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(NASA-CR-181088) A 30/20 GHz FSS FEASIBILITY STUDY Final Report (Signatron) 296 p Avail: NTIS HC A13/MF A01 CSCL 17B

N87-24592

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30/20 GHz FSS FEASIBILITY STUDY

FINAL REPORT

JPL Contract No. 957641

12 February 1987

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This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration.

FOREWORD

This is the final report under the Feasibility Study of Interactive Low and Medium Data Rate Satellite Links in the High Frequency Fixed Satellite Services (FSS) Bands. The principal authors of this report are Mr. William T. Ralston and Mr. John A. Kilpatrick, the SIGNATRON project manager. Significant contributions were also made by Dr. Brian E. White, formerly of SIGNATRON, and Mr. Wayne T. Chen of W.T. Chen & Co., Inc. a market analysis consultant.

ABSTRACT

This study was performed to determine the near term feasibility of direct-to-subscriber services using the 30/20 GHz Fixed Satellite Services frequency bands, and to identify those technologies which need to be further developed before such a system can be implemented.

To determine this feasibility, dozens of potential applications were examined for their near-term viability, and the subscriber base of three promising applications were estimated. The system requirements, terminal design, and satellite architecture were all investigated to determine whether a 30/20 GHz FSS system is technically and economically feasible by the mid-1990s.

We have concluded that such a system is feasible, although further maturation of some technologies is needed. This system would likely consist of one or two multibeam satellites serving hub/spoke networks of simple user terminals and more complex, multi-channel terminals of the service providers. Rain compensation would be accomplished non-adaptively through the use of coding, non-uniform satellite TWT power that is a function of a beam's anticipated downlink fading, and signal regeneration of traffic to the wettest climate regions. We also estimate that a potential market of almost two million users could exist in the mid-1990s time frame for home banking and financial services via Ka-band satellite.

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SECTION 1
INTRODUCTION

1.1 PROBLEM ADDRESSED

The history of satellite communications has shown a marked trend towards placing the earth terminals with the end users. Early systems employed large terminals and very simple bent-pipe transponders; the users would interface to the ground stations via landline or other established media. As satellite technology has matured, more and more of the system complexity has been placed in the space segment resulting in ever simpler (and smaller) earth terminals. Some examples of this trend are the VSATs (Very Small Aperture Terminals) operating in the Ku-band, ACTS (Advanced Communications Technology Satellite) with its Micro-1 terminals, and the portable terminals being used by many television news organizations. It seems inevitable that this trend will continue.

Along with this shift towards the end user is an associated shift to higher frequencies. This is mainly due to the competition for lower frequency bands. The Mobile Satellite Service (MSS) was unable to get the UHF frequencies it has fought for and instead was awarded spectrum at L-band. Likewise, C-band is nearing saturation with satellites now being placed at 2° orbital spacing. The spectrum of the future would appear to be the Ku- and Ka-bands. Aside from bandwidth competition, the shift towards small terminals has also focused attention on higher frequencies since smaller antennas are able to achieve the necessary gains.

The combination of these two trends in the satellite communications industry has led to this study effort: determine the feasibility of using the 30/20 GHz band (or higher) for low and medium data rate applications of Fixed Satellite Services (FSS). A complete list of the frequency bands allocated to the FSS is given in Table 1-1 [Reinhart, 1981]. It shows that as much as 3 GHz of bandwidth is allocated to FSS at Ka-band. In that no U.S. satellite which would use these frequencies has yet been placed in orbit (ACTS is scheduled for launch in 1990), one can see that tremendous spectrum availability exists at Ka-band.

A number of potential applications have been identified for direct-to-subscriber FSS. These applications include home shopping, rural telephone, utility meter reading, electronic mail delivery, at home education, opinion polls, and financial transactions; the list is virtually endless. One of the tasks of this study was to examine as many potential applications as possible and identify those that are the most promising.

With these applications as a focal point, the main thrust of this feasibility study was to:

1) determine the requirements of a satellite system to serve these applications,
2) propose the design of both the space and ground segments,
3) identify those areas of the design which are constrained technologically, and

Table 1-1
Fixed-Satellite Service Allocations

BAND	FREQUENCY RANGE (GHz)	RESTRICTION
	2.5-2.535	1n, 2d, 3d
S	2.535-2.655	1n, 2d, 3n
	2.655-2.690	1n, 2b, 3u
	3.4-4.2	d
4	4.5-4.8	d
	5.725-5.85	1u, 2n, 3n
6	5.85-7.075	u
7	7.25-7.75	d
8	7.9-8.4	u
11	10.7-11.7	1b*, 2d, 3d,
12	11.7-12.3	1n, 2d, 3n
	12.5-12.7	1b,2n,3d
	12.7-12.75	1b, 2u, 3d
	12.75-13.25	u
14	14.0-14.5	u
	14.5-14.8	u*
	17.3-17.7	u*
	17.7-18.1	b*
20	18.1-21.2	d
	27.0-27.5	1n, 2u•, 3u•
30	27.5-31.0	u
	37.5-40.5	d
	42.5-43.5	u
	47.2-49.2	u*
	49.2-50.2	u
	50.4-51.4	u
	71-74	u
	74-75.5	u
	81-84	d
	92-95	u
	102-105	d
	149-164	d
	202-217	u
	231-241	d
	265-275	u

* uplink limited to Broadcasting Satellite Service (BSS) feeder links
• intended for but not limited to BSS feeder links

KEY:				
	1	Region 1	n	Not Allocated
	2	Region 2	u	Uplink (earth to space)
	3	Region 3	d	Downlink (space to earth)
			b	Bidirectional

4) estimate the potential subscriber base that could be served by such a system.

These results should assist the Jet Propulsion Laboratory (JPL) and NASA in determining whether this is a viable area for further study and what technologies in particular on which to concentrate.

1.2 POTENTIAL SOLUTION

Our study has identified those techniques which we view as the most promising candidates in providing a feasible direct-to-subscriber FSS system. This system includes:

1) Two types of earth stations to serve the end users and service providers;

2) Relatively inexpensive single channel user terminals which interface to a personal computer, consisting of 2.5 foot (0.8 m) dish antennas, 500°K low noise amplifiers (LNAs), one to five watt high power amplifiers (HPAs), and rate 1/2 convolutional encoders;

3) More expensive supplier terminals with multiple channel capacity, consisting of 17 foot (5.3 m) dish antennas, 400° LNAs, and 50 watt HPAs;

4) Either Modified Pure ALOHA or spread spectrum multiple access schemes for the user terminals to minimize their timing and control functions;

5) Straight TDMA at the supplier terminals to make efficient use of the spectrum;

6) A pilot tone transmitted through the satellite to achieve better frequency accuracy at a lower terminal cost;

7) Multiple spot beams on both the uplink and downlink to the user terminals to compensate for their small antennas;

8) One CONUS beam to the supplier terminals so that beam to beam routing is not required;

9) Separate TWTAs in the satellite for each channel of traffic to compensate for rain attenuated signals and to permit saturated operation;

10) Signal regeneration by the satellite of supplier traffic to the wettest climate region; and

11) Public key techniques to provide the required privacy and user authentication.

This proposed system would be capable of providing 0.995 availability to 1 million users and several hundred service providers of low and medium data rate applications.

1.3 STUDY CONCLUSIONS

1.3.1 Applications

After sorting and evaluating hundreds of potential applications of this direct-to-subscriber FSS (see Figure 1-1), SIGNATRON and its market consultants, W.T. Chen & Co., Inc. (WTC), concluded that three market segments were the most promising:

1) Home banking/finance,

2) Home shopping, and

3) Consumer electronics.

The banking and finance applications dealt with making financial transactions (transfer between accounts, pay bills, buy and sell stock, etc.) via a home computer interfaced to the user terminal. Home shopping, in this context, does not refer to the same type of shop-at-home services that currently appear on cable television, but rather represents the interactive examination and buying process of user specified products from hundreds of retail companies. Finally, the consumer electronics segment does not refer to specific end user applications, per se, but instead deals with the market forces which have brought the personal computer (PC), video cassette recorder (VCR), and television receive only (TVRO) equipment into our homes. These forces will soon be introducing high resolution TVs, digital audio tapes, and smart homes which integrate many of these audio/visual products.

A market analysis of these potential applications concluded that the home banking/finance application had the most promise for market acceptance in the 1995 time frame. The estimated market potential for this area of direct to subscriber applications was 1.75 million users. It should be noted that this estimate presumed that many interrelated requirements were fulfilled prior to this time period. These include the further research and development of Ka-band components so that the terminals contain only mature technology; that government regulations involving financial transactions be properly addressed, and if needed, changed; and that existing companies or entrepreneurs will innovatively package and market the services to be attractive to both service providers and consumers. If any one of these requirements is not met by the mid-1990s, then the introduction of the Ka-band direct to subscriber services will be pushed into the next century. In an historical perspective, it is likely that some delay would occur resulting in a late 1990s (or beyond) introduction of these services.

1.3.2 System Design

From the start of this study effort, SIGNATRON believed that the satellite and overall system architecture were the critical parts in creating a feasible FSS design. This was because the user terminals had to be simple and relatively inexpensive in order to be successful. Therefore the satellite

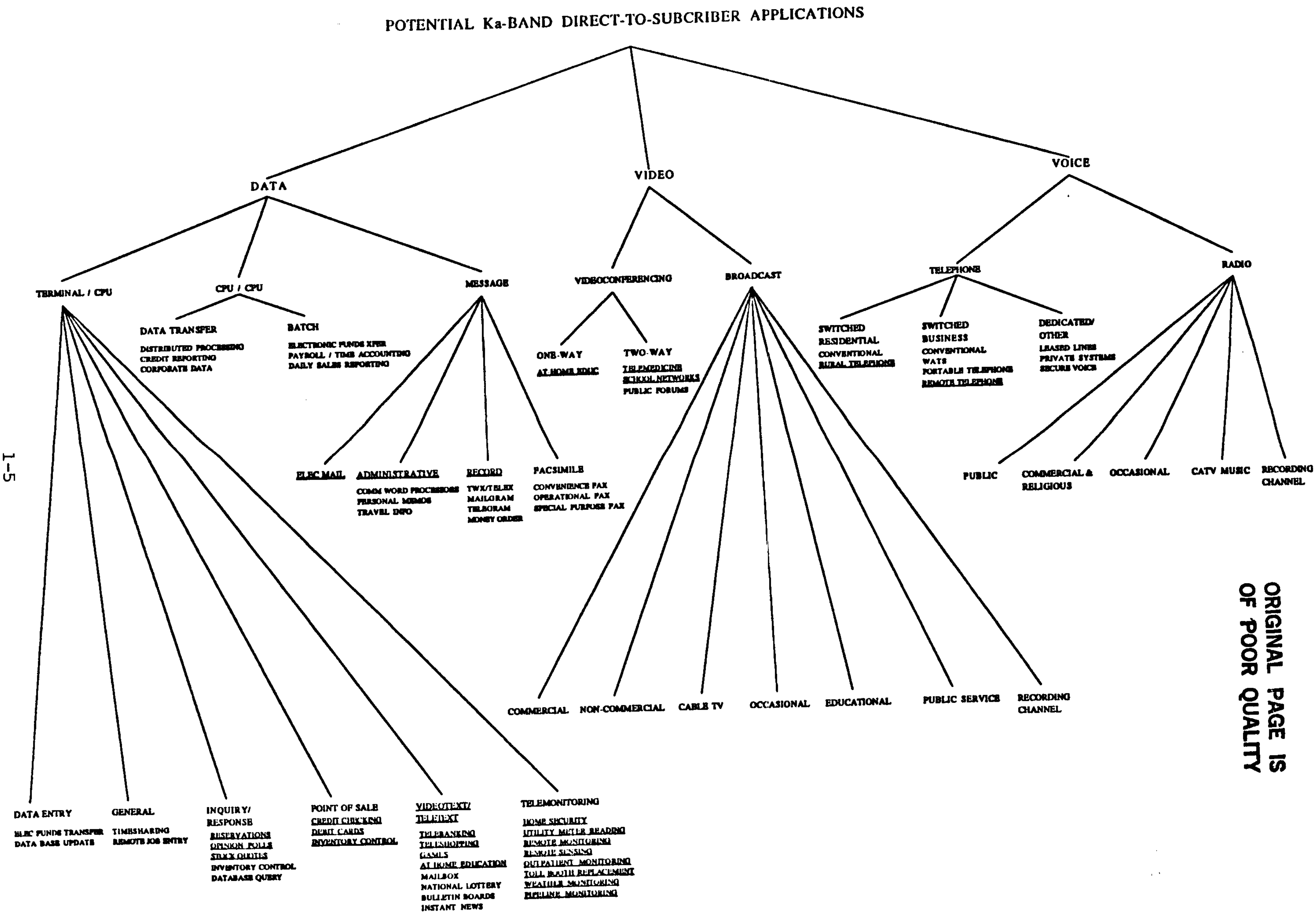

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Figure 1-1 Potential Ka-Band Direct-to-Subscriber Applications and system architecture had to be selected carefully so that the space segment did not become prohibitively complex.

With the help of JPL, we feel that this goal has been accomplished. Several system components stand out as being significant in their contribution to a viable design. First, the applications lent themselves to a hub/spoke network architecture. This allowed us to eliminate the user-to-user link from the design and instead to propose two separate terminal designs: a simpler user terminal and a more complex ground station for the service providers. This also greatly simplified the satellite design since routing between users was no longer required. Second, either Pure ALOHA into one of several FDMA channels per beam or Spread Spectrum Multiple Access (SSMA) is recommended for the user terminals' access scheme. Both of these approaches allow the traffic in each beam to be variable (simply add more channels or bandwidth to accommodate more traffic) and individual small TWTAs can be dedicated to each channel and run at saturation. This TWT approach also provides for rain compensation as more powerful tubes can be allocated to those beams destined for wetter climates and attenuated uplink signals can be amplified to the fullest extent possible (not limited by a stronger adjacent signal amplified by the same tube). The choice between Pure ALOHA and SSMA is not clear at this time since further research is needed into several terminal RF components which are key to one or the other of these access schemes.

1.3.3 Key Terminal Technologies

This study has identified several areas where further research is required before the technology is sufficiently mature for a consumer market. In particular, these include the RF portions of the user terminal -- the low noise amplifier (LNA), high power amplifier (HPA), frequency reference components, and large array antennas. Because these components have not been produced in large quantities, they are currently prohibitively expensive. More research into their production is required to enable the costs to drop. Although the array antennas are not required for their performance -- conventional dish antennas would provide adequate gains -- we feel that consumer preference and local restrictions would not tolerate large (6 ft) dishes and that flat, roof-top array antennas would lead to a much more palatable system.

Figure 1-2 presents a block diagram of the user terminal design.

1.3.4 Space Segment Developments

In contrast to the user terminals, the space segment can afford to be complex and costly. A simple bent pipe transponder with CONUS beams is totally inadequate given the task of linking small terminals in an environment of up to 30 dB of rain attenuation (combined uplink and downlink fades). This has driven the satellite design to multiple beams, higher power, and some signal regeneration. By making use of the traffic characteristics of the assumed applications which consists of hub/spoke networks (the service providers being the hubs), we have avoided the need for on-board switching and traffic routing. A forward link takes traffic from all the suppliers in a CONUS beam, and by simple frequency translation, divides the traffic into its destination spot beams. Conversely, a backhaul link funnels all the uplink

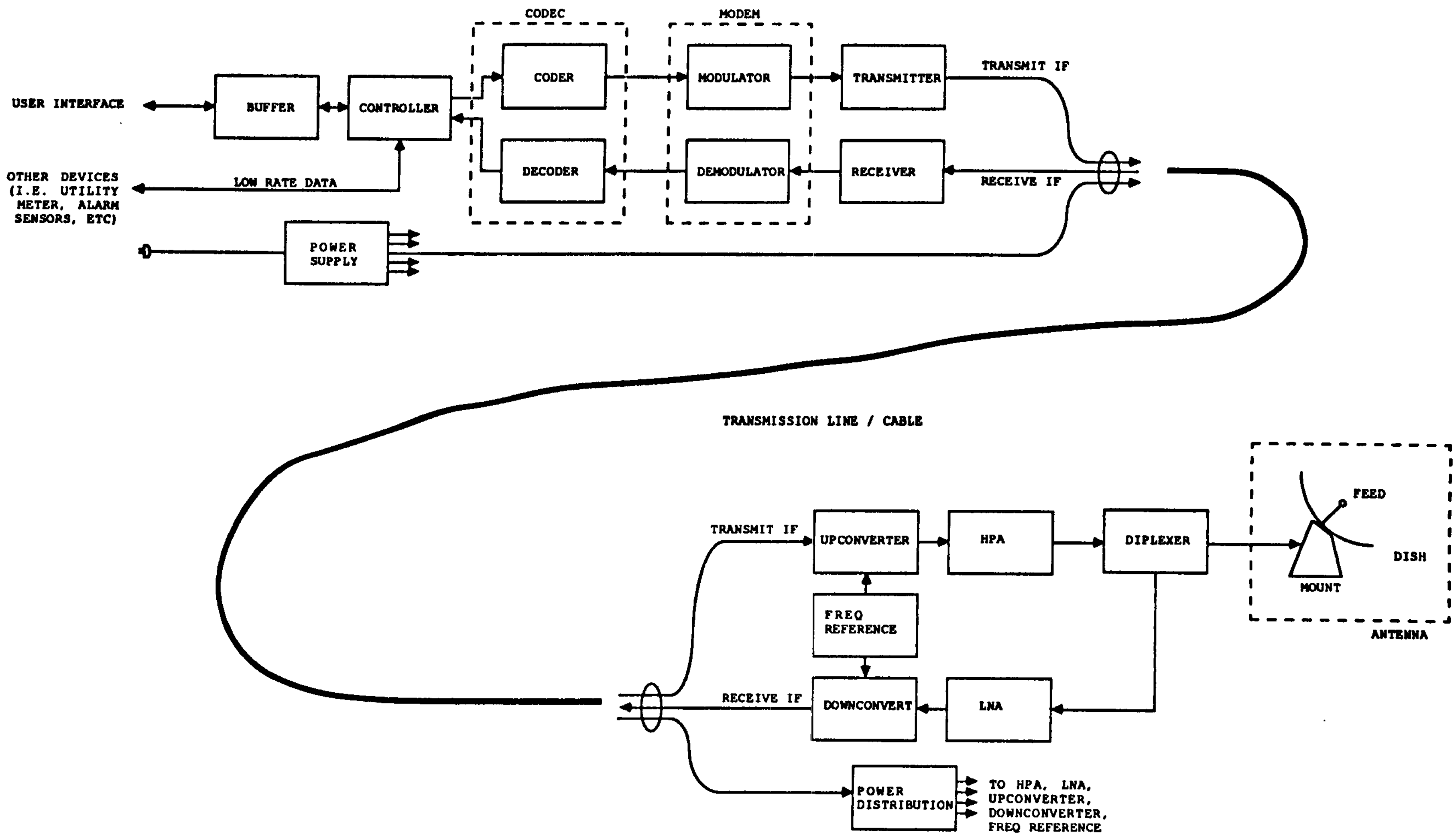

Figure 1-2 Subscriber Terminal Block Diagram

spot beam traffic from the users into the CONUS downlink to the suppliers. Again, simple frequency translation is employed. This frequency plan is illustrated in Figure 1-3. In this figure, M is the number of spot beams and N is the number of unique frequency patterns used. The frequency reuse factor is therefore M/N.

Because of this design, the areas which will push technology are the multibeam feed and the power requirement. Although multibeam satellites have already been designed and built, further maturation of this technology will be necessary to support a 32 beam design. The prime power requirement of this satellite is over 5 kW, significantly greater than any previous commercial satellite built to date. This will stress all areas of power generation including the solar cells, the DC to RF conversion process, and the TWT efficiencies. In addition, this high power requirement also leads to a heavy payload. More than one satellite may be required.

1.3.5 Recommendations

We have concluded that a significant market could exist for direct-to-subscriber FSS and therefore recommend that the terminal and satellite technologies listed above should be pursued by NASA. Since only a maturation of existing technology is required in order to implement this system, we also feel that the logical next step is the planning and design of a proof-of-concept system. This experimental system would be a scaled down version of our recommended system with fewer beams, less coverage, lower availability, and less capacity. Ku-band should be examined as a possible lower cost alternative to Ka-band, at least for the demonstration. Such an experiment would focus technical and business interests on this area of satellite communications and, in parallel with the technology developments, hasten its implementation.

It may be possible to run an FSS experiment using ACTS. The planned Micro-2 ACTS terminals have data rates as low as 56 kb/s and use FDMA access from three stationary beams to the Microwave Switch Matrix. These terminals could therefore be used to test both the system concept and new technology components.

1.3.6 System Costs

Estimating costs for a consumer system when much of the technology is still immature is at best difficult and at worst misleading. The assumptions and methods used to obtain the estimates have more impact on the costs than the components themselves. In spite of these difficulties, we feel that the user terminal cost could come down from their present $30,000 to $45,000 costs to a more reasonable cost of several thousand dollars. A more detailed cost estimating exercise is warranted for the satellite should this FSS system be pursued.

1.4 ROADMAP TO REPORT

This report essentially follows the tasks of the statement of work (SOW). The differences are that the ground and space segment block diagrams (Task 3) were broken into separate report sections, and that the Privacy/ Security Task (Task 4) was shifted toward the end of this report.

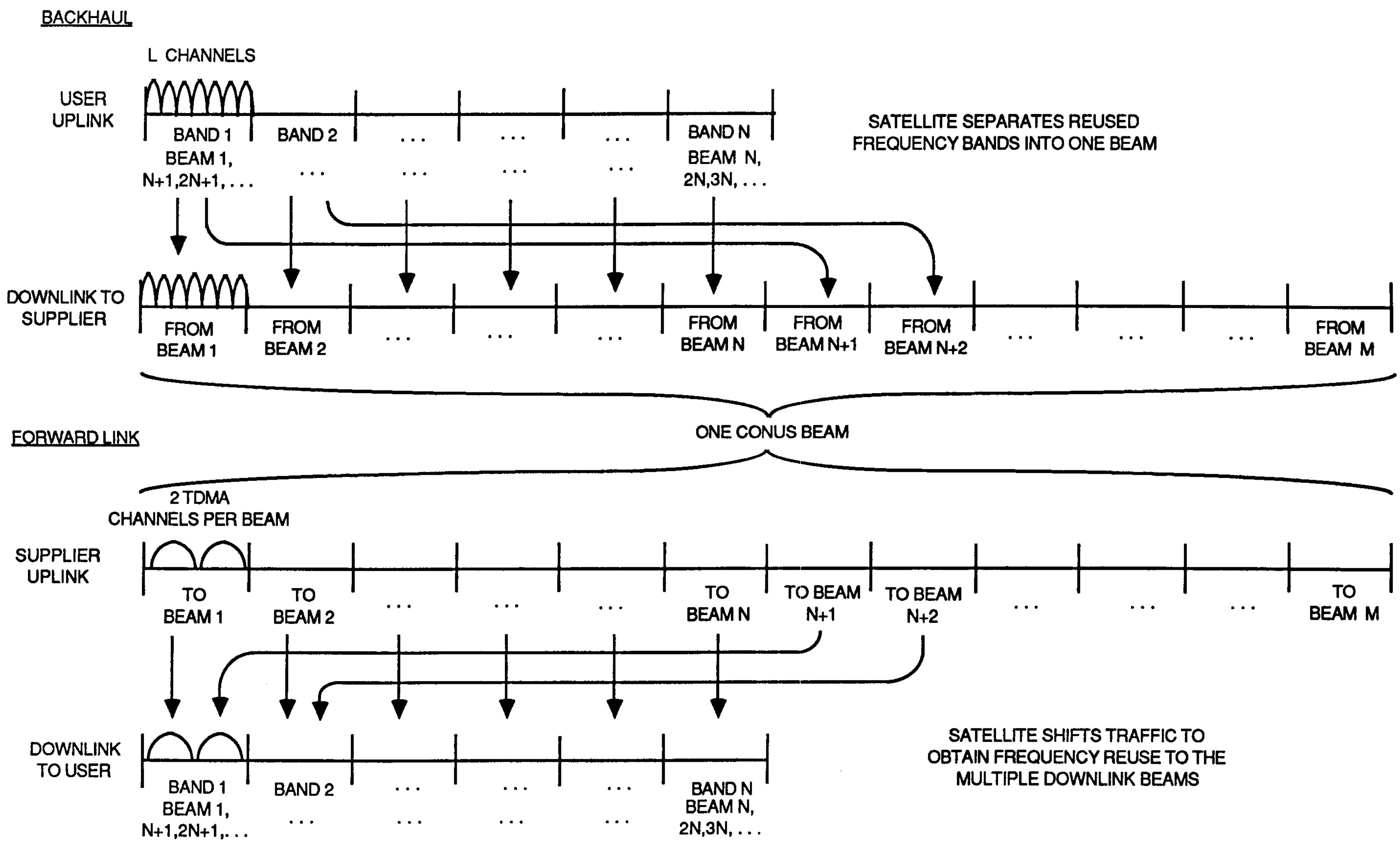

Figure 1-3 FDMA/TDMA Frequency Plan

Following this introduction, Section 2 addresses the potential applications and recommends those for further study. WTC assisted SIGNATRON in making these evaluations. Section 3 examines the system requirements of a direct-to-subscriber FSS system including the topics of frequency stability, multiple access, signal structure, and multiple satellite beams. The terminal design and components are evaluated in Section 4 while the satellite design is discussed in Section 5. Section 6 finally puts the system together by proposing a strawman system design, calculating the link budgets, and then performing trade-offs among various satellite and terminal alternatives to obtain the necessary link margins. Section 7 summarizes the technology constraints and cost drivers of this system while Section 8 addresses the privacy/security issues of the various applications and how to incorporate these requirements in the system design. Finally, Section 9 presents the market analysis of the three applications selected in Section 2. This analysis, performed by WTC, estimates the potential subscriber base of these applications by the mid-1990s and recommends the most promising application on which to concentrate.

SECTION 1
REFERENCES

[Reinhart, 1981] E.E. Reinhart, "The Impact of the 1979 World Administration Radio Conference on the Fixed-Satellite, Inter-Satellite, and Mobile-Satellite Services," IEEE Trans. on Communications, Vol. COM-29, August 1981, pp. 1182-1192.

SECTION 2
FIXED SATELLITE SERVICES APPLICATIONS

This section summarizes the potential applications considered for the FSS. The applications examined are those listed in the SOW and the Proposal, with additional applications that were suggested by JPL, SIGNATRON, and WTC during the course of the study. These applications are defined and sorted into a hierarchical tree structure based loosely on the communications requirements of the various applications. Applications which are out of scope for the study are eliminated, and the remaining applications are then evaluated with respect to technology requirements, direct-to-subscriber suitability, potential demand, and current competitive situation. Promising applications will be selected and grouped based on common system requirements, and potential users then defined. Finally, a few of the most promising applications will be focused on in order to evaluate the market potential.

2.1 LIST OF POTENTIAL SERVICES

Over 100 potential applications were identified during the proposal and study, many of which were similar, overlapped partially, or were subsets or supersets of other applications. In order to manage this large quantity of data, applications were sorted into a hierarchical grouping based along the lines of previous studies of market demand for satellite communications. We have used esssentially the same groupings as [Stevenson, et al., 1984] with some combining and rearranging of categories.

The possible satellite communications services are divided into three major categories: voice, data, and video. Each of the major categories is divided into a number of sub-categories. The resulting sorted list of applications can be illustrated in a tree structure as in Figure 2-1, where applications originally identified in the SOW and proposal have been underlined.

In the following paragraphs we define each of these groups of applications, and eliminate groups of applications that are clearly out of scope for this study.

2.1.1 Data Services

The first major category of services, Data, contains the majority of the applications investigated. These applications are subdivided into three categories: Terminal/CPU, CPU/CPU, and Message, with further groupings in each of these three categories.

2.1.1.1 Terminal/CPU

Terminal/CPU applications are those involving the transfer of data between remote terminals and centralized computers. A variety of subclasses for this type of data transfer have been identified and are summarized in Table 2-1.

The Data Entry class of applications are those providing for remote entry of data into a centralized data base via a general purpose or application unique terminal. Typical uses include electronic funds transfer and data base update, where operators manually enter information into the system.

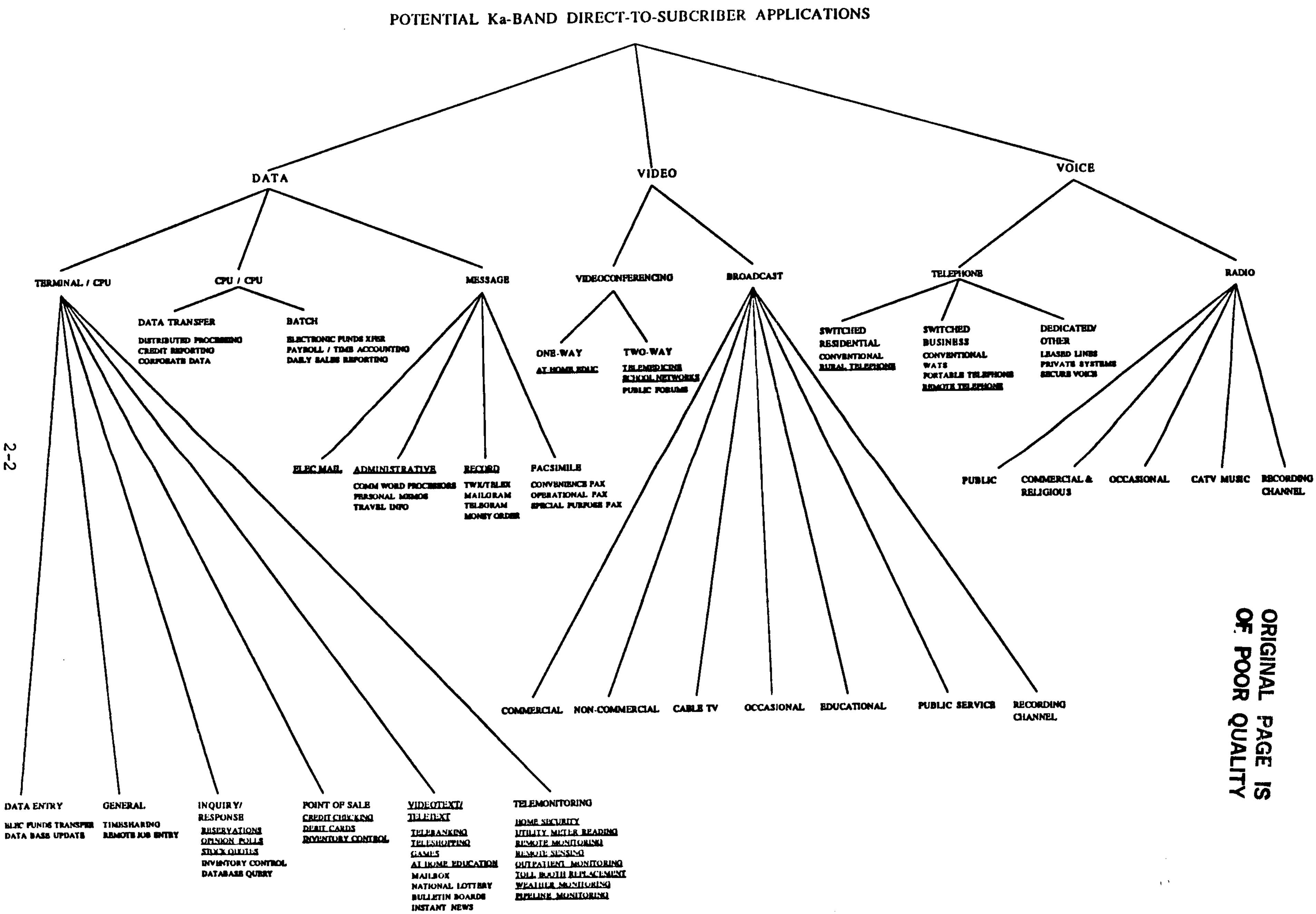

Figure 2-1 Potential Ka-Band Direct-to-Subscriber Applications

Table 2-1
Data-Terminal/CPU Definitions

Group	Definition	Data Rates	Duty Cycle	Duration of Use
Data Entry	Remote Data Entry	2.4 - 56 kb/s	Low or Medium	Short (Min-Hr)
General	Remote Job Entry or Time Sharing	1.2 - 9.6 kb/s	Low	Long (Hours)
Inquiry/ Response	Real Time Interaction with Remote Database	1.2 - 9.6 kb/s	Low	Short (Mins)
Point of Sale	Automatic Charge/Check Approval/Deposit	4.8 kb/s	Low	Continuous
Videotext/ Teletext	Transmission of Frames of Information to a User	Various (Medium)	Low/Medium	Long (Hours)
Telemonitoring	Monitoring at a Central Location of Remote Devices	Various (Low)	Very Low	Continuous

The General group of applications are those where remote terminals are used for interactive timesharing or remote job entry. Users are typically large institutions and businesses which have distributed computing resources or buy computer time at remote locations. Examples of this type of application include TELNET, TYMNET, and ARPANET which provide for remote access into computer networks.

Inquiry/Response applications are those requiring real-time interaction with a database by a remote operator. Typical examples of this type of application are the networks for making airplane, car, and hotel reservations. Other uses would include obtaining stock quotations, checking inventory status, etc.

The Point of Sale applications are those where intelligent sales terminals enter charge, check, and debit card transactions directly into a banking system or perform automatic credit checking, deposit, and inventory regulation.

Videotext/Teletext services provide for the interactive transmission and display of "frames" of information retrieved from a database. Although these terms have come to be used generically, teletext refers specifically to the transmission via broadcast TV or cable, and is essentially a non-interactive service; videotext refers to transmission via telephone and provides for interactive services. Services offered through videotext/teletext systems range from simple continuously updated news/weather information to interactive bank-at-home (telebanking) and shop-at-home (teleshopping) services. Although these systems were originally targeted at consumers, much business use has been made of videotext, particularly of services providing financial information, electronic mailboxes, and other specialized services.

Telemonitoring is the final grouping of services in the Terminal/CPU category, and includes those applications providing for the electronic monitoring of the status or condition of remote devices from a central location. Examples of telemonitoring systems are many, and include such systems as automated weather/environmental reporting and burglar/fire alarm systems.

2.1.1.2 CPU/CPU

CPU/CPU applications are those where the communications are entirely between computers. This category is broken into two categories: Data Transfer and Batch. Both categories have essentially the same system requirements, the primary difference being in the type of availability/access to a communication channel that is required. This category is summarized in Table 2-2.

Data Transfer applications are those requiring high speed transfer of data between computers on a demand basis. This would encompass such uses as distributed processing systems, distributed data bases that must be kept up-to-date in a real-time sense, and any other application requiring high volume data transfer with little time delay.

Batch Applications operate on a more scheduled basis, and would include such uses as transferring weekly payroll information, daily sales orders, etc. Because of its scheduled nature, Batch does not result in high

Table 2-2
Data - CPU/CPU Definitions

Group	Definition	Data Rates	Duty Cycle	Duration of Use
Data Transfer	Data Transfer from Computer to Computer on a Demand Basis	56 kb/s and greater	Medium	Various
Batch	Data Transfer from Computer to Computer on Scheduled Basis	56 kb/s and greater	Low	Various

peak loads or very low duty cycle demands being placed on the communications network.

2.1.1.3 Message

The final category of Data services are the Message based services. This category is distinguished from the previous two in that messages are person-to-person in nature, rather than being originated by and/or delivered to a computer system. This category is divided into four groups as summarized in Table 2-3.

Electronic-mail (E-mail) provides for the point-to-point transmission of formal text in a manner analogous to first class mail. Moderate delay (hours or overnight) in delivering E-mail is acceptable. Note that E-mail is different than the electronic mailbox services offered on videotext systems. In an electronic mailbox system, the user must log into the network and check his mailbox to see if there is anything for him, whereas with electronic mail, the message is delivered directly to the user.

Administrative traffic is generally short person-to-person messages of an informal nature, requiring fairly rapid delivery (i.e., within the hour). Examples of applications in this group include communicating word processor systems, distributing product announcements, travel reports, field marketing reports, etc.

The Record services group contains applications which provide the transfer of highly formalized written information such as the TWX, Telex, Telegram, Money Order, etc.

The last group of applications is Facsimile ("FAX"), which provides for the transmission of document reproductions. Approximately 86 percent of the FAX machines in use are the "convenience" facsimile which operate over normal telephone lines [Kratochvil, et al., 1983]. The remaining 14 percent of FAX machines in use are "operational" FAX (which use higher data rates and leased lines) and special purpose wideband FAX such as for high resolution weather maps and police fingerprints.

2.1.2 Video Services

The second major category of applications is video. Video is broken into two categories, Videoconferencing and Broadcast. Unlike the data services which generally require data rates below 64 kB/s, video information requires very high bandwidths. Bandwidth requirements range from 4.5 MHz for analog video channels to 27 MHz for digital television (at 54 Mb/s) [Habibi, 1977]. Lower bandwidth data rate requirements can be achieved using motion compensation, compression, and slow scan TV. Because the scope of this study was limited to low/medium data rates, only bandwidth limited video was considered.

2.1.2.1 Videoconferencing

Teleconferencing provides for either point-to-point or point-to-multipoint limited distribution of video information. Both one and two-way communication links are used. These applications would include videoconferencing aimed at businesses, picturephones which provide telephone plus video, at-home education and telemedicine.

Table 2-3
Data - Message Definitions

Group	Definition	Data Rates	Delivery Delay
Electronic-Mail	Point-Point Transmission of Formal Text, Analogous to First Class Mail	various	Hours-days
Administrative	Personal Messages of Informal Nature, Including Communicating Word processors	1.2 - 9.6 kb/s	Minutes
Record	Formal Written Records, i.e., TWX Telegram, Money Order, etc.	< 150 b/s	Hours
Facsimile	Point-Point Transmission of Reproductions	2.4 - 56 kb/s and Higher	Minutes

2.1.2.2 Broadcast

Broadcast provides for the essentially unlimited distribution of video information. Because of the wide audience intended for broadcast applications, standard video formats are used. As normal video does not fall into the class of low/medium data rates, this entire grouping was viewed as out-of-scope for the study effort and was not considered further.

2.1.3 Voice Systems

The last of the three major categories covers voice systems, which includes two categories: Telephone and Radio.

2.1.3.1 Telephone

Telephone services are divided into three groups: Switched Residential, Switched Business, and Dedicated/Other, as summarized in Table 2-4.

Switched Residential telephone includes, in addition to normal telephone service, rural telephone service via satellite where no service is currently available.

Switched Business telephone includes, in addition to normal telephone service, portable and remote telephone.

Dedicated/Other is a catch-all grouping and includes dedicated lines, private switching systems, and direct access to the switching system at the trunk level (bypassing local switches).

2.1.3.2 Radio

The radio category encompases the distribution of broadcast quality audio. Most radio requires 50 to 60 kHz bandwidth, and is usually distributed via subcarriers "piggy-backed" on satellite video links, with a small portion going via terrestrial leased lines. Since the bulk of this category does not fall into the class of low/medium data rates, this entire category was also viewed as out-of-scope for the study effort and was not considered further.

2.2 TECHNOLOGY, DEMAND AND COMPETITIVE EVALUATION

Of the original listing, five of the seven categories of applications; Terminal/CPU, CPU/CPU and Message oriented Data services, Videoconferencing services, and Telephone services; were deemed within the scope of the study and were evaluated with respect to their feasibility, demand, and competition.

The purpose of this evaluation was to select only applications that are feasible within the realm of this study, had a significant demand, and were not being addressed by other development programs.

Feasible applications were those that (1) a low cost terminal could be possible - i.e., complex or expensive interfacing would not be required, (2) require only low or medium data rates as specified in the SOW, and (3) are appropriate for an on-premises terminal.

Table 2-4
Voice - Telephone Definitions

Group	Definition	Duration of Use
Switched Residential	Normal Everyday Telephone Including Rural Telephone	Minutes-Hours
Switched Business	Normal Everyday Telephone Including Remote and Portable Phones	Minutes-Hours (Some Continuous)
Dedicated/ Other	Leased Lines, Secure Voice, Private Networks, Direct Access At Trunked Level	Continuous with Low Duty Cycles

Demand was evaluated based on a combination of market studies done recently for NASA [Gamble, et al., 1983], [Kratochvil, et al., 1983], and information collected from a variety of sources during the course of the study. Many new applications appear to have become possible since the studies done in 1983, largely because of the large interest in and effort being expended in the development of Very Small Aperture Terminals (VSATs) in the last few years [AWST, 1986a].

Competition was also addressed during the early part of the study, not for the purpose of evaluating overall market potential, but to eliminate those applications that overlapped other development efforts. We wish to propose new ideas and approaches rather than re-invent existing concepts.

A large number of systems providing similar or related services to those proposed for this study were reviewed in order to gain a feel for the current situation with respect to the demand and competition for various services. Table 2-5 presents a summary of the different systems examined.

Based on the evaluation of each application group with respect to these criteria, many of the applications were eliminated, and the remaining applications were rated as either primary or secondary. Primary applications are those with the greatest potential and should be provided by the system. Hence primary applications determine the system requirements. Secondary applications are those that have potential, but due to either limited demand, technical problems, or extensive competition are not "sure winners". Secondary applications are to be accommodated by the system design only to the extent possible without them becoming drivers from either a cost or technological standpoint.

In the following paragraphs each applications group is evaluated with respect to these criteria.

2.2.1 Data

Data Services are by far the most promising applications identified for a direct-to-subscriber low/medium data rate system. Almost all of the data services were ranked as either primary or secondary applications.

2.2.1.1 Terminal/CPU

All of the Terminal/CPU groups are considered appropriate for a direct-to-subscriber system. The very nature of the systems is where large numbers of remote terminals access a central computer or database. Therefore, there is a need to provide many low data rate communications links from a large number of separate locations.

The terrestrial telephone network currently addresses these requirements quite adequately, and generally most of these applications use telephone lines, although Teletext is offered via broadcast TV and Cable, and Telemonitoring is also done via radio/satellite links.

For applications currently using telephone lines (both switched and dedicated) the need for more economical communications exists. As satellite technology becomes less and less expensive, the distance at which satellite links become cheaper than terrestrial links is becoming shorter. A large portion of the Terminal/CPU traffic already travels distances which have passed the breakeven point.

Table 2-5
Summary of Related Services

Name	Provider	Description	Users	Notes	Source
ZapMail	Federal Express	transmission of high quality document reproductions	a few hundred	56 kb/s Ku-band double hop star network new defunct	[Stephens, 1986a] [AWST, 1986c]
TABS	Aviotex	weather charts/data via videotext		via phone $30/month uses NAPLPS	[Perry, 1986]
--	Xerox Computer Services	medium rate data for timesharing	currently 100 2000 terms ordered	9.6 kb/s inbound Ku-band 56 kb/s outbound	[Stephens, 1986b]
--	Commodity Quotations	commodity/stock quotes "sportsticker" network		distributed by phone and satellite	[ST, 1986]
Ad/Sat	Robert Wold Co & Mitsui Co	newspaper advertising distribution (facsimile)		4.5 minutes to transfer ad $40 per transmission shares AP distribution facility	[Smith, 1985a]
MutuaLink	Mutual Broadcasting Systems	radio programming data up to 56 kb/s		fm subcarriers via satellite $3-$7K term w/2-12 ft dish	[Smith, 1985b]
Multcomm	Mutual Broadcasting Systems	data up to 4.8 kb/s distribution of newsletters		fm subcarriers, $200 for decoder $25/month lease receiver/decoder data to uplink stn via phone, downlink rcvd directly	[Smith, 1985b]
--	GTE	data/video for K-mart stores	2100 stores plus regional centers and headquarters	star network Ku-band 9.6 and 56 kb/s inbound 56 and 256 kb/s outbound 3.9 or 5.9 ft dish	[AWST, 1985] [AWST, 1986b]
--	Comsat Technical Products	data logging network for Williams Pipeline	2 hubs, 120 VSAT's	Ku-band star network	[AWST, 1986b]
Compuserve	Compuserve	ASCII-based information retrieval service	190,000 users	national system via telephone	[Fletcher, 1985]

Table 2-5 (Concluded)

Name	Provider	Description	Users	Notes	Source
Dow Jones News/Retrieval	Dow Jones	ASCII-based financial info	200,000 users	national systems via phone	[Fletcher, 1985]
The Source	Readers Digest	ASCII-based information accessible w/PC	63,000 users	national system via phone	[Fletcher, 1985]
Viewtron	Knight-Ridder	videotext	3100 users peak	Miami Beach, FL--now defunct	[Fletcher, 1985]
Gateway	Times-Mirror	videotext	poor response	So. CA area only--now defunct	[Fletcher, 1985]
Keycomm Keyfax	Centel-Honeywell-Field Ent.	videotext	100's of users	$350/terminal $9/month Chicago area - now defunct	[Fletcher, 1985]
Prestel		British natl videotext sys	63,000 54% business	311 thousand frames avail from 2100 sources, accessed 7.3 M per day	[Woolnaugh, 1986]
Viatel		Australian videotext	12,000	currently fastest growing system	[Woolnaugh, 1986]
--	various	home security systems	1 of 3 homes has some sort of system	$20 for minor items $1300-$2500 installed system $20-$25/month for service	[Ingersoll, 1986]
--	Corvidea Corp.	new natl videotext will feature telebanking targetted at PC users	will pick up 40,000 users currently on BoA and ChemBank system	new joint venture of ATT, Bank of America, Chemical Bank, and Time	[Fletcher, 1985]
Teletel	Intelmatique	French natl videotext sys	1.5 million	terms $650 to buy, $10/month to lease (1 M given away)	[Solomon, 1986]
Spacetel	Microtel Ltd	portable telephone		2.4 m dish, Ku-band	[Stephens, 1986a]
TCS9000	Comsat-Telesystems	portable terminal for voice and data		115 lbs suitcase L-band $40K C-band $50-60K	[Stephens, 1986a]

There is some competition to provide these types of services however, as manufacturers have begun to market Ku-band VSATs to address some of these applications. However, current VSATs are generally targeted at higher data rates, and are targeted at business markets, not consumer markets, and are thus quite expensive.

The overall evaluation of the groups in this application is illustrated in Table 2-6. All applications were viewed as appropriate for the study, as they are ideal for on-premise terminals, could (with some limitations) potentially be accommodated by low cost terminals, and required only fairly low data rates.

Figure 2-2 shows a histogram of the data rates required for the total Data demand (including also CPU/CPU and Message services) based on user surveys done by [Kratochvil, et al., 1984]. As can be seen from this table, the majority of the applications require data rates of 9.6 kb/s or less. For Terminal/CPU applications, the only group requiring data rates of greater than 9.6 kb/s was Remote Data Entry. Thus, the system design can be limited to 9.6 kb/s or less and still address a large percentage of the demand for these applications.

In Table 2-6, the demand for each application is also ranked. The Data entry group represents the highest demand, and Telemonitoring was the lowest. Point of Sale was one area where very large growth was predicted. Currently, only about 6 percent of all charge authorization/deposits are done automatically; it is expected by the year 2000 that nearly 100 percent of these transactions will be processed automatically [Kratochvil, et al., 1983].

Videotext/Teletext is an uncertain area, as many businesses have been unsuccessful in providing these services in a local market area and have dropped out of the business. A second wave of ventures has now started with several large consortia intending to provide national services. For the Videotext/ Teletext application it was assumed that an essentially ASCII based service would be provided rather than using the NAPLPS standard, a complicated graphics based system used by some Videotext systems. The most successful systems currently are ASCII based, while the graphics based systems, using the NAPLPS standard, have suffered rather poor acceptance [Stapleton, 1986]. In addition, the need for a NAPLPS decoder would also add between $300 and $700 (1986 dollars) to the cost of the terminal.

The demand for videotex services is quite large. In the United States, national videotext systems currently have over 400 thousand subscribers. France, which has subsidized the system by having the government give away approximately a million terminals, has over 1.5M users of their national system. However, West Germany and Britain (which require users to purchase terminals) have been only marginally successful with approximately 40 thousand and 63 thousand subscribers, respectively [Fletcher, 1985]. Providing videotext-teletext type services via satellite is thus a primary application for this study.

Telemonitoring, from a technical viewpoint, is a perfect application for a small on-premises terminal envisioned by this study. However, it is an area with a considerably smaller demand than the other classes. Current techniques used are to send data via phone lines where available, or via HF,

Table 2-6
Data - Terminal/CPU Assessment

Group	Low Cost	Low/Med	CPS Accept	Demand**	Competition	Conclusion
Data Entry	Yes	Yes	Yes	High #1	Phone/Ku-band	Primary
General	Yes	Yes	Yes	High #4	Phone	Primary
Inquiry/Response	Yes	Yes	Yes	High #5	Phone	Primary
Point of Sale	Yes*	Yes	Yes	High #6	?	Primary
Videotext/ Teletext	Yes	Yes	Yes	High #3	Phone/TV	Primary
Telemonitoring	Yes	Yes	Yes	Low #12	Ku-band	Secondary

* Not Including Cost of Sales Register

** Number refers to ranking among Terminal/CPU applications from [Kratochvil, et al., 1983]

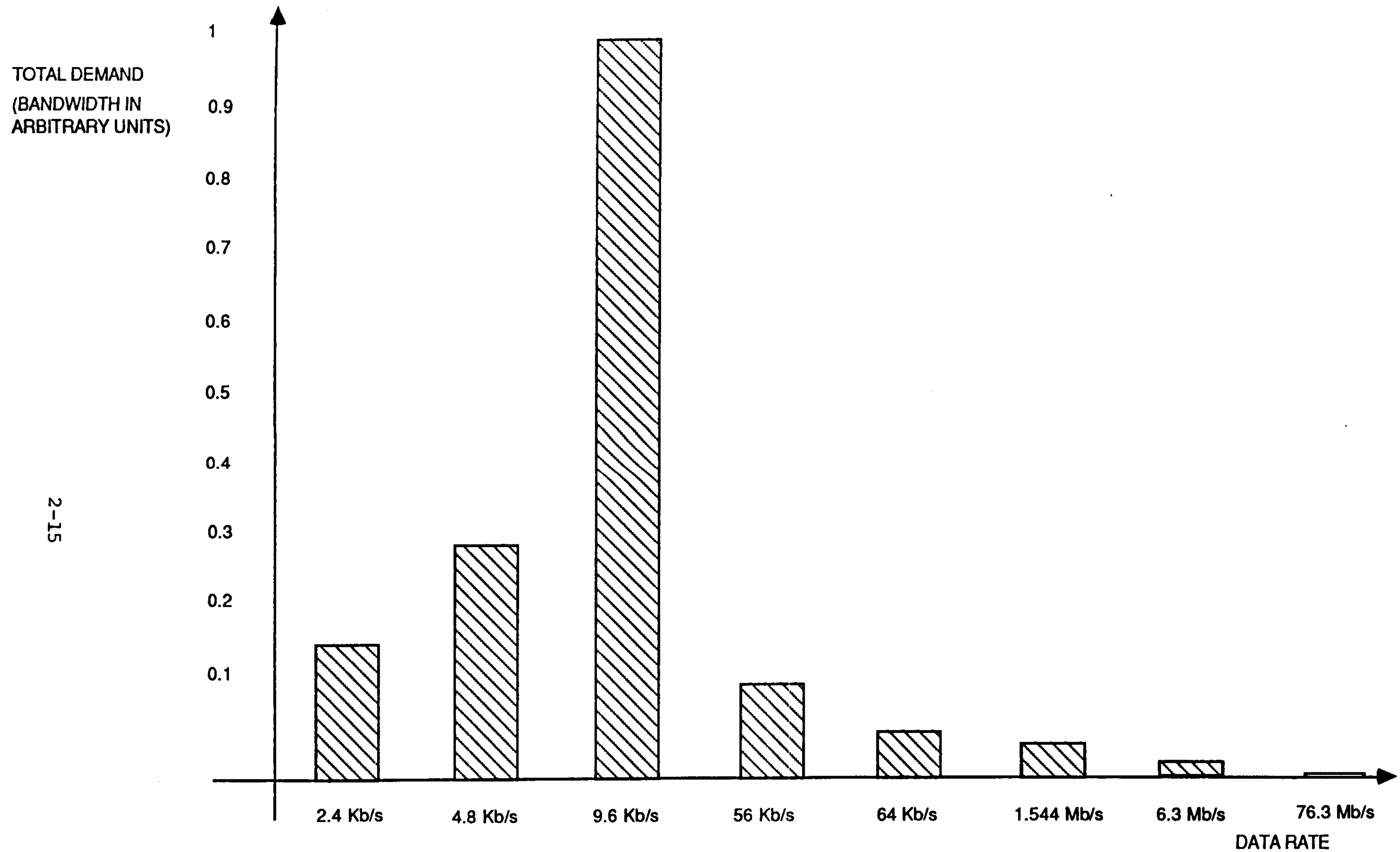

Figure 2-2 Data Rate Requirements for CPS Addressable Satellite Communications

VHF, or UHF, where phone lines are unavailable. Most telemonitoring users are businesses and the cost of the terminal is not as large an issue as it is for consumers. The recently available Ku-band VSATs have done much to address the demand in this area. Two applications in this group, however, are targeted at consumers: home security and utility meter reading, but only represent a small fraction of the telemonitoring demand. Because of the fairly low demand predicted in this area and the large activity in providing VSATs for this group of applications, it was ranked as secondary.

2.2.1.2 CPU/CPU

The overall assessment of CPU/CPU services is summarized in Table 2-7. Although these applications were acceptable with respect to the potential for low cost terminals and were also well suited to customer-premises terminals, we decided not to consider these applications for a number of reasons. As the CPU/CPU services require data rates from 56 kb/s up to T1 (1.544 Mb/s) rates, only a portion of these services fall into the realm of low/medium data rates. Furthermore, many different companies are attempting to address this demand with VSAT development efforts [AWST, 1986a]. The ACTS program is also investigating providing data communications services for customer-premises small aperture terminals. As only a portion of the CPU/CPU applications fall into the scope of our study, and are being addessed in whole by other programs, they were not considered further by this study.

2.2.1.3 Message

The groups in the category of Message based services varied widely in how they ranked with respect to the evaluation criteria as summarized in Table 2-8.

Although the Electronic-Mail application can be handled well via Ka-band CPS, it suffers from one major problem: origination and delivery of mail to users who do not have terminals. Once this problem is solved, the use of such a system could become quite extensive. However, potential competition from the USPS, Federal Express, and other organizations which have well in-place terrestrial delivery systems will make it difficult to achieve a foothold in this market. The USPS even abandoned its attempts to provide an Electronic-mail system, the USPS Electronic Mail Switching System, due to poor acceptance [Stevenson, et al., 1984]. Because of these kinds of logistical (rather than technical) problems, Electronic-mail was ranked as a secondary application.

Administrative services were applications that although currently little used, ranked very high in the demand forecasts. This is an area where little research has been done into the needs of the users and how to provide for these needs. Overall, these applications ranked second in channel usage among the data category, and hence are considered primary applications for this study.

Record services were eliminated from consideration because of their very low demand (last place). New technologies such as overnight mail, Electronic mail, and direct CPU/CPU data transfer are replacing most of these services.

Table 2-7

Data - CPU/CPU Assessment

Group	Low Cost	Low/Med	CPS Accept	Demand	Competition	Conclusion
Data Transfer	Yes	Some Medium	Yes	Moderate #8	Ku-Band Phone	Don't Consider
Batch	Yes	Some Medium	Yes	Moderate #9	Ku-Band Phone	Don't Consider

Table 2-8
Data - Message Assessment

Group	Low Cost	Low/Med	CPS Accept	Demand	Competition	Conclusion
Electronic Mail	Yes	Yes	Yes	Low #10	USPS	Secondary
Administrative	Yes	Yes	Yes	High #2		Primary
Record	Yes	Yes	Yes	Low #11	Phone Wire Svcs	Don't Consider
Facsimile	No	Yes	Yes	Moderate #7	Phone Fax	Don't Consider

For Facsimile, a large portion of the demand can be addressed by a low/medium data rate communications link. There are some problems associated with cost, however as the terminal will require the facsimile scanner. Federal Express started a facsimile service (Zap-Mail) which provided high quality facsimile service via satellite [Ott, 1986]. After losing millions of dollars, they cancelled the service after only two years [AWST, 1986c]. The service was unsuccessful for a number of reasons, one of which was the availability of new, high performance, low cost, telephone facsimile machines. In light of these developments, this application was eliminated from further consideration.

2.2.2 Video

The only video applications under consideration were those that could use bandwidth compression techniques to lower the required data rate. These were applications such as videoconferencing aimed at businesses, picturephones which could provide telephone plus video, at-home education, and telemedicine.

These applications fail to meet the low cost criteria, however, as in all cases, fairly complicated equipment is required in order to achieve the required amount of compression. Video compression is still an active area of research and development, and it seems unlikely that widespread use of video compression will occur in time to make the required hardware economical. Furthermore, we feel it is likely that the ever-decreasing cost of bandwidth is likely to continue to beat out the cost of bandwidth compression, and most systems will continue to use full-motion, uncompressed video.

2.2.3 Voice

The voice applications that are under consideration are a limited subset of the overall voice communication market. The specific applications under consideration and their evaluations are summarized in Table 2-9.

Remote or thin-route telephone service was initially viewed as one of the most promising applications for the 30/20 GHz FSS. This is because there is currently no service provided for this market. However, in the future, competition can be expected from services such as mobile satellite and other primarily business-oriented system. Potential users would include rural areas, off-shore oil rigs, and users needing portable field communications capability.

2.2.3.1 Switched Residential - Rural Telephone

The demand for rural telephone is not known, as there are no systems currently providing this type of service. Some idea of how this market could grow, however can be gained from the wide acceptance of the Television Receive Only (TVRO) satellite systems, which were originally targeted at Rural areas that did not receive television. Over 1.5 million TVRO systems have been sold, although not all sales have been to rural users [Doherty, 1986].

A possibility for the mobile satellite service to provide communications for this type of application exists. Although the mobile satellite (MSAT) systems are intended for mobile users, these systems could certainly

Table 2-9
Voice - Telephone Assessment

Group	Low Cost	Low/Med	CPS Accept	Demand	Competition	Conclusion
Switched Residential*	Maybe	Yes	Yes	?	MSAT	Secondary
Switched Business**	Maybe	Yes	Yes	Large	Considerable	Don't Consider
Dedicated/ Other	No	Some	Yes	Large	ACTS, Ku-band	Don't Consider

* Rural Telephone Only

** Portable/Remote Telephone Only

accommodate a fixed user in a remote area. The MSAT systems, however, are targeted primarily at business users, and thus may not be priced low enough to attract consumers.

Due to this uncertainty and the possibility of the MSAT Systems accommodating remote rural users, this application was ranked as secondary.

2.2.3.2 Switched Business - Portable/Remote Telephone

The need for portable and remote telephones targeted at business is an application already being addressed by a number of companies which have either built or announced plans to build portable telephones that operate via satellite [Stephens, 1986].

These needs could also be met to some degree by the MSAT systems. In light of the number of options already available to address this application, these applications were not considered further.

2.2.3.3 Dedicated/Other

For both long haul private links, and direct "bypass" trunk access, there is large competition to capture these markets. The ACTS program is also targeted at this type of application. Therefore, these applications were not considered further as they are already being addressed by other development efforts.

2.2.4 Summary of Applications Selected for Consideration

In summary, of the original thirty groups of applications, nine were deemed to be appropriate for the type of system to be examined during this study. These applications are summarized in Table 2-10.

2.3 END-USER IDENTIFICATION AND APPLICATIONS GROUPING

After having made a preliminary investigation of the potential applications and selecting a set of the more promising applications, the end-user requirements were then examined. From the applications characteristics and user requirements, requisite system requirements were then defined which would allow the system to support the selected applications. Table 2-11 provides a cross reference of the potential applications to the various end-user markets.

2.3.1 Consumer Oriented Services

Consumer services are those applications targeted at the residential consumer. These would be applications where the home user would interact with either other users, or providers of services via the satellite system. Consumer end-users are the primary target of this feasibility study. Most of the suggestions in the SOW were for consumer videotext type services; overnight news, overnight mail, and electronic banking.

2.3.1.1 Consumer Users

All of the applications suggested in the SOW are currently available via terrestrial phone or cable, with the exception of automatic utility meter reading. However, few of the services are integrated. For example,

Table 2-10
Summary of Primary and Secondary Applications

DATA

Terminal/CPU Applications:
- Data Entry
- General
- Inquiry/Response
- Point of Sale
- Videotext/Teletext
- Telemonitoring (Secondary)

Message Applications:
- Electronic Mail (Secondary)
- Administrative

VOICE

Telephone:
- Switched Residential - Rural Telephone (Secondary)

Table 2-11
Cross Reference of Applications Versus End Users

	DATA								VOICE
	Data Entry	General	Inquiry/ Response	Point of Sale	Videotext/ Teletext	Telemonitoring	Electronic Mail	Administrative	Remote Telephone
CONSUMER									
Urban/Suburban			X		X	X	X		
Farms/Ranches			X		X		X		X
BUSINESS									
Manufacturing	X		X				X	X	
Transportation	X		X	X		X	X	X	X
Utilities						X	X	X	X
Retail/Wholesale	X			X			X	X	
Financial/Insurance	X	X	X	X			X	X	
Professional	X	X	X				X	X	
INSTITUTIONS									
Educational		X						X	
Health Care				X		X			
Religious								X	
GOVERNMENT									
Federal	X	X				X	X	X	X
State	X	X				X	X	X	X

there are three successful national suppliers of videotext, but each service provides different features. Accessing more than one service requires subscribing to each system, dialing up the system separately, and using different access procedures.

An integrated system providing a number of features could have much more appeal to the consumer. However, it is likely that the service will be bought on the basis of one or two applications. Electronic banking is an application that seems to have this appeal, as the number of subscribers to home banking, while still only 65,000 in the US, has risen threefold to fourfold in the last year [Fletcher, 1985].

It is important that the system be interactive in order to provide services, such as electronic banking, which require two-way communications. Although the original videotext offerings were primarily informational (and thus essentially non-interactive), there was little demand for these types of services. Consumers were far more interested in interactive services such as bulletin boards, electronic messaging, and transactional services (such as electronic banking) [Fletcher, 1985].

Targetting the services at users who already have a PC makes good sense. Over 33 million PCs have been sold to both businesses and consumers. Currently 16 million PCs are installed in households, representing a sizeable potential market. In addition, PC owners will already feel comfortable with the prospect of interacting with the system and conducting transactions electronically.

Of utmost importance with a consumer targeted application is the overall cost of the service. Acceptance of the system will be highly dependent on both the cost of the terminal (either purchase price or leasing cost), and the cost for monthly access.

2.3.1.2 System Requirements for Consumer Applications

The applications of interest to consumers included primarily data oriented services, with the exception of rural telephone, which is discussed in a later section.

The consumer applications have the need for the transfer of text and graphics, with high quality facsimile, voice and video being unneeded. Graphics can be accommodated by a number of means, using either the existing NAPLPS protocol, GKS standards, local generation of graphics, or other means.

The services will need to be provided by supplier "superterminals" which will communicate with a large number of subscribers simultaneously. Thus, each supplier terminal will become the "hub" of a star network. Many different hubs supplying a variety of services will ultimately exist. For example, there may be a number of banks which provide for electronic banking services via the network, but only a single national electronic message board.

As far as channel utilization is concerned, it is quite low due to the bursty nature of the links. Basically two sorts of transmissions exist: fairly short interactive messages (prompts, inquiries, etc.) and longer data messages (bulletin board announcements, data base records, etc.) Short transmissions occur quite frequently (every few seconds) and require fairly low delays (less than a second). Longer transmissions occur less frequently (a few per day) and can tolerate moderate delays (tens of seconds or several minutes) [Rosner, 1982].

A bursty factor [Lam, 1978] can be defined as

$$\beta = \frac{\delta}{T}$$

where δ is the message delay constraint, and T is the average message interarrival time. For these applications, β is on the order of 0.1 for interactive traffic, and 0.01 for longer data messages. This bursty factor is essentially an upper bound on the duty cycle of the traffic source. For sources with very small bursty factors, some sort of multiplexing or message switching is clearly desirable.

Data rate requirements for the most part are quite low, as most of the information being passed back and forth will be either manually typed or read by the user. Data rates of less than 9.6 kb/s can easily accommodate such uses and meet the delay constraints. However, in some applications, transfer of moderate volumes of data may occur, such as downloading of software. Thus, the ability to operate at higher data rates on some links would be desirable.

The use of a personal computer as the terminal places limitations on the maximum allowable data rate. Many existing PC data transfer applications (Kermit, X-modem, etc.) are able to pass data at the 9600 baud rate, but there are virtually no applications using higher rates.

The data formats to be used will vary somewhat, although ASCII will clearly be predominant. For all the consumer applications except telemonitoring (home security, utility meter reading) ASCII will be used. However, graphics capability not provided by ASCII may be required for some applications in addition to ASCII text. For example, graphics will be needed to reproduce pictures, company logos, etc. for teleshopping, news and weather, and games. Telemonitoring applications are not tied to ASCII because the information transferred is not textual. This information would be strictly binary, although it could be handled by the terminal in an identical manner to ASCII without unduly contraining the telemonitoring applications.

Some security and privacy features are necessary, both for the protection of information such as account numbers, passwords, or credit card numbers, and to ensure privacy for the users conducting transactions via the network.

The system availability should be at least as good as the terrestrial telephone system, as users are accustomed to that level of availability. It is likely that the usage of the system will have the same sort of peak usage characteristics as telephone switching systems, although possibly at different times.

Reliability (accuracy) of data transfer is also of concern. Terrestrial telephone lines can be quite poor in this respect, especially with respect to the typical cheap microcomputer modem. Considerably better capability should be possible with the satellite network. The degree of accuracy required varies with the application. For transfers of software, Electronic mail, etc. very high accuracy is necessary. However, for much of the interactive transfers (prompts, news briefs, etc.) a slightly lower reliability is acceptable. Bit error rates of 10^{-5} result in errors every 10 seconds at 9600 baud, which is probably the limit of acceptability for purely interactive communications links. For data transfer requiring higher accuracy, bit error rates of 10^{-8} or less should be provided.

A summary of the system parameters for the various applications targeted at consumers is shown in Table 2-12.

2.3.2 Business Oriented Services

Another promising area is the possibility of providing communications services to businesses, government, or public organizations. Some of the previously described consumer services have appeal to business also. In addition, increasing numbers of corporations are finding the need to conduct transactions and transfer information electronically. Extensive use is made of dedicated and leased lines currently, although the potential exists to move these links to satellite and obtain a reduction in cost.

2.3.2.1 Business Users

Business needs cover a wider ground than consumer needs. Although businesses, like the consumer, need access to the types of informational services provided via teletext, they have greater needs in providing for intra-company and inter-company transfer of information electronically.

Currently when faced with the need for providing additional communications capability, companies have few options: either lease dedicated telephone lines, use the switched telephone network, or install specialized communications links (microwave, HF/VHF/UHF radio, or satellite). Use of leased or switched telephone lines has generally been the preferred option, primarily due to cost. However, the cost of leasing satellite links has come down to the point that it is often cheaper in many cases to maintain satellite links. Costs of terrestrial links continue to increase, while advances in satellite technology have continued to reduce costs associated with satellite links. This is reflected in the break-even points (the point were the satellite links are equivalent in cost to terrestrial telephone) becoming shorter and shorter. Currently, break-even points are in the range of 1000 miles.

2.3.2.2 System Requirements for Business Applications

The business applications can largely be divided into two categories: consumer-like Business Services, and Business Communications. Business Services are those where the satellite system is used just to get access to a service supplier, exactly as for the consumer applications described previously. The Business Communications applications are those where an essentially custom communications network is needed by the business.

The major difference between the consumer services and business services are the type of service provided. The satellite communications network operates identically, and the system requirements have been adequately described above for the consumer applications.

Table 2-12
Summary of Consumer Applications System Requirements

Application	Message Frequency	Message Length	Delay	Call Duration	Connectivity	Secure/Private	Link Reliability
Inquiry/ Response	1/second--1/minute	1-200 chars	≈second	minutes	mult users to/ from central hub	no	BER* $< 10^{-5}$
Videotext/ Teletext	1/second--1/minute	1-600 chars	≈second	hours	mult users to/ from central hub	yes	BER $< 10^{-8}$
Tele-monitoring	1/minute	≈100 bits	1-10 seconds	continuous	mult users to/ from central hub (local coverage)	yes	BER $< 10^{-8}$
Electronic Mail	5/day	10,000 chars	non-critical	one message	point-point all users (could be relayed)	yes	BER $< 10^{-8}$

* BER = Bit Error Rate

The business communications applications under consideration in this study have the need for the transfer of data exclusively. In other respects, however, the needs vary considerably depending on the end-user's particular application.

Unlike the service applications, which resulted in a number of star networks with each service provider as a hub, the communications applications will probably need a variety of connectivity options. For example, for the Terminal/CPU category of applications, a star network will be used, where the CPU is the hub. However, for the Electronic Mail or Administrative traffic, point-to-point communications is ultimately desired. This could still be provided via a hub, but would require a two-hop transfer to get the data from point-to-point. Due to routing considerations, two-hop networks are often required anyway.

A variety of data rate requirements are needed, depending upon the applicaton. The bulk of the applications can use data rates lower than 9.6 kb/s although a few need higher data rates, particularly for Data Entry. Administrative traffic can also require high data rates, as transfer of large volumes of text could be possible in a communicating word processor system. An excellent example of this is a proposal writing activity where portions of the proposal are being written by two widely separated divisions of a company.

The privacy and security requirements for the business world are stringent. A fairly recent concern over the susceptibility of communications has surfaced in the last few years. As more and more sensitive information is transmitted via essentially unsecure communications links, the likelihood of financial loss increases. Financial loss could occur due to either the destruction or modification of information being sent over a link, or use being made of private, sensitive information.

Although Congress has recently tightened up the laws concerning communications privacy, these laws do little to discourage the determined eavesdropper. For communications via satellite it is virtually impossible to detect an evesdropper anyway. Therefore, we see an insistence on the part of businesses that secure communications links be provided. By providing such security inherently in the system design, rather than placing the burden upon the user (as is currently the case for terrestrial and satellite links), the system proposed by this study could find considerable acceptance.

The required system availability is a function of the applications. Applications such as Data Entry, General, Inquiry/Response, Point of Sale, and Administrative need very high levels of availability. Downtime could represent loss of sales to a merchant using the system to provide Point-of-Sale automated charge verification/deposit. The system availability must be as good or better than that of the current telephone system.

Reliability of data transfer is of the utmost importance. Large volumes of data will ultimately be transferred, very little of which can be checked by any other means. Even minor errors can result in major problems, loss of data, or loss of revenue.

Of concern is also the reliability of the communications link. In particular, for some applications there needs to be a high degree of confidence that the data was received at the other end of the link. For many of the business application, data should be delivered with probability of failures less than 10^{-5}.

A summary of the system parameters for the various applications targeted at businesses is shown in Table 2-13.

2.3.3 Rural/Remote Telephone

The rural/remote telephone application is discussed separately because the system requirements are so different from the other applications.

The interface to the user can no longer be accomplished with a PC, but a telephone type handset is necessary. Dialing and ringing equipment is also necessary. In order for the terminal to remain low cost, any type of voice-coding is clearly out of the question, limiting the waveform selection to either analog or fairly straightforward sampled digital. With digital voice, a data rate of 64 kb/s is generally required for adequate quality.

The system must at some point interface to the public telephone network in order for it to have any acceptance. Thus, a gateway into the terrestrial telephone system will be required. This gateway could perform waveform translation if the waveform selected for use in this system was different from the standard telephone transmisson waveforms, although this would considerably increase the overall cost of the system.

Voice results in particularly difficult system requirements as opposed to data. This is due to the real-time nature of voice. The one-quarter second delay due to the satellite range is already enough to bother most people. Additional delays must clearly be minimized. System schemes that introduce additional delays, although acceptable for data transmission, cannot be used for voice communications. This leads to the need for dedicated channels for the transmission of voice.

A summary of the system characteristics that should be provided for voice communications is contained in Table 2-14.

2.4 APPLICATIONS FOR MARKET ANALYSIS

Although we have narrowed down the large list of potential applications to several general categories, these categories still include a large number of specific applications. We have grouped these applications by the system requirements which allow us to develop a generic system design that can accommodate these many different applications. For the subscriber base estimation, however, we need to focus on the specific applications, as the market forces involved are widely different depending upon the application. In order to understand the forces affecting the development of particular applications, a market perspective rather than a technological perspective must be taken.

The direct-to-subscriber system might ultimately accommodate a number of different services once it is operational. Large numbers of service would not, however, become available immediately. Rather, a few key "trigger" applications will be needed in order to provide the impetus for developing the infrastructure necessary to support the system. Thus, we now examine the various market forces that are expected to converge in the mid-1990s in order to determine which applications might be the first to use this system. It is for these most promising applications that we will perform the subscriber base estimation.

Table 2-13
Summary of Business Applications System Requirements

Application	Message Frequency	Message Length	Delay	Call Duration	Connectivity	Secure/ Private	Link Reliability
Data Entry	1/second--1/minute	1-10,000 chars	≈ second	minutes--hours	mult users to/ from central hub	yes	*BER $\leq 10^{-8}$ **LPR $\leq 10^{-5}$
General	1/second--1/minute	1-600 chars	≈ second	hours	mult users to/ from central hub	yes	BER $\leq 10^{-8}$
Inquiry/ Response	1/second--1/minute	1-200 chars	≈ second	minutes	mult users to/ from central hub	yes	BER $\leq 10^{-5}$ LPR $\leq 10^{-5}$
Point of Sale	1/minute	100 chars	1-10 seconds	one message	mult users to/ from central hub	yes	BER $\leq 10^{-8}$
Telemonitoring	10/minute-- 1/minute	10-100 chars	1-10 seconds	continuous	mult users to/ from central hub	yes	BER $\leq 10^{-8}$
Electronic Mail	1-100/day	10,000 chars	hours	one message	point-point	yes	BER $\leq 10^{-8}$ LPR $\leq 10^{-5}$
Administrative	various	1,000-10,000 chars	seconds-- hours	various	various	yes	BER $\leq 10^{-8}$

* BER = Bit Error Rate

** LPR = Lost Packet Rate

Table 2-14
Summary of Voice Communications System Requirements

Call Frequency:	same as normal telephone
Call Duration:	same as normal telephone
Delay*:	up to 0.1 s if digital none if analog
Connectivity:	multiple user to/from gateway into PSTN
Security:	yes--as necessary for billing and access restriction
Privacy:	no
Reliability:	same as normal telephone
Data Rate or Bandwidth:	64 kb/s if digitized approximately 3 kHz if analog

* in addition to propagation delay

2.4.1 Historical Perspective

New technology more often than not takes a circuitous path with many false starts and failures, and requires decades before reaching full market potential. Some examples of this include the automobile, airplanes, telephones, and computers. Although all of these examples are integral parts of our lives today, all of them nearly failed in their original introduction due to a variety of reasons. None of these examples were in widespread use until many years after the original development of the technology.

The automobile, for example, nearly failed due to the lack of a proper infrastructure; there were no roads, service stations, or widely available repair services. Thus, before automobile sales became widespread, this infrastructure had to be developed. Because a need for the automobile existed, this infrastructure was eventually developed. As this infrastructure developed, car sales increased, and new businesses were developed around this infrastructure (i.e., the service stations, road contractors, etc.). Thus, the whole market changed and grew.

In many cases, the finally achieved market is often different than what had originally been expected. For example, the telephone was originally viewed as a business tool. Business organizations would have a single telephone in a centralized location. The telephone was not originally intended for such widespread use as there is today, yet now hardly a home or individual's office is without a telephone.

Both of these examples serve to illustrate that independently, a new technology will usually not become exploited. There needs to exist both a need for the technology, and an infrastructure to support the use of the technology. Once a technology begins to enjoy widespread use, however, the availability of the technology can result in many changes in the overall markets. Many times, applications for the technology not originally imagined will become widespread. An example of this is the TVRO industry.

The various market forces involved in the development of new technologies are illustrated in Figure 2-3. These various forces are interdependent, and work in concert to determine the success or failure of a new technology.

We have already considered two requirements for the successful development of new technologies; the infrastructure to support the use of the technology, and the need or demand for that technology. Other factors that will impact the success of the technology include competitive business strategies and government regulations which may hinder or help the adoption of the technology, economic considerations, and entrepreneurship. Entrepreneurs are often critical in making a new technology viable economically.

2.4.2 Market Trends

A preliminary investigation of the market trends was conducted in order to determine which of these forces are converging in the consumer market place. By examining the expected areas of convergence in the mid-1990's, direct-to-subscriber applications that seem most likely to be developed were determined.

The forces that seem to be shaping the demand for direct-to-subscriber communications links seem to be primarily driven by the consumer industries. Consumer service providers are looking for new ways to reach

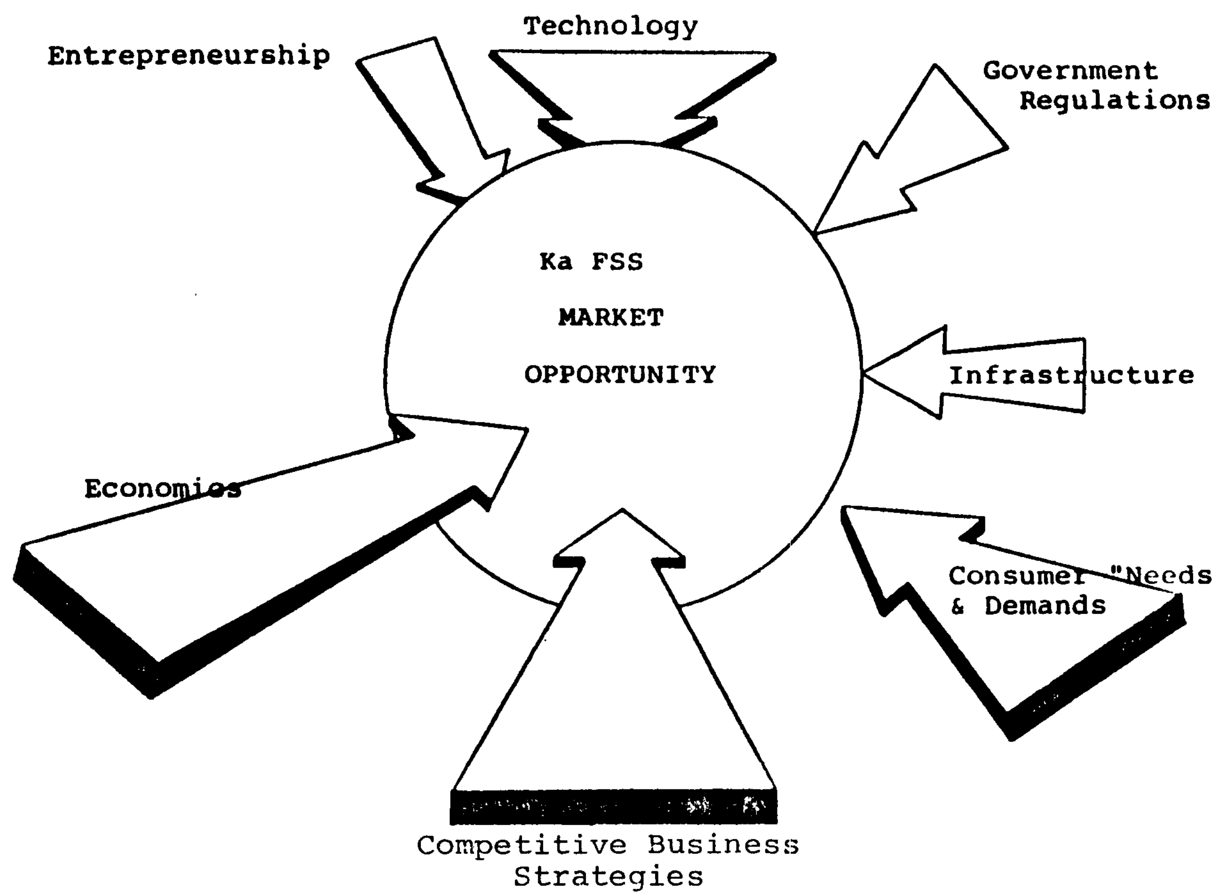

Figure 2-3 Converging Market Forces

their customers in order to maintain existing markets and capture new markets, such as the dual career families and invalids who either do not have the time or cannot physically get to the service provider's premises.

Consumers are also fueling the demand by insisting on easier access to the services they must deal with everyday: banks, retailers, financial services, and utilities. Changing consumer lifestyles are also a factor, as consumers utilize more electronic gadgets at home, use computers more at work and become more familiar with interacting with machines, rather than people. The explosive growth in the use of automatic teller machines illustrates these trends.

The type of communications link needed between the suppliers and the consumers must support an interactive and transaction oriented relationship. Many pilot programs are being adopted by consumer industries where they are testing new distribution channels such as cable television and videotext/teletext. Unfortunately, these communications channels have a number of shortcomings in providing the required degree of interaction desired. Since interactive satellite links can provide the required communication link, and may be able to do so ecconomically in the near term, the development of a direct-to-subscriber system in the near future may be likely.

The pioneers in this area are likely to be the banking and financial service industries and the retailers. These businesses already have a start on developing the required infrastructure through pilot programs utilizing cable television, broadcast television, and videotext/teletext systems to provide home-shopping and home-banking services. The specific applications suggested in Table 2-15 appear likely to be the first applications that would be provided via a direct-to-subscriber system.

Table 2-15
Promising D-T-S Applications

Home Banking Services
Home Financial Services
Home Shopping Services

Another factor that will be key in the development of direct-to-subscriber communications links will be the efforts of the consumer electronics industry. The consumer electronics industry has enjoyed tremendous growth in the past, and will most likely play a key role in the development of the direct-to-subscriber terminals. Consumer expenditures in home entertainment electronic equipment are expected to grow substantially in the next decade, and thus represent an attractive area for the development of new products, such as those required for access to a direct-to-subscriber system.

Thus, the market forecast will concentrate on the applications thought to be most likely: banking, financial services, and home shopping/ retail, while also examining the trends and strategies of the consumer electronics industry. If a direct-to-subscriber system using Ka-band satellite technology is developed in the near term, it will most likely be an outgrowth of these market segments.

SECTION 2
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SECTION 3
SYSTEM REQUIREMENTS

This section addresses some of the system aspects of the FSS design. In particular, frequency stability, method of access, throughput/delay, on-board processing, signal structure, and multiple beams will be investigated here.

3.1 FREQUENCY UNCERTAINTY

3.1.1 Doppler Shift

One source of frequency uncertainty is generated by satellite motion. The resulting Doppler shift in frequency can be estimated by v/λ, where v is the spacecraft velocity relative to the ground terminals and λ equals 0.01 m at 30 GHz. The spacecraft velocity should be on the order of several meters per second and should not exceed 10 m/s. The resulting maximum Doppler shift is therefore 1000 Hz.

3.1.2 Frequency Stability

In order for low-cost acquisition and tracking circuitry to be used in the ground terminals, the frequency must be known to a fair degree of accuracy. The lower the terminal burst rate, the more accurate this knowledge must be. Because of this relationship, the frequency stability requirement will place a lower bound on the uplink burst rate in order to minimize the terminal cost.

An accurate reference at 20 GHz is cost-prohibitive. A 10^{-3} accuracy (±10 MHz) currently sells for roughly $800, even in large quantities. An ovenized or phase-locked version providing 10^{-6} accuracy would be considerably more expensive. Since at least 10^{-6} accuracy is required (±30 kHz), some other mechanism for frequency stability is therefore required.

Including a pilot tone in the system architecture is one alternative to precise standards in each terminal. Some form of frequency locked loop (FLL) or phase locked loop (PLL) would be used to track out most of the frequency error of the local oscillator. A simple block diagram of the receiver circuitry is shown in Figure 3-1.

The 20 GHz RF is bandpass filtered and downconverted to a high (say 200 MHz) IF by a harmonic mixer. A FLL would use a discriminator to locate the pilot tone and a 10 GHz voltage-tuned, dielectric-stabilized oscillator (DSO) to mix (its second harmonic) with the RF to produce the IF locked to the pilot signal. This DSO would require much less accuracy than the 10^{-6} LO since the pilot tone discriminator could have a ±10 MHz search window. The resulting 10^{-3} accuracy requirement for the DSO would still be quite expensive but the cost should fall in coming years as that technology matures. An alternative to the voltage tuned DSO is the less expensive but less accurate Gunn diode oscillator. Accurate oscillator technology for consumer Ka-band applications would therefore be an area for future research.

The accuracy of the high IF generated by the FLL would be a function of the quality of the discriminator. By itself, the discriminator accuracy would still be on the order of several MHz. However, by locking the discriminator to a 200 MHz source, accuracies of several kHz should be possible.

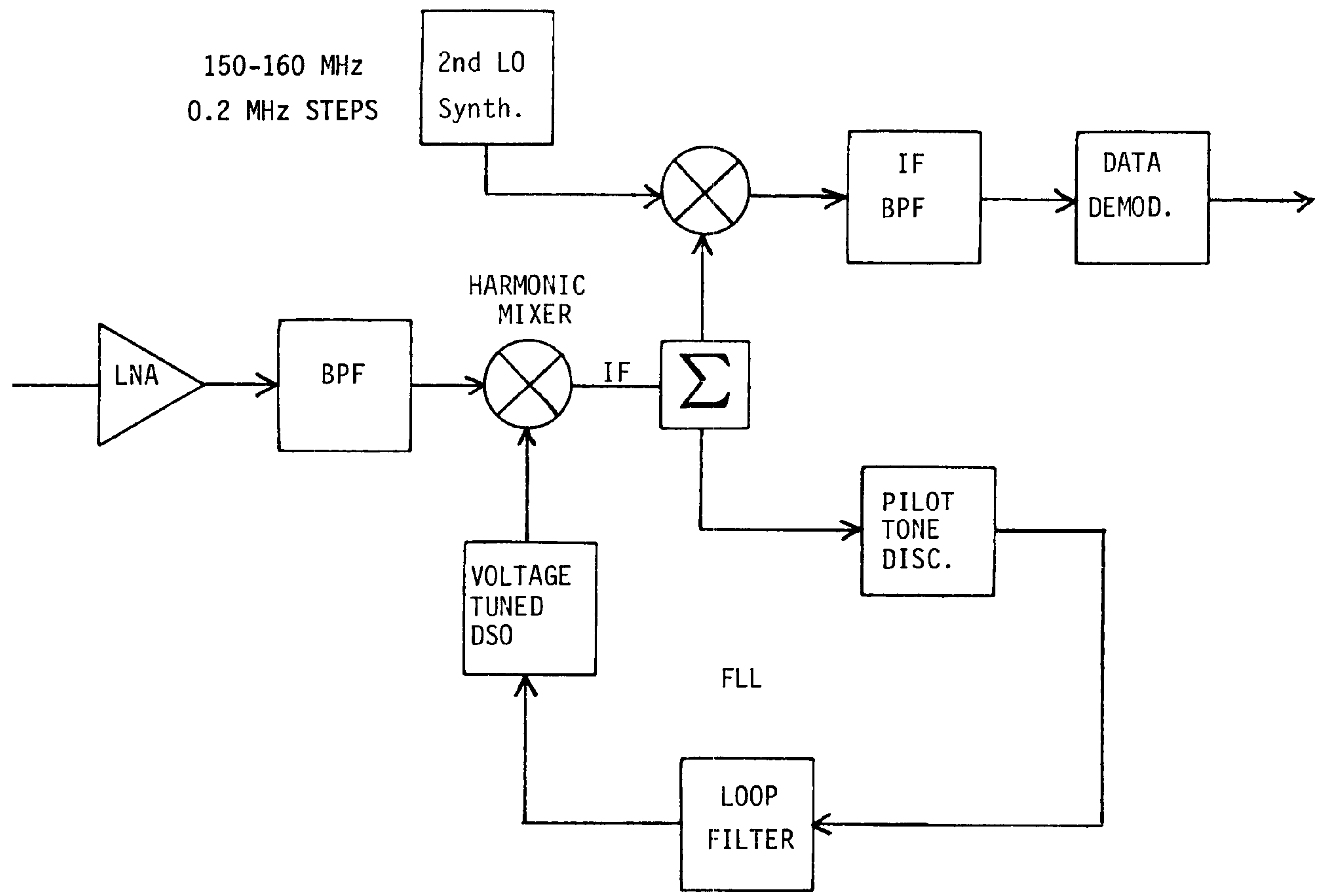

Figure 3-1 Frequency Acquisition Circuitry

Once an accurate IF is obtained through the FLL, a lower cost local oscillator/synthesizer accurate to within tens of Hz or less could then be used to tune to the desired channel. The stable source located in this synthesizer could also be used as the reference for the FLL's discriminator.

The overall accuracy of this approach is determined by the accuracy of pilot tone (Doppler error), the accuracy of the transponder frequency source (translation error), the accuracy of the terminal transmit frequencies which are obtained through the FLL, and the accuracy of the IF produced by the FLL.

The Doppler error was found to be no more than 1000 Hz without a pilot tone. With a pilot tone transmitted by or through the satellite, this Doppler error should be reduced since all terminals will be locked to the pilot with only the difference in aspect angle contributing to a residual error. The CONUS covers an angle of roughly 8° from geostationary orbit, so the resulting differential Doppler error is just 1000 Hz • sin(8°) or 140 Hz.

It is assumed that the frequency translation on the satellite will be quite accurate since considerable funding can be allocated towards the space segment. One hundred Hz accuracy is assumed.

The remaining frequency error is due to the FLL and the generation of a transmit carrier based on the frequency locked to. A couple kHz of error seems to be a reasonable goal although this may not be possible with low-cost circuitry.

The sum of these error sources is on the order of 2 kHz although this presumes some reduction in current costs. For the sake of this study, we will assume frequency errors of 10-20 kHz. To limit this frequency uncertainty to 10 percent (10%) of the transmit bandwidth (roughly the maximum uncertainty desirable for a relatively low cost acquisition and tracking loop), the uplink burst rate must be at least 200 kb/s. Since the data rates of the potential applications are far lower than this (see Section 2), some form of TDM burst format would be necessary.

3.2 MULTIPLE ACCESS

We have shown in the preceding section that moderate burst rates are required for frequency stability reasons. Straight FDMA is therefore not feasible since the application data rates are much less than this burst rate. Pure TDMA is also impractical because the large number of network terminals and low duty factor would lead to inefficient channel usage and long delays. Also the strict timing requirements and high (multi-Mb/s) burst rates would result in high terminal costs. Instead, a network of many, low volume users such as this lends itself to either random access (RA), demand assignment (DA), or spread spectrum multiple access (SSMA) schemes. These three techniques will be examined in this subsection.

3.2.1 Random Access

Random access is probably the simplest access scheme available and hence the least expensive to implement. However, due to the inherent delays resulting from the inevitable packet collisions, RA is restricted to non real-time communication. Pure ALOHA is the least complex form since it requires no timing information. For this reason, it is quite attractive for this FSS application. The penalty one pays is the low maximum throughput of 1/2e (18.4%); the typical operating point is between 10 and 15 percent throughput which reduces delay and maintains stability.

By adding timing information to each terminal, Slotted ALOHA can be used which effectively doubles the channel throughput. The timing requirement can be expensive to implement as guard times of <5% of the slot duration must be enforced. For a 500 b packet and a 200 kb/s burst rate, the timing uncertainty must be reduced to <125 μs. If shorter packets are envisioned, than even more stringent timing must be maintained.

To achieve this accuracy, one of the two approaches described in Subsection 3.1 can be taken: 1) very stable local oscillators can be used so that timing corrections are not necessary; or 2) a FLL can be used in each terminal to track a pilot tone with time ticks transmitted by a network reference [Emerson, 1985]. Option 1 is impractical since to achieve the necessary timing stability for even one hour would require a LO accuracy of $125\ \mu s/3600\ s = 3.5 \times 10^{-8}$, clearly too expensive given the current cost of Ka-band oscillators. The second option has been shown to be advisable for frequency accuracy considerations and could therefore be used to maintain timing.

In either case, to use a slotted access scheme, relative timing must be obtained at the time of net entry. This relative timing is needed to account for the propagation delay to or from the satellite. (Round-trip propagation delay is not important in this context since the ultimate network timing originates at the satellite.) Part of the propagation delay uncertainty is due to the terminal position uncertainty which can introduce up to 16 ms of delay bias. The removal of this bias requires either a two-way communication with the network reference or the broadcast of the satellite range by the reference and the entry of the terminal's location by the user into the terminal's data base. For consumer products, it is usually advisable to make operation as simple as possible so the two-way communication is the preferred approach.

This two-way communication for a terminal to achieve network synchronication can be done automatically when the terminal is turned on. The requesting terminal would include its own time of transmission in the log-on message and the network controller would respond with its time of arrival (of the request) and time of transmission (of the response). The originating terminal would measure the time of arrival of the assignment and, with the other parameters known, would be able to accurately measure the round-trip delay through the satellite. The timing uncertainty at the start of the message transmission should then be quite small. [Emerson, 1985] has shown that accuracies to a fraction of a millisecond can be obtained using a standard 1 MHz clock. If done in software, the marginal cost of this capability should be minimal. Maintaining slot timing may be a good improvement to the low throughput of Pure ALOHA. However, if bandwidth is of less concern than terminal cost, then obtaining slot timing is not cost-effective.

Both Pure and Slotted ALOHA are inherently unstable since each collision generates more traffic. For this reason, random access networks typically operate well under their maximum throughput. These ALOHA schemes can, however, be made more stable through a modification to the baseline access algorithm which increases the randomization interval following each successive collision. By doubling this interval after each collision, throughputs close to the theoretical maximum can be achieved. The drawback is that average delay increases exponentially as one nears the maximum throughput point.

3.2.2 Demand Assignment

The main alternative to RA is DA channel capacity. Here a central controller would be responsible for assigning all channel traffic. Requests for channel capacity are made over common reservation channels using either RA or TDMA. With a large number of users, RA on the reservation channels is preferable. DA makes good sense when long or real-time connections are needed. Throughputs much greater than possible with RA can be achieved.

No timing requirement need be associated with a DA algorithm. Pure ALOHA can be used for the requests, and channels can be assigned asynchronously on a first-come/first-serve basis. The assigned channel would be relinquished by the terminal on the reservation channel at the completion of the message. However, with overhead including requests, assignments, relinquishments, and acknowledgments, and with round-trip propagation delays of 1/4 s, the message length should be longer than several seconds in order to achieve good throughput. At 200 kb/s, this would require messages at least 500 kb in length, longer than most applications. We can conclude, then, that DA without such timing is not a practical alternative for the 30/20 GHz FSS.

Timing for DA must be synchronized only for the duration of the message, since RA could be used for the request and the relinquishment. For example, with an application data rate of 16 kb/s, 12 users could be time multiplexed on one 200 kb/s uplink channel. The network controller would assign the beginning slot time and the slot interval, and the terminal would transmit in those assigned slots until finished. In the Subsection 3.2.1 description of Slotted ALOHA, we showed that a timing accuracy of 125 μs would be required to achieve 5% guard times for 500 b packets. The same two-way communication could be used to provide this timing accuracy. If a FLL is used to track a pilot channel, then this timing acquisition need be performed only once, at terminal log-on. With a 10^{-6} LO instead of a FLL, the acquisition procedure must be repeated for each request (demand) as slot timing to within the necessary guard time could be maintained for only 2 min. This should be long enough for many applications, however. If longer packet lengths could be used (several thousand bits), then less stringent timing would be required.

It is therefore possible to provide DA channel slot time to those applications which require either real-time service (voice), or very long messages for which pure RA would be inefficient. The added terminal complexity to provide this service is not significant, requiring a software routine to calculate the round-trip propagation delay and more sophisticated timing control to stay within the TDM slots.

3.2.3 Spread Spectrum Multiple Access

Much has been made of SSMA in recent years, both for military and commercial applications. Equatorial Communications Co. has a system of C and Ku-Band satellite terminals which employ this method of access; many thousand terminals have been sold and networks of over one thousand terminals now operate successfully [Katsaros, 1986]. Although SSMA can refer to either direct sequence (DS) or frequency hopping (FH) methods of spectrum spreading, we will confine ourselves to DS approaches because of the prohibitive cost of frequency hopping synthesizers.

There are a number of advantages to such an access scheme. A principal advantage is that, like Pure ALOHA, terminals may transit at any time without need for accurate knowledge of system time. Second, the transmit power required for SSMA is far less than for a burst communications system using TDM. The power required is simply a function of the data rate and not the burst rate. For 9600 b/s applications, this results in a 13 dB advantage over the TDM architectures discussed previously which burst at 200 kb/s. Other advantages of SSMA are 1) no collisions and hence no need for message acknowledgments, and 2) less required central control than either RA or DA.

[Viterbi, 1985], and [Weber et al., 1981] have evaluated SSMA systems to determine their performance. The results of these analyses are:

1) SSMA is always power limited and never bandwidth limited.

2) There is a threshold in the number of users of a SSMA system beyond which performance degrades quite rapidly.

3) Use of coding is especially beneficial in SSMA since the system is already spread, although little performance improvement is obtained for a code rate $r < 1/3$.

4) Unless spectrum efficiency is of little concern, then TDMA and FDMA systems outperform SSMA in terms of required carrier-to-noise power ratio (CNR).

5) For small terminal commercial systems, link margins are already limited without introducing the self-interference associated with SSMA.

6) For unequal signal powers, a signal α times stronger than a weak (attenuated) signal acts like α other equal power signals to the weaker user.

Several figures illustrate these conclusions. First Figure 3-2 [Weber et al., 1981] shows the degradation factor (DF) versus total number of users for a coded system with spreading factors, i.e., ratio of chip rate to bit rate (R_c/R_b), of 200 and 2000. (DF factor is the amount of excess signal required to maintain a given error rate as compared to a single user case.) Note that beyond some point, no amount of extra power will enable more users to successfully communicate as the system becomes interference limited, not

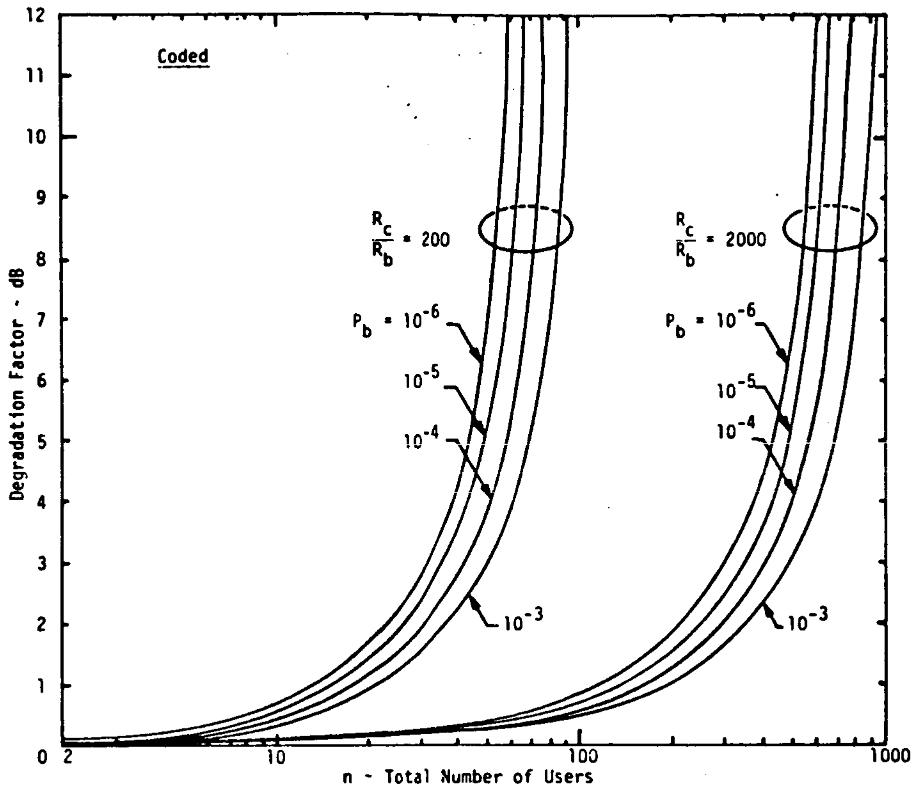

Figure 3-2 Degradation Factor Versus Total Number of Users with K = 7, R = 1/2 Convolutional Coding and Viterbi Decoding with Soft Decisions.

noise limited. Also, Figure 3-3 [Viterbi, 1985] illustrates the efficiency of SSMA versus FDMA/TDMA for various code rates. It shows that SSMA efficiency (using BPSK) never exceeds 0.4 b/s/Hz and then only at high values of CNR (throughput taking coding into account).

These two figures were used to compute channel efficiency as a function of the DF. This is provided in Table 3-1 below at a 10^{-5} bit error rate and two coding rates. Again BPSK is assumed.

This table provides good insight into the penalty one pays for using SSMA instead of conventional FDMA or TDMA systems. For example, if one could obtain 0.25 channel efficiency using demand assigned TDMA or FDMA and rate 1/2 coding (quite attainable), then it would take a little more than an additional 5 dB in the system design, either in larger antennas, more power, lower noise amplifiers, etc., to obtain the same 10^{-5} BER and 0.25 efficiency using SSMA. Conversely, if one were willing to give up only 1 dB in system design, then efficiencies of less than 0.09 b/s/Hz would result using SSMA. Slotted ALOHA with r = 1/2 would provide much better efficiency (0.12 - 0.15 b/s/Hz) and even Pure ALOHA could provide comparable efficiency. In clear conditions when no rain compensation (coding) is required, then both Pure and Slotted ALOHA are more efficient then SSMA and require less carrier power, per bit transmitted.

Table 3-1
Degradation Factor of SSMA
for Given Channel Efficiency
(BER = 10^{-5})

DF (dB)	Efficiency (b/s/Hz)	
	r=1/2	r=1/3
1	0.07	0.085
2	0.125	0.15
3	0.17	0.20
4	0.21	0.24
5	0.24	0.275

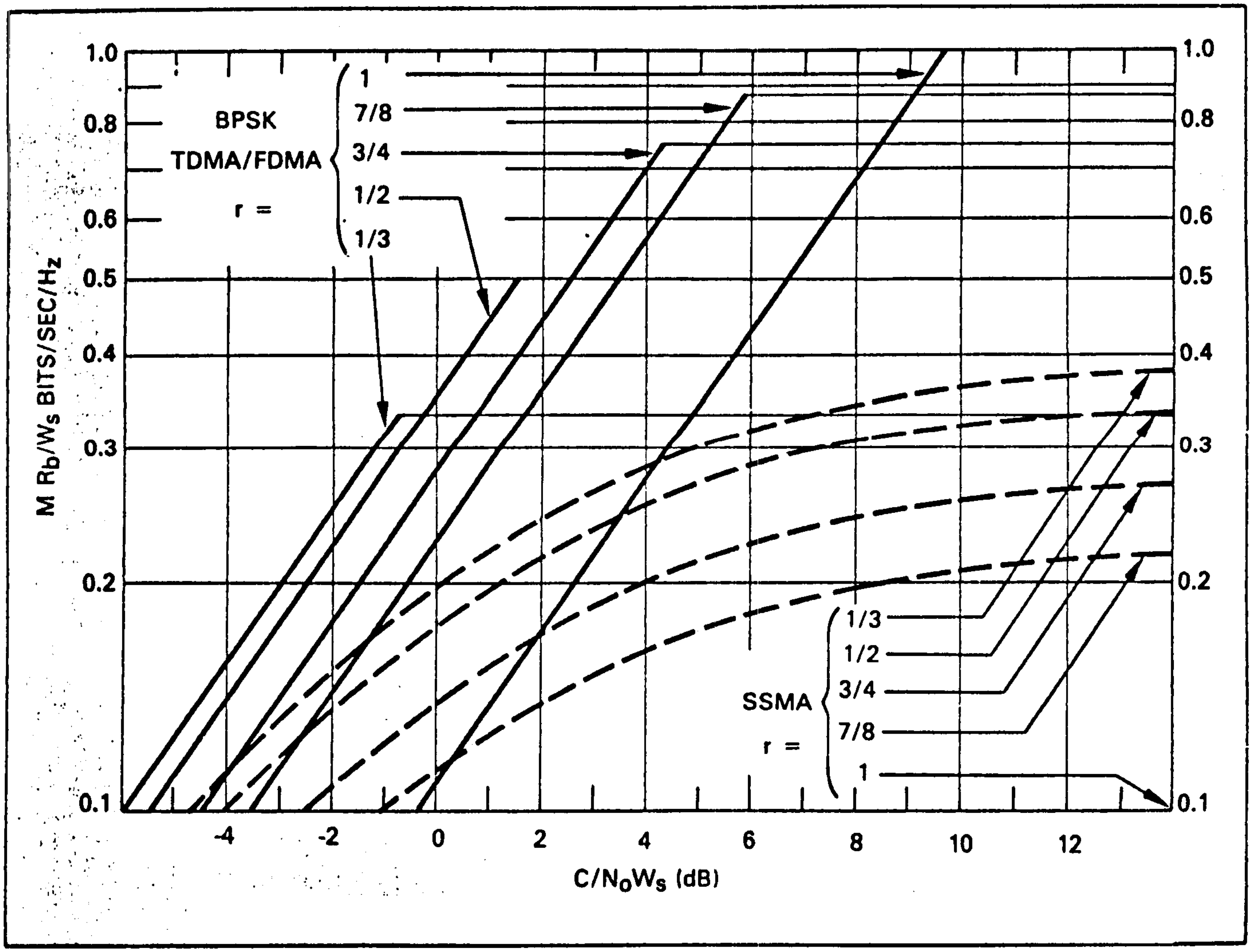

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Figure 3-3 Channel Efficiency as a Function of C/N_0W_s.

These efficiencies have assumed equal power users of the spread spectrum system. At Ka-band, rain will cause up to 19 dB of signal attenuation and unless some form of power control is used, the signal powers could vary considerably (see Section 3.5.1.3). In order to allow 10 dB differences between signal powers in the link budgets, the spreading factor must be increased 10 dB to compensate for the many stronger (unattenuated) signals. For example, if 10 out of 100 users are attenuated 10 dB because of heavy rain, then to these weak users, the system interference is equivalent to 909 (90 x 10 strong signals + 9 weak) competing equal power users. The achievable efficiencies must therefore be reduced by the maximum expected ratio of user powers. In this case, the efficiencies would be between 0.01 and 0.04 b/s/Hz.

In addition to these performance issues, synchronization of the receiver constitutes a major design problem of SS communication systems. For the low-duty factor applications considered, signal acquisition will be necessary for each message sent. Numerous acquisition circuits have been proposed and demonstrated, but one popular method is the use of a sliding correlator. The incoming signal is correlated with the local PN sequence at each chip interval (or fraction of a chip) until the correlator output exceeds a given threshold. At that point, acquisition is completed and signal tracking commences. Additional circuitry such as a PLL or τ-dither loop is necessary to perform this tracking.

Once the signal is despread, the demodulator can detect the data. Unfortunately, any frequency error due to LO instability or Doppler offset will be significant given the relatively low data rate. For example, a 20 kHz frequency uncertainty provided by 10^{-6} LO is far too large to properly demodulate a 9600 b/s signal. Even the 1 kHz Doppler induced by satellite motion produces a substantial frequency uncertainty at the given application data rates. A pilot tone to provide a frequency standard to all users therefore will be more necessary for SSMA than for burst type TDM access schemes.

3.2.4 Access Recommendations

We have shown in this section that both RA and DA are viable access methods and have a place for certain applications. We have also seen that SSMA has several significant advantages and disadvantages with respect to RA and DA. However, it is felt that since bandwidth is of secondary importance to system cost, then SSMA and Pure ALOHA are the two most promising methods of access for short, interactive applications. DA still may be the preferred approach for long data transfers. The remainder of this study will focus on SSMA and Modified Pure ALOHA since, as concluded in Section 2, interactive applications hold more promise than data transfer.

3.3 THROUGHPUT AND DELAY

In the preceding subsection, the throughput of both Pure ALOHA, Slotted ALOHA, and DA access techniques were addressed. In this subsection, the capacity of a direct to subscriber system using these access schemes is estimated. In addition, the delay performance of RA is calculated.

3.3.1 System Capacity

To make an estimate of the capacity of an RA FSS system in terms of the number of users it can support, several assumptions must be made. These are:

Average data rate (R)	9600 b/s (see Figure 2-2)
Available bandwidth (W)	100 MHz
User duty factor (δ)	10% (see Table 2-13, Point of Sale)
Channel efficiency (S) Pure ALOHA	0.125
Number of beams (M)	32
Number of frequency subbands or designs (N) (for frequency reuse)	4
Single-user time-bandwidth product (TB)	0.75 Hz/b/s (for quadrature modulation)

The user therefore transmits at an average rate of

$$R \cdot \delta = 960 \text{ b/s},$$

and the data capacity of the spectrum (per 100 MHz) can be calculated as:

$$\frac{W \cdot M}{(TB) \cdot N} = \frac{100 \text{ MHz} \cdot 32}{0.75 \text{ Hz/b/s} \cdot 4} = 1.07 \text{ Gb/s} . \tag{3.1}$$

With a 12.5% channel throughput, Pure ALOHA therefore has a capacity of 133 Mb/s. The number of RA users that can be supported is therefore 133 Mb/s / 960 b/s = 139 thousand. Again it should be noted that this is for each 100 MHz of bandwidth.

This assumption of 10 percent duty factor was based on a point-of-sale business application. The consumer user would have a duty factor several order of magnitude lower so the 139,000 users can be thought of as a lower bound. Millions of consumer users could easily be served.

3.3.2 Delay

Delay is only meaningful for RA since DA provides real-time communication. For ALOHA, the probability of successful transmission is S/G, where S is the normalized input traffic and G is the normalized channel traffic. Each unsuccessful transmission incurs a delay of $t_0 + k\tau/2R$ seconds where t_0 is the timeout period, k is the retransmission interval in packet lengths, and τ is the packet length in bits. The timeout period must be greater than twice the round-trip propagation delay (d_p) plus the message and acknowledgment lengths. For a 200 b acknowledgment, this corresponds to a t_0 of 0.5 s + $(\tau + 200)/R$. A successful transmission takes $d_p + \tau/R$. The average transmission delay is therefore:

$$D = (t_0 + k\tau/2R)(G/S - 1) + d_p + \tau/R \ . \tag{3.2}$$

For Pure ALOHA the G/S term can be approximated as e^{2G} for a large number of users as long as k is large. In practice, $k > 15$ provides good randomization of the collisions. Figure 3-4 plots the delay as a function of S for several values of τ. A 9600 b/s data rate is assumed. For a 600 b message, throughput is limited to 0.15 to keep the average delay to under 0.7 s. This is also a practical limitation on throughput necessary to maintain stability. If longer delays are acceptable, Modified Pure ALOHA (MPA) could be used to realize throughputs above 0.15. Nearly identical delay performance is obtained with Slotted ALOHA with the difference being that nearly twice the throughput can be achieved for the same average delay.

3.4 ON-BOARD PROCESSING

3.4.1 Features of On-Board Processing

The type of advanced domestic satellite envisioned for lower data rate communications applications may include a regenerating repeater. This portion of the satellite demodulates uplink signals to baseband; processes the data bits by performing error control, baseband switching, and reformatting; and remodulates the data for the downlink.

3.4.1.1 Signal Regeneration

The regeneration of data by the baseband processor has the advantages of either improving performance or permitting smaller terminals and a lighter satellite to maintain a given margin. These reductions are due to lower power and smaller antennas and result in lower cost. Conventional transponder satellites simply hard-limit, frequency translate, and amplify the incoming signals. This repeats uplink noise and introduces on-board intermodulation products due to satellite nonlinearities. These degradations imply the need for higher power, larger antennas, and lower-noise receivers to ferret out the useful signals.

On the uplink, the terminals can burst at much lower rates with FDMA then with TDMA. This difference can be significant in reducing terminal cost since it implies less effective isotropic radiated power (EIRP) for the same energy per bit and a more relaxed timing requirement.

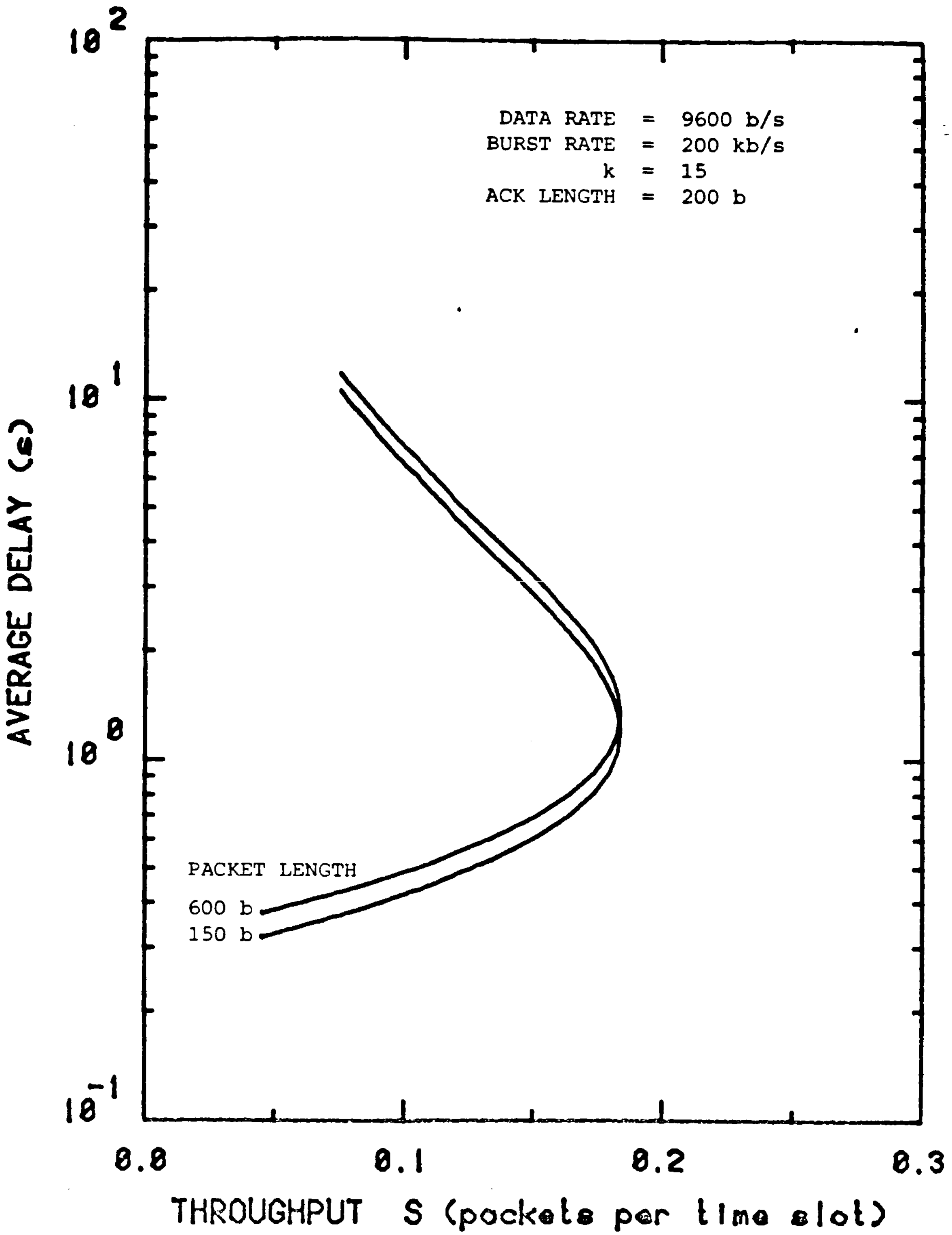


Figure 3-4 Average Packet Delay of Pure ALOHA Through Geostationary Satellite

Another issue is the degree to which terminals must be coordinated as members of a network with respect to transmission timing, frequency, and power. Many existing bandwidth-efficient modulation schemes do not require stringent network coordination (see Subsection 3.5). In this case, the burden of demodulating simultaneous signals from independent terminals is placed on the satellite. Although this increases satellite complexity, it can simplify the terminals, and this philosophy may be economically attractive in a system of many more terminals than satellites.

Since signals are regenerated by demodulation and remodulation on-board the satellite, there is the opportunity for choosing a different down-link signal format than used on the uplink. In particular, TDM downlinks which may operate at many times the uplink burst rates, are possible. In the FDMA mode of operation, several signals coming from separate earth terminals are simultaneously demodulated by the satellite. These data are switched, reformatted, and combined with data from other uplink beams into a set of TDM downlinks, one for each downlink beam. Each TDM downlink data stream is broadcast from the common satellite platform and received by all active terminals in the coverage region of that downlink beam. Destination terminals select portions of this TDM traffic addressed to them. This FDMA/TDM multiple access/multiplexing scheme leads to lower cost terminals and minimizes inter-modulation problems of the satellite.

The fundamental reason for a TDM rather than an FDM downlink is the desire to avoid unnecessary intermodulation interference arising from generating too many downlink signals at distinct carrier frequencies with the simultaneous operation of nonlinear power amplifiers on-board the satellite. The higher downlink burst rate implied is more manageable in this case because all downlink signals emanate from the same platform, which may employ a common master timing reference. This makes the task of acquiring, tracking, and demodulating downlink bursts in the terminal much easier, compared to a situation where bursts from different terminals are generated from separate clocks (as on the uplink).

3.4.1.2 Baseband Switching

A much more important advantage of on-board processing in the form of satellite regenerative of the signal may be the great increase in flexibility for switching and interconnecting users on a bit or packet level basis. With the regenerative repeater, one is no longer restricted to a point-to-point network structure. One-to-many and many-to-one applications can be envisioned as well. By demodulating the lower rate data, opportunities for on-board storage with buffers or bulk memory are introduced. This can be advantageous for collecting data to a destination not yet in a scanning beam coverage area, for example. It can also be useful for error control, link protocols, and reformatting data for the downlink, as noted.

3.4.2 Demodulation/Remodulation

Major contributions to spacecraft weight and power, resulting from the baseband processor and its communications related interfaces, are implied by on-board demodulation, especially if an all-digital implementation is selected for the demodulators. Several alternatives for accomplishing the demodulation of uplinks, all-digital, hybrid analog/digital, and all-analog, are indicated in the general block diagram of Figure 3-5. Each of these alternatives is discussed in some detail in an attempt to ascertain the most suitable approach.

3.4.2.1 All-Digital Implementations

The all-digital approach necessarily involves an RF mixing of the incoming signals to an IF bandwidth, followed by an analog-to-digital (A/D) conversion process with some level of input amplitude scaling and quantization, and subsequent purely digital arithmetic and accumulation operations assuming a strategy of rounding or truncation. The required high speed multiplications can be either performed with b-bit read-only memories (ROMs), b-bit high speed multiplier logic elements ($b < 5$, typically), or with CORDIC rotators [Haviland, Tuszynski, 1980]. High power consumption of the digital circuitry required to perform demodulation of multiple signals in a single relatively wide IF bandwidth may suggest that each signal be converted separately to its own IF bandwidth by an individual RF mixer.

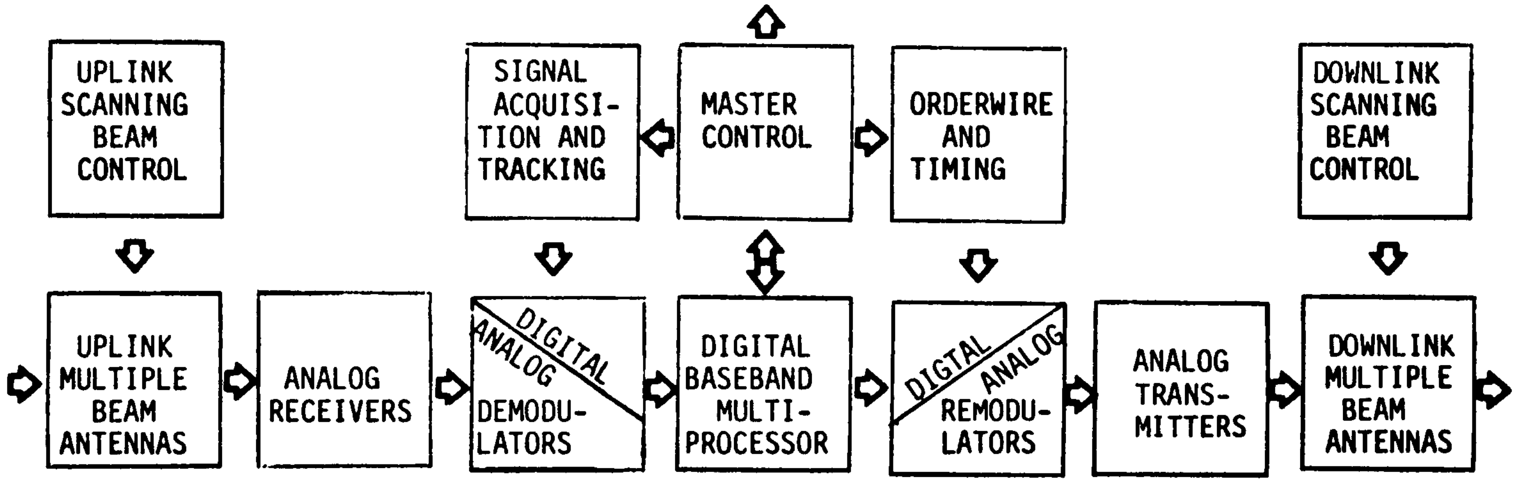
The preferred alternative is the group demodulation of several signals within a subband after they pass through a single IF mixer and A/D converter. The state-of-the-art of A/D converters and power consumption calculations may suggest that this group demodulation approach is not feasible for too wide a bandwidth. If it is feasible with respect to A/D conversion, there should be some advantages, including lower weight and power, to group demodulation as a compromise between simultaneous demodulation of completely synchronized signals using an (FFT) algorithm and separate demodulation of individual signals.

Signals with the same relative received power level could be allocated to the same subband according to either on-board processing or ground control protocols. This would result in either low crosstalk, or permit the closer packing of the FDMA signals in the subband for a given crosstalk level. A closer packing of carriers would imply a narrower subband and the possibility of a lower A/D conversion sampling rate and less power consumption.

3.4.2.2 Hybrid Realizations

The hybrid method of demodulation may involve an analog/ digital demodulation technique utilizing surface acoustic wave devices (SAWDs) and/or charged coupled devices (CCDs). With either family of devices, the basic signal processing and output detection involves analog quantities. The relative avantages and disadvantages of SAWDs and CCDs are listed in Table 3-2. This qualitative characterization should not be taken too literally because there is a large region of overlap in the bandwidth/time-delay space where either SAWDs or CCDs can be applied. (See Figure 3-6.) Also, not all of the devices in either family possess every property shown in the table.

It is recommended that SAWDs and CCDs be examined as serious candidates for implementing spacecraft demodulators. Their main advantage is in the potential for low volume and power consumption. Although much has already been done in attempting to apply these analog devices to digital demodulaton, additional development is both warranted and on-going. SAWDs and CCDs may represent a higher risk for spacecraft implementation than the all-digital aproach for lower rate signals. However, higher data rates may make



REGENERATION OPTIONS

- ALL DIGITAL
  - MULTIPLIERS
  - CORDIC ROTATORS
- ANALOG/DIGITAL
  - SAWD/CCD HYBRIDS
- ALL ANALOG
  - MICROWAVE CIRCUITRY

Figure 3-5 Fundamental Baseband Processing Configurations

Table 3-2

Qualitative Comparison of SAWDs and CCDs

Surface Acoustic Wave Devices	Charged Coupled Devices
Wideband (good for spread spectrum and combatting multiple access interference)	Narrowband (can handle low data rates easily)
Operate at IF or RF (mixers not required at VHF/UHF)	Operate at baseband (mixers usually required)
Passive by high insertion loss (non-volatile but amplifiers required)	Active but no insertion loss (volatile and power required)
Radiation insensitive (good for operation in near-earth space)	Vulnerable to radiation (requires shielding in space)
May be temperature unstable (oven may be required)	Temperature stable (good for space operation)
Frequency may be imprecise (tuning may be required)	Frequency stable (clocked operation)

Power, size, cost can be comparable
CCDs may have longer Mean Time Between Failure (MTBF)

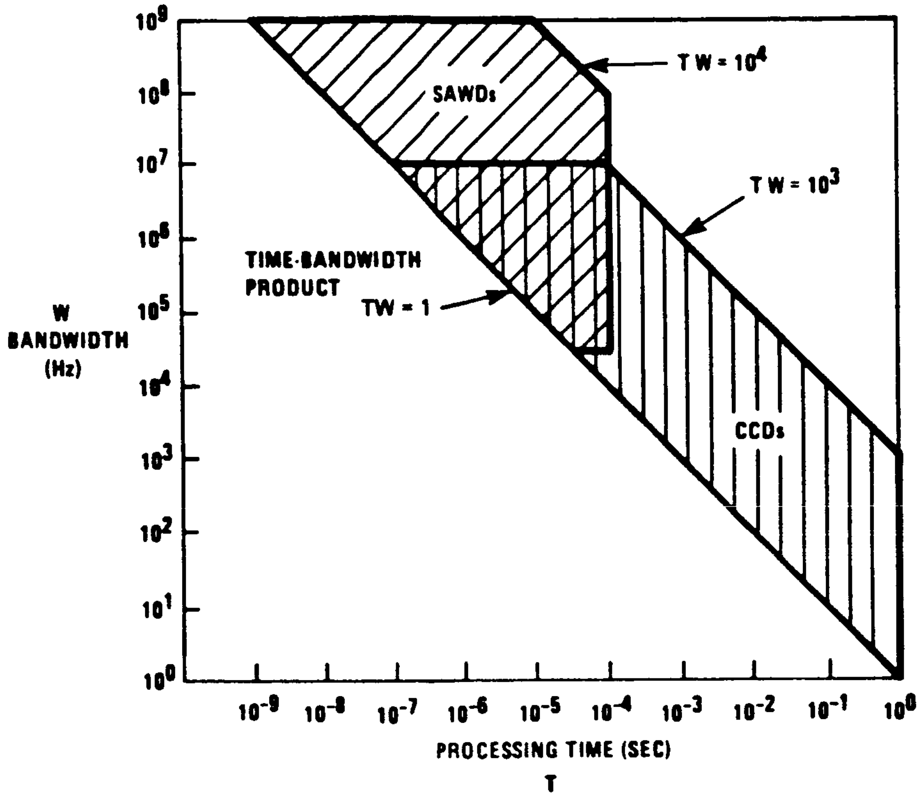


Figure 3-6 Approximate Operating Ranges of CCDs and SAWDs

SAWDs and CCDs quite attractive for spacecraft implementation. In this case the space qualification of these signal processing devices should have high priority.

3.4.2.3 Microwave Demodulation

The final alternative is a purely analog demodulation utilizing standard microwave circuitry [Amadesi, et al., 1978]. This approach has the outstanding advantage of being very low power. For standard digital modulation schemes like quadriphase shift keying (QPSK) and offset or staggered QPSK (SQPSK), these devices are conceptually very simple and presumably can be packaged into small volumes. On the other hand, this microwave approach may not lead to the same high density level of VLSI circuitry achievable with the all-digital approach or with SAWDs and CCDs. More importantly, the microwave circuits cannot be used with more advanced bandwidth efficient modulation schemes where the baseband modulation shape is not rectangular, as it is with QPSK. If there is a way of demodulating more sophisticated waveforms in a completely passive and analog fashion using microwave circuits, there does not seem to be any available literature on such techniques.

3.4.3 Baseband Processor Example

In a narrow sense, a baseband processor is the subsystem of the satellite communication payload that manipulates bits (b) or sequences of bits (packets) of information gleaned from the digital signals received on the uplinks. The inputs and outputs of this subsystem are binary data only. The input bits are derived from incoming intermediate frequency (IF) bandwidth signals by the process of demodulation which converts individual signals to their relatively smaller information bandwidths (basebands) through detecting the bits of data imparted to the transmitted signals. The output bits are the basis for the remodulation process whereby uplink signals are regenerated for the satellite downlinks.

In a wider sense, the baseband processor includes the demodulators and remodulators, because they constitute the interfaces through which the on-board digital processor communicates with the outside would. The uplink interface is emphasized in this subsection since the demodulators potentially have the greatest impact on communications payload weight and power.

3.4.3.1 System Assumptions

The essential ingredients of an advanced domestic satellite communication system are multiple beam antennas for frequency reuse, bandwidth efficient modulation and coding for spectral and power conservation, and on-board processing and switching for servicing many different traffic and user requirements.

Satellite weight and power constraints which might be associated with baseband processing are expected to be in the order of 400 kg and 2 kW. This would include the functions of uplink demodulation, baseband processing of data packets, remodulation, and downlink transmission power; antenna weight is not included. With this weight and power budget, one can expect to support as much as 100 MHz of spectral bandwidth devoted to signals to be processed at baseband [White, et al., 1980].

3.4.3.1.1 Uplink and Downlink System Interfaces

In the example design, it is assumed that there are 16 independent uplink beams and 16 independent downlink beams associated with the baseband processor. Each uplink beam uses the same 100 MHz bandwidth in the uplink frequency allocation, and similarly on the downlink. Assuming a spectrally efficient modulation scheme which yields one b/s per Hz, the baseband throughput of the satellite will be approximately 1.6 Gb/s.

For the sake of illustration, the 16 uplink or downlink beams are arbitrarily divided into 8 fixed beams and 8 scanning beams. A common 1 ms frame interval, subdivided into eight 125 μs slots, is assumed. The beam and slot organizations permit a combination of FDMA and TDMA operation on the uplinks. In a fixed beam, a number of FDMA carriers, each employing TDMA within a frame may be used. In a scanning beam, a number of FDMA signals operating in a single channel per carrier (SCPC) mode are present in the beam during a given dwell interval. In this case, each carrier is associated with a different terminal user. At the end of each 125 μs slot, a scanning beam is free to move to another coverage area. The period of every scanning beam is one frame or 8 slots. Thus, nominally, a scanning beam would return to the same coverage area every 8 slots, although the 8 specific coverage areas visited could be reprogrammed from epoch to epoch. A fixed beam can be viewed as a special case of the scanning beam where the coverage area does not change.

In order to maintain a given data rate R, a terminal located in a scanning beam coverage area must burst its data at a channel rate of 8R. Similarly, in a fixed beam with a carrier utilizing TDMA, a given terminal must burst at 8R. Consequently, if TDMA is not used on a fixed beam carrier, the burst rate is equal to R.

The nominal user data rate in this example is 1.544 Mb/s. This is equivalent in data rate but not necessarily in signal structure to a T1 carrier. The example design could also incorporate lower rate users typically in the order of 64 kb/s.

A T1 rate user in a scanning beam must burst at aproximately 12.4 Mb/s channel data rate during a scanning beam dwell. This, along with the one bit per cycle assumption implies that eight FDMA carriers at the burst rate may be accommodated in the 100 MHz bandwidth of the scanning beam. Note that in this sense, the 1 b/s per Hz assumption (which is optimistic; see Subsection 3.5.2.2) applies to the center frequency spacing between carriers. This implies that 64 T1 class users may be serviced concurrently within a scanning beam. With 8 scanning beams and 8 fixed beams, each interpreted as a special case of the scanning beam, a total capacity equivalent to 1,024 T1 users is implied.

On the downlinks each beam contains only one TDM carrier. Each 125 μs slot of the 1 ms frame contains eight subslots each of 15.625 μs duration to accommodate the 8 FDMA uplinks. The downlink burst rate is therefore 64R = 98.8 Mb/s, nominally.

3.4.3.1.2 Rationale for System Parameter Selection

It is important to understand the fundamental reasons for a given frame period and for the need for scanning beams. Although the particular values selected for the frame duration and the number of slots per frame are only nominal, some explanation of how they were selected follows.

It is assumed that the satellite is in either a geostationary or a near-geostationary orbit. This implies a round trip propagation delay of approximately a quarter of a second. For real-time traffic, it is desirable that any satellite processing delay not contribute significantly to the overall delay.

One potential source of processing delay on-board the satellite derives from the possible accumulations of several bursts of uplink data from one source terminal in an FDMA mode to produce a single, higher rate burst of data to a single destination terminal in a TDM downlink mode. Assuming that each uplink burst is received in the same slot of the periodic satellite frame, and that the downlink burst will occupy the same slot duration, the key parameters are the frame duration and the number of frames required to accumulate the downlink burst data. In the most straightforward realization of the present approach, the ratio of the downlink burst rate to the uplink burst rate is equal to the number of slots in a frame. Thus, if an uplink user has access to only one slot per frame and the satellite is accumulating data from that user for one particular downlink user, it takes a number of frames equal to the number of slots per frame to accumulate the entire downlink burst data. The parameters of 1 ms per frame and eight slots per frame imply a typical processing delay of 8 ms. Since this is much less than a one-way propagation delay, the integrity of real-time data will be preserved even though such on-board processing is performed.

Another form of on-board processing delay is that incurred by waiting for an appropriate downlink slot and/or beam for the destination of accumulated uplink data. This type of delay is typically upper bounded by the frame duration rather than some multiple of the frame period. Accordingly, this constraint is less stringent than the one implied by the FDMA/TDM conversion technique discussed above. For real-time data, the frame could be in the order of 10 ms long if it were determined just by the tolerable waiting time for downlink slots or beams. This would be possible if every packet received during an uplink slot always was retransmitted in a downlink subslot of one-eighth a slot duration within the next frame.

For non-real time data, much longer frames could be utilized. This could be advantageous for smaller, less expensive, low duty factor terminals which might employ ground-packet-radio type protocols with high channel efficiency.

The number of slots in a frame was selected to be a power of two for convenience of binary representation in the baseband processor and in the order of ten to construct an illustrative system without too large a burst rate disparity between the uplinks and downlinks. The 1 ms frame is of the right order of magnitude to avoid excessive processing delay, and when subdivided into 8 slots, a standard 125 μs slot duration compatible with T1 signal structures results. Uniform slot durations have been assumed in the example design for simplicity and to provide a convenient means of determining

determining and controlling required burst rates and scanning beam dwell distributions. Although the resulting design would probably be more complex, it is certainly possible to envision non-uniform slot durations in conjunction with variable and programmable frame partitions.

The rationale for scanning beams follows from the basic system design objective of complete coverage of the continental United States (CONUS) and the highly non-uniform population density in this country. A reasonable engineering judgment for the baseline design is that a collection of fixed beams only would be an inefficient realization of spacecraft hardware and platform space. An alternative recommendation is a combination of fixed beams and scanning beams, where the scanning beams would be time-shared to cover the less densely populated and more remote regions of the country. The fixed beams would be designed for the metropolitan area surrounding the major cities. (Unfortunately, the scanning beams would necessitate more complexity in the ground terminals to maintain strict network timing. More on this subject is contained in Section 6.)

Each scanning beam would be preprogrammed to visit a given coverage area with a cumulative dwell time that is proportional to the population of that area. This schedule would normally be followed automatically on-board the spacecraft without any ground control. Perturbations from the average scanning beam dwell distribution would be specified by central ground command on a relatively infrequent basis to reflect gradual shifts in traffic demand.

3.4.3.2 Sizing the Baseband Processor

The example baseband processor services 16 uplink and 16 downlink beams. There are 8 fixed beams and 8 scanning beams for both the uplink and the downlink. The fixed beams can be implemented by using scanning beams that are programmed to scan the same coverage area continuously. All transmissions over the satellite links are synchronized within 1 ms frames. Each frame consists of 8 scanning beam dwell intervals (slots). Every slot is 125 μs in length. Ten microseconds of each slot is reserved as an interblock gap (message guard band) while the remaining 115 μs are used for the actual transmission. (This increases the required terminal burst rates by a factor of 125/115 = 1.09.)

The satellite links are organized so that each uplink beam contains eight FDMA channels per slot. Each downlink beam contains 8 TDM channels per slot. A channel is defined as a instantaneous signal from or to a distinct user or terminal, from the satellite's point-of-view. Once assigned to a particular slot, a channel must share its slot with seven other channels.

On board the satellite, there is one demodulator for each uplink channel. The downlinks have 1 TDM modulator per beam. Since there are 16 uplink and 16 downlink beams that each support 8 channels/slot, signals on 128 unique channels will be arriving at the satellite simultaneously while 128 downlink channels are also active during each slot. Therefore the baseband processor must contain 128 demodulators and 16 modulators.

By using baseline assumptions concerning the beams, the throughput and switching requirements of the processor can be determined. The following assumptions are made concerning the satellite beams:

1. 16 uplink and 16 downlink beams to be serviced by the baseband processor;

2. Frame period = 1 ms;

3. 8 slots per frame implies 1 slot = 125 μs;

4. 8 channels per slot; and

5. Channel capacity = 1 packet per frame.

The uplink throughput of the baseband processor is:

Total number of packets per frame =

$$\text{\# of beams} \times \frac{\text{\# of channels}}{\text{slot}} \times \frac{\text{\# of slots}}{\text{frame}} \times \frac{\text{1 packet}}{\text{channel}} \text{ per beam} \tag{3.3}$$

= (16) x (8) x (8) x (1) packets/frame

= 1024 packets/frame.

If we allocate one packet per user per frame, 1024 users can be serviced by the baseband processor:

Total number of users serviced =

$$\frac{1}{\frac{\text{\# of packets}}{\text{user} \cdot \text{frame}}} \times \frac{\text{\# of packets}}{\text{frame}} = \frac{1}{1} \cdot 1024 \text{ users} \tag{3.4}$$

An additional baseline assumption is that users are to transmit at an average T1 rate of 1.544 Mb/s. Using this value, the requirements of the satellite links and the baseband processor can now be specified in more detail. Since a user's data is collected over a 1 ms frame interval, the packet size for the T1 data rate is 1544 bits. This packet is sent over the satellite link within one slot. Since the uplink slots provide the networks with a 115 μs transmission period, a user's channel must be capable of an uplink burst rate of 13.4 Mb/s. Each uplink beam supports 8 channels. Therefore, the total uplink bandwidth per beam is 107.4 MHz if a 1 b/s/Hz modulation is employed. Since each downlink beam supports 8 TDM channels at 8 times the uplink burst rate, the downlink bandwidth per beam is also 107.4 MHz, again assuming a 1 b/Hz modulation. Since the processor services 1024 T1 users, the satellite throughput is 1024 x 1.544 Mb/s = 1.6 Gb/s.

3.5 SIGNAL STRUCTURES

Bandwidth-efficient but particularly power-efficient modulation and coding schemes are of interest. There should be ample bandwidth available for these applications but it should certainly not be squandered just to accommodate low cost terminals. The conservation of uplink bandwidth is particularly important for FDMA architectures because of potential crosstalk (interchannel interference) problems with many unsynchronized uplink transmissions at different power levels.

With a baseband processing satellite which separates the uplinks from the downlinks, different modulation and coding schemes could be employed on the downlinks. In an FDMA/TDM architecture, for example, a less bandwidth-efficient but more power-efficient modulation such as multiple frequency shift keying (MFSK) might be employed if it simplifies the terminal receiver. If coding is used on the downlink to mitigate rain attenuation, a simpler decoding procedure, e.g., using hard decisions rather than soft decisions, might also be recommended for less complexity at the terminal.

3.5.1 Modulation and Coding

The required uplink carrier frequency spacing depends on the bit error rate (BER) requirement, type of modulation and coding employed, any transmitter filtering at the terminals or receiver filtering at the satellite, and propagation attenuation of signals in adjacent frequency channels, due to rain, etc., relative to that of the signal being demodulated at the satellite.

For the purposes of this small study, and for reasons to be given shortly, admissible uplink waveforms will be limited to constant-envelope, continuous-phase, offset-quadrature minimum shift keying (MSK)-type modulations, with convolutional encoding and Viterbi decoding.

Constant-envelope modulation is attractive for high efficiency operation of nonlinear power amplifiers, not only in the satellite (for downlink(s)), but especially on the uplinks for lower cost terminals. MSK-type modulations are very power and bandwidth efficient, having the same performance as binary phase shift keying (BPSK) or quadriphase shift keying (QPSK) in additive white Gaussian noise (AWGN) and much lower crosstalk than QPSK on the FDMA uplinks. MSK-type modulations are quite reasonable to implement, although they are not as simple as BPSK or QPSK.

The performance of nearly-constant-envelope, MSK-type modulations have been studied extensively through analysis and computer simulation for use in non-linear non-regenerative satellite channels subject to bandwidth limitations, interchannel interference, rain attenuation, etc., [Fang, 1981]. These results showed that this family of offset-quadrature modulation with some baseband pulse shaping consistently outperforms conventional QPSK with filtering. This lends further evidence supporting the selection of MSK-type modulation as a robust class of waveforms for this present application.

Other non-constant-envelope modulations such as quadrature overlapped raised-cosine modulation [Austin, Chang, 1981], filtered PSK [Prabhu, 1977], or filtered MSK [Amoroso, 1979] can be more bandwidth efficient but are usually less power efficient, introduce intersymbol interference, and/or require additional filtering or automatic gain control (AGC) (implying additional insertion losses, complexity, etc.). More general continuous-phase modulations [Anderson, et al., 1981] can also be more bandwidth and power efficient, but they are more complex to implement and more difficult to synchronize. Furthermore, the crosstalk performance of most non-MSK-type modulations is still unknown.

In contrast to most other approaches to bandwidth-efficient modulation, we handle crosstalk not in terms of the power spectrum of a modulation (mainlobe width, sidelobe level, fraction of out-of-band power, etc.) but in terms of the effect of the interfering signal on the predecision output of the receiver. This leads to a more direct way of measuring crosstalk and its potential impact on BER.

Convolutional codes are relatively simple to implement, especially at the transmitting terminals. The Viterbi decoding procedure, which should now be feasible in a processing satellite, is a powerful way of combating uplink rain attenuation on 30 GHz (and above) uplinks. It might be feasible to use coding only when necessary, as long as this does not unduly increase terminal complexity.

Viterbi procedures lend themselves more easily to soft-decision decoding for better performance (more coding gain) than block codes. As more is learned about integrated, continuous-phase modulation/coding schemes, Viterbi decoding techniques can be applied naturally because of structural similarities [Mazur, Taylor, 1981].

In this section a signal-to-noise ratio (SNR) model for handling crosstalk and interbeam interference is developed. The relative amplitude of interfering carriers in adjacent channels due to differences in rain attenuation is treated. An optimum way of specifying uplink margins as a function of typical rain region fades is derived. A discussion of block versus convolutional coding is presented.

3.5.2 Effective Signal-To-Noise Ratio

An effective SNR including the effects of interchannel interference (crosstalk), co-channel interference and channel (receiver) noise is derived in this section [MITRE, 1981]. This is useful for estimating the interchannel spacings and interbeam isolations required for FDMA waveforms. The results obtained hold for any modulation in a large class of constant-envelope, offset-quadrature, MSK-type modulations having the same BER performance as BPSK or QPSK in AWGN. Complex variable notation is employed for ease in derivation.

Consider a desired signal at a carrier frequency ω(rad/s) of the form $s(t)\ \exp(j\omega t)$ where the baseband signal

$$s(t) = \sum_{\substack{n \\ \text{even}}} b_n\, v(t-nT) + j \sum_{\substack{n \\ \text{odd}}} b_n\, v(t-nT) \tag{3.5}$$

is composed of data symbols $b_n = \pm \sqrt{E_b}$ (E_b is the energy per data bit and the elementary signals are antipodal) and a baseband window defined as

$$v(t) \equiv 0, \ |t| > T \qquad \text{(finite support)} \qquad (3.6a)$$

$$\int_{-T}^{T} v^2(t)\, dt = 1 \qquad \text{(unit energy)} \qquad (3.6b)$$

$$v^2(t) + v^2(t-T) = \frac{1}{T}, \ t \in (0,T) \ \text{(constant envelope)} \qquad (3.6c)$$

($R = 1/T$ (b/s) is the data rate).

The window $v(t)$ is rectangular for offset or staggered QPSK (SQPSK) and a half sinusoid for MSK. Many other windows are also possible. More specifically

$$\text{SQPSK:} \quad v(t) = \frac{1}{\sqrt{2T}}, \quad |t| < T \qquad (3.7a)$$

$$\text{MSK:} \quad v(t) = \frac{1}{\sqrt{T}} \cos \frac{\pi t}{2T}, \quad |t| < T \qquad (3.7b)$$

$$\text{SFSK:} \quad v(t) = \frac{1}{\sqrt{T}} \cos \left(\frac{\pi t}{2T} - \frac{1}{4} \sin \frac{2\pi t}{T}\right), \quad |t| < T \qquad (3.7c)$$

$$\text{"Optimum":} \quad v(t) = \frac{1}{\sqrt{T}} \cos \left(\frac{\pi t}{2T} + a \sin \frac{2\pi t}{T}\right), \quad |t| < T \qquad (3.7d)$$

("a" is a parameter to be optimized)

The shape and degree of continuity of the baseband window affects the extent to which multiple FDMA carriers can be packed into a given bandwidth, i.e., $v(t)$ determines bandwidth efficiency or crosstalk performance. In a digital system, windows of different shapes can easily be stored in programmable read only memories (PROMs).

Interchannel and co-channel interference can be expressed as summations of signals of the same format as the desired signal. By definition, they have arbitrary relative amplitudes, symbol timing, and frequency and phase offsets, except for the co-channel interfering frequency which is the same as that for the desired signal carrier. In this model the data rates of all the interfering signals are the same as the desired signal data rate. The usual channel noise is taken as zero-mean AWGN with a single-sided power spectral density of N_0.

The coherent, correlation receiver statistic is the real (imaginary) part of r_n for determining the b_n's for n even (odd), where

$$r_n = \int_{(n-1)T}^{(n+1)T} [s(t) \exp(j\omega t) + (\text{interchannel interference}) \tag{3.8}$$

$$+ (\text{co-channel interference}) + \text{AGWN}]\ v(t) \exp(-j\omega t)\ dt$$

and the decision rule is

$$b_n = \begin{cases} +\sqrt{E_b}, & \text{Re } (r_n) > 0 \\ -\sqrt{E_b}, & \text{Re } (r_n) < 0 \end{cases}, \quad n \text{ even} \tag{3.9a}$$

$$b_n = \begin{cases} +\sqrt{E_b}, & \text{Im } \{r_n\} > 0 \\ -\sqrt{E_b}, & \text{Im } \{r_n\} < 0 \end{cases}, \quad n \text{ odd.} \tag{3.9b}$$

Statistical independence among user signals, types of interference, and random variables representing data symbols is assumed. Relative signal amplitudes, symbol timing, frequencies and phases, and the neglect of sum-frequency terms are also assumed. In what follows, sin $\Delta_i\tau$ is an odd function of τ and cos $\Delta_i\tau$ and $\rho(\tau)$ are even functions of τ.

It can be shown that ensemble averaging yields a mean and variance of

$$\overline{r}_n = \begin{cases} b_n, & n \text{ even} \\ jb_n, & n \text{ odd} \end{cases} \tag{3.10a}$$

$$\left.\begin{aligned} &\overline{(R_e\ \{r_n\} - b_n)^2},\ n \text{ even} \\ &\overline{(I_m\ \{r_n\} - b_n)^2},\ n \text{ odd} \end{aligned}\right\} = \begin{cases} \dfrac{E_b}{T} \left(\sum_i \overline{A_i^2} \int_0^{2T} \rho^2(\tau) \cos\Delta_i\tau d\tau\ + \right. \\ \left. \sum_k \overline{B_k^2} \int_0^{2T} \rho^2(\tau) d\tau\right) + \dfrac{N_0}{2} \end{cases} \tag{3.10b}$$

where the autocorrelation function of the baseband window is

$$\rho(\tau) = \begin{cases} \int_{-T}^{T} v(t + \tau)\ v(t)\ dt, & |\tau| < 2T \\ 0, & \tau > |2T| \end{cases} \tag{3.11}$$

where the radian frequency offset of the ith crosstalk term is

$$\Delta_i = \omega_i - \omega \tag{3.12}$$

and where $\overline{A_i^2}$ and $\overline{B_k^2}$ are the second-order moments of the ith interchannel and kth co-channel interfering signal amplitude random variables, respectively.

The effective SNR is defined as the magnitude squared (E_b) of the mean of Equation (3.10a) divided by the variance of Equation (3.10b). In the absence of crosstalk and co-channel interference, this would be $2E_b/N_0$ which is the correct SNR at the output of a coherent correlation receiver for antipodal elementary signals in AWGN.

For simplicity of calculation it is assumed that there are I (even) interchannel interferers all of second moment $\overline{A_i^2} = A^2$ and carrier offsets selected as follows

$$\Delta_i \in \{\pm \Delta, \pm 2\Delta, \pm \ldots \pm \frac{I}{2} \Delta\} \tag{3.13}$$

around the desired signal carrier, and K co-channel interferers with the same second moment $\overline{B_k^2} = B^2 = A^2 Z^2$, where Z^2 is determined by interbeam isolation. With the mean-square crosstalk from the ith interferer at the same amplitude but $\Delta_i/2\pi$ Hz away from the desired signal

$$C(\Delta_i) = \frac{1}{T} \int_0^{2T} \rho^2(\tau) \cos \Delta_i \tau \, d\tau \tag{3.14a}$$

the effective SNR becomes

$$SNR_{eff} = \frac{1}{2A^2 \sum_{m=1}^{I/2} C(m\Delta) + KA^2 Z^2 C(0) + \frac{N_0}{2E_b}} \, . \tag{3.14b}$$

3.5.2.1 Typical Crosstalk Results

Let r be the code rate (so far, r = 1), i.e., the ratio of the number of bits into a coder to the number of bits out of the coder. The normalized carrier frequency spacing is defined as

$$\beta = \frac{\Delta \cdot r}{2\pi R} \, . \tag{3.15}$$

(Note that R/r is the burst rate in b/s.) Then typical crosstalk levels for SQPSK, MSK and sinusoidal frequency shift keying (SFSK) are as listed in Table 3-3 along with an optimum window [Eaves, Wheatley, 1979].

Typical crosstalk levels from a single interferer should not exceed approximately -30 dB to ensure no more than a 1 dB degradation in performance compared to AWGN only [White, 1977] [Kalet, 1977]. Since crosstalk scales linearly with A^2, this implies that only crosstalk values in Table 3-3 below about -40 dB would be acceptable with a 10 dB larger interferer.

On the other hand, there is no point in selecting a crosstalk level much below the quantization noise level in a digital implementation. For purposes of comparison, the variances of quantization noise for a real signal of unit amplitude are listed in Table 3-4 for one to eight bits of quantization. Thus, at least 5b, and probably 6b, of quantization would be appropriate for $A^2 = 10$ and about a 1 dB crosstalk-induced degradation in E_b/N_0 for a given BER.

3.5.2.2 Methodology for Determining Channel Spacings

An example is used to illustrate the procedure for determining the necessary carrier frequency spacing between unsynchronized signals of the same type traffic, modulation, and data rate. Suppose R = 300 kb/s uncoded (r = 1) data is to be communicated with a BER of $P_b < 10^{-6}$. This requires an E_b/N_0 of 10.5 dB in AWGN only as determined from the standard BER curve for antipodal signals of probability of bit error

$$P_b = \frac{1}{\sqrt{2\pi}} \int_{\sqrt{2E_b/N_0}}^{\infty} \exp(-x^2/2)\, dx \qquad (3.16)$$

as a function of E_b/N_0.

It seems to be good design practice to ensure that the AWGN term in the denominator of Equation (3.14b) dominates the crosstalk and co-channel interference terms. Toward this end we restrict the degradation beyond that of AWGN only performance, to a factor L > 1 (say, L = 1.26 = 1 dB). Assuming a balanced design where the crosstalk and co-channel interference terms are equal, we must have

$$\sum_{m=1}^{I/2} C(m\Delta) < \frac{L-1}{8A^2(E_b/N_0)} \qquad (3.17a)$$

$$Z^2 < \frac{L-1}{4KA^2C(0)(E_b/N_0)} \qquad (3.17b)$$

Table 3-3

Crosstalk Level $C(2\pi R\ \beta/r)$ (dB) from Equiamplitude ($A^2 = 1$) Interfering Carrier $\beta R/r$ Hz Away in Frequency

	β					
Modulation	0.0	1.0	1.5	2.0	2.5	3.0
SQPSK	-1.75	-16.0	-19.0	-21.5	-23.5	-25.0
MSK	-2.32	-21.5	-30.6	-36.2	-40.4	-43.7
SFSK	-3.09	-16.4	-22.6	-33.9	-41.1	-56.1
Optimum		-22.1	-31.6	-46.0	-48.3	-59.1
	C(0):	-2.16	-2.41	-2.64	-2.73	-2.95

N.B. The $C(\Delta > 0)$ values are 6 dB larger than those of Table 1 in [Eaves, Wheatley, 1979] because of a different normalization on ρ. We calculated the C(0) values.

Table 3-4

Quantization Noise for Real Signal of Unit Amplitude

Number of Bits (b) in Quantization	Quantization Noise Variance $2^{-2b}/12$ (dB)
1	-16.8
2	-22.8
3	-28.9
4	-34.9
5	-40.9
6	-46.9
7	-52.9
8	-59.0

Now suppose that $L = 1.26$, and that $A^2 = 10$ represents a rain fade in the desired signal of 10 dB compared to all the surrounding signals. Next, suppose that there are $K = 4$ adjacent antenna beam cells operating at the same frequency which introduce significant co-channel interference. Computing $C(0) = -3.1$ dB for the selected modulation, say SFSK (see Table 3-3), the required interbeam isolation can be determined from Equation (3.17b) to be $Z^2 < -35.3$ dB for $E_b/N_0 = 10.5$ dB. This must be accomplished by a combination of beam separation, beam shaping and cross-polarization. (See Section 3.6.)

Similarly, a carrier frequency separation must now be selected so that the crosstalk interference satisfies, cf., Equation (3.17a)

$$\sum_{m-1}^{I/2} C(m\Delta) < -35.3 \text{ dB} . \tag{3.18}$$

From Eaves and Wheatley's crosstalk curves for equal amplitude users and SFSK, it can be seen that only the first ($m = 1$) term is significant, and that ($C(\Delta) = -35.3 -6 = -41.3$ dB, with their normalization) $\beta \approx 2.2$ is sufficient. This means that without additional channel filtering, the 200 kb/s data channels can be spaced no more than 200 β kHz = 440 kHz apart.

The crosstalk curves also show that MSK has less crosstalk than SFSK for $\beta \lesssim 2.3$. In this instance MSK yields a β of about 1.9, or a channel spacing of approximately 200 β kHz = 380 kHz. The so-called optimum window does considerably better; the window with $a \approx -0.05$, cf. Equation (3.7d), requires $\beta \approx 1.6$ or only a 320 kHz separation.

3.5.3 Specification of Rain Margins

Recall that $A^2 = \overline{A_i^2}$ represents the average power of an interfering signal at a receiver relative to the desired signal. This quantity is called the residual fade margin because it is assumed that some form of network control compensation for rain attenuation may already have been made. Compensation would be necessary if the required center frequency spacing or interbeam isolation implied by a large A^2 cannot be achieved within the allocated bandwidth or spacecraft antenna implementation, respectively. On the other hand, exact compensation may be infeasible because of imperfections in measuring rain attenuation and the sheer complexity of perfect network control.

The smaller A^2 is, the smaller are the crosstalk and the co-channel interference. Strategies for minimizing and estimating A^2 are discussed in the following paragraphs.

3.5.3.1 Key Ideas and Issues

The centralized assignment of the carrier frequency of each channel transmitted is a basic notion. The key idea for minimizing A^2 with respect to the vast majority of signals is to further constrain carrier frequency assignments so that signals of roughly the same strength occupy any portion of the frequency band. Thus, the frequency assignment problem for minimizing A^2 on FDMA uplinks may be reduced to that of compensating for differences in uplink fades from different terminal locations. Proper frequency assignment could therefore permit the maintenance of an A^2 within the uplink rain fade compensation error, at least locally in any sub-band containing the center frequencies of a few adjacent signals. This may be adequate since it is only necessary to maintain a reasonably small A^2 within one or two adjacent signals with the low crosstalk modulations being contemplated.

Co-channel interference will be affected mainly by differences in uplink fade compensation errors among different beam locations. It remains to estimate rain fade compensation errors based on rain statistics for the various beam areas and representative power control strategies. Before doing this, a few practical issues are considered.

Downlink fading can be compensated by using power diversity in several ways. The most specific method is to further amplify only the affected signals before transmission either at the satellite or at the terminals (for a non-processing satellite).

Practical difficulties of hardware proliferation and protocol complexity can arise if there is an attempt to compensate downlink rain fades exactly. For example, the number of downlink power amplifiers in a beam must be finite, which implies an equal number of possible instantaneous gains. It would be desirable to be able to adjust the gain of each amplifier so that no amplifier is idle for want of signals needing the proper gain factor.

Another issue concerns the fact that the crosstalk and co-channel interference model presented earlier applies only for signals of the same data rate. In practice, it may be convenient to determine center frequency assignments in such a way that signals adjacent in frequency are not necessarily at the same data rate. In this case, it is not clear what the center frequency spacing should be between a given signal already assigned and a newly assigned signal at a different data rate. Since the higher rate signal would tend to produce more crosstalk in the band of the lower rate signal than the reverse, the center frequency spacing should probably be governed by the higher rate using the crosstalk model. This will not be as bandwidth efficient as the procedure of assigning signals of approximately the same data rate, as well as power level, to the same part of the frequency band. Both approaches should be tried through simulation and experiment, not only to test the validity of the crosstalk model but to also establish the more attractive operational procedure.

3.5.3.2 Optimization of Relative Uplink Margins

Attention now returns to the task of minimizing and estimating A^2. Rather than computing a true mean of the relative power level of interfering signals nearby in center frequency, a more pessimistic viewpoint is adopted. Let only the desired signal be attenuated by uplink rain at a 0.995 level of link availability, a value considered acceptable for Customer Premises Service (CPS) traffic [MITRE, 1981]. Nominal uplink attenuations for the seven regions of CONUS according to a Crane model [Crane, 1980] are shown in Figure 3-7; thirty degree elevation angles are assumed. A conservative estimate of A^2 for each region is computed as follows.

Let P_r be the ratio of the traffic from region r to the total traffic from all regions. These ratios will serve as probabilities that

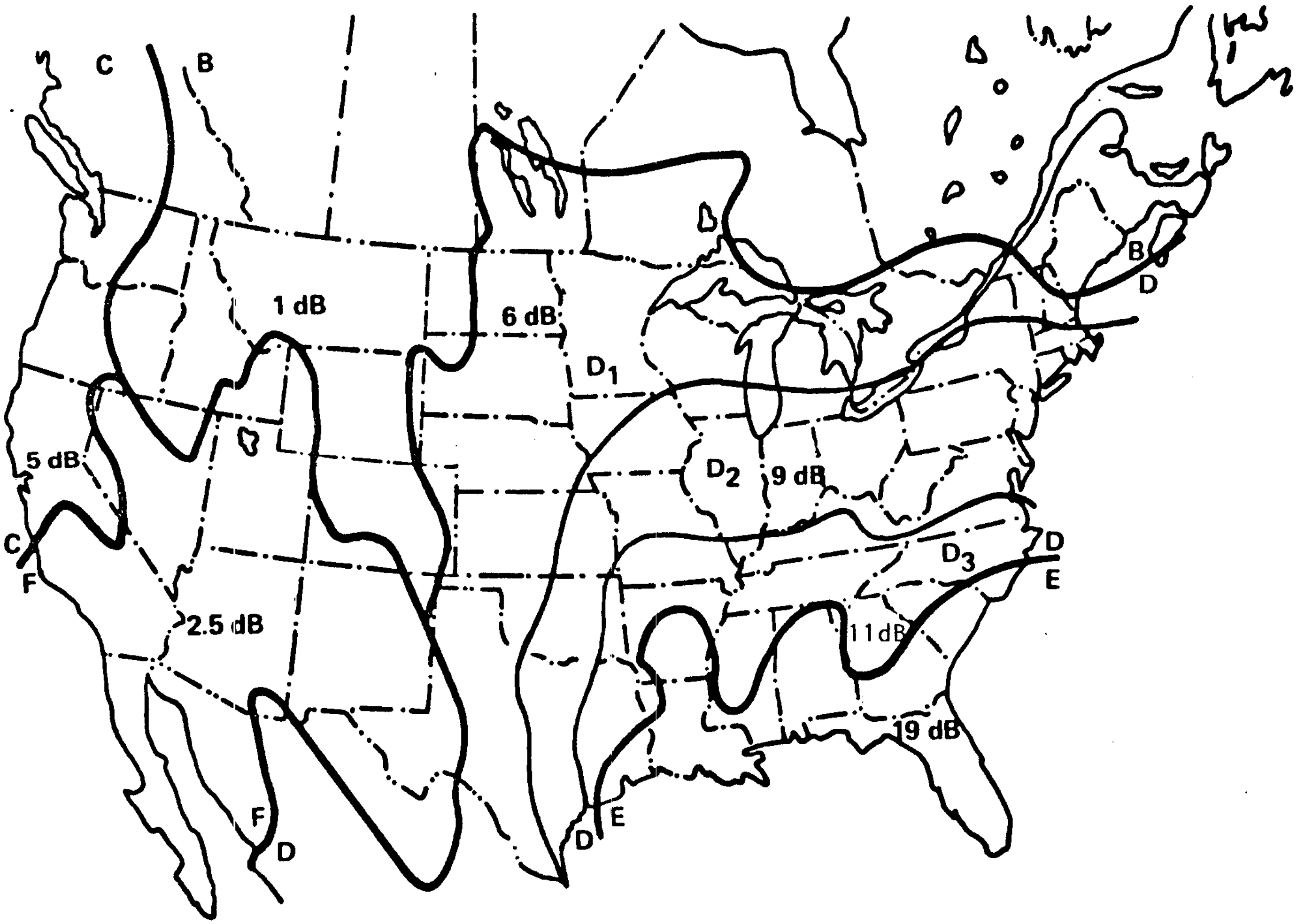


Figure 3-7 Rain Regions of the United States with Nominal Uplink Attenuation F_r in Region r (30 GHz, 0.995 Availability, 30° Elevation).

determine the likelihood of an adjacent signal from each of the seven regions. Let F_r denote the loss factor due to uplink rain fading of a desired signal in region r, e.g., the rain attenuation is expressed as $10 \log_{10} F_r$ (dB) in Figure 3-7. Let M_r be the relative margin or factor by which power is boosted by each terminal in region r relative to a nominal uplink reference power. Therefore, if a desired signal from region s starts with margin M_s but experiences an uplink fade F_s, and if an interfering signal from region r has a margin M_r but is unfaded, then the relative power of the interfering to desired signal at the satellite is $M_r F_s / M_s$; the average relative power for that desired signal is

$$A_s^2 = \sum_r P_r M_r F_s / M_s = \frac{F_s}{M_s} \sum_r P_r M_r \quad . \tag{3.19}$$

The objective here is to select the unknown margins M_r to minimize the average of A_s^2 over the seven regions, again weighted according to the probabilities P_s. Thus, the margins M_r will be optimized to minimize

$$A^2 = \sum_s P_s A_s^2 = \sum_s P_s \frac{F_s}{M_s} \sum P_r M_r \tag{3.20}$$

by using Equation (3.19). Zeroing the derivatives of Equation (3.20) with respect to M_k, one obtains

$$\begin{aligned} 0 = \frac{dA^2}{dM_k} &= - \frac{P_k F_k}{M_k^2} \sum_{r \neq k} P_r M_r + \sum_{s \neq k} P_s \frac{F_s}{M_s} P_k \\ &= P_k \sum_r P_r \left(\frac{F_r}{M_r} - \frac{F_k}{M_k^2} M_r \right) \qquad , \text{ for all k.} \end{aligned} \tag{3.21}$$

One solution of Equation (3.21) arises from setting each term to zero, i.e.,

$$M_k = \sqrt{F_k / F_r}\, M_r, \text{ for all k.} \tag{3.22}$$

By substituting Equation (3.22) into Equation (3.20), A^2 becomes

$$\begin{aligned} A_{min}^2 &= \sum_s \sum_r P_s P_r F_s \frac{M_r}{M_s} = \sum_s \sum_r P_s P_r F_s \frac{\sqrt{F_r}}{\sqrt{F_s}} \\ &= \sum_s P_s \sqrt{F_s} \sum_r P_r \sqrt{F_r} = \left(\sum_s P_s \sqrt{F_s} \right)^2 . \end{aligned} \tag{3.23}$$

This corresponds to a minimum because the second derivatives of the objective function are positive, i.e.,

$$\frac{d^2A^2}{dM_k^2} = \frac{2P_kF_k}{M_k^3} \sum_{r \neq k} P_r M_r > 0, \text{ for all k.} \tag{3.24}$$

The first part of Equation (3.21) is used, and P_r, F_r, and M_r are all positive quantities.

The optimum (relative) margins are determined by selecting an arbitrary reference value of unity for Region B (r = 1), and setting r = 2 for Region C for example, and using Equation (3.22):

$$M_1 = 1 \text{ and } M_2 = \sqrt{F_2/F_1} = \sqrt{3.16/1.26} = 1.58 = 2\text{dB}.$$

The other margins determined by using Equation (3.22) are shown in Table 3-5 along with F_r and specific P_r (for a CPS traffic model based on population density [MITRE, 1981]) and A_r^2.

The main conclusion of this analysis is that A^2 = 10 dB is an excellent value to employ in the modulation and coding model of crosstalk and co-channel interference. (See Equation 3.14b.) This value is conservative since it was computed by assuming that only the desired signal experiences uplink rain fading and that center frequencies are not influenced by uplink margins.

Given a beam plan and a traffic model, the A_r^2 column of a table like Table 3-5 may be used to determine the appropriate A^2 value to employ in any uplink beam according to its region. Again, it is emphasized that the effective A^2 values will be smaller to the extent that center frequencies are assigned according to expected signal strengths at the satellite. The uplink margins M_r of Table 3-5 are good average indicators of relative signal strengths expected.

3.5.3.3 Downlink Rain

The rain attenuation problem is not as severe on the ~20 GHz downlink. [Hogg and Chu, 1975] and [Arnold et al., 1980] have evaluated the attenuation due to rain at several frequencies and both conclude that the attenuation (dB/km) at 18.5-19 GHz is approximately half that occuring at 28-30 GHz. The maximum downlink attenuation for a 0.995 availability should therefore be approximately 10 dB in region E of Crane's model. The estimated downlink fading by region is given in Table 3-6.

The compensation for downlink rain attenuation can be performed by combinations of coding, higher terminal G/Ts, variable satellite EIRP (by beam), power control, or large link margins.

Table 3-5
Optimization of Relative Uplink Margins M_r to Minimize Relative Power Level A^2 of Interfering Signal

Region Index r	Region Name	Probability P_r^*	Uplink Fade F_r^{**}	Uplink Margin M_r	Net Fade F_r/M_r	Relative Power A_r^2
1	B	0.013	1.26 = 1 dB	1 = 0 dB	1.26 = 1 dB	3.59 = 5.55 dB
2	C	0.068	3.16 = 5 dB	1.58 = 2 dB	2 = 3 dB	5.7 = 7.56 dB
3	D_1	0.074	3.98 = 6 dB	1.78 = 2.5 dB	2.24 = 3.5 dB	6.38 = 8.05 dB
4	D_2	0.463	7.94 = 9 dB	2.51 = 4 dB	3.16 = 5 dB	9.01 = 9.55 dB
5	D_3	0.094	12.6 = 11 dB	3.16 = 5 dB	3.99 = 6 dB	11.4 = 10.6 dB
6	E	0.118	79.4 = 19 dB	7.94 = 9 dB	10 = 10 dB	28.5 = 14.5 dB
7	F	0.170	1.78 = 2.5 dB	1.19 = 0.75 dB	1.50 = 1.75 dB	4.28 = 6.31 dB

NOTES: $\sum_r P_r M_r = 2.85$

$A^2_{min} = 10.2 = 10.1$ dB

*CPS Traffic Model [MITRE, 1981]
**0.995 Availability, 30° Elevation Angle, 30 GHz

Table 3-6
Estimated Downlink Fading

Region Index r	Region Name	Probability P_r^*	Downlink Fade F_r^{**}
1	B	0.013	1.12 = 0.5 dB
2	C	0.068	1.78 = 2.5 dB
3	D_1	0.074	2.0 = 3.0 dB
4	D_2	0.463	2.82 = 4.5 dB
5	D_3	0.094	3.55 = 5.5 dB
6	E	0.118	8.9 = 9.5 dB
7	F	0.170	1.33 = 1.25 dB

*CPS Traffic Model [MITRE, 1981]
**0.995 Availability, 30° Elevation Angle, 20 GHz

C-2

3.5.4 Intermodulation

In an FDM system, in-band intermodulation (IM) products can arise due to nonlinearities in the transponder HPA. Generally, the degradation in SNR is due primarily to the third-order IM products. In a K-band system where rain attenuation may result in a few weaker carriers in the band of interest, the weak signals may not survive due to power robbing and/or suppression due to IM interference.

Suppose the central carrier of I channels is assumed to be weaker than the other carriers by $Y = A^2$ (dB). Suppose the minimum acceptable carrier to IM interference ratio (C/I) is Z (dB). Then if the weaker carrier is to satisfy this requirement, each of the other carriers will have a C/I of at least Y + Z (dB). This ratio may be difficult to achieve in a nonlinear power amplifier unless the output power backoff is so great that the device efficiency is unacceptable. On the other hand, if the backoff is limited to provide some minimally acceptable efficiency, the weak carrier will not be detectable with the desired reliability because IM interference in that channel will be too large.

This is illustrated with the typical C/I vs. backoff characteristic of Figure 3-8 [MITRE, 1981]. Suppose there are I = 10 carriers and that the saturated output power of the amplifier is 20 W. Then each of the stronger carriers would be allocated

$$20/(9+10^{-Y/10}) \text{ W}$$

and the weaker carrier would receive only

$$20/(1+9\times10^{+Y/10}) \text{ W.}$$

If all the carriers were of equal power, then $A^2 = 1$ and Y = 0 dB. This implies that each carrier would receive 2 W of saturated output power and that C/I = 14 dB, according to Figure 3-8. However, suppose that the minimum acceptable C/I is Z = 16 dB. This would imply a 3-dB backoff for equal carriers and 1 W per carrier.

Alternatively, a 6-dB backoff implies that the weaker carrier can be no more than Y = 19.5 - 16 = 3.5 dB down for an acceptable C/I in that channel. This corresponds to 0.24 W in the weak channel and 0.53 W in the strong channels. If Y = 10 dB, then a 10-dB backoff is necessary to maintain the weak channel quality. This would mean a C/I = Y + Z = 26 dB in the strong channels, cf. Figure 3-8. This corresponds to 0.022 W in the weak channel and 0.22 W in the strong channels. Unfortunately, a 10-dB backoff usually implies an intolerably low power amplifier efficiency. Thus, the depth of the weak signal may have to be limited to several dB in order to maintain acceptable HPA efficiency.

To some extent, a regenerative satellite would solve this problem. Each regenerated signal could be allocated equal power permitting less HPA backoff. Alternatively, a separate HPA could be assigned to each channel.

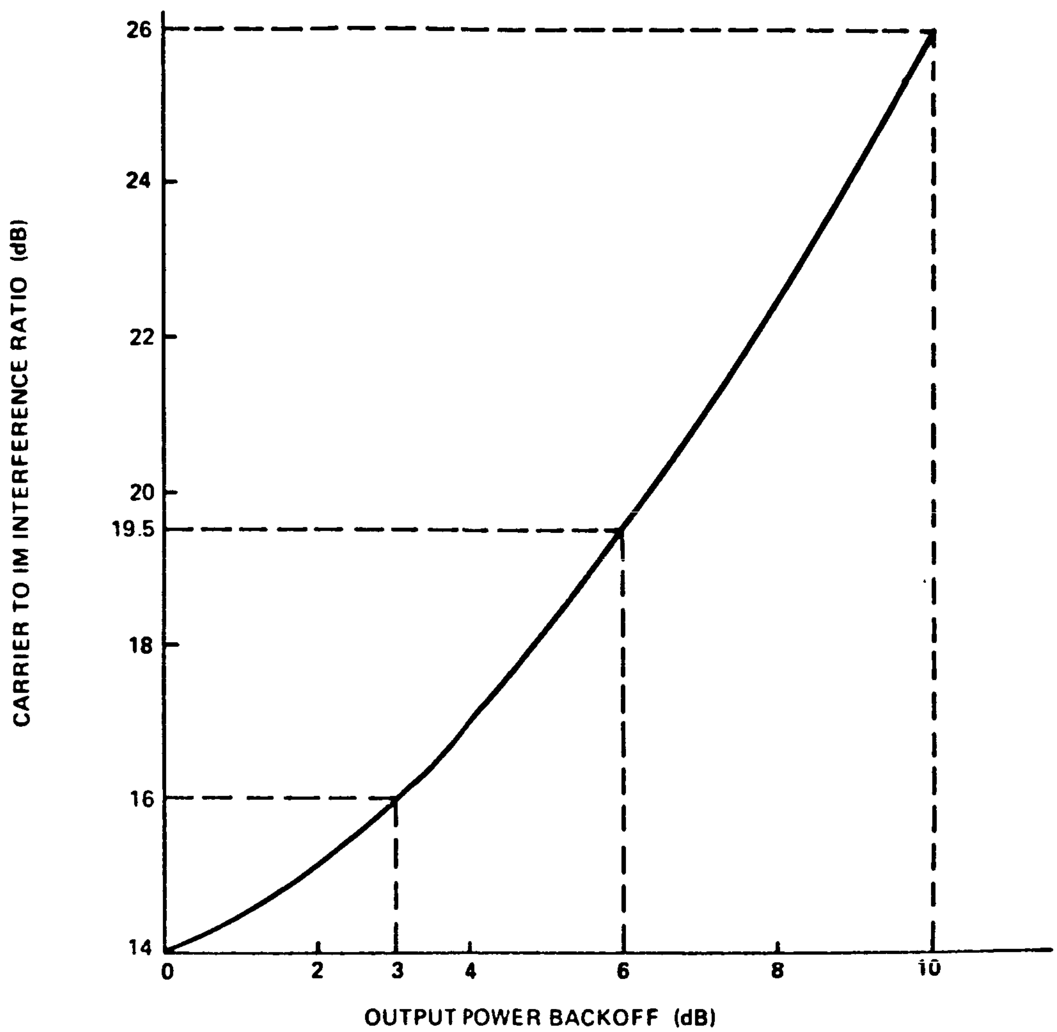


Figure 3-8 Typical Behavior of Nonlinear Power Amplifier

3.5.5 Error Correction Coding

At this point various options for error control coding are discussed. The two usual types of linear codes -- block or convolutional -- as well as the choice between a hard-decision or soft-decision demodulator are available. Throughout the discussion it is assumed that the channel is memoryless, as will be the case for the relatively low burst rates and 30/20 GHz and above bands considered in this study. The first topic discussed is quantization of the received signal.

In a binary system like MSK, the demodulator is said to have made a hard decision if it decides that a 0 or 1 was sent by the modulator. An unquantized decision is made when the demodulator determines the probability of a 0 or 1 being sent directly from the received version of the elementary signal. Between these two extremes lie the soft decisions wherein the demodulator estimate of the signal must assume one of m discrete values. Typically, m is a power of two. Receiver quantization destroys some of the information which was presented to the receiver about the data; the coarser the quantization, the more information is lost. As has been shown [Viterbi, Omura 1979] usually less than 0.25 dB is lost with 3-bit ($m = 8$) quantization compared to unquantized decisions, while hard decisions typically imply a loss of between 2 and 3 dB. Note that finite quantization is required by any digital implementation of a decoder. Quantization is usually done uniformly although this is not necessary.

When the interference is AWGN, a quantized receiver constitutes a discrete memoryless channel which can be chracterized by its transition probabilities; that is, the receiver must be able to determine the probability of obtaining each quantization level for either 0 or 1 being sent. These probabilities depend on noise background and signal level. Thus, in order to make use of soft decisions, the receiver must employ some form of AGC. Not needing AGC for hard decisions is an advantage of a hard-decision receiver for antipodal signals like MSK. The baseband complexity of terminal receivers can be simplified if no downlink coding is required or if hard-decision decoding is adequate.

Block codes can operate at very high speeds and can be chosen to make error rates quite low. A 100 Mb/s Reed-Solomon decoder can be fairly inexpensive to build [Berlekamp, 1980]. However, the well known algebraic decoding techniques for block codes force the demodulator to make hard decisions, since the decoder requires 0s and 1s in order to operate in a finite field. Although there is still a coding gain, at least for reasonable SNRs, there is a 2 dB loss when the Reed-Solomon decoder is compared to an unquantized decoder.

Block codes or convolutional codes, either linear or nonlinear, can be decoded with soft decisions via correlation decoding, which compares the quantized version of the received signal with each possible codeword and chooses the codeword which is closest in some predetermined metric. This method is impractical for any but the smallest codes since the work factor is proportional to 2^k, where k is the number of information bits per codeword. Many ideas have appeared in the literature on methods of approximating correlation decoding with soft decisions via algorithms which are claimed to be faster and easier to implement. The greatest drawback of such algorithms is that they are still fairly slow and expensive and require significant processing. For this reason, it is asumed that a block code would make hard decisions using an algebraic decoding algorithm.

For comparison purposes, the ten error-correcting Bose-Chaudhuri-Hocquenhem (BCH) (127,64) code and the (24,12) Golay code have been selected. The latter is capable of correcting all codeword error patterns of less than four bits and 8855 of the 10,626 possible error patterns of weight four, i.e., a complete decoder instead of the more usual bounded distance decoder is used. As is shown in Figure 3-9, the BCH code is superior for the range of BERs from $10^{-7}$to 10^{-2}. The decoding of the BCH code is easily accomplished via the Berlekamp-Massey algorithm [Massey, 1969].

A convolutional code (CC) of constraint length K, memory M = K-1, and rate r = 1/2 consists of a K-stage shift register which has two sets of taps, each with a different ouput, which are interleaved to produce a codeword. The results presented for a certain constraint length do not hold for all CCs of that length, but only for the non-catastrophic codes with maximal free distance. The maximal free distance, a nondecreasing function of the constraint length, determines performance. As a result, an increase in constraint length can lead to a better code. However, the traditional maximum likelihood decoder -- the Viterbi algorithm -- has a work factor which is proportional to 2^K. Thus, increasing the constraint length, while increasing the maximal free distance, makes the decoder more complex as well as slower. The constraint length K = 7 is generally accepted as a good compromise between free distance and decoder speed and complexity.

One of the great advantages of CCs is that the Viterbi algorithm can be applied not only to the hard-decision channel, but also in the quantized output of a soft-decision demodulator. As shown in Figure 3-9, the BCH (127,64) code requires slightly less E_b/N_0 than the K = 7 CC on a channel with hard decisions. However, on the 8-level quantized channel, the CC achieves more than a 1.5 dB advantage over the BCH code.

The error curves for the CCs are obtained via the union bound on an unquantized channel and the Viterbi algorithm. However, the original algorithm requires large memory since a decision is made on the entire message. Traditionally, the path memory (the length of the path through the code's trellis) is truncated at roughly four times the constraint length, or about 32 bits for K = 7. That is, a decision is made, at a certain time, on the bit which was sent 32 bit-times earlier based on all bits received in between.

Heller and Jacobs did extensive simulations of CC performance with 8-level quantization and 32-bit path memory (Heller, Jacobs, 1971). The results show a loss of only 0.25 dB compared to the theoretical performance without quantization and with no path memory truncation. This suggests that the K = 7 convolutional code would provide very good performance.

It is felt that error rates from 10^{-6} to 10^{-2} and reasonable data rates can be handled quite well with the convolutional code. However, block codes could also be considered.

As seen from the net fade column of Table 3-5 and the 3 to 5 dB coding gains (K = 7, r = 1/2) of Figure 3-9, uplink convolutional coding and

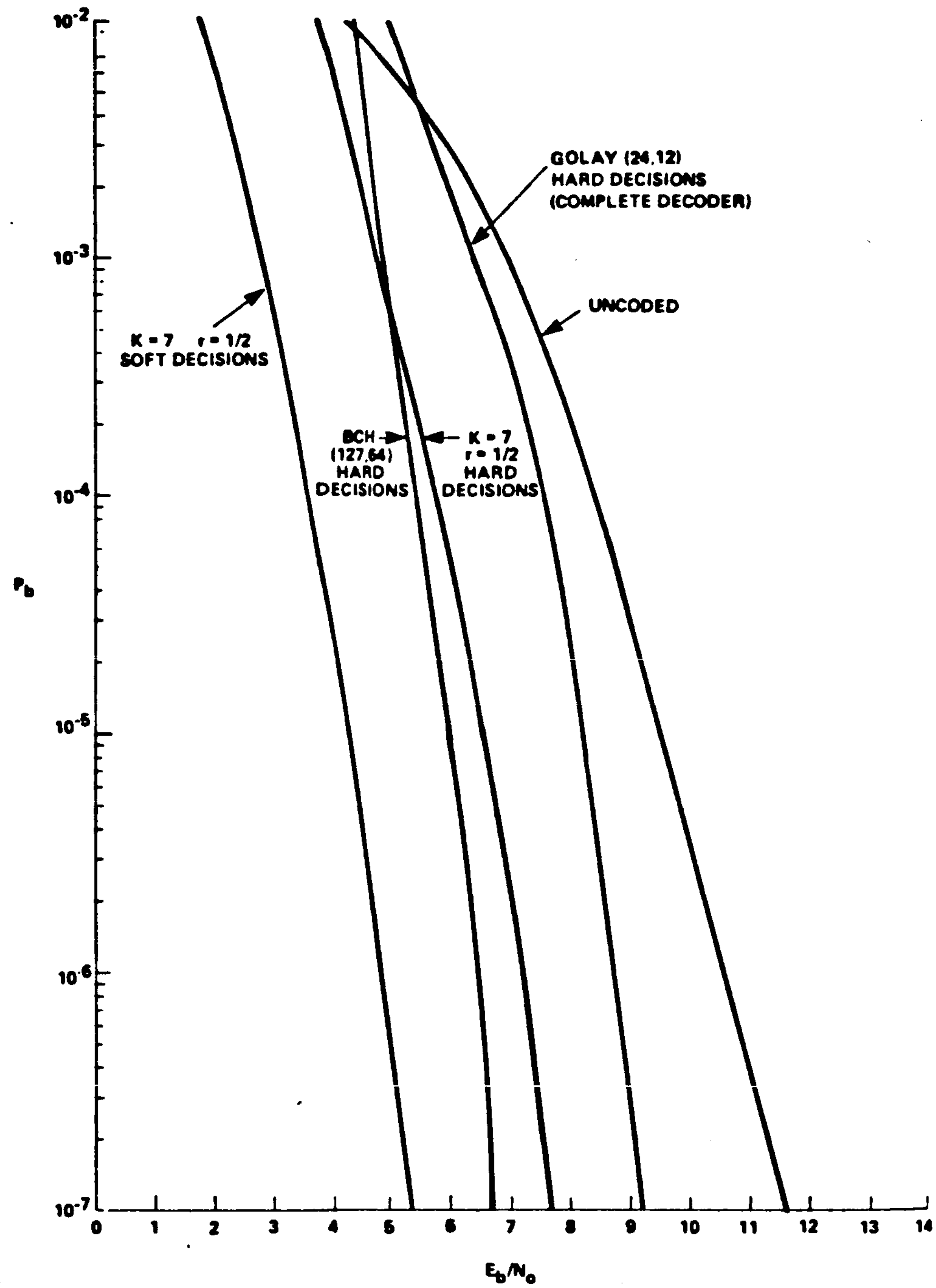


Figure 3-9 Performance of Several Rate 1/2 Binary Codes

Viterbi decoding in the satellite can essentially compensate for excess fading except in the rainiest Region E, where coding cannot overcome an average net fade of 10 dB. This suggests that the uplink margins be increased uniformly by roughly 5 dB and that uplink coding would be required only for terminals in the southeastern U.S.; soft decision decoding would be required in the satellite only for Region E.

The fades on the downlink can be as much as 9.5 dB (see Table 3-6). To compensate for this fading, either 9.5 dB of additional margin would be required or 3 dB margins could be used to provide 64% of the U.S. at least 0.995 availability. The southeastern third of the country would need either more downlink power or soft-decision decoding to make up the necessary margin.

3.6 MULTIPLE SATELLITE BEAMS

In this subsection the theory of multiple beam patterns, interbeam isolation, and frequency reuse are discussed. Implications for the spacecraft realization of on-board power and multiple beam antennas are also developed.

3.6.1 Definitions

Assume that the geographic coverage of a single satellite beam cell is defined by the physical area (footprint) where the received signal does not vary by more than X dB of the peak gain, where X is a constant in the 3 to 6 range. The coverage area of the cell is enclosed by the X dB-down contour; see Figure 3-10. The -X dB contours touch each other and form a multiple beam pattern of cells.

If adjacent cells use the same frequency, significant signal interference will generally result. However, cells which are farther away may use the same frequency with some tolerable level of mutual interference. The situation can be visualized by selecting designs (frequency plans) for the cells; all cells using the same frequency will be of the same design. Example cell designs will be shown later.

3.6.1.1 Beam Isolation

If d is the angular distance between the centers of two beams, and if $G(\theta)$ denotes the gain of each singlet beam as a function of beamwidth θ_0 defined by the X-dB down contour, then the isolation between the beam patterns of Figure 3-11 is defined as

$$I(d) = \frac{G(\theta_0/2)}{G(d-\theta_0/2)} = G(0) - X - G(d-\theta_0/2) \text{ (dB)} . \qquad (3.24)$$

3.6.1.2 Cross-Polarization

Different polarization assignments of the radiated beams may be used to increase the isolation as we shall see in later examples. Cross-polarization isolation, usually employing orthogonal vertical and horizontal polarizations rather than left and right-hand circular polarizations, is limited to roughly 20 dB at 30/20 GHz [Arnold, et al., 1980].

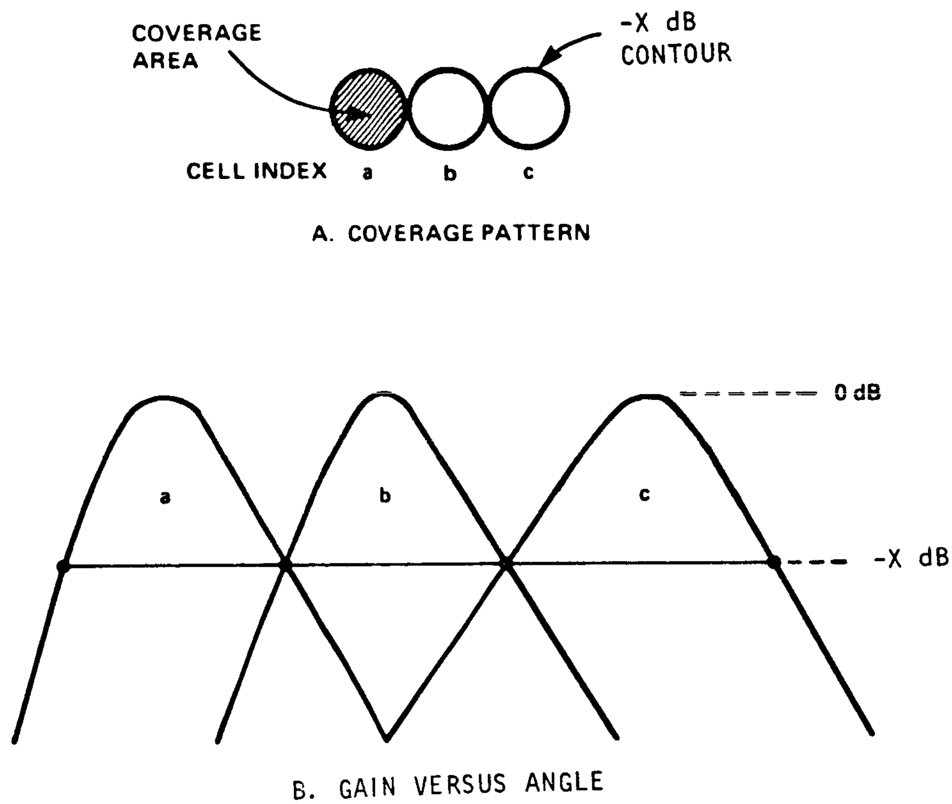


Figure 3-10 Definition of Multiple Beam Cells

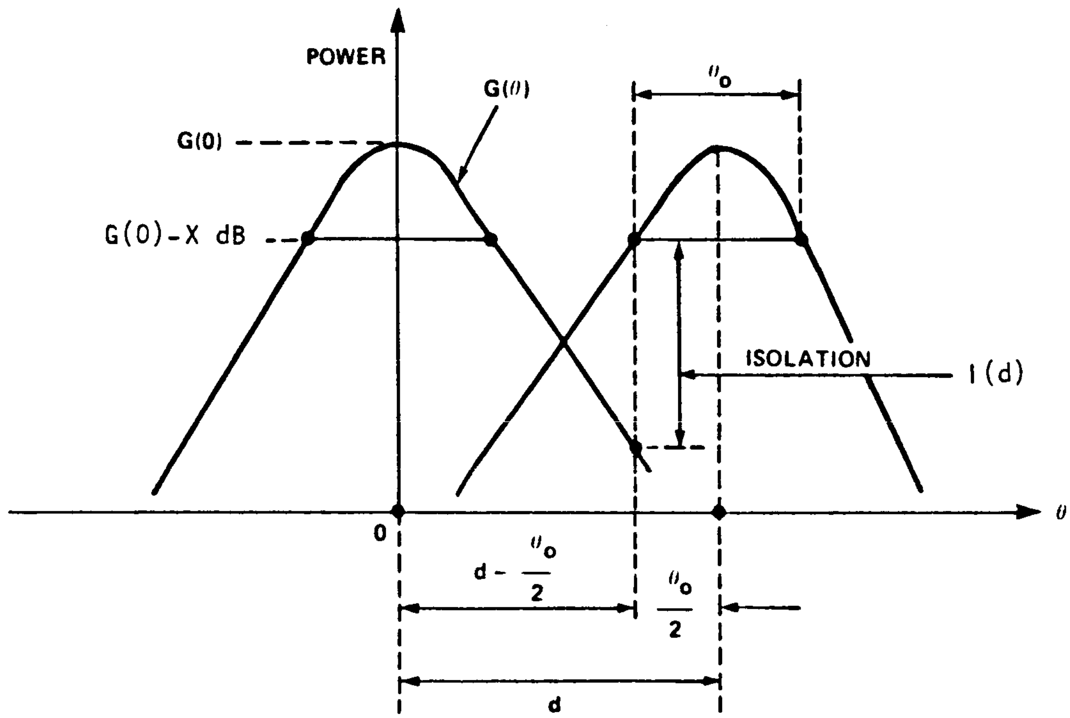


Figure 3-11 Inter-beam Pattern Isolation

3.6.1.3 Frequency Reuse

Multiple beam satellite antennas allow: 1) earth terminals to have lower values of effective isotropic radiated power (EIRP) and gain to noise temperature ratio (G/T), which is very desirable for small earth stations; and 2) frequency reuse.

Two links will operate with acceptably low mutual interference on the same frequency if the isolation between them is sufficiently large. If the allocated bandwidth for a particular satellite system is W, frequency reuse increases the effective bandwidth to FW, where F is the frequency reuse factor defined as

$$F = M/N, \tag{3.25}$$

where M is the number of beams, and N is the number of designs or disjoint frequency bands.

The factor F should be as large as possible, i.e., for fixed M, N should be as small as possible. However, a small N means less isolation between the beams.

The number of frequency bands, N, imposed by the beam isolation will also depend on the system requirements. These, in turn, will be determined by the desired link quality and the type of modulation, since some modulations are less susceptible to co-channel interference.

3.6.2 Close-Packed Circular Cell Arrays

Consider the four-design example of Figure 3-12 where the cells are packed close together to reduce gaps in coverage above the X dB-down gain level. As shown in Figure 3-12A, the smallest distances between cells of the same design are

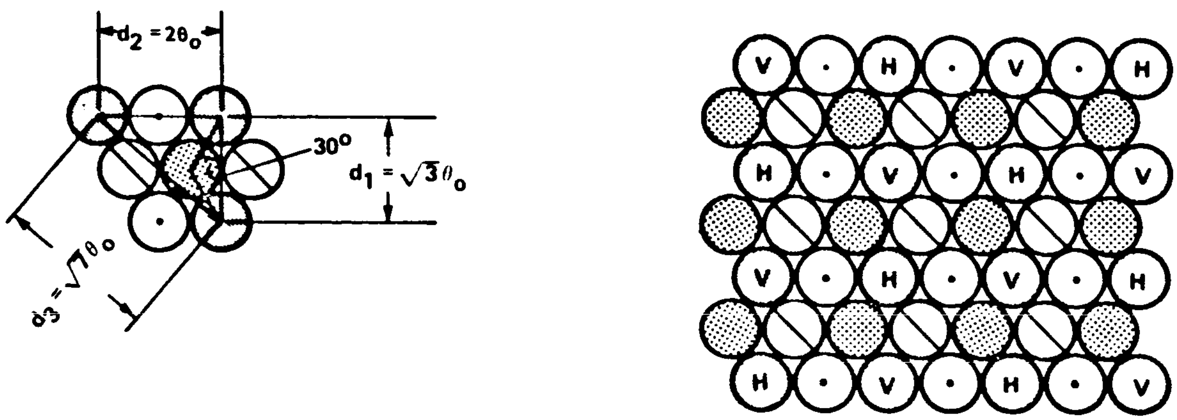
$$d_1 = \sqrt{3}\,\theta_0 \tag{3.26a}$$

$$d_2 = 2\,\theta_0 \qquad \text{(close packed; } N = 4\text{),} \tag{3.26b}$$

$$d_3 = \sqrt{7}\,\theta_0 \tag{3.26c}$$

where θ_0 is the single cell beamwidth. If horizontal (H) and vertical (V) cross-polarizations are used as indicated in Figure 3-12B, then typically d_3, the shortest distance between cells of the same frequency band and polarization, will determine the minimum interbeam isolation according to Equation (3.24).

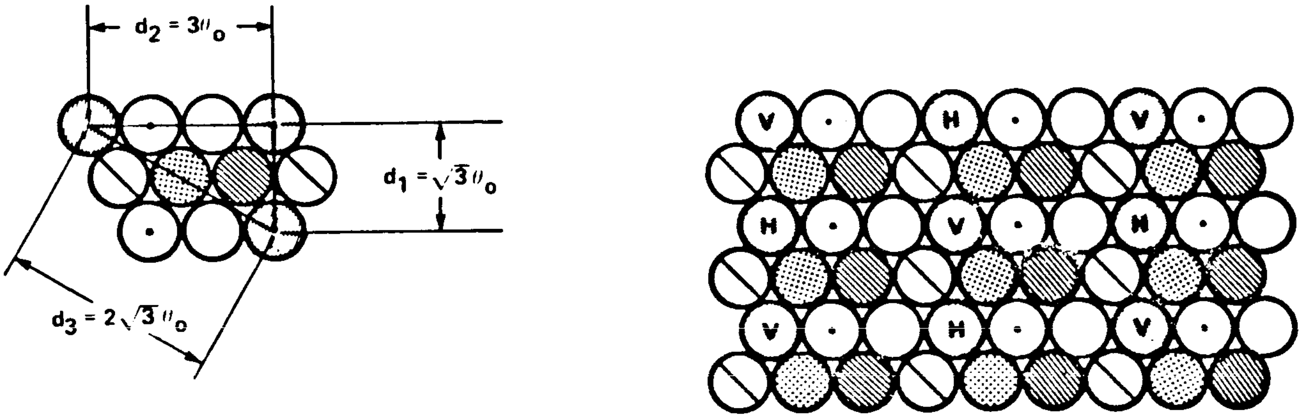
A non-symmetrical array like that of Figure 3-13 may be needed to achieve a specified isolation. However, this cell pattern would require two more frequency bands than that of Figure 3-12.



A. BASIC CLUSTER

B. LARGER ARRAY

Figure 3-12 Close-Packed Circular Cell Four-Design Configuration



A. BASIC CLUSTER

B. LARGER ARRAY

Figure 3-13 Close-Packed Circular Cell Six-Design Configuration

3.6.3 Satellite DC Power Implications

The relationship between antenna beam cell size and the DC power required on the satellite is investigated in this subsection. It is assumed that user terminals are distributed uniformly throughout the coverage area and that each beam is driven by a dedicated traveling wave tube (TWT). Two cell sizes of 1.2° and 0.6° beamwidths are considered in the following examples. It is shown that the 0.6° cells lead to better frequency reuse, i.e., more users can be served, and that less DC power is required on the satellite. Smaller beams provide greater antenna gain but imply a larger number of beams for CONUS and a more complex spacecraft antenna implementation. The exchange of a larger antenna for lower power is considered to be a favorable trade-off in spacecraft weight.

Recall that N is the number of disjoint frequency subbands used in a multiple beam plan of M individual beam cells and that $F = M/N$ is defined as the frequency reuse factor. Let U be the number of simultaneous users, and let B be the bandwidth available to a single user. A nominal total bandwidth of $W = 100$ MHz is taken as fixed. It is apparent that bandwidth is conserved, i.e., $BU = WF$, or

$$U = \frac{W}{B} F = \frac{W}{B} \frac{M}{N} \quad . \tag{3.27a}$$

The number of users per beam is

$$u = \frac{U}{M} = \frac{W}{B} \frac{1}{N} \quad . \tag{3.27b}$$

The two beam/frequency plan examples considered are shown in Figure 3-14A and 3-14B. The following assumptions are common to these 10 and 40 beam CONUS coverage plans: Each user is characterized by an $R = 1$ Mb/s signal occupying $B = 1.25$ MHz, and a single-channel earth station with a 2 m diameter antenna and a $T = 1000°K$ system noise temperature. The satellite is assumed to be a collection of transponders in this case (no on-board demod/remod) with a DC to RF power conversion efficiency of $\eta = 10\%$, and a power amplifier back-off $BO = 3$ dB. (A power back-off is required to reduce inter-modulation interference.)

Suppose the desired signal-to-noise ratio (SNR) is $E_b/N_0 = 8.5$ dB and there is an implementation loss of $L = 3.5$ dB. Then the required overall carrier-to-noise ratio (CNR) is approximately

$$C/N_0 = (E_b/N_0)\ L\ R = 72 \text{ dB-Hz}. \tag{3.28}$$

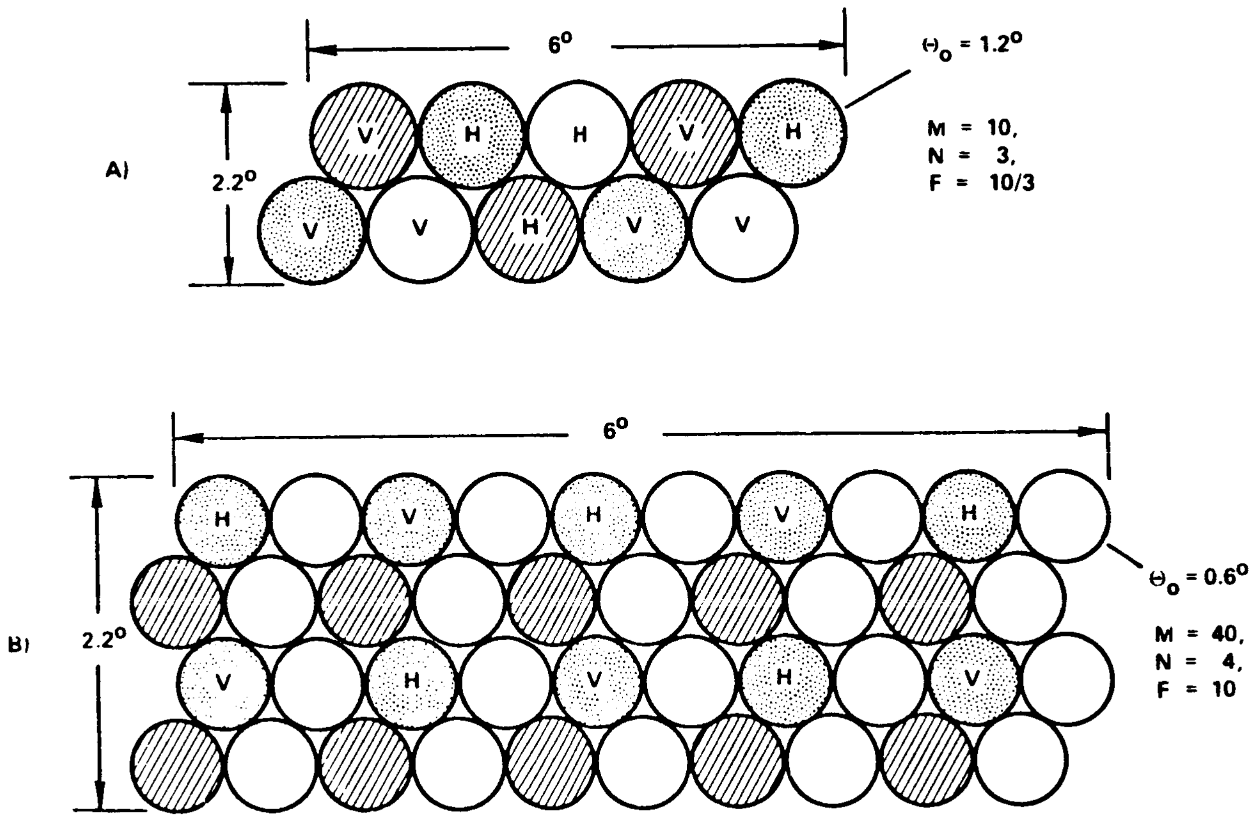


Figure 3-14 Two Possible Beam/Frequency Plans for Conus Coverage (not to scale)

For the $\theta_0 = 1.2°$ cell of Figure 3-14A, suppose the CNRs for the uplink and downlink are

$$\frac{C}{N_0}_u = 79 \text{ dB-Hz} \quad \text{and} \quad \frac{C}{N_0}_d = 73 \text{ dB-Hz} \tag{3.29}$$

(The uplink is 6 dB better to provide for more rain margin.)

since

$$\frac{1}{\frac{C}{N_0}} \approx \frac{1}{\frac{C}{N_0}_u} + \frac{1}{\frac{C}{N_0}_d} \quad . \tag{3.30}$$

A simple downlink budget calculation shows that for a 1 Mb/s user the RF power at a satellite TWT output is

$$P = \frac{(EIRP)_d}{G_{sd}} = \frac{(C/N_0)_d \; k \; L_d T}{G_{sd} \; G_{ed}}$$

$$= 73 \text{ dB-Hz} - 228.6 \text{ dB-J/°K} + 210 \text{ dB} + 30 \text{ dB-°K}$$

$$- 42.7 \text{ dB} - 49.8 \text{ dB}$$

$$= - 8.1 \text{ dBW} = 0.155 \text{ W}. \tag{3.31}$$

Here $k = 1.38 \times 10^{-23}$ J/°K (Boltzmann's constant), L_d is the downlink path loss at 20 GHz, and G_{sd} and G_{ed} are the spacecraft and earth station downlink antenna gains, respectively. Therefore, the total satellite DC power in this case is (The BO factor is retained assuming it is desirable to have the capability to saturate the TWT.)

$$P_{TDC} = M \; P_{DC} = M \frac{(BO)P_{RF}}{\eta} = \frac{(BO)(UP)}{\eta}$$

$$= \frac{(BO)}{\eta} \; \frac{W}{B} \; \frac{M}{N} \; P = 830 \text{ W} \quad , \tag{3.32}$$

where P_{DC} and P_{RF} are the satellite DC and RF powers per beam The number of simultaneous users served is U = Mu = 267, from Equations (3.27a) and (3.27b).

With the $\theta_0 = 0.6°$ cells of Figure 3-14B, the uplink satellite antenna gain is 6 dB larger. Since nothing else has changed to affect the uplink power budget, $(C/N_0)_u$ = 85 dB-Hz, cf., Equation (3.29). Now only about $(C/N_0)_d$ = 72.2 dB-Hz is required to maintain the desired C/N_0 of 72 dB-Hz, according to Equation (3.30). Since G_{sd} has also increased by 6 dB in this case,

$$P = -8.1 - 0.8 - 6 \text{ dBW} = -14.9 \text{ dBW} = 0.032 \text{ W} \quad .$$

The total satellite DC power drops to P_{TDC} = 512 W, using Equation (3.32), since M = 40 and N = 4. In this case, U = 800 users are served.

Since P_{TDC} is proportional to the total data rate UR, the satellite DC power consumption is constant for a fixed total data rate. The principal conclusion is that the 40-beam system can serve three times the users with 62% of the spacecraft power compared with the 10-beam system. Two-meter earth terminals spread uniformly over CONUS can even be supported by a single 1985-vintage satellite using 1982 technology which promises 5 kW of DC power.

3.6.4 Implementation Considerations

A $\theta_0 = 0.3°$ beamwidth is chosen as an example to provide a satellite antenna sufficient to support a relatively heavy traffic volume and to minimize interbeam interferences. Signals originating in or intended for one area in a given frequency band must not be intercepted at too high a level in another beam using the same band; unacceptable co-channel interference would result. Thus, the sum of the in-band sidelobe powers from all other beams (four, say) falling in any footprint should not exceed about -30 dB relative to the peak gain of the beam (see Subsection 3.5.2.2).

The co-channel interference requirement will be the driving consideration in this example antenna design. Other considerations include beam distortion and minimization of the number of antenna reflectors that the spacecraft must carry. The continental United States (CONUS) subtends an azimuthal angle of 6.8° and an elevation angle of 3.0° from a geostationary satellite located at 90°W longitude. Thus, for single-satellite coverage if the axis of a satellite-borne reflector were aimed at the center of the country, the extreme beams would have to point 3.4° east and west of the axis if all beams were to emanate from one reflector. (Note that Figure 3-14 covers only about 6.2° by 2.1°.)

3.6.4.1 Coma

When a beam is pointed (scanned) off axis in a reflector, coma distortion results, i.e., the antenna pattern sidelobes become wider and higher. The first lobe joins the main beam on one side of the antenna pattern, thus reducing gain and increasing the potential for beam interferences. A well-known rule [Silver, 1949] states that the limit for scanning a beam off the axis of a reflector is five beamwidths before coma becomes too severe. This would be 1.5° for 0.3° beams, casting doubt on the azimuthal coverage of the country by one antenna using this beamwidth. Two reflectors, one for the eastern half and the other for the western half of the United

States, could help. However, different size reflectors would be needed for the uplink and downlink satellite beams. Using two reflectors for the downlink beams and two for the uplink beams will give the satellite a complement of four reflectors.

Coma can be reduced by locating feed-horns radially out of the focal plane. Therefore, a design study might be carried out to determine whether only a single reflector could be used for all downlink beams and another single reflector used for all uplink beams. This is an effort of some magnitude and is beyond the scope of the current study.

3.6.4.2 Number of Reflectors

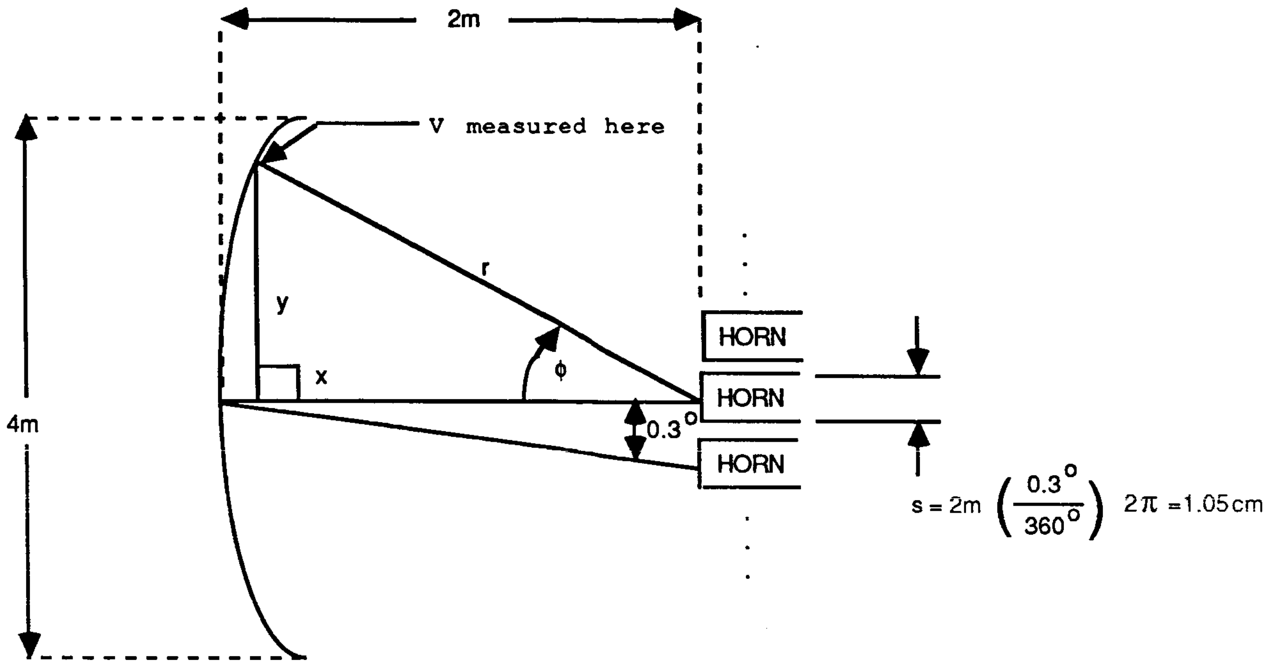
Spacecraft antenna complexity could be reduced if the same set of feed-horns could be used for both uplink and downlink beams. There is no barrier to diplexing the uplink and downlink frequency bands onto the same horn. However, the fixed horn aperture will give a different beamwidth from the horn for each band, and one of these necessarily will inefficiently illuminate a reflector of the size needed to give a 0.3° beam. In order to design an effective antenna, the designer must be able to control both the reflector and the horn aperture, i.e., there must be freedom to design the uplink and downlink antennas independently. Thus, the hope of having only two reflectors depends on the success of a program to reduce coma by refocusing. Beam interferences are not affected whether or not refocusing is successful. A requirement of two reflectors each for both uplink and downlink will not change the principles discussed below.

3.6.4.3 Reflector Illumination

As already mentioned, the reduction of beam interference requires low sidelobes in each beam pattern. This can be accomplished by illuminating the reflector most intensely at the center and tapering off the intensity toward the reflector edges. Illumination taper is controlled by the primary beam from the illuminating horn. If a narrow beam is achieved by using a larger opening on the horn, then the intensity, high at the center of the reflector, will drop off enough at the edges to give low secondary beam sidelobes. Thus, large horn apertures may be required, and it is necessary to determine what horn aperture sizes a given beam system permits.

Each beam requires a separate horn. The horns are positioned relative to the axis of the reflector in the same way as the beams, but in mirror image locations because of the laws of reflection. Thus, we may speak of relative horn positions just as if the beams were the horns. Horns located at adjacent angular positions can be enlarged until the horns just touch. That and the lowest downlink frequency, 17.5 GHz, determine the largest possible horn size. A reflector diameter of 4 m is needed to produce a 0.3° beam at this frequency.

A common value of focal length to diameter ratio for reflectors is 0.5. Thus, the focus of the reflector is expected to be 2 m from the vertex. Horns will be positioned on a surface at approximately this distance, and the angular separation of the horn centers of two touching beams will be 0.3° subtended at the vertex of the parabola as shown in Figure 3-15. The arc length corresponding to this angle will also be the aperture opening of the



REFLECTOR (Parabolic Dish: $y^2 = (2m\text{-}x)\,8m$; $\tan \phi = \frac{y}{x}$)

Figure 3-15 Horn - Reflector Geometry

horn. This is found from the relationship among radius and angle to be s = 1.05 cm. The question next arises as to how much amplitude taper a horn aperture of such a size produces. This requires a formula for the pattern of a horn.

A simple closed form for the pattern of an electromagnetic horn does not exist; the phase front curvature emanating from the horn does not lead to mathematical functions integrable in closed form. However, if the horn sides are not flared at too wide an angle, a condition easy to satisfy with the small horns used in the 30/20 GHz band, it is possible to derive an approximate formula.

The formula is accurate enough for finding amplitude taper on reflectors when the curvature of the phase front in the horn aperture is less than a quarter wavelength, $\lambda/4$ (4.3 mm at 17.5 GHz). Then, the phase front may be taken to be plane which leads to integrable functions.

As indicated in Figure 3-15, let the horn have a square cross-section s = 1.05 cm on a side. Let ϕ be the angle between the central horn-reflector axis and the line of length r from the horn aperture to the point on the reflector where the relative electric field intensity $V = |E(\phi)|/|E(0)|$ is measured. A simplified approximate expression for V is [Wolff, 1966]

$$V = \frac{(1 + \cos\phi)}{r(\phi)} \cdot \frac{\sin\left(\frac{\pi s}{\lambda} \sin\phi\right)}{\frac{\pi s}{\lambda} \sin\phi} \tag{3.33}$$

The lowest (downlink) frequency, f = 17.5 GHz (λ = 1.7 cm), in the 30/20 GHz frequency band yields the worst-case for (zero) horn separation, i.e., s/λ = 0.61. Given ϕ, r is a solution to the quadratic equation

$$r^2 \sin^2\phi + 8m\ r \cos\phi - 16m^2 = 0 \tag{3.34}$$

Table 3-7 shows that the illumination taper produces a level only -7.6 dB down relative to the center (ϕ = 0). The secondary pattern of a 4 m antenna illuminated by this distribution may be deduced using the well-known family of patterns [Sciambi, 1966] for a round aperture derived from an in-phase illumination with amplitude distributed according to the parametric formula

$$v^2 + (1 - v^2)\ [1 - (\tfrac{y}{Y})^2]^p \tag{3.35}$$

where

V^2 is the uniform component of aperture illumination which is also the relative intensity at the edge ($V^2 = 0.17$ for the -7.6 dB of Table 3-7),

y is the distance from the vertex axis to a point on the aperture inside the outer circumference,

Y is the distance from the vertex axis to the aperture circumference (or edge), and

p is the algebraic power which determines how fast the intensity falls off from the peak value.

Table 3-7
Aperature Distribution for 4 m Reflector and 1.05 cm Horn at f = 17.5 GHz (λ = 1.7 cm)

ϕ (rad)	$\cos\phi$	$\sin\phi$	$r(\phi)$ (m)	V	$10\log_{10}V^2$ (dB)
0	1	0	2.0	1	0
0.64	0.8	0.6	2.2	0.64	-3.8
0.93	0.6	0.8	2.5	0.42	-7.6

The pattern resulting from the aperture illumination of Table 3-7 (curve fitting is used to find p) yields first sidelobes that are only about 21 dB down; the first two sidelobes are at too high a level for the addition of sidelobes of several antennas to produce an acceptably low carrier-to-interference ratio. It would be necessary to use a larger horn to further reduce the sidelobes. However, the horns would clash if their apertures were made larger.

3.6.4.4 Dual Focal Plane Technique

A second focal surface could be provided by using a polarization sensitive reflecting/transmitting screen. The screen reflects vertical polarization, say, and transmits horizontal polarization. The screen, reflector, and horns are shown in Figure 3-16. An offset reflector is used so that, although it has a 4 m aperture, the horns are below the reflector and do not block the transmitted or received energy. Half the (rear) horns are behind the screen but are horizontally polarized so their radiation passes through to the reflector. The other horns are in front of the screen, and their patterns reflect off the screen to illuminate the reflector properly. These front horns are the same optical distance from the reflector as the rear horns on the original focal surface. In effect, the screen provides two focal surfaces so that the horns can be larger. Since half the horns are located on

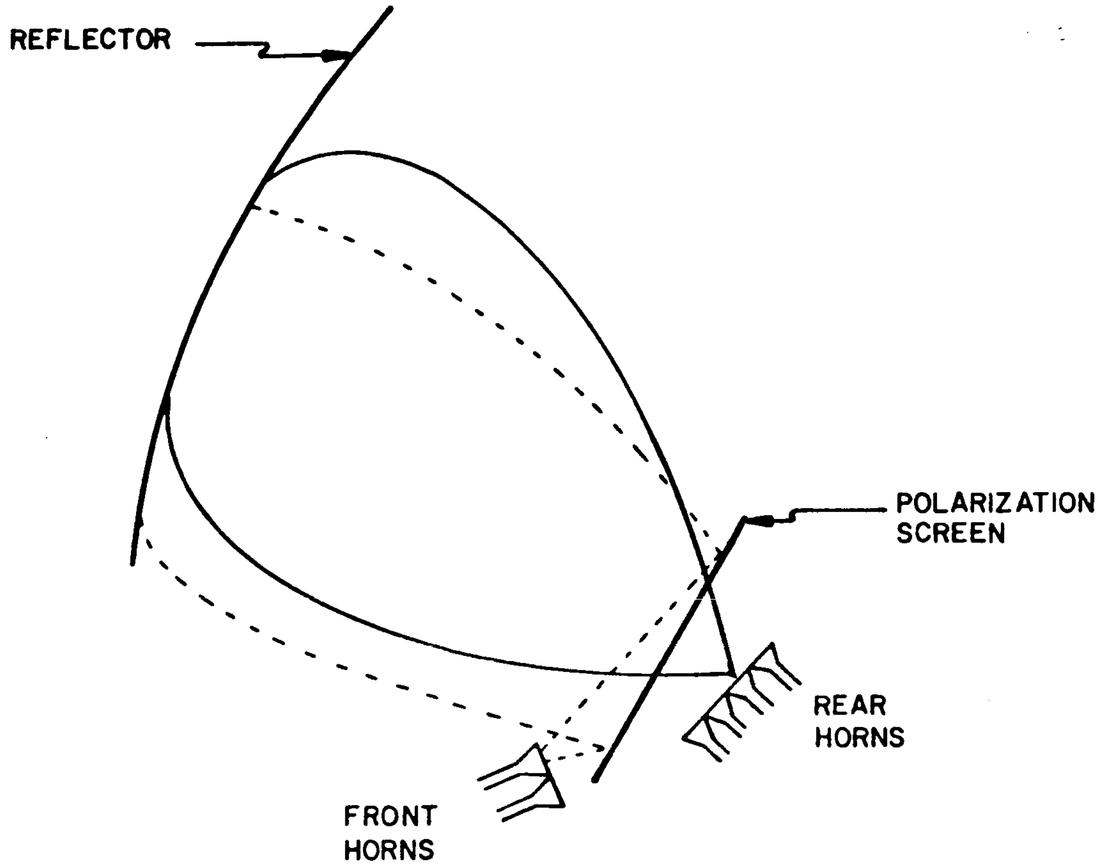


Figure 3-16 Dual Focusing Surface

the front, and half on the back focal surfaces, the horns can be twice as large or 2.1 cm in both a and b horn dimensions. Using Equation (3.33) with $s/\lambda = 1.22$, the amplitude taper on the reflector for this case is given in Table 3-8.

Table 3-8
Aperture Distribution for a 4 m Reflector and 2.1 cm Horn at f = 17.5 GHz (λ = 1.7 cm)

ϕ (rad)	$\cos\phi$	$\sin\phi$	$r(\phi)$ (m)	V	$10 \log_{10} V^2$ (dB)
0	1	0	2.0	1	0
0.64	0.8	0.6	2.2	0.26	-12
0.93	0.6	0.8	2.5	0.013	-38

The 2.1 cm horn provides a much lower edge illumination than the 1.05 cm horn. The secondary pattern shape can be estimated as before from the class of canonical antenna patterns. The first sidelobes should be at least 35 dB down as required in Subsection 3.5.2.2.

3.6.5 Key Beam Plan Interference Characteristics

Various beam/frequency/polarization plans can be devised for close-packed beams of beamwidth θ_0. The purpose of this section is to tabulate the key parameters

d = center-to-center beam separation for same polarization and frequency subband

K(d) = number of interfering beams (with same polarization and frequency subband) at distance d

for various beam plans with M beams, N frequency subbands, and frequency reuse factor F = M/N. Most of the devised plans are not shown but see Figure 3-14 for the first two examples of Table 3-9.

Observe that for many interesting plans $K(d_{min})$ is only 1 or 2. This implies that the co-channel interference from a single beam need only be at least 29 dB down and 32 dB down, respectively, to meet the criterion of Subsection 3.5.2.2. Typically, d_{min} will dominate the calculation of inter-beam interference.

Table 3-9
Number (K) of Interfering Beams at a Distance (d) for Various Beam Plans

M	N	F	d/θ_0	K(d)	θ_0(CONUS coverage)
10	3	3.3	3	1	1.2°(6° x 2.2°)
40	4	10	$\sqrt{7}$	2	0.6°(6° x 2.2°)
			4	2	
160	5	32	$\sqrt{7}$	2	0.3°(6° x 2.1°)
			$2\sqrt{3}$	2	
			$\sqrt{13}$	1	
			5	2	
			$2\sqrt{7}$	1	
			$2\sqrt{13}$	1	

Infinite Tessellations:

3		$\sqrt{3}$	2
		3	2
		$2\sqrt{3}$	6
4		$\sqrt{7}$	4
		4	2
5		$\sqrt{7}$	2
		$\sqrt{13}$	2
5		$\sqrt{7}$	2
		$2\sqrt{3}$	2
6		$\sqrt{7}$	2
		$\sqrt{19}$	2
6		$2\sqrt{3}$	6

SECTION 3
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SECTION 4
TERMINAL DESIGN

This section addresses the terminal design issues. The requirements for both supplier (provider) and subscriber (user) terminals are defined, and baseline designs are presented. The design of the subscriber terminals is emphasized, as they are the most constrained with respect to size and cost. A high level block diagram of user terminal architectures is presented, and various design tradeoffs are investigated.

4.1 TERMINAL DESIGN REQUIREMENTS

4.1.1 Subscriber Terminal

Subscriber terminals are the on-premises terminals that support the users of the communications system. Large numbers of this type of terminal could ultimately be installed, and consequently the cost of the subscriber terminal is a key issue.

In order to minimize the cost of the terminal, the use of mature technology is required. Unfortunately, at 30/20 GHz, little mature technology exists. However, there is a definite state-of-the-art limit that has been established. Nearly all of the components of the terminal have at least been developed and demonstrated at performance levels required for the FSS, even though they may not have been produced in quantity. Thus, new technology development is not needed in order to make the proposed system technically feasible. To achieve economic feasibility, however, will require a maturization of this technology. This maturization can be expected to happen naturally. A simple terminal design placing the least performance demands upon the SHF/EHF components will aid in achieving this goal.

A consideration in the design of the user terminal is the single versus multi-channel capability. A single channel terminal can accommodate the bulk of the applications which are interactive in nature. However, to support background processes such as batch file transfer, home security, or utility meter reading, multi-channel capability would be required. Including the multi-channel capability will of course increase the cost of the terminal. The data rates required for home security and utility meter reading are quite low, and could be accommodated by low rate channels. It may be possible to build a terminal with a single channel RF, where low rate secondary channels are digitally multiplexed with the primary medium rate channel.

4.1.2 Supplier Terminal

The supplier terminals accommodate the providers of services via the satellite network. It is via the supplier terminals that the services accessed by the subscriber are made available on the satellite network.

Supplier terminals are necessary to provide interfaces between the satellite network and other systems/networks, telephone systems, and services. Thus, the supplier terminals must interface to a variety of special equipment (i.e., computers, telephone network, billing equipment, etc.) in order to provide the various services.

Supplier terminals will also need to accommodate multiple users simultaneously, and will thus be considerably more complicated than the user terminals.

The cost of the supplier terminal is not as sensitive an issue as for the subscriber terminal. A single supplier terminal can provide services to a large number of users; the cost of the terminal can thus be spread over many users through access charges and/or usage fees. Furthermore, as the supplier terminals will use much of the same technology as the subscriber terminals, the cost of the supplier terminal will also fall as the cost of the subscriber terminals are reduced.

4.1.2.1 Modules

Supplier terminals will ideally be built using many of the same modules as for the subscriber terminals. This will reduce the cost of the supplier terminals as they will benefit from the economy of scale enjoyed by the subscriber terminal production.

A set of "plug-in" modules might be developed. Terminals for different applications would be configured by selection of the appropriate type/number of modules.

4.1.2.2 Interfaces

Whereas the subscriber terminals generally have only a few interfaces, supplier terminals will need to interface to a variety of specialized equipment. Some of the interfaces likely are discussed below.

4.1.2.2.1 Telephone System

For the rural telephone service application, a gateway into the public switched telephone network (PSTN) would be required. This gateway allows the interconnection of telephone calls between the satellite network and the PSTN.

For outgoing calls (originated by a rural user via satellite) the gateway must establish a connection with the PSTN. The gateway maintains the connection for the duration of the call. For incoming calls (initiated from the PSTN) the gateway must establish a connection to the rural user via the satellite network. The gateway must also provide any required translation of signaling between the rural user and the PSTN.

Depending upon the details of the system design, the gateway might also be involved in requesting/relinquishing channel assignments.

4.1.2.2.2 Other Communications Networks

Interfaces into other communications networks might also be necessary. For example, interfaces into networks such as Tymnet and Telnet would be used by remote timesharing users. For banking transactions or electronic mail, other networks might be involved.

Interfaces into these external communications networks will also need a gateway. The operation of a gateway for any network is in principle the same as described above for the PSTN. Specific details of operation, of course, depend upon the protocols of the two networks being interfaced.

Adoption of recognized standards would considerably simplify the interfacing of networks, and hence simplify the gateway design.

4.1.2.2.3 Billing Equipment

With most services, it is necessary to provide for determination of the authorization of the user, and to provide some mechanism for charging the user for use of the system.

The billing problem can actually be divided into two portions: the bill for the use of the communications facilities, and the bill for the use of the service provided via the communication facility. Currently, the trend is for the cost of the communications facilities to be included in the cost of the services. Examples of this are businesses which provide toll-free 800 numbers and include the cost of the 800 number in their basic fees; magazine subscriptions include the cost of postage; cable TV subscription fees include the cost of installing/maintaining the cable, etc.

Thus, it seems likely that the cost of the communications system would be charged to the businesses providing services via the system. These businesses would in turn recover this cost from the users via their fees. Thus, the billing problem would be addressed on an individual application basis.

A variety of approaches are possible in addressing this requirement. One simple approach would be to charge a flat fee for access to the service. Thus, for the flat fee, the user would be given the proper keys to access the service or the satellite network. At the other extreme, authorization for each transmission of a terminal could be verified, a record of activity maintained, and users billed based upon their usage. In any case, some interface between the supplier terminal(s) and a billing subsystem would be required. Information taken off the air would be fed into the billing subsystem which would verify access authorization and generate appropriate usage fee bills. Ideally, the usage bills would be distributed and paid electronically through the system.

4.1.2.2.4 Computers

Many of the applications involve direct access to a computing system, or require a computing system to implement the features of the particular service. Thus, the main interface point for the supplier terminals will generally be some sort of special purpose or general purpose computing system.

For example, interactive videotext and database systems are generally supported directly by a computer system. Each of the users are essentially logged into the system and running a particular program which provides the videotext service.

4.2 SUBSCRIBER TERMINAL DESIGN

The terminal design is described at a fairly high level, independent of the particular network architecture selected. A high level block diagram of the terminal design is shown in Figure 4-1. This high level block diagram is not affected by the particular system design selected, but

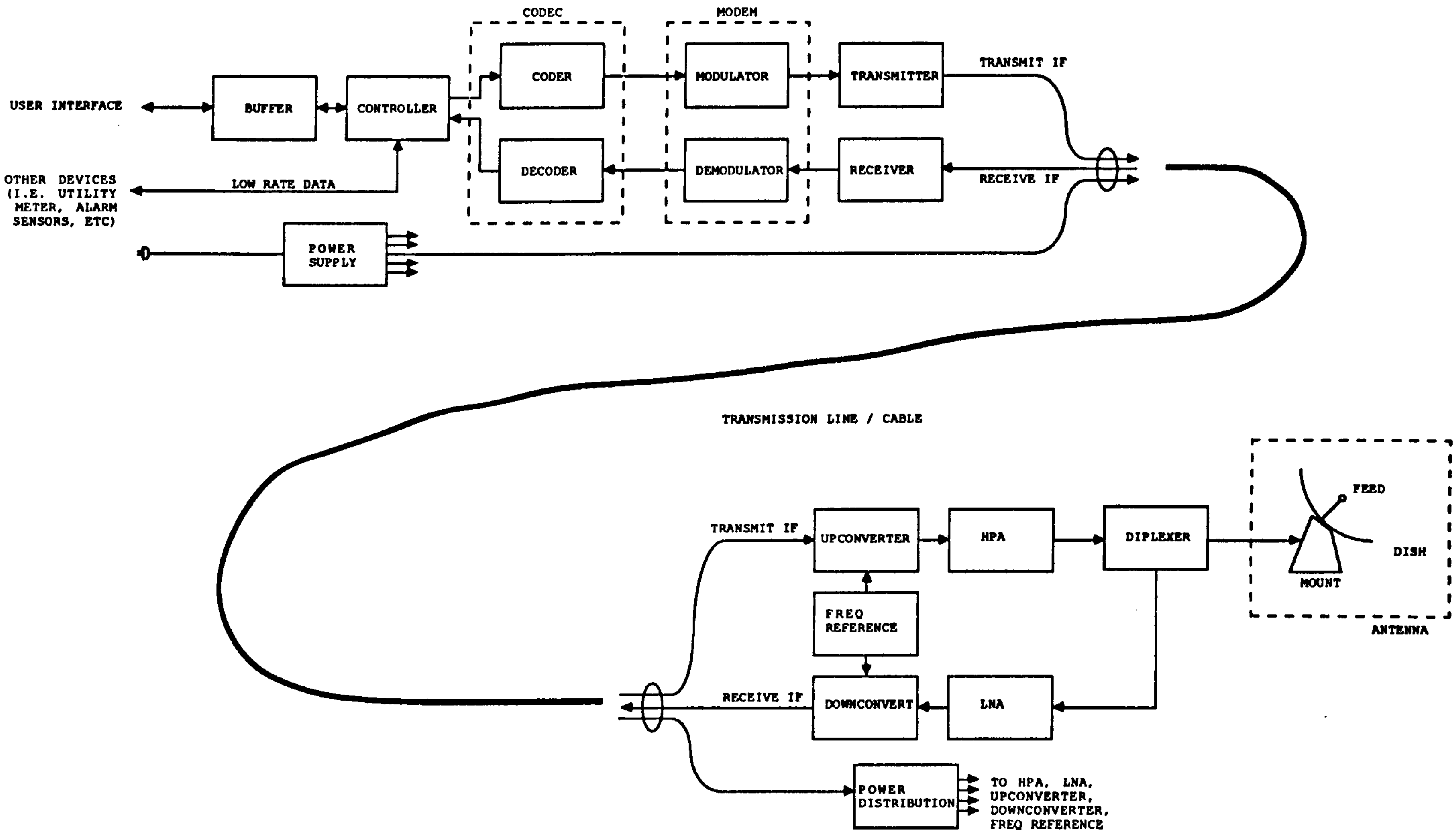

Figure 4-1 Subscriber Terminal Block Diagram

the detailed functioning of the various blocks is dependent upon the overall system design.

In the following paragraphs, the various components of the terminal illustrated in Figure 4-1 are discussed, and system design requirements are translated into constraints on the components. Implications of various system architectures are discussed relative to the terminal subsystems they would effect.

Cost and technology constraints placed upon the terminal hardware are discussed later in Sections 6 and 7.

4.2.1 Antenna

Two different antenna designs could be considered for the FSS: parabolic dishes and phased arrays. Parabolic dishes consist of a passive reflector illuminated by a feed located at the focus of the dish. The gain of the parabolic dish is determined by the size of the passive reflector. Phased arrays consist of a number of smaller antennas (i.e., dipoles) which are fed in an appropriate phasing relationship in order to form the desired beam pattern.

A phased array type antenna has the advantage that a conformal antenna can be built. Thus, an antenna flush to the roof of a house is possible, yielding obvious asthetic advantages. Unfortunately, phased array antenna technology is quite immature at 30/20 GHz, and presently appears that it would be prohibitively expensive [Dybdal, 1983].

Parabolic dishes are quite mature technology, and have been built to operate at 30/20 GHz and above. Large numbers of antennas for the TVRO industry operating at 4 and 12 GHz have been manufactured. Thus, a parabolic dish antenna appears to be the most economical choice.

4.2.1.1 Size

The antenna provides for the transmission of the 30 GHz uplink signal and reception of the 20 GHz downlink. A high gain/narrow beamwidth antenna will be required in order to establish reasonable link margins and to operate with close satellite spacing (assuming a 2° satellite spacing at 30/20 GHz). This results in a lower limit on the antenna size.

The minimum antenna size can be determined from the spacing requirement. The receive requirements are most stringent, due to the reduced gain/beamwidth at the receive frequency. For adequate rejection of adjacent satellites, the antenna gain should be down by at least 20 dB at the adjacent satellite. The gain loss of the main lobe of the antenna (as a function of the angle off beam center, θ) can be approximated by

$$L_P = 12\left(\frac{\theta}{\theta_0}\right)^2 \qquad (4.1)$$

where θ_0 is the half-power beamwidth [Frediani, 1978].

We solve this expression for the half-power beamwidth such that the gain will be down 20 dB at a 2° angle (the assumed spacing). This yields a minimum required half-power beamwidth of 1.5°.

We can solve for the antenna diameter knowing that the half-power beamwidth is related to the diameter, D, by,

$$\theta_0 = 70\left(\frac{\lambda}{D}\right) \text{ degrees ,} \tag{4.2}$$

where λ is the receive wavelength (λ = 1.5 cm at f = 20 GHz).

A minimum antenna diameter of 2.3 feet (0.7 m) is thus required. Smaller antennas are possible if satellite spacing wider than 2° is used.

An upper bound on the antenna size also exists. It is highly desirable that a fixed pointed antenna be used, thus avoiding the additional expense and complexity of an antenna pointing/tracking system. For a fixed antenna, there will be pointing errors due to errors in the initial alignment of the antenna, and drift of the satellite. As the antenna diameter is increased, the beamwidth narrows, and these losses increase. The transmit requirements are more stringent, due to the decreased beamwidth.

To find the maximum antenna size, we use the same relationships as above, although using the transmit frequency (λ = 1 cm at f = 30 GHz). About ±0.05° of satellite station keeping accuracy is expected for the ACTS satellite [ACTS, 1986], so we will allow about 0.1° for pointing error due to the combined effects of satellite drift and antenna alignment. We want the loss to be less than 1 dB with this offset. Solving (4.1) and (4.2) for θ = 0.1°, and L_p = 1 dB, yields the minimum θ_0 = 0.35°, corresponding to a maximum antenna diameter of 6.6 feet (2 m).

FCC requirements for earth terminals place constraints on the sidelobe characteristics of the antenna. These requirements should be fairly easy to meet for these size antennas at 30/20 GHz. The antenna efficiencies assumed allow for tapered aperture illumination as may be required in order to achieve the required sidelobe levels.

4.2.1.2 Surface Accuracy

The main lobe gain of the antenna is given by

$$G_0 = \eta\left(\frac{\pi D}{\lambda}\right)^2 e^{-(4\pi\sigma/\lambda)^2} \tag{4.3}$$

where D is the antenna diameter, and η is the antenna efficiency [Ruze, 1966]. In the second term, σ is the RMS surface accuracy of the antenna dish. At 30/20 GHz the surface accuracy of the antenna is quite important, and this term may represent a significant loss. The loss due to surface roughness can be expressed as,

$$L_r = 686\left(\frac{\sigma}{\lambda}\right)^2 \text{ dB} \quad . \tag{4.4}$$

For losses due to surface roughness to be less than 1 dB at 30 GHz, surface accuracies on the order of 0.015 inches or less are required.

4.2.1.3 Feed

The antenna feed acts as the collection point for receive power, and the launching point for transmit power, which is reflected off the parabolic dish. The antenna feed will probably need to be a dual 30/20 GHz design, rather than two side-by-side feeds, due to the required tolerances.

Both centered and offset feeds are a possibility. Offset feeds provide an advantage in reduced sidelobe levels, although we do not believe this to be an issue.

Asymmetric antennas are also a possibility. The asymmetric antenna allows the size to be increased in one dimension as required for close satellite spacing, without needing to increase the size in the other dimension. Such antenna designs have been built although not in large quantity, but should present little risk.

The selection of the specific antenna design approach will be cost driven. As center-fed parabolic antennas are the most common for mass production applications (VSATs and TVRO), it is likely they will also prove most economical for the FSS applications under consideration.

4.2.1.4 Mount/Positioner

Some sort of antenna mount is obviously necessary. We have assumed a fixed pointed system in order to reduce the cost of the terminal. This is consistent with the use of a geostationary satellite. The requirement for fixed pointing does, however, result in an upper limit on the size of the antenna (as pointed out above).

With a fixed pointed antenna, an adjustable mount is still necessary to allow initial alignment of the antenna. In line with the allowable pointing errors assumed above, the mount should allow positioning of the antenna to within the 0.1° accuracy assumed.

4.2.2 Diplexer

A diplexer is required in order to separate the transmit and receive signals. A diplexer consists simply of a pair (or more) of filters. At microwave frequencies, the filters can be implemented by means of waveguide cavities. These filters provide isolation between the transmit power going into the antenna, and the receive power coming out of the antenna. Since the receive signal level is considerably lower than the transmit signal, very good isolation between transmit and receive is required in the diplexer. Typically 30 to 60 dB isolation is provided, with further filtering done in the receiver.

4.2.3 HPA/Upconverter

The upconverter and high power amplifier (HPA) will frequency translate and amplify the uplink signal to the frequency and power levels that are provided to the antenna.

A key issue in the terminal design is the location of the HPA. Guided transmission of signals in the EHF band is very difficult. Figure 4-2 shows the loss of various types of transmission lines computed from [ITT, 1979]. As can be seen in Figure 4-2, flexible coax, the most economical cable, is excessively lossy. Expensive rigid coax and copper waveguides are also very lossy, ranging from 10 to 30 dB/100 feet. The best that can be done is silvered waveguide which results in minimum losses of 6 dB/100 feet, although at considerable expense. A run of 100 feet between the terminal and antenna is quite possible.

This problem can be avoided by locating the HPA and upconverter at or near the antenna. This allows the transmission line from the terminal to the antenna to operate at a lower intermediate frequency (IF), where less expensive and less lossy cables can be used.

If the HPA/upconverter is located at the antenna, it is necessary to provide power to the antenna. Either a TWT or a solid state amplifier could be used. TWT type amplifiers require high voltage supplies and are generally quite bulky. Solid state amplifiers are smaller and require lower voltage. Although solid state amplifiers are less efficient than TWTAs, this is not an issue in the terminal design, especially considering the fairly low power levels involved.

Using a TWTA at the antenna would also require locating the high voltage supply at the antenna, or it would be necessary to provide high voltage to the antenna via a cable. Neither option is particularly attractive.

A solid state HPA would only require a fairly simple voltage regulator at the antenna, and the low voltages required could be transmitted via a conventional cable. Thus, the use of a solid state HPA appears preferable.

The IF frequency to be used is a compromise between the complexity of the upconverter, and the difficulty in relaying the signal between the terminal and antenna. As a lower IF is used, the transmission line problem is simplified at the cost of increased upconverter complexity; as a higher IF is used, more transmission line loss occurs while the upconverter is simpler.

A final issue in the design of the HPA is the output power. The power output of the HPA is the primary factor in determining the uplink margin, as the antenna size is constrained. Thus, the HPA output power should be maximized.

4.2.4 LNA/Downconverter

The low noise amplifier (LNA) amplifies the weak downlink signal collected by the antenna, and the downconverter translates it to an IF. As for the transmitter, a similar problem exists with getting the signal from the antenna to the terminal due to the inherent loss of cables at 20 GHz. In fact, the signal level from the antenna is so low that amplification must be done at the antenna before any losses are encountered, otherwise the desired signal will be buried in the thermal noise of the subsequent equipment. This problem can be solved by locating the LNA and downconverter at the antenna, and transmitting the signal to the terminal at IF.

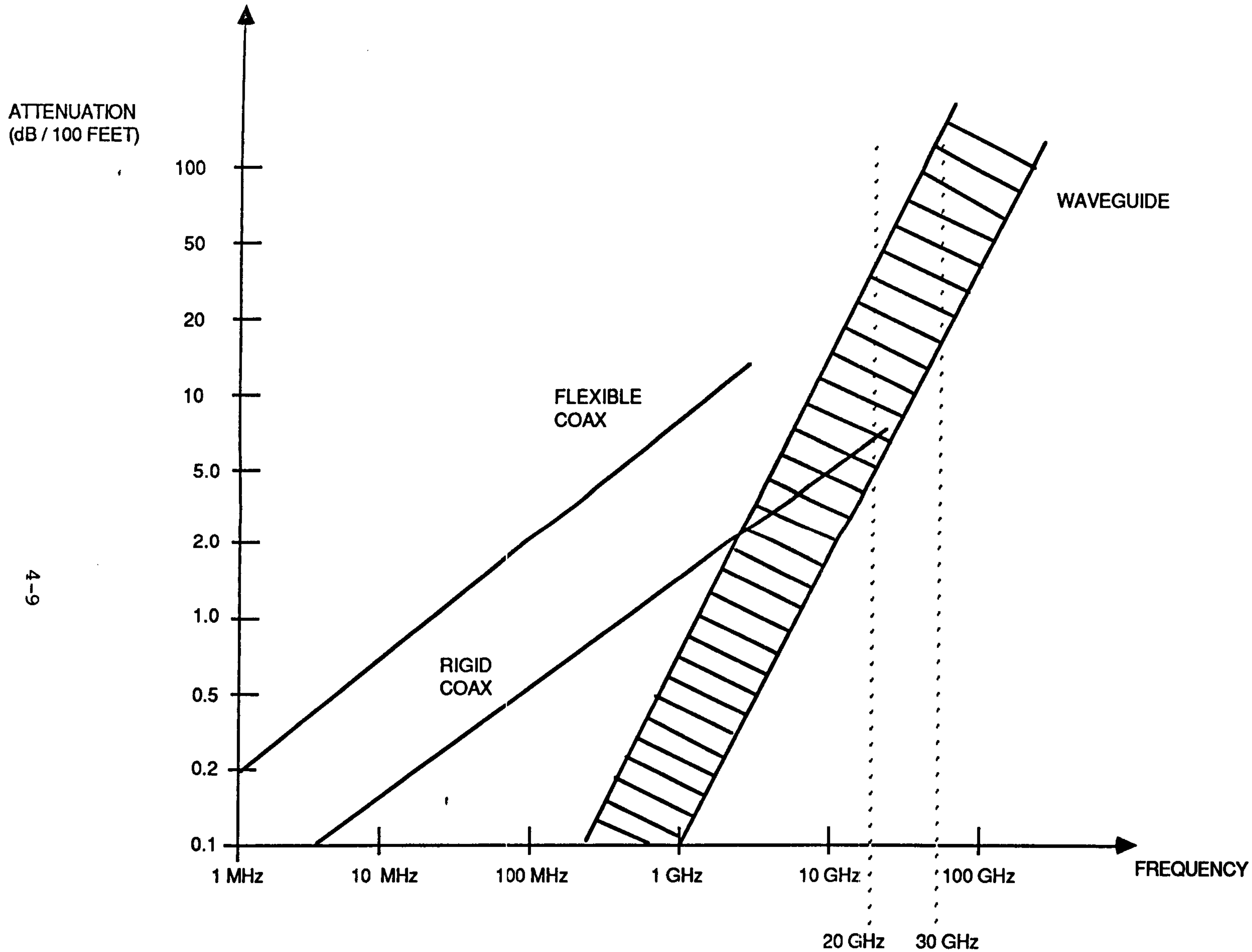

Figure 4-2 Transmission Line Attenuation vs. Frequency

For the receiver, an IF in the 950-1400 MHz range would seem to make sense, as this is the IF frequency used for the TVRO systems. Thus, a fairly good technology base should exist for receivers in this frequency range, allowing reasonably economical equipment to be developed.

Sky background sets a lower limit on the noise temperature of the system. Although usually about 20-50°K, the sky background can increase to as high as 275°K during rain [Frediani, 1979]. Using LNA's with noise temperatures lower than this is obviously not sensible. Practical LNAs have noise figures of 3.5 dB or more (360°K), and thus will set the noise floor. Thus, the noise temperature of the LNA is the primary contributor to the overall receiver noise temperature, T. Added sky noise during rain will contribute a small additional degradation of no more than 2.0 dB.

4.2.5 Transmission Line

The transmission line to the antenna must carry three different signals; the receive IF from the antenna/LNA/downconverter, the transmit IF to the upconverter/HPA/antenna, and the DC power going to the antenna electronics.

It would be possible to combine all three of these signals in a single cable, provided that the receive and tranmit intermediate frequencies are sufficiently different. The DC, transmit IF, and receive IF can then be isolated by simple passive filters. By combining all three signals in a single coaxial cable, the cost of the transmission line becomes negligible, on the order of $5 to $10. The additional hardware required to separate the signals is also insignificant.

4.2.6 Transmitter

The transmitter will provide additional upconversion from the modulator output to the IF used to relay the transmit signal to the antenna. In many cases, it is desirable to generate the modulation directly at IF, thus eliminating this component.

4.2.7 Receiver

Additional amplification and downconversion from the IF will be required prior to demodulating the signal. The receiver will perform downconversion to the baseband or IF required by the demodulator, automatic gain control, and possibly other functions that may be required by the network design (i.e., pilot tone tracking, etc.).

4.2.8 Modem

The modem contains both the modulation and demodulation functions. Since the burst rates will probably be fairly low (200 kb/s), modem technology in this range is relatively mature. A number of implementation approaches appear feasible.

The block diagram assumes a transmit modulation is generated at baseband and then upconverted. For many modulation schemes, however, it is possible (and often easier) to produce the modulation directly at an IF (or even in the extreme, to directly modulate the transmit carrier).

Likewise for the receiver, demodulation can be done at IF rather than baseband. For example, if DPSK modulation is used, demodulation can be done using Surface Acoustic Wave (SAW) demodulators which perform demodulation directly at an IF. A 70 MHz IF is the standard most frequently used.

If a direct sequence spread spectrum access scheme is used, the modem will also be involved in the spreading/despreading process. This could be done by using a modulator at the chip rate to spread the carrier. Data could be modulated onto the carrier separately (either before or after spreading), or could be added into the PN-sequence. The demodulator could recover the receive data by using the known PN-sequence to despread the receive signal, and then performing normal demodulation. The modem would need to achieve and maintain timing synchronization of the PN-sequence.

4.2.9 Codec

The terminal may include a coder and/or decoder (codec) function to provide additional link margin. The codec may not always be used, as it does reduce the bandwidth efficiency. Thus, coding might be switched in or out as required to combat rain, or to accommodate applications requiring very reliable transmission.

The implementation of the codec could be in either hardware or software, depending upon the complexity of the coding scheme. For long constraint length convolutional codes, microprocessor decoder implementations are limited to fairly low data rates, and are probably inadequate. Thus, if coding is used, hardware for the decoding operation will be required. Software encoding, however, is feasible at the low and medium data rates.

4.2.10 Controller

The terminal controller exercises the network protocols; it determines the time/frequency for transmission, selects receive messages that are of interest to the user or addressed to that terminal, and maintains synchronization in the network.

The complexity of the network synchronization function depends on the networking scheme. Pure ALOHA requires no synchronization of individual net members. More complicated schemes, such as DA/TDMA require very accurate timing and strict protocols. The access schemes that appear the most feasible are generally simple, requiring little complexity in the controller. It may thus be possible to implement the controller functions in software in the user's PC (see Subsection 4.3.6).

An additional function of the controller is to multiplex/demultiplex the low rate channels for such applications as utility meter reading or home security.

4.2.11 Interfaces

The terminal must interface to the user and low bit rate monitoring equipment (utility meter reading, home security). The interface to the user is provided by a PC, which includes the keyboard and screen needed to interact with the user. The interface to the low rate equipment can be standard (inexpensive) RS-232 serial.

The PC should include software to provide a friendly user interface, and provide any special control to the rest of the terminal needed to configure it for operation.

4.2.12 Frequency Reference

The terminal must include a frequency reference function which generates accurate frequency references and stable timing. Limits on affordable frequency accuracies are discussed in Subsection 3.1.

An alternate approach to generating a stable frequency reference in the terminal is to use a pilot tone from the satellite. The receiver would then need to include a pilot tone tracking function. The receiver frequency reference would be frequency or phaselocked to the pilot tone, thus achieving a reasonable receive frequency accuracy, plus or minus whatever Doppler exists. The frequency accuracy requirement will drive the cost of this component.

The point at which the most accurate frequency reference is necessary is in the HPA/Upconverter and LNA/Downconverter, since these are the subsystems operating at the highest frequency. Since both of these subsystems are located at the antenna, it seems the frequency reference will also need to be located at the antenna. This may represent a problem if the pilot tone approach is used, since the pilot tone tracking would be done in the receiver, not at the antenna.

As generation of accurate 30/20 GHz frequency references is difficult and expensive, this is a very sensitive area of the terminal design. It is thus a candidate for possible tradeoff in the system design.

4.3 TERMINAL DESIGN TRADEOFFS

In areas where ample link margin exists, it is possible to make tradeoffs in the terminal design. Several potential areas for such tradeoffs are discussed below. It should be noted that these tradeoffs are not independent.

4.3.1 Antenna Size vs HPA Power

To some degree, antenna size can be traded for HPA power. As more HPA power is available, less antenna gain is needed, so a smaller antenna can be used. This would be desirable, as smaller antennas are likely to have a larger potential market.

4.3.2 Antenna Size vs LNA Temperature

Antenna size can also be traded for LNA effective noise temperature. As a lower noise LNA is used, less antenna gain is necessary to achieve the same G/T. Again, this would be desirable. Unfortunately, the cost of LNAs increases rapidly as better performance is required. Generally, large antennas are a cheaper way to get more G/T, thus making this a poor trade-off.

4.3.3 Antenna Size vs Pointing Accuracy

A tradeoff also exists with respect to the antenna size versus the required pointing accuracy. As larger antennas are used, the beamwidth becomes narrower, and more accurate pointing is required to reap the full benefit of the increased gain of the antenna.

For the narrowest beamwidths likely to be used (6.6 ft antennas), the pointing accuracy required to maintain a loss of less than 1 dB is assumed to be on the order of 0.1°. The mount must therefore allow for pointing with this fine a resolution.

For the smallest antenna likely to be used (2.3 ft) the equivalent 1 dB loss occurs with a pointing accuracy of only 0.4°.

Thus, it can be seen that the required antenna pointing accuracy is not particularly sensitive to the antenna size for the limited range we are considering.

4.3.4 Antenna Size vs Consumer Preference

A final consideration in the antenna size is the preference of the end users. Generally smaller, less obtrusive antennas are desired by consumer users. Smaller antennas have the advantages that they are easier to install, more aesthetically pleasing, and minimize regulatory/zoning problems.

Larger (6 to 12 feet diameter) antennas are necessary for TVRO terminals, and do not appear to have had a major adverse impact of the acceptance of TVRO, as over 1.5 million TVRO terminals have been sold to date. However, the large size of these antennas has resulted in public concern over their appearance resulting in pressure on local communities to pass antenna ordinances restricting or disallowing the satellite dishes. Many communities have already done so. In addition, new "planned" communities are often being designed with cable TV in place and deed restrictions disallowing the erection of antennas. Although the legality of many of these types of ordinances is still being determined, this is an area that is likely to remain unsettled for a number of years. In any event, the general climate is likely to remain hostile towards large satellite dishes. For this reason, it is felt the size of the antenna must be minimized.

One possible approach to minimize the obtrusiveness of the antenna is to get away from the parabolic dish structure, and instead build a conformal antenna (i.e., a phased array). Such an antenna could be placed on the rooftop, and would be virtually invisible. As noted previously, the technology is still relatively immature and such an approach would probably be far too costly. Technology development to be done for military EHF airborne antennas may, however, bring some of this technology to maturity.

4.3.5 Use of PC for Baseband Hardware

A final tradeoff is to what extent the PC is used to implement the functions of the terminal. When the user already has a PC, considerable savings can be achieved by placing as many of the terminal functions as possible into the PC. However, the more extensively the PC is used, the less flexible the terminal becomes. Doing many functions in the PC may require specialized software and/or hardware, which may not be transportable to other brands of PCs.

The use of the PC for the user interface and buffer functions has already been assumed. The PC could also implement some of the control and modem functions. Many of the control functions are executed at a fairly low rate and could easily be accommodated by the user PC. For example, in the Pure ALOHA access scheme, the PC would simply transmit packets as soon as they are available to transmit. The packets would be held in a buffer until the acknowledgment is received, after which they would be flushed. If no acknowledgement is received within a fixed time delay, the unacknowledged packets would be retransmitted. The overall delay in this process is not critical, thus the PC is allowed many milliseconds in which to process the acknowledgments (a not unreasonable amount of time for modern microcomputers). Thus, depending upon the access schemes utilized, much of the terminal control could possibly be done in the PC, thus reducing the cost of the terminal.

SECTION 4
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SECTION 5
SATELLITE DESIGN

In this section, we will examine a number of potential satellite configurations for this 30/20 GHz FSS. These will include those architectures studied for possible implementation on the Advanced Communications Technology Satellite (ACTS) as well as other variations which are attractive for this program. Block diagrams of several of these architectures will be presented. We will also address several of the major components which will drive the satellite design.

5.1 MULTIPLE BEAM SATELLITE ARCHITECTURES

The use of multiple beams provides many performance gains as noted in Section 3.6. These included improved bandwidth efficiency through frequency reuse, more gain on the uplink, less noise insertion on the downlink, and either lower downlink burst rates (TDMA systems) or less TWTA backoff (FDMA systems). The penalty one pays for the use of multiple beams is the increased complexity in the transponder to perform routing between beams and in the antenna design to form the multiple beams. In this subsection we will present three satellite architectures which can provide the beam-to-beam routing.

5.1.1 Satellite-Switched TDMA

Satellite-Switched TDMA (SS-TDMA) is an architecture which has received much attention in recent years for applications at K-band. The Japanese have been using this technique on their CS-1 and CS-2 satellites to provide trunk routing between several beams covering the islands making up that country. It has also been selected as the architecture for ACTS.

Basically, SS-TDMA uses a baseband processor to demodulate the various uplink TDMA signals and route the traffic to the appropriate downlink beam based upon the slots used. A simple example of the TDMA routing is shown in Figure 5-1. In it, the processor takes the first slot from uplink 1 and route it to downlink 4. The second slot from uplink 1 is sent to downlink 3, and so forth. Some slots may not be full due to uneven distribution of traffic between beams. The processor may be reconfigured to route the traffic in any manner desired to best serve the actual traffic generated.

SS-TDMA has several advantages. First, it is the only processing satellite architecture to have already been tested and placed in use. Second, it requires less satellite weight and power than other processing approaches since all signals are wideband TDMA. Few multiplexers, filters, and demodulators are required and the satellite HPAs can operate at saturation. Third, since no channelization is required for TDMA signals, the terminals do not require synthesizers and can be preset to one carrier frequency.

This architecture does have one major disadvatage for this application. High burst rates are required on the uplinks which pushes up the cost of the terminals. Rates of several Mb/s would be required to provide sufficient capacity. These terminals would then be roughly equivalent to the Micro-1 terminals being designed for ACTS. The current estimated cost of

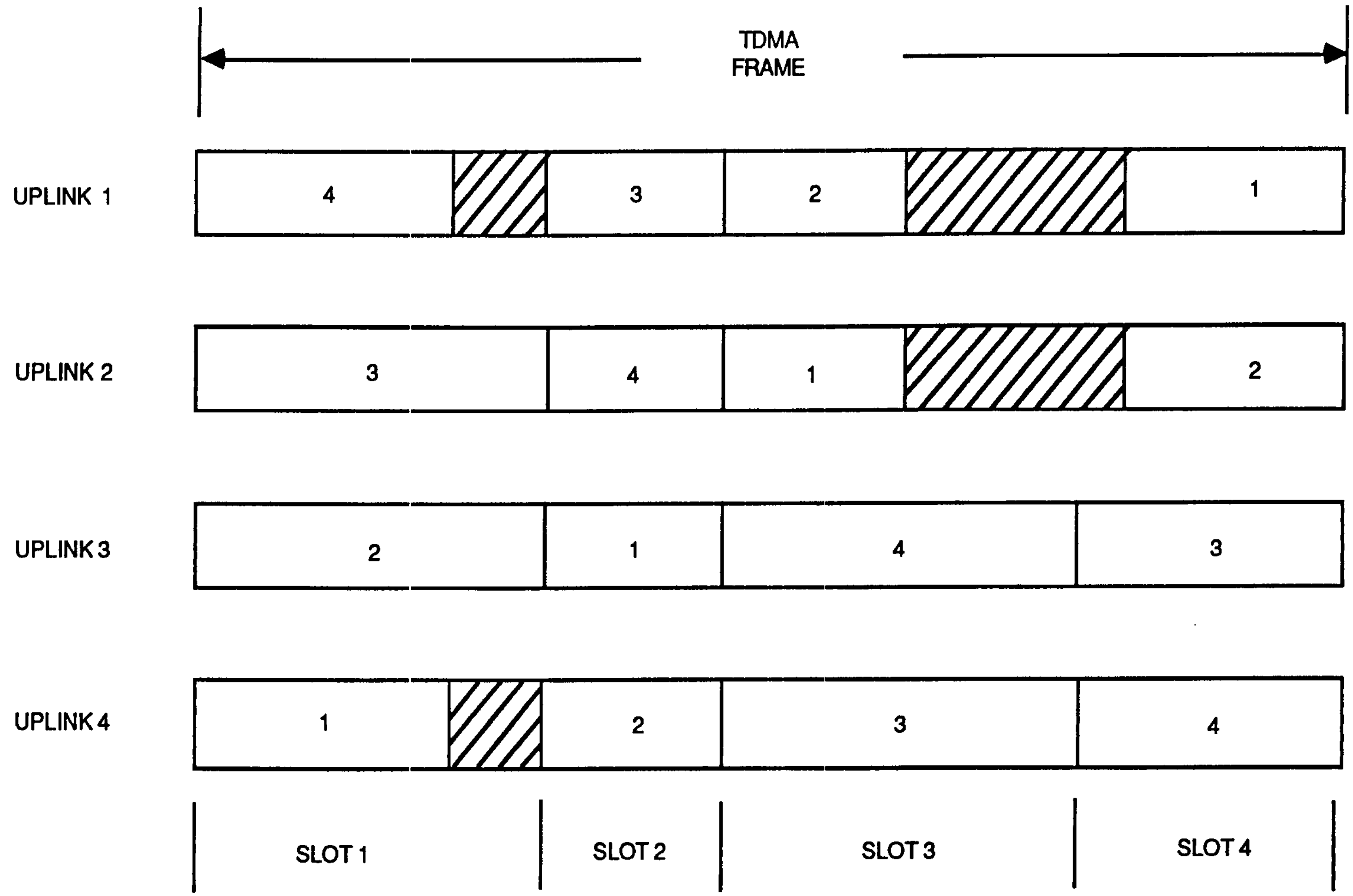

Figure 5-1 Example SS-TDMA Frame Structure

these terminals is between \$50K and \$100K. Obviously, this eliminates SS-TDMA from serious consideration for the consumer market.

5.1.2 Frequency-Routed TDMA

Another satellite architecture which uses baseband processing is frequency-routed TDMA (FR-TDMA). Figure 5-2 illustrates the concept for a 32-beam system. In each uplink beam, one carrier is used for each destination beam, resulting in 32 carriers per beam. The satellite gathers the 32 x 32 uplink carriers, demodulates each, and then multiplexes the traffic destined for each downlink. This data traffic is then remodulated on one or two downlink carriers per beam at an appropriately higher TDMA burst rate. This provides the best of both FDMA and TDMA in that the terminals' uplink burst rates are minimized (like FDMA) but the transponder may operate at saturation (as in TDMA).

Two carriers may be amplified by the same transponder TWTA without introducing any intermodulation products within the transponder bandwidth. This reduces by one-half the required receive burst rate of the terminals but introduces the need for two receivers or some algorithm which tells a terminal when to listen to each carrier.

Figure 5-3 shows a block diagram of this FR-TDMA architecture. Only the traffic destined for one carrier of downlink beam 1 is shown. For the 32 beam system, 64 processors are required each containing 16 demodulators, multiplexers, and pairs of shift registers. These registers provide the buffering which allows the rate-change operation on the data; one is being written at the uplink burst rate while the other is being read from by the output multiplexer. This figure illustrates the major disadvantage to FR-TDMA -- satellite complexity. The number of components increases almost as the square of the number of beams (M). Table 5-1 lists the various components and their respective weight and power requirements. Not including the TWTAs which will be examined in Section 6, this processing satellite transponder would weigh 1300 lbs and consume 1600W of DC power. The data is several years old [MITRE,1982] and therefore may be somewhat outdated. However, it does represent a decent approximation of the satellite complexity.

5.1.3 Satellite-Routed FDMA

A baseband processor is not required to perform routing between beams. This can also be done through the use of IF filtering and multiplexing. Satellite-Routed FDMA (SR-FDMA) is such an approach for an all FDMA system. Figure 5-4 presents a block diagram of this architecture. In this particular example, the traffic is grouped into six regions (R = 6) to simplify the design. Each beam from a given region uses separate frequencies so that they may be combined and placed in one input MUX per region (MUX1 - MUX6). All the traffic to the same destination (region) is then grouped together and downconverted to an IF. Another set of multiplexers (MUX7, MUX8, etc.) divides this regional traffic by channel which are then grouped by downlink beam. A set of mixers is necessary to adjust the various frequencies so that they are contiguous. The resulting band, amplified and transmitted on downlink beam 1, contains 6 groups of FDMA channels containing the traffic of the 6 regions destined for beam 1 of region 1.

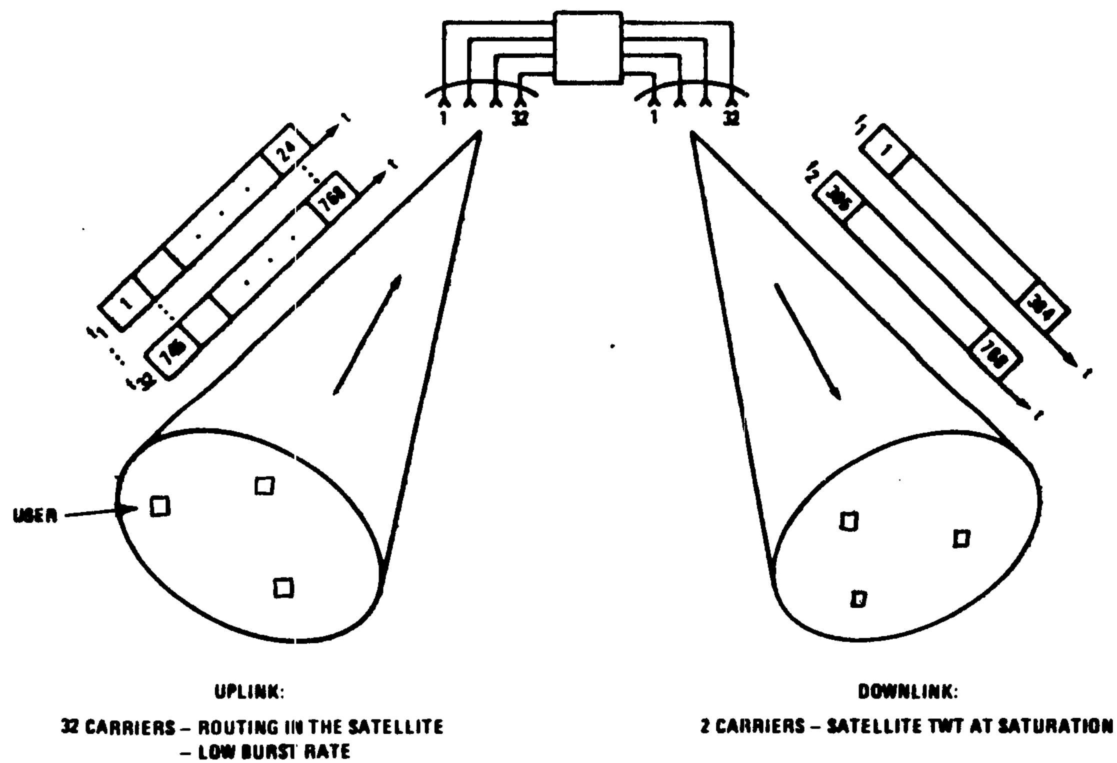

Figure 5-2 Time and Frequency Assignments in an FR-TDMA System

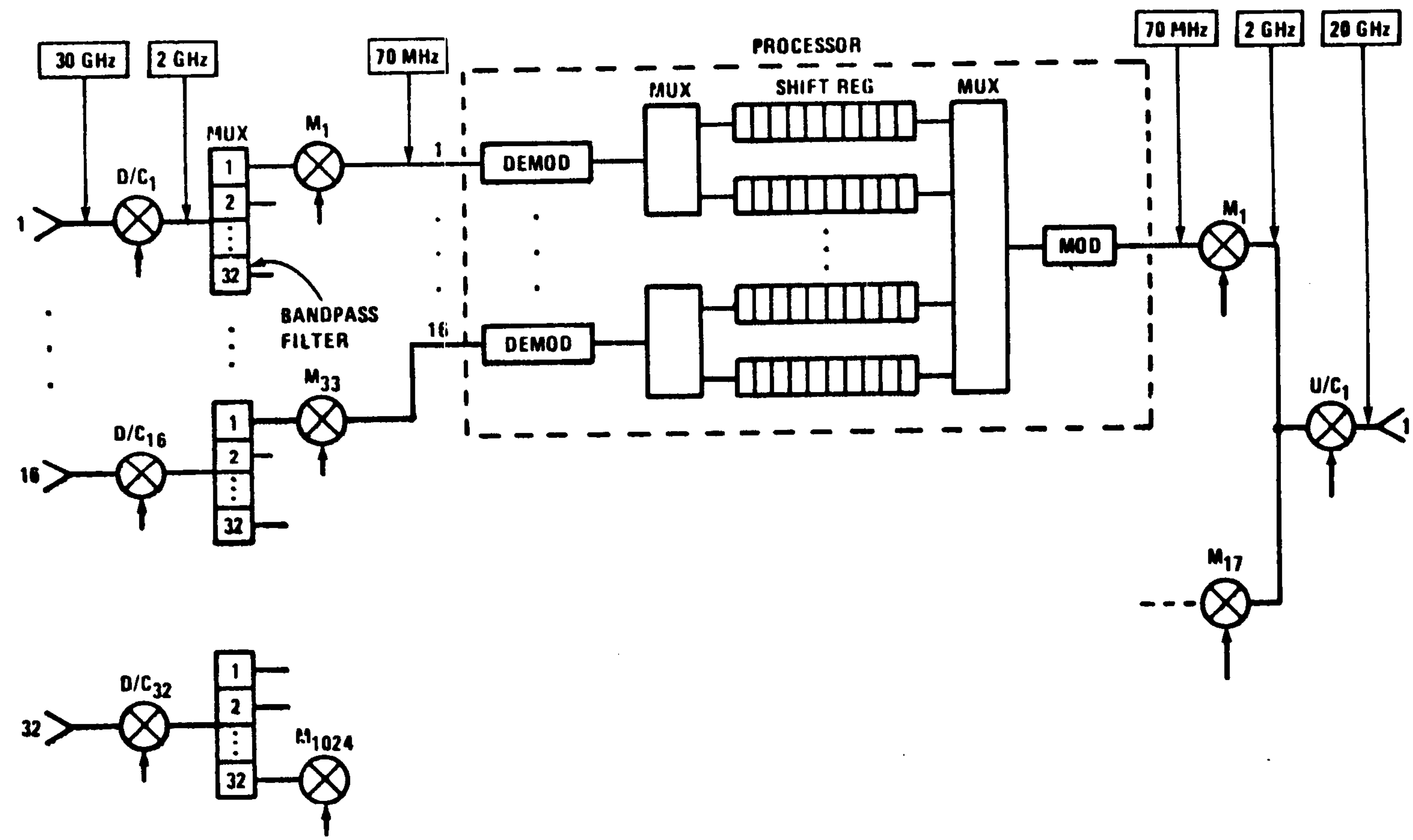

Figure 5-3 Transponder Block Diagram for FR-TDMA Satellite.

Table 5-1
FR-TDMA Transponder Weight and Power Budget

			No. Units	Unit Wt (oz)	Unit Pwr (W)	Weight (oz)	Power (W)
LNA	30 GHz, 20 dB	M	32	8	1.5	256	48
FILT	30 GHz	M	32	6	-	192	-
D/C_1	30/2 GHz	M	32	16	-	512	-
AMPL	2 GHz, 20 dB	2M	2x32	6	1.5	384	96
MUX	2 GHz	M	32	20	-	640	-
D/C_2	2/0.07 GHz	M^2	1024	2	-	2,048	-
FILT	70 MHz	M^2	1024	2	-	2,048	-
AMPL	70 MHz, 40 dB	M^2	1024	2	-	2,048	-
PROC		2M	64	42	12	2,688	768
DEMODS		M^2	1024	6	0.5	6,144	512
MODS		2M	64	32	2	2,048	128
U/C_1	0.07/1.5 GHz	2M	64	2	-	128	-
MUX	1.5 GHz	M	32	20	-	640	-
AMPL	1.5 GHz, 12 dB	M	32	6	1	192	32
U/C_2	1.5/20 GHz	M	32	16	-	512	-
FILT	20 GHz	M	32	6	-	192	-
AMPL	20 GHz, 12 dB	M	32	8	1.2	256	38
TWTA	20 GHz	M	32				
TOTALS						20,928	1,622

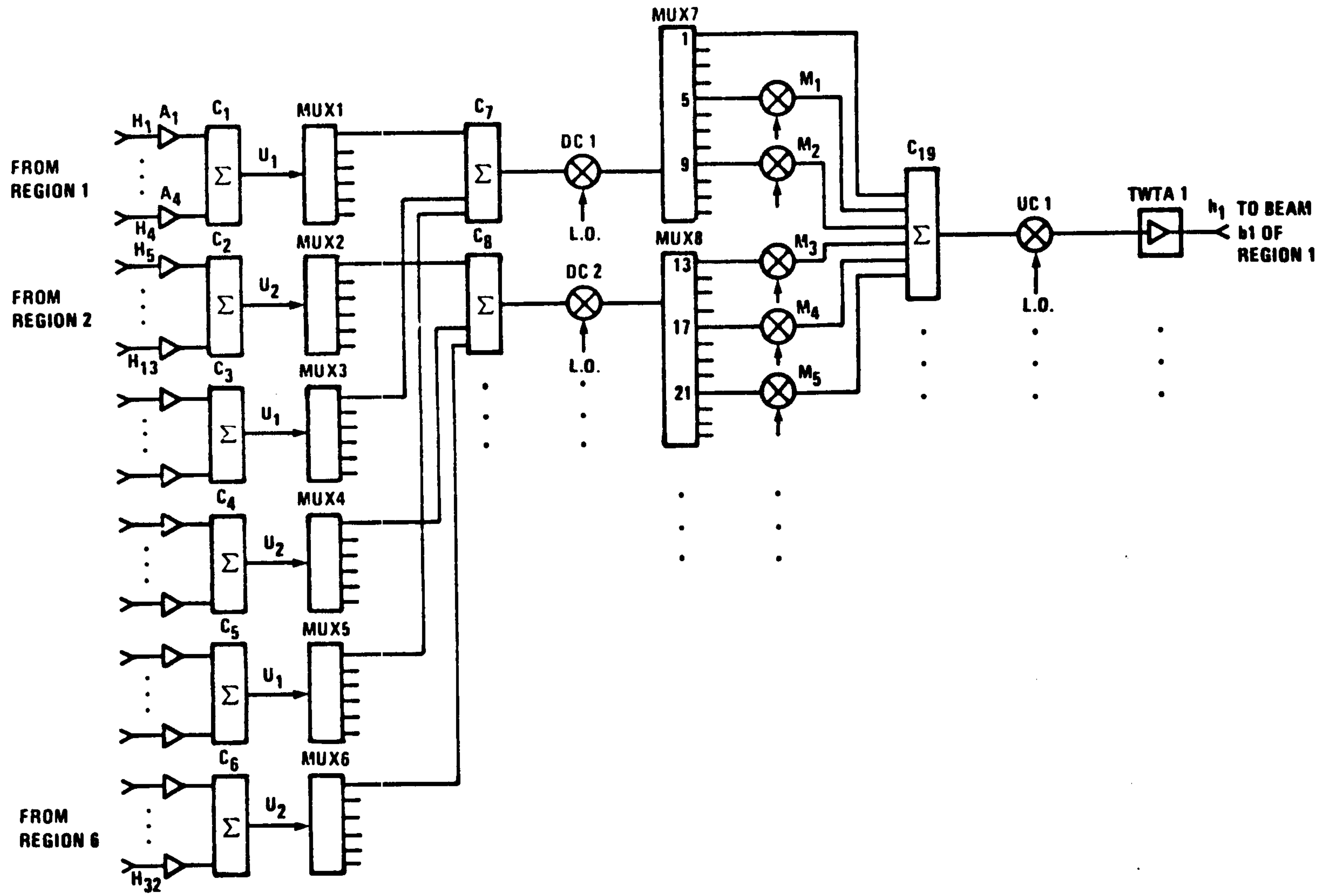

Figure 5-4 A Simplified Block Diagram of an FDMA Satellite Transponder for a Six-Region Network.

The main drawback of this all-FDMA approach is the power efficiency of the TWTAs. For a single TWTA to be used to amplify many carriers, the output power must be backed off several dB so that it operates in the linear region of its power curve. This backoff requirement is typically between 3 and 5 dB. This approach also has some of the same complexity problems as FR-TDMA. However, through the use of the regional concept, the order of the component count can be kept to $M \cdot R$ instead of M^2. A list of the components for the SR-FDMA transponder along with their power and weight requirements is given in Table 5-2. The numbers here are much less than that of a processing satellite with a total weight (excluding TWTAs) of 224 lbs and a 384 W power consumption. It should be noted that the numbers tabulated for both this architecture and FR-TDMA assume 32 beams; fewer beams would produce less difference in the power and weight requirements between the two approaches.

5.2 FDMA/TDM USING CAPTURE ALOHA

In any processing satellite with RA uplinks, a technique known as Capture ALOHA can be used to improve the efficiency of the downlinks. This section describes this technique and demonstrates its performance advantages.

5.2.1 System Concept

n = number of uplink frequency channels per uplink beam ($n > 1$)

K = number of uplink packet slots per satellite frame ($K >> 1$)

Each user employs Pure ALOHA random access transmitting in any one of these nK frame slots within an uplink beam. The user does not need to maintain any absolute timing reference to determine the beginning of a slot or a frame. The satellite demodulates these uplink packets asynchronously during each frame and stores successfully demodulated packets for subsequent transmission in the appropriate downlink beam in a TDM format.

With Modified Pure ALOHA (MPA), each user can assist in creating a stable access scheme (Pure ALOHA is inherently unstable) by doubling K with each unsuccessful transmission and halving K (but to no less than the original K value) with each successful transmission. This is transparent to the operations performed at the satellite, i.e., the satellite utilizes a K-packet frame only in the read/write buffer case (see Subsection 5.2.2.1).

S = throughput, the expected number of successful packets per downlink packet slot ($0 < S < 1$)

R_d = downlink data rate (b/s)

P_d = downlink transmitted power (W)

α = efficiency with which bus power is converted to P_d ($0 < \alpha < 1$)

P_o = other on-board processing power (e.g., demod, remod, switching, L.O.'s, etc.) (W)

Table 5-2

SR-FDMA Transponder Weight and Power Budget

		No. Units	Unit Wt (oz)	Unit Pwr (W)	Weight (oz)	Power (W)
LNA	M	32	8	1.5	256	48
FILT	M	32	6	-	192	
COMBINERS	R*	6	10		60	
MUX	R	6	20	-	120	
COMBINERS	2R	12	10		120	
D/C	2R	12	2		24	
BPF	MR	192	2		384	
AMP	MR	192	6	1.5	1152	288
MIXER	(M-1)R	186	2		372	
COMBINERS	M	32	10		320	
AMP	M	32	2	1.5	64	48
U/C	M	32	16		512	
TWTA	M	32				
TOTALS					3,576	384

*R is number of regions

The satellite power allocated to the on-board communications subsystem is

$$P = P_o + P_d/\alpha \quad (W) \tag{5.1}$$

The downlink power figure-of-merit, μ, is defined as the useful downlink data rate, SR_d, per unit of satellite power allocated to the communications subsystem

$$\mu = \frac{SR_d}{P} = \frac{R_d S}{P_o + P_d/\alpha} = \frac{\alpha(R_d/P_d)S}{1 + \alpha P_o/P_d} \quad (b/s/W) \tag{5.2}$$

The ratio P_d/R_d is held constant for equivalent downlink communications performance. The condition for the downlink figure-of-merit to increase nearly linearly with throughput is

$$\alpha P_o/P_d \ll 1 \quad .$$

If this condition is satisfied, e.g., if $\alpha \lesssim 0.3$, and if $P_o/P_d \lesssim 0.5$, then it may make good sense to increase S. As will be seen this can be accomplished by increasing n (consuming uplink bandwidth and increasing P_o) and adding on-board storage (again, increasing P_o).

We note that this discussion derives from a single uplink beam and single downlink beam case, where the baseline comparison on satellite power efficiency is with a non-processing transponder satellite. In comparison to a processing FDMA/TDM satellite which does not use Capture ALOHA, the figure-of-merit would show more of an improvement since P_o would increase relatively little from a non-zero value.

A bandwidth efficiency figure-of-merit, ε, is also defined as follows. Given a burst rate B in symbols per second (sym/s), we define the ideal bandwidth as B (Hz). This corresponds to the single-sided, first-null bandwidth for a rectangular pulse of duration 1/B (s). The bandwidth figure-of-merit is taken as the fraction of ideal downlink bandwidth actually utilized on the average, SB_d, normalized by the total bandwidth employed on the uplink and downlink, $W_u + W_d$, where

W_u = uplink bandwidth (Hz)

W_d = downlink bandwidth (Hz),

i.e.,

$$\varepsilon = \frac{SB_d}{W_u + W_d} \quad (0 < \varepsilon < 1/2) \ . \tag{5.3}$$

Note that ideally $W_u = W_d = B_d$ and $S = 1$ for this satellite system which implies $\varepsilon_{ideal} = 1/2$; ε_{ideal} would be unity for a terrestrial system employing a single ideal bandwidth allocation of $B = B_d$. Thus, there is a factor of two penalty inherent in ε to account for the usual double frequency band allocation in satellite communication.

B_u = uplink burst rate (sym/s or Hz)

βB_u = uplink frequency channel spacing (Hz) $(0 < \beta)(\beta = 1$ for $n = 1$; as seen in Subsection 3.5.1.1, β can be less than unity for $n > 1$).

For Pure or Slotted ALOHA with $n > 1$ channels, the figure-of-merit ε is simply

$$\varepsilon = \frac{S}{2\beta} \, . \tag{5.4}$$

For $n > 1$ uplinks and one downlink in this Capture ALOHA FDMA/TDM scheme, ideally $W_d = B_d$ and $W_u = n\beta B_u$, so ideally

$$\varepsilon = \frac{SB_d}{n\beta B_u + B_d} = \frac{S}{n\beta(B_u/B_d) + 1} = \frac{S}{n\beta + 1} \quad (n > 1) \tag{5.5}$$

for the normal Capture ALOHA design constraint $B_d = B_u$. We note that ε eventually decreases with increasing n when S increases slower than linearly with n. This starts to occur as S approaches unity. Therefore, there is an optimal bandwidth efficiency point for Capture ALOHA beyond which the added uplink bandwidth is counterproductive. However, even if this scheme sacrifices bandwidth efficiency for power efficiency, at 30/20 GHz and above, this strategy may be satisfactory, since ample bandwidth may be available.

A comparison of Capture ALOHA and Pure ALOHA will be made by taking the ratio of the two figures-of-merit for bandwidth efficiency at the same value of packet delay:

$$\frac{\varepsilon(\text{Capture ALOHA})}{\varepsilon(\text{Pure ALOHA})} = \frac{2\beta}{n\beta + 1} \cdot \frac{S(\text{Capture ALOHA})}{S(\text{Pure ALOHA})} \Bigg|_{\text{same D values}} \quad (n > 1) \tag{5.6}$$

5.2.2 Pure ALOHA Performance

[DeRosa, et al., 1979] computed the throughput and delay performance of the Capture ALOHA concept using Slotted ALOHA which requires user terminals to know absolute slot timing within a certain accuracy. We have followed these procedures for the case of Pure ALOHA which eliminated absolute timing requirements at the terminals. This is done by simply replacing G by 2G whenever G appears in the exponent of an expression in DeRosa's work.

It is noted that the delay formulas utilize the original, nominal value of K and do not reflect the delay experienced by using an MPA algorithm at a terminal.

5.2.2.1 Read/Write Buffer Case

Successfully demodulated packets are accumulated in a write buffer during a satellite frame while packets accumulated during the preceding frame are transmitted on the TDM downlinks as they are read from another buffer. The roles of these two buffers are interchanged at the end of each frame.

$p_s = \frac{G}{n} e^{-\frac{2G}{n}}$ is the probability of exactly one uplink success ($0 < p < 1/2e$)

$p_j^f = \binom{nK}{j} p_s^{\,j} (1-p_s)^{nK-j}$ ($0 < p_j^f < 1$)

is the probability of j successful packets per frame assuming independent trails.

The throughput is given by

$$S = 1 - \sum_{j=0}^{K} \left(1 - \frac{j}{K}\right) p_j^f \,.$$

R = nominal roundtrip delay between earth and satellite (measured in packet lengths)

G = total (new and retransmitted) packets per packet slot ($0 < G < \infty$)

q = S/G is the probability of successful end-to-end packet transmission ($0 < q < 1$).

The average end-to-end delay between terminals is

$$D = R + 1 + K + \left(R + 1 + 2K + \frac{K-1}{2}\right)\frac{1-q}{q} \qquad (5.7)$$

(measured in packet lengths)

5.2.2.2 FIFO Buffer Case

L = FIFO buffer length (in packets)

π = $[\pi_0, \pi_1, \ldots, \pi_L]$ steady state vector such that

π = $\pi \underline{M}$

where $\underline{M}$ is a transition matrix, defined below, and

π_i = probability of i packets in satellite queue in steady state ($0 < i < L$)

with the constraint

$$\sum_{i=0}^{L} \pi_i = 1$$

The transition matrix $\underline{M}$ is given by:

$\underline{M}$ = $[m_{ij}]$ is the queue occupancy transition matrix, i.e., m_{ij} is the probability of going from state i to state j.

$$m_{ij} = \begin{cases} 0, & j < i - 1 \\ 0, & j > n + i - 1 \\ p_0 + p_1, & j = i = 0 \\ \sum_{k=L-i+1}^{n} p_k, & j = L,\ i > L - n + 1 \\ p_{j-i+1}, & \text{otherwise} \end{cases}$$

and this time

$$p_j = \binom{n}{j} p_s^j (1 - p_s)^{n-j} \quad (0 < p_j < 1)$$

is the probability of j successful packet arrivals per packet slot.

Now the throughput and delay formulas are

$$S = 1 - \pi_0 p_0$$

and

$$D = R + 1 + \sum_{i=0}^{L} i\pi_i + \left(R + 1 + L + \frac{K-1}{2}\right)\frac{1-q}{q} \tag{5.8}$$

DeRosa calculated the performance of capture ALOHA with Slotted ALOHA uplinks. The throughput performance with a FIFO buffer is given in Figure 5-5. Figure 5-5a shows the performance with a zero queue length for various numbers of uplinks. The n = 1 curve is the standard S versus G curve for Slotted ALOHA, which peaks at 1/e throughput. When even a small buffer is added (Figure 5-5b), significant throughput improvements can occur. For an

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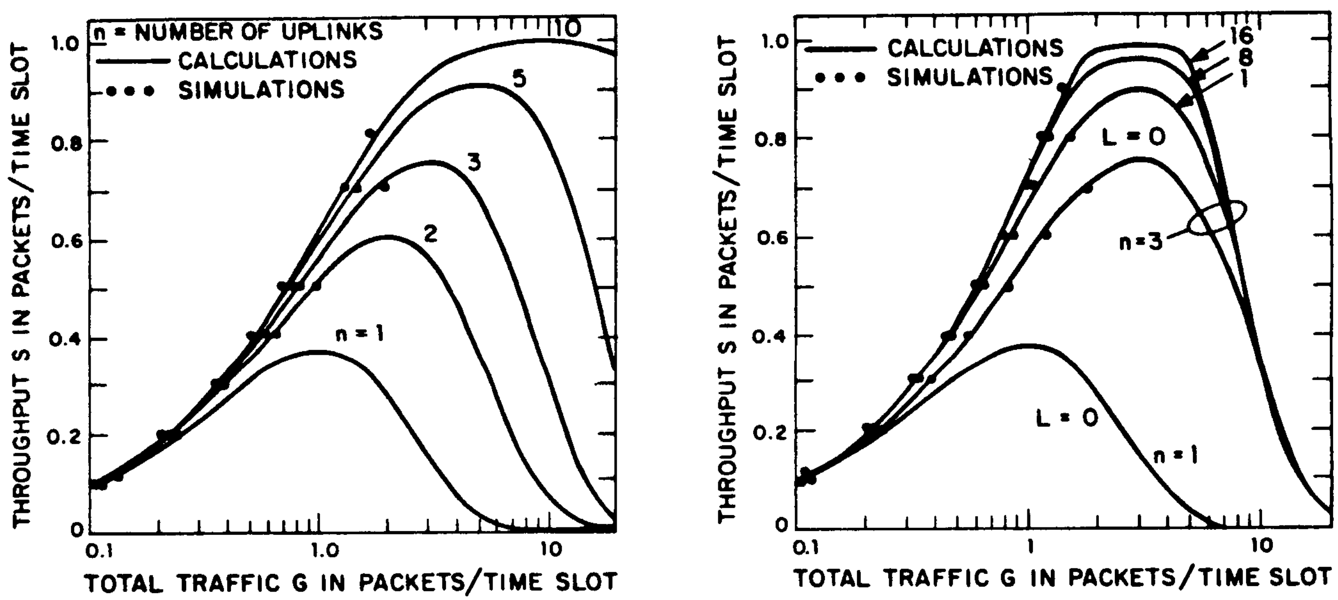


a) Throughput for Slotted ALOHA with Blocked Packets Cleared (queue length L = 0).

b) Throughput for Slotted ALOHA with FIFO Buffer to Length L Packets.

Figure 5-5 Throughput Performance of Capture ALOHA with FIFO.

eight packet buffer and three uplinks, near-unity downlink throughput can be achieved. Note also that the peak broadens as the buffer length increases, indicating an increase in stability.

For Pure ALOHA, the resulting curves are similar for twice the number of uplinks. For example, n = 2 performance is identical to n = 1 with Slotted ALOHA. Also, n can increase to 6 before the downlink saturates.

Figure 5-6 plots the delay performance of Capture ALOHA. Without buffering, an increase in throughput (via a larger n) also incurs an increase in delay. With buffering, however, the delay can decrease as throughput increases. However, increasing L too much causes the delay to increase for little gain in throughput. L should therefore be kept relatively small.

5.2.3 Capture ALOHA Performance Comparison

We can now compare the bandwidth efficiency of Capture ALOHA to that of Slotted ALOHA. By using Equation (5.6) with $\beta = 1.9$ (for MSK; see Subsection 3.5.1) and by keeping the average packet delay equal for both systems, the bandwidth effciencies can be compared. For Slotted ALOHA with a throughput of 0.25, the resulting delay from Figure 5-6a is approximately 22 packets (time slots). At the same delay for Capture ALOHA using three channels (n = 3) and an eight packet FIFO buffer (L = 8) the throughput is 0.62. Equation (5.6) yields the ratio

$$\frac{\varepsilon(\text{Capture ALOHA})}{\varepsilon(\text{Slotted ALOHA})} = \frac{2 \cdot 1.9}{3 \cdot 1.9 + 1} \cdot \frac{0.62}{0.25} = 1.41 \ .$$

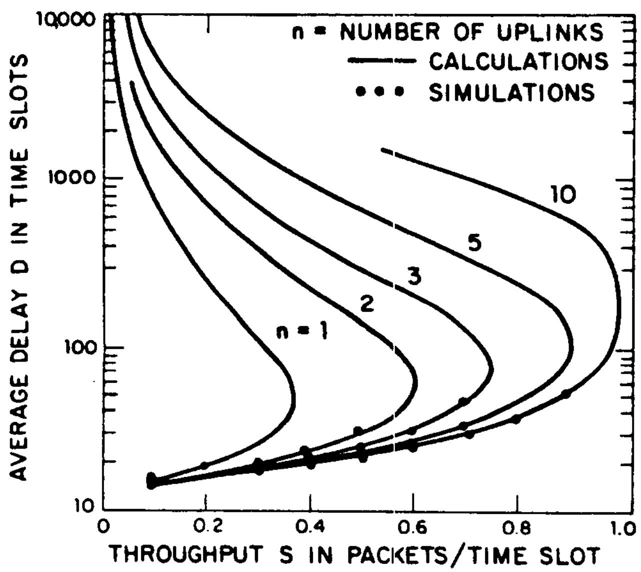
If we assume that Pure ALOHA has half the throughput for the same delay, then by using n = 6 and S(Pure ALOHA) = 0.125, Equation (5.6) results in

$$\frac{\varepsilon(\text{Capture ALOHA})}{\varepsilon(\text{Pure ALOHA})} = \frac{2 \cdot 1.9}{6 \cdot 1.9 + 1} \cdot \frac{0.62}{0.125} = 1.52 \ .$$

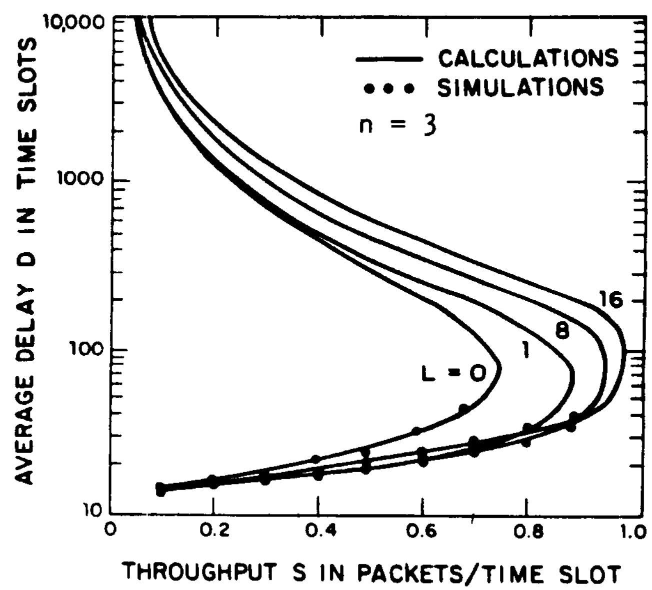
Therefore, we can conclude that for these typical delays, Capture ALOHA can improve throughput by forty to fifty percent. Even more improvement is possible by increasing n until the throughput of Capture ALOHA nears unity.

5.3 FSS CONSIDERATIONS

The architectures presented thus far have presumed that all terminals were alike or that a connection was desirable between any pair of end users. These assumptions do not hold up for the FSS applications. As shown in Section 2, must of the promising applications were user/supplier type connections where consumers would communicate with central facilities such as banks or retail centers. Applications which require connections between end users, such as rural telephone, were determined not to be as promising. Even electronic mail does not require connectivity between the end users since a double-hop through a central facility could link these users with a small delay. Zap-Mail by Federal Express was such a scheme. It is evident that the type of networks required are hub-spoke type networks.



a) Delay for Slotted ALOHA with Blocked Packets Cleared (queue length L = 0).



b) Delay for Slotted ALOHA with FIFO Buffer to Length L Packets.

Figure 5-6 Delay Performance of Capture ALOHA with FIFO.

Hub-spoke architectures usually have very different requirements for the traffic flowing in or out of the central hub. This implies that the user and supplier terminals may be quite different. The user terminals, as we have shown, must be relatively inexpensive and will have a low duty factor. Because of this low duty factor, the traffic originating from these user terminals must somehow be coordinated to permit the sharing of the common links to the hub. ALOHA schemes or SSMA were determined to be the best alternatives for these links, which we will refer to as backhaul traffic. The central hubs, on the other hand, do not have to be inexpensive, and typically will not be since many connections must be handled simultaneously. These supplier terminals can therefore have larger antennas providing more gain and requiring less downlink satellite EIRP. Because of this, multiple spot beams are not as important for the suppliers. One CONUS beam may be sufficient to service the many suppliers. Each supplier could be assigned a group of frequencies or a collection of time slots. The hubs would be fairly high duty factor users and could make efficient use of fixed frequency or time slot assignments. We will call this traffic originating from the central hub the forward links.

The optimal design for the FSS satellite would be one that made best use of the different requirement of the two terminal types. It would provide spot beams for the user terminals and perhaps one beam for the suppliers. This would greatly simplify the transponder architecture since routing between beams would not be necessary. Basically the transponder would consist of two halves: one which funnels the backhaul traffic into the one supplier beam, and a second which separates the forward link traffic by destination spot beam.

It was determined in Section 3 that the optimal access for the end users was either Pure ALOHA or SSMA. It was also determined that some combination of FDM and TDM would minimize the terminal complexity and cost. Therefore the backhaul links should be channelized. The number of channels per beam is no longer dependent on the number of beams (as in FR-TDMA or SR-FDMA) but can be optimized to the particular requirements. In this case there should be as many channels as needed to support the given traffic with the amount of traffic per channel determined by the method of access. For Pure ALOHA, we have assumed a 200 kb/s burst rate so this would be the size of one channel. For SSMA, we showed that a spreading factor of roughly 100 times the number of simultaneous users is required to limit the degradation factor due to self-interference to a few dB. At a 9600 b/s data rate, the chip rate should be roughly 1 Mc/s per simultaneous user.

A system servicing 1M users with 32 beams would have 31250 users per beam. If the average user transmitted one hundred, 600 b messages per day, then his throughput would be 60 kb daily. Using Pure ALOHA with S = 0.125, the expected number of attempts to send one message is G/S = 1.43. The average user would then generate 60 kb x 1.43 = 85.8 kb a day. The amount of interactive data traffic per beam would then be 31250 x 85.8 kb = 2681 Mb daily. In the Public Switch Telephone Network (PSTN), the four busiest hours (10 am to 2 pm) each carry approximately 10 percent of the total daily traffic [SIGNATRON, 1985]. If we make the same assumption here, then during the peak traffic hours, an average user will send 10 messages per hour and the peak volume per beam will be 31250 x 10 x 600 b x 1.43 /3600s = 74.5 kb/s. Each 200 kb/s Pure ALOHA channel should be able to provide 25 kb/s throughput. A few such channels should therefore be sufficient to provide the necessary service to all the users of one beam even during peak traffic hours. The actual number of channels per beam could be variable, based on the expected traffic volume from each area. Thus the scanning beams of Subsection 3.4.3 for low density areas would not be needed.

For an SSMA system, no collisions would occur so the peak volume would be 31250 x 10 x 600 b / 3600s = 52 kb/s. This is equivalent to almost 5.5 simultaneous users (at 9600 b/s) per beam and would necessitate a chip rate of 5.5 times 1 Mc/s or 5.5 Mc/s. Thus for SSMA, one channel per beam would be sufficient for the assumed traffic load.

On the forward links, any combination of FDM and TDM access schemes can be feasibly implemented in a supplier terminal. If a straight TDMA approach is taken, then a processing satellite would be required to perform rate changing and distribute the slots to the appropriate downlink beam. A much simpler approach would provide one or two separate uplink channels for each downlink beam so that no processing would be needed on the transponder. Since the suppliers would only respond to user transmissions, having two carriers per beam would not present a problem for the user terminals; they would know on which channel to listen.

Within each TDM carrier, time slots would be allocated to each supplier according to their traffic needs. This FDM/TDMA architecture for the forward links would be quite bandwidth efficient per channel since the duty factor of the suppliers should be reasonably high. With only one CONUS beam for the suppliers, no frequency reuse would be possible so that more overall bandwidth may be required for the forward links than on the backhaul (assuming equal throughput). The overall bandwidth efficiency is given by

$$E = F \cdot S/\beta \text{ (b/s/Hz)} \tag{5.9}$$

where

- F is the frequency reuse factor
- β is the channel spacing parameter, and
- S is the channel throughput.

For the backhaul links, F is assumed to 8 (32 beams ÷ 4 colors), β is 1.9 for MSK, and S = 0.125 for Pure ALOHA. The backhaul efficiency, E_B, is then 0.53 b/s/Hz. The forward link would require 100 percent channel throughput to achieve the same bandwidth efficiency.

Figure 5-7 illustrates the frequency plan of this FDMA/TDMA architecture. The satellite performs frequency translation of the bands in order to transition from multiple beams to a single beam and vice-versa. The number of bands required for the user terminals is just the number of distinct frequency patterns or colors N. The CONUS beam requires M bands corresponding

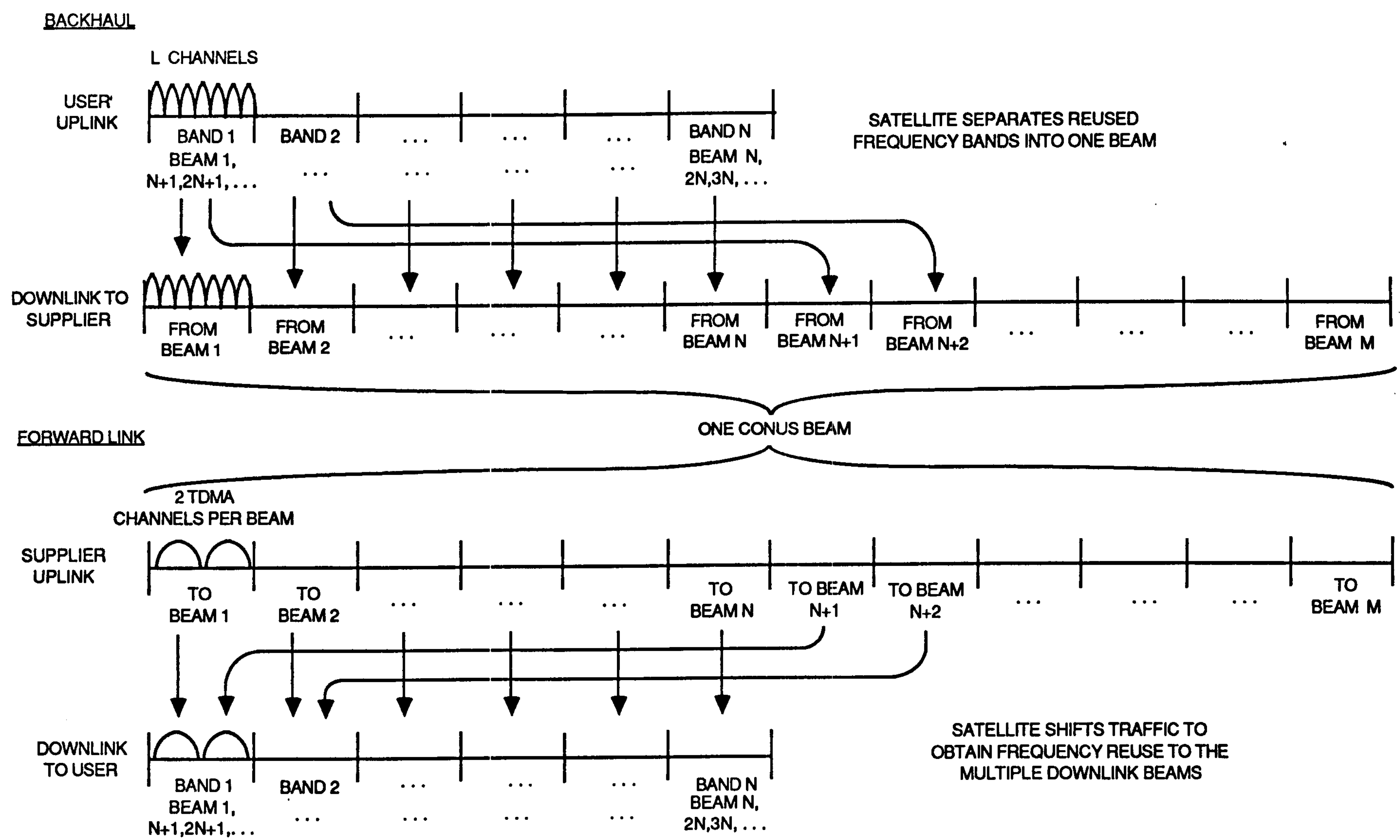


Figure 5-7 FDMA/TDMA Frequency Plan

to the M user spot beams. The L channels per band would depend on the volume of traffic and the method of access as described previously.

Figures 5-8 and 5-9 are block diagrams of the transponder for the backhaul and forward links respectively. It is a simple architecture in comparison to either FR-TDMA or SR-FDMA. Table 5-3 lists the major components and estimates the transponder weight and power (minus the TWTA requirements). The totals are nearly half that of even SR-FDMA since the order of the components is approximately M (as opposed to M • R for SR-FDMA and M^2 for FR-TDMA). Only one TWTA is shown for the backhaul links but most likely several will be required to provide the required power over the bandwidth of interest.

Other variations of this basic architecture are possible. Instead of TDMA carriers for the forward links, FDMA channels could also be used. This would reduce the receive burst rate required for the user terminals at the expense of less efficient use of transponder power because of the intermodulation problem. No significant change to the transponder design would result.

Another option is to dedicate a separate satellite HPA to each FDMA channel in the forward link. This would allow all amplifiers to be run at saturation without causing intermodulation products. Because only a small amount of power would be required for each, solid state amplifiers could be used. The number of HPAs and filters would increase from M + 1 to L • M where L is the number of FDMA channels per beam. As long as L remained fairly small, this could be an advisable tradeoff. Further examination of this topic will be presented in later sections.

5.4 SPACEBORNE POWER AMPLIFIERS

Through the use of multiple spot beams, the EIRP requirement of the satellite is not totally borne by the power amplifiers (PA). This is not to say that high power amplifiers are not needed for this Ka-band FSS transponder. The very fact that such high frequencies are being considered for the system results in difficulties. As one moves up in frequency, the ability to produce RF power becomes more difficult. At 20 GHz, much research still remains to be done before truly high power outputs are possible. This subsection summarizes the current and projected state-of-the-art in satellite PAs. Much of the data reported herein was collected by the US Air Force Space Division in 1985 [Space Division, 1985] so it is fairly recent information.

5.4.1 Traveling Wave Tube Amplifiers

For applications requiring the highest power levels, traveling wave tube amplifiers (TWTAs) are most viable. There are currently two types of TWTAs, coupled-cavity and helix tubes. The helix tubes are quite popular in that they can produce high power over a wide bandwidth. They do have temperature limitations, however, which must be overcome in order to increase their power levels.

Coupled-cavity tubes can produce higher power with low distortion and high efficiency over slightly lower bandwidths. However, they do require more complex power supplies, higher beam voltage, and currently cost considerably more than the helix tubes. In 1982, the cost per cavity was $100 [MITRE,

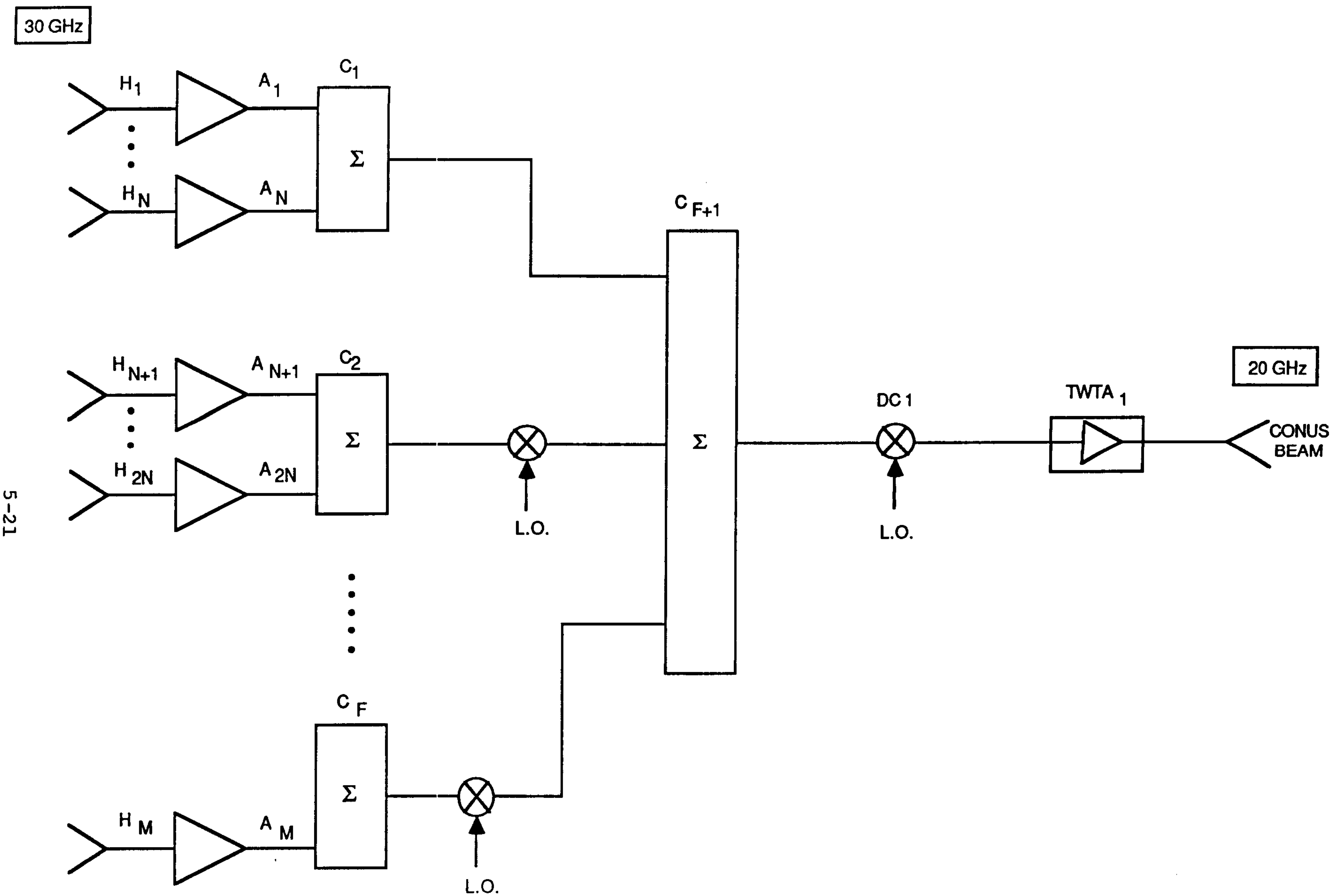


Figure 5-8 Block Diagram of FDMA/TDMA Transponder - Backhaul Link

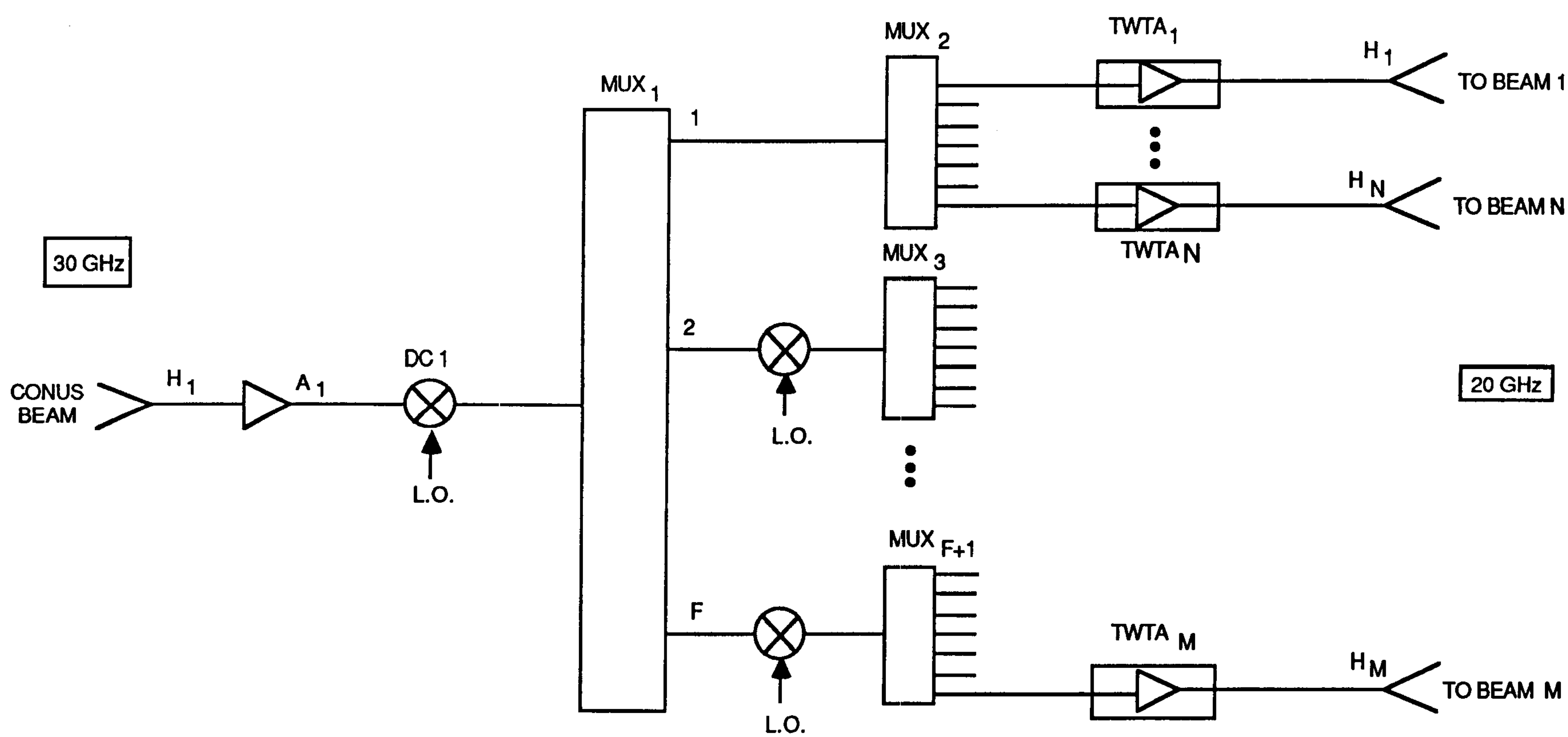


Figure 5-9 Block Diagram of FDMA/TDMA Transponder - Forward Link

Table 5-3

FDMA/TDMA Transponder Weight and Power Budget

		No. Units	Unit Wt (oz)	Unit Pwr (W)	Weight (oz)	Power (W)
LNA	M+1	33	8	1.5	264	50
FILTER	M+1	33	6	-	198	
COMBINER	F+1	9	10	-	90	
MULTIPLIER	2(F-1)	14	32	2.0	448	28
FILTER	2F	16	6	-	96	
MUX	F+1	9	20	-	180	
D/C	2	2	16	-	32	
FILTER	1+M	33	6	-	198	
AMP	1+M	33	2	1.5	66	50
TWTA	1+M	33				
TOTALS					1,572	128

1982]. There are about 150 cavities in a coupled-cavity TWT assembly so the cost at that time just for materials was $15K. Significant cost reductions are anticipated in the coming years.

The current availability of 20 GHz TWTAs is exemplified by the Hughes model 292H 4 W helix tube. This tube was developed for the Japanese CS program and seventeen were delivered. Five are now in operation and one has failed; the tubes have a design life of approximately three years. Several years ago Hughes developed a multimode helix TWTA at 20 GHz for Bell Laboratories with variable output power levels. A follow-on to that development was performed for NASA for a tube designated the 918H. It had four saturated power levels of 7.5, 12, 25, and 75 W. Hughes is currently providing this tube to TRW for the ACTS program with power levels of 12 and 45 W. The efficiency of this tube ranges from 27 to 45%, depending on the output power level. A 25 W tube is also being developed by Hughes for the MILSTAR program. It is rated at 37% efficiency and weighs 3 lbs.

Figure 5-10 projects TWTA efficiency through the end of this century for several frequency bands. There is a tradeoff between efficiency and reliability. Higher efficiencies can usually be obtained if one accepts a reduction in tube reliability. Improved processing and screening techniques are required to compensate for this problem.

5.4.2 Solid State Power Amplifiers

There is a great deal of interest in replacing TWTAs with solid-state PAs because of the significant improvements in life and reliability of solid-state devices over vacuum tubes. Although solid-state amplifiers do not offer the same power levels or efficiencies of tubes, their use with circuit and array power combining technology offers practical alternatives to TWTAs.

Gallium arsenide field effects transistors (GaAs FET) are currently the most promising technology for solid-state amplifiers. When compared to IMPATT diodes, FETs offer the advantages of more stability, linear amplification, good input-output isolation, and broad bandwidths. Unfortunately, they provide less power and lower efficiencies then IMPATTs above 30 GHz. Texas Instruments has been working on this technology with the goal of 0.25 to 0.3 W per module at 30 GHz. These could be used to produce 8 W by power combining several of these modules. Approximately 1.5 GHz of bandwidth and 8% efficiency has been demonstrated.

IMPATT (Impact Avalanche Transit Time) devices are generally capable of higher power outputs than FETs. Several companies are currently working to produce IMPATT diode amplifiers with 20 W of output power and 20% efficiencies. So far bandwidths of these devices have been rather low (100-500 MHz). More testing is needed to determine what lifetimes can be expected with these devices.

In order to obtain reasonable powers for solid-state amplifiers, power combining techniques must be employed. Figure 5-11 illustrates the paths which may be taken starting with either FETs or IMPATT diodes and ending with 10 to 40 W amplifiers. Two levels of power combining are performed; the

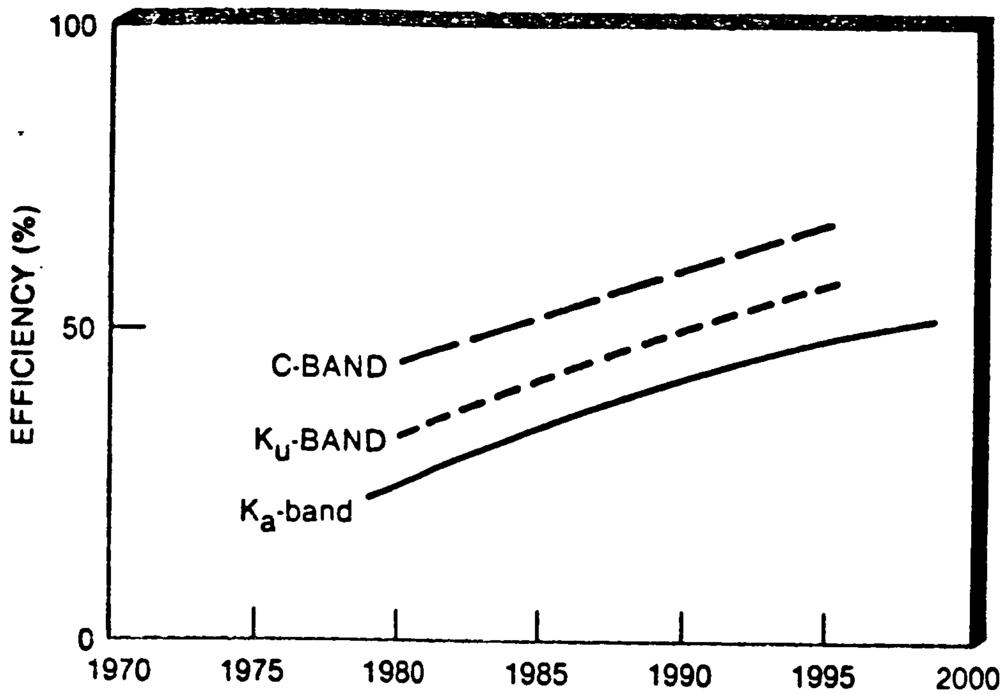


Figure 5-10 TWTA Efficiency Projections

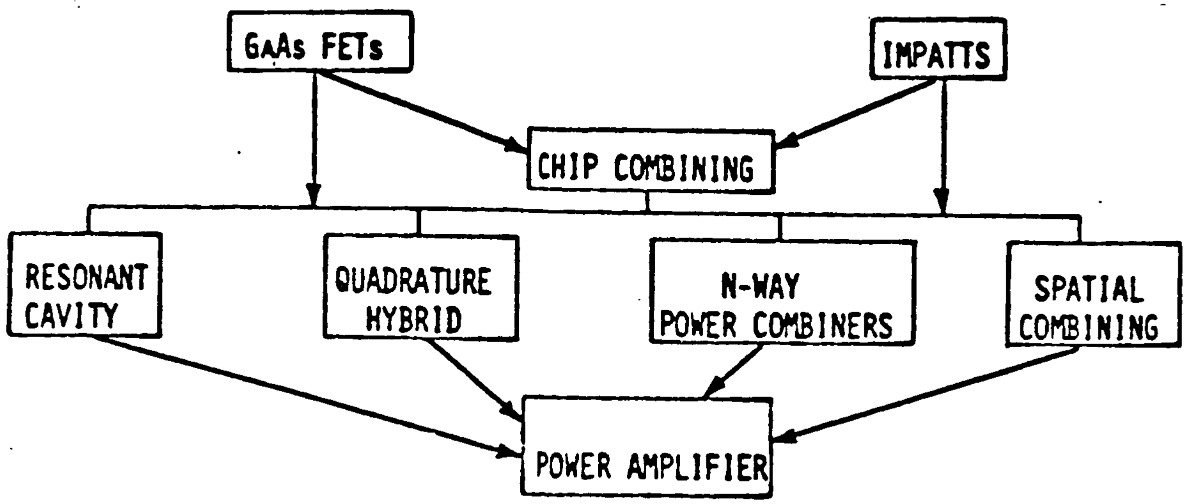


Figure 5-11 Power Combining

first level is chip combining while the second is some form of circuit combining. The advantages and disadvantages of several power combining techniques are listed in Table 5-4. Research in all of these areas are needed before high power solid-state amplifiers will be used for spaceborne applications.

5.5 MULTIPLE BEAM ANTENNAS

So far we have simply stated that multiple beams will be necessary to provide the required gain for the weak uplink signals from the user terminals. In this subsection we will attempt to quantify the multi-beam requirements.

5.5.1 Number of Beams

Figure 5-12 modified from [NASA, 1986] shows the number of spot beams required to cover the CONUS as a function of the antenna diameter or 3 dB beamwidth. It is assumed here that full CONUS coverage is desired and that scanning beams will not be an option due to the higher burst rates and synchronization required. Table 5-5 lists several beam configurations covering the range of possibilities. At the top is a seven beam system with 2.2° beamwidths. It provides only 36 dB of gain (assuming 40% antenna efficiency) which is probably inadequate given the terminal characteristics (see Tradeoffs, Section 6). At the bottom is the 0.32° beams similar to those of ACTS. Roughly 52 dB of gain can be obtained with these beams. However, to obtain full CONUS coverage, roughly 140 spot beams would be needed. The feed structure for this many beams is deemed to be much too complex for at least an initial FSS system. We feel that the range of interest is from 16 to 47 beams, corresponding to beamwidths of 1.2 to 0.6° and gains of 41 to 47 dB. The achievable frequency reuse assuming four unique frequency patterns (colors) is also listed to illustrate the amount of bandwidth reduction possible with multiple beams.

With satellite architectures such as FR-TDMA or SR-FDMA, the complexity of the satellite may be dominated by the component count since they respectively require M^2 and R•M quantities of some components (R is the number of regions). For these architectures, M should be limited to the lower portion of the above range, i.e., roughly 16. The hybrid FDMA/TDMA architecture of Subsection 5.3 requires far fewer components and hence more beams could be supported with the same complexity. For this system, the multi-horn feed will be the limiting factor.

In most existing commercial satellites, one reflector is shared between the uplink and downlink beams. As the number of beams grows, the feed structure becomes increasingly complex, making it difficult to share the reflector. In ACTS, two reflectors are employed, each with identical gains and beamwidths. It is envisioned that the satellite for this FSS would similarly have two reflectors for the spot beams.

5.6 30 GHz LOW NOISE RECEIVER

Current satellite receivers utilize an image rejection enhanced mixer followed by an IF amplifier. The mixers are extremely difficult to optimize at high frequencies and are therefore labor intensive and constitute

Table 5-4
Power Combining Techniques for GaAs FET Amplifiers

Combining Technique	Attractive Features	Disadvantages
Chip level	Compact, simple matching	Limited by thermal constraints, close control over device and package element parameters
Cascade Lange coupler	Planar, good VSWR	High loss, high resolution fabrication required
Cascaded Wilkinson in-phase power splitter	Planar, simple fabrication	High loss, poor VSWR
Matched tee paralleling balanced stages	Planar, good VSWR, low loss	Reduced isolation
Nagal N-way planar splitter	Planar, simple fabrication low loss	Requires careful phase matching
Radial splitting	Low loss, inherent phase symmetry, good isolation	Not planar, complex assembly

Table 5-5
Beamsize Tradeoff

3-dB Beamwidth (°)	Number of Beams	Frequency Reuse (1)	Gain (dB) (2)
2.2	7	1.75	36.0
1.2	16	4.0	41.3
1.0	22	5.5	42.8
0.7	38	9.5	45.9
0.6	47	11.75	47.3
0.5	70	17.5	48.9
0.32	140	35.0	52.8

(1) Assumes four colors (F=4)
(2) Assumes 40% antenna efficiency

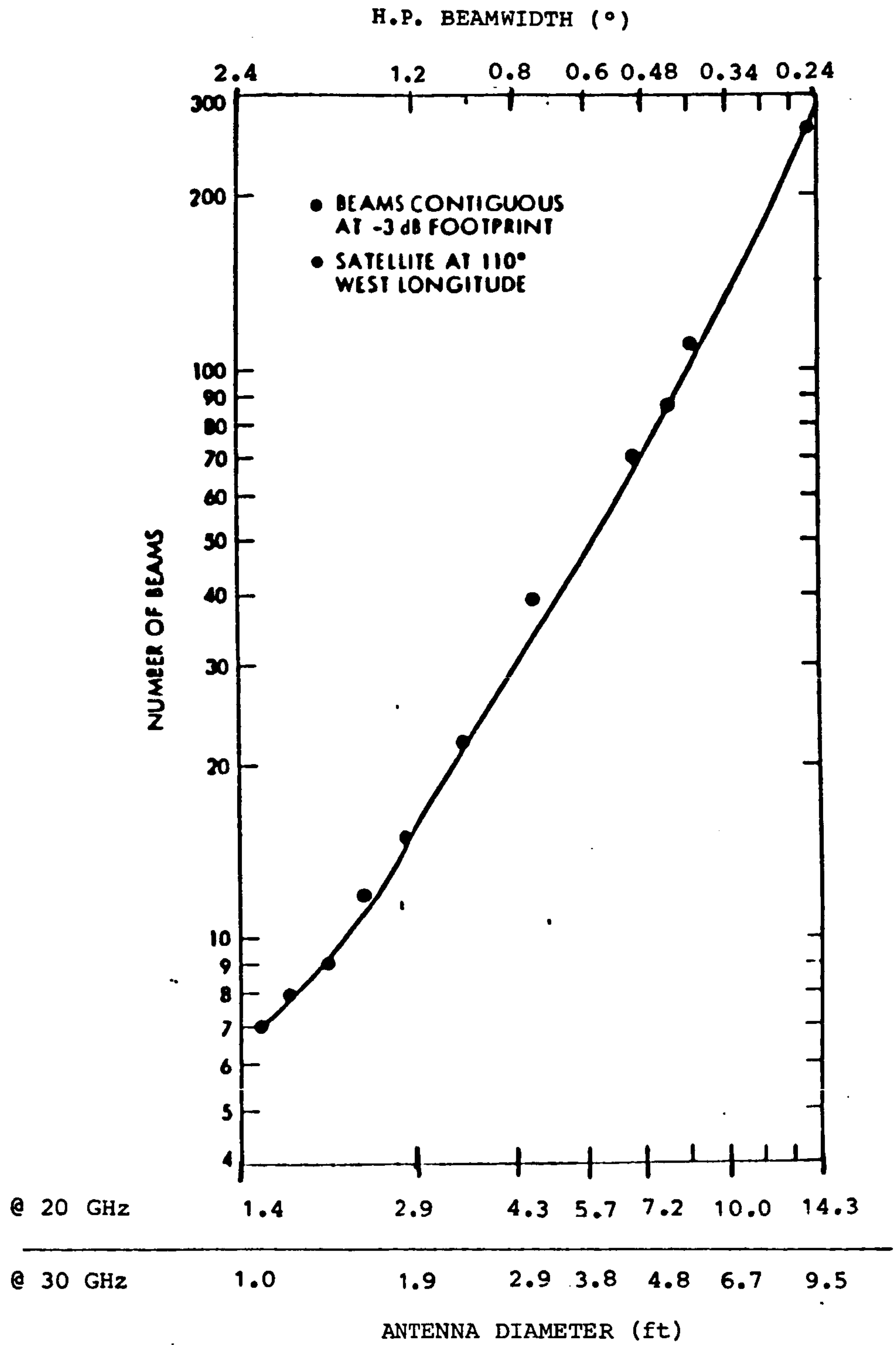


Figure 5-12 Number of Spot Beams Required to Cover Conus

a significant recurring cost in satellite construction. ITT and LNR, Inc. [Microwave, 1984] have each developed 30 GHz LNRs using this approach, with the design goal of a 5 dB noise figure across a 2.5 GHz bandwidth. Only a 6.5 dB noise figure has been achieved.

NASA is also sponsoring the development of LNRs which use FETs for RF preamplification. This approach offers lower cost and higher performance than the front end mixers. Hughes has developed a 4 dB NF receive over a 2.5 GHz bandwidth. It is this technology that is being flown on ACTS.

SECTION 5
REFERENCES

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SECTION 6
SATELLITE/TERMINAL TRADE-OFFS

In the preceding sections, we have examined various alternatives for both the ground and space segments and have only eliminated those options which were not feasible. As yet we have not made any concrete recommendations since this can be done only when looking at the whole picture. This section:

1) Proposes a strawman system consisting of the most promising and least technology constrained system components,

2) Derives link budgets for this strawman system,

3) If this strawman design is inadequate, determines the most cost effective methods of closing the link margins,

4) Proposes a revised system design which meets the performance requirements in at least the dry climates,

5) Performs tradeoffs of alternatives which provide rain compensation in the wetter climates, and finally

6) Estimates the ground and space segment costs.

6.1 STRAWMAN SYSTEM DESIGN

We showed in Section 5 that a hybrid satellite architecture with FDMA links from the user terminals and TDMA links from the supplier terminals would best serve the hub-spoke nature of the postulated applications. Therefore the baseline system design contains the FDMA/TDMA hybrid architecture described in Subsection 5.3. The satellite is a bent pipe transponder with no on-board processing (non-regenerative). A single CONUS beam serves the suppliers and $M = 32$ spot beams cover the users. Pure ALOHA is assumed for the backhaul traffic (users) while straight TDMA is employed on the forward links (suppliers).

We make the assumption that the forward link contains twice the traffic volume as the backhaul since most applications contain a request from the user for some data response from the supplier. Even so, the higher throughput of TDMA results in less bandwidth being required for the forward links than for the Pure ALOHA backhaul. From Subsection 5.3, we concluded that only a few 200 kb/s FDMA channels are required per beam for the backhaul traffic. If four channels are allocated and a 12.5% throughput is assumed for Pure ALOHA, then the maximum practical throughput per beam is 4 x 200 kb/s x 0.125 = 100 kb/s. With a 600 b average packet length for this traffic, the maximum arrival rate λ will be 100 kb/s ÷ 600 b = 166.6 packets per second. If the length of the TDMA slot is set at 2000 b, then the maximum forward traffic volume would be 166.6 x 2000 b = 323 kb/s. The average delay of a M/D/1 queue (exponentially distributed arrival times, deterministic service times, and a single server) can be shown to be

$$\bar{d} = \frac{h}{2} \frac{\rho}{1 - \rho} \qquad (6.1)$$

where

ρ = the ratio of arrival rate λ to service rate μ, or the percent of used slots.

h = $1/\mu$, the constant service or holding time.

If we assume that there are 100 suppliers which serve each beam and that only two channels are permitted per beam so that the TWTAs can run at saturation, then the service time h is just

$$h = \frac{100}{2} \times \frac{2000\ b}{R} \qquad (6.2)$$

where R is the TDMA burst rate. The value of ρ can likewise be calculated from the ratio λ/μ. With λ already set at 166.6 user messages (requests) per second and μ defined as $2 \times R/2000$ b, then

$$\rho = \frac{166.6 \times 2000\ b}{2 \times R} \ . \qquad (6.3)$$

Table 6-1 presents the average delay from Equation (6.1) as a function of R.

Table 6-1
Delay Performance of Forward TDMA Link

R(kb/s)	h	ρ	$\bar{d}$ (s)
100	1.0	1.66	1.25
200	0.5	0.83	0.21
300	0.33	0.55	0.21
400	0.25	0.42	0.09

An average processing delay of under a quarter second would seem reasonable given the half second in propagation delay associated with the two links making up a connection. A 300 kb/s burst rate and 55% throughput on the forward links is thus obtained.

The waveform is assumed to be MSK with non-coherent detection. This requires approximately 10.5 dB E_b/N_0 for a 10^{-5} BER and a channel spacing β of 1.9 (see Subsection 3.5.2.2). Four colors or frequency patterns (N=4) are used, providing a frequency reuse factor F of eight. The total required bandwidth allocation for this strawman system is computed in Table 6-2 below.

Table 6-2
FSS Bandwidth Requirement

Forward		
Uplink	N x 4 x 200 kb/s x 1.9 =	6.08 MHz
Downlink	M x 4 x 200 kb/s x 1.9 =	48.64 MHz
Backhaul		
Uplink	M x 2 x 300 kb/s x 1.9 =	36.48 MHz
Downlink	N x 2 x 300 kb/s x 1.9 =	4.56 MHz
TOTAL BANDWIDTH		95.76 MHz

A simple user terminal design is proposed based on the results of Section 4. A low terminal EIRP (1 W HPA with a 2.5 ft dish) and G/T (15 dB/°K based on the above antenna size and a 500°K LNA) is assumed. From Subsection 3.5.3 we include 6 dB of uplink rain margin and 3 dB of downlink rain margin This will provide at least 0.995 availability to the dryer climate regions. Between 0.75 and 9 dB of additionl EIRP will be required from terminals in wetter regions (see Table 3-5), and in the southeast (Region E) soft decision convolutional coding will be needed to produce the same 0.995 availability.

The supplier terminal can be more complex. We have assumed a 10 ft dish, an 8 W HPA, and a 400°K LNA. This provides over 66 dBWi of effective radiated power and a G/T of almost 26 dB/°K.

The satellite is assumed to contain 64 TWTAs. The spot beams use 20 W TWTs. This provides up to 10 dBW of power for each of the two TDMA channels run at saturation. A 1 dB output backoff may be needed to prevent the suppression of small (rain attenuated) signals. When combined with the 0.8° spot beams which yield 45 dBi of on-axis gain and a 3 dB loss of the multibeam antenna and waveguides, this produces almost 51 dBWi of effective radiated power. The CONUS beam has only 26 dBi of antenna gain. Although only one HPA is needed for this single beam, multiple TWTs are again used here to provide the necessary power. A 75 W tube with a 6 dB output backoff is assumed for each of the 32 uplink beams' traffic. This is the most powerful TWT built to-date at 20 GHz. When divided between the four FDMA channels per beam, these tubes will provide 6.7 dBW of output power per channel. The low noise receiver (LNR) on-board the spacecraft is assumed to have a 4 dB noise figure (438°K).

A complete list of assumptions for the strawman system design is presented in Table 6-3.

6.2 LINK BUDGETS

Given the baseline system described above, link budgets can be derived for both the forward and backhaul links. These link budgets are presented in Tables 6-4 and 6-5 respectively. They are for terminals operating in the dryest climate (Region A) and hence as much as 13 dB more uplink margin will be require for terminals in wetter climates. Those additional margins are given in Table 3-5 by region.

Worst case assumptions have been made in most cases. The edge of beam spacecraft antenna gain is used for both the uplink and downlink. A 10 dB fade is assumed for the signal of interest relative to the other signals. This reduces the fraction of power allocated by the spacecraft TWTA to the weak signal to as little as 1/31 of the total (four carrier per TWTA backhaul link) and 1/11 of the total (two carrier per beam forward link).

As one can see, this baseline system does not meet the data rate requirements. In particular, the backhaul downlink falls over 6 dB short of its requirement. This is principally due to the low gain of the CONUS downlink beam. Obviously additional gains are necessary in either the spacecraft, terminals, or both.

Table 6-3
Strawman System Design

System Architecture

Frequency Source
- One pilot tone per beam
- FLL in each terminal

Backhaul Links
- FDMA - 200 kb/s
- Pure ALOHA access
- ACK/NAK returned by supplier

Forward Links
- TDMA - 300 kb/s
- Fixed TDMA slot assignments
- Twice as much traffic as on the backhaul

Rain Compensation
- 6 dB uplink margin
- 3 dB downlink margin
- 1 to 9 dB additional EIRP for wet climates
- Soft decision decoding of backhaul link from Region E

Waveform
- Minimum Shift Keying (MSK)
- 1.9 Hz/b/s channel spacing noncoherent detection
- 10.5 dB E_b/N_0 for 10^{-5} BER

Satellite Design

Non-regenerative
FDMA/TDMA hybrid
32 spot beams to user terminals
- 4.3 feet (1.3 m) downlink reflector at 20 GHz
- 2.9 feet (0.87 m) uplink reflector at 30 GHz

4 colors - 8 times frequency reuse
1 CONUS beam to supplier terminals
20 W TWTAs for the downlink spot beams
- 1 dB output backoff

75 W TWTAs for each uplink spot beam's traffic
- 6 dB output backoff

4 dB noise figure 30 GHz LNR

Table 6-3
Strawman System Design (Concluded)

Terminal Design

User Terminal
- 2.5 ft dish
- 1 W HPA
- 500°K LNA
- Rate 1/2 convolutional encoder for Region E terminals
- 200 kb/s burst rate
- Pure ALOHA access

Supplier Terminal
- 10 ft dish
- 8 W HPA
- 400°K LNA
- Soft decision decoder
- 300 kb/s TDMA burst rate

Table 6-4
Strawman Design Forward Link Budget

Uplink		
EIRP		66.0 dBWi
Miscellaneous loss		- 5.0 dB
Rain margin		- 6.0 dB
Path loss (30 GHz)		-213.0 dB
Power at S/C ant.		-158.0 dBW
S/C ant. gain (CONUS beam)		26.0 dBi
Edge of beam loss		- 3.0 dB
		-135.0 dBW
k	228.6	
T (4dB NF)	- 26.4	
N_0		202.2
C/N_0 uplink		67.2 dB-Hz
Downlink		
S/C ant. gain		45.0 dBi
Feed losses		- 3.0 dB
TWT power per channel		- 1.6 dBW
EIRP		43.6 dBWi
Path loss (20 GHz)		-210.0 dB
Rain margin		- 3.0 dB
Miscellaneous loss		- 5.0 dB
Edge of beam loss		- 3.0 dB
Power at Terminal		-177.4 dBW
k		228.6
G/T (terminal)		14.5 dB/°K
C/N_0 downlink		65.7 dB-Hz
Overall C/N_0		63.4 dB-Hz
Req data rate (300 kb/s)		- 54.8 dB
Achieved E_b/N_0		8.5 dB
Req E_b/N_0 for 10^{-5} BER		- 10.5 dB
Margin		- 1.9 dB

Table 6-5
Strawman Design Backhaul Link Budget

Uplink

EIRP		45.3 dBWi
Miscellaneous loss		- 5.0 dB
Rain margin		- 6.0 dB
Path loss (30 GHz)		-213.0 dB
Power at S/C ant.		-178.7 dBW
S/C ant. gain (0.8° beamwidth)		45.0 dBi
Edge of beam loss		- 3.0 dB
		-136.7 dBW
k	228.6	
T (4dB NF)	- 26.4	
N_0		202.2
C/N_0 uplink		65.5 dB-Hz

Downlink

S/C ant. gain	26.0 dBi
Feed losses	- 1.0 dB
TWT power per channel	- 2.2 dBW
EIRP	22.8 dBWi
Path loss (20 GHz)	-210.0 dB
Rain margin	- 3.0 dB
Miscellaneous loss	- 5.0 dB
Edge of beam loss	- 3.0 dB
Power at Terminal	-198.2 dBW
k	228.6
G/T (terminal)	27.4 dB/°K
C/N_0 downlink	57.8 dB-Hz
Overall C/N_0	57.1 dB-Hz
Req data rate (200 kb/s)	- 53.0 dB
Achieved E_b/N_0	4.1 dB
Req E_b/N_0 for 10^{-5} BER	- 10.5 dB
Margin	- 6.4 dB

6.3 SYSTEM COSTING

Before trade-offs between satellite and terminal performance can be made, some understanding of the cost relationships of various components is required. This subsection derives some of the simple cost relationships that will be required for the trade-offs.

6.3.1 Ground/Space Segment Relationships

Typically, one attempts to minimize system cost by spending roughly equal amounts on the ground and space segments. In this direct-to-subscriber FSS system, the goal is to bring the services to millions of consumers. This enables one to spend millions on the satellite(s) for each dollar of terminal cost. There reaches a point with this number of terminals, however, where one reaches an absolute minimum terminal cost because of system and technology constraints. In this case, one can attempt to minimize the terminal costs and then minimize the space segment costs which meets the performance requirements.

6.3.2 Space Segment Costs

6.3.2.1 Satellite Weight Optimization

Satellite cost is proportional primarily to satellite weight which in turn is a function of satellite EIRP and other factors. The approach taken in this first examination of the problem is to determine the minimum weight satellite as a function of EIRP. In order to accomplish this, a model is suggested. It should be recognized that the results which derive from the model will change if the model is changed.

For a specific system performance level, the only variables which significantly affect satellite weight are the antennas and the RF power amplifiers. The weight of the satellite antennas, including the feeds and transmitters (and the weight due to thermal power control and primary electrical power), can be modeled.

According to a Bell Telephone Laboratory report [Bell, 1968] performed for NASA, a rigid reflector of the type required for use at 20/30 GHz, has a weight proportional to antenna diameter, i.e., Wt = 10D, where D is in feet. For the purposes of this analysis, the antennas being modeled include the reflector, feeds, and structure. For an M-beam antenna, the weight model is:

Item	Weight (lbs)
reflector	10D
feed	M/10
structure	15% (10D + M/10)

Therefore,

$$W_{ant} \approx 12D + M/9 \text{ (lbs)}, \tag{6.4}$$

where

D = diameter in feet,

and

M = number of feeds.

For two reflectors, one for the 30 GHz uplink and another for the 20 GHz downlink, this becomes

$$W_{ant} \approx 12\left(D_{30} + D_{20}\right) + M/9$$

$$\approx 20\ D_{20} + M/9,$$

for equal size uplink and downlink beams.

Available data [Hughes, 1984] indicate that the TWTA weight (for power levels greater than 1 W) is

$$W_{TWTA} \approx 1 + P/12 \text{ (lbs)} \tag{6.5}$$

where P = RF power of TWT in watts. This is illustrated in Figure 6-1. An old curve [Bell, 1968] was also plotted for comparison.

The prime power weight burden is also estimated as

$$W_{pp} \approx 0.4\ P/\eta \text{ (lbs)} \tag{6.6}$$

where η = DC to RF efficiency. This overall efficiency is actually the product of two efficiency factors

$$\eta = \eta_{PS}\ \eta_{TWT} \tag{6.7}$$

where

η_{PS} is the power supply efficiency, roughly 0.85, and

η_{TWT} is estimated at 0.4 when at saturation and 0.3 when backed off.

Thus η falls in the range of 0.25 to 0.35.

By quantifying the relationship between beam size and the number of beams to cover CONUS (see Figure 5-12), we will be able to determine the optimum satellite design for a fixed EIRP requirement. This relationship can be approximated as

$$M = 1.4\ D_{20}^2 + 3.5 \tag{6.8}$$

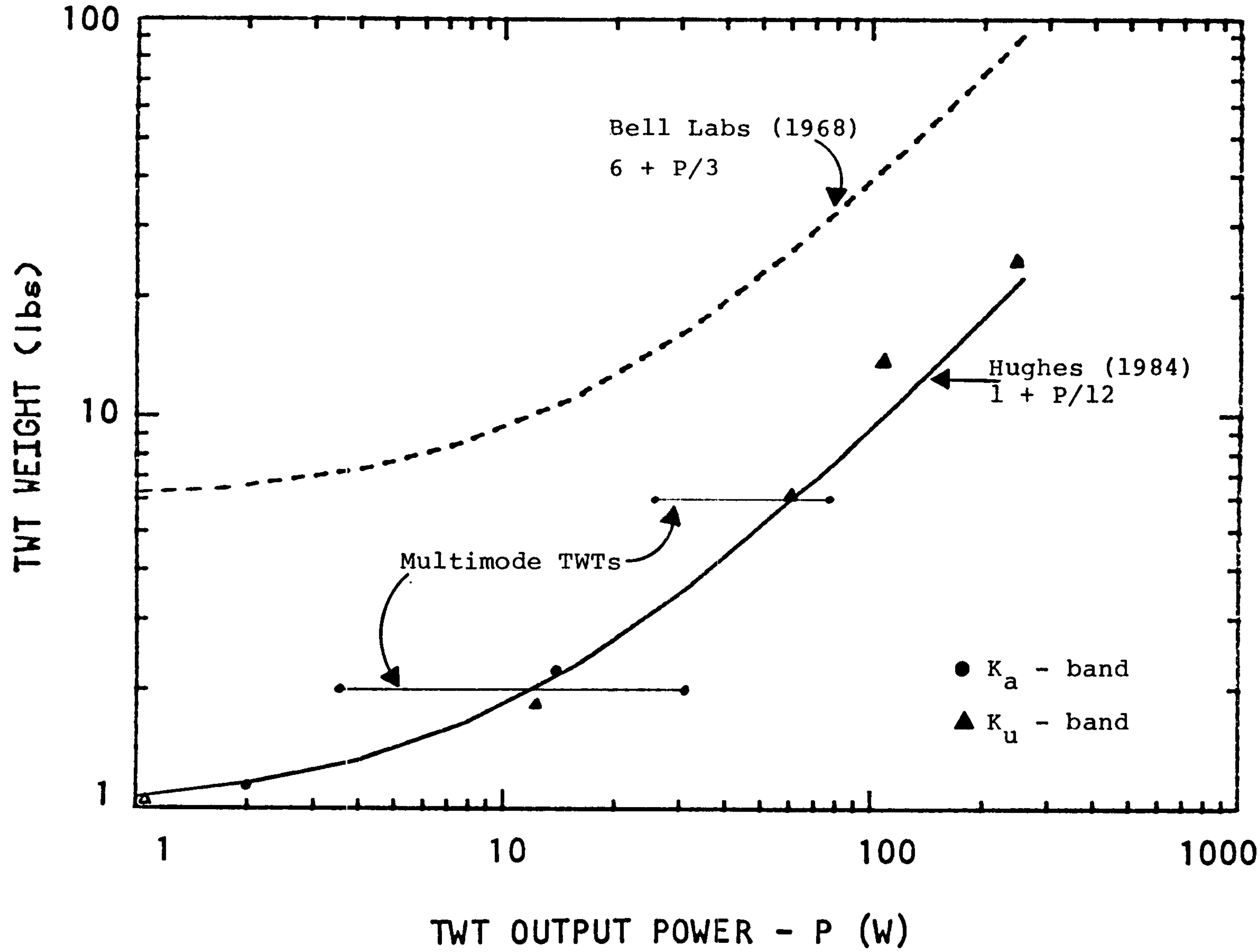

Figure 6-1 TWT Weight Versus Power

where D_{20} is the downlink antenna size in feet.

Since the antenna gain can be shown to be

$$G = 10.2\ \eta_a \left(D\ F_{GHz}\right)^2 \tag{6.9}$$
$$= 1630\ D_{20}^2$$

(assuming the antenna efficiency η_a is 0.4) the required RF power per beam is just

$$P = EIRP/1630\ D_{20}^2\ . \tag{6.10}$$

The overall antenna and transmitter weight can therefore be approximated as

$$W_t \approx 20\ D_{20} + M\left(1 + P/12\right) + 0.4\ MP/\eta \tag{6.11}$$
$$\approx 20\ D_{20} + \left(1.4\ D_{20}^2 + 3.5\right)\left[1 + \frac{EIRP}{1630\ D_{20}^2}\left(1/12 + 0.4/\eta\right)\right].$$

This is plotted in Figure 6-2 as a function of downlink antenna size for several EIRP values. It shows that the prime power weight burden dominates W_t for small antenna sizes but quickly reaches an optimum (minimum weight) antenna size. Beyond this optimum value, the curves rise gradually indicating that smaller (but more) beams can be added without significantly impacting satellite weight.

The satellite EIRP requirement must at least be greater than 45 dBWi (from Table 6-4). This would indicate an optimum downlink antenna size of 2 to 3 feet, corresponding to between 9 and 16 beams. However, an increase to 32 beams would require over a 4 ft antenna which increases the weight only slightly.

6.3.2.2 Satellite Cost Estimation

Satellite cost estimation can be based upon the very detailed SAMSO Unmanned Spacecraft Cost Estimation Model or on a simpler rule-of-thumb basis which relates the cost of the spacecraft to its total weight. The latter approach is selected as most appropriate for this study. It has been shown [MILSATCOM, 1976] that the recurring cost, C_R, and non-recurring (development) cost, C_{NRE} are given approximately by

$$C_R\ (\$M) \approx 0.031\ (\text{on-orbit weight, lbs})^{0.93} + \text{launch} \tag{6.12}$$

and

$$C_{NRE}\ (\$M) \approx 0.016\ (\text{on-orbit weight, lbs})^{1.15}. \tag{6.13}$$

These relationships are admittedly somewhat outdated, but should be sufficient for our purposes (terminal cost is far more important).

The launch cost is ignored in this report. It can be shown that the on-orbit weight of a communications satellite is directly related to the weight and power requirements of the communications package.

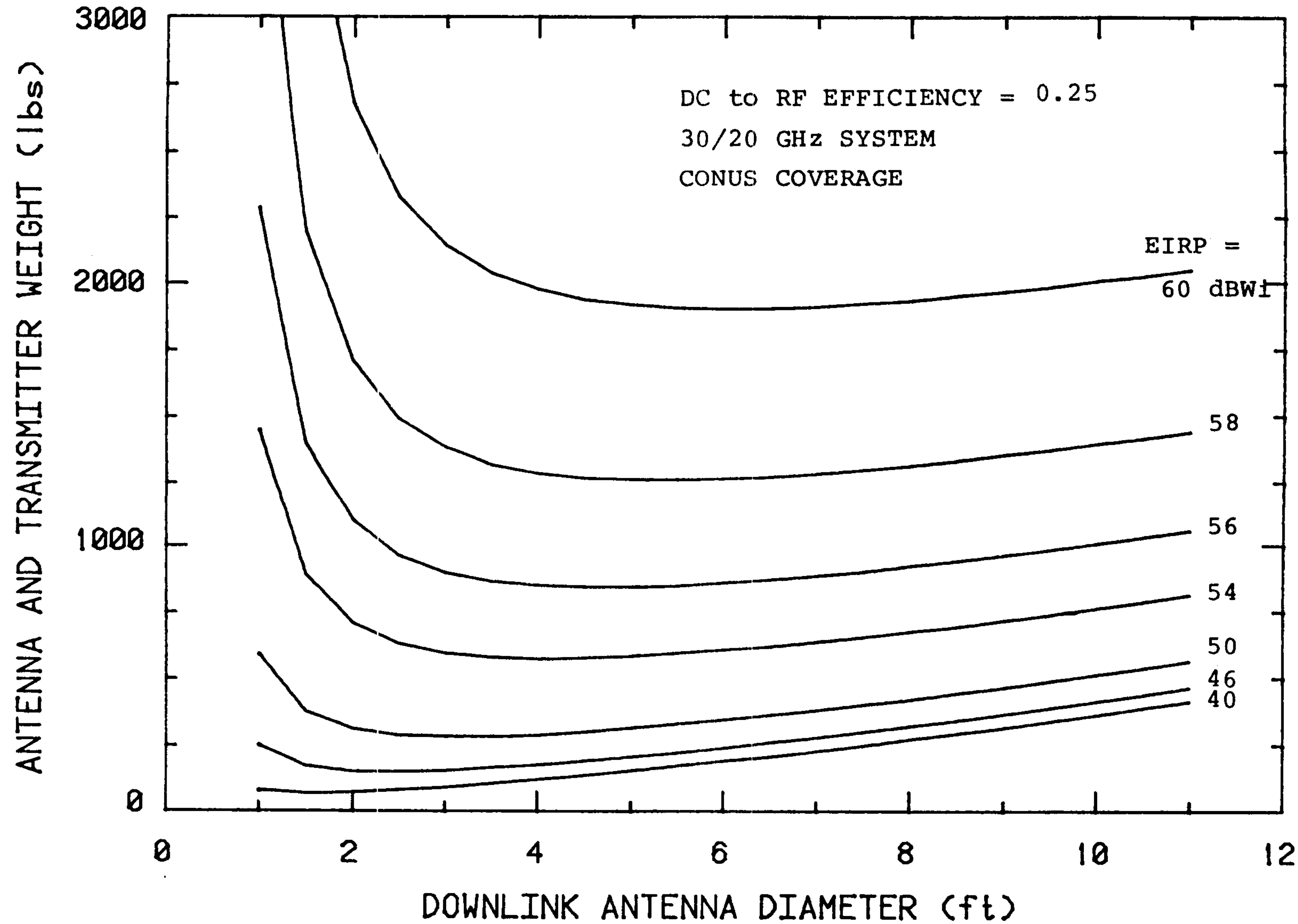

Figure 6-2 Satellite Weight Versus Beamsize Relationship

An approximation for the beginning of mission (BOM) weight (lbs) and power (watts) for a communications satellite is:

$$W_{sat} \approx 800 + 1.53W_c + 0.8P_c \tag{6.14}$$

$$P_{sat} \approx 240 + 1.26\ P_c \tag{6.15}$$

where, W_c is the weight of the communications package and P_c is the DC power required by the communications package. The validity of Equation (6.14) and (6.15) were checked by using figures from ACTS. The multibeam communication package on ACTS weights 730 lbs and consumes 822 lbs of power. With these inputs, Equations (6.14) and (6.15) calculate the BOM satellite weight and power to be 2575 lbs and 1275 W. This is quite close to the actual values (not including laser package) of 2400 lbs and 1600 W.

Once the communications payload requirements have been estimated for the FSS transponder, then the total weight and power requirements (and hence cost) can be derived.

6.4 TRADE-OFFS

In this subsection, we examine various options which can provide the additional margins necessary, or may be less costly to implement. For example, there are many combinations of satellite and terminal complexities which provide the same performance. In general, one should increase the complexity of the satellite before the terminal, although at some point this ceases to be a beneficial trade-off.

6.4.1 Baseband Processing

Baseband processing offers several significant advantages to satellite performance. These are: 1) no noise amplified on the downlink; 2) weak signal compensation; and, 3) both bandwidth and delay can be reduced through the use of Capture ALOHA (see Subsection 5.2). For equal uplink and downlink signals, the first property yields a 3 dB improvement in overall C/N_0 or allows almost a 3 dB reduction in both uplink and downlink carrier powers. If the uplink is 6 db stronger than the downlink to minimize the required downlink power, then regeneration will improve the overall C/N_0 by only 1 dB but will also permit a 6 dB reduction in the uplink signal.

The second property of weak signal compensation is quite significant for a Ka-band satellite system since the variation between signal levels can be quite large. In terms of intermodulation, a 6 dB output backoff will not be required if all signals are of equal amplitude; a 3 dB backoff should be sufficient. Also, since each signal is regenerated, the total TWTA power can be equally divided among the carriers. In terms of the link budgets presented above, the forward downlink TWT power per channel would rise from 1.6 dBW to 10 dBW (TWT at saturation) and the corresponding figure for the backhaul downlink would leap from -2.2 dBW to 9.7 dBW.

If baseband processing were to be implemented, Capture ALOHA could provide additional advantages on the Pure ALOHA backhaul link without a significant increase in cost or complexity. As shown in Subsection 5.2, roughly a 30 percent reduction in required bandwidth for the backhaul link could be achieved by using Capture ALOHA while also reducing delay.

The C/N_0's of both forward and backhaul uplinks of the baseline system would be sufficient to achieve a 10^{-5} BER at the satellite (10.5 dB E_b/N_0 plus 2 dB implementation loss). The regenerated signals should therefore be essentially error-free and the baseband processing would provide an 8.5 dB improvement in the C/N_0 at the receiver on the forward link and an 11.9 dB improvement to the backhaul link. Thus, a regenerative satellite would provide more than enough additional gain to achieve positive link margins. Other processing such as decoding, rate changing, and encoding would not be necessary.

Unfortunately, processing satellites are more complex and less flexible than conventional design. Additional modulators, demodulators, filters, and other components are required for each channel processed. For our baseline design, this would correspond to 128 of each for the backhaul (4 channels times 32 beams) and 64 of each for the forward link. Even if processing were limited to the backhaul traffic where it is needed more, this results in a considerable increase in weight and power requirement. Subsection 3.4.3.1 quoted figures of 400 kg and 2 kW as being necessary to process 100 MHz of spectral bandwidth. Our baseline system contains 128 x 200 kb/s x 1.9 = 48.6 MHz of bandwidth on the backhaul and 64 x 300 kb/s x 1.9 = 36.5 MHz on the forward links. Since the downconversion to baseband is already required in order to regenerate the uplink signals, then one might as well also implement the baseband processing of FR-TDMA on the backhaul links. No routing would be necessary here but the processor would perform the rate change operation so that a single TDM downlink carrier exists from each beam (multiplex the four FDMA channels). The TWTAs could then run at saturation. The estimated unit power and weight (from Subsection 5.1.2) for the components necessary for this baseband processing of the backhaul links is given in Table 6-6. When multiplied by the number of components needed for this baseline design, the total weight and power required are 324 lbs and 544 W. We view this as an upper bound for these figures since considerable progress has been made in power and weight reduction since these figures were published. A current data point is the ACTS baseband processor which serves two 110 Mb/s channels. This processor contains two switchable FEC units, two rate changes, and a switch in addition to the modulators/demodulators and weighs 119 lbs and consumes 218 W.

We can conclude, therefore, that on-board signal regeneration is not impractical from a power and weight perspective. In fact, the TWTA weight could be reduced by using lower power tubes, i.e., 45 W on the backhaul, and their power efficiency would be increased by running at saturation.

The other drawback to a processing satellite is its inflexibility. The demodulators and modulators can operate only at a limited number of input data rates. This is in contrast to bent pipe transponders which repeat whatever they receive. However, for our baseline system which relies on fixed burst rates (200 or 300 kb/s), this inflexibility is unimportant. The suppliers can specify any data rate they desire up to the 200 kb/s backhaul burst rate. The only force limiting the possible data rate is the desire for terminal compatibility with the data source (personal computer). Since all of

Table 6-6
Added Components to Baseline Design
Needed for Baseband Processing
of Backhaul Links

	No Units	Unit Wt (oz)	Unit Power (W)	Total Weight (lbs)	Total Power (W)
D/C_1	M	16	-	32	
D/C_2	4M	2		16	
Filter	4M	2		16	
Amplifier	4M	2		16	
Demodulator	4M	6	0.5	48	64
Processor	M	42	12	84	384
Modulator	M	32	2	64	64
U/C_1	M	2	-	4	
Amplifier	M	6	1	12	32
U/C_2	M	16	-	32	
Totals				324	544

the applications considered have data rates which are much less than the proposed burst rates, then the satellite modulators and demodulators can be built for one specified burst rate without limiting their applicability. A processing satellite is therefore a viable method of picking up the necessary margin on the backhaul links; it may be a bit excessive for the forward links.

6.4.2 Spread Spectrum

By separating the forward and backhaul links as we have done with our baseline design, SSMA becomes a viable means of closing the margin on the backhaul. This is because of the difference in noise bandwidths seen by the demodulator. Once the signal is despread, the receiver looks at a noise bandwidth equal to the data rate, not the burst or chip rate. The rate change from 200 kb/s to 9600 b/s corresponds to a 13 dB reduction in required power. (Up to 5 dB of this would be given back in the degradation factor - see Subsection 3.2.3.) The user terminal EIRP requirement would therefore drop to as little as 32.3 dBWi (for the driest climate regions) and a maximum of 41.3 dBWi in Region E. This would allow very small antennas and fractional watt HPAs. On the downlink, the same (baseline) C/N_0 would be sufficient to create a positive (although small) margin for backhaul links.

SSMA is therefore another alternative which would perform adequately. Since the backhaul link goes from the user terminals to the suppliers, no despreading operation (acquisition and tracking of the spread waveform) is required at the user terminals. The spreading operation (to >5 Mc/s, see Subsection 5.3) which is required is not difficult or expensive to implement.

There are, however, drawbacks to SSMA which we addressed in Section 3. The first is the large bandwidth requirement, between five and ten times the spectrum needed for Pure ALOHA. This by itself is not necessarily critical since bandwidth in the 30/20 GHz region is currently plentiful. A far more important consideration is the frequency accuracy requirement. This frequency stability is directly proportional to the data rate which must be demodulated. The 9600 b/s data rate therefore requires a frequency knowledge, in both the transmitter and receiver, twenty times more accurate than that required for the 200 kb/s burst rate. This is made easier by the fact that no channelization will be needed in the user terminals. Each uplink spot beam would contain a single spread carrier so that a stable source set at that beam's prescribed frequency could be employed in the user terminals and no synthesizer would be required. However, it is the microwave components of the terminal's frequency acquisition circuitry (voltage tuned DSO and pilot discriminator) which will drive the cost, and not the IF components (VHF synthesizer, etc; see Figure 3-1).

Whether it is worth trading the added complexity of a more accurate frequency reference for a less powerful HPA is difficult to determine at this time. Much work remains to be done on Ka-band components for earth stations. Solid-state HPAs at 30 GHz are currently too expensive no matter what power output is needed. If a 0.1 W amplifier is developed which is inexpensive and one or more watts stays prohibitively expensive, then the spread spectrum terminal may actually be the first to become affordable. However if the difference in cost between 0.1 and 1 W amplifiers is small, then SSMA will not offer any advantages to the service providers.

6.4.3 Spacecraft/Terminal Trade-offs

The baseline system was selected so as to offer the simplest possible design and thereby minimize the system cost. However, because this design did not meet the performance requirements, alternatives must be investigated which are perhaps more complex and costly. We have already examined two alternatives (baseband processing and spread spectrum) which would provide significant improvements to the backhaul link performance. In this subsection, other more subtle alternatives to the satellite and earth terminal designs will be investigated. The goal here is twofold: first, we hope to identify ways in which both forward and backhaul link deficiencies can be overcome; and second, variations to the baseline system which may be more cost effective may be discovered. In particular, we will be looking for trade-offs which can shift more of the burden from the terminals to the satellite, e.g., higher spacecraft EIRP for a smaller terminal antenna gain.

6.4.3.1 Satellite TWTA Alternatives

The baseline design already contained 64 TWTAs, half of which were at the limit of current technology in terms of power output. This leaves little room for improvement. The forward link, however, specified 20 W tubes which could be increased. For example, if 45 W tubes were used in their place, then the required link margin could be met. The penalty for increasing the downlink power is in both satellite weight and DC power. The satellite DC power requirement of the baseline design, just for the power amplifiers, is:

32 beams x 75 W/4.0/0.25 = 2400 W (backhaul link TWTAs)

plus

32 beams x 20 W/1.26/0.4 = 1270 W (forward link TWTAs).

The 4.0 and 1.26 represent the respective 6 and 1 dB output backoffs of these tubes while the 0.25 and 0.4 are the DC to RF efficincies of the tubes. TWTAs become much less efficient when operating with large backoffs. As can be seen, the power amplifiers are already consuming 3670 W of DC power. Increasing the forward link TWTAs to 45 W would use an additional 1590 W. We do not feel this is a feasible alternative due to the power generation and weight constraints of current satellite technology. A 5000 W satellite is assumed to be an upper bound on the total satellite power. The baseline system already exceeds this limit when all the other components are considered.

Since, to a large degree, the backhaul link is limited by the spacecraft EIRP, we also should look for alternatives to the 75 W TWTAs being used there. By replacing the single 75 W TWTA with two 20 W tubes, each serving two channel instead of four, the output backoff can be reduced from 6 to 1 dB. This reduces the weak carrier problem (worst case for a 10 dB fade is the weak signal getting 1/11 of the tube power instead of 1/31 as with four channels), and permits a higher operating efficiency for the tubes. This change would pick up 3.8 dB in the worst case EIRP and would increase the power requirement by only 128 W. This would actually reduce the overall weight of the TWTAs by roughly 60 lbs.

We could go one step further and assign a tube to each of the 128 channels. For example, if 7.5 W TWTs were selected, then the overall power requirement would be the same as the baseline system (2400 W). However, now the weak carrier problem would disappear; each uplink channel could be amplified to the 7.5 W saturation without having to share power with a stronger adjacent signal. For this case, the downlink EIRP could be improved almost 11 dB which would increase the margin to +0.3 dB. Since there are really no disadvantages to this approach (total TWT weight should not change significant), this is a significant improvement to the baseline design.

Essentially the same change can be applied to the forward link. The 20 W TWT amplifying two carriers per downlink beam can be replaced with two 5 W tubes, one for each TDMA channel. Again, no backoff or weak signal problems would be inherent in this design so each downlink signal could be amplified to be full 5 W output power. This would increase the EIRP 5.4 dB and yield a 0.4 dB margin. An added benefit would be a decrease in required satellite DC power of approximately 470 W.

These smaller tubes (7.5 W and 5 W) being used to amplify individual channels are now in the range where they could be replaced by solid state devices. Although higher reliabiities are offered by solid state HPAs, their lower efficiencies would require considerably more satellite DC power. TWTAs are still recommended for this application.

6.4.3.2 Beam Size

In Subsection 5.5.1, we determined that the optimum number of beams would fall in the range of 16 to 47; the baseline system contains 32. If this number were increased to 47, the 3 dB beamwidth would decrease to 0.6° and the gain would increase 2.3 dB to 47.3 dBi. This added spot beam gain would be beneficial to both the backhaul uplink and forward downlink. On the former, it could reduce the required user terminal G/T while on the later, it could ease the EIRP requirement of these terminals. This reduction in EIRP is especially important because of the rain attenuation problem.

With 47 beams, the number of FDMA channels per beam could be reduced to three and the forward link TDMA burst rate could be lowered to 250 kb/s. The TWTA power should be reduced to roughly 3 W so as not to increase the satellite power requirement.

The revised forward link budget using these higher gain beams, shows a 1.4 dB margin. This increased margin is principally due to the decreased burst rate. The 98 required 3 W TWTs would actually decrease the satellite power requirement but slightly increase the satellite weight.

The higher gain on the backhaul uplink does not result in a corresponding decrease in required terminal EIRP. If the user terminal EIRP is reduced 2.3 dB to maintain a fixed uplink C/N_0, then more satellite power will be required on the downlink because more channels exist (3 x 47 = 141 as opposed to 4 x 32 = 128). To avoid this satellite power increase, the TWT power per channel must be reduced to 6.5 W. This effectively reduces the downlink C/N_0. To make up this difference, the uplink C/N_0 must be increased 1 dB. The terminal EIRP can therefore be reduced 1.3 dB and still maintain a positive margin.

There are two drawbacks to increasing the number of beams. As shown in Figure 6-2, transponder weight increases slightly for antenna diameters above 2 feet (9 beams). It is estimated that the total increase in satellite weight resulting from the greater number of beams is under 100 lbs (antenna, mount, TWTs and components). The second disadvantage occurs in the supplier terminal. We have already seen that the supplier must have a receiver for each beam in which he hopes to do business, up to a maximum of M. This increase in M from 32 to 47 represents a significant increase in supplier terminal costs. Because of these drawbacks and the limited gains associated with the smaller beams, we view this as a trade-off of last resort. Other trade-offs which we have examined appear to be more promising.

6.4.3.3 Revised Link Budget

Of the trade-offs examined in this subsection, the improvement which closes the link margins for the least expense is the assignment of a TWTA to each channel of traffic. The on-board processing would provide several additional dB of improvement because uplink noise is not amplified on the downlink. At least for the dryest climate region, this processing is not needed.

Tables 6-7 and 6-8 present the link budgets for this revised baseline system design. As can be seen, positive margins exist on both links, and each is uplink power limited.

6.4.4 Rain Compensation

The revised system design and link budgets shown in Tables 6-7 and 6-8 are for the dryest regions of the country, and provide a 6 dB uplink margin and 3 dB downlink margin for fading. In the wettest regions of the country, however, additional margins of up to 13 dB on the uplink and 6.5 dB on the downlink are required. As has been suggested for region E, one approach to reduce this requirement is to use coding. We now consider a number of alternatives for providing the required margin.

6.4.4.1 Increased Terminal Power

The most straightforward approach to achieving the required uplink margin is to increase the EIRP of the terminals by increasing either the antenna size or the power output of the HPA.

For the supplier terminals (forward link), this may be possible. The baseline system design assumes an 8 W HPA amplifier with a 10 foot dish. The required 13 dB uplink margin could be obtained by increasing the HPA power to 160 W. 200 W amplifiers are currently available at 30 GHz.

For the user terminals (backhaul link), however, achieving the required uplink margin by increasing the power may not be possible. Currently 1 W solid state devices are available at 30 GHz, and 5 W amplifiers have been built (using a number of lower power devices and combining). Thus, up to 7 dB more EIRP could possibly be achieved in this manner. Although price versus performance relationships are not available yet for these amplifiers (30 GHz

Table 6-7
Revised Forward Link Budget

Uplink

EIRP		66.0 dBWi
Miscellaneous loss		- 5.0 dB
Rain margin		- 6.0 dB
Path loss (30 GHz)		-213.0 dB
Power at S/C ant.		-158.0 dBW
S/C ant. gain (CONUS beam)		26.0 dBi
Edge of beam loss		- 3.0 dB
		-135.0 dBW
k	228.6	
T (4dB NF)	- 26.4	
N_0		202.2
C/N_0 uplink		67.2 dB-Hz

Downlink

S/C ant. gain	45.0 dBi
Feed losses	- 3.0 dB
TWT power per channel	7.0 dBW
EIRP	49.0 dBWi
Path loss (20 GHz)	-210.0 dB
Rain margin	- 3.0 dB
Miscellaneous loss	- 5.0 dB
Edge of beam loss	- 3.0 dB
Power at Terminal	-172.0 dBW
k	228.6
G/T (terminal)	14.5 dB/°K
C/N_0 downlink	71.1 dB-Hz
Overall C/N_0	65.7 dB-Hz
Req data rate (300 kb/s)	- 54.8 dB
Achieved E_b/N_0	10.9 dB
Req E_b/N_0 for 10^{-5} BER	- 10.5 dB
Margin	0.4 dB

Table 6-8
Revised Backhaul Link Budget

Uplink

EIRP		45.3 dBWi
Miscellaneous loss		- 5.0 dB
Rain margin		- 6.0 dB
Path loss (30 GHz)		-213.0 dB
Power at S/C ant.		-178.7 dBW
S/C ant. gain (0.8° beamwidth)		45.0 dBi
Edge of beam loss		- 3.0 dB
		-136.7 dBW
k	228.6	
T (4dB NF)	- 26.4	
N_0		202.2
C/N_0 uplink		65.5 dB-Hz

Downlink

S/C ant. gain	26.0 dBi
Feed losses	- 1.0 dB
TWT power per channel	8.8 dBW
EIRP	33.8 dBWi
Path loss (20 GHz)	-210.0 dB
Rain margin	- 3.0 dB
Miscellaneous loss	- 5.0 dB
Edge of beam loss	- 3.0 dB
Power at Terminal	-187.2 dBW
k	228.6
G/T (terminal)	27.4 dB/°K
C/N_0 downlink	68.8 dB-Hz
Overall C/N_0	63.8 dB-Hz
Req data rate (200 kb/s)	- 53.0 dB
Achieved E_b/N_0	10.8 dB
Req E_b/N_0 for 10^{-5} BER	- 10.5 dB
Margin	0.3 dB

solid state power technology is still immature), it is clear that increasing the terminal HPA power could be a very expensive proposition. The cost of the user HPA is already an issue without further worsening the situation by pushing the technology to the limit. Thus, we view this approach as a last resort; other more economical approaches need to be considered.

6.4.4.2 Increased Terminal Antenna Size

Another option for providing both the required uplink and downlink rain margin is to increase the terminal antenna sizes, thus increasing both the terminal EIRP and G/T.

For the supplier terminals, increasing the antenna size may have unfortunate effects on both the cost of the antenna and the tracking hardware. As higher gain antennas are used, the antenna must be pointed more accurately. Technology limits in tracking equipment result in an approximately 0.02° minimum tracking error. This sets an upper bound on the antenna size of approximately 49 feet. To gain the required 13 dB of uplink margin would require an increase of the antenna diameter to 45 feet, just barely within the limits of the tracking hardware. The cost of this antenna would be considerably greater. Moderate increases in the antenna gain should be quite acceptable, and would have the advantage of providing the required downlink margin also.

For the user terminal, increasing the antenna size has several problems. An upper limit on the antenna size (6.6 feet) limits the possible increase in gain to 6 dB. A larger antenna would also increase the user terminal cost, and could impact the acceptance of user terminals for reasons noted in subsection 4.3.4. Because of the last problem, it is felt increasing the user antenna from the baseline 2.5 feet diameter is not a feasible option.

6.4.4.3 Use of Coding

One approach to providing the required margin is to use coding on the communications links to reduce the required E_b/N_0. This coding would be optimized for performance in Gaussian noise, and in addition to any message block coding (parity tail, checksum, etc.) and ARQ codes that might be required to achieve the very high probability of receiving error free data required by some applications.

Figure 3-9 showed the performance of several rate one-half codes that could be applied to this system. Although in theory as much as 9 dB could be gained by using coding, practical codes generally provide no more than 5 dB gain, depending upon the specifics of the coding used. As lower rate codes are used, higher gains are possible. For the sake of establishing the feasibility of using coding, we will limit ourselves to codes of rate approximately one-half as a reasonable compromise between coding gain and bandwidth expansion.

Both convolutional and block codes could be applied to this system. Since the data will be in a packetized format, a block code seems quite a natural choice. Numerous block codes with good performance have been discovered for operation with various size blocks and error correcting/ detecting capability. As this point, we are concerned only with the error correcting capability of the code in order to improve the basic error rate of the communication link. (Other error detecting codes may be required outside this coding.) Bose-Chaudhuri-Hocquenghem (BCH) codes [Bose, Chaudhuri, 1960], [Hochquenghem, 1959] are a fairly general class of codes which provide for multiple error detection and correction. Many of the smaller length block codes are actually special cases of BCH codes.

Decoding of BCH codes is unfortunately rather laborious. Numerous different algorithms have been invented for decoding BCH codes, each providing efficient operation in various applications, and are summarized in [Michelson, Levesque, 1985]. As the processing required to implement a BCH decoder is fairly complex, it requires specialized hardware in order to achieve the required decoding times.

BCH codes have been used with success in a number of different applications, but generally with differing block sizes and redundancy. Standard hardware for the decoding of BCH codes is thus not available, and would need to be developed for this system. This requirement for additional hardware for the decoding function would result in an additional cost in the terminal.

Convolutional codes are related to block codes, and can be decoded using maximum likelihood techniques [Viterbi, 1967]. Convolutional codes are slightly easier to decode than BCH codes, although a large quantity of processing is still required with longer constraint lengths. Convolutional codes may present an advantage from the implementation standpoint, as there are a limited number of "good" codes, and some standardization has taken place. Many communications systems make use of the rate one-half constraint length seven code, and integrated circuits to implement soft decision decoders have been developed by several companies. Although these decoders are currently commanding prices of several hundred dollars, these prices can be expected to drop in the next few years.

Software decoders have been built, but are generally limited to fairly low data rates (few kb/s) and may not be adequate for rates on the order of 9.6 kb/s. Encoders are very easy to build, and can be implemented in either software or a single programmable logic array, and thus would cost on the order of $5 to $50 depending on the data rate required. It thus appears that at the present, use of a convolutional code is probably more economical.

For the backhaul link, using coding would require the user terminal to include the coding function (a trivial expense), and require the supplier terminal to include a decoding function. The supplier terminal decoding would need to operate at the 200 kb/s channel burst rate, since there may be many different user packets on the channel. The available decoders can operate at this rate. As the supplier terminal may have M different receiver channels (one for each uplink beam), each receiver channel will need a decoder. Although this does not represent a trivial cost, it should be acceptable (it would add no more than $16 K to the cost of the supplier terminal).

By including coding, 5 dB less overall C/N_0 would be required. Thus, in the event of fading on both the uplink and downlink, the baseline design would be only uplink limited. As shown in Table 6-9, to achieve the same performance as in the unfaded environment the forward link would require an additional 8.8 dB EIRP on the uplink with no change to the downlink. For the backhaul link, we have traded some downlink margin for uplink margin (since the user terminals are EIRP limited), to arrive at requirements of +7.0 dB on the uplink and +4.8 dB on the downlink.

Table 6-9
Rain Compensation With Coding

Backhaul Link

	No Rain	Rain	Rain w/Coding	Rain w/Coding and Compensation
Uplink C/N_0	65.5	52.5	52.5	59.5 (+7.0 dB increase)
Downlink C/N_0	68.8	62.3	62.3	67.1 (+4.8 dB increase)
Overall C/N_0	63.8	52.1	52.1	58.8
Required C/N_0	63.5	63.5	58.5	58.5
Margin	0.3	(11.4)	(6.4)	0.3

Forward Link

	No Rain	Rain	Rain w/Coding	Rain w/Coding and Compensation
Uplink C/N_0	67.2	54.2	54.2	63.0 (+8.8 dB increase)
Downlink C/N_0	71.1	64.6	64.6	64.6
Overall C/N_0	65.7	53.8	53.8	60.7
Required C/N_0	65.3	65.3	60.3	60.3
Margin	0.4	(11.5)	(6.5)	0.4

Since the cost of the encoder added to the user terminal is considerably less than the expense that would be incurred in raising the terminal EIRP, it is therefore recommended that coding be used on the backhaul links. It is furthermore recommended that coding be used on all backhaul links. Since decoders will be needed anyway in any supplier terminals which service areas including wet regions, no additional requirements are imposed on these terminals. Supplier terminals serving exclusively dry regions would not need the coding, but since they would only service a single beam (and thus have a single, rather than M receivers) they would be considerably cheaper than other supplier terminals anyways. By including coding in all user terminals, a common terminal and system design would be achieved.

For coding to be used on the forward link, the supplier would be required to encode transmissions, and the user terminal would need to include a decoding function. In the worst case, a 300 kb/s decoder would be required, since all downlink trnasmissions would need to be decoded by the user terminal in order to determine which transmissions were addressed to it. If some other means of determining which slots to decode was available (i.e., unencoded addressing or fixed/dynamic slot assignments) then the terminal would need to decode just certain slots, and the rate of the decoder could be dropped down to the user data rate (i.e., 9.6 kb/s). The added cost to the supplier terminal would be just a few hundred dollars. The added cost to the user terminal would unfortunately also be a few hundred dollars, depending on the cost of the decoders. Since the effect of the coding is to aid the supplier terminal most, at the expense of the user terminal, coding on the forward link does not appear to be the most economical approach.

6.4.4.4 Site Diversity

Another technique that can be used to mitigate the effects of rain fading is the use of site diversity [Hogg, Chu, 1975]. Site diversity makes use of the fact that the high attenuations resulting from rain is generally uncorrelated between sites many kilometers apart. Diversity gain is defined by [Hodge, 1974] as the difference in fading between a single terminal and a pair of terminals for a fixed outage probability. It has been noted by [Goldhirsh, Robison, 1975] that the diversity gain as a function of the site separations at a fixed attenuation level is approximately independent of frequency. This conclusion seems to be supported by data from [Vogel, 1976] taken at 20 and 30 GHz. Thus, although higher frequencies may suffer more severe attenuation, they also benefit more from the diversity. Conversely, sites with fairly low attenuation will benefit little from site diversity. Achievable diversity gain as a function of site separation is shown in Figure 6-3 as extracted from [Goldhirsh, Robison, 1975].

Table 6-10 shows the uplink diversity gain that would be realized with a 12 km spacing for various regions of the country. Roughly half the fading and half the gain would exist on the downlink. These are the maximum gains, assuming the stations are located along a line perpendicular to the line-of-sight path. It can be seen that by using site diversity, the required margins cold be reduced considerably in the rainy portions of the country, from 19 dB to 6.5 dB. Little improvement is obtained in drier areas. The site diversity would improve both the backhaul downlink and the forward uplink.

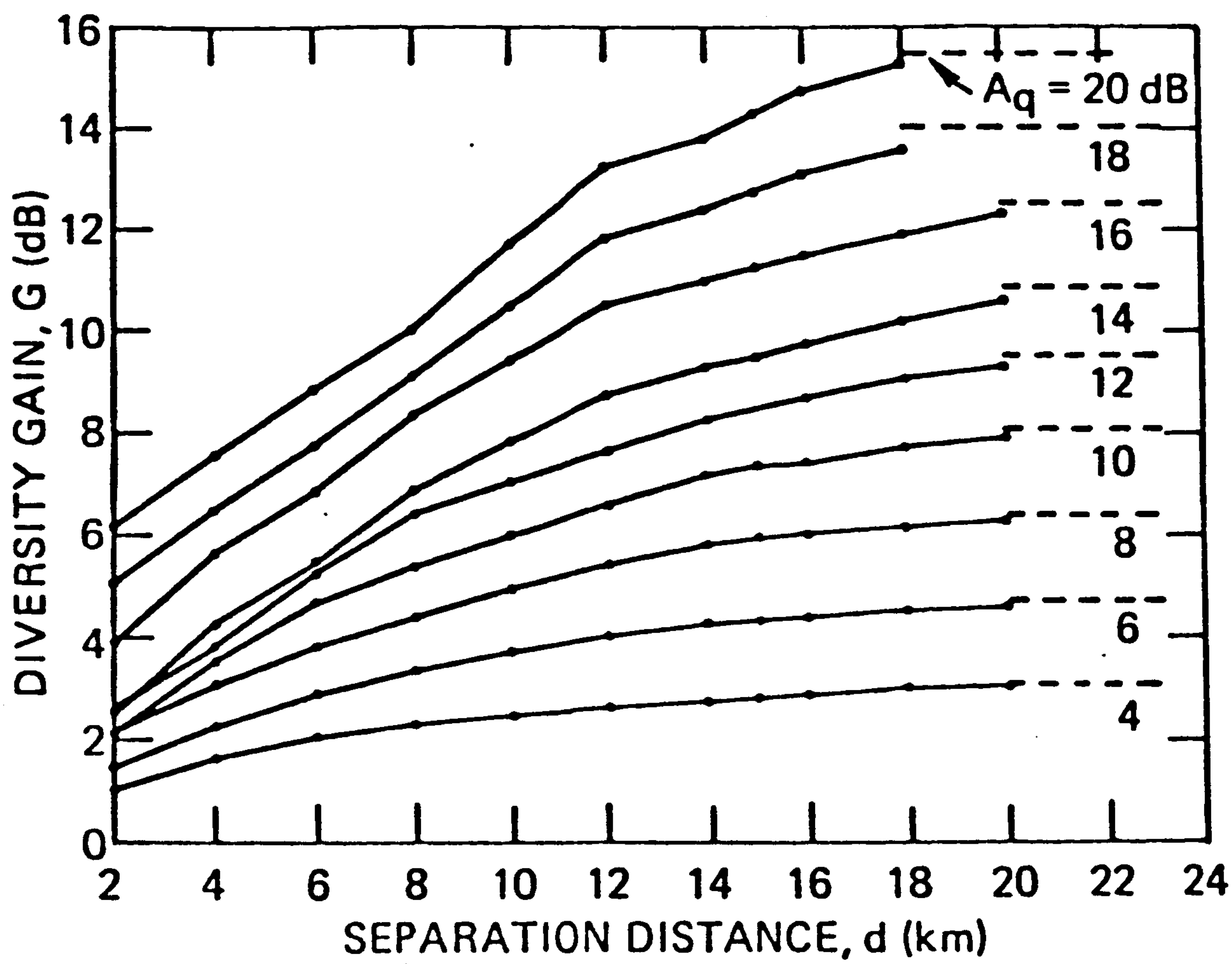

Figure 6-3 Diversity Gain versus Site Separation for Various Fade Depths (A_q).

C-3

Table 6-10
Site Diversity Improvement

Region	Uplink Fading	Site Diversity Improvement	Residual Fading
B	1 dB	0.5	0.5
C	5 dB	3.5	1.5
D_1	6 dB	4	2
D_2	9 dB	6	3
D_3	11 dB	7	4
E	19 dB	12.5	6.5
F	2.5 dB	1.5	1.0

Unfortunately, the site diversity approach requires not only a complete second station (thus doubling the cost of the supplier terminal), but also a link between the two stations such that the traffic can be switched between the two stations. Additional equipment would also be required to monitor the 20 GHz downlink and select the stronger station for operation. (Since fading between the two frequency bands is correlated, the same station should be used for both receive and transmit).

Since the required margins can be obtained via other techniques (larger supplier antenna and more power), use of site diversity does not appear economical. Site diversity may however be a worthwhile option when the required reliabilty of supplier terminals is considered. Since high reliability equipment required redundancy, essentially two stations would be needed anyways, thus the cost of an additional site might not be prohibitive. Since this study focused primarily on the user terminal trade-offs, this issue was not investigted further.

6.4.4.5 Reduced Beam Size

It is also possible to provide additional margin by altering the satellite design. The baseline satellite design assumes state-of-the-art LNR and TWT performance, so no improvement here is possible. On the other hand, the antenna beam size could be reduced thus increasing the antenna gain.

A straightforward increase in the number of beams from M=32 to M=47 would yield a gain of 2.3 dB on the backhaul uplink and forward downlink. Unfortunately, as noted in subsection 6.4.3.2, supplier terminals serving large coverage areas would need more receiver channels in order to receive information from all beams. In light of the small improvement that can be achieved this way, it is not recommended.

A slightly different approach is to use different beam sizes for the various regions. The dry regions could be covered by large beams (and hence less gain) while the wetter regions would be covered by smaller beams (and hence more gain). An approach for generating three different beam sizes (common to uplink and downlink) from two sets of horns and a single sandwiched reflector has been suggested by [Berk, et.al., 1981], but problems with physically arranging the feeds were noted. Assuming these problems could be solved, variable uplink compensation could be built into the satellite as shown in Table 6-11. The number of beams is held constant at M=32, but the number of beams in dry areas is reduced (and the beam size increased), while the number of beams in wet areas is increased. Although only 4 dB of the 19 dB fade is gained back using this approach, the difference between maximum fades is reduced 28 percent (18 to 13 dB). The results shown in Table 6-11 are a best case scenario. Geographical limitations will generally not allow such a neat solution, hence a slightly larger number of beams (or less gain) will result.

In order to develop the differing beam sizes, the reflector size is increased as needed for the smallest beams. For the wider beams, the feeds illuminate only a portion of reflector surface. In order to achieve the beam sizes shown, the satellite downlink reflector size would need to be increased from 4.5 feet (1.3 m) to 6.9 feet (2.1 m).

Little information is available concerning the construction of multi-beam satellite antennas with differing beam sizes. In light of the

Table 6-11
Variable Beam Size Approach to Rain Compensation

Region	Relative Area	Uplink Fading	No. of Beams (0.8° Spots)	No. of Beams (Variable Spots)	Beam Size	Gain	Residual Fading
B	0.15	1.0 dB	5	4	1.0°	-1.0 dB	2.0 dB
C	0.07	5.0 dB	2	2	1.0°	-1.0 dB	6.0 dB
D_1	0.23	6.0 dB	7	6	1.0°	-1.0 dB	7.0 dB
D_2	0.17	9.0 dB	6	6	0.7°	+1.0 dB	8.0 dB
D_3	0.10	11.0 dB	3	4	0.7°	+1.0 dB	10.0 dB
E	0.09	19.0 dB	3	5	0.5°	+4.0 dB	15.0 dB
F	0.19	2.5 dB	6	5	1.0°	-1.0 dB	3.5 dB
	1.00		32	32			

relative immaturity of this type of antenna, and questions regarding the physical arrangement of the beams, it is not recommended as an approach to providing the required margin. This is an area that should be considered for future study.

6.4.4.6 Satellite Processing and Power

Baseband processing was investigated in subsection 6.4.1 as an alernative for gaining link margin, but was discarded in favor of other approaches. We now reconsider the use of baseband processing (demod/remod) in order to provide some additional margin.

For the revised baseline design, adding demod/remod in the satellite would provide approximately a 2 dB margin on the uplink, and a 5 dB margin on the downlink due to the decoupling of the uplink and downlink noise. The added weight and power for simple demod/remod processing is fairly small, so this is an atrracive option.

We could also modify the satellite downlink power allocation for the various spot beams. The baseline design provides the same power to all beams. This results in excess margin for dry areas, and inadequate margin for wet areas. Without increasing the total power demand, we can re-allocate the power for each beam according to the expected fading.

Table 6-12 shows how we could vary the power for the various regions; PA's for beams covering region E would be increased 5.2 dB from the baseline 5 W amplifiers to 16.5 W; PA's for regions B would be reduced 3.8 dB, to 2.1 W, etc. This results in the same margin for all links when downlink fading is taken into account. Unfortunately a deficit of 1.3 dB exists in all cases.

Table 6-13 shows the results of a combined approach. Baseband demod/remod is used on beams in region E (gaining 5 dB of downlink margin for those links). Again, the total power is left constant, but since less gain variation is required, a positive 0.5 dB margin is achieved on all links.

Since the baseband processing is done just in region E, it is only needed on approximately 3 beam x 4 channels = 12 channels. Thus, the impact on satellite weight is minor, estimated at less than 20 lbs. The satellite power is increased only by the added baseband processing hardware (the total transmit power was left unchanged) by about 20 watts. Thus, this combined approach looks quite good for combating the forward downlink fading.

6.4.4.7 Spread Spectrum

In a spread spectrum multiple access system, vastly different approaches to rain compensation are possible. In particular, increased margin can be obtained by merely increasing the spreading factor (bandwidth) of the system.

Note that since the SSMA system is interference limited, increasing all of the terminal's EIRP will not provide any increased margin. The required margin can be obtained by increasing the spread factor. Providing the required 19 dB margin for region E would thus require increasing the spreading factor by 79.4.

Table 6-12
Downlink Power Adjustment for Fading

Region	Number of Beams	Power Adjustment	Downlink Fading	Rain Margin	Total Margin
B	5	0.42 = -3.8 dB	0.5 dB	3.0 dB	-1.3 dB
C	2	0.66 = -1.8 dB	2.5 dB	3.0 dB	-1.3 dB
D_1	7	0.74 = -1.3 dB	3.0 dB	3.0 dB	-1.3 dB
D_2	6	1.05 = 0.2 dB	4.5 dB	3.0 dB	-1.3 dB
D_3	3	1.32 = 1.2 dB	5.5 dB	3.0 dB	-1.3 dB
E	3	3.31 = 5.2 dB	9.5 dB	3.0 dB	-1.3 dB
F	6	0.50 = -3.05 dB	1.25 dB	3.0 dB	-1.3 dB

Table 6-13
Downlink Power Adjustment for Fading
with Baseband Processing

Region	Number of Beams	Power Adjustment	Downlink Fading	Rain Margin	Total Margin
B	5	0.63 = -2.0 dB	0.5 dB	3.0 dB	0.5 dB
C	2	1.00 = +0.0 dB	2.5 dB	3.0 dB	0.5 dB
D_1	7	1.12 = +0.5 dB	3.0 dB	3.0 dB	0.5 dB
D_2	6	1.58 = +2.0 dB	4.5 dB	3.0 dB	0.5 dB
D_3	3	2.00 = +3.0 dB	5.5 dB	3.0 dB	0.5 dB
E	3	1.58 = +2.0 dB	9.5 dB	8.0 dB	0.5 dB
F	6	0.75 = -1.25 dB	1.25 dB	3.0 dB	0.5 dB

Since the traffic of each beam uses a separate SSMA channel, all the users of a particular beam will have similar rain attenuation statistics. Therefore, the spread factor for each beam could be optimized for the worst case rain fade. Table 6-14 lists the additional spread factor and the percentage of traffic expected of each region. The sum of their products yields the total additional bandwidth spread factor needed to compensate for the uplink rain attenuation.

The drawback to this approach is the non-uniform chip rates of the user terminals. Some additional bandwidth could be traded for more uniform chip rates (two or three rates used to cover all seven regions).

Other alternatives are the non-uniform spot beam sizes of Subsection 6.4.4.5, or a reduced availability in the wetter climates.

6.4.4.8 Rain Compensation Conclusions

We have found techniques to achieve the required margin on three of the four links; the backhaul downlink, and the forward uplink and downlink. We have also achieved a portion of the required margin on the backhaul uplink. Table 6-15 summarizes the selected approaches. Our only remaining problem is to provide an additional 7 dB of margin on the forward uplink.

Unfortunately, little can be done in the satellite to help the backhaul uplink; the satellite LNR is already state-of-the-art; smaller beams and baseband processing provide little additional margin at considerable cost. Thus, the only available options for gaining the required 7 dB are to 1) increase the user antenna size to 4.6 ft, 2) increase the user HPA power to 5 W, or 3) employ non-uniform spot beam sizes.

None of these approaches are particularly desirable. Although the first two are technically feasible, they have other problems. Increasing the amplifier gain is economically unattractive. Increasing the dish size not only is economically unattractive, but may impact consumer acceptance of the system. Building conformal phased array type antennas would solve the acceptance problem, but is currently economically unattractive. Further examination of non-uniform beam forming is needed before the last option can be recommended. Thus, for terminals in region E, these technology areas become major issues.

6.5 RECOMMENDED SYSTEM DESIGNS

This tradeoff section has identified two alternative system approaches for the FSS system: one based on Pure ALOHA access to 200 kb/s FDMA channels, and a SSMA system at the user data rate. We will summarize these two approaches here and present estimates of the total system cost.

6.5.1 Pure ALOHA System

This system is the most straightforward approach to a FSS design; all of its components are proven technology. Table 6-16 summarizes this design. Even with the additional power, larger terminal antenna sizes, and multibeam satellite antenna, the backhaul uplink is still 7 dB shy in the wettest climate region. (The required link margin is met in all other regions.) Thus cost of terminals in this region will have to be more expensive or the 0.995 availability will not be met.

Table 6-14
Rain Compensation for SSMA

Region	Probability P_r(%)	Uplink Fade Margin F_r and Spread Factor	P_rF_r
B	1.3	1 dB = 1.26	0.0164
C	6.8	5 dB = 3.2	0.218
D_1	7.4	6 dB = 4	0.296
D_2	46.3	9 dB = 7.9	3.66
D_3	9.4	11 dB = 12.6	1.2
E	11.8	19 dB = 79.4	9.37
F	17.0	2.5 dB = 1.8	0.306
		Total Bandwidth Increase	15.1

Table 6-15
Rain Compensation Approach

	Backhaul Uplink	Downlink	Forward Uplink	Downlink
Coding (Backhaul)	+6 dB	+1.7 dB		
Larger Supplier Antenna to 17.4 feet		+4.8 dB	+4.8 dB	
Satellite Demod/Remod Region E and Non-uniform Beam Powers				+7.0 dB
Increase Supplier Transmit Power to 53 W			+8.2 dB	
TOTAL	6.0 dB	6.5 dB	13.0 dB	7.0 dB
Required	13.0 dB	6.5 dB	13.0 dB	6.5 dB
Excess Margin	(7.0) dB	0 dB	0 dB	0.5 dB

Table 6-16
Recommended System Design

User Terminals

Pure ALOHA Access
200 kb/s burst rate
2.5 foot antenna
1 to 5 W HPA
500°K LNA
Rate 1/2 convolutional encoder
FLL receiver accuracy of 10 kHz

Supplier Terminals

TDMA access
300 kb/s burst rate
17.4 foot antenna
53 W HPAs
400°K LNAs
Soft-decision Viterbi decoders

Satellite

FDMA/TDMA hybrid
32 spot beams (0.8°) to user terminals
- 4.3 foot donwlink reflector
- 2.9 foot uplink reflector

1 CONUS beam to supplier terminals
Separate TWTA for each channel of traffic (saturated operation)
TWTA power on spot beams based on maximum fade margin
- 3.2 W to region B
- 10 W to region E

Signal regeneration of region E traffic
Number of channels per beam proportional to expected traffic
4 dB noise figure LNR
Pilot tone in CONUS beam

6.5.2 Spread Spectrum Multiple Access System

Because of the many advantages and disadvantages of an SSMA system relative to Pure ALOHA, and due to the uncertainty of the cost of the RF components of the user terminals, we recommend that SSMA be left open as an alternative for the backhaul links. Since the 9600 b/s data rate would require up to 13 dB less C/N_0 on this link, the necessary link margins could be easily met. This would enable both the user terminals and satellite to operate with less power. The penalties are 1) a factor of ten more bandwidth required on the backhaul link (533 MHz vs 55 MHz), and 2) a factor of twenty more accuracy in the terminal's frequency tracking circuitry (500 Hz versus 10 kHz). At Ka-band, the former is not necessarily disasterous, and the latter can be dealt with by further research and larger production quantities.

6.5.3 Cost of Recommended System

6.5.3.1 Satellite Cost

In subsection 6.3.2, we presented some rule-of-thumb relationships between satellite cost and weight. Although these relationships are gross estimates at best, they will provide some information for future use if this FSS concept is pursued.

Equation (6.14) approximates the BOM satellite weight as a function of its communications package power and weight. We can use Equations (6.4) through (6.6) to derive the weight of the satellite antenna and transmitter and the other components were estimated in Tables 5-1 and 5-3. Since the forward and backhaul links are completely separate and use separate components, both must be accounted for in the calculations. These weight calculations are shown in Table 6-17. The prime power calculation uses Equation (6.7) to obtain the DC to RF efficiency. Since the HPAs can operate at saturation, we have assumed a η_{TWT} of 0.4 and therefore η is 0.34.

Similarly, the communications package power requirement can be derived. The primary power consumers are the HPAs. We showed in Subsection 6.4.3.1 that approximately 3200 W of power are required by the 192 TWTAs onboard the spacecraft. The power requirement of the other components of the FDMA/TDMA hybrid satellite architecture from Table 5-3 is 128 W, and the signal regeneration of region E traffic consumes 20 W. The total of these components' power requirements is 3350 W. When the power supply efficiency η_{PS} is taken into account, the power requirement of the communication package (P_c) is 3350 W/0.85 = 3940 W.

Equation (6.14) can then be solved by using these values of W_c and P_c:

$$\begin{aligned} W_{sat} &= 800 + 1.53(2000) + 0.8(3940) \\ &= 7000 \text{ lbs.} \end{aligned}$$

This is a very heavy satellite, beyond capabilities of most launch vehicles. Presently, only the US space shuttle (STS) has the capability of lifting a payload of this size.

The total satellite power can also be calculated. By using Equation (6.15), this power requirement is:

Table 6-17
Satellite Communications Package Weight

W_{ant}	$= 20\ D_{20} + M/9$ $= 20(4.265) + 32/9$	=	90 lbs
W_{TWTA}	$= M \times L \times (1 + P/12)$ $= 32\ [4 \text{ channels} \times (1 + 7.5/12)$ $+ 2 \text{ channels} \times (1 + 5/12)]$	=	300 lbs
W_{pp}	$= 0.4 \times M \times L \times P/\eta$ $0.4 \times 32 \times [4 \times 7.5 + 2 \times 5]/0.34$	=	1505 lbs
Other components		=	98 lbs
Demod/remod of 12 channels		=	14 lbs
W_c			2000 lbs

$$P_{sat} = 240 + 1.26(3940)$$
$$= 5200 \text{ W of DC power.}$$

Using current solar panel efficiencies of almost 9 W/ft^2, this satellite would need roughly 580 ft^2 of panels.

The last step is to use the weight figure to estimate the costs of the spacecraft development. From Equation (6.12), the recurring cost is

$$C_R = 0.031 \ (7000 \text{ lbs})^{0.93}$$
$$= \$116.7M.$$

The non-recurring cost from Equation (6.13) is

$$C_{NRE} = 0.16 \ (7000 \text{ lbs})^{1.15}$$
$$= \$422.7M.$$

At first glance, these values seem unrealistic. However, as we have noted, these cost relationships are old and of questionable accuracy. A more detailed cost analysis is warranted if a FSS system is to be pursued. The SAMSO Unmanned Spacecraft Cost Estimation Model developed by Aerospace for the US Air Force Space Division could potentially be used for this purpose.

An alternative is the use of more than one satellite. By using two satellites, each generating half (16) the spot beams, many of the power and weight problems would be solved. For example, the payload weight would be quite manageable for several available lauchers, and the non-recurring, developmental cost could be halved.

It should be noted that the satellite power, and hence the weight, is driven by the backhaul TWTAs which amplify the signals destined for the CONUS beam. With 128 tubes each consuming 7.5 W of output power, 2400 W (or 72% of the satellite's total power requirement) are needed by this backhaul link. Since this link is uplink limited, especially from region E, the downlink power could be cut in half with only a 0.4 dB reduction in margin (to -6.8 dB) for that region. All other regions would have positive link margins. This would reduce the communications package power requirement P_c to 2530 W and weight W_c to 1400 lbs. This in turn cuts the overall satellite weight and power to 5000 lbs and 3430 W. These totals would be more realistic for a single satellite system design.

6.5.3.2 Ground Segment Costs

Determining the ground segment costs is unfortunately rather difficult due to the current immaturity of components operating in the 30/20 GHz range. These components are only available in quite limited quantities, if available at all. Furthermore, since most development efforts in the millimeter wave region are military sponsored, the costs of these components are generally quite extreme. Cost data for consumer versions of 30/20 GHz electronics is simply not available.

Thus, two approaches to estimating the terminal costs have been taken. The first is to compare the capabilities and costs of current small aperature terminals with the capabilities required for the 30/20 GHz terminals envisioned by this study. By comparing the required capabilities of our baseline terminals with existing C and Ku-band terminals for which there is cost data available, we can at least get an order of magnitude idea of what the cost should be. The second approach is to estimate the cost of terminals on a component basis, using a combination of current cost data, learning curve relationships, and educated guesses.

Although neither of these techniques will yield particularly accurate results given the rather sparse data available, we feel that the results will provide a bound on the cost of the terminals, and at least highlight those areas of the terminal that impact the cost the most.

Only the user terminals are considered, since their cost is so important. Because there could be so many user terminals, any increase or decrease in their cost would be multiplied. Improvements in the cost of the user terminals would most likely be in the RF areas and would be shared by the supplier terminals. Thus, inexpensive user terminals are the key to economic feasibility.

6.5.3.2.1 Small Aperature Terminal Costs

Cost ranges for small aperature terminals were obtained from a variety of sources and have been compiled in Table 6-18. The frequency and performance capabilities of these terminals is from C-band receive only terminals to Ku-band full duplex, high data rate terminals. The far right column of Table 6-18 shows an extrapolated terminal cost based upon a million terminal production quantity, using the learning curve relationships from [Berk, et al., 1981].

Besides the obvious difference in frequency from our 30/20 GHz terminals, these terminals also have other more subtle differences which make them generally more complex than our 30/20 GHz terminals would be. C-band TVRO terminals, for example, require antenna pointing systems since there are a number of satellites that a user may wish to watch. TVRO terminals are also designed for relatively wide bandwidth analog television channels. On the other hand, they do not include any transmission or access control equipment. Frequency accuracy is also not as much of an issue as it is at Ka-band.

Both C-band and Ku-band VSATs generally use TDMA access schemes, and thus require more control hardware than would be required for our simpler access schemes. VSAT antennas are also usually larger, in the 4 to 6 ft range.

Thus, the complexity of the terminals required for the FSS system should lie somewhere between the complexity of the TVRO and full duplex VSATs, probably closer to the VSATs. Thus, Ka-band FSS terminals would cost at least $4,000 (Ku-band low data rate terminals), and would probably cost about $10,000 (the same as the most expensive Ku-band terminals).

Of course, this is a rather crude estimate. An estimate based upon the various components of the block diagram is done below to further refine this estimate.

Table 6-18
VSAT and TVRO Terminal Cost Data

Frequency	Capability	Quantities	Cost (K$)	Quantity Cost (K$)
C-band	Receive Only Television	millions	1-2	1-2
C-band	Receive Only ~ 19 kb/s	30,000	2	1.5
C-band	Full Duplex ~ 19 kb/s		5-6	3-4
Ku-band	Receive Only	1,000(?)	1-5	1-3
Ku-band	Full Duplex ~ 19 kb/s	1,000	7-10	4-5
Ku-band	Full Duplex	100	15-20	7-11

6.5.3.2.2 Terminal Component Costs

The second approach to estimating the terminal cost is to sum up the cost of the components of the terminal. For some portions of the terminal, cost data for Ka-band components is available, where for other portions cost data must be extrapolated from similar equipment operating at different frequency bands. Detailed derivation of cost/performance relationships for the RF components (LNA, HPA, and antenna) is presented in Section 7.1.

Cost data for currently available LNAs operating at 30 GHz was obtained from several sources. LNAs with noise temperatures as low as 300 K are currently available as catalog items, with prices running in the range of $5,000 to $10,000. LNAs for commercial purposes in large production quantities should be considerably cheaper. Quantity prices for LNAs was extrapolated from C-band and Ku-band TVRO data which indicates that the prices of commercial quantity LNAs could come down to as low as $100-$300 in the near term if large production volumes are realized.

1 Watt solid state amplifiers in the 30 GHz range have just recently become available as catalog items. Currently solid state HPAs cost about the same as TWTAs for low power levels. Both types of amplifiers are currently commanding prices of about $20,000-$30,000, although significant price drops are likely in the near term for the solid state amplifiers.

If we assume the solid state amplifiers will show similar price drops in the future as those indicated by the LNAs, 1W solid state HPAs might be available for $400 to $900 by the mid 1990s.

For the antenna, most currently available antennas operating in the 30/20 GHz bands are quite expensive, but are also considereably more complex and higher performance than required for this application. Based on the cost of C and Ku-band dishes, a 2.5 ft 30/20 GHz antenna should run about $150 to $200 in production quantities. Existing C or Ku-band antennas could probably be adapted to Ka-band use by installing a Ka-band feed on an existing dish design, resulting in a $500 to $1000 antenna in the near term.

The cost associated with the pilot tone tracking receiver is likely to be a significant contributer to the overall cost. The pilot tone tracking receiver will require components operating in the 30 GHz range. We have assumed the cost of this circuitry would be about $2,000 currently, possibly coming down to $500 in the mid 1990s. Major breakthroughs in this area may be required in order to achieve these estimates.

Of the upconverter and downconverter, most of the cost is in the downconverter; no upconverter is necessary if a direct carrier modulation scheme is used. TVRO receivers/downconverters run about $400 currently, and are probably more complex than would be required for the Ka-band system. TVRO receivers must tune various frequencies, control the antenna positioner, and tune over fairly wide bandwidths, and generally provide user-features such as frequency memories, etc. Fairly little tuning capabilities would be required for the FSS receiver, and no user interface would be required (any required channel selection would be done automatically by software in the PC). Thus, the increased cost of doing downconversion from Ka-band rather than C or Ku-band should be offset by the less complicated design required. Intially these receivers would of course be more expensive, probably $1000 or so.

Other components of the terminal are less critical as they do not require any millimeter wave circuitry. This includes the modem and control/ interface hardware. A 300 kb/s demodulator and 200 kb/s modulator are also required (modem). The cost of the modulator and demodulator are fairly low, and the required components are available off-the-shelf.

Some control hardware is required for the forward link in order to extract the desired packets of information and demultiplex the 300 kb/s data stream from the demodulator. This would be beyond the capability of the PC, making this additional hardware necessary. Only a small amount of hardware would be required to implement this control. The remaining control could be done in software in the PC (formatting and buffering packets and processing acknowledgments, etc.).

Table 6-19 shows the estimated components cost of the terminal, both for 1986 and as extrapolated in the mid 1990s. These cost figures are in 1986 dollars. Complete terminal costs would range higher, as assembly and testing costs are not included. It can be seen that although to build a 30/20 GHz user terminal would cost at least $29,000 to $45,000 now, this price could drop considerably by the mid 1990s. This would require, however, that volume production of commercial components occur for the millimeter wave components, and may require a breakthrough in achieving the required frequency accuracy (i.e., a more economical scheme than the pilot tone tracking, or inexpensive millimeter wave sources). By optomistically assuming these developments occur in the near term, terminal prices are envisioned to come down into the $2,000 range. A more conservative estimate would place the terminal price in the $5,000 to $10,000 range in the mid 1990s.

Table 6-19
Terminal Component Costs

Component	1986	mid 1990s	Required Development
Antenna	500-1000	150-200	--
LNA	5,000-10,000	100-300	mass production
HPA	20,000-30,000	400-900	mass production
Pilot Tone Receiver	2,000 (?)	500 (?)	breakthrough
Up/Down Converter	1,000	400	mass production of mm wave components
Modem	500	100	--
Control/Interface Hardware	200	50	--
TOTAL	29,200-44,700	1,700-2,450	

SECTION 6
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SECTION 7
TECHNOLOGY CONSTRAINTS AND COST DRIVERS

In this section we summarize the current status of the technology required for the proposed system. We focus first on the ground terminal technology required to implement the user terminals. We consider primarily the millimeter wave components, for which we derive cost versus performance relationships where ample data is available. We then examine some of the key technologies required for the satellite design.

7.1 USER TERMINAL

Our baseline design has resulted in a terminal design that requires component performance levels that are within the demonstrated state-of-the-art. This was done intentionally in order to achieve a technically feasible terminal design. This does not mean, however, that the components are readily available or easily manufactured. Many of the required components are currently extremely expensive. Thus, we now examine these key components with an eye towards their relative maturity. Specifically, we are concerned with the mass producibility and cost of the components.

7.1.1 Terminal Antenna Manufacture

The terminal antenna does not appear to be a terminal cost driver or represent a technological risk. For small antennas in the range of interest (2.3 to 6.6 feet), a number of manufacturing techniques are possible; stamping (sheet metal), spinning (fiberglass), molding, and machined casting, depending upon the required surface accuracy [Frediani, 1979].

In subsection 4.2.1.2 it was shown that surface accuracies on the order of 0.015 inches are required in order to limit the loss due to surface roughness to less than 1 dB at 30 GHz. Achieving this accuracy would require expensive precision spinning or molding, the more expensive techniques. Stamping the antennas out of sheet metal would result in surface accuracies of only about 0.025 inches, corresponding to a loss of 2.7 dB at 30 GHz and 1.2 dB at 20 GHz.

Currently TVRO antennas are mass produced by assembling panels of stamped sheet metal. This results in surface accuracies of 0.020 to 0.025 inches, quite acceptable for the 4 and 16 GHz bands on which they are used. These antennas are fairly low cost, ranging from $200 to $900, depending on size. Smaller antennas built using this technique would be quite inexpensive.

For the 30/20 GHz band, this low cost manufacturing technique could be used if manufacturing tolerances could be improved. Improving the surface accuracy from 0.025 to 0.015 inches would yield a 1.7 dB improvement at 30 GHz. This should be possible with the small 2.5 foot dishes. Molded fiberglass might also be able to inexpensively provide 0.015 inch surface accuracy from a one piece mold.

A more difficult problem with the manufacture of antennas for 30/20 GHz is the difficulty of properly aligning the feed [Berk, et.al., 1982]. This is caused by the very tight tolerances and narrow beams resulting from the small wavelength. Assembly of the antenna may be the limiting factor in the the manufacturing process.

Figure 7-1 illustrates the gain that can be expected at 30 and 20 GHz for parabolic antennas in the 2.3 to 6.6 foot range. This gain assumes aperature effeciencies of 55%, and the worst case 0.025 inch surface accuracy, and thus represents a lower bound on the antenna gain.

Price versus performance for parabolic dishes at 30 GHz is illustrated in Figure 7-2. This price relationship was obtained by scaling the price versus performance relationship for 4 and 12 GHz TVRO antennas. Price information from a number of commercial TVRO dealers was obtained. Since the same manufacturing techniques are used, the same cost versus size relationship for the basic dish was assumed. The cost of the Ka-band feed will be higher, and was estimated from a comparison of C and Ku-band feed costs.

Since the prices on 4 and 12 GHz equipment represent different points on the learning curve (millions of 4 GHz antennas have been built, where only thousands of 12 GHz antennas have been built), these prices were corrected for varying quantities using a learning curve relationship for millimeter wave equipment suggested by [Berk, et.al., 1981]. The price of the n^{th} terminal C_n is given by

$$C_n = C_1 n^{-0.074}$$

where C_1 is the cost of the first terminal. It is assumed that component costs follow this same learning curve. A sales volume of 500 thousand was assumed in computing the cost of the Ka-band antennas.

Phased array antennas are another option that has been suggested, and may provide some solutions to the problems with parabolic dishes. Phased array antennas can be built using microstrip technology. Microstrip is an easily fabricated structure, where parallel plate waveguide is implemented by fabricating a circuit board trace over a ground plane. Microstrip circuits can thus be produced by etching printed circuit boards in the usual manner.

Although single microstrip elements have low gain and bandwidth, phased arrays can, and are, being built [Ladrach, et.al., 1982]. Such antennas should be quite easy to manufacture. We envision it might be possible to manufacture a phased array antenna by simply printing the array pattern with a conductive ink on to a flexible substrate.

Thus, it might be possible for the cost of this type of antenna to be considerably less than that for the parabolic dishes. In addition, phased arrays also present the advantage of being less conspicuous. Achieving gains with the phased array similar to the parabolic dish will require arrays of comparable area (i.e. 5 to 30 square feet).

There is considerable interest in the development of conformal antennas for military airborne applications. We expect considerable progress in this area is likely in the next few years. This technology should be monitored for possible application to the 30/20 GHz FSS.

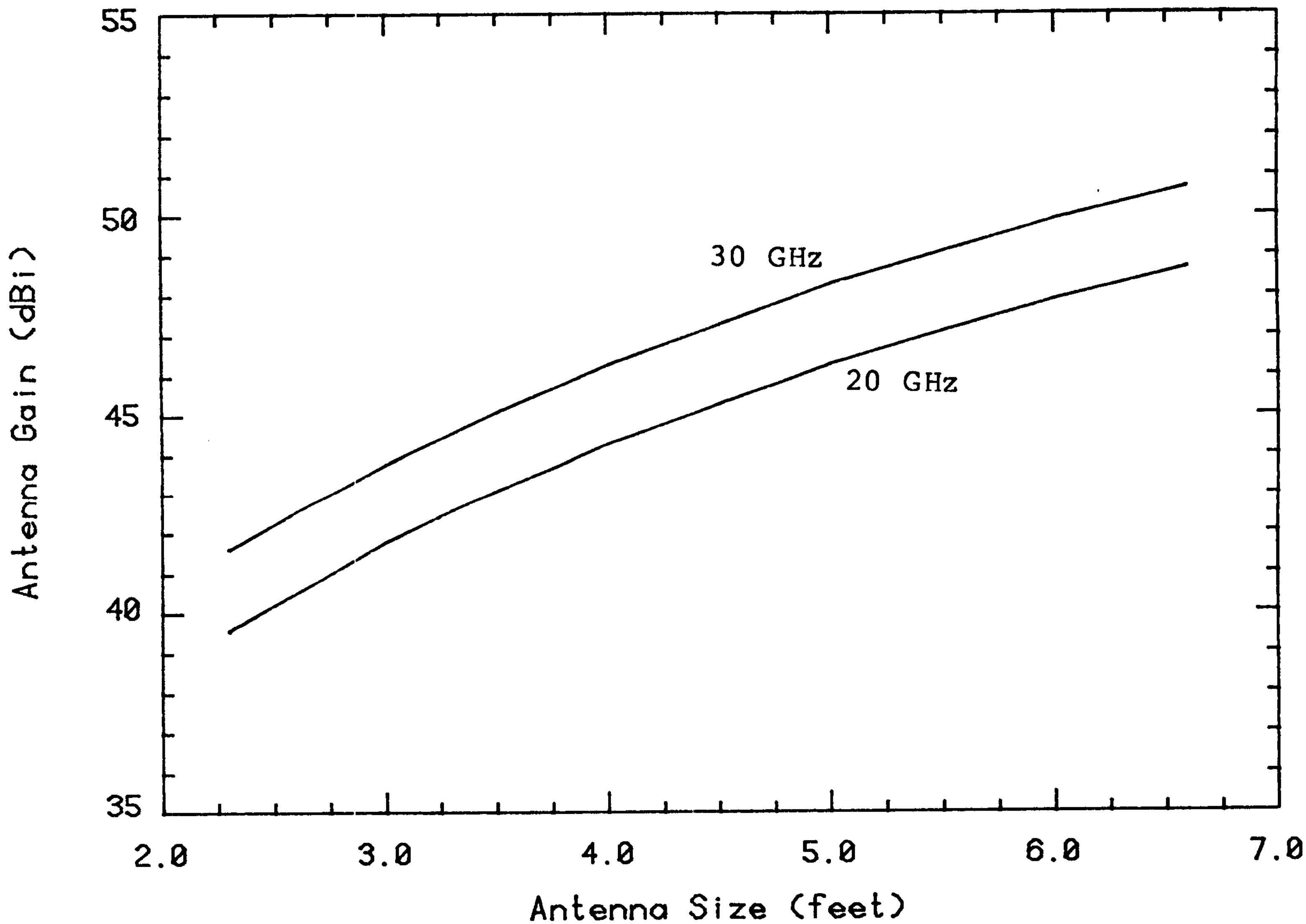

Figure 7-1 Antenna Gain versus Antenna Size.

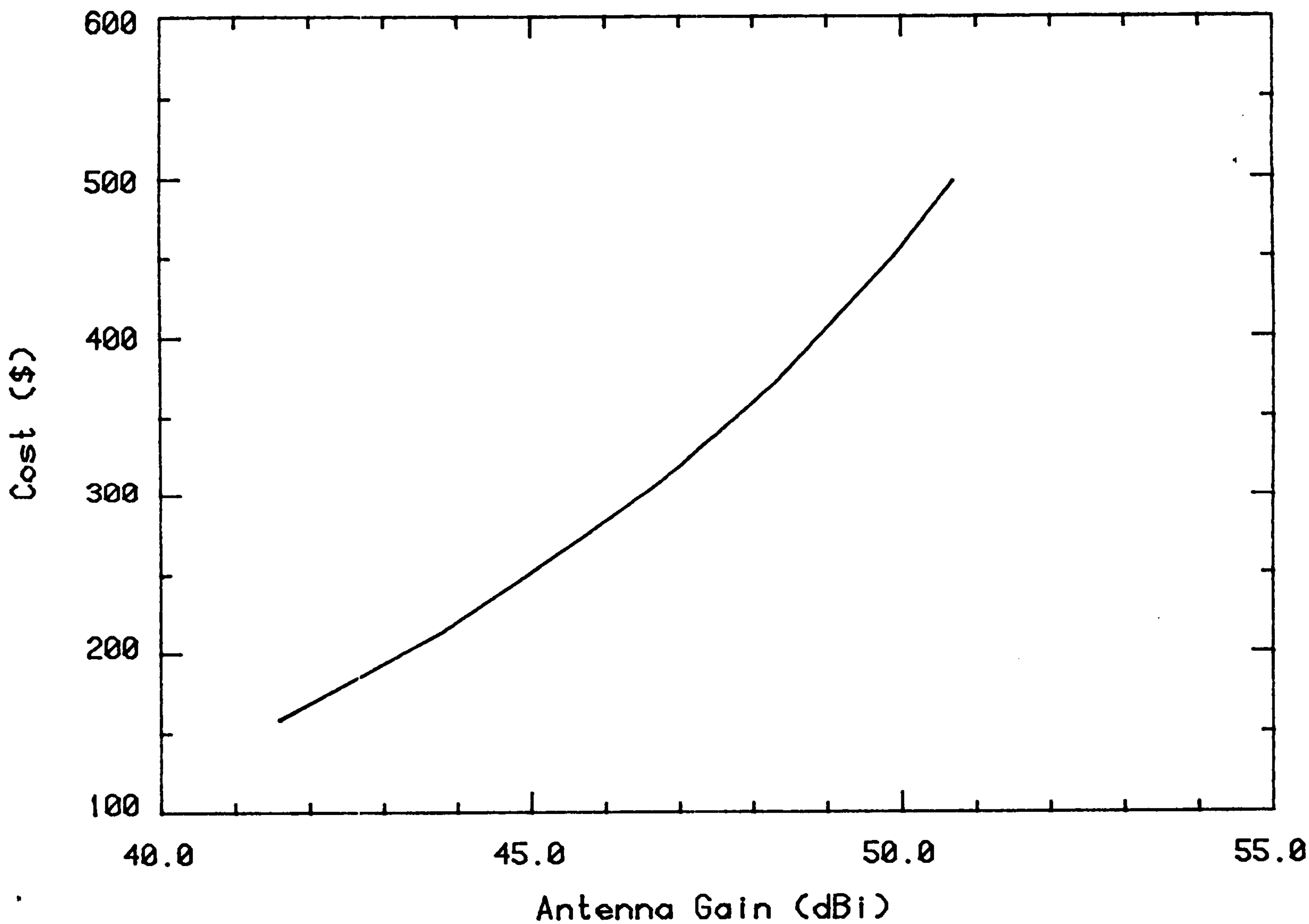

Figure 7-2 Antenna Cost versus Antenna Gain at 30 GHz.

7.1.2 Terminal HPA

The terminal HPA may represent a significant cost driver in the overall terminal design. Although a fair amount of development of solid state power amplifiers in the millimeter wave bands has been done, to our knowledge, no large scale production has been done.

The most commonly used power device for 30 GHz and above is the IMPATT diode. As of 1983, pulsed amplifiers with peak outputs of up to 28 W, and CW amplifiers with outputs of up to 2.5 W had been demonstrated at 30 GHz [Blakey, et.al., 1983]. The higher power amplifiers are built by combining a number of lower power devices (see Subsection 5.4.2). More recently, solid state amplifiers with up to 35 W have been available in the millimeter-wave bands.

The individual device power is currently limited to about one watt, and high output devices do not appear likely in the near term, as the output power of IMPATTs is limited by electronic and thermal mechanisms. Thus, 5 to 10 W amplifiers will probably continue to require multiple devices and combining. The combining circuitry is usually implemented in microstrip. Figure 7-3 extracted from [Ying, 1983] illustrates the state-of-the-art in solid state HPAs. Not too much improvement has been achieved in the last few years except at 20 and 44 GHz where higher power amplifers are being built for military systems [AFSC, 1985].

No information concerning the mass producibility of these amplifiers was available; it is believed that little work has been done in establishing repeatability and mass producibiity for these amplifiers. Thus, future efforts in these areas should be encouraged. TI has recently been awarded a million dollar contract to develop "affordable" amplifiers for operation in a 60 to 18 GHz range [MSN, 1986].

7.1.3 Terminal LNA

A conservative terminal design was selected with respect to the LNA performance requirement. A 500°K device (4.4 dB noise figure) was assumed which is well below the current state-of-the-art. Currently 3.5 dB noise figure devices are available off-the-shelf (although at considerable expense). Higher performance devices have been demonstrated, as low as 2.0 dB [Sakurai, 1986]. Since sky background sets a limit on the improvement that can be obtained by better noise figure amplifiers, no advancement of the state-of-the-art in LNAs is required for the baseline system design.

The ability to build, in quantity, affordable LNAs at lower frequencies has been demonstrated by the TVRO industry. It seems reasonable to expect the same will be possible at the higher frequencies. Currently, however, there is a large gap in the price of LNAs for consumer use at 4 and 12 GHz which run between $100 and $400, and the prices for LNAs at 20 GHz which can be on the order of $5000. It should be noted that LNAs for 20 GHz are primarily targeted at military users and thus are produced in small quantities and enjoy relatively little competition.

Price reduction in LNAs seem quite likely in the future, especially if large consumer volumes can be established as was the case for TVRO. Figure 7-4 illustrates the price versus performance relationship for 20 GHz LNAs extrapolated from the TVRO data. Again, the prices have been corrected for the learning curve relationships. A sales volume of 500 thousand was assumed.

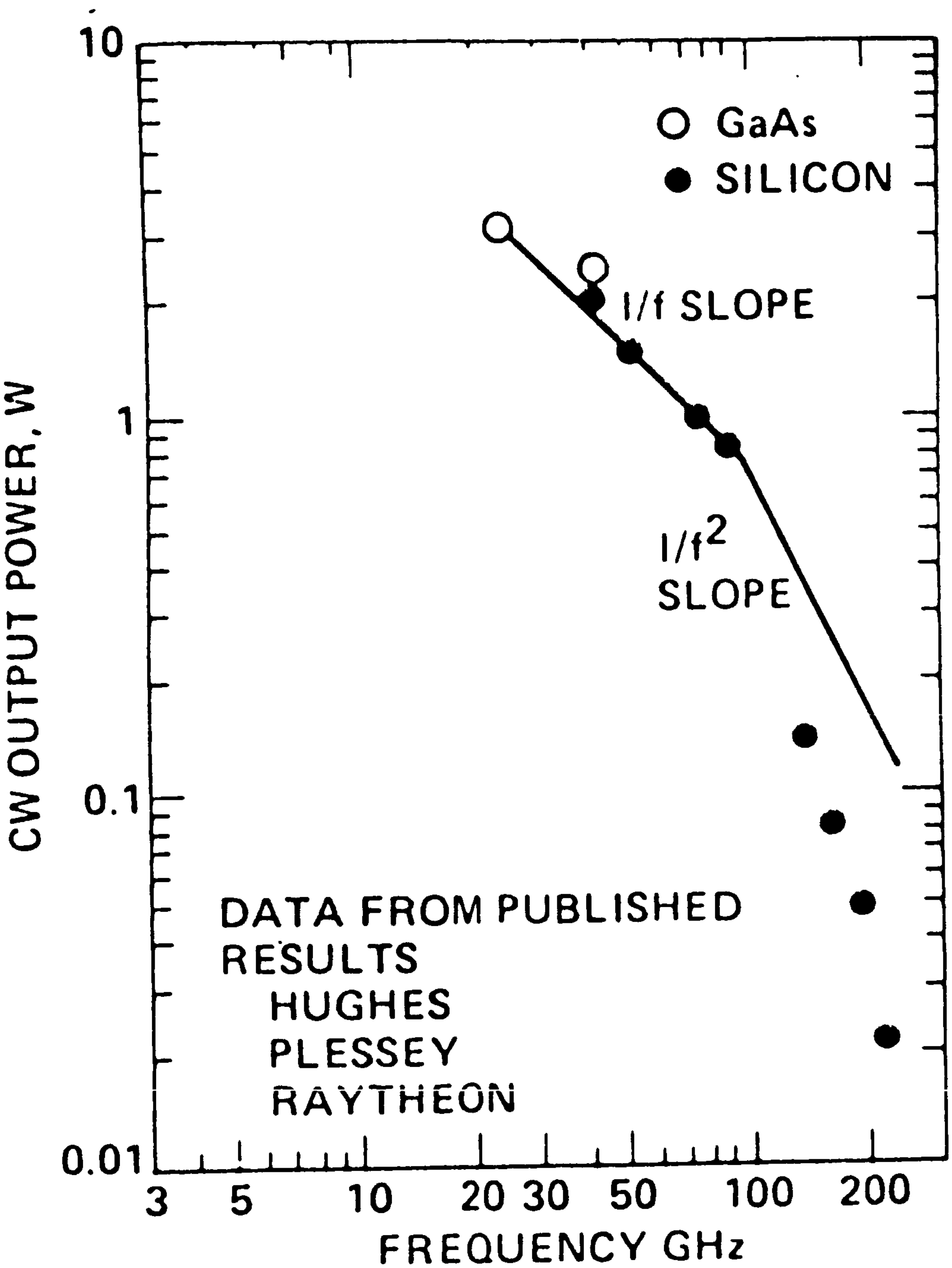

Figure 7-3 State-of-the-art in Solid State Millimeter Wave Amplifiers (circa 1983).

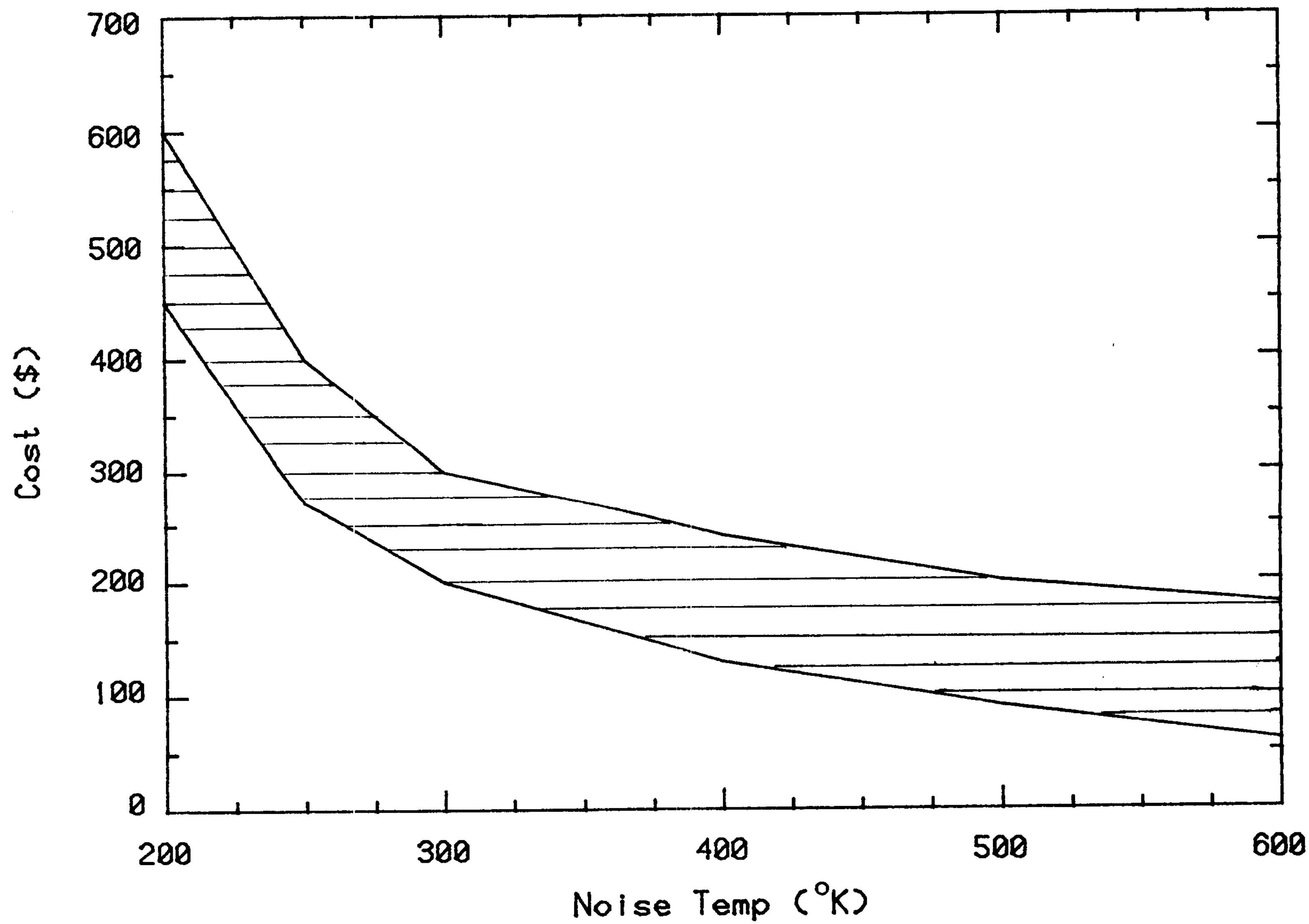

Figure 7-4 LNA Cost versus Noise Temperature at 20 GHz.

7.1.4 Frequency Accuracy

A final area of concern in the terminal design is the frequency accuracy that can be achieved. Most systems being designed or considered for operation in the 30/20 GHz band do not have a tight frequency accuracy requirement as very high (Mb/s) burst rates are generally used. For our system with lower burst rates and FDMA design, frequency accuracy becomes an issue.

Although it is technically feasible to achieve quite good frequency accuracies in the terminal design, the cost could be prohibitive. Millimeter wave sources can be purchased for about $1000 to $3000, but exhibit accuracies of only about ±5 MHz (1 part in 10,000). Phaselocked sources can be built with accuracy to a few Hz, but the higher accuracies require considerable expense. Frequency accuracies of 30 kHz or better (1 part per million) are required for the FDMA system design assumed.

The cost of the frequency reference subsystem is a direct function of the frequency accuracy to be developed. Cost versus frequency accuracy for lower frequencies (10 MHz range) are listed in Table 7-1. Achieving the desired accuracy at just 10 MHz is quite expensive, requiring the use of temperature compensated ovenized oscillators. Although similar accuracies could be achieved at 30 GHz by using a PLL to lock a 30 GHz source to such a reference, this would result in the additional cost of the tunable 30 GHz oscillator and millimeter wave PLL.

Table 7-1
Cost versus Frequency Accuracy at 10 MHz

Frequency Accuracy	Cost
10^{-4}	$10
10^{-6}	$100
10^{-8}	$500
10^{-10}	$9,000
10^{-11}	$25,000

Although ovenized sources at millimeter wave bands might eventually become available, they will probably also be prohibitively expensive. It is also likely that these millimeter wave sources will exhibit frequency accuracies on the order of 1 part in 10,000, an order of magnitude short of the requirement. Thus, achieving the required frequency accuracy with the terminal alone in this manner appears to be prohibitive.

The baseline design has therefore assumed that the satellite will provide a pilot tone on the downlink which is used as the primary frequency reference for all the terminals. It is still necessary, however, for the terminals to phaselock a 30 GHz transmit source to the 20 GHz pilot tone. Upon initial start-up, the terminal may have very poor frequency accuracy, and an acquisition problem then results; the terminal would need to search a 10 MHz or more frequency uncertainty for the pilot tone.

Thus, even with the recommended approach, a 30 GHz source and PLL circuitry is required in the terminal. In order to implement this PLL, harmonic mixers, downconversion, and phase detectors operating in the millimeter wave region will be neccesary. All of these components are currently very expensive.

Providing the required frequency accuracy is thus an area that could benefit from additional study. Other techniques might need to be developed or new, more economical, stable sources might be required.

7.2 SATELLITE

For the satellite, technology limitations rather than cost considerations are the driving factor. Although devising low cost terminals was very important, a low cost satellite is not as critical, since the cost of the satellite will be borne by the business developing the system, and can be spread out over all the users.

The baseline satellite design assumes technology that is believed to be feasible, but has not yet been demonstrated. In some areas, advancement in the state-of-the-art will be required in order to build the satellite with the desired performance. Some components of the satellite are also critical in that the high performance required is necessary in order to accommodate the small earth terminals.

7.2.1 Multi-Beam Antennas

The satellite antenna for the FSS design will require a multi-beam antenna design. Multi-beam antennas can be built using phased arrays, parabolic reflectors, or lens technology. Phased arrays are generally heavy and complex and permit only a single beam to be generated. Lens antennas are also heavy and complex, and are generally more lossy than other techniques. Reflector antenna designs provide the highest gain, are lightweight, and are adaptable to a number of simultaneous beams [Frediani, 1979].

The reflector type multi-beam antenna design has been used in both the Japanese CS satellites, and has been proven in breadboards for the ACTS program, both operating at 30/20 GHz [Myhre, 1983]. The reflector type multi-beam antenna probably represents the best choice antenna for the FSS antenna design. A typical multi-beam reflector antenna design is shown in Figure 7-5.

Multi-beam antennas demonstrated to date, however, have only generated a limited number of beams. The Japanese CS satellite generates four spot beams; the ACTS satellite will generate two scanning beams and ten fixed beams. The satellites use a number of feed horns to illuminate the reflector for each spot beam.

For the ACTS satellite, beams are formed by illuminating a set of seven horns, with most of the power going to the center horn, and the surrounding six horns receiving some additional power in an appropriate phase relationship. This is necessary in order to achieve the required sidelobe levels [Scott, et.al., 1982]. For closely spaced cities, this means that some horns are involved in generating more than one beam. Thus diplexers are used in order to combine the two (or more) signals together before being fed to the horn [Chen, et.al., 1982].

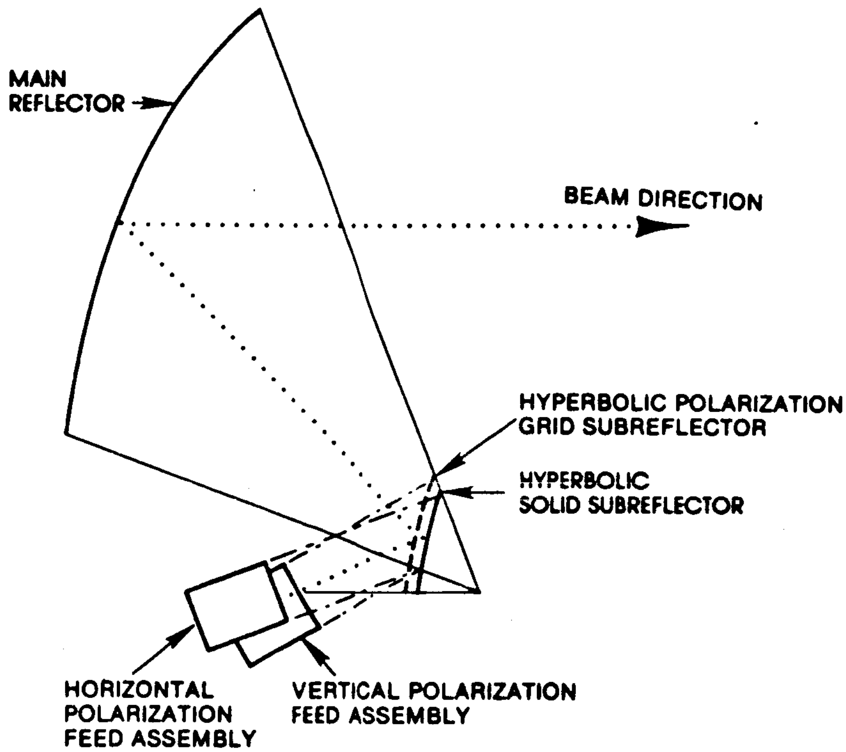

Figure 7-5 Typical Antenna System Configuration

In order to build an antenna with continuous earth coverage using narrow spot beams, a more complicated beam forming network than has previously been demonstrated would be required. An alternative where a single feed horn per beam is utilized would simplify the beam forming network, but there may be difficulties in achieving the required sidelobe levels as was noted in Subsection 3.6.4. The effect of this would be to increase the interference between beams using the same frequencies. By reducing the amount of frequency reuse, however, the sidelobe problem could be eliminated.

Development of the multi-beam antenna feed may thus present some technical challenges. Under the ACTS program, an operational satellite with 18 fixed beams and 6 scanning beams is envisioned, with beam widths on the order of 0.3°. This should be similar in complexity to the 32 fixed beam design we envisioned for this FSS system, which would require 0.8° beamwidths. Thus, the design although difficult, should be feasible.

The size of the reflectors that will be required to achieve the 0.8° beamwidth of our baseline satellite design is 4 ft for the downlink and 3 ft for the uplink. This should be quite feasible, as it is roughly a third the size of the antennas to be flown on ACTS (11 ft downlink reflector and 7 ft uplink reflector).

7.2.2 Low Noise Receivers

The baseline design assumes a 4 dB noise figure low noise receiver on the satellite. User terminals have limited EIRP, hence the satellite LNR performance is critical because it sets the C/N for the backhaul uplink. The uplink is the limiting factor in the backhaul link performance. Better LNR performance would provide a direct improvement in the system performance, up to the limit set by the earth background temperature (about 290°K).

Although the noise figure of a receiver is usually set entirely by the first stage for conventional designs, this is not the case for millimeter wave LNRs in that the gain of low noise devices is usually fairly low. Thus, the noise figure of the overall receiver is determined by the first several stages of amplification. Noise figure performances are thus a function of the gain required.

Low noise receiver designs can use a variety of techniques to maintain a low noise figure; mixer/IF amplifiers, parametric amplifiers, and low noise FET or HEMT amplifiers.

For mixer/IF amplifier designs, noise figures as low as 2.5 dB are theoretically possible at 30 GHz, but require cryogenic cooling. Uncooled designs show noise figures in the 6 to 8 dB range. Mixer/IF amplifier designs are also difficult to optimize and thus extremely labor intensive, resulting in high recurring costs as additional satellites are built [AFSC, 1985].

Parametric amplifiers are not generally used for satellite designs due to the added weight and complexity of the required pumping source. Paramps can, however, achieve very low noise figures, from 3 dB to as low as 1 dB at 30 GHz, depending upon whether they are cooled or not [Frediani, 1979].

FET, and more recently HEMT amplifiers, appear to provide the most logical choice. Complete receivers with noise figures of as low as 2.0 dB appear theoretically possible even with uncooled designs. FET devices have been demonstrated to have the required reliability and been utilized on a number of programs. HEMT designs are slightly risky, but have high potential for demonstrating the required reliabilty and possibly even outperforming FET designs.

Table 7-2 summarizes the state-of-the-art for recent developments in low noise receivers and amplifiers at 30 GHz. Devices with noise figures as low as 2 dB have been demonstrated. Complete receivers with noise figures as low as 4.6 dB have been demonstrated, with preliminary results indicating performance as good as 4.0 dB may have been achieved [Sholly, et.al., 1985], [Santarpia, Bagwell, 1985]. Thus, our requirement for a 4 dB noise figure receiver should be easily achieved by the mid-1990s timeframe.

7.2.3 Power

The baseline satellite design resulted in a power consumption of 5200 watts. This is significantly greater than any existing satellite as can be seen in Table 7-3, which shows a summry of part satellite power requirements. This power requirement does not, however, appear infeasible. For example, NASA has been studying the concept of large geostationary communications platforms that could require as much a 7000 to 8000 watts [Brown, Barberis, 1985]. The platforms would provide an aggregate of services such as C, Ku, and Ka-band transponders.

The primary impact of this large power requirement is the need for a large solar array and batteries. This results in a very heavy satellite. Power dissipation might also be a problem, as the overall efficiency of the satellite would be fairly low. This area would warrant further study if such a power hungry satellite design was selected.

The approach of using several smaller, lower power satellites would thus be quite attractive from the power generation point-of-view. By cutting the power requirement to 3430 W as suggested in subsection 6.5.3.1, a quite feasible requirement would be obtained. Using multiple satellites might result in even lower power requirements per satellite. This would then be well within demonstrated power generation capabilities.

Further study is needed to determine the tradeoffs involved in going to multiple satellites versus a single satellite. Advances in other areas of technology such as the satellite antenna (going to non-uniform beam sizes) or solid state amplifier efficiency could also help reduce the overall power requirement.

7.2.4 Weight

The estimated on-orbit weight of the satellite required by the baseline design is approximately 7000 lbs. A summary of previously deployed geostationary satellites is shown in Table 7-4, from which it can be seen that this satellite would be considerably heavier than any previously deployed geosynchronous satellite.

On the other hand, it will probably be possible in the near term to launch such a satellite. Table 7-5 contains a summary of US current and future launch capability compiled from [Scherer, 1985] and [Ordahl, et.al., 1985]. It can be seen that although 7000 lbs is above the current launch

Table 7-2
30 GHz LNA/LNR State-of-the-Art

Noise Figure		Company
Devices	Receivers	
7 dB	8 dB	NTT
3 dB	4.0-4.6 dB	Hughes
	6.5 dB	ITT
	6.5 dB	LNR
3 dB	4.0-4.6 dB	TRW
2-3 dB		Rockwell

Table 7-3
Summary of Past Satellite Power Requirements

Satellite	Year	Power
INTELSAT-IVA	1975	500 W
INTELSAT-V	1980	1200 W
INTELSAT-VA	1985	1400 W
ACTS	----	1660 W
FLTSAT	1978	1800 W
INTELSAT-IV	----	2100 W
TDRSS	1983	1700 W
HST	----	3800 W

Table 7-4
Summary of Past Satellite Weight

Satellite	Year	Weight (lbs)
INTELSAT-IVA	1975	1900
FLTSAT	1978	2000
INTELSAT-V	1980	2266
INTELSAT-VA	1985	2266
ACTS	----	2800
TDRSS	1983	3200
INTELSAT-IV	----	4906

Table 7-5
Summary of US Launch Capability

	Vehicle	Capacity (lbs)	Orbit
Present	DELTA	2,800	Transfer
	ATLAS/CENTAUR	5,200	Transfer
	TITAN 34D	4,200	Geostationary
	SHUTTLE/PAM-D	2,750	Transfer
	SHUTTLE/LEASAT	3,100	Geostationary
	SHUTTLE/IUS	5,000	Geostationary
Future	ATLAS/CENTAUR	5,800	Transfer
	TITAN 3407	10,000	Geostationary
	SHUTTLE/TOS	13,400	Transfer
	SHUTTLE/TOS/AMS	19,500	Transfer
	SHUTTLE/TOS/AMS	6,500	Geostationary
	SHUTTLE/CENTAUR-G	10,000	Geostationary
	SHUTTLE/CENTAUR-G'	13,200	Geostationary

capability, several possible launch methods will be available in the near future, such as the upgraded Titan or Space Shuttle with the Centaur-G transfer vehicle. It should be noted that these future launch capabilities are currently under development, and should be available in the next couple of years.

Although lower weight satellites would result from a multiple satellite design, more satellites would need to be launched. The total weight that would need to be launched would probably be greater. The cost of launching the multiple satellites could thus be even greater than this single satellite design. Due to some uncertainty in the status and availability of future launch capability, it is not possible at this time to come to a definite conclusion regarding this tradeoff. Future study should be conducted to define the satellite payload in more detail.

SECTION 7
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SECTION 8
PRIVACY AND SECURITY

This section summarizes the issues of privacy and security for the applications under consideration for the FSS. The requirements for privacy and security are discussed first, and then specific techniques for addressing these requirements are identified. Finally, the system impact and cost of the various techniques are investigated.

8.1 OVERVIEW

Historically, communications links for other than military purposes have been in the clear, i.e., no special attempts at providing any privacy was made. This was possible because eavesdropping would require physical access to the telephone lines and installation of a wire-tap running the risk of detection. As more communications are provided via microwave and satellite links, however, eavesdropping has become a passive activity with little risk of detection.

The use of scrambling and encryption techniques have increased markedly in the recent past due to concern over the interception of satellite transmissions. Most notable is the addition of scrambling on satellite video links used to distribute programming to cable systems. Electronic Funds Transfer (EFT) systems use encryption schemes to provide both privacy and authentication for transactions. In addition, introduction of the Data Encryption Standard (DES) has helped to rapidly increase the use of encryption on communications links.

Privacy and Security are two separate, although related, issues. Privacy refers to the confidentiality of the information sent through the communications network. Privacy is desired by the users of the system to protect their confidential information, and is necessary to protect information, such as account numbers, vital to the security of the system. Security, on the other hand, refers to the integrity of the system, i.e., its resistance to the injection of false messages, use of resources without proper authorization, or compromise of the privacy of the system by breaking the codes used for encryption.

Providing both privacy and security is necessary to a varying degree for each of the potential applications of the FSS investigated by this study. Both application specific requirements and system-wide requirements are addressed in the following paragraphs.

8.2 SYSTEM SECURITY

First we consider the fairly general system-wide security issues. There are a number of considerations in the design of the system with respect to the overall security.

It is desired to protect both the communications channels and the command/telemetry channels of the satellite. Protection of the command/telemetry channels of military satellites is standard practice, but has not been done for commercial satellites until fairly recently [Sood, 1984]. Current trends, however, are to provide increasing security with respect to satellite channels.

The command/telemetry channels are usually protected by encrypting the command channel. Only the authorized control station has the key. These techniques are fairly well developed for military satellites, and are now also being used for commercial payloads.

The security of the communications channels presents a more interesting problem, and raises some new issues in the context of an interactive FSS system where there are very large numbers of users.

The potential problems result from the existence of such a large community of users. It may be possible for users to "pirate" satellite time by using the satellite channels for private, unauthorized communnications. As the number of users increases and the required equipment becomes widely available, the potential for pirating increases. With a large number of users of the system, tracking down an individual signal would be difficult. We can envision the selling of illegal "black boxes" that would convert the normal terminals into a "pirate" terminal, allowing free long distance communication between terminals without paying for the channel.

This is currently not a problem with satellite communications systems due to the fairly small number of users and relative sophistication required; unauthorized users are fairly easy to detect and track down.

It would be desirable to design the system in a way that would preclude this sort of activity. One extreme approach, applicable to a processing TDMA satellie, would require each user to request transmission time from the satellite. The satellie would verify the user's identity, and only grant transmission time to those users who were authorized. By repeating only authorized transmissions, unauthorized users would be prevented from using the satellite. Such an approach, however, could be prohibitively expensive.

As less complicated access schemes are used, it becomes easier for unauthorized terminals to gain access to the satellite. However, complicated access schemes alone do not solve the problem completely. For example, in a DA/TDMA system, a pirate could still achieve a reasonable throughput provided there were some unused slots in the network. The pirate would not need to conform to the access scheme but could utilize empty slots by transmitting randomly, repeating his message until it got through. In this case, the control processing required in the pirate is simpler than that of the authorized terminals.

Another related concern is intentional interference. Recent events have shown the need for increasing the security of satellite links [Doherty, 1986], [Newsweek, 1986]. Unfortunately, there is little that can be done to protect satellite channels from either unintentional or intentional interference, or from a determined pirate. Techniques used for military communications usually resort to spread-spectrum techniques that are applicable to a single channel satellite. These techniques, in addition to being prohibitively expensive, are not easily applied to a multi-channel satellie.

A final requirement of system security is to ensure that valid messages are delivered. It should be impossible for an interferer to change the content of messages or to inject forged messages into the system.

When addressing possible solutions to these problems, the cost-benefit tradeoff must also be considered. Using a processing satellite simply to eliminate unauthorized users is probably not worth the investment. As some of these issues are new and unique to this type of satellite system, new solutions may need to be developed.

One partial solution is to provide security at the provider end of the link. The identity of the user must be verified before any services will be provided via the network. Possible means for identifying the user identity include passwords, and digital signatures. (User and message verification is discussed in subsection 8.4).

This solution does not eliminate a direct user-user connection between two unauthorized users. Currently the most economical solution to this problem appears to be a concerted detection and prosecution effort by the various service providers early in the development of the system. By making an example of the first offenders, future pirates should effectively be discouraged.

8.3 SYSTEM PRIVACY

A number of privacy issues also exist with respect to the FSS system design. Although the basic privacy issues have long been a subject of attention, for the particular applications under consideration by this study some new and unique problems result.

The privacy issues can be divided into three parts: the privacy problem, preventing the interception of information on the channel; the user authentication problem, verifying the source of the message; and the message authentication problem, verifying the accuracy of the message. The solutions to these various problems are interrelated and make use of common cryptographic tecniques.

8.3.1 Privacy Requirement

The types of information being sent back and forth in many of the applications (i.e., home banking, home shopping) are not particularly sensitive. Even if it were possible to eavesdrop on someone conducting transactions via the system, there is little motivation for third praties to do so, as there is no financial gain likely. (This would not be true for business users of such a system). Users would most certainly object, however, if it was simple for anyone to eavesdrop on their transactions. Hence, some modest amount of privacy needs to be provided by the system.

The types of transactions in the system are from many different individual users to a centralized hub. Encrypting all the traffic with a single key is not adequate, as it is also desired to keep users from being able to receive each other's messages. Hence, each user-hub link must have its own set of keys.

This results in an astronomical key distribution problem, especially when there may be several different hubs serving millions of users. Each of the hubs would be required to keep track of millions of keys. As each transmission is received, the hub would be required to look up the correct key to decode the transmission. One solution to this problem is the use of public key systems.

8.3.2 Public Key Systems

Public key systems (PKS) were first suggested in the late 1970s [Diffie, 1976], [Merkle, 1978]. In a public key system, the enciphering and deciphering processes are split. The enciphering process maps a message into a new message, which has no obvious relationship to the original message. This process can be represented,

$$C = E_k(D)$$

where $C, D, \varepsilon \{M\}$ where $\{M\}$ is the set of all possible messages (for example n-bit vectors). D is the clear-text and C is the resulting cipher-text. E_k is the encryption algorithm.

The deciphering process is thus,

$$\tilde{D} = D_k(C)$$

where D_k is the decryption algorithm. Obviously, D_k must be the inverse of E in order to recover the original message text (i.e., $\tilde{D} = D$).

A public key system can be built when $\{D_k\}$ and $\{E_k\}$ satisfy the following properties:

(1) D_k is computationly infeasible to compute from E_k for all k.
(2) $D_k(M)$ and $E_k(M)$ are easy to compute for all M.
(3) A D_k and E_k pair are easy to generate from k for all k.

Thus, to select a key, a user picks some k randomly, and generates D_k, and E_k. D_k is kept private (we will refer to it as the private key) and E_k (the public key) is released publicly. Property (1) ensures the privacy of the private key, since releasing E_k does not compromise the security of D_k.

The {k} must be fairly large (i.e., there are many non-equivalent D_k, E_k pairs) in order to preclude an exhaustive key search. A {k} of size 10^{10} is probably quite adequate.

It should be noted that the selection of k must be truly random, or a potential weakness exists. A would-be interceptor would normally be faced with a computationally infeasible key search problem requiring searching all possible keys. If, however, some information about k can be obtained, the size of this search could be reduced proportionally.

The system is secure because of the one-way nature of E_k. Although all users can generate encrypted traffic using E_k, only the owner of private key D_k can decrypt that traffic.

Several possible sets of $\{E_k\}$ and $\{D_k\}$ have been suggested; [Rivest, 1978], [Merkle, 1978a], and [McEliece, 1978] all propose public key systems using particular classes of functions.

The RSA algorithm [Rivest, 1978], uses a set $\{E_k\}$ where the encryption algorithm is

$$C = E(M) = M^e \text{ modulo } n$$

where $M \varepsilon \{0, 1, \ldots n-1\}$ and (n,e) is the public key. The decryption process is

$$M = (C) = C^d \text{ modulo } n$$

using the private key (n,d).

The generation of d and e, and the selection of n are rather complicated. The security of the system lies in the fact that n is selected as the product of two relatively large primes p and q, such that

$$n = p \cdot q.$$

The factors p and q are kept private. From p and q it is fairly straightforward to compute e and d. However, knowing just n and e makes computing d very difficult.

8.3.3 Application of PKS to FSS

The PKS would be applied to the FSS system in the following manner. Each of the main hubs would have its own key, for which the encryption key is released publicly, allowing all terminals to communicate directly with the main hub. Likewise, each user has their own key for which the encryption key is released publicly and the decryption key is held privately.

Backhaul communications going into the hub can be encrypted by anyone using the hub's private key, but can only be decrypted by the hub. For forward link transmissions going outbound from the hub, the hub encrypts the transmissions for each user with that particular user's key, thus ensuring that only that user can decrypt the message. Figure 8-1 illustrates such a network.

Electronic mail needs to be handled differently, as it is an application where the information is sent from one user to another, rather than being sent between a user and a central node.

The electronic mail problem can also be satisfied within the public key system, and in fact this is the only practical way to solve the problem and ensure complete privacy to the two users.

The basic problem is this: the two users exchanging the electronic mail need to be able to decode traffic without any other user being able to listen in. Hence, it is not possible for a third party to distribute keys to the two users without compromising the security of the link. With conventional cryptographic systems, it would thus be necessary for one of the users to send a key via some outside secure channel to the other user (i.e., via registered mail). This would thus result in the necessity of preparing for the link some time in advance, a considerable inconvenience, and may make little sense. (Given that one must send the key via this other channel, one could just send the entire message and be done with it!).

The problem is solved by using public keys in the following manner. A user wishing to send electronic mail to another user first establishes a connection with a service provider that provides the electronic mail forwarding service. The user then requests the public key for the destination

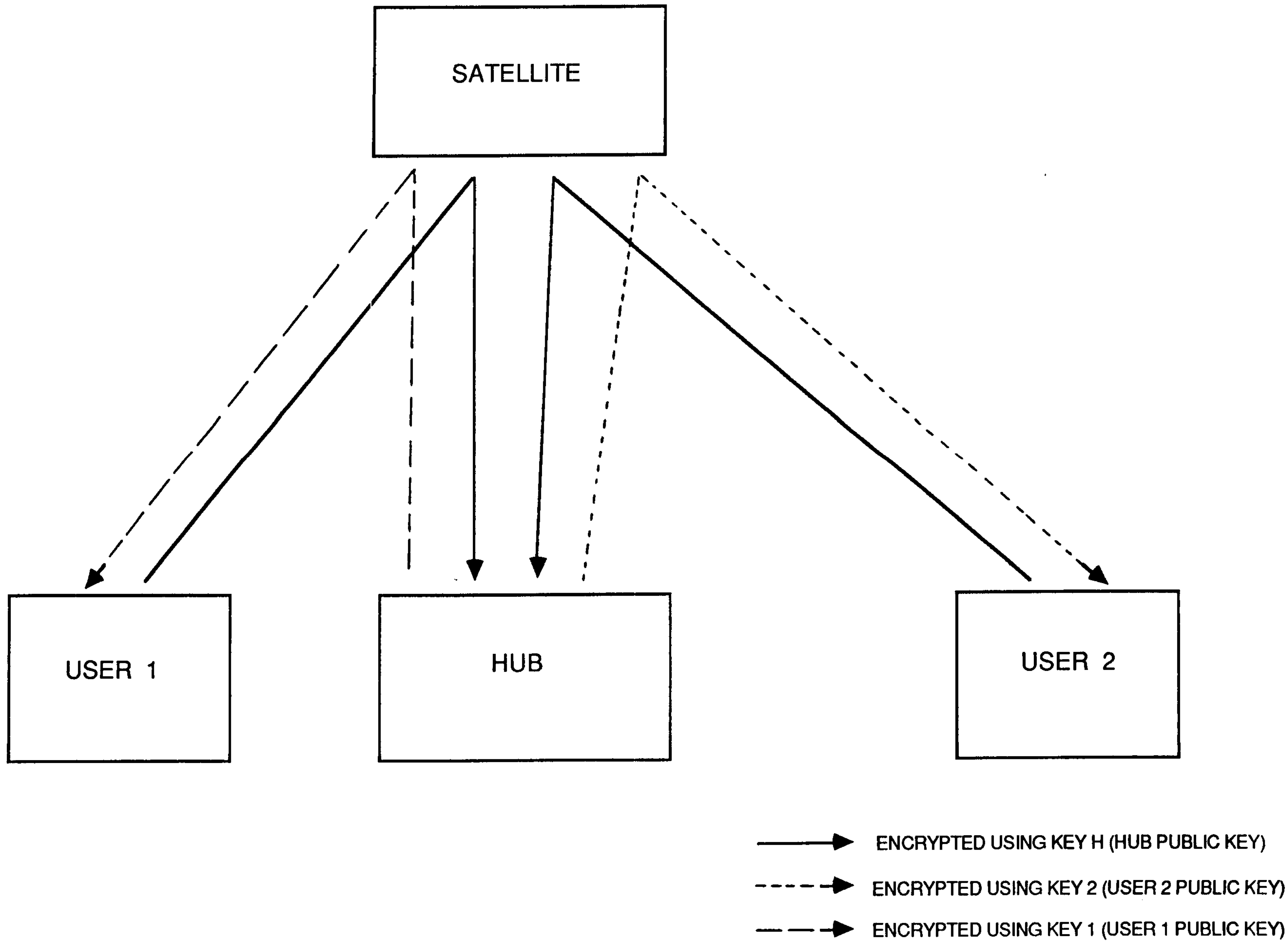

Figure 8-1 Public Key Cryptosystem for the FSS

of the message from the service provider. The user then encrypts the entire message (except for the routing instructions) using the key of the recipient rather than the hub, and transmits the message to the hub for relay. The hub can then relay the message to the user (provided the address is unencrypted!). Since the message has been encrypted with the recipient's key, only the desired recipient can decipher the message. This process is illustrated in Figure 8-2.

8.4 USER AUTHENTICATION

A serious issue still exists with respect to the authentication of users of the system. Clearly, it is necessary to restrict access to information to those who have paid for the service. For applications such as home banking, some means of verifying that it is the account owner on the other end of the link is necessary, (e.g., a digital signature). For applications such as home shopping or reservation making, it is necessary to ensure the validity of orders, and to be able to bill the correct person. Obviously, it should not be possible for an eavesdropper to obtain the necessary information in order to appear to be a valid user of the system.

The user authentication requirements are even stricter than the privacy requirements. This is because failure of the user authentication could have dire consequences. The user authentication is analagous to the signature on a check; if it possible to forge this signature, one could masquerade as the user. Such an imposter could then access services at no cost to himself, and even possibly steal money (i.e., by transferring money electronically) from the legitimate user's on-line accounts.

Some form of digital signature is necessary. By the very digital nature of the system, such a concept appears impossible; any bit pattern can be reproduced identically by anyone. There is a solution, however, provided by public key systems. This is possible provided that the public key system also has the property that the encryption algorithm E_k is an inverse of the decryption algorithm D_k. (Remember, we previously only required D_k to be an inverse of E_k, but not vice-versa). Thus, messages "encrypted" with the private decryption key algorithm can be "decrypted" with the public encryption key. To sign a message, the sender encrypts all or a portion of the text using his private key. Anyone can recover the original text by decrypting the message using that user's public key. The verification comes from the fact that only the person with the private key matching that public key could have encrypted the message such that the original recognizable text could be recovered by using the public key. Because the public keys and their owners ae a matter of public record, it is a simple matter to verify the identity of the user.

This user authentication scheme also solves the problem of dispute where it is desired to establish legal proof of the sender's identify. The various applications providers can require requests from users to be signed with this digital signature. The service providers can then retain audit logs of the received transaction requests which include the (undecoded) digital signatures. These logs could then serve as legal evidence.

It is important that the "signed" portion of the message (the portion encrypted with the private key) be integral to the message or time-

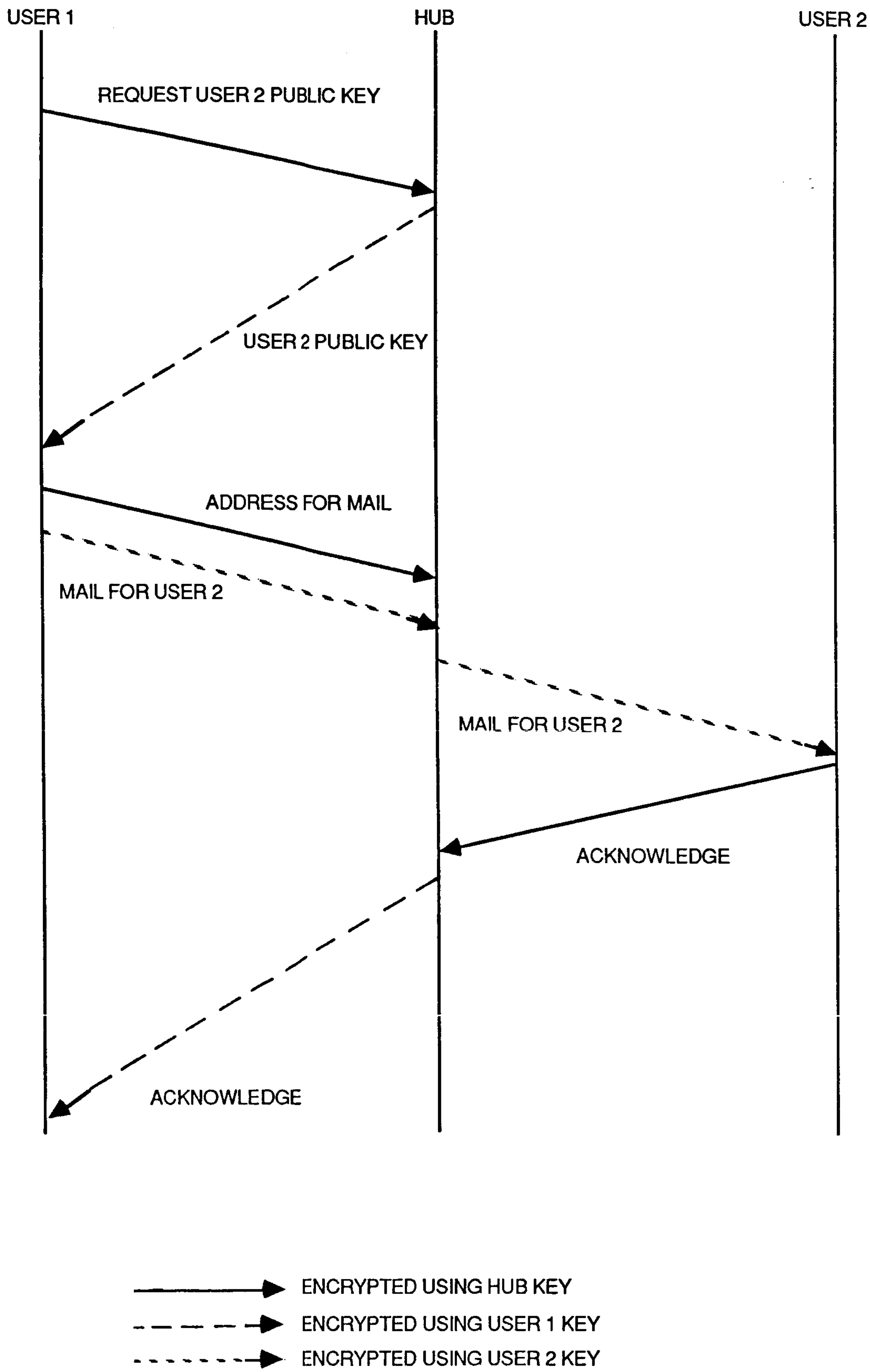

Figure 8-2 Electronic Mail Using Public Keys

tagged in order to prevent a would-be imposter, or even the hub, from merely copying the signature block and then appending it to his own messages. A standard format for the use of an RSA public key system with signatures has recently been suggested [Zimmerman, 1986].

Another important aspect is that the public data base of keys be protected such that unauthorized persons cannot modify the data base. Since the data base would naturally be maintained by one of the providers, this should not represent any difficulty.

8.5 MESSAGE AUTHENTICATION

A final issue closely related to the user authentication problem is the message authentication problem. It is necessary to ensure not only that the message was sent by a particular user, but that the contents of the message have not been altered either accidentally (channel errors) or intentionally (interferer). It may also be desired to establish legal proof that the sender sent the particular message (i.e., requested a particular transaction).

For example, consider a stock transaction executed via the system. If there was no message authentication, two potential scenarios could develop. In the first scenario, suppose an investor requested the purchase of 100 shares of stock which, due to transmission errors, was executed as a purchase of 900 shares. In the event that the stock lost value, the investor could consider the system operator liable for any loss due to the error. The second scenario is similar, but our hypothetical investor requests the purchase of 500 shares of stock. It later turns out that this was a bad decision on his part; the investor could claim that he had requested the purchase of 100 shares, and that the system made an error. Providing a message authentication component to the system would alleviate these potential scenarios.

Adding a simple checksum to the message will solve the problem of accidental channel errors, but will not solve the problem of an intentional interferer. Random channel errors will be caught when the checksum fails to match. An intentional saboteur could, however, change the data in the message and change the checksum to match, thus escaping detection.

The would be saboteur can be defeated provided that the text of the message and checksum are encrypted. Good encryption algorithms have the property that a change in a single bit of clear text results in many bits of the ciphertext changing (and vice-versa). Thus, to successfully modify a transmitted message (i.e., have it still pass checksum) becomes equivalent to the problem of determining the deciphering key. This does not, however, solve the problem of dispute, as the transmitter can always claim that errors were introduced after the decryption process.

To solve the problem of dispute, we thus require not only the users to "sign" the message as described in the previous section, but to include a message digest (a hashed version of the message, similar to a checksum) in the signature. The verification process is then as follows: The message is decrypted by the receiver using the receiver's private key. The signature is then decrypted using the public key of the transmitter. The successful decryption of the signature verifies the transmitter identity. The signature contains the message digest. The message digest is computed from the message text and compared to the signature. If the two match, then the content of the message is validated.

A potential vulnerability exists if a poor hashing function is selected for generating the message digest. A receiver could search for another message that has the same checksum and substitute it for the actual message. This problem is solved by selecting a hashing functon that 1) is essentially one way (like the basic encryption/decryption algorithms), and 2) results in a sufficiently large message digest that an exhaustive search for messages with the same digest is infeasible. Message digests of 56 bits are probably more than adequate.

Note that the requirements for a good hashing function are compatible with good error detection capability. Obviously, if changing a few bits in the message text could yield the same message digest, the message digest would be of little value. Thus, the message digest can serve the dual function of validation and error detection.

8.6 IMPLEMENTATION CONSIDERATIONS

Unfortunately, little use of the public key technology has been made in operational systems. Consequently, little hardware specialized for the encryption/decryption of data exists. Due to the fairly extensive computations required, however, software implementations are usually quite slow. The maximum achievable data rate for a software implementation may be too low for the applications of this system.

The Data Encryption Standard (DES), however, does not pose this implementation problem. The DES is a standard encryption/decryption system utilizing 56 bit keys [FIPS, 1977]. A number of integrated cricuits are available which provide encryption/decryption functions in a compact package, at data rates well in excess of that required for the FSS applications. However, because the DES is a conventional cryptographic technique, it does not solve the authentication or key distribution problems previously discussed.

One possible approach would be to use a hybrid of DES and PKS technology. The PKS could be used to securely distribute DES keys and provide the required user authentication at the beginning of a transaction session. Once DES keys are distributed and the user authenticated, the fast DES algorithm could be used for encryption of the subsequent transactions.

This is a rather cumbersome approach, however, and would complicate the design of the terminal. A far more preferable approach would be the development of LSI circuits that would perform the PKS algorithms, analogous to the currently available DES chips. We believe the development of such chips to be likely in the near future if use of the PKS technology becomes widespread.

As the cost of custom IC's continues to drop, it may eventually become feasible for a would-be service provider to procure a custom chip for this purpose. The cost of the custom chip development could be spread out over the millions of terminals built for the system. There might also be potential to market such a chip directly, especially if standards for the use of PKS could be agreed upon.

A software encryption/decryption scheme might be feasible if only portions of the data sent across the links are encrypted. Sensitive portions of the messages (i.e., account numbers, balances, order quantities, etc.) would be encrypted, while other portions of the text would not. This would thus reduce the processing load since only a portion of each message would need to be encrypted/decrypted. This is somewhat cumbersome, as it requires the encryption/decryption processing to know how messages are structured in order to protect the correct information. The hardware encryption/decryption scheme described above would appear more desirable.

SECTION 8
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SECTION 9
SUBSCRIBER BASE

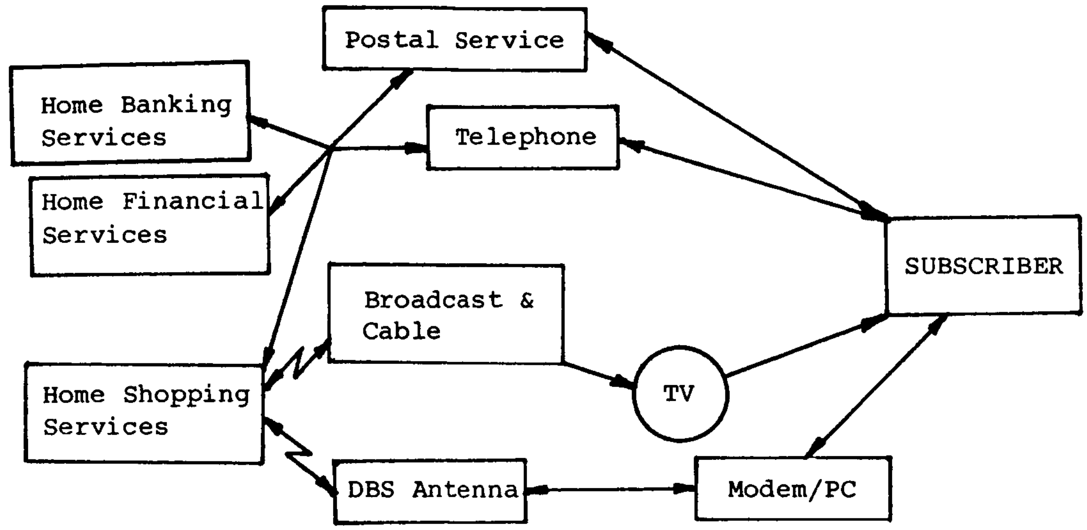
This section presents information on the various markets for and potential subscribers to home banking, financial and shopping services delivered through electronic media such as direct broadcast satellite links. The purpose was to develop a basis from which to estimate the size of the subscriber base as a function of key market, technology, business and cost variables.

9.1 MARKET STUDY OBJECTIVES

In order to develop an estimate of the number of potential subscribers from the consumer marketplace for electronic information services transmitted directly through satellite links, an analysis of several different but complementary markets was conducted. The markets specifically examined were: 1) Consumer Electronics; 2) Home Banking and Financial Services; and 3) Home Shopping Services. The subsegments of the markets served by satellite links shall be referred to as the "direct-to-subscriber" or D-T-S segment throughout the remainder of this section. All were reviewed for their current size and maturity, growth potential, timeframe in which the growth is expected to occur, competitive business strategies, service technology requirements, and penetration potential by D-T-S based services.

The focus of the analysis of the Consumer Electronics markets was on the following product segments: 1) personal/home computers; 2) modems; 3) direct-broadcast satellite (DBS) antennas; and 4) TV monitors with an emphasis on high definition digital televisions (HDD TVs). The rationale behind selecting these product categories was that, collectively, they presently are and will probably continue to be for the foreseeable future, the primary communication links through which consumers would gain access to satellite based electronic information products and services offered by the Home Banking/Financial and Home Shopping Service providers. Figure 9-1 illustrates the relationships between the service providers, consumer electronic products and competing access channels, and the service subscribers.

Figure 9-1
* Home Service Provider/Subscriber Relationships *



Home Banking/Financial Services are defined to be the services that enable consumers to electronically transfer, balance, debit, manage and invest funds in their private accounts from their homes or other convenient locations. For the purposes of this analysis, banking services are considered to be distinct and different from financial services; and because of various federal and state regulations, are provided by different types of businesses. Home Banking Services are designed to enable consumers to balance, debit or credit funds in a their personal accounts.

Based upon today's regulations, these services are provided primarily by banks and savings and loan institutions. Financial services, however, are oriented toward managing and investing account funds. These services are provided primarily by brokerage, investment and credit firms, credit card companies, and even retailers.

Home Shopping Services are the category of services that enable consumers to purchase goods and services from their homes or other convenient location other than a retail outlet. Presently, the primary channels of distribution for these services are through product catalogues, and broadcast or cable TV programs. The three major providers of these services are retailers, catalogue/discount showrooms, and television programmers.

9.2 METHODOLOGY

In order to achieve the objectives of this study, trend and content analysis were used to: 1) estimate the overall number of potential subscribers for each major market segment (i.e. Home Banking, Home Financial Services, and Home Shopping Services); 2) calculate the probability of achieving each of the estimates by the mid-1990's timeframe based upon several key interdependent variables; 3) estimate the maximum number of subscribers in each of the major markets that could be served by D-T-S services; and 4) develop a more realistic weighted estimate of the penetration potential by D-T-S services in terms of the number of subscribers.

A basic assumption in this methodology is that in order for a viable D-T-S market to exist for any of the services, the probability and potential for success of any of the major market segments would have to be high. However, success for any of the services would not necessary translate into success for the D-T-S market segment.

The data and other background information used to determine the estimates of market size potential were acquired from available industry market reports, trade and professional associations and publications, personal contacts and interviews, and the proprietary databases and knowledge of the contractor.

The probability of achieving those levels of market growth were developed for each of the home services examined. The probability estimates were based upon several interdependent market, business and technology criteria, weighting factors, and assumptions which are used by industry analysts as accepted indicators of the potential for success or failure of a selected product or service in the marketplace.

The criteria and rationale used are described in the following summary.

CRITERIA/RATIONALE FOR DETERMINING THE PROBABILITY OF MARKET SUCCESS

1. MARKET SEGMENT STATUS & PROJECTIONS

   a. Overall Subscriber Growth Rate - This is a key indicator of the viability of the market segment. A growth rate of 20% per year is considered to be necessary to generate sufficient revenues and incentives by businesses to invest in the development of additional or niche market services. Rates below this level become less attractive and more difficult to penetrate.

(cont'd)

b. Overall Growth Timeframe - From the perspective and requirements of the developers of Ka band satellites, the growth rates described above should be achieved within the mid-1990 timeframe. If they are achieved earlier, the impetus to expedite the development of this technology becomes greater; if achievement is not possible or possible in a later timeframe, the urgency is reduced.

c. Geographic Distribution of Subscribers - Also from the perspective of the developers of Ka band satellites, the more geographically dispersed the subscriber base is, the more attractive D-T-S satellite links become to businesses to provide its home services. Therefore, the greater the dispersion, the higher the probability that satellite links will be used. Conversely, the more clustered the subscriber base, the less attractive that technology becomes.

2. BUSINESS DEVELOPMENT

a. Competing Business Development Strategies - If businesses are already actively developing and trying to implement strategies to offer home services using information technologies and other electronic media, then the probability of achieving success in the mid-1990's timeframe is higher than if they are deciding to defer action until the late 1980's. This is because any major new consumer product or service that requires a change in consumer buying behavior as well as an infrastructure to support its use requires at least 5 - 10 years to fully and properly commercialize.

b. Strong Competitors to Serve Markets - The type of home services described in this study will require substantial long-term commitments from businessnes in terms of financial, marketing and technological resources. Unless there are major commitments from strong competitors, the probability of success will be low. Conversely, the larger the number of major corporations that are involved in trying to commercialize these home services, the higher the probability of success.

(cont'd)

3. TECHNOLOGY REQUIREMENTS

a. Commercial Availability - Although the basic information technologies exist to provide the first generation of home services, several new technologies need to be developed, including Ka band satellites. If these technologies do not or can not become commercially available within the mid-1990's timeframe, then the probability of achieving the subscriber growth goals will decline.

b. Competing Technologies - The primary ground and satellite based communications technologies that Ka band satellites will be competing against to link home service providers with subscribers are T1, microwave, C and Ku band satellites. The capacity of these technologies to support the transmission requirements of providers in the mid-1990 timeframe is expected to be more than adequate. In order for Ka band to be an attractive alternative, it will not only have to be cost competitive but demonstrate that its use will enable service providers to gain better access to existing markets or serve as a means for developing new ones. However, as was stated in (3a), the availability of competing technologies will serve to strengthen rather than impede the development of the home services markets, and, therefore, the opportunities of Ka based applications.

Weighting Factors on a scale of 0 - 1.0 were used to determine how close to achieving the requirements of each criterion the marketplace will come in the mid-1990's timeframe. The Weighting Factors for each criterion are summarized in the following chart.

CRITERION	WEIGHTING FACTORS 0 .1 .2 .3	.4 .5 .6 .7	.8 .9 1.0
1a. Overall subcriber growth rate	5%	10%	20%
1b. Overall growth timeframe	Beyond 2000	Late 1990's	Mid 1990's
1c. Geographic distribution	Local	Regional	National
2a. Competing business development strategies	Few	Some	Many
2b. Strong competitors to serve markets	Few	Some	Many
3a. Commercial availability (Ka satellites)	None	Some	All
3b. Competing technologies	None	Some	All

The estimate of the maximum size of the subsegment of each market that could be served by D-T-S services was based upon the assumption that it would be equal to the total number of DBS antennas in the marketplace. However, a more realistic estimate of the market penetration potential was based upon the assumptions that only a small percentage of the installed base of DBS antennas as well as the associated consumer electronic products would be used for D-T-S subscriber services.

Finally, after these subsegment estimates were developed, each D-T-S opportunity was ranked in priority order in terms of their probability of success as well as potential number of subscribers. An opportunity was ranked "High" if its probability estimate was in the .6 - 1 range; "Moderate" if it fell within .3 - .5; "Low" if it was in within .1 - .2; and "Reject" if its value was less than .1.

9.3 MARKET SEGMENT OVERVIEW - CONSUMER ELECTRONICS

9.3.1 Market Status and Projections

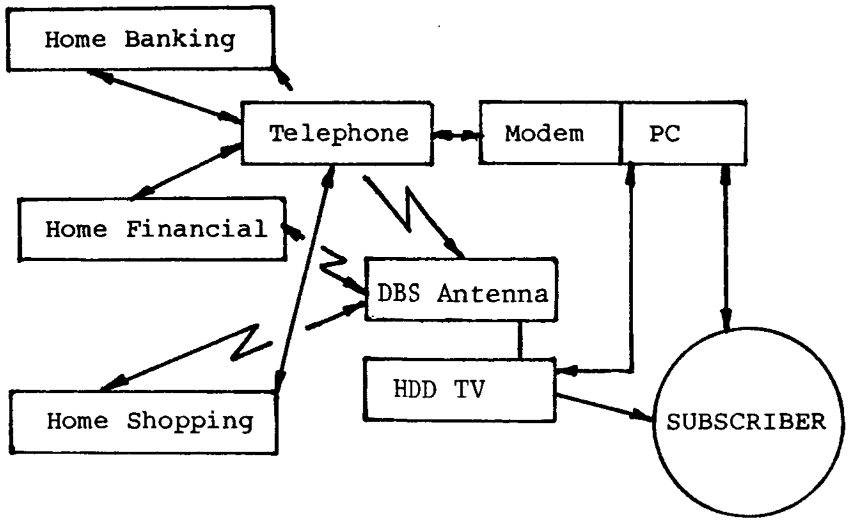
In general, the consumer electronics marketplace has been undergoing dramatic changes since the mid 1970's in terms of growth and product entries. The industry was once considered a haven for officianados of gadgets. It has rapidly changed its orientation toward home and portable entertainment products, and is expected to evolve toward a "lifestyle" emphasis by the early 1990's. A "lifestyle" emphasis in products is defined to mean systems that combine design and function to provide entertainment as well as perform business and operational functions such as controlling home security systems and conduct home banking services.

The consumer electronics industry sold $5.2 billion worth of products in 1975. Sales increased sharply to $23.4 billion in 1984 and $35 billion in 1985. More than two-thirds of these sales were generated from products that did not even exist in 1975, most notably personal/home computers, large screen TVs, video cassette recorders, and compact disk players. Because of advances in semiconductor and VLSI (very large scale integrated) chip technologies, even more sophisticated, easy-to-use, multi-functional products will be introduced that could revolutionize the way consumers incorporate electronics into their lifestyles. These developments could propel sales to the $60 billion level by the mid-1990's.

The potential for using these products for home banking, financial and shopping services is high because they would fit into the "lifestyle" applications viewed by industry analysts as the next major shift in utilization emphasis. On the forefront of this trend are households defined by market reasearchers as "Technologically Advanced Families" (TAFs). The characteristics of TAFs are that they are willing to spend larger than average sums on technologically advanced products to perform functions that will save them time or offer convenience as well as provide entertainment value. In essence, they are seeking function as well as design in their products. Today, there are an estimated 9.2 million TAF households. This segment of the consumer marketplace could serve as the core of early adopters for electronic home services in the 1990's.

This study focused on four product categories as the basis for determining whether or not an adequate infrastructure to support and utilize electronic home services would be in place by the early to mid-1990's. The product categories were: 1) Personal/Home Computers (PCs); 2) Modems; 3) Direct Broadcast Satellite (DBS) antennas; and 4) High Definition Digital TVs (HDD TVs). These specific product categories were selected because today's version of home banking, financial and shopping services are currently designed for access through PCs, telephones, 300-1200 baud modems, or broadcast and cable TV programs. It is also anticipated, that the services provided in the mid-1990's will continue to rely heavily upon these access channels. These relationships are depicted in Figure 9-2.

Figure 9-2
* Home Service Access Channels *
via Selected Consumer Electronic Products



9.3.2 Description of Product Categories

Personal/Home Computers & Modems

PCs are defined to be micro-computers selling in today's market for between $500 and $2,500 and used primarily in the home. However, because of declining prices and increased functionality and capability, the distinction between a home and an office based product is becoming blurred. Notwithstanding, the configuration and functionality of PCs are expected to change from its present stand-alone design to be integrated with other product categories such as home monitoring, security and entertainment systems with large screen TV monitors.

Modems are simply devices that enable PCs to interactively communicate, primarily in ASCII protocol, via telephone or other communications interface with another party. Although the basic function of modems will remain essentially the same through the mid-1990's, their transmission speeds will continue to increase and a greater percentage will be internal rather than stand-alone units. In 1983, most of the modems sold were designed to transmit at either the 300 or 1,200 baud rate. The design rate for most modems in the late 1980's will be 2,400 baud, and even higher by the mid-1990's.

Direct Broadcast Satellite Antennas

Today's generation of DBS antennas are simply parabolic dish antennas designed to receive broadcasts in either C or Ku bands. Consumer versions are approximately 5 ft. (1.5 m) to 10 ft. (3.0 m) meters in diameter. Currently, 70% of all installations are in rural locations; 29% in suburban locations; and only 1% in urban areas. In the future, however, flat phased array antenna designs could be developed and installed in places where the conventional dish antennas would violate zoning ordances or esthetic considerations.

High Density Digital Televisions (HDD TV)

Although still in the developmental stages, HDD TVs are expected to have a significant impact on the next generation of TV buyers. Not only will picture clarity be dramatically improved, but HDD TVs will also have the capability to serve as a 2-way home communications hub for audio, video and videotext programming, as well as perform computerized home monitoring functions.

Specifically, HDD TV's technological features will be able to scramble, enhance, and compress transmitted signals. These features will enable consumers to see multiple images on a split or freeze-frame basis as well as simultaneously process signals from regular TV stations, videotext services and computers. Beyond home entertainment, security and other monitoring functions, these capabilities could serve as the access channel through which providers of home banking, financing and shopping services are obtained.

Picture clarity improvements will be achieved through projected images composed of 1,125 horizontal scan lines rather than today's 338 scan line rate. Home catalogue shopping services could take particular advantage of this advance.

The major disadvantages of HDD TV technology in terms of its application to these home services, however, is that they not only need high bandwidths in the 20 to 30 MHz range, but the equipment that will be needed by broadcasters to transmit these signals will have to be specially designed. Thus, the conversion costs to provide programming via HDD TVs could be too high for businesses to invest for several years to come.

9.3.3 Major Product Providers

The major vendors of PCs are listed in Table 9-1.

Table 9-1
* Major PC Vendors *
1985

Rank	Vendor	Sales or % MarketShare (1985)
1	IBM	29.6%
2	Apple	16.5
3	Commodore	14.4
4	Tandy	7.4
5	Atari	5.5
6	Compaq	3.6
7	AT&T	3.1
8	Hewlett-Packard	2.3
9	Zenith	1.7
10	Wang	1.3
11	All others	14.6
	U.S. Total	100.0%

Source: Sales & Marketing Management, April 1986

The major vendors of modems are listed in Table 9-2.

Table 9-2
* Major Modem Vendors *
1984

Rank	Vendor	Sales or % Market Share
1	Hayes	35%
2	Novation	18
3	U. S. Robotics	10
4	All others (approx. 40 other vendors)	37

Source: Electronics Business, April 1, 1985

The major developers of HDD TVs are listed in Table 9-3.

Table 9-3
* Major HDD TV Developers *
1986

Rank	Vendor	Sales or % Market Share
NA	ITT Sony Panasonic Matsushita Toshiba Grundig RCA Zenith Radio Corp.	Product still under development. Product introduction in U.S. anticipated for late 1987.

Source: Popular Science, January 1987.

9.3.4 Estimated Product Sales

The actual and estimated sales volume for each of these product categories are summarized in Table 9-4.

Table 9-4
* Product Sales *

PRODUCT	UNIT SALES/YR. (millions) 1985 (Actual)	UNIT SALES/YR. (millions) 1995 (Estm.)	ESTM. ANNUAL SALES GROWTH PER YEAR (%)	TOTAL ESTM. INSTALLED BASE (by 1995)
PCs	13.0	37.00	11	55 million
Modems	1.3	12.00	36	25 million
DBS Anten.	0.65	4.00	20	6.7 million
HDD TV	N.A.	0.35	*25	1.3 million

* Based on estimated sales beginning in 1990.

Source: "Consumer Electronics U.S. Sales," Electronic Industries Association, October 1986

The unit sales per year figures are based upon actual sales in 1985 and estimated sales volumes in the 1995 timeframe by industry analysts. Although these figures are for the various product categories as whole, it is worth noting that the eventual segmentation of the DBS antenna marketplace will have a greater impact on the development of the D-T-S Ka band based service marketplace than for PCs, modems, and HDD TVs.

Virtually all of the 1985 DBS antenna sales were for designs to receive C band transmissions, primarily cable TV feeds. By 1995, the product mix is expected to include designs to receive C, Ku and some Ka band transmissions as well. The researchers for this section of this study have assumed for the purposes of the remainder of this report that approximately 25% of the DBS antennas market in 1995, will be for Ka band designs. This estimate was based upon the assumption that by 1995 Ka satellite availability will have only achieved limited commercial availability; and, as a consequence, will have served to generate only a moderate response from home service providers to transmit there services through Ka links.

The total estimated installed base of products is defined as the probable number of units actively being used in households. These estimates were based upon the assumptions that each product unit will have a three year life-cycle and that on an on-going basis, many will be replaced, and some upgraded or simply discarded without being replaced. Therefore, the installed base is not the sum of the units sales over the growth period, but a smaller amount. The estimates presented in Table 9-4 are based upon the opinions of industry analysts as well as the researchers of this section of this report.

9.4 MARKET SEGMENT OVERVIEW - HOME BANKING/FINANCIAL SERVICES

9.4.1 Market Status and Projections

Home Banking

Although packaged under a variety of names, virtually all electronically based home banking services are designed to enable consumers to gain access to their checking and savings accounts for the purpose of transferring, depositing, crediting, debiting or balancing funds without the use of paper checks. In some instances, purchases of financial instruments such as money market certificates and certificates of deposit are possible. And although many of these services are marketed under the umbrella of "home" banking services, they are in fact accessable through some form of terminal/CPU link located at banking, retailing and other public locations.

The underlying motivations of banks for providing these services are to reduce their operating costs and, because of competition resulting from deregulation, to increase and broaden their customer bases. In 1985, the volume of personal check transactions processed exceeded 35 billion. By the mid-1990's, approximately 90 million households will have checking accounts and the transaction volume is expected to surpass 62 billion personal checks. The average cost, in 1986 dollars, to process a check ranges from $0.50 - $1.00. Various electronic methods for processing equivalent transactions, such as automated teller machines (ATMs) costs between $0.35 - 0.50. In the past, most if not all of the processing costs were passed along to the consumer either directly on a fee-per-check basis, monthly service charges or minimum balance requirements. Today, however, with the growing competition facing all banks and savings and loan institutions for customers, it is becoming increasingly difficult to either pass along or absorb these costs and maintain one's competitive advantage.

Recent marketing studies estimate that by the mid-1990's between 20-30 million of the 90 million households will be utilizing some form of electronic home information system to perform banking, shopping, budgeting, ticketing and home security monitoring functions. Assuming that these households represent approximately 14 - 20 billion of the overall transactions, the savings in bank operating costs, and fees that can be earned from additional home banking services could amount to more than $10 billion in revenues per year and serve as the major incentives for moving ahead and implementing services based upon these systems.

Financial Services

The major products and services offered by the financial services industry are designed to facilitate the purchasing, selling and managing of stock, bonds and related investment packages as well as the purchasing of goods and services via credit cards. Like the home banking services, they are packaged and marketed under a variety of trade names, and are accessible through a variety of electronic media. Since this industry is governed by rules and regulations which are different and, until recently, less restrictive than those of the banking industry, the number and type of businesses that can offer these services is greater. For example, the participants in this industry range from traditional stock brokerage firms such as Merrill Lynch to major retailers such as Sears Roebuck and Company.

However, because of recent rulings, the banks may eventually have more latitude to offer the same type of services. Under the National Bank Act and interpretive rulings of the Comptroller of the Currency, national banks are now permitted to offer banking, financial and economic products and information to subscribers; perform data processing activities in connection with banking, financial, and economic data; perform payments processing and financial record keeping for subscribers, packagers and service providers; and execute funds transfers between various parties. Additionally, with respect to bank holding companies, the Federal Reserve Board in recent amendments to Regulation Y (which implements the Bank Holding Company Act) determined that home banking activities and data processing for financial data are "closely related to banking" and thus permissible activities.

In some cases, these rulings have enabled banks and financial institutions to engage in joint ventures such as the relationship between Citibank and VISA. If these ventures continue to prove profitable, then the trend is expected to continue as well as expand into the future. The net result will be that there may be no discernable difference to the consumer between the home services being provided by the two types of institutions.

To a large degree, the providers of financial services compete for the same customers being pursued by the home banking industry. This is not surprising since the fees earned for financial services exceed $6 billion per year by serving over 40 million investors, virtually all of whom require banking services as well.

9.4.2 Description of Major Home Banking/Financial Services

Despite the packaging and promotional campaigns, today's Home Banking and Financial Services fall into one or a combination of the following three categories: 1) checking account management; 2) debit and credit card transactions; and 3) investment and portfolio account management.

Checking Account Management

This service simply enables consumers to access their checking accounts via telephone or PC to determine balances, pay bills, write checks and transfer funds into other accounts.

Debit and Credit Card Transactions

These services enable consumers to simultaneously purchase goods and services or obtain cash, and directly debit their accounts for payment. The transactions may be conducted via private telephones, Automated Teller Machines (ATM's), or Point-of-Sale (POS) terminals.

Investment & Portfolio Account Management

Directed at investors, these services not only enable consumers to check on the status of a variety of investment vehicles (such as stock, bonds, and money market certificates), but to purchase and sell them as well. In addition, they may also enable the consumer to transfer funds into their checking and savings accounts located at other financial institutions.

9.4.3 Major Service Providers and Competitive Business Strategies

Home Banking Services

The major providers of home banking services today are listed in the table below.

Table 9-5
* Current Home Banking Service Providers *
1986

Service Provider	Region	# of Users	Protocol
ADP Telephone Computing Services/Home Banking Interchange	Nationwide	2,000	NAPLPS
Anacomp/Videoserv	Nationwide	NM*	Prestel
Bank of America/Home Banking	California	20,000	ASCII
Chase Manhattan Bank/ Consumer Home Banking	New York	200	ASCII
Chemical Bank/Pronto	New York	11,000	ASCII
Citibank/HomeBase	New York	1,000	ASCII
Continental National Bank/Home Banking System	Miami	200	ASCII
Empire of America, Macrotel/TransTouch	Buffalo	NM*	NAPLPS
Farmers State Bank and Trust, BankWork/ Farmers Home Banking	Jacksonville, IL	20	ASCII
First Interstate Bank/ Day-and-Night Video Banking	Los Angeles	250	ASCII
Horizon Bancorp/ Horizon Home Banking	New Jersey	NM*	ASCII
Huntington Bank/Bank Share	Ohio	NM*	ASCII
Madison National Bank/ Home Teller	Washington, D. C.	300	ASCII

(cont'd)

Table 9-5 (cont'd)
* Current Home Banking Service Providers *
1986

Service Provider	Region	# of Users	Protocol
Manufacturers Hanover Trust	New York	NM*	ASCII NAPLPS
National Bank of Detroit, Applied Communications/ Video Informaiton Provider	Detroit	NM*	Prestel
NCR Universal Credit Union/Companion-at-Home	National	100	ASCII
Penn Security Bank & Trust/People Server Videotex Service	Scranton, PA	50	ASCII
Shawmut Bank of Boston/ Home Banking	Massachusetts	NM*	ASCII
Toledo Trust/VistaBanc	Toledo, OH	120	ASCII
United States Trust Co./ UST Master Account	New York	70	ASCII
VideoFinancial Services, Viewdata Corp. of America/Applause	South Florida	850	NAPLPS

NM*: Not meaningful, in startup phase
Source: "Teleservices Report" from Arlen Communications

It is the consensus of banking industry analysts that the major "high tech" banks on the leading edge of developing new consumer banking products and services for the 1990's are:

- Mellon National Corporation
- Mercantile Texas Corporation
- Wachovia Corporation
- Banc One Corporation
- Citicorp
- Bank of Boston Corporation
- Irving Bank Corporation
- First Interstate Bancorp
- NBD Bancorp

Financial Services

The major publicly held providers of today's financial services are listed in the table below.

Table 9-6

Rank	Financial Institution
1	Merrill Lynch & Company
2	E. F. Hutton & Company
3	Paine Webber Inc.
4	Dean Witter Reynolds
5	Goldman Sachs & Company
6	Bache Halsey Stuart
7	Salomon Brothers
8	Stephens Inc.
9	Shearson Loeb Rhodes
10	First Boston Corp.

Home banking and financial services providers reach and distribute their services to their customers through a variety of distribution channels. As a major integral part of their business development strategies, these providers will continue to refine and expand those channels, namely: 1) automated teller machines (ATMs) and/or point-of-sale (POS) terminals located at banks and retail outlets; 2) debit cards; 3) videotext; 4) telephones; and 5) telephone & on-line databases/personal computers. Although most of these channels are technically not "home" based, they do enable consumers the flexibility to conduct their transactions in a number of geographically dispersed areas. However, their evolution toward and integration with true home based systems are expected to occur by the late 1990's.

ATMs/POS Terminals

ATMs are essentially remote terminals combined with cash dispensing capabilities which are tied to a mainframe computer of an individual bank or of a regional or nationwide network. Although ATMs were located primarily outside of a bank and used to supplement the regular bank teller staff, the trend has been for banks to expand their potential customer base by becoming part of regional or national ATM networks. There are presently approximately 5,000 banks that belong to 100 regional ATM networks. The number of ATM terminals in these networks are expected to grow from the current installed based of approximately 25,000 units to over 75,000 by the end of the 1980's. The largest regional ATM networks are listed in the following Table.

Table 9-7

MAJOR REGIONAL ATM NETWORKS

Network Name	Service Area	Number of Member Banks	# ATMs
Plus	AZ, CA, CO, IW, KN, LA, NB, NV, NM, OR, SD, UT, WA, WY	260	300
Instant Teller	CA, WA, OR, AZ	78	230
Day & Night Teller	AZ, CA, CO, ID, MT, NV, NM, OR, UT, WA, WY	21	600
NETS	NB	95	250
Exchange	WA, OR	50	176
Iowa Transfer System	IW	570	232
Fast Bank	MN, WI, ND, SD, MT	92	170
Instant Cash	MN, MT, ND, SD, WI	157	165
Tyme	WI	330	360
Cash Station	IL	50	75
MAC-Link	MI	176	200
MAC	PA, NJ	54	215
Jeanie	OH, KY, IN, VA, MD, D.C.	23	150
Network Exchange	MD, VA, D.C.	7	250
Mid-Atlantic Exchange	MD, VA, D.C.	8	500
Owl	OH, IN, KY	26	205

(cont'd)

Table 9-7 (cont'd)

MAJOR REGIONAL ATM NETWORKS

Network Name	Service Area	Number of Member Banks	# ATMs
Pulse	TX, LA	400	400
MPACT	TX, OK, AK, LA	217	257
CheckOKard	OK	36	122

Source: Business Week: January 18, 1985

Approximately a dozen banking consortia are planning to develop nationwide ATM networks. An additional twenty-seven other banks are considering the option of joining this network. The consortium of the Chase Manhattan Bank and the Colorado National Bank appear to be taking the lead with establishing the most extensive national networks. Presently, there are five major national ATM networks. They are: 1) Plus System; 2) Cirrus System; 3) Nationnet; 4) MasterTeller; and 5) Visa Travel Network.

Not all the networks, however, are to serve strictly banking interest. Some of the networks are serving the requirements and interest of retailers and credit card companies. The first major national retail-banking network was established and evaluated by First Interstate Bancorp, the nation's largest multibank holding company, along with the Bank of Montreal, Manufacturer's Hanover, and First Chicago. In addition, Visa International and MasterCard are providing national consumer credit and retail purchasing services through a national network. The J. C. Penney Company, all the major airlines, shopping malls, and convenience stores are offering ATM based services on a nationwide basis. Finally, supermarket chains are beginning to offer ATM based services. For example, Publix Super Markets headquartered in Lakeland, Florida has placed ATMs in 255 of its stores.

Thus, present and future uses and applications of ATMs are gaining popularity and acceptance by the home banking services industry as well as its competitors.

Debit Cards

Although debit cards may be used to purchase goods and services in much the same way as credit cards, they differ in two fundamental ways. First, Debit Cards are usually issued by banks rather than retailers, credit card companies, or other financial institutions to enable the cardholder to gain access to and use the funds in his/her account for routine transactions as well as for obtaining cash from ATMs. In limited circumstances, they may also be used to purchase goods and services from retailers that are part of a bank's debit card network. Home banking analysts anticipate that the capabilities of ATMs and POSs will be merged into a new generation of "direct debit POS systems" that will faciliate purchasing transactions between retailers and consumers which would result in a greater use of the banks' services and greater competition for the credit card companies. Second, because Debit Cards are instruments of banking institutions, they are presently more restricted than credit cards in terms of their uses beyond bank related transactions. However, if current regulatory issues can be resolved involving the inconsistencies between the Truth-in-Lending Act and its implementing Regulation Z (which governs credit transactions) and the Electronic Funds Transfer Act and its implementing Regulation E, this barrier can eventually be eliminated.

Despite current restrictions, however, the use of Debit Cards is extensive. According to The Nilson Report, a banking industry newsletter, there are approximately 50 million proprietary Debit Cards in use. This is triple the number from two years ago and equal to the domestic circulation of VISA credit cards.

Videotext

To a limited degree, banks are using videotext on an experimental basis to provide home banking services to its customers. Videotext rather than teletext is being evaluated because of its interactive and transaction capabilities. These systems are based primarily on ASCII rather than NAPLPS (North American Presentation Level Protocol Standard).

Videotext based home banking services are presently being offered by new business alliances such as the IBM, Sears, and CBS consortium which is providing "Trintext." Other groups include Time Inc. with Chemical Bank, ATT and Bank of America which are providing "Covidea"; and Citicorp, NYNEX Corp. and RCA Corp. which provides "Direct Access/Dollars and Sense." All of the services are transaction rather than strictly information oriented.

Preliminary reaction to these services indicate that they will have to be provided on a national basis to be cost effective to the providers. From the consumers' perspective, the monthly service fee will have to be less than $15 and the number of other banking, financial and purchasing services will have to be increased in order to remain attractive and be used on an ongoing basis. What this means to the providers is that the service itself will have to be subsidized by the revenues generated from the cash float or related sources resulting from consumer transactions or deposits.

Services based upon the ASCII protocol and provided on a high volume regional or national basis costs approximately $20 per month per customer.

The ability to provide the required additional services in an appealing graphic or visual format desired by consumers, however, is limited. The projected costs for using the more flexible NAPLPS are expected to fall in the future (early 1990's) to around $20-25 per month on a volume basis. Thus, it appears that regardless of the approach selected, the providers will have to subsidize a significant percentage of the costs of the home banking services.

Telephone

By far the simplest and most widely used distribution channel for home banking and financial services is the telephone. Approximately 36 million pay-by-phone transactions were conducted in 1982, a fourfold increase from 1980. The major draw-back to this technology, however, is that it is more labor and, therefore, cost intensive for banks and financial institutions than the other electronic channels being evaluated. In addition, a telephone based service is more constrained in terms of the number and volume of transactions that can be handled per unit of time.

Additional experiments are being conducted to integrate the telephone with other technologies to take advantage of the natural affinity and familiarity consumers already have with it. The other technologies include personal and home computers, videotext terminals, and high resolution TV/home entertainment centers.

Telephone & On-line Databases/Personal Computer

To date, only a few home banking services are being offered that are designed for an integrated telephone/modem/personal computer system. The home banking industry estimates that there are approximately 44,000 consumers and small business owners now using personal computers to do their home banking.

Some of the more extensive services are:

1) "HomeBanking" and "Dollars and Sense" being marketed by Bank of America. The two services are linked by a proprietary PC software package called Moneylink and is designed to run on either and IBM PC or Apple II.

2) "Banc Once" and "Videofinancial Services" are being offered by Knight-Ridder.

3) "Spectrum" is a service which enables customers to balance their accounts, pay bills, transfer funds, and to write and send checks. The service is being provided by Chase Manhattan Bank.

4) "Pronto" and "Business Banker" are services similar to the ones mentioned above with an emphasis on the small business marketplace.

Several other banks are presently developing their strategies to implement niche oriented PC driven home banking services. Some of the more aggressive ones include Security Pacific National Bank in Los Angeles, Continental National Bank in Miami, and Madison National Bank in Washington, D.C.

Some of the major PC based home financial services include:

Table 9-8

* Top PC Based Home Financial Service Providers *
1985

Company	Type of Service	Revenues (millions $'s)
Reuters	Commodities and securities quotes and news	$505
Dun & Bradstreet	Credit and miscellaneous business information	325
Quotron	Securities quotes	187
TRW	Credit checks	160
Telerate	Commodities and securities quotes	149
McGraw-Hill	Financial information	120
Dow Jones	Securities and general business formation	100

Source: BusinessWeek, August 25, 1986

9.4.4 Home Banking/Financial Service Subscriber Estimates

Based upon the data presented and the opinions of banking and financial institution analysts, the estimated number of present and projected subscribers to true home services are summarized in Table 9-9.

Table 9-9
* Overall Home Service Subscribers Estimates *

Service Category	Estm. # of Subscribers 1985	mid-1990's	Estm. Compounded Annual Growth Rate
Home Banking	36,000	30 million	95%
Home Financial	57,000	10 million	70%

Source: Datamation: September 1985

The dramatic increases in the number of subscribers are based upon the assumptions that: 1) PC/Home computers and modems will continue to be pervasive consumer products; 2) the cost of providing services based upon ASCII or NAPLPS protocols will continue to decline; and 3) the services will be properly packaged, marketed and priced with other transaction oriented, easy and convenient to use features that serve actual rather than perceived consumer needs.

9.4.5 Technology Requirements

Although no major technological breakthroughs are required to enable the home banking and financial service industries to grow, several components to the delivery system need to be refined. More sophisticated applications PC software needs to be developed to provide consumers with easier access to the variety of services being offered. Some industry experts believe that the integration of videotext terminals with PCs will serve as an even greater catalyst for consumer acceptance and market growth. And although the preferred communications link between the service providers and their subscribers remains the telephone and is deemed adequate for the forseeable future, some strategies are being refined to use alternative links such as DBS antennas in addition to FM carrier frequencies.

Therefore, if these markets are inhibited from achieving their projected growth rates, it will be because of business, market, regulator or other related barriers, and not because of the lack of available communications and information processing technologies.

9.5 MARKET SEGMENT OVERVIEW - HOME SHOPPING SERVICES

9.5.1 Market Status and Projections

Home shopping services are older than the Sears Roebuck and Company catalogue which was started in 1886. Although originally designed to serve populations in remote geographic locations throughout the country, the concept has undergone dramatic changes over the past ten years. Shopping at home by virtually all segments of the buying public is now so common that it is considered to be a permanent and pervasive part of the retail industry, and is expected to represent a major competitive threat to traditional retail outlets such as stand-alone stores and shopping malls. The forces driving this threat are the conveniences afforded to shoppers through home shopping services, and changes in consumer buying behavior because of altered work schedules and lifestyles of all members of the households of today and the future.

In 1985, the retail industry sold approximately $250 billion worth of goods and services. The Home Shopping segment of the retail industry accounted for roughly $50 billion or 20% of those sales. Almost $49.2 of the $50 billion were generated through catalogue sales. Sears, the nation's largest retail business, was responsible for $4 billion of those sales through its catalogue ordering service. The balance of the sales (approximately $800 million) were generated through specialty cable and broadcast TV programs designed specifically as home shopping services.

Retail sales are expected to exceed $370 billion by the mid 1990's. Industry analysts estimate that by that time at least 30% of those sales, or $111 billion, will be generated through home shopping services.

The implications of these trends are that the number of consumers will not only increase, but will be spending more money per transaction as well. Presently, approximately 25 million individuals purchase goods and services through home shopping services each year. That number is expected to at least double by the mid-1990's. Although traditional catalogue and telephone based shopping services are expected to continue to represent a significant share of the home shopping industry, TV based services, many of them provided on a 24-hour basis, will possibly make significant in-roads, represent the fastest growing segment of the home shopping industry, and capture at least 25% of marketplace.

There are several reasons for the move toward using more advanced electronic and information technologies in this industry. The major providers of home shopping services believe that, if effectively applied, they would serve to: 1) lower the cost of sales; 2) increase profit margins; and 3) develop and penetrate additional market segments such as the millions of consumers that work between 4 p.m. to midnight, and those that are homebound because of handicaps. And because of changing lifestyles, consumers are expected to make greater use of these type of services because of: 1) greater convenience to their personal schedules; and 2) easier and quicker access to a broader selection of goods and services.

Because of this anticipated growth, several strategies are evolving by traditional retailers and newcomers to use information technologies to capture more segments of the marketplace (more commonly referred to in the trade as "niche markets"). It is anticipated that there will be fewer general home shopping services such as the Sears catalogue and more electronically based "niche" services to serve specific sub-segments of consumers by demographic category or by product and service preferences. Some examples of the demographic categories that will probably be used include: a) income; b) profession; c) geographic location; d) male/female; e) age; f) marital status; g) family status; h) ethnic background; i) political affiliation; j) religious affiliation; k) leisure activities; and l) type of housing owned/rented. These categories will be cross-referenced with product/service categories ranging from inexpensive and expensive holiday gifts to furniture and home furnishings, clothing, toys, appliances, food, automobiles, tools, and vacations.

9.5.2 Description of Major Home Shopping Services

The major home shopping services fall into three categories. They are 1) mail-order; 2) telephone ordering; and 3) interactive TV/telephone ordering. Although some home shopping services are being provided through videotext based programs, they are still considered to be in the experimental and evaluation stages with a questionable future because of the difficultly in presenting quality graphic and textual materials as well as simultaneously providng data inquiry and processing capabilities in a cost effective manner. For those reasons, a rigorous analysis of this type of service was not undertaken for this study.

Mail-Order

Ordering by mail is the oldest home shopping service available to consumers today. Originally designed to enable individuals located in geographically isolated locations to purchase products from retailers headquartered in urban areas, mail-order is now commonplace and used by virtually every segment of the population. In response to an item described in a catalogue or newspaper insert, a consumer may now simply fill out an order form, include a credit card number or personal check, then mail it. Presently, the major limitations to this service are: a) ensuring that the appropriate consumers receive catalogues or inserts in a timely fashion; and b) the response time to fulfill orders has been typically two weeks to several months, depending upon the type of item ordered.

Telephone Ordering

Telephone ordering, or "pay-by-phone," is simply a quicker method than the ordering by mail method. Most services provide a toll-free 1-800 number and the ability to have purchases charged to credit cards. Although it also enables consumers to interact with the retailers to have questions regarding products and services to be answered, this method still has the same limitations as the mail-order method.

Interactive TV/Telephone Ordering

Interactive TV/telephone ordering which is presently available on a limited basis is the newest home shopping service for consumers. Through this service an individual may select a cable or broadcast home shopping service program, see and hear about selected items being sold, then order it by telephone through a toll-free number and charge it to his or her credit card. These type of services are often available on a 24 hour basis. Although this type of service appears to have a significant amount of appeal, some of the major limitations include the slow rate at which products can be introduced (an average of one every 5-10 minutes), and the inability to visually examine the product for extended periods as can be done with a photograph in a traditional catalog. Order fulfillment, however, is a strong feature of this service. Products are usually received within 4-10 days of ordering.

9.5.3 Major Service Providers and Competitive Business Strategies

The major providers of the home shopping services described in Section 9.5.2 are: 1) both large and small department and specialty stores; 2) catalogue merchandisers; and 3) broadcast and cable TV based retail operations.

Department and Specialty Stores

Of the $250 billion in retail sales generated in 1985, approximately $133 billion were from department and specialty stores. An estimated 15% of their sales were generated through a combination of mail and telephone orders. Although there are over 400 national and regional department and specialty store chains, almost $93 of the $133 billion (or 70%) resulted from sales from 10 major national department store chains. The major companies are presented in Table 9-10.

Table 9-10
* Top 10 Deparment and Specialty Stores *
in Terms of 1985 Sales

Industry Rank	Name	Retail & Catalogue Sales (billions $'s)
1	Sears Roebuck & Company	$22.8
2	K Mart Corporation	16.8
3	J. C. Penney Company, Inc.	14.7
4	Federated Department Stores	7.5
5	Montgomery Wards	6.8
6	Dayton Hudson Corporation	4.4
7	May Department Stores	3.9
8	Carter Hawley	3.1
9	Allied Stores Corporation	2.9
10	R. H. Macy & Company	2.7
	Total	$92.8

Source: Ward's Directory of 55,000 Largest U.S. Corporations

These companies are expected to continue to play significant roles in developing and refining home shopping services for the retail markets of the 1990's. However, in order to maintain their market positions and to encourage and facilitate greater consumer expenditures, several companies such as Sears, K Mart and J. C. Penney are developing business strategies to exploit consumer electronic and information technologies beginning as early as 1987.

Catalogue Merchandisers

There are over 900 major catalogue merchandisers in the U. S. that also use mail and telephone order services as well as discount retail showrooms to generate sales. The following table lists the leading companies in this industry segment.

Table 9-11
* Top 10 Catalogue Merchandisers *
1985

Industry Rank	Name	Catalogue Sales (billions $'s)
1	Service Merchandise Company	$2.900
2	Best Products	2.254
3	Consumer's Distributed	0.903
4	Brendles	0.240
5	L. Luria & Sons	0.184
6	United Jewelers & Distributors	0.176
7	W. Bell & Company	0.150
8	Jewelcor, Inc.	0.130
9	Kay's Merchandise Mart	0.126
10	McDade & Company	0.112

Source: National Catalogue Merchandisers Assoc. (Dec. 1986)

In addition to individual merchandisers, cooperative marketing and sales efforts amongst large numbers of non-competing companies are beginning to be formed to help minimize costs, increase profitability, and to implement other selling strategies and technologies. The largest cooperative effort has been formed by Mann Media, Inc. which promotes the goods and services of its 100 members under the trade name of "American Catalog Shopper Network."

Like the department and specialty stores, the catalogue merchandisers believe that their traditional channels of marketing, sales and distribution have matured; that the life styles, buying patterns, and purchasing sources of their customers are changing; and that in order to maintain their competitive edge, they will have to use other methods and technologies such as electronic media in the future.

Broadcast & Cable TV Services

Presently, there are only 25 companies providing home shopping services via broadcast or cable TV programming. Although the number appears to be small, it has been estimated that the number of potential consumers reached through these programs exceed 30 million with approximately 3 million active buyers. The leading services and companies in this industry are summarized in Table 9-12.

Table 9-12
* Leading TV Based Home Shopping Service Providers *
1986

Service	Audience Reached (millions)	Owners
24-HOUR CHANNELS		
• Home Shopping Network	15.0 (cable)*	Publicly held
• Cable Value Network	9.0 (cable)	COMB and 18 major cable operators
• QVC Network#	7.6 (cable)	Public, cable operators**
• Shop Television Network	5.0 (cable)	Publicly held
• Sky Merchant	0.8 (cable)	Jones Intercable
PART-TIME CHANNELS		
• Telephone Auction	40.0 (broadcast)	Publicly held
• Valuetelevision	21.0 (broadcast)	Horn & Haordart, Lorimar Telepictures, and Fox TV
• Tempo Galleria	12.5 (cable)	Private
• Telshop	10.0 (cable)	Financial News Network

(cont'd)

Table 9-12 (cont'd)

Service	Audience Reached (millions)	Owners
• Entertainment Marketing	2.0 (cable)	Publicly held
• Crazy Eddie	1.5 (satellite)	Crazy Eddie, Inc.
• Video Shopping Mall	0.5	Publicly held

* May have an additional 25 million broadcast viewers by the end of 1986.
** Sears has an option to buy 2 million shares.
# Will go to 24 hours in Jan. 1987.

Note: Audience reached column is not additive.
Source: Business Week/December 15, 1986

Today, TV based home shopping services are demanding a lot of attention from corporate planners and investors representing major department store chains and catalogue merchandisers because of early and dramatic financial successes by a handfull of pioneering companies. Some industry analysts estimate that by the mid-1990's, this type of service will be available to approximately 50 million TV viewers, which represents almost half of the projected viewing public. Although sales in 1986 are expected to be in the $500 million range, this type of omnipresent exposure in the future is expected to generate over $36 billion in retail sales via TV based home shopping services. Today, the major competitors in the TV home shopping service marketplace are Home Shopping Network (HSN), Cable Value Network (CVN), and QVC.

Between its fiscal years 1985 and 1986, HSN's sales increased tenfold to $160.1 million, with earnings of $17 million. In 1987 sales are expected to increase to $714 million with earnings of $78.8 million. In addition, HSN reaches 12 million homes through its cable TV network, and presently has an estimated 500,000 regular customers.

CVN is an affiliate of COMB, one of the world's largest merchandisers of liquidated goods. CVN formed a joint venture with several of the country's biggest television cable companies, including number 1 Tele-Communications, Inc. before it began nationawide 24-hour programming in September of 1986. With CVN's 22 cable partners, it now has approximately 10 million subscribers which represents almost 25% of the current cable subscriber marketplace.

Adding further credibility to the TV based home shopping service industry, Sears, Roebuck & Company, the nation's number 1 retailer has given exclusive rights to QVC Network, Inc. to merchandise the company's brand name products to over 7.6 million viewers.

A small niche already exists for home shopping services delivered via home satellite dish antenna owners. For example, Crazy Eddie, Inc., a highly successful New York based retailer of consumer electronics started its broadcast retailing show in October of 1986, promoted as "Crazy Eddie World of Home Entertainment Shopping Network." It is beamed via satellite to over 1.6 million viewers as part of a larger programming package. Data is presently not available as to how many of these viewers are active buyers of the goods sold on the Network.

As digital TV, direct broadcast satellite antennas, and personal computer technologies become more sophisticated and easier to use and less costly, greater interactive and integrated capabilities are expected to develop, which, in the TV home shopping service industry will lead to greater market penetration and utilization of its services.

9.5.4 Home Shopping Service Subscriber Estimates

Based upon the estimates of several industry analysts, the number of actual users of home shopping services are expected to grow from today's level of 25 million consumers to more than 50 million by the mid-1990's. This represents an average compounded annual growth rate in the marketplace of 7% per year for the next ten years. The only service that may continue to require subscription fees in the future will be the ones based upon cable or direct broadcast satellite TV transmissions.

Presently, approximately 3 million of today's 25 million home shopping service users subscribe and purchase through TV/telephone based services. That number may grow to over 10 million by the mid-1990's, representing an average compounded annual growth rate of just over 15%.

These major trends are summarized in Table 9-13.

Table 9-13
* Estimated Home Shopping Service Subscribers *

Home Shopping Market Segment	Estm. # of Subscribers		Growth Rate
	1985	mid-1990's	
• Mail & telephone ordering services	21 million	40 million	7%
• Broadcast, cable, and DBS services	3 million	10 million	15%

There are a number of technological as well as business factors, however, that will serve to inhibit or facilitate the development of the sub-segment of the interactive TV/telephone market using satellite, particularly Ka band, technologies during the mid-1990's timeframe.

The most aggressive estimates assume that a large majority (i.e. 80% or more) of the estimated 6.7 million home satellite antennas that are expected to be purchased by the mid-1990's will automatically be used for home shopping as well as entertainment services. Other assumptions in these estimates are that the interactive features and capabilities of satellite based services that will be required by consumers will be mostly if not entirely available by the mid-1990 timeframe; and that the programming and service costs will be brought down to a level to where they can be partially subsidized by the providers and the balance incorporated into the price of the goods and services sold to the subscribers.

More conservative analyses assume that only a small percentage (i.e. 5 - 10%) of antenna sales will translate into on-going subscribers to home shopping services; and that the technological and business issues will only be partially resolved by the mid-1990's. Under these conditions, these analyses also assume that the subscribers will represent the "early adopters" segment of the consumer market. These type of individuals have traditionally taken the lead over the general population by an average of 5 - 10 years in terms of using a new technology. This market phenomenon is not new. Recent examples of "early adopters" include air travelers, and owners of automobiles, color televisions, personal computers, and video cassette recorders. In essence, some industry experts do not believe that the satellite based home shopping service marketplace will undergo significant expansion until the early 2000's.

Therefore, based upon the aggressive and conservative analyses, the best estimates of the number of subscribers to satellite based home shopping services by the mid to late 1990's range from 700 thousand to 5.4 million.

9.5.5 Technology Requirements

Ka band based home shopping services will be in direct competition with existing voice, broadcast and cable TV technologies. The major strengths of these competing technologies are that they are: 1) pervasive with extensive installed infrastructures; 2) available and easy to use; 3) familiar and accepted by consumers; and 4) relatively cost affective.

The major weaknesses of these existing technologies in terms of their use for interactive home shopping services are: 1) products can only be demonstrated and sold in series, which makes it difficult to present large volumes of goods and services per unit of programming time; 2) the consumer must wait or pre-schedule his/her time to view products of interest; and 3) consumer interaction is limited to asking questions about or purchasing products that have recently been demonstrated during the program.

In order for Ka band based services to compete against these established technologies, they must enable service providers and subscribers to:

- Eliminate the need for "Live" performance oriented programming.
- Randomly request and transmit information on product categories or individual products. Still-frame or videotext type of formats would be acceptable.
- Simultaneously transmit, verify and complete orders and credit/debit card transactions.

Beyond the data and transmission rate capabilities of Ka band satellites, these capabilities will evolve only if a host of supporting and complementary technologies and their infrastructures are developed as well. The major developments required are in: 1) software which will enable both the service providers as well as subscribers to request, transmit and receive the desired product graphics and data as well as to verify and conclude financial transactions; 2) communications networks between the product providers, service programmers, and consumer credit or banking institutions; 3) transferring enormous amounts of product information from graphic and textual form to digital format in timely and cost effective ways; and 4) the availability of consumer electronic products with the required integrated, transaction oriented capabilities.

9.6 MARKET POTENTIAL AND SUBSCRIBER ESTIMATES

Based upon the criteria and weighting factors described in Section 9.2 as well as the quantitative and qualitative information presented in Sections 9.3 thru 9.5, the calculations to determine the potential number of D-T-S subscribers are summarized in the following tables.

9.6.1 Probability & Weighted Market Potential Estimates

The probability and weighted market potential estimates are presented in Tables 9-14 thru 9-17.

Table 9-14

* Probability Estimates for Achieving *
Home Banking Market Development Goals

MARKET SEGMENT: Home Banking Services

Category/Criteria	Weighted Potential Estimates
1. Market Segment Status & Projections	
a. Overall subscriber growth rate	1.0
b. Overall growth timeframe	1.0
c. Geographic distribution of subscribers	0.8
2. Business Development	
a. Competing business development strategies	1.0
b. Strong competitors to serve markets	1.0
3. Technology Requirements	
a. Commercial availability	0.9
b. Competing technologies	1.0
Probability Estimate (product of 1a. x 1b. x ... 3b.)	0.72

Table 9-15

* Probability Estimates for Achieving *
Home Financial Service Market Development Goals

MARKET SEGMENT: Home Financial Services

Category/Criteria	Weighted Potential Estimates
1. Market Segment Status & Projections	
a. Overall subscriber growth rate	1.0
b. Overall growth timeframe	1.0
c. Geographic distribution of subscribers	0.9
2. Business Development	
a. Competing business development strategies	1.0
b. Strong competitors to serve markets	1.0
3. Technology Requirements	
a. Commercial availability	0.9
b. Competing technologies	1.0
Probability Estimate (product of 1a. x 1b. x ... 3b.)	0.81

Table 9-16

* Probability Estimates for Achieving *
Home Shopping Market Development Goals

MARKET SEGMENT: Home Shopping Services - Mail/Telephone

Category/Criteria	Weighted Potential Estimates
1. <u>Market Segment Status & Projections</u>	
a. Overall subscriber growth rate	0.8
b. Overall growth timeframe	1.0
c. Geographic distribution of subscribers	1.0
2. <u>Business Development</u>	
a. Competing business development strategies	1.0
b. Strong competitors to serve markets	1.0
3. <u>Technology Requirements</u>	
a. Commercial availability	1.0
b. Competing technologies	1.0
Probability Estimate (product of 1a. x 1b. x ... 3b.)	0.8

Table 9-17

* Probability Estimates for Achieving *
Home Shopping Market Development Goals

MARKET SEGMENT: Home Shopping Services - TV Based

Category/Criteria	Weighted Potential Estimates
1. <u>Market Segment Status & Projections</u>	
a. Overall subscriber growth rate	1.0
b. Overall growth timeframe	0.9
c. Geographic distribution of subscribers	0.8
2. <u>Business Development</u>	
a. Competing business development strategies	0.9
b. Strong competitors to serve markets	0.9
3. <u>Technology Requirements</u>	
a. Commercial availability	0.8
b. Competing technologies	1.0
Probability Estimate (product of 1a. x 1b. x ... 3b.)	0.47

Based upon the probability estimates calculated in the previous tables, the Weighted Market Potential Estimates are presented below.

Table 9-18

* Weighted Market Potential Estimates *

MARKET SEGMENT	ESTM. # OF SUBSCRIBERS	PROB. ESTM.	WEIGHTED SUBCRIBER POTENTIAL
Home Banking	30 million	.72	21.6 million
Home Finance	10 million	.81	8.1 million
Home Shopping			
- Mail/Tel.	40 million	.80	32.0 million
- TV	10 million	.47	4.7 million

9.6.2 D-T-S Subscriber Estimates

The researchers of this section of this report were tasked to determine the relationship between the cost of a Ka band based system for consumers and the potential number of subscribers to services that would be provided through that communications link. This relationship could not be defined at this point in time for the following reasons.

Accurate cost vs sales estimates for consumer as well as industrial products and services are not based on linear relationships, even for well established items in mature markets. They are based upon several inter- as well as independent business, technological, market, and economic variables such as: 1) investment and market penetration strategies; 2) return on investment (ROI) requirements; 3) alternative market options and development opportunities; 4) product or service development, distribution, marketing, selling, and maintenance costs; 5) internal operating costs; 6) tax incentives and barriers or incentives from government regulations; 7) fluctuating market demand; 8) competitive business strategies; and 9) alternative technologies and channels of distribution. For new, evolving services such as the ones described in this section it is even more difficult to define the relationship between any one of these variables and the potential number of subscribers that may develop.

Some recent examples of how complex these relationships are and how seemingly independent the number of users are from the cost of the delivery system for services include:

- Air Transportation - Although the cost of aircraft is incorporated into the price of airfares, aircraft costs do not directly influence the number of airtravelers that will fly on a particular plane or with a specific airline.

- Local/Long-Distance Telephone Service - The cost of the installed based of telephone equipment and capacity is no longer the major factor for determining the rates which the various telephone companies charge their non-business customers.

- Cable TV - Despite the fact that cable TV programers have lowered their monthly fees to subscribers, the overall market continues to stagnate, and, in some segments, is declining. The major issue is the quality of the programs being provided rather than the cost of the service.

Based upon the data analyzed, the home services described in this section of the report will continue to evolve and be packaged and priced to accommodate market and business requirements and needs, and not solely upon the cost of providing the service nor the communications technology upon which it is based. If Ka satellite technologies become available within the mid-1990 timeframe and if they can be used to develop or penetrate markets for home services, their costs may or may not be directly incorporated into the fees charged to subscribers. Home service providers may elect to partially subsidize these system costs or imbed them into the cost of other services or products sold through the subscription service.

Minitel of France, for example, is using this strategy to provide its videotext service to its subscribers. The government's telecommunications authority, Direction General des Telecommunications, that operates the network provides the videotext terminals to users at no cost. The cost of today's home services provided by U. S. companies are based upon similar strategies, albeit not as dramatic. Telephone based banking services cost consumers between $0.00 to $0.50 per transaction. Many electronic fund transfer payments costs between $5 - $10. Subscription fees for cable TV based home shopping programs costs between $25 - $50 per month. However, broadcast TV based programs are free to the viewers. On-line data base services for financial information can cost between $50 - $200 per month depending upon usage and the type of information extracted from the data bases. None of these fees to the subscribers reflect the full costs for providing the services. Likewise, the number of subscribers to these services do not depend on price alone.

Table 9-19 presents the maximum and, in the opinion of the researchers of this section of the report, a more realistic estimated potential of the number of D-T-S subscribers that may develop for the home services examined in this study.

Two different but related sets of non-Ka system cost assumptions were used to estimate the potential number of subscribers to Home Banking and Financial services, as well as to Home Shopping services. The underlying assumption that was applied to both market segments was that the maximum number of D-T-S subscribers can not be greater than the total estimated installed base of DBS antenna users in the 1995 timeframe. This is simply because that D-T-S services can not be received without them. The rationale for this assumption is explained in Section 9.3 of this report.

For the Home Banking and Financial services marketplace, it was further assumed that 25% of the DBS antenna marketplace will be for Ka band designs and capabilities and be used to acquire these services via PC link. For the Home Shopping services marketplace, it was assumed that 80% of the Ka band antenna owners also owned either conventional or HDD TVs. This subsegment of the antennas marketplace translated into approximately 20% of the weighted market potential for TVs.

Table 9-19

* Estimated D-T-S Subscribers *

Service	Weighted Market Potential	Max. D-T-S Potential	Estm. D-T-S Market Penetration
Home Banking	21.6 million	*6.7 million	1.75 million (@25% penetration)
Home Financial srv.	8.1 million	*6.7 million	1.4 million (@25% penetration)
Home Shopping			
- Mail/telephone	32.0 million	NA	NA
- TV Based	4.7 million	#4.7 million	1 million (@20% penetration)

* Based on Table 9-4
# Assumes that all DBS antennas owners also own a conventional or HDD TV.

The maximum number of D-T-S subscribers assumes that all the required interactive and integrated consumer electronic products are available and that 100% of all the owners of these systems become home service subscribers. However, since this scenario is highly unlikely and because of the technology requirements and limitations of the TV based services, it appears that the home banking and financial service markets will have greater potential than the home shopping programs, at least through the mid-1990's.

These estimates should not be representative of the total potential of each of these service categories, but rather as an indicator of the early stages of adoption in each of the market segments. The trends and data analyzed suggest that significant market growth may in fact be several times greater than these numbers indicate, albeit in the late 1990's to early 2000's.

9.6.3 Rankings & Conclusions

Based upon the estimates developed, the Home Banking, Financial Services and mail/telephone based Home Shopping markets ranked "High" in terms of their potential. The TV based services of the Home Shopping markets ranked "Moderate." Likewise the greatest opportunity for D-T-S services appear to be in the Home Banking and Financial Services markets. Because of the business and technological barriers to entry, the Home Shopping market does not appear to represent as significant an opportunity in the mid-1990's timeframe for Ka based services.

None of the markets, however, will probably experience the explosive growth predicted for these markets as a whole. Although there are exceptions, most successful services and technologies have been developed and commercialized over a period of several years and at relatively modest growth rates. It should also be noted that in general any new product or service has a low probability (2-5%) of long-term success in the competitive marketplace, and that the commercialization cycle for new technologies such Ka band satellites has historically ranged from 10 - 25 years despite their attractive functional features. Even the telephone took over 25 years before it was able to be used by businesses on a low level, intermittent basis.

Therefore, even the weighted subscriber estimates may be considered optimistic. Based upon what is believed to be a realistic assessment of the market potential for the home services described in this section, the following recommendations are offered as the concluding remarks to this study:

1. Ka band satellite technology should continue to be developed to the proof-of-concept stage. Only after that milestone is achieved should the cost of a commercial system and its potential impact on subscriber fees be examined.

2. The satellite(s) should be designed to provide home service companies and subscribers the capability to encrypt, transmit and decrypt banking and financial service information on an interactive basis.

3. TV based Home Shopping Services should not be pursued as a primary target of opportunity. However, the developers of Ka band satellites should monitor developments in the consumer electronics and home shopping service industries and re-examine trends within the next 3 years to determine whether or not any significant changes have occured to warrant placing this market segment at a higher priority.

* * *

SECTION 9
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SECTION 10
NEW TECHNOLOGIES

There are no new technologies presented in this report.

GLOSSARY

Acronyms

ACTS	Advanced Communications Technology Satellite
BER	Bit Error Rate
CATV	Cable Television
CONUS	Continental United States
CPS	Customer Premises Service
CPU	Central Processing Unit
DA	Demand Assigned
FSS	Fixed Satellite Services
JPL	Jet Propulsion Laboratory
MSAT	Mobile Satellite
PC	Personal Computer
PSTN	Public Switched Telephone Network
R	Random Access
SOW	Statement of Work
SSMA	Spread Spectrum Multiple Access
TVRO	Television Received Only
VSAT	Very Small Aperture Terminal
WTC	W.T. Chen & Co., Inc.

Variables

A	Relative amplitude of interchannel interferer
β	Normalized carrier frequency spacing
B	Single user bandwidth (burst rate), also, relative amplitude of co-channel interferer
CNR	Carrier-to-noise power ratio
δ	Burst factor; also, user duty factor
d	Distance
D	User transmission delays frequency; also, diameter of parabolic antenna
f	Frequency
F	Frequency reuse factor (M/N)
G	Channel traffic (normalized)
IF	Intermediate frequency
K	Number of co-channel interferers; also, code constraint length; also, number of uplink packet slots per satellite frame
λ	Wavelength
m	Number of Capture ALOHA channels per uplink beam
M	Number of beams
n	Number of uplink frequency channels per uplink beam
N	Number of frequency subbands
P	Power
r	Code rate; also, rain region index
R	Channel data rate; also, roundtrip delay in packet lengths
RF	Radio frequency
S	Channel throughput or efficiency
T	Average message interarrival times; also, half of baseband modulation window support; also, receiver system noise temperature
TB	Single-user time-bandwidth product
U	Total number of simultaneous users
U_T	Total number of users
W	Total available bandwidth