 7.4 dB. This bit error rate is also maintained if rain fades occuring on both the uplink and the downlink are less than 4 dB. These rain fades correspond to outages occuring 0.014 percent, or 74 minutes, in one year [24].

Broadcasting only one T1 channel, however, utilizes only a fraction of the RF bandwidth available in a satellite transponder. Typical bit duration-bandwidth products (T_bB) for QPSK transmissions using raised cosine filtering range from 0.55 to 0.7 [22]. For a T_bB product equal to 0.6, a QPSK T1 transmission requires approximately 930 kHz of bandwidth. In theory, 36 QPSK T1 channels can fill up the entire 43 MHz of available transponder bandwidth, assuming that each channel occupies 930 kHz and that the center frequency of each channel is separated by 1.19 MHz. This separation produces a 260 kHz guard band between each channel to significantly reduce adjacent channel interference. Unfortunately, transmitting 36 carriers would create many

Table 5 - 5. **Power Budget Analysis for Single T1 Television Transmission to the EMC in Leesburg**

Antenna/Station	
Uplink Antenna:	SBS 5.5 meter
Downlink Antenna:	SBS 5.5 meter
Transmitting Earth Station:	Virginia Tech - Blacksburg, VA
Receiving Earth Station:	Equine Medical Center - Leesburg, VA
Uplink	
Earth Station Transmitted Power	5.06 dBW
Waveguide Loss	0.17 dB
Earth Station Antenna Gain	56.72 dB
Antenna Pointing and Polarization Loss	0.50 dB
Atmospheric Attenuation	0.50 dB
Free Space Loss	207.08 dB
Transponder Antenna Gain	31.99 dB
Transponder Carrier Level	-114.48 dBW
Transponder Noise Power	-137.43 dBW
Transponder C/N	22.94 dB
Downlink	
Satellite EIRP With Backoff	30.43 dBW
Free Space Loss	205.62 dB
Atmospheric Attenuation	0.50 dB
Antenna Pointing and Polarization Loss	0.50 dB
Earth Station Antenna Gain	55.25 dB
Waveguide Loss	0.17 dB
Earth Station Carrier Level	-121.11 dB
Earth Station Noise Power	-144.43 dB
Earth Station C/N	23.31 dB
Overall C/N	20.11 dB

Table 5 - 6. Rain Fade Performance Analysis for Single T1 Television Transmission to the EMC in Leesburg

Uplink Fade	Overall E_b/N_o	Final BER	Downlink Fade	Overall E_b/N_o	Final BER
0.0	17.91	$< 1x10^{-12}$	0.0	17.91	$< 1x10^{-12}$
1.0	16.91	$< 1x10^{-12}$	1.0	16.91	$< 1x10^{-12}$
2.0	15.91	$< 1x10^{-12}$	2.0	15.91	$< 1x10^{-12}$
3.0	14.91	$< 1x10^{-12}$	3.0	14.91	$< 1x10^{-12}$
4.0	13.91	$< 1x10^{-12}$	4.0	13.91	$< 1x10^{-12}$
5.0	12.91	$1.62x10^{-10}$	5.0	12.91	$1.64x10^{-10}$
6.0	11.91	$1.11x10^{-8}$	6.0	11.91	$1.12x10^{-8}$
7.0	10.91	$3.35x10^{-7}$	7.0	10.91	$3.37x10^{-7}$
8.0	9.91	$4.25x10^{-6}$	8.0	9.91	$4.28x10^{-6}$
9.0	8.91	$3.89x10^{-5}$	9.0	8.91	$3.90x10^{-5}$
10.0	7.91	$1.94x10^{-4}$	10.0	7.91	$1.95x10^{-4}$

Uplink Fade	Downlink Fade	Overall E_b/N_o	Final BER
0.0	0.0	17.91	$< 1x10^{-12}$
0.0	1.0	16.91	$< 1x10^{-12}$
0.0	2.0	15.91	$< 1x10^{-12}$
0.0	3.0	14.91	$< 1x10^{-12}$
0.0	4.0	13.91	$< 1x10^{-12}$
1.0	0.0	16.91	$< 1x10^{-12}$
1.0	1.0	15.91	$< 1x10^{-12}$
1.0	2.0	14.91	$< 1x10^{-12}$
1.0	3.0	13.91	$< 1x10^{-12}$
1.0	4.0	12.91	$1.63x10^{-10}$
2.0	0.0	15.91	$< 1x10^{-12}$
2.0	1.0	14.91	$< 1x10^{-12}$
2.0	2.0	13.91	$< 1x10^{-12}$
2.0	3.0	12.91	$1.63x10^{-10}$
2.0	4.0	11.91	$1.12x10^{-8}$
3.0	0.0	14.91	$< 1x10^{-12}$
3.0	1.0	13.91	$< 1x10^{-12}$
3.0	2.0	12.91	$1.63x10^{-10}$
3.0	3.0	11.91	$1.12x10^{-8}$
3.0	4.0	10.91	$3.36x10^{-7}$
4.0	0.0	13.91	$< 1x10^{-12}$
4.0	1.0	12.91	$1.62x10^{-10}$
4.0	2.0	11.91	$1.12x10^{-8}$
4.0	3.0	10.91	$3.36x10^{-7}$
4.0	4.0	9.91	$4.27x10^{-6}$

All values except bit error rate are in dB.

third-order intermodulation products within the various channel bandwidths. These intermodulation products are caused by non-linear behavior of the satellite transponder amplifier, and they can significantly reduce the performance of any channels within the 43 MHz bandwidth, particularly channels lying in the middle of this bandwidth. Increasing the transponder backoff can reduce the power of the individual intermodulation products, but the number of products remains the same. Unfortunately, increasing the transponder backoff also reduces the power of the desired signal.

For adjacent channels i, $i+1$, and $i+2$, the third-order intermodulation products produced by n equally spaced carriers are formed by combining the frequencies of each channel in two ways: $2\omega_i - \omega_{i+1}$, and $\omega_i + \omega_{i+1} - \omega_{i+2}$ [22]. For the $2\omega_i - \omega_{i+1}$ type of third-order intermodulation, the distribution of intermodulation products falling within the rth channel is

$$D_{2,1}(r,n) = \frac{1}{2}\left\{n - 2 - \frac{1}{2}[1-(-1)^n](-1)^r\right\} . \qquad (5-3)$$

For $\omega_i + \omega_{i+1} - \omega_{i+2}$ third-order intermodulation, the distrubution of intermodulation products falling within the rth carrier is

$$D_{1,1,1}(r,n) = \frac{r}{2}(n-r+1) + \frac{1}{4}[(n-3)^2 - 5] - \frac{1}{2}[1-(-1)^n](-1)^{n+r} . \qquad (5-4)$$

Consequently, with 36 equally spaced T1 carriers, there exists 459 intermodulation products in the pass band of the 18th channel. If the transmitted power per channel, however, is held at 5.06 dBW (20.62 dBW total transmitted power for the entire transponder) the carrier-to-third-order intermodulation ratio due to amplitude non-linearity becomes 16.05 dB. The overall carrier-to-intermodulation ratio is around 14 dB if phase non-linearity in the transponder is also included [22]. The intermodulation products produced by 36 carriers at 20.62 dBW total power cause significant degradation of the received signal. Calculations for carrier-to-third-order intermodulation ratios are discussed in Appendix C.

A more reasonable carrier-to-third-order intermodulation (C/I) ratio is obtained by reducing the total number of transmitted channels. If 8 equally spaced channels were transmitted, only 18 third-order intermodulation products exist within the pass band of the 4th channel. The resulting C/I ratio due to amplitude non-linearity is 31.61 dB. The overall C/I ratio in the 4th channel is approximately 30 dB. With this C/I ratio, the overall C/N ratio at the receiving stations will be degraded by less than 0.5 dB.

The cost of implementing a communications system with several T1 carriers increases somewhat as the required amount of modulation equipment increases. Anticipated usage ultimately determines the appropriate amount of equipment to procure.

5.1.4 Medical Image Transmission

The overall performance of this image transmission system will not differ from any other digital transmission between Virginia Tech and the EMC. The power budget and performance analyses shown in Table 5-5 and Table 5-6 respectively also remain valid for this transmission system. Received bit error rates less than 10^{-6} are desirable for image transmissions. Forward error correction as mentioned in Section 5.1.2 can further reduce this received bit error rate. For image transmission, however, transmissions can be held at a T1 bit rate despite the rate of convolutional coding used. For instance, if 1/2 rate convolutional coding is used, transmission can occur at T1 while the bit rate leading to and from the image capture add-on boards would be 1/2 that rate, or 772 kbps.

5.1.5 Token Ring

As with the previous section, the performance of the token ring will not differ much from the performance of other digital transmissions. Since a token ring implies distrubuted control of a network, the individual nodes of a satellite token ring probably will be equipped with a relatively large antenna such as a 5.5 meter diameter for Ku band operation. Tables 5-6 and 5-6 provide an example of one T1 link in a token ring between two 5.5 meter diameter antennas. Although Tables 5-5 and 5-6 describe compressed video transmission, the data still hold for T1 data transmissions.

5.1.6 VSAT Network Link Performance

The proposed system will be configured as a star network. The operation of this network is described in the following subsection.

First, suppose that the hub station is transmitting. Satellite transmission is legally power limited according to a recent FCC document calling for a blanket licensing of VSAT stations which limits the downlink EIRP density to 6 dBW per 4 kHz [34]. For QPSK 56 kbps data streams transmitted within 40 kHz (using a BT_b product of 0.7), this downlink EIRP density translates to 16 dBW. For purposes of analysis, assume a VSAT station is located at 39° North latitude and 77.5° West longitude; we wish to determine the required receiving equipment. In order to reduce the cost of configuring each station, the antenna size for each receiver should be as small as possible while providing adequate gain for system performance. Assume that the receiving station has a noise temperature of 250 K and uses a 1.2 meter diameter antenna with a nominal gain of 41.0 dBi at 12 GHz. By performing a power budget analysis, one can calculate that the proposed hub station can transmit at -9.73 dBW to produce an output EIRP of 16 dBW at the satellite. This transmitted power is the maximum allowable power level that does not cause the downlink EIRP of the satellite transponder to exceed 6 dBW per 4 kHz. The overall C/N calculated for a VSAT station using a 1.2 meter diameter antenna is 8.49 dB. Unfortunately, an overall C/N of 8.49 dB corresponds to a received bit energy-to-noise power density ratio of 7.03 dB which is very marginal in providing adequate system performance, even under clear air conditions and with forward error correction. With the FCC proposal limiting downlink EIRP densities, 1.2 meter diameter antennas do not offer a feasible of means handling QPSK 56 kbps transmission. For this reason, tables depicting the performance of this link are not presented.

The preferable configuration for the VSAT station would be a 1.8 meter antenna with a nominal gain of 44.87 dBi at 12 GHz. As shown in Table 5-7, this antenna would provide the VSAT with an overall C/N of 11.78 dB. Table 5-8 describes the anticipated performance of the link carrying 56 kbps transmissions in a 40 kHz bandwidth. The theoretical performance of this system under rain fade conditions, as seen in this table, still remains marginal. Bit error rates for received text should be below 10^{-6}. An error correction scheme could be employed to maintain a low bit error rate. Forward error correction at a 1/2 convolutional coding rate can provide up to 5.2 dB coding gain [19]. This coding gain allows for data reception during periods of uplink-only rain fades of 5 dB, and downlink-only rain fades of 3.5 dB. These rain fades correspond to outages occuring 0.12 percent of the time, or 10.5 hours in one year for both stations located in Virginia [24].

At some time the remote station may wish to communicate with the hub in Blacksburg. According to the recent FCC order mentioned earlier, the transmitting power density of a VSAT station is limited to -14 dBW per 4 kHz entering the antenna terminals [34]. This would allow the remote station to transmit at -4.00 dBW over 40 kHz bandwidth. The overall C/N at the hub station, shown in Table 5-9, would be 14.38 dB. Even though the theoretical performance of this link is better than that of the hub-to-remote link, Table 5-10 suggests that forward error correction is still in order for adequate reception when uplink only and downlink only rain fades are greater than 2.5 dB. With 1/2 rate convolutional coding adequate reception is possible during uplink only and downlink only rain fades up to 7.5 dB. These fades correspond to an outage for approximately 8.75 hours in one year for both stations located in Virginia [24].

5.1.7 Land Mobile Earth Station Experiment Transmissions

In an experiment the proposed earth station would transmit digital information at a bit rate around 50 kbps to one or more mobile earth stations. The broadcast bit rate will depend on the manufacturer's specifications for the operating digital modem. Transmission of wideband analog

Table 5 - 7. VSAT Link Analysis for 56 kbps Data Transmissions with a 1.8 m. Remote Station Antenna

Antenna/Station	
Uplink Antenna:	SBS 5.5 meter
Downlink Antenna:	1.8 meter
Transmitting Earth Station:	Virginia Tech - Blacksburg, VA
Receiving Earth Station:	VSAT Station
Uplink	
Earth Station Transmitted Power	-9.37 dBW
Waveguide Loss	0.17 dB
Earth Station Antenna Gain	56.72 dB
Antenna Pointing and Polarization Loss	0.50 dB
Atmospheric Attenuation	0.50 dB
Free Space Loss	207.08 dB
Transponder Antenna Gain	31.99 dB
Transponder Carrier Level	-128.91 dBW
Transponder Noise Power	-151.09 dBW
Transponder C/N	22.18 dB
Downlink	
Satellite EIRP With Backoff	16.00 dBW
Free Space Loss	205.62 dB
Atmospheric Attenuation	0.50 dB
Antenna Pointing and Polarization Loss	0.50 dB
Earth Station Antenna Gain	44.92 dB
Waveguide Loss	0.20 dB
Earth Station Carrier Level	-145.90 dB
Earth Station Noise Power	-158.10 dB
Earth Station C/N	12.20 dB
Overall C/N	11.78 dB

Table 5 - 8. VSAT Rain Fade Performance Analysis for 56 kbps Data Transmissions with a 1.8 m. Remote Receiving Station Antenna

Uplink Fade	Overall E_b/N_o	Final BER	Downlink Fade	Overall E_b/N_o	Final BER
0.0	10.32	$1.55x10^{-6}$	0.0	10.32	$1.55x10^{-6}$
1.0	9.32	$1.67x10^{-5}$	1.0	8.58	$6.72x10^{-5}$
2.0	8.32	$1.03x10^{-4}$	2.0	7.08	$6.52x10^{-4}$
3.0	7.32	$4.62x10^{-4}$	3.0	5.71	$2.90x10^{-3}$
4.0	6.32	$1.65x10^{-3}$	4.0	4.44	$8.29x10^{-3}$
5.0	5.32	$4.07x10^{-3}$	5.0	3.24	$1.96x10^{-2}$
6.0	4.32	$9.07x10^{-3}$	6.0	2.08	$3.38x10^{-2}$
7.0	3.32	$1.85x10^{-2}$	7.0	0.96	$5.15x10^{-2}$
8.0	2.32	$3.06x10^{-2}$	8.0	-0.13	$7.40x10^{-2}$
9.0	1.32	$4.52x10^{-2}$	9.0	-1.20	$1.01x10^{-1}$
10.0	0.32	$6.40x10^{-2}$	10.0	-2.26	$1.33x10^{-1}$

Uplink Fade	Downlink Fade	Overall E_b/N_o	Final BER
0.0	0.0	10.32	$1.55x10^{-6}$
0.0	1.0	8.58	$6.72x10^{-5}$
0.0	2.0	7.08	$6.52x10^{-4}$
0.0	3.0	5.71	$2.90x10^{-3}$
0.0	4.0	4.44	$8.29x10^{-3}$
1.0	0.0	9.32	$1.67x10^{-5}$
1.0	1.0	7.58	$3.17x10^{-4}$
1.0	2.0	6.08	$2.08x10^{-3}$
1.0	3.0	4.71	$6.71x10^{-3}$
1.0	4.0	3.44	$1.71x10^{-2}$
2.0	0.0	8.32	$1.03x10^{-4}$
2.0	1.0	6.58	$1.26x10^{-3}$
2.0	2.0	5.08	$5.00x10^{-3}$
2.0	3.0	3.71	$1.42x10^{-2}$
2.0	4.0	2.44	$2.92x10^{-2}$
3.0	0.0	7.32	$4.62x10^{-4}$
3.0	1.0	5.58	$3.24x10^{-3}$
3.0	2.0	4.08	$1.09x10^{-2}$
3.0	3.0	2.71	$2.60x10^{-2}$
3.0	4.0	1.44	$4.33x10^{-2}$
4.0	0.0	6.32	$1.65x10^{-3}$
4.0	1.0	4.58	$7.42x10^{-3}$
4.0	2.0	3.08	$2.18x10^{-2}$
4.0	3.0	1.71	$3.91x10^{-2}$
4.0	4.0	0.44	$6.16x10^{-2}$

All values except bit error rate are in dB.

Table 5 - 9. Remote-to-Hub Station Link Budget Analysis for 56 kbps Data Transmissions

Antenna/Station	
Uplink Antenna:	1.8 meter
Downlink Antenna:	SBS 5.5 meter
Transmitting Earth Station:	VSAT Station
Receiving Earth Station:	Virginia Tech - Blacksburg, VA
Uplink	
Earth Station Transmitted Power	-4.00 dBW
Waveguide Loss	0.20 dB
Earth Station Antenna Gain	46.44 dB
Antenna Pointing and Polarization Loss	0.50 dB
Atmospheric Attenuation	0.50 dB
Free Space Loss	207.13 dB
Transponder Antenna Gain	31.99 dB
Transponder Carrier Level	-133.91 dBW
Transponder Noise Power	-151.09 dBW
Transponder C/N	17.18 dB
Downlink	
Satellite EIRP With Backoff	11.00 dBW
Free Space Loss	205.57 dB
Atmospheric Attenuation	0.50 dB
Antenna Pointing and Polarization Loss	0.50 dB
Earth Station Antenna Gain	55.25 dB
Waveguide Loss	0.17 dB
Earth Station Carrier Level	-140.49 dB
Earth Station Noise Power	-158.09 dB
Earth Station C/N	17.60 dB
Overall C/N	14.38 dB

Table 5 - 10. Remote-to-Hub Station Rain Fade Performance Analysis for 56 kbps Data Transmissions

Uplink Fade	Overall E_b/N_o	Final BER	Downlink Fade	Overall E_b/N_o	Final BER
0.0	12.92	1.59×10^{-10}	0.0	12.92	1.59×10^{-10}
1.0	11.92	1.10×10^{-8}	1.0	11.92	1.08×10^{-8}
2.0	10.92	3.32×10^{-7}	2.0	10.92	3.24×10^{-7}
3.0	9.92	4.22×10^{-6}	3.0	9.93	4.10×10^{-6}
4.0	8.92	3.86×10^{-5}	4.0	8.93	3.77×10^{-5}
5.0	7.92	1.93×10^{-4}	5.0	7.93	1.89×10^{-4}
6.0	6.92	8.13×10^{-4}	6.0	6.93	7.94×10^{-4}
7.0	5.92	2.41×10^{-3}	7.0	5.93	2.37×10^{-3}
8.0	4.92	5.70×10^{-3}	8.0	4.93	5.61×10^{-3}
9.0	3.92	1.23×10^{-2}	9.0	3.94	1.21×10^{-2}
10.0	2.92	2.38×10^{-2}	10.0	2.94	2.36×10^{-2}

Uplink Fade	Downlink Fade	Overall E_b/N_o	Final BER
0.0	0.0	12.92	1.59×10^{-10}
0.0	1.0	11.92	1.08×10^{-8}
0.0	2.0	10.92	3.24×10^{-7}
0.0	3.0	9.93	4.10×10^{-6}
0.0	4.0	8.93	3.77×10^{-5}
1.0	0.0	11.92	1.10×10^{-8}
1.0	1.0	10.92	3.27×10^{-7}
1.0	2.0	9.92	4.13×10^{-6}
1.0	3.0	8.93	3.79×10^{-5}
1.0	4.0	7.93	1.89×10^{-4}
2.0	0.0	10.92	3.32×10^{-7}
2.0	1.0	9.92	4.17×10^{-6}
2.0	2.0	8.92	3.81×10^{-5}
2.0	3.0	7.93	1.90×10^{-4}
2.0	4.0	6.93	7.98×10^{-4}
3.0	0.0	9.92	4.22×10^{-6}
3.0	1.0	8.92	3.83×10^{-5}
3.0	2.0	7.92	1.91×10^{-4}
3.0	3.0	6.93	8.00×10^{-4}
3.0	4.0	5.93	2.38×10^{-3}
4.0	0.0	8.92	3.86×10^{-5}
4.0	1.0	7.92	1.92×10^{-4}
4.0	2.0	6.92	8.03×10^{-4}
4.0	3.0	5.93	2.39×10^{-3}
4.0	4.0	4.93	5.64×10^{-3}

All values except bit error rate are in dB.

signals or bit rates higher than 50 kbps will include too much noise bandwidth at the receiving earth station in comparison to the small antenna gain. With the currently available SM290V digital modem produced by Fairchild Data Corporation, transmissions would be at 48 kbps with 1/2 rate convolutional coding [17]. This digital information can be transmitted in a 33.6 kHz bandwidth after coding using QPSK modulation at a T_bB product of 0.70. Because of the small size of the receiving earth station antennas, signal transmission is power limited according to the FCC proposal for blanket licensing of stations in a VSAT network. According to the proposal, a hub station is power limited so that the downlink EIRP from the satellite does not exceed 6 dBW per 4 kHz [35]. This proposal limits the signal power of the hub station in Blacksburg. After the satellite transponder amplifies the transmitted signal, the resulting EIRP from the satellite is no greater than 15.24 dBW. As shown in Table 5-11 the power level at the transmitting hub station is limited to -10.13 dBW to remain within the FCC satellite EIRP specifications. The antenna used to receive these signals will be as small as possible to allow ease in mobility. Microspace Communications Corporation, for instance, manufactures a 0.75 meter antenna designed for Ku-band communications [27] . The antenna gain would be 37.27 dBi at 12 GHz assuming it has a 60 percent aperture efficiency. Unfortunately, use of this antenna at a land mobile station provides an overall received C/N of only 4.55 dB, assuming that the mobile station has a 250 K noise temperature. Since the T_bB product is 0.70 the received E_b/N_o ratio is only 3.00 dB. Very poor reception will occur.

A significantly higher overall C/N ratio can be obtained with a 1.2 meter receive antenna at the remote mobile stations. Table 5-11 gives the power budget for a link using a typical 1.2 meter receiving antenna. At 12 GHz the receiving antenna has gain of 41.35 dBi for an aperture efficiency of 60 percent. This antenna, in turn, can provide the mobile station with an overall C/N ratio of 8.53 dB. The corresponding E_b/N_o ratio is 6.98 dB for a T_bB product of 0.7. As shown in Figure 5-1, this received E_b/N_o ratio produces a bit error rate less than 10^{-6} under clear sky conditions [17]. During any rain fades the system performance is significantly reduced. Table 5-12 gives the received E_b/N_o ratio under uplink and downlink rain fades. In comparing the received signal quality to the curve shown in Figure 5-1, it is seen that the received bit error rate quickly increases above 10^{-5} as rain fades increase.

Now consider mobile station-to-hub station communications. The gain of the transmitting remote 1.2 meter antenna is approximately 42.69 dBi at 14 GHz and a 60 percent aperture efficiency. As with the hub station-to-remote mobile station link, transmissions consist of 48 kbps QPSK transmissions within a 33.6 kHz bandwidth. This transmission rate corresponds to a 24 kbps user data rate before coding. With the remote-to-hub link, however, transmissions are power limited to -14 dBW per 4 kHz entering the terminals of the transmitting antenna [35]. This allows the remote station to transmit at -4.76 dBW. Table 5-13 gives the power budget for this mobile station-to-hub station communications link. As shown in this table the overall C/N at the hub station is 10.90 dB. Note that the remote-to-hub link can obtain a higher C/N ratio than the hub-to-remote link. This is because the difference between the receiving gain of the hub station and the receiving gain of the mobile station antenna is larger than the difference between the satellite transponder EIRPs generated by a transmitting remote station or hub station. The remote-to-hub link would generate a bit error rate at the hub station less than 10^{-10} with the use of the SM290V modem.

To account for rain fade conditions, compare the E_b/N_o values in Table 5-14 to the performance curve in Figure 5-1. According to the curve, bit error rates less than 10^{-6} can be achieved during uplink only and downlink only rain fades up to 4 dB. Rain outages can be expected for 0.14 percent, or 12.3 hours, in one year.

5.1.8 Environmental Monitoring Stations

The performance of transmissions from an environmental monitoring station will not differ from that of the transmissions from the VSAT-to-hub station transmissions presented in Section 5.1.5. The power budget and performance analysis shown in Tables 5-9 and 5-10, respectively, also remain valid for this transmission system. Received bit error rates less than 10^{-6} are desirable for

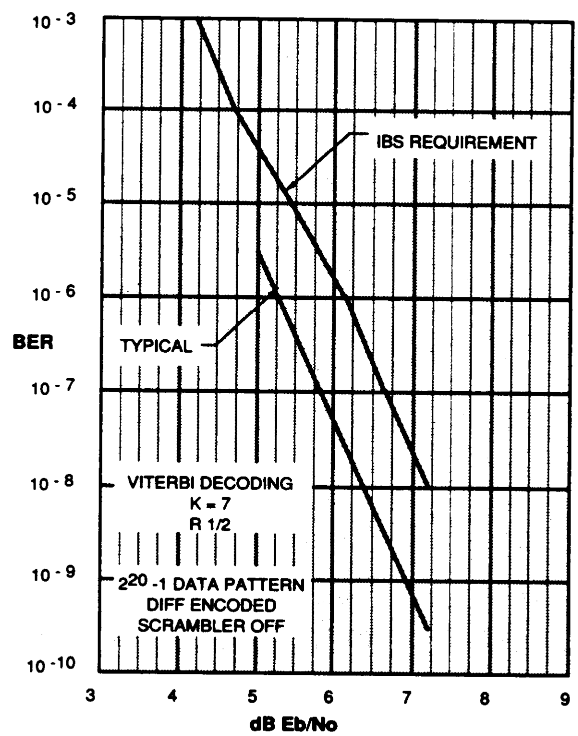


Figure 5 - 1. Typical Performance of SM290V Modem at 1/2 Rate Coding: (Obtained from Fairchild Data Corporation product literature on the SM290V Satellite Modem.)

Table 5 - 11. Link Analysis for 48 kbps QPSK Hub Station-to-Remote Land Mobile Station Transmission with 1.2 meter Receive Antenna

Antenna/Station	
Uplink Antenna:	SBS 5.5 meter
Downlink Antenna:	1.2 meter
Transmitting Earth Station:	Virginia Tech - Blacksburg, VA
Receiving Earth Station:	Land Mobile
Uplink	
Earth Station Transmitted Power	-10.13 dBW
Waveguide Loss	0.17 dB
Earth Station Antenna Gain	56.72 dB
Antenna Pointing and Polarization Loss	0.50 dB
Atmospheric Attenuation	0.50 dB
Free Space Loss	207.08 dB
Transponder Antenna Gain	31.99 dB
Transponder Carrier Level	-129.67 dBW
Transponder Noise Power	-151.85 dBW
Transponder C/N	22.18 dB
Downlink	
Satellite EIRP With Backoff	15.24 dBW
Free Space Loss	205.57 dB
Atmospheric Attenuation	0.50 dB
Antenna Pointing and Polarization Loss	0.50 dB
Earth Station Antenna Gain	41.40 dB
Waveguide Loss	0.20 dB
Earth Station Carrier Level	-150.13 dB
Earth Station Noise Power	-158.86 dB
Earth Station C/N	8.73 dB
Overall C/N	8.53 dB

Table 5 - 12. Rain Fade Performance Analysis for 48 kbps QPSK Hub Station-to-Remote Mobile Station Transmission with 1.2 m Receive Antenna

Uplink Fade	Overall E_b/N_o	Final BER	Downlink Fade	Overall E_b/N_o	Final BER
0.0	6.98	7.39×10^{-4}	0.0	6.98	7.39×10^{-4}
1.0	5.98	2.27×10^{-3}	1.0	5.17	4.62×10^{-3}
2.0	4.98	5.39×10^{-3}	2.0	3.62	1.51×10^{-2}
3.0	3.98	1.17×10^{-2}	3.0	2.22	3.19×10^{-2}
4.0	2.98	2.31×10^{-2}	4.0	0.94	5.20×10^{-2}
5.0	1.98	3.51×10^{-2}	5.0	-0.28	7.75×10^{-2}

Uplink Fade	Downlink Fade	Overall E_b/N_o	Final BER
0.0	0.0	6.98	7.39×10^{-4}
0.0	1.0	5.17	4.62×10^{-3}
0.0	2.0	3.62	1.51×10^{-2}
0.0	3.0	2.22	3.19×10^{-2}
1.0	0.0	5.98	2.27×10^{-3}
1.0	1.0	4.17	1.02×10^{-2}
1.0	2.0	2.62	2.71×10^{-2}
1.0	3.0	1.22	4.69×10^{-2}
2.0	0.0	4.98	5.39×10^{-3}
2.0	1.0	3.17	2.05×10^{-2}
2.0	2.0	1.62	4.05×10^{-2}
2.0	3.0	0.22	6.61×10^{-2}
3.0	0.0	3.98	1.17×10^{-2}
3.0	1.0	2.17	3.26×10^{-2}
3.0	2.0	0.62	5.80×10^{-2}
3.0	3.0	-0.78	8.98×10^{-2}

All values except bit error rate are in dB.

Table 5 - 13. Link Analysis for 48 kbps QPSK Land Mobile Station-to-Hub Station Transmission

Antenna/Station	
Uplink Antenna:	1.2 meter
Downlink Antenna:	SBS 5.5 meter
Transmitting Earth Station:	Land Mobile
Receiving Earth Station:	Virginia Tech - Blacksburg, VA
Uplink	
Earth Station Transmitted Power	-4.76 dBW
Waveguide Loss	0.20 dB
Earth Station Antenna Gain	42.92 dB
Antenna Pointing and Polarization Loss	0.50 dB
Atmospheric Attenuation	0.50 dB
Free Space Loss	207.08 dB
Transponder Antenna Gain	31.99 dB
Transponder Carrier Level	-138.14 dBW
Transponder Noise Power	-151.85 dBW
Transponder C/N	13.71 dB
Downlink	
Satellite EIRP With Backoff	6.77 dBW
Free Space Loss	205.57 dB
Atmospheric Attenuation	0.50 dB
Antenna Pointing and Polarization Loss	0.50 dB
Earth Station Antenna Gain	55.25 dB
Waveguide Loss	0.17 dB
Earth Station Carrier Level	-144.72 dB
Earth Station Noise Power	-158.85 dB
Earth Station C/N	14.13 dB
Overall C/N	10.90 dB

Table 5 - 14. Rain Fade Performance for 48 kbps QPSK Land Mobile Station-to-Hub Station Transmissions

Uplink Fade	Overall E_b/N_o	Final BER	Downlink Fade	Overall E_b/N_o	Final BER
0.0	9.35	1.55×10^{-5}	0.0	9.35	1.55×10^{-5}
1.0	8.35	9.77×10^{-5}	1.0	8.36	9.70×10^{-5}
2.0	7.35	4.42×10^{-4}	2.0	7.36	4.37×10^{-4}
3.0	6.35	1.60×10^{-3}	3.0	6.36	1.59×10^{-3}
4.0	5.35	3.96×10^{-3}	4.0	5.37	3.91×10^{-3}
5.0	4.35	8.86×10^{-3}	5.0	4.37	8.75×10^{-3}

Uplink Fade	Downlink Fade	Overall E_b/N_o	Final BER
0.0	0.0	9.35	1.55×10^{-5}
0.0	1.0	8.36	9.70×10^{-5}
0.0	2.0	7.36	4.37×10^{-4}
0.0	3.0	6.36	1.59×10^{-3}
1.0	0.0	8.35	9.77×10^{-5}
1.0	1.0	7.36	4.39×10^{-4}
1.0	2.0	6.36	1.59×10^{-3}
1.0	3.0	5.36	3.92×10^{-3}
2.0	0.0	7.35	4.42×10^{-4}
2.0	1.0	6.36	1.60×10^{-3}
2.0	2.0	5.36	3.93×10^{-3}
2.0	3.0	4.36	8.78×10^{-3}
3.0	0.0	6.35	1.60×10^{-3}
3.0	1.0	5.36	3.94×10^{-3}
3.0	2.0	4.36	8.80×10^{-3}
3.0	3.0	3.36	1.80×10^{-3}

All values except bit error rate are in dB.

the received data. In refering to these tables, acceptable performance is maintained during uplink only and downlink only rain fades of 4 dB. These fades correspond to a link outage of 12.3 hours in one year. Forward error correction as mentioned in Section 5.1.2 can reduce the received bit error rate and decrease the probablilty of link outage. With a 5.2 dB theoretical coding gain from 1/2 convolutional coding, the the probablilty of link outage can be reduced to 74 minutes in one year [19], [24].

5.1.9 Summary

This subsection summarizes the network configurations described in this section.

Compressed digital video can be broadcast throughout Virginia to extension locations already equipped with 2.75 meter (9 foot) diameter antennas. Received bit error rates less than 10^{-6} can be obtained with forward error correction as long as uplink only and downlink only rain fades do not exceed 8 dB and 7 dB, respectively. Installation of a 5.5 meter antenna at the Equine Medical Center in Leesburg, Virginia, also can allow the Northern Virginia Graduate Center to receive compressed video. Without forward error correction received bit error rates less than 10^{-6} can be obtained during uplink only or downlink only rain fades up to 7.4 dB. A terrestrial microwave link would carry the received signals from the EMC to the Graduate Center.

T1 Transmission of high definition medical X-rays from the Equine Medical Center to Virginia Tech is possible with the aid of video scanners and image capture add-on boards for a personal computer. Image transmission will allow radiologists at the College of Veterinary Medicine to examine X-rays for expedient diagnosis of medical problems. The performance of this network is the same as the performance of T1 compressed television transmissions.

Participation in a satellite token ring network linking Virginia Tech to the Continuous Electron Beam Accelerator Facility (CEBAF) in Newport News, Virginia, offers another possible application. Because token rings have not been developed for use with a satellite communications network, further investigation is necessary before implementing such a system.

A statewide VSAT network carrying digital text and pictorial information is possible for stations located throughout Virginia that are equipped with 1.8 meter antennas. Bit error rates less than 10^{-6} for hub station-to-remote station transmission can be obtained using 1/2 rate convolutional coding for uplink only and downlink only rain fades of 6 dB and 4 dB, respectively. Remote station-to-hub station transmissions acheive this bit error rate for uplink only and downlink only rain fades up to 4 dB. Investigation of network protocols and system throughput is necessary before implementing such a system.

Land mobile earth station experiments can be performed using the proposed facility at Virginia Tech. Each mobile station equipped with a 1.2 meter diameter antenna can receive digital transmissions to study multipath propagation effects. Bit error rates less than 10^{-6} can be obtained for uplink only and downlink only rain fades up to 4 dB.

Monitoring environmental conditions through the eastern United States is possible by equipping existing remote stations with a 1.8 meter antenna and a digital modem. These stations may be used either to monitor conditions affecting crop growth or provide an early warning system during periods of potential flooding. The performance of these stations is the same as the remote station-to-hub station transmissions in a VSAT network.

Experiments with spread spectrum communications and techniques at Ku-band can be performed with the proposed facility at Virginia Tech. Before experimentation is possible, additional investigation into various techniques are needed.

5.2 Cost Considerations

5.2.1 Bandwidth versus Cost

The usable frequency spectrum for satellite communications is limited. For Ku-band commmunications with SBS satellites the carrier frequencies typically extend from 14.025 GHz to 14.466 GHz for transmitting stations and from 11.725 GHz to 12.166 GHz for receiving earth stations. Hence, all communications traffic one-way at Ku-band must lie within a bandwidth of about 500 MHz. However, with the exception of spread spectrum communications, in order for any intelligible information to be obtained at a receiving earth station, little or no overlap of the frequency spectrum of other signals can be allowed within the bandwidth of a desired signal. All transmitted signals from earth stations, in turn, are restricted to specific frequency "slots". The carrier frequency and bandwidth of each "slot" may vary somewhat from one transponder to the next in a satellite.

A satellite broker sells time for the use of frequency "slots" in a transponder of a satellite. A typical satellite offering Ku-band service has 16 transponders which can carry about 54 MHz of contiguous bandwidth each [49]. (SBS satellites only have 10 transponders carrying 43 MHz each.) Wideband transmissions such as full transponder or half transponder analog video take up a large portion of a transponder's bandwidth during a single transmission. Narrowband transmissions such as T1 digital data take up a relatively small portion of a transponder. A single transponder can provide simultaneous service for many narrowband transmissions. Since the use of a wideband broadcast precludes other stations from using much if not all of a particular transponder during a single transmission, a broker will charge a wideband user more money than a narrowband user. Smaller transmitted bandwidth typically result in lower operating costs for satellite transponder use. The operating cost for satellite service using narrowband digital transmissions, in turn, becomes very attractive in comparison to the operating costs for wideband analog transmissions.

Consider the following break even analysis between narrowband digital transmission and wideband analog transmissions. Initial first costs associated with a digital system are high compared to those of an analog system, but this cost difference is offset by differences in the cost of transponder use. Currently, the lowest priced codec providing compressed video costs about $26,000 each. Analog television modulators typically cost around $15,000. Compressed digital television transmission, however, requires much less bandwidth, and hence, a smaller portion of a satellite transponder. Transponder time for full duplex T1 links cost about $26 per hour, whereas half trasponder analog video at Ku-band costs approximately $350 per hour. With only 34 hours of transmission time, the T1 television system becomes a less expensive means of transmitting point-to-point video.

A similar cost analysis can be perfomed for more than one receiving station. The break-even point for ten receiving earth stations occurs after 340 hours of operation. The break-even point for twenty earth stations occurs after 679 hours. Figure 5-2 depicts the break even characteristic for wideband versus narrowband transmissions. As the amount of transmit time for a given number of stations increases beyond the break even point, the operating costs for wideband transmissions exceed the costs for narrowband transmissions. Hence, T1 video transmissions become more cost efficient.

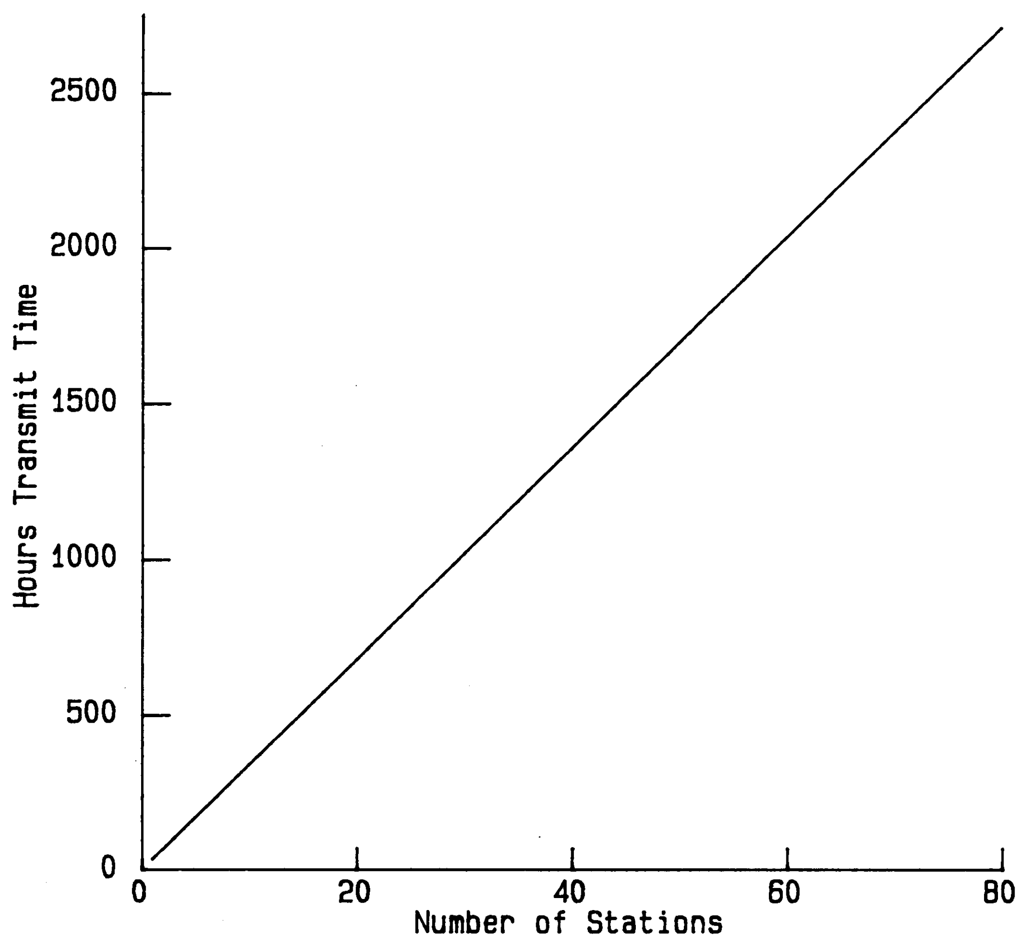


Figure 5 - 2. Break Even Point for Hours of Transmit Time versus Number of Stations for T1 Digital Video versus Analog Video Transmissions

5.2.2 T1 Video Transmissions to the EMC

In this section costs incurred in configuring the earth station at the Equine Medical Center (EMC) in Leesburg, Virginia are considered. All prices mentioned here are approximate.

First, consider the costs in constructing the earth station facility in Leesburg. The antenna, modulating equipment and shelter have already been purchased; they are not included here. Due to the location of the EMC in relation to Washington, D.C., civil engineering costs are significantly higher than costs in Blacksburg. After the foundation pad is poured, approximately 650 man hours of construction and testing time are expected in assembling the earth station. The price of a digital modem is also somewhat elevated in order to provide capabilities for 1/2 rate convolutional coding, remote control, and performance at several bit rates.

Fixed Costs

Item	Price
Civil Engineering Costs	$20 000
Construction Labor	16 200
Video Codec	26 000
Digital Modem	8 500
Miscellaneous (labor, cables, and parts)	20 000
	$90 700

The following list contains some of the approximate costs that can be expected through the first year of operation. The transponder costs are determined by estimating 950 hours of transmit time at $26 per hour for use of the transponder. Labor for maintaining operation of the equipment may take up to 400 hours during the first year. Utility costs are based on a rate of 6 cents per kilowatt hour.

Operating Costs

Item	Price
Transponder Time	$25 000
Labor (maintenance)	6 000
Utilities	200
Miscellaneous Costs	500
	$31 700

5.2.3 Medical Image Transmission

The costs presented in this section are additional to those presented in the previous section. The material presented here is based on the assumption that the earth station in Leesburg is operational for T1 transmissions.

Item	Price
Personal Computer	$5 000
2 MB Hard Disk	1 000
Image Capture Add-on Board	2 500
Support Software	400
Video Camera	1 500
Miscellaneous Supplies and Cables	200
	$10 600

With recent developments in image processing and graphics systems hardware, image capture add-on boards can be found at variety of prices. The cost of a desired add-on board may vary significantly from one company to the next.

5.2.4 Remote Station Configuration

The costs presented below apply to the configuration of both new VSAT stations and environmental monitoring stations.

Item	Price
1.8 meter Antenna with receive RF equipment	$11 500
Modulation Equipment	2 000
Digital Modem	8 500
Personal Computer	5 000
Digital Buffer	100
Miscellaneous Supplies	1 000
	$28 100

An operational VSAT station will also need the following items:

Item	Price
Graphics Printer	$ 500
Facsimile Machine	1 500
Cables	100
	$2 100

The hub station computer should also be equipped with a 2 MB Hard disk memory expansion module.

5.2.5 Land Mobile Stations

The costs presented below apply to new equipment puchases necessary for land mobile/satellite communications experiments.

Item	Price
1.2 meter Antenna with RF equipment	$9 500
Modulation Equipment	2 000
Digital Modem	8 500
Personal Computer	5 000
Digital Buffer	100
Small Trailer to Pull Antenna	500
Miscellaneous Supplies	2 000
	$27 600

5.3 Recommendations for Network Development

5.3.1 Suggested Configurations

The following subsection proposes development of several networks based on the analyses of the network configurations presented in Sections 5.1 and 5.2. The configurations in this section have been selected for development based on technical feasibility and the user costs.

As far as equipment recommendations are concerned, the digital modem selected for operation at any facility should be able to implement 1/2 rate convolutional coding. Coding is necessary to maintain link availability in the presence of rain attenuation. The modem also should be able to operate at a variety of bit rates. The bit rates specified in this document have been T1 (1.544 Mbps), 56 kbps, and 48 kbps.

Transmission of T1 compressed video from Virginia Tech remains a principal application for the facility in Blacksburg. An Extension Office already equipped with a 2.75 meter diameter antenna can receive transmissions after purchasing and installing a Ku-band feed. Although the digital codec required for each station costs more than a FM television demodulator, the point-to-point operating costs for digital T1 transmissions are more attractive compared to those of half transponder analog video. The break even point of FM television versus T1 compressed video for point-to-point transmission occurs after 34 hours of transmission time. The break even point increases by approximately 34 hours for each station added to the television network. (See Section 5.2.1.)

Implementing a statewide VSAT network is another possible use for the Virginia Tech facility. Configuring the earth station at the Virginia Tech teleport to operate as a hub station in a satellite based star network can provide a digital communications network serving Extension locations and Government offices throughout the state. Implementation of a digital network can help reduce costs associated with inter-office communications. For a network containing many stations the operating costs for a satellite network are lower than those for leasing many dedicated terrestrial lines, particularly if the stations are very far apart [29]. The recommended configuration for this network involves 56 kbps tranmissions to VSAT stations equipped with 1.8 meter diameter antennas. The operational modem suggested for this network employs 1/2 rate convolutional coding to reduce link outage during periods of heavy rain fading. Extension stations already equipped with a 2.75 meter diameter antenna can receive transmissions without having to procure a new antenna; however, these antennas still have to be equipped with a Ku-band feed. The approximate costs to configure each VSAT station are given in Section 5.2.4.

Environmental monitoring stations also may be incorporated into an operating VSAT network. These stations can provide a vast amount of environmental and weather data gathered throughout the eastern United States. Collecting and assimilating large amounts of data also can be helpful in analyzing the dynamic behavior of an operating VSAT network. The approximate cost for each remote terminal is given in Section 5.2.4.

An area of research which uses the Virginia Tech facility involves an investigation of land mobile satellite communications. These experiments, as discussed in Section 4.6, would investigate multipath propagation and shadowing effects at 12 GHz. Results obained from these experiments can help determine the feasibility of mobile station digital communications at Ku-band. Each station should be configured with a 1.2 meter diameter antenna and operate at 48 kbps. Transmissions should implement 1/2 rate convolutional coding to reduce link outage during periods of rain fading. Approximate costs associated with configuring these stations are given in Section 5.2.5.

5.3.2 Further Development

The hardware components required for transmission of compressed digital video are such that once the equipment is purchased and configured, the network can be operational immediately. Since transmission of compressed digital television is a form of a point-to-multipoint broadcast data network, a network designer is not concerned with network access for transmitting data and station addressing for receiving data. Consequently, no further development concerning television or image transmissions are presented in the remainder of this text.

However, development of network access strategies and alogorithms for controlling the flow of data among stations is required to successfully implement a VSAT network. Multiple access strategies for a shared remote-to-hub transmission channel must be investigated. Control algorithms also must be developed to specify procedures for processing data packets transmitted and received by all network stations. Specific strategies need to be developed for retransmission of data packets corrupted by noise and interference. Topics concerning any further development required to implement a VSAT network are discussed the remaining chapters of this text.

Chapter 6: Operation of the VSAT Stations

6.1 Hub Station Services

This section reviews the network requirements that affect the design of a VSAT network. These network requirements were described briefly in Chapter 2 and are summarized in Table 6-1. The VSAT network described subsequent sections of this chapter is designed to meet the requirements presented in this section.

The communications anticipated between the Virginia Tech Extension offices consist of file transfers between stations. The content of each file can consist of news items and information on current Extension activities in various regions of Virginia. Personal computers can send and store text information in an ASCII format. Facsimile machines can send and receive photographic and pictorial information in a binary format.

Similar traffic is anticipated among Virginia state government offices. An example of state government communications is transmission of logistics and progress reports from road crews located throughout the state. Text information can be sent and received with a personal computer, and pictorial information can be exchanged with a facsimile machine.

The environmental stations are expected to transmit one page of text information per transaction. All information can be stored by a personal computer before transmission. Each transmission from a station can occur once per day.

Because of the three distinct groups of users in this network, the network design presented in the following sections considers the needs of three subnetworks. As shown in Table 6-1, the requirements placed by the Extension office and the government office subnetworks are similar. The major difference between these two subnetworks is the terminal addressing and channel access scheme used in station-to-station communications. Each station in these subnetworks can send files to any other station in the two subnetworks. Interactive communication between these stations is not required. The environmental stations' subnetwork transmits data to the hub station only. No method for communicating with stations in the other subnetworks is necessary.

Table 6 - 1. VSAT Station Summary

Subnetwork	Estimate Number	Data Type	Estimated Bytes/Transaction
Virginia Tech Extension Offices	54	Text, Facsimile	10^4
Virginia State Government Offices	50	Text, Facsimile	10^4
Remote Environmental Stations	30	Text	10^3

6.2 Packet Communications Overview

Telecommunications in a wide area satellite network uses either circuit-switching or packet-switching techniques. Circuit-switched networks provide a direct, time continuous connection between two users. Even if no data are transmitted, a connection in a circuit-switched network is maintained until one station breaks the connection in the link. Circuit-switched networks are suitable for analog communications or digital communications where large amounts of data are transmitted on a continual basis. Circuit-switched networks, however, are inefficient when carrying digital communications between stations that do not transmit data continually.

The anticipated communications traffic in the VSAT network described in this chapter occurs at high peak-to-average, or "bursty," traffic rates. A packet-switched network is designed to carry messages in networks characterised by bursty traffic rates.

In packet-switched networks a transmitting station groups together digital data into blocks of bits, or packets. This station transmits packets to a node where they are stored temporarily before being forwarded to another node. This store-and-forward operation continues until the packets arrive at their proper destinations. Data describing the destination address is contained within each packet to ensure proper routing of the data.

Packet-switched communications can establish either a *datagram* service or a *virtual circuit*. With a datagram service each transmitted packet contains a complete set of data required for message transfer. Datagram service is applicable for point-of-sale transactions such as the brief data exchanges between an automatic teller and a computer. In the VSAT application described in this chapter, sending a complete message requires transmission of more than one packet. The packet-switched network establishes a virtual circuit in which the order of the transmitted packets is maintained through the network. Station-to-station communications appears to exist through a circuit-switched network, but since a constant link is not maintained between the transmitting and receiving station, other stations also may send packets through the same nodes of the network.

A virtual circuit can be implemented as either a switched virtual circuit (SVC) or a permanent virtual circuit (PVC) [38]. A switched virtual circuit maintains a temporary virtual circuit between two stations. It is initiated by the transmitting station sending a call request packet. A permanent virtual circuit is analgous to a point-to-point dedicated line. Call requests are not necessary with a permanent virtual circuit.

The VSAT network described in this document uses packet-switching techniques to establish both switched virtual circuits and permanent virtual circuits. Switched virtual circuits allow individual stations in the Extension office and government office subnetworks to communicate with other individual stations. Permanent virtual circuits maintain a link between the environmental monitoring stations and the hub station.

Typically, a packet-switched network enables transfer of data among many stations through the store and foreward operation of several nodes; however, a VSAT network uses only one node. The intermediate node for the network described here is the hub station in Blacksburg, Virginia. Because all transmitted packets pass through a single node, the network can be pictured as a star network as shown in Figure 6-1. In network terminology each remote station is known as the *data terminal equipment* (DTE), and each network node is known as the *data communication equipment* (DCE) [44]. In a VSAT network each DTE assembles packets and transmits them to a central DCE. The DCE then transmits received packets to all the network DTEs. Packets designated for reception at certain stations are dissassembled by the specific DTEs. All DTEs transmit in one shared inbound channel. The DCE transmits in one broadcast outbound channel.

Packet transmission in a star satellite network can be controlled by either polling or contention techniques. Polling of all the VSAT stations by the hub station, however, is time inefficient. Stations ready to transmit packets must wait until all previous stations in the polling sequence respond to the hub poll. Polling techniques require poll requests and acknowledgements to enable transmission of each packet. Because each request and acknowledgement for each station experiences a single hop propagation delay through the satellite, the overall network communication delays can become very large.

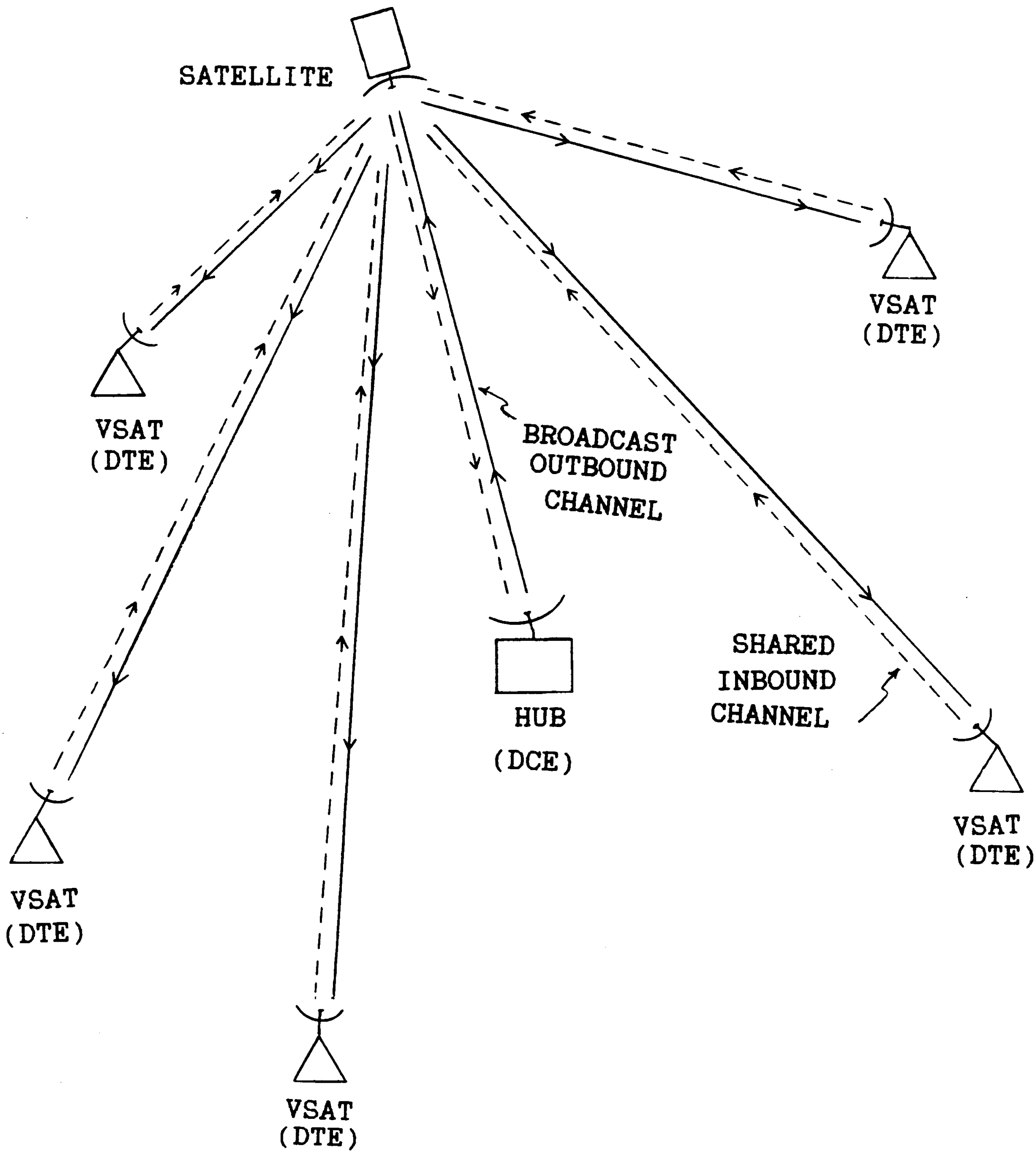


Figure 6 - 1. The VSAT Star Network

Contention techniques can alleviate the delays inherent in a polling stategy. Using a pure contention strategy, a station transmits packets as soon as they are assembled. This strategy significantly reduces overall network delays because each station does not have to sit idle until a request to transmit is received from the hub station. With no polling synchronization the packet transmissions from VSAT stations occur as random time events. Contention introduces the probability that data packets can be corrupted when two or more stations transmit at the same time.

In accounting for packet collisions, the overall throughput, or the percentage of packets transmitted sucessfully, becomes a concern to the network designer. As the number of corrupted packets increases, the rate of packet retransmission and overall network delays increase. Consequently, a second concern for the network designer is the stability of the network, or the susceptibility of a network to experience very long delays due to packet retransmission. A very stable network is desirable, but the trade-off for network stability is typically an increase in the complexity of the employed multiple access system. Stations in a network also must transmit and identify packets in a manner consistent with the other network stations. Consequently, a designer must devise a strategy to allow stations to access the network and develop a standard to control the flow of information among the stations in the network.

6.3 The Seven Layer ISO Model

Communications among the stations occurs in the form of transmitted individual packets. The means of transferring this information must obey a protocol used by all the stations in the network. It is desirable to implement a standardized protocol because it allows the network to expand and provide service to users in other networks that use the same protocol. A widely used packet-switching protocol may allow interfacing with another network more easily than a nonstandard protocol.

One popular protocol scheme is based on a model for Open Systems Interconnection (OSI) developed by the International Standards Organization (ISO). The Seven Layer ISO model depicted in Figure 6-2 makes use of specific protocols recommended by the Consultative Committee for International Telegraph and Telephone (CCITT).

Sucessive layers in the model are ordered according to their application specific nature and level of abstraction above an actual physical connection. Each layer in the model is intended to add value to the more primitive operations performed in the lower layers, and is designed to perform independent of the other layers in the model [15] . To the network user, exchanges of control and information appear to traverse a network between layers having the same number. During actual network operation, however, OSI level operations pass through all lower layers in the model until an information exchange occurs at a physical connection [4].

A brief description of each layer and its relevance to implementing a VSAT network is provided below. The individual layers described in the following pages are described in more detail in [4] and [15] .

Level 1: Physical Layer

This layer establishes the electrical, and mechanical requirements for the maintenance and release of binary information. The physical connection and means of transferring information are specified. No significance is placed upon any bit values. Signal carrying lines are specified between the the data communications equipment (DCE), or node, and the data terminal equipment (DTE), or station. A common physical connection is made with an RS232-C connector based on the CCITT V.24 or X.21 standard.

In a VSAT network stations transmit packets at Ku-band to a hub station after passing through a satellite transponder. The stations in the network described here transmit at 56 kbps using QPSK modulation.

Level 2: Link Layer

The ISO model specifies that this layer provides an error-free virtual connection over the error prone physical layer. The link layer performs error detecting and correcting on exchanged data. This level also provides flow control so that a receiving station or a node can control the rate of data flow. Messages are exchanged accross the link layer in the form of *frames*.

Flow control procedures utilize the CCITT recommeded X.25 level 2 protocol which is compatible with the high-level data link control (HDLC) procedures standardized by the ISO [38]. The HDLC procedures work to establish a virtual connection, or link, between a DTE and DCE. These procedures specify guidelines for frame transmission, acknowledgement, and possible retransmission. Once a link is established, packet transfer in several virtual channels can occur. HDLC also performs error detection using a sixteen bit frame check sequence. If an error is detected, the receiving node or station discards the data in the transmitted frame, and the transmitting station retransmits the information.

In a VSAT network some bit error detection and correction is performed by the operating digital modem. Data flow control also is determined by the operating network access strategy. Possible network access techniques are described in Section 6.4.

Level 3: Network Layer

Building upon the low level flow control of the second layer, the third layer establishes logical channels between stations within a network. Information transfer at this level occurs in the form of packets. Specific channels associate the addresses of network stations with the contents of a packet. Packets also contain control and acknowledgement information to ensure that stations receive the correct data.

Network layer operation is enabled through the CCITT recommended X.25 level 3 packet-switching protocol. This protocol establishes logical channels that carry data between two DTEs accross a network. This procedure specifies guidelines for packet transmission, acknowledgement, and retransmission. Procedures for sequential transfer of data packets in a virtual circuit also are specified.

In a VSAT network many remote stations communicate through a central node at the hub station. Each packet from a VSAT station contains logical channel information specifying which other VSAT stations in the network can receive the transmitted message. Data flow and acknowledgement of transmitted packets are governed by the hub control software. Further description of the transmitted packet contents is provided in Section 6.5.

Level 4: Transport Layer

This layer concerns requirements specified by equipment that provide connections between the nodes in a network. The transport level also may specify paths to be taken through a network to provide optimum throughput and lower delays.

There exist five different classes of the transport layer [15]. Class 0 adds extra addressing capability and the ability to segment messages. Class 1 adds sequence numbers to all messages to enable recovery from network level resets or disconnects. Class 2 allows multiplexing of several connections to one station, but does not provide error recovery from resets and disconnects. Class 3 provides both the error recovery and multiplexing of class 1 and class 2. Class 4 adds to class 3 in providing messages with a checksum as well as a sequence number. The class 4 characteristics are the most desirable for a VSAT network [45].

In a VSAT network all messages pass through a hub station. No change in the network path is possible, but multiplexing of data once obtained at a VSAT station is possible. The CCITT X.25 level 3 protocol, however, allows for multiplexing at a station through the use of subaddresses. This protocol also provides sequence numbers for data transfer. The X.25 level 2 protocol also provides a checksum for detection of errors in a received frame. With the implementation of the X.25 packet-switching protocol for VSAT networks, level 4 of the Seven Layer model becomes a null layer [38].

Level 5: Session Layer

This layer sets up services for an operational session between stations. Control at a node specifies whether a DTE or DCE may send data at a given time. This control also provides markers that identify the different phases of a message transfer.

In VSAT network applications this layer identifies the beginning and end of a file transfer. Stations in this network can receive only one file at a time. These control functions are usually provided by the software operating at the hub station [45]. These functions are described in more detail in Section 6.6.

Level 6: Presentation Layer

This layer specifies interpretation of the data by the terminal equipment. In a VSAT network for instance, data must be interpreted as either ASCII characters for use at a personal computer or as binary information for use by a facsimile machine. As with the session layer, this function is provided by the operating control software [45].

Level 7: Application Layer

This layer defines the services required by the network. In a VSAT network this layer performs the packet assembly and disassembly (PAD) operations that allow file transfer between the user equipment at different stations [45]. Like Levels 5 and 6, PAD operations are implemented with the VSAT station control software.

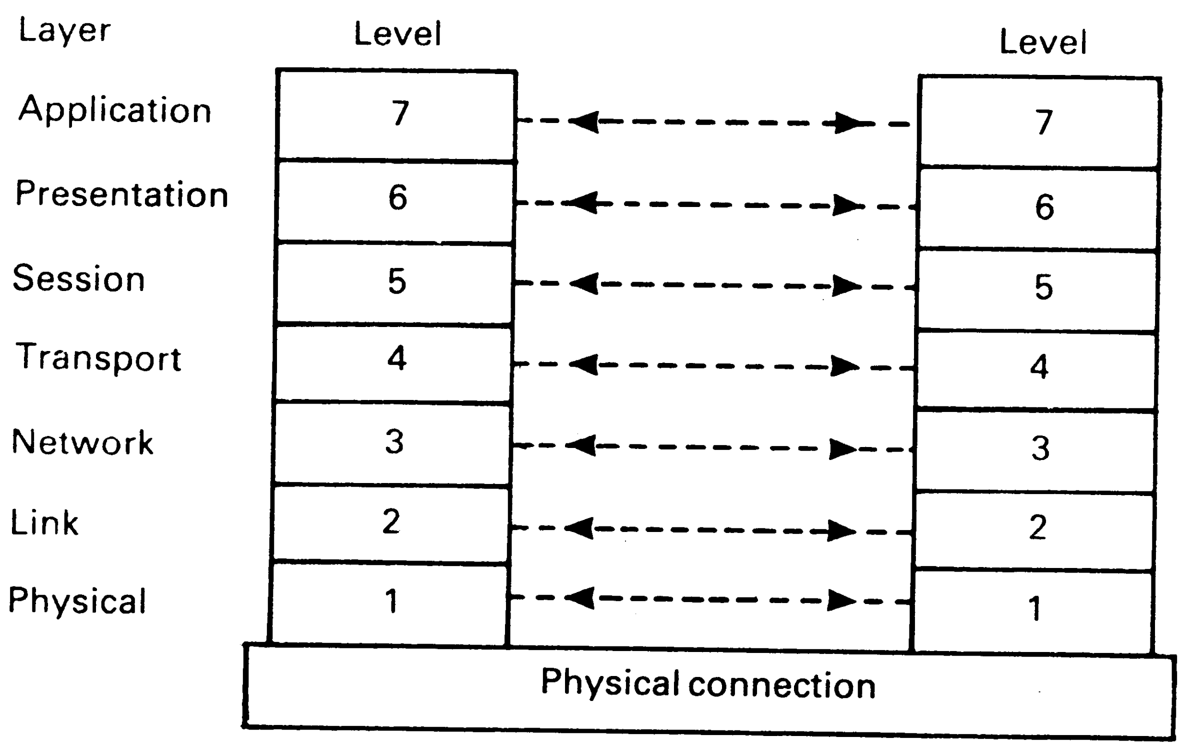


Figure 6 - 2. The Seven Layer ISO Model for Open Systems Interconnection: (Obtained from R. L. Brewster, *Telecommunications Technology*, John Wiley & Sons, New York, 1986.)

6.4 Network Access

6.4.1 Overview

Satellite network access can be classified in one of three types of access strategies: fixed assignment, contention, or reservation access [35] . These types of strategies for satellite network access are described in this section. A summary of the access techniques presented in this subsection is provided in Table 6-2 [9], [35], [33].

6.4.2 Fixed Assignment

The fixed assignment strategies presented in this section currently are not under consideration. They are presented briefly as a basis of comparison against the contention techniques presented later.

Fixed assignment access strategies typically use single channel per carrier frequency division multiple access (SCPC/FDMA) or time division multiple access (TDMA). Each channel carrying data between stations would require a separate allocation of bandwidth. A large amount of bandwidth is required to accomodate many channels.

TDMA is better suited for high speed digital data transmissions, but it requires a great deal of coordination among all the stations in a network. TDMA in a VSAT network makes use of periodic time intervals for station access, the TDMA frame. This frame is divided into many time slots. Each slot is assigned to an earth station in the network. The TDMA frame also consists of reference bursts and guard times separating the time slots. Stations ready to send data must transmit a traffic burst within the time slot assigned to that earth station. Each burst contains preamble bits which carry management and control information.

Table 6 - 2. Summary of Multiaccess Protocol Techniques

Protocol	Maximum Throughput	Stability	Implementation Complexity
TDMA	0.7-0.8	good	high
Aloha	0.13-0.18	poor	very low
Slotted Aloha	0.25-0.37	moderate	low-med
SREJ-Aloha	0.2-0.3	moderate	low
RAN	0.7-0.8	good	high
Roberts'	0.5-0.6	moderate	med
DAMA/TDMA	0.7-0.8	good	high

The complexity in implementing such an access scheme is undesirable for most VSAT networks [35]. TDMA also has a disadvantage in that the time delay for station-to-station communications increases with the number of stations in the network. The traffic throughput with TDMA, however, is very good (around 70 to 80 percent). Traffic congestion is not a major problem in a TDMA network. As the number of transmitted packets increases, the number of filled time slots in the TDMA frame increases until the TDMA frame is saturated. A fixed TDMA network does not collapse when too much traffic is generated by the stations.

6.4.3 Contention Strategies

In a random access strategy many stations contend for the use of a satellite transponder. This contention usually takes place over a small portion of the transponder bandwidth. All stations in the VSAT network described here contend for approximately 40 kHz of a satellite transponder, the bandwidth required to carry 56 kbps QPSK transmissions.

The simplest contention protocol to implement in a satellite network is the Aloha protocol developed by the University of Hawaii. Aloha requires no synchronization among the stations in a system [22]. Stations transmit information packets as soon as they have been assembled. If a packet from one station is corrupted due to a collision with a packet transmitted from another station, the two stations retransmit their respective packets after a random time delay. These time delays are on the order of one second to allow for propagation delay and querying at the hub station [36]. A fixed time delay is not desirable because packet collision would just occur again upon retransmission. An example of pure Aloha operation is shown in Figure 6-3.

As the number of stations in the network grows very large and the random time delay for retransmission is sufficiently large (one second or longer), the arrival of packets at the satellite can be modeled as a Poisson process [22]. Assuming that all packets are of equal length, the probability that k packets will arrive during a time interval of t packet lengths is as follows:

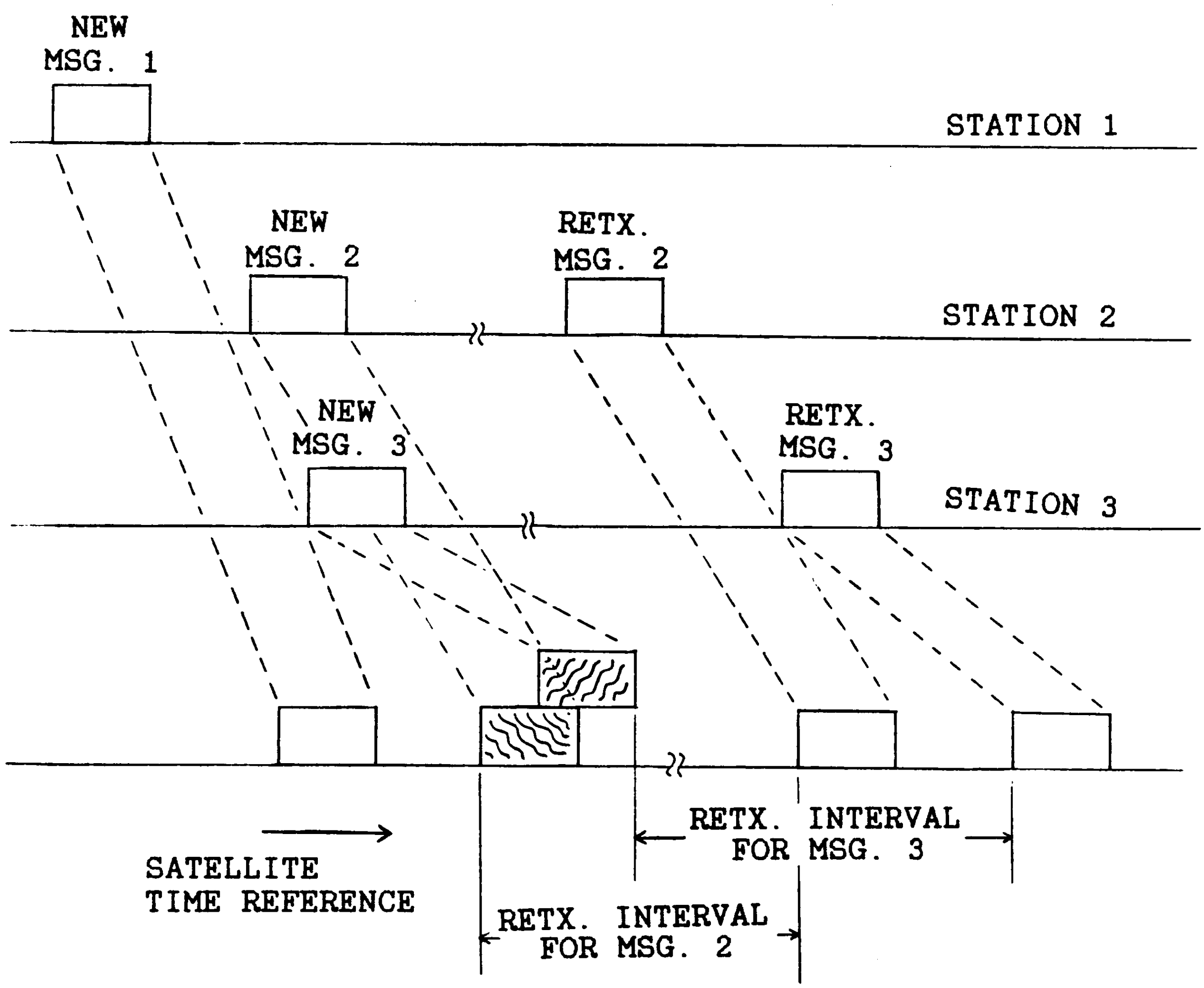


Figure 6 - 3. Pure Aloha Packet Transmission

$$P[k,t] = \frac{(Gt)^k}{k!} \exp(-Gt) \qquad (6-1)$$

where G is the average number of packets arriving in time interval t . In refering to Figure 6-3, packet number 2 is vulnerable to corruption from packet number 3 from the time beginning one packet length before packet 2 to the time at the end of packet 2. The probability that packet number 2 is not corrupted equals the probability that no other data packets are transmitted during a period of two packet lengths.

$$P[k=0, t=2] = \exp(-2G) \quad . \qquad (6-2)$$

The channel throughput S is determined by multiplying the average amount of traffic G by the probability that packets from G units of traffic can be successfully transmitted [22].

$$S_{P-Aloha} = G \exp(-2G) \qquad (6-3)$$

The maximum throughput expected with an Aloha contention protocol is approxmately 18 percent, occurring when $G = 0.5$ packets per time interval. For variable length messages the maximum throughput may be lowered to about 13 percent [35].

Somewhat better throughput performance is obtained by using slotted Aloha. Slotted Aloha differs from pure Aloha in that transmission of packets begins only at regular time intervals. In the event of packet collision, retransmission of corrupted packets occurs after a random number of time intervals. This event is shown in Figure 6-4. The improvement in the throughput of a slotted Aloha protocol is determined upon realizing that packets are successfully transmitted if no other data packets are transmitted within the same time interval. In other words, packet transmissions are either successful or completely overlapped by another packet. By following an analysis similar to the one described with a pure Aloha network access scheme, one can derive the following throughput characteristic:

$$S_{S-Aloha} = G \exp(-G) \quad . \qquad (6-4)$$

which gives a maximum throughput of 36.8 percent at a traffic rate of one packet per packet interval. Because the time slots are used in this access scheme to improve the network throughput, the length of one slotted Aloha packet should not exceed the length of one time slot.

Selective reject (SREJ) Aloha is an unslotted contention strategy in which each packet is subdivided into several fixed length subpackets, each with its own header and acquisision preamble. The advantage of subpacketizing is shown in Figure 6-5. Since random packet transmission among stations usually generates only a partial overlap of the packet data, only the data in the corrupted subpackets need to be retransmitted. The maximum useful throughput with this contention scheme is around 20 to 30 percent, approaching that of slotted Aloha [35] . The disadvantage of SREJ-Aloha is the additional overhead required to transmit each packet.

Additional contention techniques also exist but are not as popular with current Ku-band VSAT networks. Because of the apparent lack of use of these access techniques, they are not discussed in this chapter. Information on other random access techniques can be found in [35].

The stability of a network is an aspect of a contention scheme that requires some attention. A problem presented by the throughput/traffic rate equations shown above is that as the traffic rate passes a critical level, the number of packets requiring retransmission becomes greater than the probable number of packets that can be successfully transmitted. In this situation the network begins to collapse. This concern is discussed further in Chapter 7.

6.4.4 Reservation Access

Dynamic network access protocols have been devised to combine the short delay characteristic of a contention access protocol under low traffic conditions and the stability of TDMA under high traffic conditions. One such dynamic multiple-access protocol is Random Access Notification (RAN) [9]. Using RAN, the shared channel used by the VSAT stations is divided into two parts: a fixed TDMA portion with a dedicated signaling slot for each VSAT station, and a slotted Aloha portion for data transmission. All signaling and data channels are divided into fixed duration

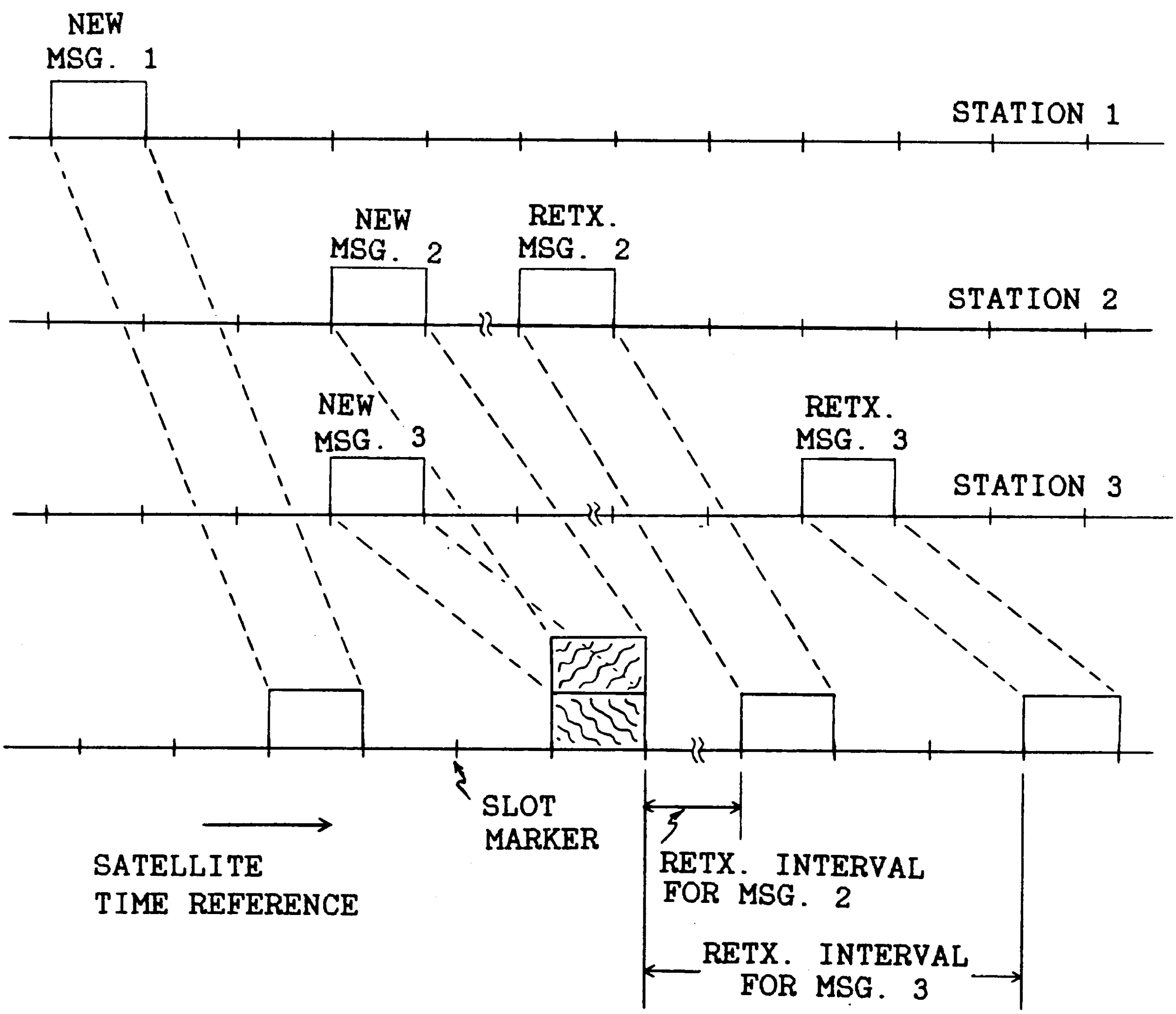


Figure 6 - 4. Slotted Aloha Packet Transmission

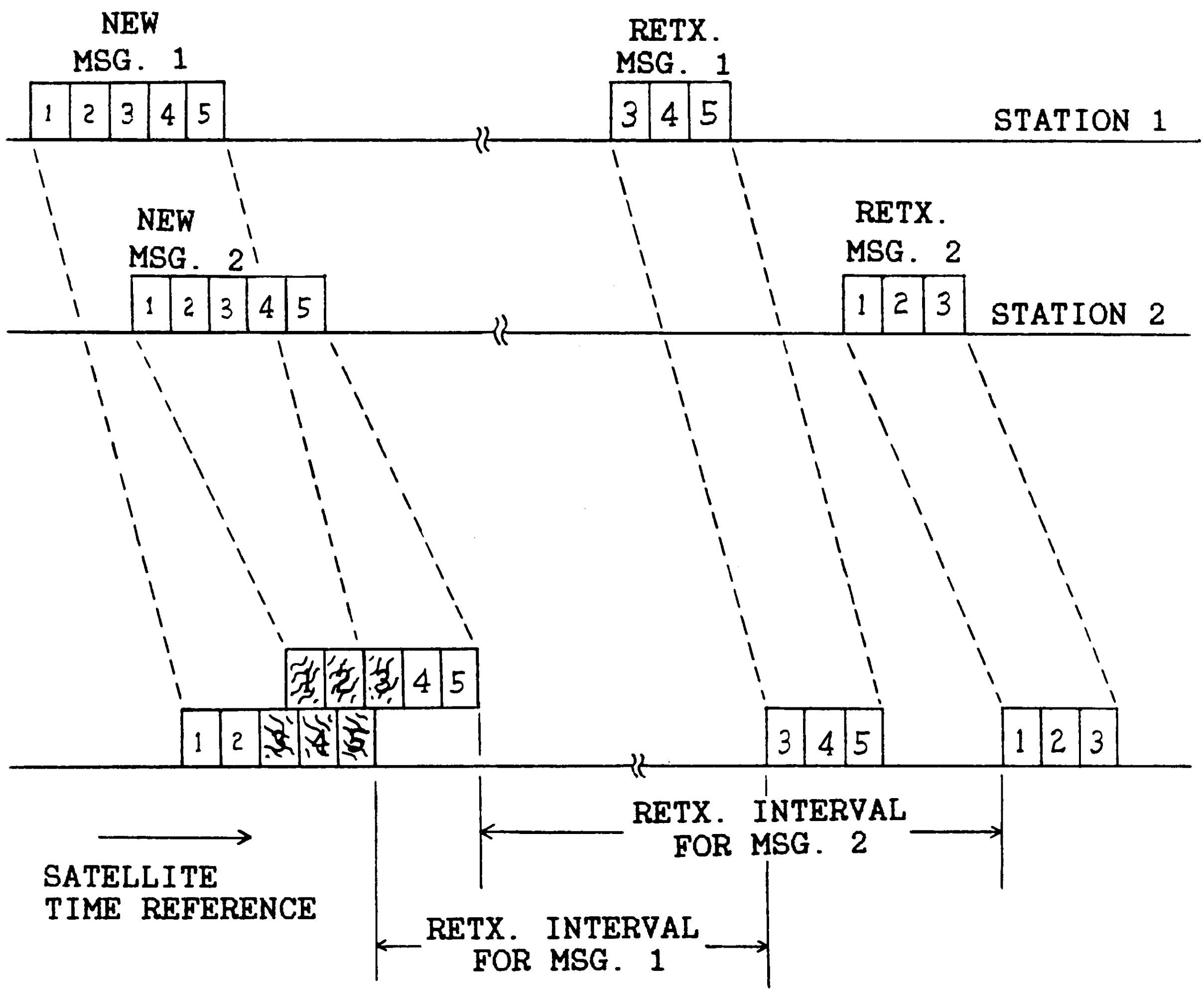


Figure 6 - 5. SREJ-Aloha Packet Transmission

frames. Each frame is subdivided into time slots, and each time slot in the TDMA frame is assigned to a VSAT station. The data channel is divided into D random access slots and R reservation slots as shown in Figure 6-6. The number and location of these slots is controlled by the hub station and is transmitted to the VSAT stations in the TDMA signaling frame.

A VSAT station ready to transmit a packet must wait for the first available random access slot in the data frame. Upon arrival of the slot, the VSAT can begin transmitting. The signaling message sent by the VSAT station then notifies the hub of the number of packets transmitted since the last signaling message.

The hub station determines the optimum number of random access and reservation slots to provide maximum throughput at varying traffic levels. First, the hub station receives information from the VSAT in both the data channel and signaling channel. Upon processing this data, the hub station acknowledges receipt of successfully transmitted packets and then transmits a retransmission schedule for corrupted packets. Packets requiring retransmission are assigned places among the reservation slots in the data channel. As the network becomes congested, the ratio of assigned packets to random access packets increases until all packet in the infomation frame are in reservation slots.

The complexity of this network is high compared to that of the Aloha protocols. However, the advantage of this system is that high levels of communications traffic do not cause the network to collapse. When using the RAN technique, increases in the traffic level cause the network throughput characteristic to change from one similar to slotted Aloha to one like that of TDMA [9].

Another controlled access technique uses a both a TDMA signaling frame and data frame like that mentioned above, except that all slots in the data frame are reservation slots. Stations transmit requests for data transfer in the TDMA frame and receive assignments for data transmissions in the data frame. This technique is known as demand assignment multiple access time division multiplexing (DAMA/TDMA) [33]. Throughput is close to that of TDMA networks.

Another reservation developed by L. Roberts is also used in some VSAT networks [2], [7]. With this scheme the channel can be in one of two states: slotted Aloha and reserved. At start up

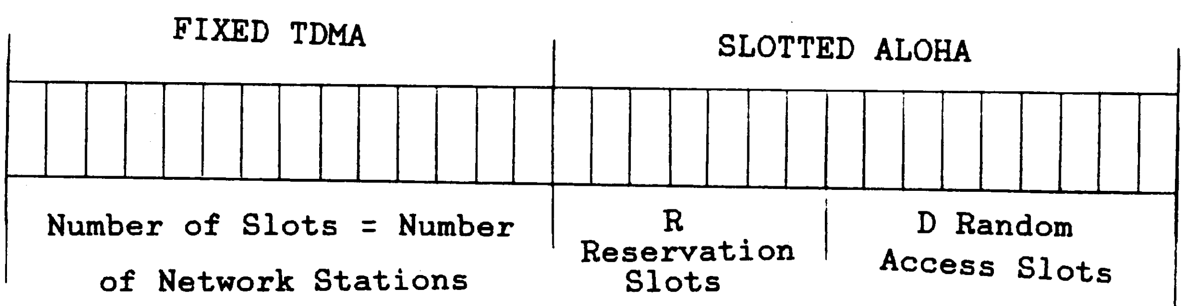


Figure 6 - 6. RAN Packet Transmission

the network is in a slotted-Aloha state. All reservation requests, acknowledgments, and small data packets are sent in this state. If a station then desires a bulk data transaction, it transmits a reservation request which when acknowledged by the hub station allows further transmission of M number of reservation data packets. As shown in Figure 6-7, these reservation packets are large in comparison to the slotted-Aloha packets. After the M reservation slots have occurred, another reservation slot divided into V smaller slots is available. If no more reservations are requested, the network returns to a slotted-Aloha state. As with the previous dynamic access sheme, the overall channel efficiency is increased with an increase in the implementation complexity.

6.4.5 Suggested Access Strategy

Slotted Aloha is suggested here as the technique of choice because of its good throughput performance and relatively low implementation complexity. Because of the fixed packet size limited by the Aloha time slots, slotted Aloha is particularly suited for networks which carry long message transactions such as file transfers [33]. With the anticipated bursty traffic expected in the network, fixed assignment TDMA is unsuitable. Implementation of fixed assignment TDMA is complex compared to other method mentioned in this section, and it is better suited for sustained high traffic rates rather than bursty transmissions. Because the traffic rate generated from any one VSAT station is not expected to be signifcantly greater than any others, a reserved access scheme such as Robert's technique is not necessary. The anticipated performance of this network using slotted-Aloha network access is discussed in Chapter 7.

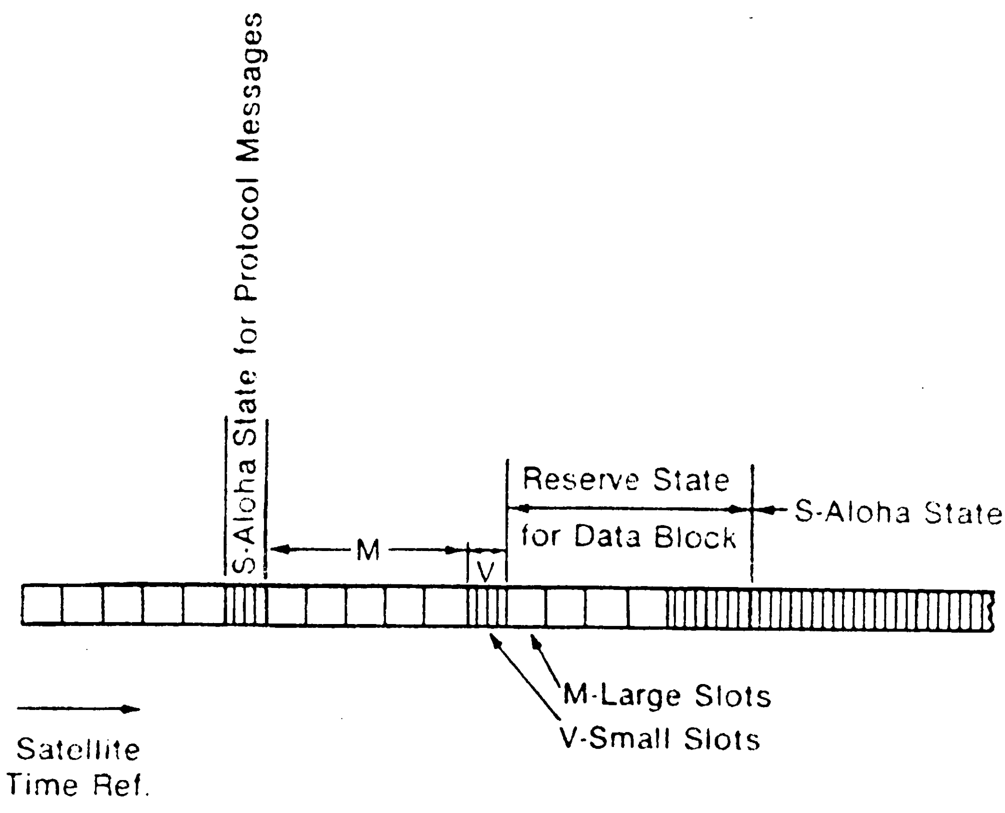


Figure 6 - 7. Roberts' Technique for Packet Transmission: (Obtained from D. Chakraborty, "VSAT Communications Networks -- An Overview," *IEEE Communications Magazine*, vol. 26, no. 5, 1988, pp. 10-23.)

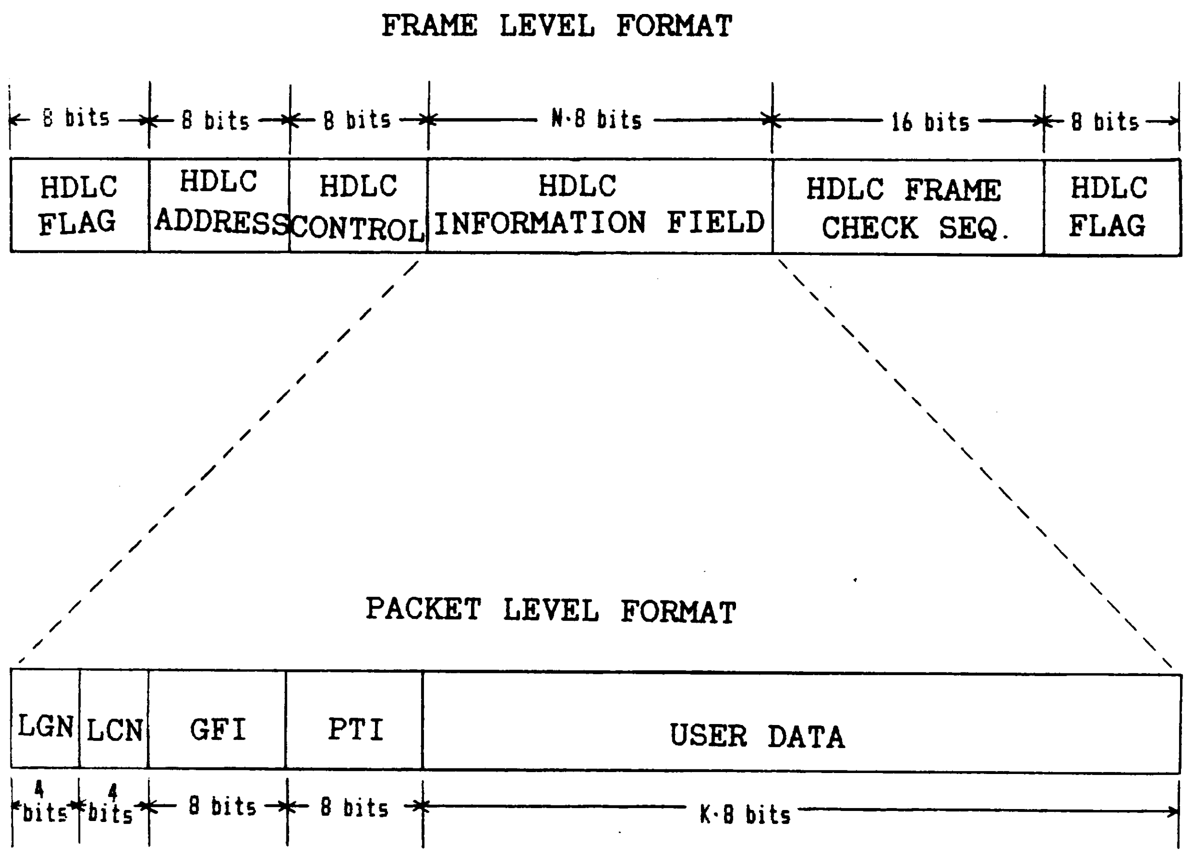
6.5 The Transmitted Frame Structure

6.5.1 X.25 Structure Levels

Sending messages through a packet-switched network ultimately occurs as transmissions of bit streams between terminals and nodes. As mentioned in Section 6.2, these bit streams are transmitted from remote VSAT stations to a central node, or hub station, and then forwarded to another remote VSAT station. This section describes guidelines for message transmission through a network as specified by the CCITT X.25 packet-switching protocol. In particular, this section emphasizes recommendations that apply for data transfer between stations in a network. The transmitted frame structure recommended here is applicable to the VSAT network specified in Section 6.1.

The X.25 protocol specifies system operation over three different levels in the ISO seven layer model [38]. The first level, or physical layer, functions according to the CCITT recommended X.21 or V.24 interface between the terminal equipment and the communications equipment. The second level, or link layer, establishes an error free communications link between a terminal and a node in a network. Message exchanges accross the link layer occur in the form of transmitted frames. The bit stream associated with the frame structure is divided into functional groups at the *frame level.* The general format for transmissions at the frame level is shown in Figure 6-8 [15], [38].

The third level, or network layer, establishes communications between individual users in a network. The portion of the transmitted bit stream associated with the packet format is divided into functional groups at the *packet level.* As mentioned in Section 6.3, each layer in the ISO seven layer model is intended to add value to any lower layers in the model. The network layer value added to the frame level is seen as the packet level information contained in the frame information field. The general packet level format and its relation to the frame level format is shown in Figure 6-8.



LGN = Logical Group Number
GFI = General Format Identifier
LCN = Logical Channel Number
PTI = Packet Type Identifier

Figure 6 - 8. General X.25 Frame Level and Packet Level Formats

6.5.2 Frame Level

The frame format consists of six parts. Each part is compatible with HDLC link control procedures [38]. A flag delimits the beginning and end of each frame. An address identifies frames transmitted between the DCE (data communication equipment) and DTE (data terminal equipment) of a network. A control word specifies the function of a frame. A frame check sequence (FCS) detects errors in the received frame at a node or terminal. The information field, if relevant, contains data pertaining to the current message transaction. Each portion of the frame is described in more detail below.

Flag

The flag words used to delimit an HDLC frame consists of a zero bit followed by six contiguous one bits followed by another zero bit [5], [15], [38]. The hardware or station software at the transmitting station prevents accidental transmission of a delimiting flag by employing a bit stuffing technique: after transmitting five contiguous one bits in a frame, the station equipment inserts a zero bit in the transmitted bit sequence. The hardware or software at the receiving station removes all inserted zero bits within the received frame.

Receipt of a flag provides frame level synchonization across a link. VSAT stations can maintain time synchronization in a slotted Aloha network by monitoring the arrival of individual frames from the hub station. In addition to a slotted Aloha synchronization pattern, the hub station continuously transmits frames on a broadcast SCPC channel at the beginning of every time interval. Transmission of frames from the VSAT stations occur on another SCPC channel at times based upon the arrival times of frames from the hub station.

Address

The address field contains one of two values labeled as either *A* or *B* [8], [15]. These addresses denote the direction of link level commands between the user station (DTE) and the network node

(DCE). The commands are specified with the frame level control word. The binary values of A and B are identified as follows:

$$\begin{aligned} A &= 1100\ 0000 \\ B &= 1000\ 0000 \end{aligned} \qquad (6-5)$$

where the left most bit is transmitted first and the right most bit is transmitted last. Value A is used both for frames containing commands issued from the DCE to the DTE and for responses from the DTE to commands of the DCE. Value B is used for frames containing commands from the DTE to the DCE and for responses of the DCE to commands of the DTE.

Control

Eight different control words specify link level commands and responses between the DTE and the DCE. These eight words are grouped into three formats: information, supervisory, and unnumbered. Information frames provide data transfer accross a link. Supervisory frames control the flow of data transfer. These two frame types contain sequence numbers identifying the order in which frames are transmitted. Unnumbered frames provide additional link control without requiring sequence numberes [15]. A brief description of the types of control words in each format is given below.

Information (I) transfers data accross a link. (Information frame)

Receiver Ready (RR) indicates to the other end of a link that the receiver is ready to accept information frames. (Supervisory frame)

Receiver Not Ready (RNR) indicates to the other end of a link that the receiver cannot accept information frames. (Supervisory frame)

Reject (REJ) requests retransmission of information frames after receipt of a frame that is out of sequence. (Supervisory frame)

Set Asynchronous Balanced Mode (SABM) indicates to the DCE, or network node, that the DTE is ready to establish a link. (Unnumbered frame)

Unnumbered Acknowledgement (UA) acknowledges receipt of an unnumbered command. (Unnumbered frame)

Frame Reject (FRMR) indicates an error condition which cannot be recovered by retransmission of a frame. (Unnumbered frame)

Disconnect (DISC) indicates to the receiver that the sender is ceasing operation of a link. (Unnumbered frame)

The control word for each frame format is encoded as shown in Figure 6-9. Bit one of the encoding scheme is transmitted first, and bit eight is transmitted last.

The poll bit (P) is set whenever a station sends a command which requires a response from equipment at the other end of a link, and the final bit (F) is set in response to a command poll [5]. Typically, the poll bit is set when a frame is retransmitted. Responses to a polled command without having a set final bit are ignored [15].

In most packet-switching networks the order of all transmitted information frames is designated by a sequence number using modulo eight arithmetic. N(R) and N(S) respectively designate the received and sent sequence numbers of a frame. During normal operation, these numbers regulate the flow of data between a single DTE and a DCE.

In a VSAT network, however, dozens of DTE's attempt to establish a link with a single DCE, the hub station. Assigning sequence numbers to all VSAT frame transmissions would restrict message exchanges at the hub. Suppose that two VSAT stations in the network monitoring N(R) and N(S) transmit frames with the same sequence numbers and in two adjacent Aloha time slots. Even if no frame collisions occur, the hub station would issue a frame rejection (REJ command) to the second transmitting VSAT station due to receipt of an out of sequence frame. In addition

Format	Commands	Responses	Encoding 8	7	6	5	4	3	2	1
Information	I		N(R)			P	N(S)			0
Supervisory		RR	N(R)			F	0	0	0	1
		RNR	N(R)			F	0	1	0	1
		REJ	N(R)			F	1	0	0	1
Unnumbered	SABM		0	0	1	P	1	1	1	1
	DISC		0	1	0	P	0	0	1	1
		UA	0	1	1	F	0	0	1	1
		FRMR	1	0	0	F	0	1	1	1

Figure 6 - 9. HDLC Control Field Formats

to the anticipated traffic capacity restricted by frame collisions, the network throughput would decrease as the hub station rejects frames with invalid sequence numbers.

In a VSAT network the frame control field can contain any of the frame control words mentioned earlier except for REJ command since sequence numbers are no longer needed. The RNR command is used by a hub station when its buffer for received frames fills to capacity. At a later time the hub transmits an RR command to notify the remote stations that the hub can receive frame transmissions again. The I command denotes message information transmitted to and from the hub station. The frame bits for N(R) and N(S) in information and supervisory frames are no longer relevant and can be reset to zero. All unnumbered commands are used for link set-up and clear-down procedures.

To describe link level operation, five system parameters are defined as follows [8], [15].

- *Timer T1* is the time period elapsed before retransmission of a frame. It is defined as a time interval greater than the time required to transmit one frame and receive two similar frames while accounting for any propagation delays through the physical link. For VSAT network applications T1 is approximately one second.

- *Timer T2* is the maximum time that may elapse before the DCE sends an acknowledgement to a frame.

- *Timer T3* is the period of time that a DCE must wait for a link set-up command before entering or re-entering the link-down state. Its value is set to T1 times the maximum number of retransmissions N2.

- *Maximum number of bits in a frame (N1)* is specified as 2128 bits for the design presented in this document. This figure accounts for transmission of 256 characters in addition to the frame level and packet level overhead.

- *Maximum number of retransmissions of a frame (N2)* limits the number of times that a station can transmit the same frame. The value of N2 in packet-switching networks can range from three to fifty. For the design presented here, N2 equals fifty.

Link Start-Up

The following paragraphs briefly describe a procedure which establishes a link level connection between a DTE and a DCE in a packet-switched network following HDLC guidelines [15]. The procedure for establishing a link is described in terms of its implementation in a VSAT network.

Every T1 seconds during the link-down state, the hub station transmits a DISC frame with the poll bit set. A station ready to send a message transmits a UA command with the final bit set. This station then transmits an SABM command within a period of T3 seconds. If the hub does not receive the SABM within this time interval, the hub station returns to the link-down and begins sending DISC commands every T1 seconds. The first transmitted DISC command has the poll bit reset. Subsequent transmissions of the DISC command have the poll bit set. If the hub station receives the SABM, it transmits a UA command back to the VSAT and the system enters the link-up state.

It is desirable, however, to initiate the link-up state from a terminal directly connected to the hub station equipment. Since the individual VSAT stations do not need to establish unique links to the hub station, a terminal local to the hub can initiate a network wide link-up state. After the local terminal establishes link level operation, the remote VSAT stations only need to transmit information frames to the hub station.

Link Operation

Once in the link-up state, stations can begin sending information frames [15]. Frames received by the hub station that contain a correct frame check sequence (FCS) are acknowledged to the transmitting station at the packet level. If the packet information is intended to be received by another VSAT station the information frame is transmitted by the hub station. Frames corrupted due to collision or an incorrect FCS are not acknowledged by the hub station. If an acknowledgement by the hub is not received at the transmitting VSAT station within T1 seconds, the transmitting station begin retransmitting frames. Positive acknowledgement of successfully transmitted frames is desirable over notification of only rejected frames because it provides feedback to the transmitting station that the network link is still operational [5].

The hub station transmits information frames to all the VSAT stations as long as its data buffer contains data but is not full. When the buffer no longer has sufficient space to hold more frames, the hub transmits an RNR frame to all the VSAT stations. Upon receipt of an RNR frame, the VSAT stations suspend transmissions. During the time VSAT transmissions are suspended, the hub transmits information frames until its buffer empties. The hub station then transmits an RR frame. If no VSAT stations transmit I frames and the buffer remains empty, the hub station continues to transmit RR frames.

Link Clear-Down

According to HDLC guidelines, the system can enter the link-down state when a DTE issues a DISC command with the poll bit set. The DCE responds to this command with a UA frame. If an SABM command is not received at the DCE within T3 seconds, the system enters the link-down state and the hub begins transmitting DISC commands.

As with the link set-up, it is desirable in a VSAT network to have control of link clear-down procedures originating from a terminal located at the hub station. With a network configured in this manner, individual VSAT stations cannot clear down an entire network.

Information

The information field of a frame contains all packet level data used in station-to-station communications. In the VSAT network described in this document, the information field is limited to a length of 260 bytes. The maximum sized frames carry data packets containing 256 characters of information, the maximum length packet currently used in VSAT networks [33] .

Frame Check Sequence (FCS)

This sixteen bit sequence is defined as the ones complement of the sum (modulo 2) of two values determined by the number of frame bits (k) that exist between but not including the last bit of the first flag sequence and the first bit of the FCS, excluding any zero bits inserted by the bit stuffing scheme [8]. The first value is defined as the remainder of $x^k(x^{15} + x^{14} + x^{13} + \cdots + x^2 + x + 1)$ divided (modulo 2) by the generator polynomial $x^{16} + x^{12} + x^5 + 1$ where x equals 10 in base 2. The second value is the remainder obtained by multiplying the content of the frame by x^{16} and dividing (modulo 2) by the generator polynomial. The FCD typically is generated and verified by hardware at the transmitting and receiving stations respectively [15].

6.5.3 Packet Level

The data packet illustrated in Figure 6-8 consists of five parts. Each part is defined according to the CCITT X.25 recommendation level 3 protocol [38]. The logical channel group number (LGN) is a four bit sequence that helps identify a virtual circuit established between two or more stations. The general format identifier (GFI) is another four bit sequence that identifies the format of the packet header [8]. For application in a VSAT network, the GFI equals 0010 where the rightmost bit is transmitted first. The logical channel number (LCN) helps identify a virtual circuit in addition to the logical group number. The packet type identifier (PTI) designates the type of packet transmitted by a station. For information packets the PTI consists of packet sequence numbers that monitor the flow or data across a virtual circuit. The packet data field contains the information transferred from station to station. The operation of each portion of a packet is described in the following paragraphs of this section.

The logical group number and logical channel number work together to identify virtual circuits in a packet-switching network. If two stations communicate with each other on a particular virtual circuit, for instance, the data packets exchanged between the two stations are identified with the same logical group and logical channel numbers. A possible method for identifying virtual channels in the VSAT network described in this document is shown in Table 6-3. With this channel scheme Virginia Tech Extension offices and Virginia state governmental offices have separate channel assignments so that the two users do not contend for logical channel assignments. Communications between these two user groups is possible with the channels associated with groups 4 and 5. Since the remote environmental stations do not need to establish switched virtual circuits (SVCs) with the Extension offices or the state government offices, they stations have been assigned to permanent virtual circuits (PVCs) to the hub station. Each environmental station is assigned a unique channel number in the range from 1 to 511. Channel 0 is not used because it is not a valid CCITT logical channel number [15].

When the network completes a link set-up, a restart procedure is used to ensure that all virtual channels are in a known state. When the procedure begins, the hub station transmits restart packets as shown in Figure 6-10 [8]. Transmission of restart packets indicates to each VSAT station that all switched virtual circuits are open for use. Note that even though the logical group and logical channel numbers are present, they both contain all zero bits. Since all virtual circuits are being cleared, it becomes irrelevant to specify any particular channel [15].

The hub station transmits restart packets at regular intervals until a confirmation is received from each station in the network [15]. The format for a restart confirmation packet is shown in Figure 6-10. In case one or more VSAT stations malfunction, the hub transmits a limited number of restart packets. A convenient guideline for the restart procedure is for the hub station operation to transmit restart packets every T1 seconds for a maximum of N2 times.

After the network channels have been cleared, stations can request use of virtual channels. A virtual channel is established using the call request packet shown in Figure 6-11. With a call request packet a transmitting station proposes use of a particular virtual channel by specifying a logical group number (LGN) and logical channel number (LCN) in the header of the call request packet. Once the channel is established, additional packets in a transmitted message only need to contain the LGN and LCN to identify a channel linking the station of the calling address to the station of the called address [15].

Table 6 - 3. Virtual Circuit Channel Assignments

User Subnetwork	Type of Service	LGN	LCN	Complete Channel Number
Remote Environmental Stations	PVC	0	1-255	1-255
		1	0-255	256-511
Virginia Tech Extension Offices	SVC	2	0-255	512-767
		3	0-255	768-1023
Combined Subnetworks	SVC	4	0-255	1024-1279
		5	0-255	1280-1535
Virginia State Government Offices	SVC	6	0-255	1536-1791
		7	0-255	1792-2047

Restart Request

Octet	Bits 8	7	6	5	4	3	2	1
1	General Format Identifier				Logical Group Number			
	0	0	1	0	0	0	0	0
2	Logical Channel Number							
	0	0	0	0	0	0	0	0
3	Packet Type Indicator							
	1	1	1	1	1	0	1	1

Restart Confirmation

Octet	Bits 8	7	6	5	4	3	2	1
1	General Format Identifier				Logical Group Number			
	0	0	1	0	0	0	0	0
2	Logical Channel Number							
	0	0	0	0	0	0	0	0
3	Packet Type Indicator							
	1	1	1	1	1	0	1	1

Figure 6 - 10. Restart Request and Restart Confirmation Packets

Call Request

Bits

Octet	8	7	6	5	4	3	2	1
1	General Format Identifier				Logical Group Number			
	0	0	1	0	x	x	x	x
2	Logical Channel Number							
	x	x	x	x	x	x	x	x
3	Packet Type Indicator							
	0	0	0	0	1	0	1	1
4	Calling DTE Address Length				Called DTE Address Length			
	DTE Addresses							
	User Data							

Call Accept

Bits

Octet	8	7	6	5	4	3	2	1
1	General Format Identifier				Logical Group Number			
	0	0	1	0	x	x	x	x
2	Logical Channel Number							
	x	x	x	x	x	x	x	x
3	Packet Type Indicator							
	0	0	0	0	1	0	1	1
4	Calling DTE Address Length				Called DTE Address Length			
	DTE Addresses							
	User Data							

Figure 6 - 11. Call Request and Call Accept Packet Formats

In the operating VSAT network, a station transmitting a call request selects the highest numbered channel number that is not in use and is within an allowed logical group. In referring back to Table 6-3, for instance, VSATs at Virginia Tech Extension offices select the highest numbered channel available beginning with channel 1023. This selection process implies that each VSAT station must monitor the virtual channels currently used by other stations.

Following the packet type identifier in the call request packet are the lengths of the addresses for the sending and receiving stations. The lengths are measured in semi-octets (four bit nibbles) and are expressed in binary coded form [8].

The address of the calling station and the called station follows the address lengths. By including both addresses, rather than just the address of the receiving station, a receiving station can identify a station transmitting data. Following the station addresses are some of the user data. Up to sixteen octets of data can be placed in the call request packet.

As with the virtual channel assignments, the address assignments also may be used to identify members of different subnetworks. The addresses shown in the call request packet are binary coded decimal (BCD) values. A typical address is twelve digits long with a two digit subaddress for multiplexing to several machines at a particular station [15] . An addressing scheme for the networks in this text can be like the one shown in Table 6-4. All numbers within a certain range are assigned as addresses to Virginia Tech Extension offices, and all numbers within a different range are assigned to Virginia state government offices. Specific numbers assigned to the first four digits of an address can represent a subnetwork such as all Virginia Tech Extension offices. Network wide addressing is desirable if one station desires to send information to all stations in the network. A subaddress scheme also is necessary to specify whether received data should be sent to a graphics printer or routed to a facsimile machine.

The hub station acknowledges receipt of a call request packet by transmitting a call accept packet. The format for a call accept packet also is shown in Figure 6-11. Once the call accept packet is received by the transmitting station, the virtual channel is established and data transfer packets are used to continue message transactions.

Table 6 - 4. VSAT Network Addressing Scheme

User Subnetwork		Address Range			
Virginia Tech Extension Offices	from	0000	0000	0000	0000
	to	0000	4999	9999	9999
Subnetwork Broadcast		1234	xxxx	xxxx	xxxx
Virginia State Government Offices	from	0000	5000	0000	0000
	to	0000	9999	9999	9999
Subnetwork Broadcast		5678	xxxx	xxxx	xxxx
Network Wide Broadcast		9090	xxxx	xxxx	xxxx

The format of a data transfer packet is shown in Figure 6-12 [15], [8]. The "Q" denotes the Qualifier bit. It is set when the data in the packet contains information that affects the operation of the receiving station's packet assembly/disassambly (PAD) software. In packets that contain message data, the qualifier bit is reset. Data packets cannot contain both PAD level information and message data. The logical group and logical channel numbers specify the virtual channel carrying the data packet. The "M" denotes the More bit. This bit is set when a received data packet is part of a series of packets that make up a single logical message. The More bit is reset when all the data in the message have been tranmitted [8]. P(R) and P(S) are sequence numbers that identify the placement of a transmitted data packet in a message consisting of more than one packet. The function of these numbers is described in following paragraphs.

P(S) and P(R) stand for the packet send count and packet receive sequence counts respectively [15]. These binary coded numbers are important in maintaining a virtual circuit in that they alert the receiving terminal when packets in a message arrive out of sequence. The send sequence count denotes the order in which packets are transmitted from a station. The receive packet count denotes the send sequence number expected in the next received packet. At the beginning of a data transfer, the packet send and packet receive counts both have values of zero. When a station sends a packet, it increments the value of the packet send count, and when a station receives a packet with the correct send sequence count, it increments the packet receive count. If a station receives a packet with an incorrect send count, it issues a reject packet (REJ) containing the receive count for the station. Both P(S) and P(R) monitor sequential data transfer using modulo 128 arithmetic.

Figure 6-13 illustrates the operation of P(S) and P(R) as data packets are transmitted between a VSAT station and the hub. Data exchange is shown in the form of interactive communication. This illustration is somewhat simplified in that it only shows operation on one virtual channel.

The data field of a packet may carry up to 256 octets, or bytes, of data. Data in a packet contain either information for the user at another station or commands controlling operation of the packet assembly/disassembly (PAD) procedures at the receiving station. This information usually pertains to interactive communications such as data required for logging on and logging off a system. Specific parameters associated with PAD commands are not presented here but can be

Data Packet

Octet	Bits 8	7	6	5	4	3	2	1
1	General Format Identifier				Logical Group Number			
	Q	0	1	0	x	x	x	x
2	Logical Channel Number							
	x	x	x	x	x	x	x	x
3	P(S)							0
4	P(R)							M
	User Data							

Figure 6 - 12. Data Packet Format

		From VSAT		From Hub		
Direction	**Packet Type**	**P(R)**	**P(S)**	**P(R)**	**P(S)**	**Remarks**
•	•	•	•	•	•	•
•	•	•	•	•	•	•
•	•	•	•	•	•	•
VSAT →	Data	126	0			
← Hub	Data			1	126	
VSAT →	RR	127				
VSAT →	Data	127	1			
VSAT →	Data	127	2			
← Hub	RR			2		
← Hub	RR			3		
← Hub	Data			3	127	
VSAT →	Data	0	3			†
VSAT →	Data	0	4			Packet is corrupted.
VSAT →	Data	0	5			Packet received out of order.
← Hub	REJ			4		Acknowledges up to †.
VSAT →	Data	0	4			
VSAT →	Data	0	5			
← Hub	Data			5	1	
← Hub	Data			6	2	
•	•	•	•	•	•	•
•	•	•	•	•	•	•
•	•	•	•	•	•	•

Figure 6 - 13. Packet Send and Receive Sequence Number Operation

found in the Yellow Book for the CCITT or Deasington's publication [15]. Packets that carry PAD information do not carry any other user data. A station sending PAD information identifies the transmitted packets by setting the Q bit in the packet header.

The hub station acknowledges successful receipt of a data packet either by sending a receiver ready (RR) packet with a packet receive count or by transmitting a data packet with an updated packet receive count. The format of a receiver ready packet is shown in Figure 6-14. When a station receives a packet with an incorrect receive sequence number, the hub station discards the packet and transmits a reject (REJ) packet containing the expected packet send count of the next expected received packet.

During data transfer, a transmitting station can transmit a limited number of unacknowledged packets. The maximum number of allowed unacknowledged packets is known as the *window*. Because of the propagation delay inherent in satellite communications, a sufficiently large window is desirable so that data transfers are not slowed significantly. An adequate window size for the VSAT network described in this section is 25 packets. The time required to transmit 26 packets at 56 kbps is approximately one second, the amount of time measured by timer T1. (See Section 6.5.2.)

After all data in a message exchange have been transmitted successfully, the calling station sends a clear request packet in a format as shown in Figure 6-15 [15]. A cause field is included with all bits reset to zero to denote that a DTE has initiated the clear request. The clearing of a virtual channel is complete when the hub station transmits a clear comfirmation packet to the remote station. The format for a clear confirmation also is shown in Figure 6-15.

6.5.4 Summary of Commands

The following section summarizes frame level and packet level commands for transfer of data between stations in a VSAT network. These commands are are shown in Table 6-5.

Receiver Ready

Octet	Bits 8	7	6	5	4	3	2	1
1	General Format Identifier				Logical Group Number			
	0	0	1	0	x	x	x	x
2	Logical Channel Number							
	x	x	x	x	x	x	x	x
3	Packet Type Indicator							
	0	0	0	0	0	0	0	1
4	P(R)							0

Reject

Octet	Bits 8	7	6	5	4	3	2	1
1	General Format Identifier				Logical Group Number			
	0	0	1	0	x	x	x	x
2	Logical Channel Number							
	x	x	x	x	x	x	x	x
3	Packet Type Indicator							
	0	0	0	0	1	0	0	1
	P(R)							0

Figure 6 - 14. Receiver Ready and Reject Packet Formats

Clear Request

Octet	Bits 8	7	6	5	4	3	2	1
1	General Format Identifier				Logical Group Number			
	0	0	1	0	x	x	x	x
2	Logical Channel Number							
	x	x	x	x	x	x	x	x
3	Packet Type Indicator							
	0	0	0	1	0	0	1	1
4	Clearing Cause							
	0	0	0	0	0	0	0	0

Clear Confirmation

Octet	Bits 8	7	6	5	4	3	2	1
1	General Format Identifier				Logical Group Number			
	0	0	1	0	x	x	x	x
2	Logical Channel Number							
	x	x	x	x	x	x	x	x
3	Packet Type Indicator							
	0	0	0	1	0	1	1	1

Figure 6 - 15. Clear Request and Clear Confirmation Packet Formats

Table 6 - 5. X.25 Data Transfer Commands Required by a VSAT Network

Link Level Commands	
VSAT	**Hub**
I	I
	RR
	RNR
Packet Level Commands	
VSAT	**Hub**
Data	Data
Call Request	Call Request
	Call Accept
Call Clear	Call Clear
	Clear Accept
	RR
	RNR
	REJ

The table is organized into two parts. Each part contains a list of commands that can be transmitted by either a VSAT station or a hub station in the network. Knowledge of the commands issued is necessary in developing algorithms that control the flow of data between stations in a network. These control algorithms are described in the following section.

6.6 Automatic Control of the Stations

6.6.1 Control Overview

This section presents algorithms that control the flow of data at the individual VSAT stations and at the central hub station. The design of these algorithms gives the hub station most of the control over regulating data flow. In accordance with the star network topology, the VSAT stations assemble and disassemble message data, and the hub station routes message data to a specified receiver [44]. The VSAT stations transmit information frames that contain either data packets, call request packets, or call clear packets. The hub station also transmits acknowledgements at both the link and network levels.

The hub station maintains synchronism of the VSAT network by transmitting a synchronization pattern every second [6]. Each VSAT station receiving the synchronization pattern divides the time separating the beginning of each pattern into twenty-five periods for slotted Aloha frame transmissions. For transmissions at 56 kbps, each 0.04 second time slot can carry 270 octets of frame information plus a 4 octet acquisition preamble produced by some digital modems and still leave a 48 bit duration guard time.

Information sent from a transmitting station passes through four stages of processing before transmission to another station. Beginning at the PAD level, software in a personal computer separates data into blocks of 256 bytes. The software routes the data blocks to a transmitting terminal where it undergoes packet and frame level assembly by the terminal software. Partially assembled frames then pass through frame level assembly hardware which adds the frame check sequence and performs a bit stuffing routine. (See Section 6.5.2.) Release of data from the hardware should be clocked so that transmissions coincide with the beginning of Aloha time slots.

Information received by a station passes through similar stages, but in reverse order. Received frames pass through frame level hardware which removes bits added from a bit stuffing routine and verifies the frame check sequence. If the received frame check sequence is not correct, the hardware discards the received frame. Successfully received frames are passed to frame level and packet level processing and then routed to personal computer for storage. PAD routines performed at the terminal convert stored packets to a usable form.

The algorithms presented in the following subsections here describe procedures for the transfer of messages accross a VSAT network. The subsections are ordered in a manner that follows the path taken by a data packet through a VSAT network. Each block in a diagram can be implemented with a separate subroutine in the station control software. The algorithms presented do not include procedures for recovery from errors caused by malfunctioning station equipment.

6.6.2 VSAT Station Data Transmission Control Procedures

The following subsection describes the procedures of packet level and frame level control software for VSAT station data transmission. The algorithms presented descirbe the path taken by a single packet.

The packet level algorithm shown in Figure 6-16 accepts a file stored in random access memory of a personal computer and generates packets containing the file data. First, the PAD generates a call request packet. The sixteen bytes of data contained in this packet can contain information such as the VSAT station identification and time of the transaction request. If necessary, this information also may be contained in one or more data packets. Since message identification is not part of the message content, the Q bit is set in all data packets containing such information.

The packet level control software sequentially accepts the message data in strings of 256 bytes. The information field of each packet contains one 256 byte string. The last packet may contain less than 256 bytes if the routine reaches the end of a file before filling an entire data field. After the PAD routine assembles the last data packet, it generates a call clear packet that designates the end of the message transmission.

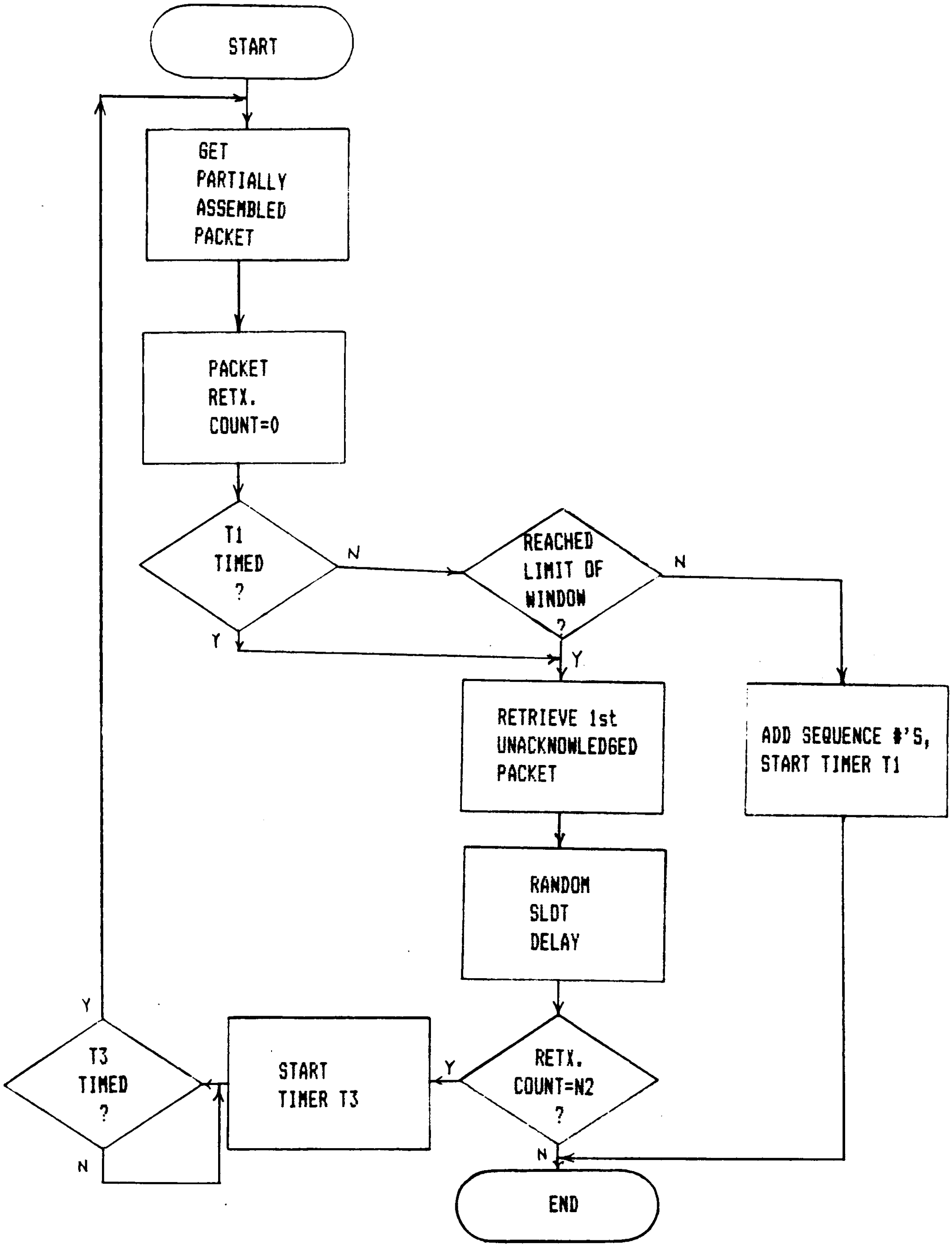


Figure 6 - 16. VSAT Station Packet Level Data Transmission Control Algorithm

The packet level routine initiates transmission of packets based on acknowledgement of previously transmitted packets. When a VSAT station transmits a packet, it starts a timer T1 which specifies the maximum amount of time that can elapse before receiving an acknowledgement from the hub. While T1 is timing, the station can transmit up to 25 packets, the unacknowledged packet window size, without receiving acknowledgements from the hub. If the timer T1 for a packet expires, all unacknowledged packets are retrieved from temporary storage and retransmitted in their original order. Packet retransmission also begins if the number of unacknowledged packets exceeds the allowed window size.

A station that does not receive an acknowledgements for its transmissions begins retransmitting packets after waiting a random number of time slots. Randomization is used to avoid having a retranmitted packet collide again with the same interfering packet. A common randomization technique for packet retransmission delay employs a uniform probability density spanning K time slots. The probability that a retransmission delay (d) lasts i time slots is [25]

$$P[d=i]=\begin{cases} 0 & i \leq R \\ \dfrac{1}{K} & R+1 \leq i \leq R+K \\ 0 & i > R+K \end{cases} \qquad (6-6)$$

where R is the number of time slots that pass before timer T1 has timed out. An optimum value for K is found in Chapter 7.

The number of retransmissions is limited to N2, 20 times, as designated in Section 6.5.2. After N2 attempts, transmission of packets halts for T3 seconds, and the transmission of the unsuccessfully received packets begins again.

The frame level algorithm is shown in Figure 6-17. These routines insert an information frame control word and address ″B″ in the frame header. The control word identifies an information frame, and the address designates VSAT to hub communication.

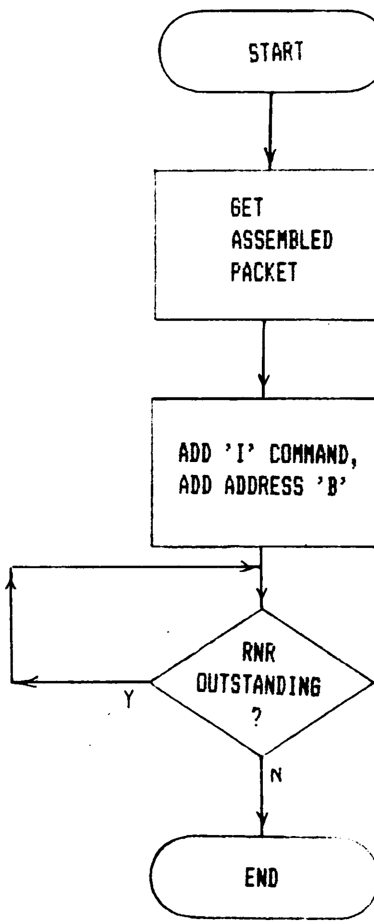


Figure 6 - 17. VSAT Station Frame Level Data Transmission Control Algorithm

6.6.3 Hub Station Data Reception Control Procedures

The following subsection describes the procedures for frame level and packet level control software for hub station data reception. The algorithms presented follow the path taken by a single packet.

Since the VSAT station transmits only information frames, the frame algorithm for data reception merely checks the address and control word of received frames. The routine permits information frames to pass to the packet level routine and discards all other frames. The frame level routine for data reception is shown in Figure 6-18.

The packet level routine for hub reception is shown in Figure 6-19. This routine first checks the packet type identifier in each packet. The hub acknowledges call request and call clear request packets by issuing their corresponding call accept and call clear packets. The software also begins monitoring logical channels specified by call requests and stops monitoring channels closed by clear requests. If a station requests an occupied channel, or if a station requests a call to a station on another channel, the hub software issues an RNR packet level command. This command then enters a queue for transmission to the calling station.

The packet level routine also checks the sequence numbers on all received data packets. The routine discards the contents of out of sequence packets, and issues a REJ command to the calling VSAT station. The REJ command acknowledges the last packet successfully received from the transmitting VSAT station.

Data packets bound only to the hub station are disassembled and routed to appropriate equipment connected by land lines to the hub station terminal. Data bound for other VSAT stations are routed to a queue for packet transmission. Packets in the queue are serviced on a first in-first out basis.

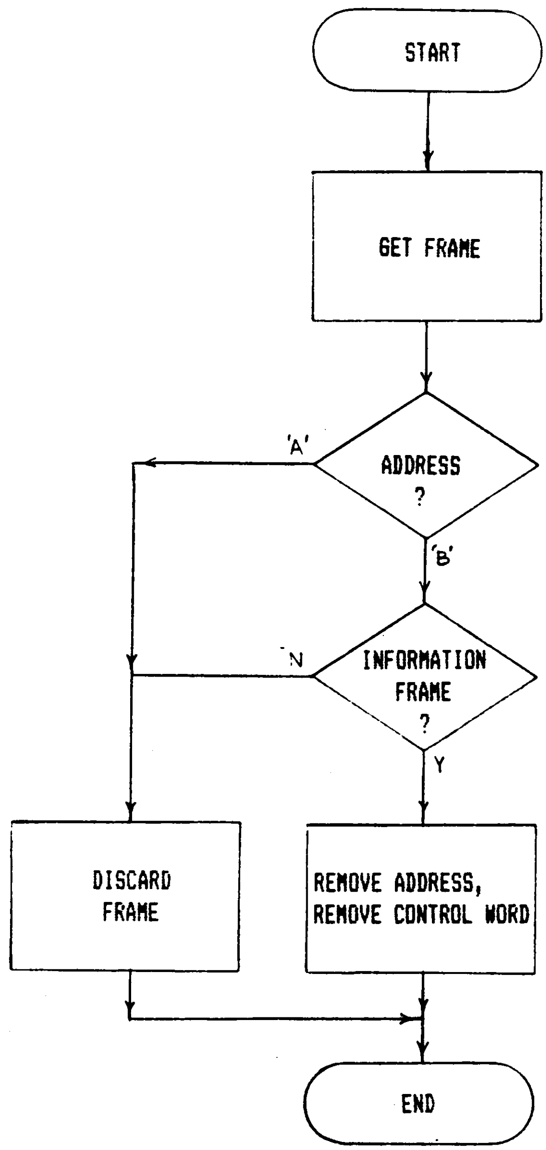


Figure 6 - 18. Hub Station Frame Level Data Reception Control Algorithm

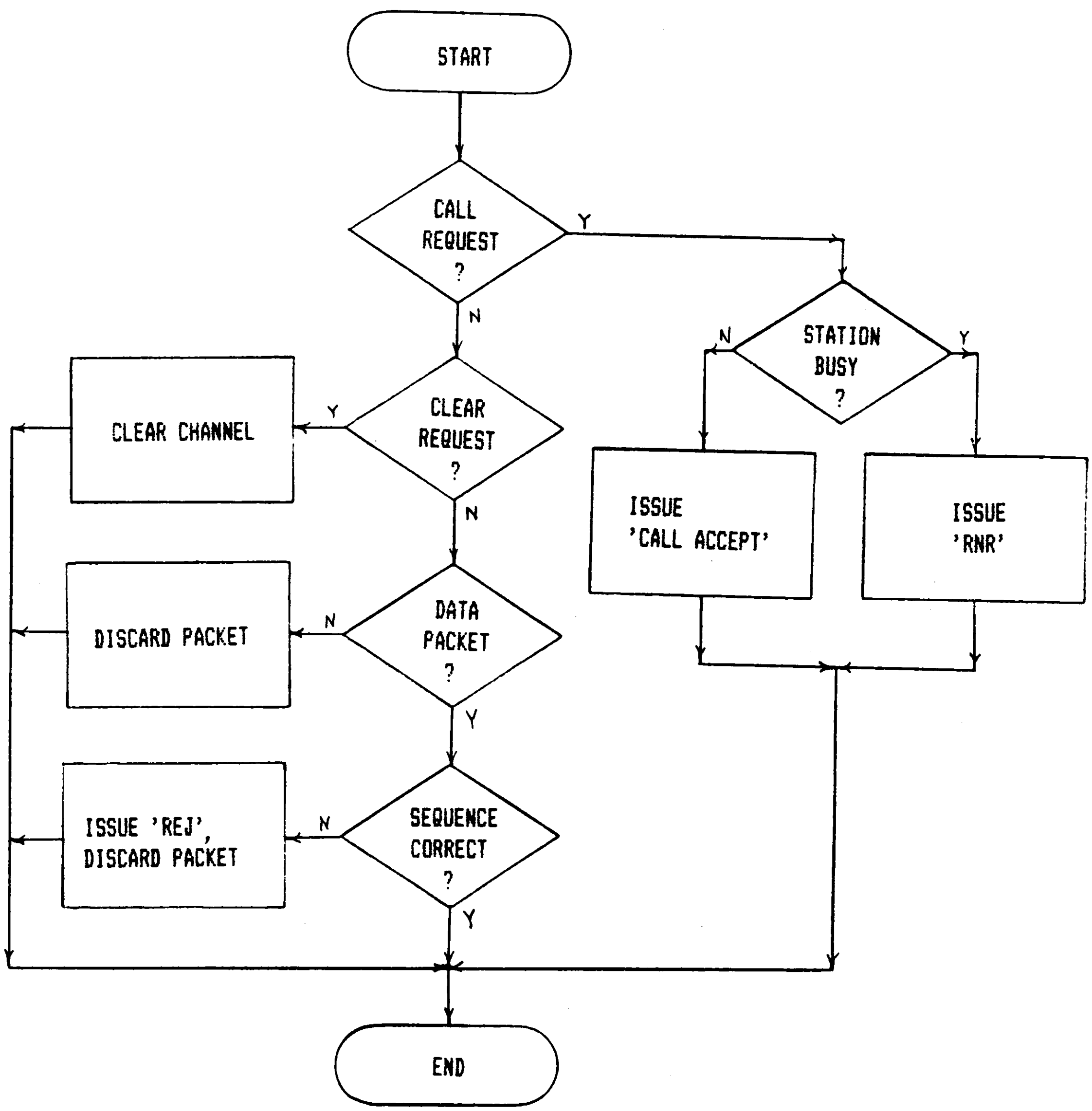


Figure 6 - 19. Hub Station Packet Level Data Reception Control Algorithm

6.6.4 Hub Station Data Transmission Control Procedures

This subsection describes the procedures of the packet level and frame level control software for hub station data transmission. The algorithms presented follow the path taken by a single packet.

Messages originating from the hub station pass through steps for packet assembly similar to that at the VSAT station. The algorithm for these steps is the same as shown in Figure 6-16. These steps generate call request, call clear, and data packet types for file transfer. Packets generated by the hub PAD software enter a queue for transmission to the VSAT stations.

Frame level control software for hub transmissions is shown in Figure 6-20. This algorithm issues RNR frames when the transmission queue is full and RR frames when the transmission queue is empty. The issuing of RR frames when no packets are ready implies that the frame level routine runs continuously. When packets are ready for transmission, this routine inserts an information frame control word and address type "A" in front of the packet level data and sends the partially assembled frame to the station's frame level hardware.

6.6.5 VSAT Station Data Reception Control Procedures

This subsection describes the procedures for frame level and packet level control software for VSAT station data reception. The algorithms presented follow the path taken by a single packet.

The algorithm for frame level control of received data is shown in Figure 6-21. The frame level procedures pass the contents of information frames to the packet level procedures. Based on whether the hub frame receive buffer is filled, they also control whether the VSAT station can transmit frames.

The packet level control algorithm for received packets is shown in Figure 6-22. This routine checks the packet type identifier for received transmissions. For received data packets containing

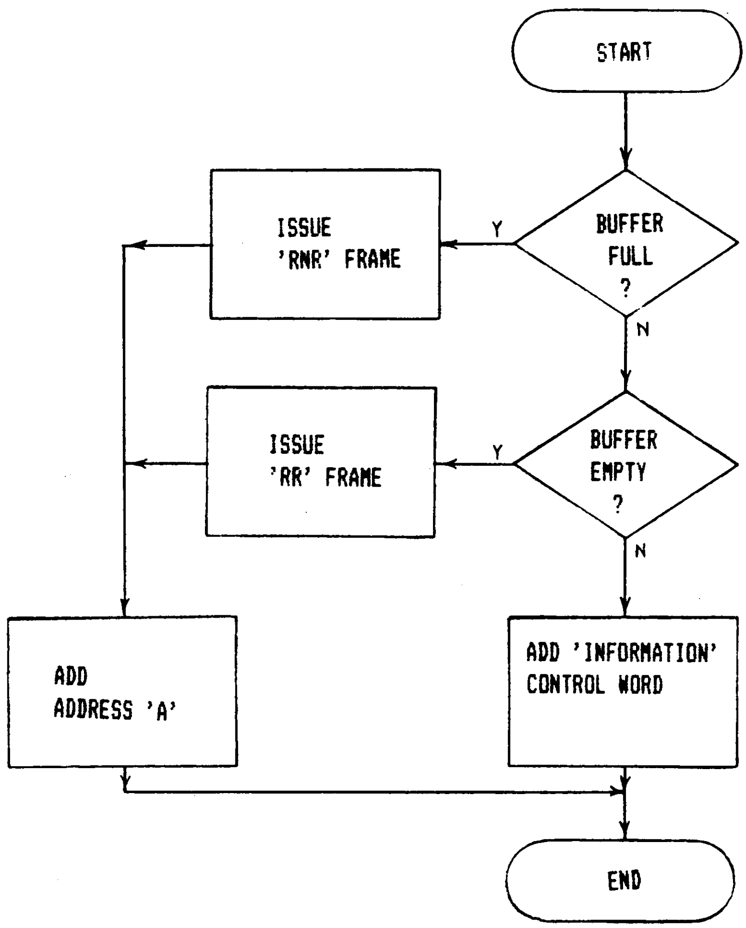


Figure 6 - 20. Hub Station Frame Level Data Transmission Control Algorithm

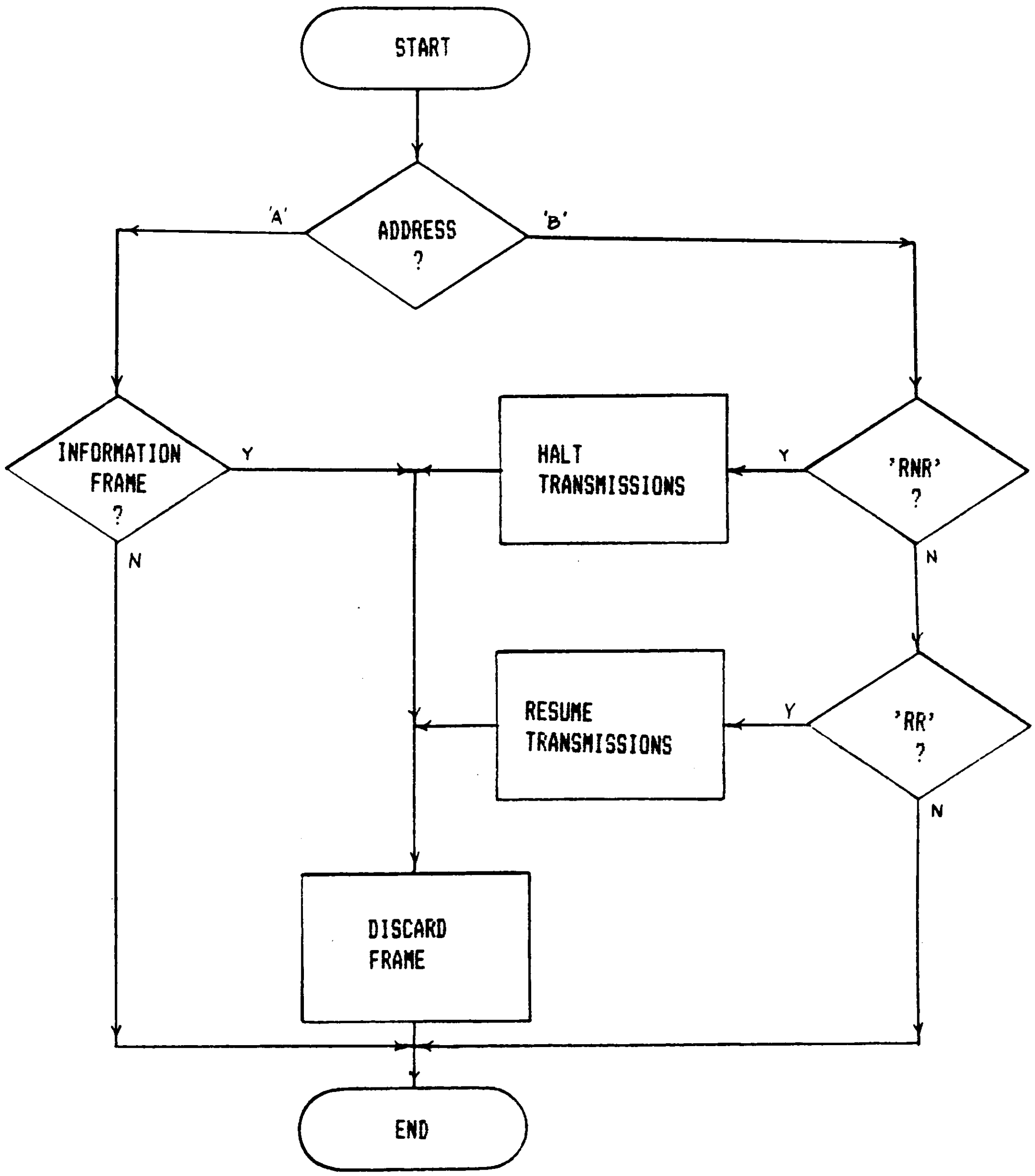


Figure 6 - 21. VSAT Station Frame Level Data Reception Control Algorithm

the correct logical channel number, the algorithm updates a record of sequence numbers acknowledged by the hub. The packet level procedures then route the information in the data field of each packet to a user file for storage and future retrieval. Data packets with an incorrect channel number are discarded.

Packet level commands received at the VSAT station also are checked for correct channel numbers. The software records the acknowledged sequence numbers of packets containing the correct channel number and discards the contents of packets containing incorrect channel numbers. Similarly, the routine checks the station addresses in received call requests and accepts, and call clears and accepts. For requests and accepts, the station monitors whether the specified channel is available or in use. For any call requests with the correct station address, the software routes the received information in the data field to a user file for retrieval by a user.

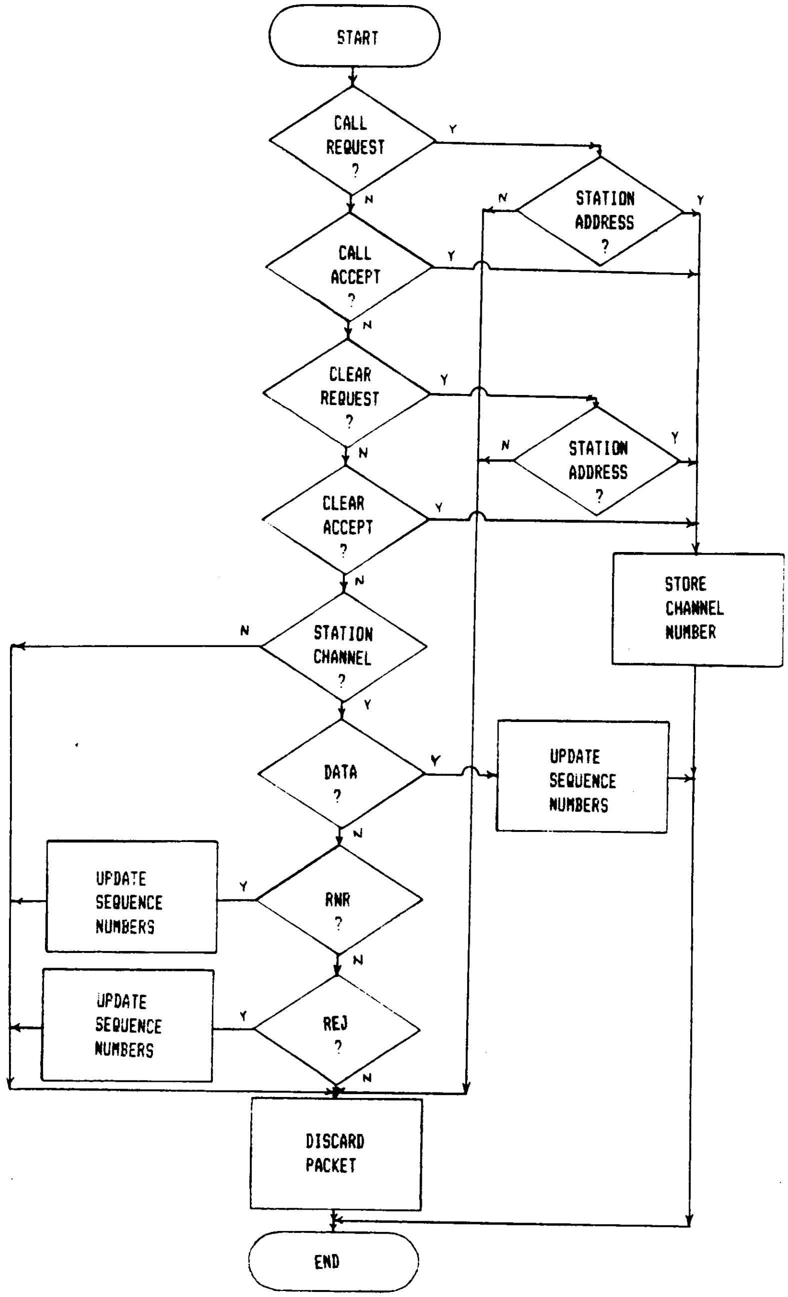


Figure 6 - 22. VSAT Station Packet Level Data Reception Control Algorithm

6.7 *Operational Software for a VSAT Hub Station*

Routines in addition to the frame level and packet level data flow procedures can be implemented in the software operating at a VSAT hub station. The overall software structure is shown in Figure 6-23.

The data control routines have been presented in the previous section. They implement X.25 packet-switching protocols for levels 2 and 3 of the ISO Seven Layer model.

The monitor and control routines control network synchronization and obtain data on the network performance. Transmission of a synchronization pattern every second allows the remote stations in a slotted Aloha multiple access network to determine the beginning of every time slot. The routines in this block also can measure the frequency of corrupted frame transmissions using a counter attached to the frame level hardware. The number of discarded frames per minute and accepted frames per minute can be recorded to determine network throughput characteristics at various time of the day. These routines also can monitor which stations make transactions in the network and how much traffic is generated by each station.

The accounting routines use the information obtained on the amount of traffic generated by each station to determine individual VSAT station user cost for network service. A useful equation to determine a monthly billing base rate in this network is as follows [39] :

$$\left(X+\frac{H}{N}\right)C+\frac{(S_1+S_2K)}{N} \tag{6-7}$$

where the variables in this equation are as follows:

X = installed cost per VSAT

N = number of VSAT stations

H = installation cost for the hub station

C = capitalization factor based on a 5 year amortization at 10 percent rate of return (0.0212)

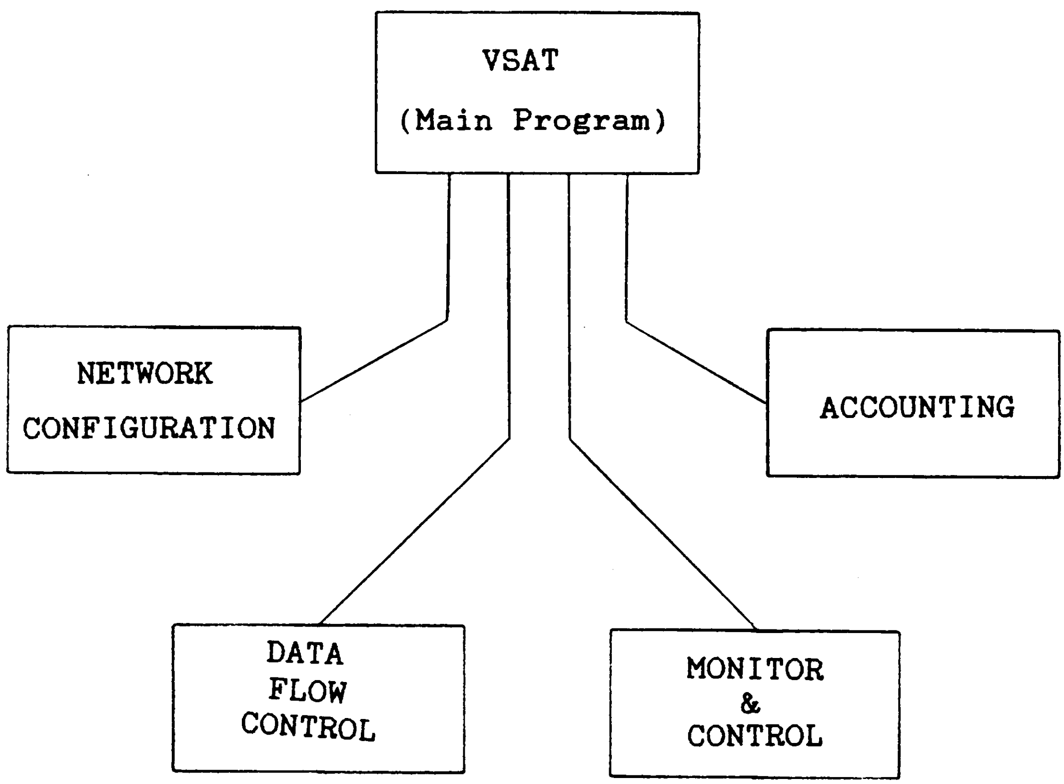


Figure 6 - 23. VSAT Network Hub Station Control Software Structure

S_1 = transponder cost per month for shared VSAT to hub station transmissions

S_2 = transponder cost per month for hub to VSAT broadcast transmissions

Additional costs per VSAT may be determined by the number of packets transmitted by each station per month. A station that transmits a very large number of packets in one month can be charged more than one that transmits relatively few packets.

Lastly, the network configuration contains a look-up table of all the stations in the network. This table contains the station identification, twelve digit network address, and any subaddresses. The routines in this block also contain procedures for adding and deleting stations from the network.

Chapter 7: Operation of a VSAT Network

7.1 Stochastic Model Description

This chapter describes the anticipated performance of the VSAT network described in Chapter 6. Performance is described in terms of the throughput and retransmission delay for the channel shared by the VSAT stations. A network employing a random access packet switching technique reaches an equilibrium state when when the number of packets entering the system equals the number of packets leaving the system. When the network is in equilibrium, the channel throughput and delay specify a channel operating point for the network. The analysis presented in this chapter is required to determine the time delay for retransmission of unacknowledged packets.

Using a slotted Aloha multiple access scheme, the throughput versus traffic characteristic for an infinite population of transmitting stations is given as

$$S = G\exp(-G) \qquad (7-1)$$

where S and G are the channel throughput and channel traffic, respectively, as defined in Chapter 6. As shown in Figure 7-1, an increase in the channel traffic causes an increase in the network throughput until the channel traffic reaches one packet per Aloha time slot. Further increase in the channel traffic rate causes more packets to collide than to be successfully received, and the network throughput decreases.

In a VSAT network using a slotted Aloha, a station whose transmitted packets are corrupted by collisions with those from other stations begins retransmitting packets after waiting a random number of slot periods. Stations assume that a packet collision has occurred if no acknowledgement from the hub is received after R time slots. Randomization is used to avoid having a retransmitted packet collide again with the same interfering packet. A common randomization technique for specifying times for packet retransmission employs a discrete uniform probability density function spanning K time slots. The probability that the packet retransmission delay d lasts i slots in a span of K slots has probability density function as shown below [25]:

$$P[d=i]=\begin{cases} 0 & i \leq R \\ \dfrac{1}{K} & R+1 \leq i \leq R+K \\ 0 & i > R+K \end{cases} \qquad (7-2)$$

If K is small, the average retransmission time is small, but the probability of colliding with the same packet is high. Conversely, if K is large, the period between retransmissions is long, but the chance of subsequent packet collisions is small. This delay/throughput trade-off is considered in finding the channel operating point.

Use of a uniform probability density for the initiation of packet retransmission creates a model that contains memory of the channel history for R time slots. For purposes of analysis, however, it is desirable to develop a model having no memory so that the anticipated network performance can be calculated on current system conditions. Simulation results have shown that slotted Aloha performance in terms of average delay and throughput is mainly dependent on the average delay between transmission attempts and is not heavily dependent on the exact probability distribution encountered [22], [25]. A probabalistic model containing no memory, or Markov model, uses the following geometric probability distrubution function to describe a delay of i time slots [25]:

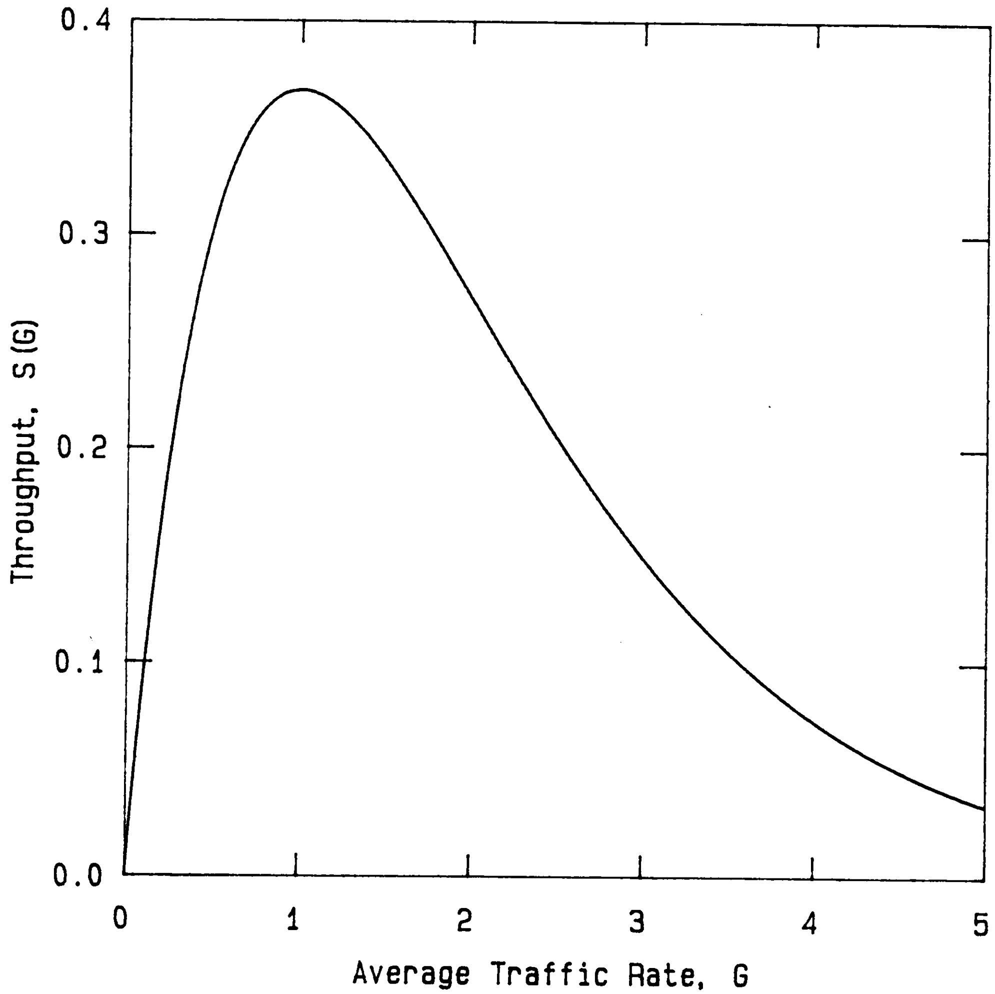


Figure 7 - 1. Throughput versus Channel Traffic for Slotted Aloha Channel

$$P[d=i]=\begin{cases}0 & i\leq 0\\ p(1-p)^{i-1} & i>0\end{cases} \qquad (7-3)$$

Once a network operating point is determined in the Markov model, its corresponding point can be found in the slotted Aloha model containing channel memory. The performance of the slotted Aloha network in terms of the results obtained from the Markov model, is found by equating the average retransmission delay from each model. From the two averages, the following relation is obtained [25]:

$$p=\frac{1}{R+(K+1)/2} \qquad (7-4)$$

Each VSAT station is in one of two states: *blocked* or *thinking* [25]. In the thinking state, a station transmits a new packet in a time slot with probability σ. In a bursty network, $\sigma << p$. In a blocked state, a station retransmits packets that were not successfully received by the hub. Packets pending retransmission are said to be *backlogged*

7.2 *Shared Channel Operating Characteristics*

This section considers the stability of a slotted Aloha network and presents a procedure for finding a stable operating point in which the channel input rate S equals the expected throughput $S(n)$ of the shared channel.

The channel input rate is the number of new packets entering the network. As described in the system model, out of N stations in the network, n are blocked, leaving $N-n$ thinking stations. The channel input rate is

$$S=(N-n)\sigma\ . \qquad (7-5)$$

When this equation is represented in the n-S plane it becomes a straight line called the *channel load line* having a slope of $1/\sigma$.

The slotted Aloha channel is described further in terms of the the total number of backlogged packets n and the throughput $S(n)$. For N VSAT stations in the network, the throughput characteristic is as follows [22]:

$$S(n) = (1-p)^n (N-n)\sigma(1-\sigma)^{N-n-1} + np(1-p)^{n-1}(1-\sigma)^{N-n} \quad . \qquad (7-6)$$

Realizing that p is a function of K, a family of curves for fixed values of K can be obtained. These curves shown in Figure 7-2 correspond to N equal to 150 VSAT stations and σ equal to 0.003. This value for σ corresponds to 250 packet transmissions per hour per station, and it is associated with networks that provide interactive communications among remote stations [33]. This particular value of σ is chosen for the network model as part of a worst case analysis.

The curves shown in Figure 7-2 are known as *equilibrium contours*. They are defined as the locus of points for which the channel input rate S equals the expected channel throughput $S(n)$ in a time slot [25]. A load line intersects an equilibrium contour at an *equilibrium point*.

Consider the intersection of the load line and the equilibrium contour for $K = 20$ in Figure 7-2. The load line intersects the contour at three points. The intersection at $n = 26$ is a stable equilibrium point. For n less than 26, the input channel rate is greater than the expected throughput, and the backlog increases. For n a little larger than 26, the throughput is greater than the input rate and the backlog decreases. This equilibrium point is considered stable because the number of backlogged packets tends to remain fixed at equilibrium point regardless of any change in the input traffic. Similarly, the equilibrium point at $n = 100$ also is a stable equilibrium point. The equilibrium point at $n = 74$ is unstable; any change in the input channel traffic causes the channel to drift to one of the stable equilibrium points.

The presence of an unstable equilibrium point in a network is not desirable because it depicts a bistable network. Fluctuations in the input traffic rate can cause the number of backlogged packets either to decrease to a lower level or to increase to the point of saturating the network. A network design described by having only one stable equilibrium point for very large values of n also

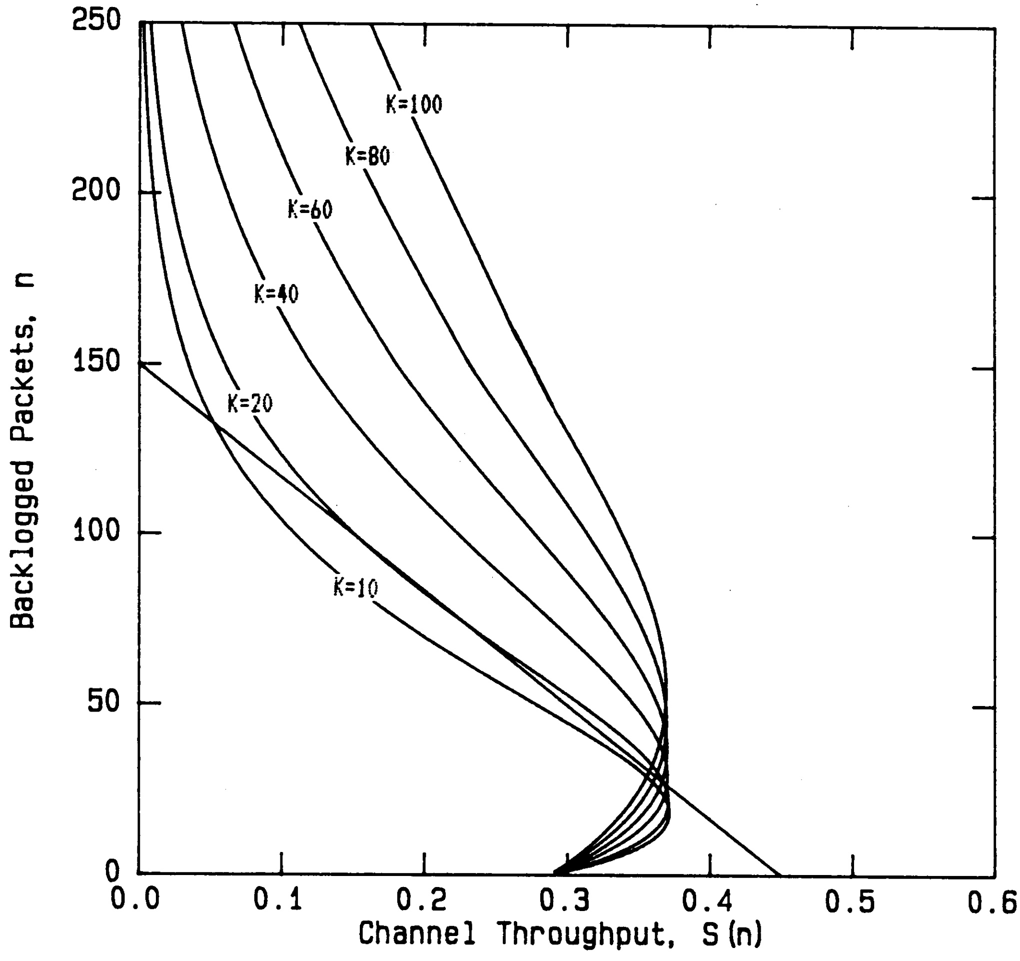


Figure 7 - 2. Slotted Aloha Channel Equilibrium Contours: $N = 150$ stations, $\sigma = 0.003$

is undesirable because the large number of backlogged packets create long delays before successful transmission of packets. An example of such a network is shown in Figure 7-2 for $K = 10$ slots; the equilibrium point corresponds to $n = 132$ backlogged packets. A globally stable network is described as having one stable equilibrium point for values of n less than the number of backlogged packets present at maximum network throughput. The VSAT described in this text should be globally stable.

An appropriate throughput/delay characteristic to implement in a VSAT network is the contour corresponding to $K = 30$ in Figure 7-2. The trade-off for network stability is the occurrence of longer network delays due to a larger value of K. However, the VSAT network is not intended to be used for interactive communications. Long network delays incurred in file transfers can be tolerated more easily than long delays in inquiry-response transactions.

As the number of stations increase, larger values of K are necessary. As shown in Figure 7-2, the present value of K cannot be used for networks much larger than 150 VSAT stations. Figure 7-3, for example, shows the equilibrium contours for N equal to 200 stations. A minimum value for K is 200 slots.

If the probability that stations generate new packets is smaller than the value stated above, smaller values of K can be used to provide a globally stable network. Figure 7-4 shows equilibrium contours for a network of 200 stations as σ varies from 0.003 to 0.0003. As the rate that new packets are generated decreases, the size of the network can increase without having to increase the average retransmission delay.

Adaptive strategies for channel control have been developed for reducing the average retransmission delay while maintaining the stability of the network. Stations using an adaptive strategy vary the average retransmission delay as a function of the total channel traffic G. Varying the network delay increases the efficiency of the network during light traffic conditions. These strategies are not presented in this text but are found in work by Lam and Kleinrock [25].

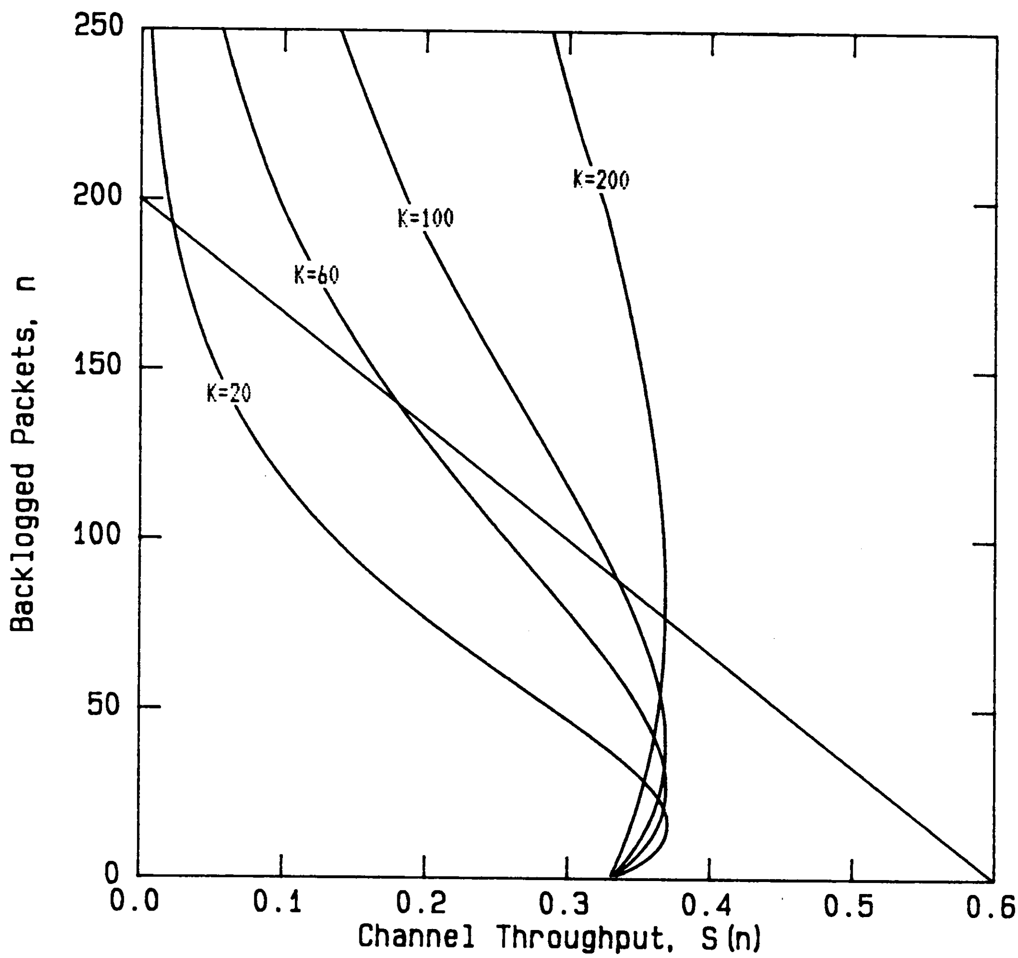


Figure 7 - 3. Slotted Aloha Channel Equilibrium Contours for 200 VSAT Stations: $\sigma = 0.003$

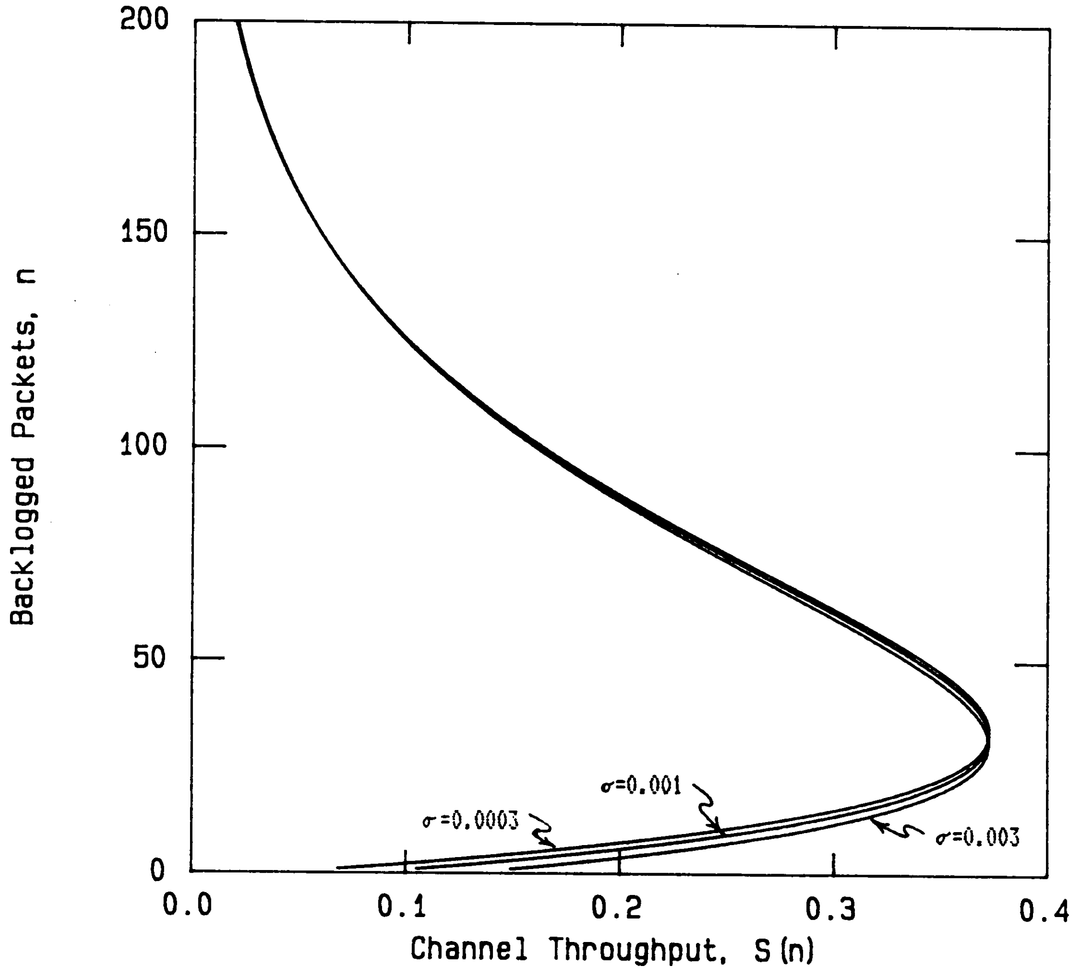


Figure 7 - 4. Shift in Slotted Aloha Channel Equilibrium Contours for Varying Rates of New Packet Generation per Station (σ): $N = 150 stations$, $K = 20$

7.3 Conclusions

To provide a globally stable VSAT network using slotted Aloha multiple access, stations retransmitting unsuccessfully received packets use a random delay described by a uniform probability distribution over K time slots. The minumum value for K in a VSAT network with 150 stations is 30 slots. The backlog associated with this channel operating point is 26 packets.

Since the analysis for a VSAT network with 150 stations used a relatively high value for the probability that a single station would transmit a new packet within a given time slot (σ), the predicted sytem performance is somewhat pessimistic. Required retransmission delays for networks containing 150 or more stations can be shorter for networks that do not provide interactive communications.

Chapter 8: Conclusions

8.1 *Summary of Designs*

This thesis began by presenting communication needs that can be fulfilled by implementing several satellite networks. The network requirements fall into four main categories: satellite television transmissions, point-to-point medical image transmission, multiple station-to-station communications, and mobile station communications.

Chapters 4 and 5 presented the system design and performance characteristics of eight satellite networks. Based on the network configurations, Section 5.3 presented recommendations for network implementation. These recommendations are summarized below:

- Digital T1 video can be transmitted to Virginia Tech Extension locations already equipped with 2.75 meter diameter antennas. Received bit error rates less than 10^{-6} can be obtained without forward error correction as long as the uplink only and downlink only rain fades do not exceed 3 dB and 2 dB respectively. Bit error rates for T1 video broadcast to a 5.5 meter antenna in Leesburg, Virginia, are less than 10^{-6} for uplink only and downlink only rain fades up to 7 dB. (See Section 5.1.3.)

- Video scanners and image capture add-on boards for personal computers can be used to for transmission of medical images from the Equine Medical Center in Leesburg to the College of Veterinary Medicine in Blacksburg. The received bit error rate for T1 transmissions of the digitized image data is the same as that for T1 video broadcasts.

- Also proposed was participation in a satellite token ring network linking Virginia Tech to the Continuous Electron Beam Accelerator Facility (CEBAF) in Newport News, Virginia. Because token rings were not originally developed for use with a satellite communications network, further investigation is necessary before implementing such a system.

- A statewide VSAT network can transmit digital information to Virginia Tech Extension locations throughout Virginia. The minimum antenna diameter suggested for each station is 2.4 meters. Digital modems should use 1/2 rate convolutional coding in order to receive bit error rates less than 10^{-6} during uplink only and downlink only rain fades of 6 dB and 4 dB respectively.

- Land mobile earth station experiments can be performed using the proposed facility at Virginia Tech. Each mobile station can be equipped with a 1.2 meter diameter antennas and can receive 48 kbps transmissions to study multipath propagation effects at 12 GHz.

- Monitoring environmental conditions through the eastern United States is possible by equipping existing remote stations with a 2.4 meter antenna and a digital modem. These stations may be used either to monitor conditions affecting crop growth or provide an early warning system during periods of potential flooding.

- Experiments with spread spectrum communications and techniques at Ku-band can be performed with the proposed facility at Virginia Tech. The specific technique chosen for study has yet to be determined.

Chapter 6 presented a detailed system design for an operating VSAT network. The network was designed to allow file transfer among Virginia Tech Extension offices and Virginia state government offices, and from environmental monitoring stations to the hub station. (See Section 6.1.) Multiple access techniques and a packet-switching protocol for station access and data flow control were presented. Chapter 7 presented an analysis of the throughput/retransmission delay characteristic for a the VSAT network. Trade-offs between network stability and delay for message transaction are considered. The recommendations for network design are as follows:

- The VSAT network is configured as a star network as shown in Figure 6-1. The hub station at Virginia Tech functions as the central node controlling packet-switching of transmitted data. Message transfers among the VSAT stations is possible using switched virtual circuits. (See Section 6.2.)

- Multiple access is obtained using a slotted Aloha protocol. This protocol is particularly suited for transfer of long messages between station [33]. (See Section 6.3.)

- Data flow techniques follow the CCITT recommended X.25 packet-switching protocol. This protocol makes use of the lower three layers of the ISO Seven Layer Model for open systems interconnection between data networks. (See Section 6.5.)

- Corrupted packets are retransmitted with a randomization strategy using a discrete uniform probability distrubution that covers 30 time slots.

The basic hardware configuration for the VSAT network is shown in Figure 8-1. The VSAT station and hub station each contain equipment that performs amplification and frequency conversion of the transmitted and received signals. The VSAT controller and hub controller each consist of a digital buffer and a personal computer operating with appropriate station control software. The VSAT controller initiates data transmissions and receives addressed messages to and from other network stations. The hub conroller monitors and directs the flow of data across the network. All message transactions occur through a shared inbound channel and a broadcast outbound channel.

8.2 Recommendations for Future Work

From the design presented for a VSAT network the following items can be considered:

- As a basis of comparison against VSAT network performance, a study can be performed on the operating characteristics and feasibility of implementing a satellite token ring network.

- A study can be performed that investigates the feasibility of using the network access and data control techniques of VSAT networks in a mobile station/satellite communications network.

- An investigation of dynamic techniques for controlling the random retransmission delay of slotted Aloha networks. A dynamic scheme can can maintain the network stability while increasing the throughput efficiency.

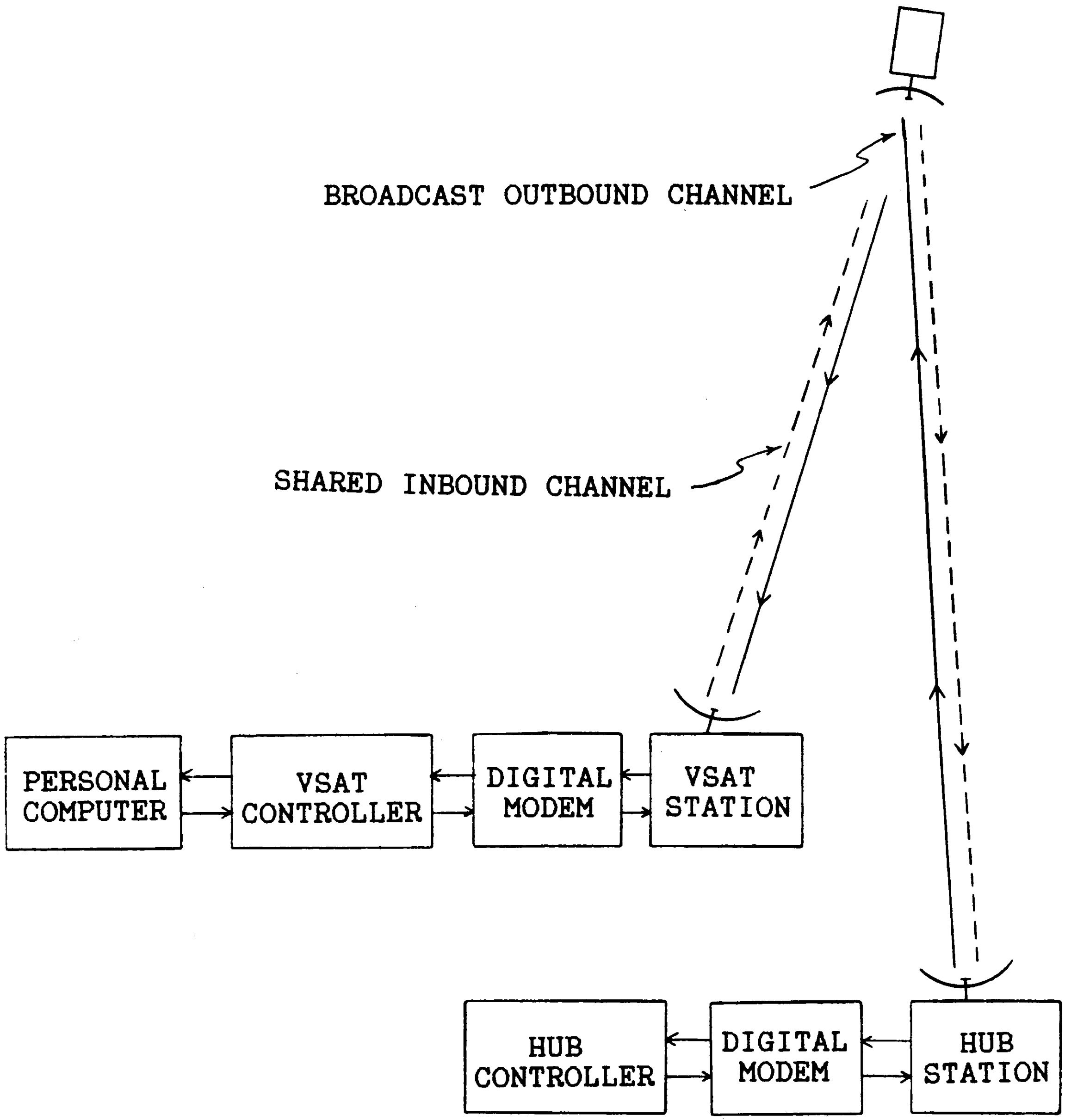


Figure 8 - 1. Basic VSAT Network Configuration

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Appendix A: LAMP Theory of Operation for Power Budget Analysis

A.1 The System Model

LAMP (*L*ink *A*nalysis *M*achine *P*rogram) is a menu driven program which calculates and displays power budget analyses for geosynchronous satellite links. It operates on an IBM PC with DOS version 2.1 or higher. *LAMP* was developed as part of the IBM/Virginia Tech Joint Development Project. The following sections describe the calculations used by *LAMP* to produce power budgets.

The program begins by displaying the main menu. By selecting choice "C" from the main menu, *LAMP* starts with parameters of the transmitting earth station and calculates the overall C/N ratio at the receiving earth station. By selecting choice "T" from the main menu, *LAMP* starts with parameters of the receiving earth station and calculates the minimum output power required by the transmitting earth station.

The communications link is modeled according to the elements illustrated in Figure A-1. The variables associated with this figure are described as follows:

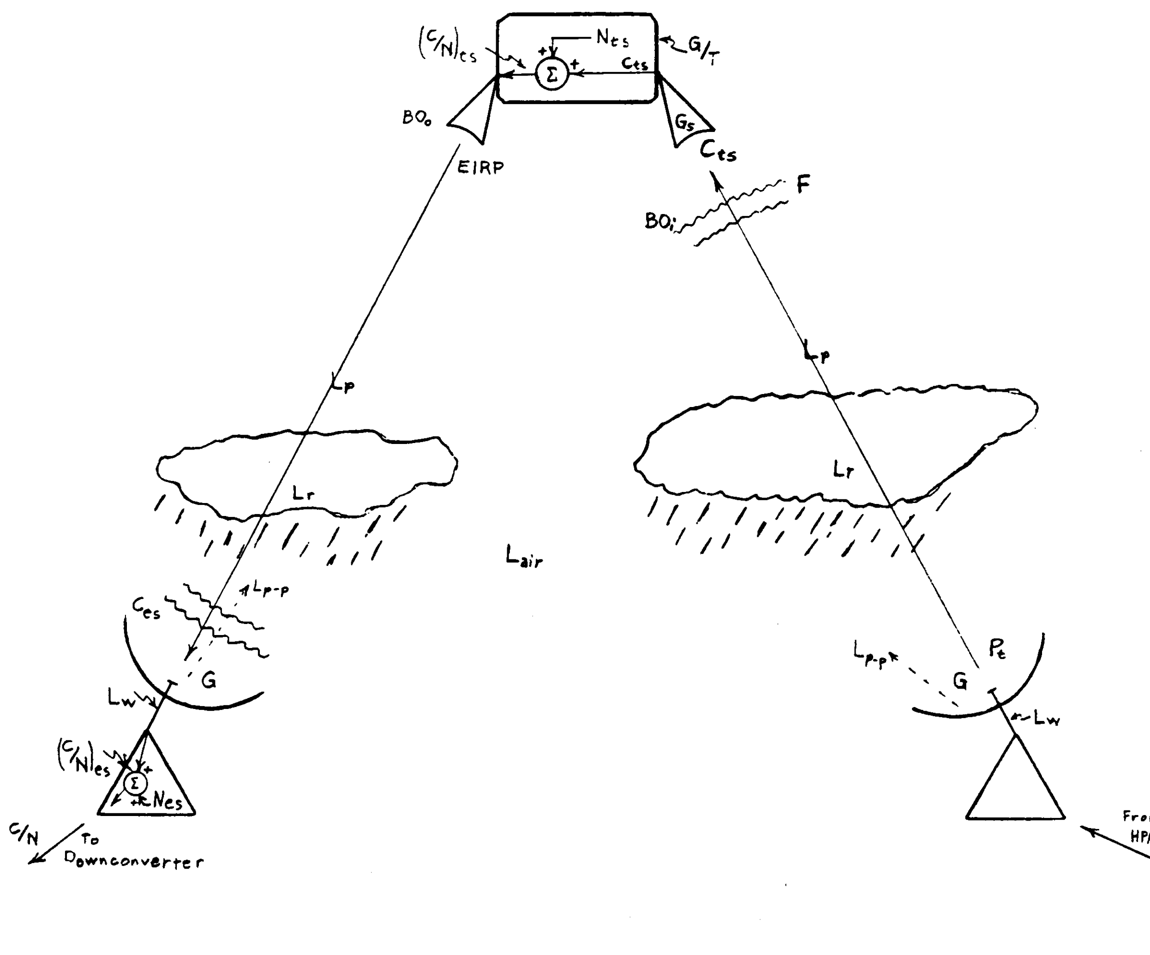

Figure A - 1. System Model for Link Analysis

Earth Station Transmitted Power (P_t) dBW -

Power entering the antenna waveguide of the transmitting earth station.

Waveguide Loss (L_w) dB -

Attenuation in the antenna waveguide for either the uplink or downlink earth station.

Earth Station Antenna Gain (G) dBi -

The gain of the earth station antenna calculated for either the specified uplink frequency or the specified downlink frequency.

Antenna Pointing and Polarization Loss (L_{p-p}) dB -

A small margin allowed for pointing and polarization misalignments between an earth station and a satellite.

Rain Margin (L_r) dB -

Rain attenuation level specified by the user for both the uplink and the downlink.

Atmospheric Attenuation (L_{air}) dB -

Clear air losses due to the atmosphere.

Free Space Loss (L_p) dB -

Also known as path loss, this is a frequency dependent loss figure accounting for the dissipation of radiative power.

Transponder Saturation Flux Density (F) dBW/m^2 -

Specified in the satellite table. This is the flux density required to drive a satellite transponder amplifier into saturation.

Effective Input Backoff ($B0_i$) dB -

The degree to which the flux density of a signal arriving at the satellite is below the specified saturation flux density.

Transponder Gain-to-Noise Temperature Ratio (G/T) dB/K -

The figure of merit for the satellite antenna as seen from the transmitting earth station.

Transponder Antenna Gain (G_s) dBi -

The calculated gain of a satellite antenna in the direction of the transmitting earth station.

Transponder Carrier Level (C_{ts}) dBW -

Power of the received signal at the antenna terminals in the satellite.

Transponder Noise Power (N_{ts}) dBW -

The sum of the thermal noise power and the estimated interference and intermodulation noise power in the satellite transponder.

Transponder Carrier-to-Noise Ratio $(C/N)_{ts}$ dB -

Carrier-to-noise ratio calculated for the transponder carrier level and transponder noise power.

Satellite EIRP ($EIRP$) dBW -

EIRP of the satellite accounting for any output backoff associated with the received signal flux density.

Earth Station Carrier Level (C_{es}) dBW -

Power of the received signal at the antenna terminals in the receiving earth station.

ver (N_{es}) dBW -

l noise power and the estimated interference noise power at the

Noise Ratio $(C/N)_{es}$ dB -

ılated for the earth station carrier level and the earth station noise

atio (C/N) dB -

h the earth station C/N ratio and the transponder C/N ratio.

scribed in Section A.2. Sample program output is provided in

Section A.3.

A.2 Numerical Procedure

A.2.1 Introduction

Although the analyses associated with choice "C" and choice "T" from the main menu are very similar, their corresponding calculations proceed in opposite directions with respect to the signal propagation. Calculations initiated by choice "C" begin with parameters of the transmitting earth station and end with parameters of the receiving earth station. Choice "T" starts with parameters of the receiving earth station and ends with parameters at the transmitting earth station.

A.2.2 Assumed Values

Although most of the power budget parameters are either calculated or user specified, antenna pointing and polarization losses and atmospheric attenuation are assumed. Antenna pointing and polarization losses, L_{p-p}, are considered together and are assumed to cause a 0.5 dB loss on both the uplink and downlink. Atmospheric attenuation for most frequency bands is assumed to cause 0.5 dB attenuation on both the uplink and downlink.

A.2.3 Standard Calculations

The following expressions are calculated in a similar manner whether "C" or "T" is selected.

Look Angles [32]

The satellite elevation angle at an earth station describes how far in degrees above the horizon the satellite is located. This angle is found by first calculating the central angle, γ, shown in Figure A-2:

$$\cos(\gamma) = \cos(L_e)\cos(l_s - l_e) \qquad (A-1)$$

where L_e = latitude of the earth station

l_e = longitude of the earth station

l_s = longitude of the satellite.

By observing the geometry depicted in Figure A-2, the distance, d, from the earth station to the satellite is found according to the Law of Cosines.

$$d = [r_s^2 + (r_e + h)^2 - 2r_s(r_e + h)\cos(\gamma)]^{1/2} \qquad (A-2)$$

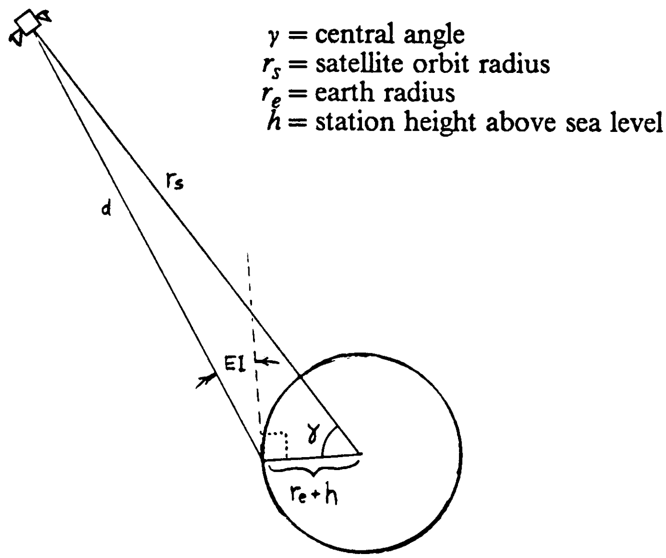

Figure A - 2. Look Angle Geometry

The elevation angle, El, is then calculated from this next relation:

$$\cos(El) = \left(\frac{r_s}{d}\right)\sin(\gamma). \qquad (A-3)$$

The azimuth angle, Az, describes how far from north the satellite is lies when its location vector is projected in the local horizontal plane. To find this angle, first define the following quantities.

$$\begin{aligned} a &= |l_s - l_e| \\ c &= |L_e - L_s| \\ s &= 0.5(a + c + \gamma) \\ \alpha &= 2\tan^{-1}\left\{\frac{[\sin(s-\gamma)\sin(s-c)]}{[\sin(s)\sin(s-a)]}\right\}^{\frac{1}{2}} \end{aligned} \qquad (A-4)$$

The last calculation for azimuth angle depends upon the earth station location with respect to the geosynchronous satellite orbit:

$$\begin{array}{ll} Az = 180° + \alpha & \text{subsatellite point SW of earth station} \\ Az = 180° - \alpha & \text{subsatellite point SE of earth station} \\ Az = 360° - \alpha & \text{subsatellite point NW of earth station} \\ Az = \alpha & \text{subsatellite point NE of earth station} \end{array} \qquad (A-5)$$

Antenna Gains [22], [32]

The transmit or receive gain, G, of the parabolic reflector antennas used by most earth stations can be described by the following relation:

$$G = G_o \log\left(\frac{f}{f_o}\right) \text{ dB} \qquad (A-6)$$

where f_o = a reference frequency

G_o = a reference gain at frequency f_o

The receive gain of a satellite antenna, G_s, can be closely approximated in terms of the satellite saturation EIRP aimed at the transmitting earth station and the maximum output power of the satellite, P_s:

$$G_s = EIRP - P_s \text{ dB} \qquad (A-7)$$

Free Space Loss [22], [32]

Free space loss, L_p, is incurred on both the uplink and the downlink. It is dependent on both frequency, f, and distance, d. In general, f and d are not the same for both the uplink and the downlink.

$$L_p = 20 \log\left(\frac{4\pi f d}{c} \right) \text{ dB} \qquad (A-8)$$

where c = speed of light in a vacuum.

Free space loss should not be confused with loss due to beam spreading, L_{spred}. For an earth station modeled as an isotropic radiation source, this latter quantity is expressed as follows:

$$L_{spred} = 10 \log(4\pi d^2) \text{ dB} \qquad (A-9)$$

Noise Power [18], [22], [32] , [49]

Thermal noise power, N, is introduced at both the satellite transponder and the receiving earth station. It is dependent upon the specified RF bandwidth, B, the system noise temperature, T_s, and Boltzmann's constant, k:

$$N = kT_s B \quad \text{Watts} \qquad (A-10)$$

Thermal noise power is calculated separately for both the satellite transponder and the receiving earth station.

The thermal noise in the transponder is found by relating the calculated antenna gain at the satellite, G_s, and the antenna gain-to-noise temperature ratio, G/T:

$$T = G - \frac{G}{T} \quad \text{dBK} \qquad (A-11)$$

Additional noise is introduced at the receiving earth station during downlink rain. The increase in thermal noise due to rain, T_r, is a function of this attenuation:

$$T_r = 273(1 - L_r^{-1}) \quad \text{K} \qquad (A-12)$$

where the downlink rain attenuation, L_r, is expressed in ratio form.

Noise due to interference sources also enter both the satellite transponder and the receiving earth station. The degree of this interference noise varies with the amount of communications traffic in the specified frequency band. Intermodulation products introduced by non-linear behavior of the satellite transponder also introduce more noise. *LAMP* accounts for this excess noise by increasing the calculated thermal noise power by the amounts designated in Table A-1. These amounts were estimated according to the present day usage of active transponders in various frequency bands [18], [49] .

Power Flux Density [22], [32]

Given the earth station transmitted power, P_t, the carrier power flux density at the satellite, F, is calculated by the following relation:

Table A - 1. Frequency Bands and Excess Noise Power

Frequency Band	Frequency Range (GHz)	Added Noise Power (dB)
L	1-2	0.5
S	2-4	0.3
C	4-8	2.5
X	8-12	0.3
Ku	12-18	0.5
K	18-27	0.5
Ka	27-40	0.3
Millimeter	40-300	0.3

$$F = P_t + G - L_w - L_{air} - L_{p-p} - L_r - L_{spred} \ \text{dBW/m}^2 \qquad (A-13)$$

where L_w = earth station antenna waveguide loss.

If the power flux density is calculated for an adjacent satellite, the earth station antenna gain is calculated in terms of the angle, θ, off the antenna boresight. Assuming that the E and H planes of the earth station antenna differ only slightly, the off-axis gain is expressed as follows:

$$\begin{aligned} G &= 29 - 25\log(\theta) \ \text{dB} \\ \text{or} \quad G &= 32 - 25\log(\theta) \ \text{dB}. \end{aligned} \qquad (A-14)$$

The gain equation used corresponds to the FCC sidelobe pattern specified for the antenna.

Backoff Characteristic [48]

The output power of the satellite transponder is a function of the input flux density. This nonlinear input/output relation is described in terms of the *input* backoff, BO_i, with respect to the transponder saturation flux density and the *output* backoff, BO_o, with respect to the saturation output power. A transponder backoff characteristic from INTELSAT V has been chosen as a typical example of satellite transponder input/output characteristics. This characteristic, shown in Figure A-3, is used in calculating the satellite EIRP from its associated saturation EIRP and input flux density [48].

A.2.4 Carrier-to-Noise Ratio Calculations

The carrier-to-noise ratio at the satellite, $(C/N)_{ts}$, is found by first calculating the carrier power level at the transponder, C_{ts}, and then dividing this quantity by the total transponder noise power, N_{ts} [22], [32].

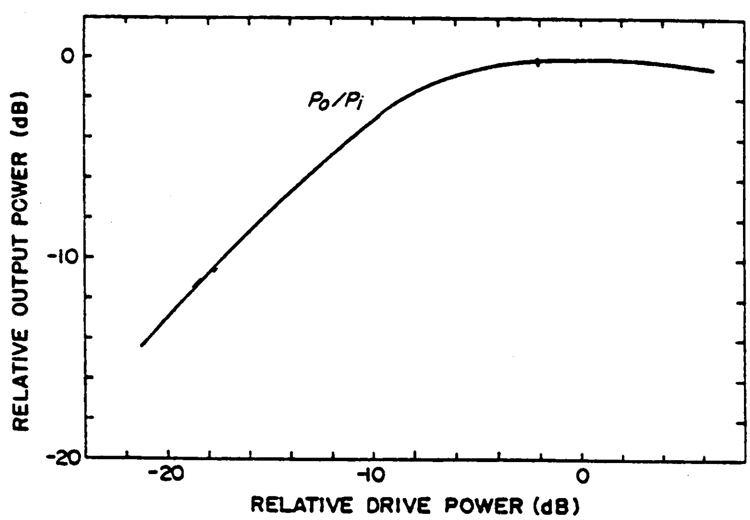

Figure A - 3. Typical Transponder Backoff Characteristic

$$C_{ts} = P_t + G + G_s - L_w - L_{p-p} - L_r - L_{air} - L_p \text{ dBW} \qquad (A-15)$$

$$\left(\frac{C}{N}\right)_{ts} = C_{ts} - N_{ts} \text{ dB} \qquad (A-16)$$

The carrier-to-noise ratio at the earth station, $(C/N)_{es}$ is calculated in a similar manner. The EIRP of the satellite, however, is a function of the input backoff power flux density. $(C/N)_{es}$ is also a function of the earth station total noise power, N_{es}.

$$C_{es} = EIRP + G_r - L_p - L_{air} - L_r - L_{p-p} - L_w \text{ dBW} \qquad (A-17)$$

$$\left(\frac{C}{N}\right)_{es} = C_{es} - N_{es} \text{ dB} \qquad (A-18)$$

The overall carrier-to-noise ratio, C/N, is then calculated as follows:

$$\frac{C}{N} = \left[\left(\frac{C}{N}\right)_{ts}^{-1} + \left(\frac{C}{N}\right)_{es}^{-1}\right]^{-1} \text{ dB} \qquad (A-19)$$

where $(C/N)_{ts}$ and $(C/N)_{es}$ are expressed in ratio form.

A.2.5 Transmitted Power Calculations

For choice "T" in the main menu, *LAMP*, first finds the earth station carrier level and earth station carrier-to-noise ratio assuming that the satellite transponder is driven into saturation. The corresponding carrier-to-noise ratio at the satellite is then calculated:

$$\left(\frac{C}{N}\right)_{ts} = \left[\left(\frac{C}{N}\right)^{-1} - \left(\frac{C}{N}\right)_{es}^{-1}\right]^{-1} \text{ dB} \qquad (A-20)$$

From this result the carrier power at the satellite is calculated.

$$C_{ts} = \left(\frac{C}{N}\right)_{ts} + N_{ts} \;\; \text{dBW} \qquad (A-21)$$

Lastly, the required transmitted power is calculated:

$$P_t = C_{ts} - G_s - G + L_{p-p} + L_{air} + L_r + L_w \;\; \text{dBW} \qquad (A-22)$$

The initial value obtained for P_t, however, may not be correct. As a check, *LAMP* performs the calculations described in Section A.2.4 until a quantity for the carrier level at the receiving earth station is found [22], [32]. If this new value for C_{es} does not match the previous value, appropriate transponder input/output backoff levels are introduced. Eventually, C_{es}, $(C/N)_{es}$, C_{ts} , $(C/N)_{ts}$, and P_t are found by seeking an iterative solution.

A.3 Illustrative Example

To provide an example application for LAMP operation, compare, the power budget elements of a hypothetical VSAT system with the same figures calculated by *LAMP*.

The following tables depict the operation of a VSAT system [6] :

Note that the C/N_o figures found in the preceding tables can be obtained by adding 77.32 dBHz (54 MHz) to the following C/N ratios calculated by LAMP.

Note also that LAMP creates a concise document containing the pertinent information found in the preceding series of tables.

Slight discrepancies in the two system descriptions are due to variations in implementation margins.

SATELLITE PARAMETERS

System	A	B	C
EIRP Range (dBW)	39–47	40–47	38–44
U.S. Coverage (dBW)	45	41	40
G/T Range (dB/K)	−1 to +6	−1.4 to +0.6	−4 to +1
U.S. Coverage (db/K)	+2	−1	−1
Saturation Flux Density (dBW/m^2)	−91 to −98	−73 to −94	−82 to −88
Transponder Bandwidth (MHz)	54	54	72
Polarization	Linear	Linear	Linear
Cross-pol	Yes	Yes	No

TRANSMISSION SYSTEM PARAMETERS

	Parameters	
Subsystem/Equipment	**Remote Terminal**	**Hub Terminal**
Antenna		
Diameters (Meters)	1.8	1.8 2.4 3.7 5.5
Transmit Gain (14 GHz) dBi	46.5	46.5 49 52.5 56.5
Receive Gain (12GHz) dBi	45	45 47.5 51 55
Noise Temp (Elevation 10°)	50	50 50 50 50
Transmitter		
Amplifier Type	Solid State	TWTA
Power Watts (Nominal)/Carrier	2	See Table 11
Modulation	Differential BPSK	Differential BPSK
FEC Coding Convolutional	Rate 1/2	Rate 1/2
Receiver		
Front End Type	LNC	FET-LNA
Noise Temp °K (Max)	290	180
Demodulation	Differential	Differential
FEC Decoding	Viterbi 3-bit Soft Decision	Viterbi 3-bit Soft Decision
Constraint Length (Cost Effective)	5	5
E_b/N_o Including Modem (dB) at 10^{-7} BER	8	8
System Noise Temp (Clear Sky) °K	370	260
G/T (Clear Sky) dB/K	19.3	20.9, 23.3, 26.9, 30.9

TRANSMISSION SYSTEM PARAMETERS (CONTINUED)

Satellite Link	
Up-Link Frequency	14.0 GHz
Up-Path Loss, Including Blue Sky	207.5 dB
Tracking Loss (Maximum)	1.2 dB
Up-Path Rain Margin for 0.995 System Availability (dB)	4
Satellite G/T (U.S. Coverage)	See Table IV
Gain of $1M^2$ at 14 GHz, Gm	44.4 dB
Down-Link Frequency	12.0 GHz
Down-Path Loss, Including Blue Sky	206.0 dB
Down-Path Tracking Loss (Maximum)	0.8 dB
Total Down-Link Margin for 0.995 System Availability (Inc. 1 dB for G/T Degradation) dB	3
Saturated Satellite EIRP (U.S. Coverage)	See Table IV
Saturated Flux Density	See Table IV
Back-Off for Multi-Carrier Operation Output	−3.5 dB
Input	9 dB
Multi-Carrier-to-Intermodulation Noise Density	94.5 dB Hz

HUB-TO-REMOTE LINK

Satellite	A	B	C
High-Gain Saturation Flux Density (dBW/m^2)	−98	−91	−88
Transponder Input Back-Off (dB)	9	9	9
G/T (dB/K)	+2	−1	−1
$(C/No)_{up}$ (dBHz)	79.2	80.2	86.2
$(C_M/No)_{Intermod}$ (dBHz)	94.5	94.5	94.5
$(C/No)_{up} + (C/No)_{Intermod}$ (dBHz)	79.1	80	85.6
$(C/No)_{Dn}$ (dBHz)	79.6	75.6	74.6
$(C/No)_T$ (dBHz)	76.3	74.2	74.3
Interference and System Implementation Margin (dB)	2	2	2
Net $(C/No)_T$	74.3	72.2	72.3
Required Eb/No (dB)	8	8	8
Maximum Link Transmission Rate (Mbps)	4.265	2.630	2.691
Single-Channel Rate Without Coding (Kb/s)	56	56	56
Single-Channel Rate With (R 1/2) Coding (Kb/s)	112	112	112
No. of 56 Kb/s Carriers Permissible	38	23	24
Backed-Off Satellite EIRP (dBW)	41.5	37.5	36.5
Satellite EIRP Carrier (dBW)	25.7	23.8	22.7
(Watts)	370	240	190

LINK BUDGET ANALYSIS

UPLINK ANTENNA: HUB DOWNLINK ANTENNA: REMOTE
SATELLITE: A 118.0 deg. W. long.
TRANSMITTING EARTH STATION: Virginia Tech - Blacksburg VA
LOOK ANGLES: El= 31.77 deg. Az= 231.81 deg.
RECEIVING EARTH STATION: Hub Station
LOOK ANGLES: El= 21.62 deg. Az= 257.94 deg.

SPECIFIED BANDWIDTH	54.00 MHz
SPECIFIED UPLINK FREQUENCY	14.00 GHz
SPECIFIED DOWNLINK FREQUENCY	12.00 GHz
SPECIFIED EARTH STATION TRANSMITTED POWER	4.40 dBW
UPLINK RAIN MARGIN	0.00 dB
DOWNLINK RAIN MARGIN	0.00 dB

UPLINK

EARTH STATION TRANSMITTED POWER	4.40 dBW
WAVEGUIDE LOSS	0.20 dB
EARTH STATION ANTENNA GAIN	52.50 dB
ANTENNA POINTING AND POLARIZATION LOSS	0.50 dB
RAIN MARGIN	0.00 dB
ATMOSPHERIC ATTENUATION	0.50 dB
FREE SPACE LOSS	207.08 dB
TRANSPONDER SATURATION FLUX DENSITY	-98.00 dBW/sq. m.
EFFECTIVE INPUT BACKOFF	9.01 dB
TRANSPONDER G/T	2.00 dB/K
TRANSPONDER ANTENNA GAIN	32.00 dB
TRANSPONDER CARRIER LEVEL	-119.38 dBW
TRANSPONDER NOISE POWER	-120.78 dBW
TRANSPONDER C/N	1.39 dB

DOWNLINK

SATELLITE EIRP WITH BACKOFF	42.69 dBW
FREE SPACE LOSS	205.95 dB
ATMOSPHERIC ATTENUATION	0.50 dB
RAIN MARGIN	0.00 dB
ANTENNA POINTING AND POLARIZATION LOSS	0.50 dB
EARTH STATION ANTENNA GAIN	45.00 dB
WAVEGUIDE LOSS	0.20 dB
EARTH STATION CARRIER LEVEL	-119.46 dBW
EARTH STATION NOISE POWER	-125.10 dBW
EARTH STATION C/N	5.64 dB
OVERALL C/N	0.01 dB

INTERFERENCE FLUX DENSITY

At 116.0 deg. W. longitude:
El= 33.11 deg. Az= 229.76 deg.
FLUX= -140.21 dBW/sq. m.

At 120.0 deg. W. longitude:
El= 30.39 deg. Az= 233.78 deg.
FLUX= -140.08 dBW/sq. m.

Appendix B: LAMP Theory of Operation for Rain Fade Performance Analysis

B.1 Introduction

In addition to calculating power budgets, *LAMP* calculates and prints rain fade performance analyses for geosynchronous satellite links. It operates on an IBM PC with DOS version 2.1 or higher. It also requires use of an IBM PC compatible graphics printer. *LAMP* was developed as part of the IBM/Virginia Tech Joint Development Project. The following sections describe the carrier-to-noise ratio, signal-to-noise ratio, and bit error rate calculations used by *LAMP* to produce rain fade performance analyses.

The overall performance analysis calculations are based on the system described in the previously calculated power budget analysis. Performance calculations involving overall carrier-to-noise ratios assume that all of the communcation system parameters except those affected by rain attenuation remain fixed. Additional calculations applicable toward specific system implementations are then performed as requested by the operator.

B.2 Numerical Procedures

B.2.1 The Overall Carrier-to-Noise Ratio

Calculation of the received overall carrier-to-noise ratio, C/N , procedes as explained in Appendix A, Sections A.2.3 (**Noise Power**) and A.2.4. In the performance calculations, however, the rain attenuation, L_r, is allowed to vary while the transmitted power remains fixed.

B.2.2 Analog System Performance

Analyses made for analog system applications calculate the received signal-to-noise ratio, S/N, associated with a certain level of rain attenuation. These signal-to-noise ratios are found for the four different applications shown on the following pages [32].

Most of the performance calculations are linear given that the carrier-to-noise ratios remain above the threshold of the FM demodulator (about 10 dB). If a threshold extension in dB is specified, then the calculations remain linear for the amount of extension below the 10 dB carrier-to-noise level. An example of this extension is shown in Figure B-1.

FDM/FM Voice Channel Performance

The worst case S/N for FDM/FM voice channel operations can be described by the following relation:

$$\frac{S}{N} = \frac{C}{N} + 10\log\left(\frac{B}{b}\right) + 20\log\left(\frac{f_{rms}}{f_{\max}}\right) + P + W \text{ dB} \qquad (B-1)$$

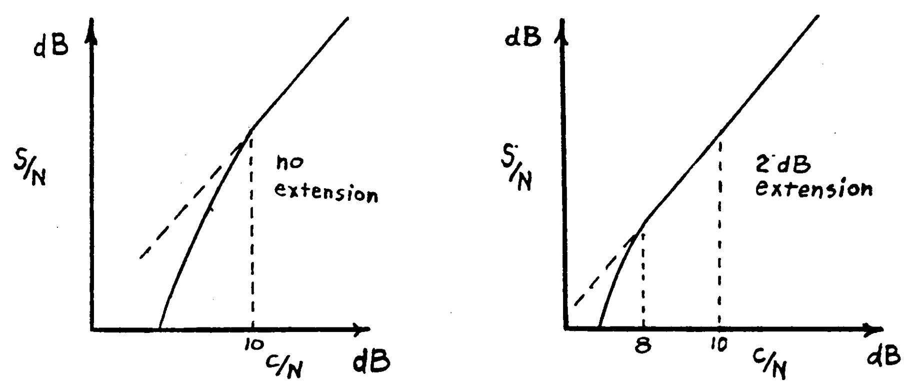

Figure B - 1. Example of 2 dB Threshold Extension

where B = transmitted RF bandwidth

b = channel bandwidth (3.1 kHz assumed)

f_{rms} = rms test tone deviation

$f_{\max}$ = top baseband channel frequency

P = preemphasis improvement (4 dB)

W = psophometric weighting (2.5 dB)

If $f_{\max}$ is unknown, *LAMP* approximates this frequency in Hertz by multiplying the number of channels by 4200. If f_{rms} is unknown, *LAMP* approximates this frequency by applying Carson's rule,

$$B = 2[3.16(l)(f_{rms}) + f_{\max}] \text{ Hz} \qquad (B-2)$$

and solving for f_{rms}. Note that the peak frequency deviation frequency is found by multiplying f_{rms} by 3.16, and by a loading factor, l. The 3.16 factor is a standard deviation value representing the 0.1 per- cent upper tail of a Gaussian distribution of signal voltages. The loading factor is a function of the number of channels, N.

$$\begin{aligned} 20\log(l) &= -15 + 10\log(N) \qquad N \geq 240 \\ &= -1 + 4\log(N) \qquad 12 < N < 240 \end{aligned} \qquad (B-3)$$

The assumed values for preemphasis improvement and psophometric weighting comply with the CCIR and CCITT standards respectively.

Single Channel per Carrier Performance

The resulting S/N for single channel per carrier systems is described below:

$$\frac{S}{N} = \frac{C}{N} - 94.5 + 20\log(f_p) + 10\log(B) \text{ dB} \qquad (B-4)$$

where f_p = peak test tone deviation.

If companding is used in this type of system, an improvement of 17 dB is usually obtained.

Companded Single Sideband Performance

Companded single sideband performance is calculated by this formula:

$$\frac{S}{N} = \frac{C}{N} + 10\log\left(\frac{B}{b}\right) \text{ dB} \qquad (B-5)$$

As before, the channel bandwidth, b, is assumed to be 3.1 kHz.

FM Television Performance

FM television performance is described in the following equation:

$$\frac{S}{N} = \frac{C}{N} + 1.76 + 10\log\left(\frac{B}{f_v}\right) + 8.16 + P + Q \text{ dB} \qquad (B-6)$$

where f_v = maximum video modulating frequency

Q = psophometric weighting

The U. S. standard for the maximum video modulating frequency is 4.2 MHz.

Psophometric weighting for video is typically much higher than that considered for voice channel. *LAMP* assumes $P + Q$ to provide 20 dB improvement.

B.2.3 Digital System Performance

Analysis for digital system applications first calculate the received bit energy-per-noise density ratio, E_b/N_o, associated with a particular rain fade. This quantity can be expressed in terms of the bit duration, T_b, and the noise bandwidth, B.

$$\frac{E_b}{N_o} = \frac{C}{N} B T_b \tag{B-7}$$

A more general approach to finding this ratio considers the symbol energy, E_s, the symbol duration, T_s, and the symbol error rate, *SER*. In binary modulation schemes symbol error and bit error are the same since one symbol represents one bit.

After calculating the E_b/N_o ratio, *LAMP* finds the bit error rate, *BER*, based on the expressions shown under the following headings [22]. Most of these expressions are given in terms of the Gaussian integral function, $Q(z)$:

$$Q(z) = \frac{1}{\sqrt{2\pi}} \int_z^{\infty} \exp\left(\frac{-x^2}{2}\right) dx \tag{B-8}$$

Because the calculated values for bit error rates are very small, *LAMP* indirectly calculates this integral function according to data obtained from [1].

Binary Phase Shift Keying (BPSK)

$$BER = Q\left(\sqrt{2\frac{E_b}{N_o}}\right) \tag{B-9}$$

Quanternary Phase Shift Keying

$$BER = Q\left(\sqrt{2\frac{E_b}{N_o}}\right) \tag{B-10}$$

Offset or Staggard QPSK (OQPSK or SQPSK)

$$BER = Q\left(\sqrt{2\frac{E_b}{N_o}}\right) \qquad (B-11)$$

Differential Encoding with Coherent Detection (DCQPSK)

$$BER = 2Q\left(\sqrt{\frac{E_b}{N_o}}\right) \qquad (B-12)$$

Differential Encoding with Noncoherent Detection (DQPSK)

$$BER = Q\left(\sqrt{\frac{2E_b}{N_o} 4\sin^2(\frac{\pi}{8})}\right) \qquad (B-13)$$

M-ary Phase Shift Keying (MPSK)

$$SER = 2Q\left(\sqrt{2\frac{E_s}{N_o}} \sin(\frac{\pi}{M})\right)$$
$$BER = \frac{SER}{\log_2(M)} \qquad (B-14)$$

Differentially Encoded Phase Shift Keying (DECPSK)

$$BER = 2Q\left(\sqrt{\frac{2E_b}{N_o}}\right) \qquad (B-15)$$

Differentially Detected Phase Shift Keying

$$BER = \frac{1}{2}\exp\left(\frac{-E_b}{N_o}\right) \qquad (B-16)$$

Fast Frequency Shift Keying (FFSK) or Minimum Shift Keying (MSK)

$$BER = Q\left(\sqrt{\frac{2E_b}{N_o}}\right) \qquad (B-17)$$

Coherently Detected Frequency Shift Keying (CFSK)

$$BER = Q\left(\sqrt{\frac{E_b}{N_o}}\right) \qquad (B-18)$$

Noncoherently Detected Frequency Shift Keying (NCFSK)

$$BER = \frac{1}{2}\exp\left(-\frac{1}{2}\frac{E_b}{N_o}\right) \qquad (B-19)$$

Noncoherent Orthogonal M-ary Frequency Shift Keying (MFSK)

$$\begin{aligned} SER &= \sum_{j=1}^{M-1}(-1)^{j+1}\frac{1}{j+1}\binom{M-1}{j}\exp\left[\frac{-j}{j+1}\frac{E_s}{N_o}\right] \\ BER &= SER\,\frac{2^{k-1}}{2^k-1} \end{aligned} \qquad (B-20)$$

where $k = \log_2(M)$

Data for the commercially produced digital modems were found in the corresponding manufacturer's equipment literature [12] . The performance curves for the ComStream digital modems are shown in Figure B-2.

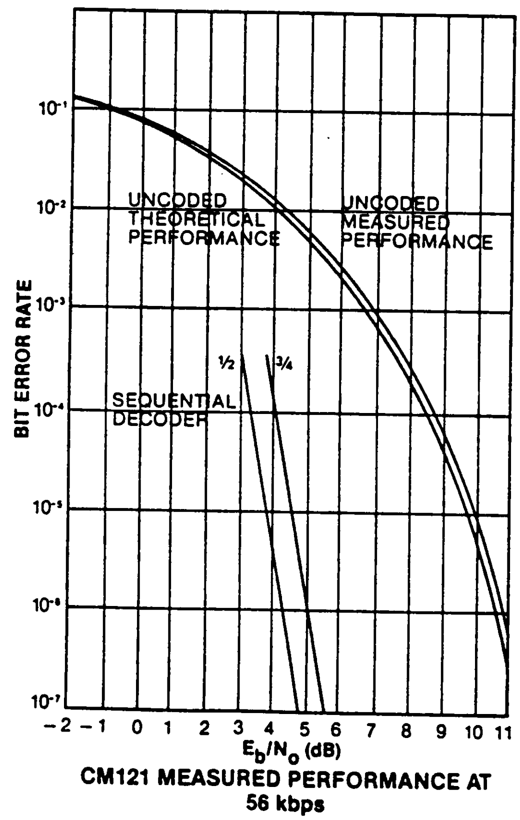

Figure B - 2. ComStream Digital Modem Performance Curves

Appendix C: Calculating Carrier-to-Third-Order Intermodulation Ratios

When three or more equal-amplitude, equally spaced carriers are received by a satellite transponder, intermodulation products appear in the pass bands of each channel. These intermodulation products are caused by the non-linear response of the satellite transponder. The most significant degradation of the channel quality is caused by the third-order intermodulation products. These occur at frequencies $2\omega_i - \omega_{i+1}$ and $\omega_i + \omega_{i+1} - \omega_{i+2}$ such that ω_i, ω_{i+1}, and ω_{i+2} are the carrier frequencies of channels i, $i+1$, and $i+2$ respectively. This appendix follows the necessary calculations for determining the overall carrier-third-order intermodulation ratio due to both amplitude and phase nonlinearities in a satellite transponder. A complete development of these calculations is described in [22].

The number of third-order intermodulation products occurring within the rth channel of n equally spaced channels is found according to the equations shown below:

$$D_{2,1}(r,n) = \frac{1}{2}\left\{n - 2 - \frac{1}{2}[1 - (-1)^n](-1)^r\right\} \qquad (C-1)$$

$$D_{1,1,1}(r,n) = \frac{r}{2}(n - r + 1) + \frac{1}{4}[(n-3)^2 - 5] - \frac{1}{2}[1 - (-1)^n](-1)^{n+r} \qquad (C-2)$$

where $D_{2,1}$ and $D_{1,1,1}$ are the number of $2\omega_i - \omega_{i+1}$ and $\omega_i + \omega_{i+1} - \omega_{i+2}$ type intermodulation products respectively.

The transfer characteristic for the satellite transponder must then be found. For an input voltage amplitude A and an output amplitude B, the characteristic is usually of the following form:

$$B = a_1 A + \frac{3}{4} a_3 A^3 + \frac{5}{8} a_5 A^5 + \frac{35}{64} a_7 A^7 + \cdots \qquad (C-3)$$

where the coefficients a_j are found by least squares fitting, and the voltage amplitudes A and B are normalized such that when $A = B = 1$ the transponder is operating at saturation. The derived transfer characteristic should correspond to the transfer curves of the desired satellite transponder.

From the transponder transfer characteristic, the output voltage amplitudes of the desired carrier and the intermodulation products are determined. First, the total input power, P_{ti}, is found from the transponder input backoff, BO_i, expressed in dB:

$$P_{ti} = \frac{1}{2} \text{ antilog} \left(\frac{BO_i}{10} \right). \qquad (C-4)$$

The output amplitude of an individual carrier, B_n is then found to be

$$\begin{aligned} B_n = a_1 \sqrt{\frac{2P_{ti}}{n}} \Bigg\{ 1 &+ 3\frac{a_3}{a_1}\left(\frac{P_{ti}}{n}\right)\left(n - \frac{1}{2}\right) \\ &+ 15\frac{a_5}{a_1}\left(\frac{P_{ti}}{n}\right)^2\left[\frac{1}{6} + (n-1)(n-2) + \frac{3}{2}(n-1)\right] \\ &+ 105\frac{a_7}{a_1}\left(\frac{P_{ti}}{n}\right)^3 [(n-1)(n-2)(n-3) \\ &+ 3(n-1)(n-2) + \frac{34}{24}(n-1) + \frac{1}{24}] + \cdots \Bigg\}. \end{aligned} \qquad (C-5)$$

Two calculations must be made for the amplitude of the third-order intermodulation products. For $2\omega_i - \omega_{i+1}$ type intermodulation, the amplitude $V_{2,1}$ is given as follows:

$$V_{2,1} = \frac{3}{4} a_3\left(\frac{2P_{ti}}{n}\right)^{3/2}\left\{1 + \frac{2a_5}{3a_3}\left(\frac{P_{ti}}{n}\right)\left[\frac{25}{2} + 15(n-2)\right] + 105\frac{a_7}{a_3}\left(\frac{P_{ti}}{n}\right)^2\left[(n-2)(n-3) + \frac{13}{6}(n-2) + \frac{7}{12}\right] + \cdots\right\}. \qquad (C-6)$$

For $\omega_i + \omega_{i+1} - \omega_{i+2}$ type intermodulation, the amplitude $V_{1,1,1}$ is given as

$$V_{1,1,1} = \frac{3}{2} a_3\left(\frac{2P_{ti}}{n}\right)^{3/2}\left\{1 + 10\frac{a_5}{a_3}\left(\frac{P_{ti}}{n}\right)\left[\frac{3}{2} + (n-3)\right] + 210\frac{a_7}{a_3}\left(\frac{P_{ti}}{n}\right)^2\left[1 + \frac{7}{4}(n-3) + \frac{1}{2}(n-3)(n-4)\right] + \cdots\right\}. \qquad (C-7)$$

It is assumed that the modulated phases and all intermodulation products are independent. This assumption allows the total power of all the intermodulation products to equal the sum of the individual powers for each intermodulation product. The resulting carrier-to-third-order intermodulation ratio in the rth channel $(C/I)_r$ due to amplitude non-linearity becomes

$$\left(\frac{C}{I}\right)_r = \frac{B_n^2}{D_{2,1}(r,n)V_{2,1}^2 + D_{1,1,1}(r,n)V_{1,1,1}^2}. \qquad (C-8)$$

where $(C/I)_r$ is expressed in ratio form.

Phase non-linearity in the satellite transponder also degrades a received channel. A first order approximation of the C/I ratios for n equally spaced carriers such that $n >> 10$ is shown below:

$$\left(\frac{C}{I}\right)_{p-2,1} = \frac{2n}{0.1516K_o} \qquad [C-9]$$

for $2\omega_i - \omega_{i+1}$ type intermodulation products, and

$$\left(\frac{C}{I}\right)_{p-1,1,1} = \frac{n}{0.1516K_o} \qquad (C-10)$$

for $\omega_i + \omega_{i+1} - \omega_{i+2}$ type intermodulation products. K_o is an amplitude modulation-phase modulation conversion coefficient. Typical values for K_o range from 0.5 to 3.

For a fewer number of channels, intermodulation noise due to phase non-linearity is small relative to that due to amplitude non-linearity. With fewer channels, the overall carrier-to-third-order intermodulation ratio is reduced about 1 or 2 dB.

The overall carrier-to-third-order intermodulation ratio is calculated from the ratios found for both amplitude and phase non-linearities in the satellite transponder. This calculation is similar to finding overall carrier-to-noise ratios in power budget analyses. All values are expressed in ratio form:

$$\frac{C}{I} = \left[\left(\frac{C}{I} \right)_r^{-1} + \left(\frac{C}{I} \right)_{p-2,1}^{-1} + \left(\frac{C}{I} \right)_{p-1,1,1}^{-1} \right]^{-1}. \qquad (C-11)$$

With the calculated overall C/I ratio for third-order intermodulation products, the feasibility of transmitting several carriers within a transponder can be determined.

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