Spread Spectrum Satellite Multiple Access and Overlay Service

by

Mark A. Maggenti

Thesis submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Master of Science

in

Electrical Engineering

APPROVED:

Tri T. Ha, Chairman

Timothy Pratt

Charles W. Bostian

March 6, 1987

Blacksburg, Virginia

Spread Spectrum Satellite Multiple Access and Overlay Service

by

Mark A. Maggenti

Tri T. Ha, Chairman

Electrical Engineering

(ABSTRACT)

This thesis presents two applications of spread spectrum technology to very small aperture terminal (VSAT) satellite communication networks. It describes two spread spectrum multiple access systems which use a form of noncoherent M-ary FSK (MFSK) as the primary modulation and analyzes their throughput. The analysis considers such factors as satellite power constraints and adjacent satellite interference. It considers the effect of on-board processing on the multiple access efficiency and investigates the feasibility of overlaying low data rate spread spectrum signals on existing satellite traffic as a form of frequency reuse.

Table of Contents

List of Illustrations

Spread Spectrum Multiple Access and Overlay Service

I. Introduction

Spread spectrum signals have been used in military satellite communications for years because of their ability to reject interference and jamming. In commercial satellite systems, where there is no intentional jamming, spread spectrum techniques were thought to provide no advantage.

For high-capacity point to point communications, satellite and fiber optic communications are cost efficient, since the substantial cost of several large earth stations or the installation of miles of optical fiber can be divided among many users. In large "thin route" networks, where the terminals are widely separated and the data rates are relatively low, the network overhead cost becomes prohibitive. The geographical spacing increases installation and networking costs for an optical fiber system dramatically. In satellite communication, the main problem would be the large number of users. The high cost of many large earth stations could not be justified for terminals transmitting low rate data.

Recently there has been a great deal of interest in satellite communication from very small aperture terminals. This paper analyzes the performance of two types of satellite communication from such terminals using spread spectrum techniques and shows that spread spectrum provides some unique advantages that make these services feasible. In addition, a small aperture terminal network using a processing transponder is presented and analyzed.

Spread Spectrum Multiple Access

The majority of current satellite traffic consists of analog television or medium to high data rate signals transmitted from a small number of large aperture earth stations. Mainly because of their large antenna diameter, these earth stations are very expensive. When there are many users, the cost of this type of earth station would make the network prohibitively expensive. Since the earth station cost is most dependent on the antenna diameter, the obvious way to reduce its cost is to reduce the antenna diameter. Earth stations that use small diameter antennas have become known as "Very Small Aperture Terminals", or VSATs.

Reducing the antenna diameter affects the system performance in two ways. First the antenna gain is reduced, lowering the link carrier to noise ratio. Second, the antenna beamwidth is broadened, increasing both the interference received from and transmitted to adjacent satellites. The signal transmitted from a small aperture earth station interferes with the operation of adjacent satellites more than the signal from a large aperture terminal on the uplink. Signals transmitted from adjacent satellites will not be attenuated significantly, increasing the interference level in the VSAT receiver. The interference rejection capabilities of spread spectrum signals make multiple access from small earth terminals feasible for a large number of low data rate users. Chapter 3 analyzes the performance of two spread spectrum multiple access systems which use a form of noncoherent M-ary FSK as their primary modulation. These performance results are then applied to practical example satellite systems using small diameter antennas.

Overlay Service

Overlay service is a method of frequency reuse which involves adding a signal to a transponder already considered to be full by overlaying the new signal within the bandwidth of the existing signal. For this type of service to work, the overlay signal must not interfere appreciably with the existing signal, and vice-versa. A spread spectrum signal with a wide, flat power spectral density (PSD) can appear noiselike to the existing signal, and will not disturb the existing signal if the power is low enough. Since the overlay signal power will be much lower than that of the existing signal, the overlay signal must be able to reject the strong interference caused by the existing signal. The VSAT receiver can use the processing gain of spread spectrum systems to achieve the required interference rejection. Chapter 4 compares various types of spread spectrum signals to find the type most suitable for overlay systems. It finds the maximum overlay data rate for three types of existing signals and calculates the improvement in overlay data rate achieved by using a representative convolutional code.

II. Overview of Multiple Access and Spread Spectrum Techniques

Conventional Multiple Access Techniques

The two major multiple access techniques in commercial use today are 1) frequency division multiple access, and 2) time division multiple access. Frequency division multiple access (FDMA) is the most mature of the multiple access technologies. In this system, each user is allocated a specific part of the transponder bandwidth for its exclusive use [1]. Figure 1 illustrates a typical four channel system.

FDMA systems require a low level of coordination among users, with only frequency band assignments to be made. The transmitting and receiving equipment is essentially the same as when there is no multiple access.

The major disadvantage of FDMA systems is that the transponder output power must be reduced, or "backed-off", to ensure that the transponder is operating in its linear

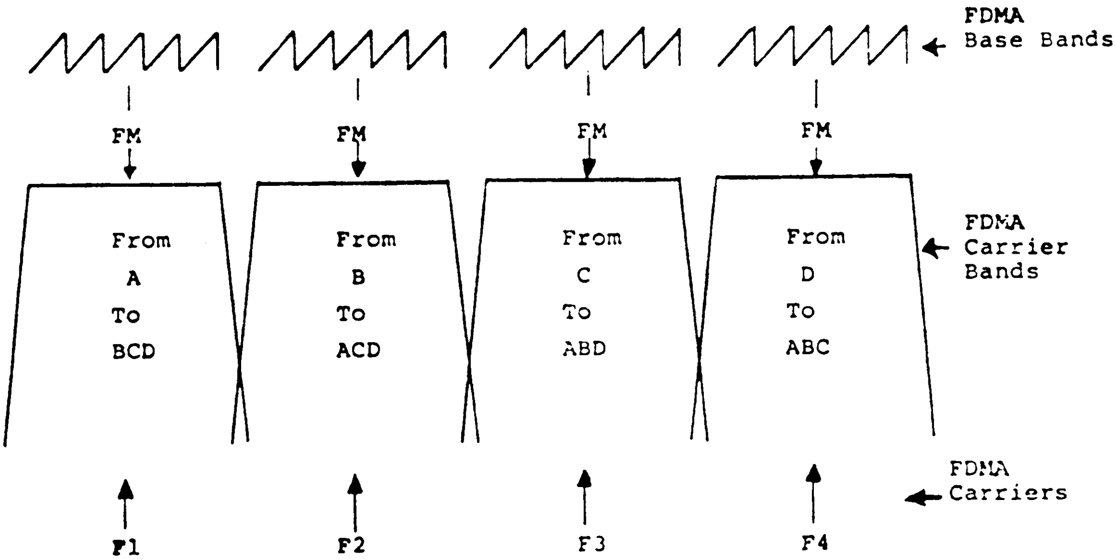

Figure 1. FDMA Signal Organization [2]

region. If the transponder is sufficiently nonlinear, intermodulation interference between different users will result [3].

Time division multiple access (TDMA) avoids the backoff problem inherent in FDMA systems by allowing only one user to occupy the transponder at a time, so that no interference between users is possible. Each user is allowed to use the entire transponder bandwidth in sequence for a short period of time. This requires accurate time synchronization between all users. Synchronization requirements make the earth terminals expensive and complicated [4]. Figure 2 illustrates the time multiplexing of TDMA signals transmitted from a three channel system.

As mentioned previously, to construct a network of small aperture earth terminals, which have wide antenna beamwidths, a modulation type which reduces adjacent satellite interference is needed. The FDMA and TDMA systems described above use conventional modulation types, such as FM for analog signals, and QPSK for digital signals. These systems use these modulations for reasons other than interference rejection. Interference control is achieved primarily by reducing the antenna gain in the direction of the adjacent satellites, several degrees off axis, by using very large diameter antennas. The interference tranmitted to adjacent satellites in VSAT networks can be reduced if the PSD of the transmitted signals is relatively low and flat.

Spread spectrum signals have features which can effectively reduce these problems. Some spread spectrum signals have relatively flat PSDs. In addition the correlation of the received signals with spreading codes in spread spectrum receivers effectively distributes the energy of uncorrelated interfering signals over a large bandwidth while simultaneously compressing the bandwidth of the desired signal. This "processing gain" is a significant source of interference rejection. In addition, most spread spectrum multiple access systems have little network overhead. Transmitters can operate asynchro-

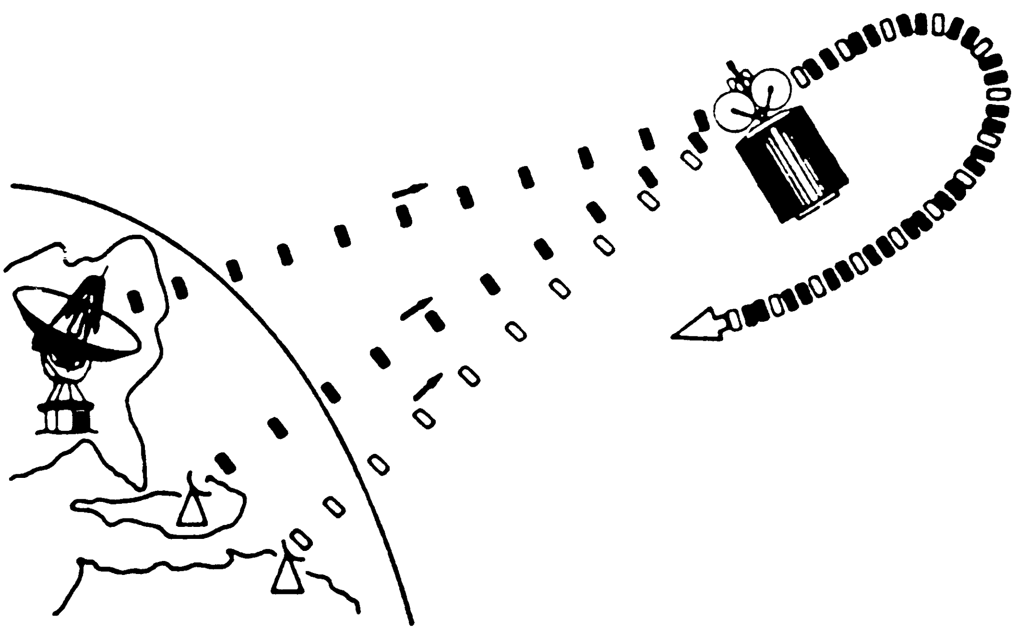

Figure 2. Typical TDMA System [5]

nously, unlike TDMA systems, and do not need to coordinate the operating frequencies as in FDMA systems.

Any type of spread spectrum signal can be used in a spread spectrum multiple access system. The two major classifications of spread spectrum signals are direct sequence and frequency hopped. Direct sequence systems spread a signal's bandwidth by mixing the signal with a relatively high rate pseudonoise (PN) code [6]. Frequency hopped systems spread the signal by using a carrier signal which hops around the channel bandwidth in a pseudorandom manner [7].

In satellite spread spectrum multiple access, also known as code division multiple access (CDMA), uplink earth stations transmit signals that share the same bandwidth and time. Each transmitter spreads its signal with a unique code. Differentiation between desired and undesired signals is accomplished at the receiver, which correlates the recieved signal with a synchronized version of the spreading code. The bandwidth of the correlated signal is collapsed to its unspread bandwidth, while the bandwidth of the other users' signals is spread further, decreasing the PSD of the interference [8].

Direct sequence SSMA systems can be either "sequence synchronous" or "sequence asynchronous" [9]. Sequence synchronous systems require the bit transitions of each transmiter's spreading code to be in synchronization when received by the satellite. These systems can achieve very low levels of inter-user interference if orthogonal spreading codes are used, but this limits the number of users to the length of the code [10]. Synchronous systems are impractical for large thin-route networks however. The synchronization of hundreds to thousands of widely spaced transmitters is an overwhelming problem, especially when the earth station cost is a major consideration. Loss of synchronization produces a catastrophic increase in the users' error rate [11].

Sequence asynchronous DS SSMA systems allow completely asynchronous transmissions. Inter-user interference is increased significantly over orthogonal synchronous

DS SSMA however. The amount of inter-user interference is dependent on the partial cross-correlations between the different spreading codes [12,13]. Sequence asynchronous DS SSMA systems are promising for practical SSMA small earth terminal systems.

Frequency hopped multiple access (FHMA) is commonly used with M-ary FSK as the primary modulation. The available channel bandwidth is divided into "slots". The MFSK signal hops from slot to slot under the control of its unique PN code. Symbol errors occur when more than one user hops into the same slot. Slow hop FHMA systems hop in frequency no more than once per symbol. Fast hop FHMA systems hop more than once per information symbol, and the receiver uses a majority logic decision circuit to estimate the transmitted symbol based on the multiple received hops. [14]

While MFSK FHMA receivers can be simplified by using noncoherent detection, the cost of a frequency synthesizer that can produce carrier frequencies over the entire 36 or 54 MHz bandwidth of a satellite transponder may be expensive, and not suitable for large thin-route networks.

One type of sequence asynchronous DS SSMA system that shows promise for multiple access from small earth terminals is an MFSK/DS SSMA system. In this system an MFSK information signal is spread by a PN code. This is the type of system analyzed in Chapter 3.

The performance of individual MFSK/DS signals in the presence of various types of jamming signals is well known [15]. The performance of MFSK/DS multiple access systems, however, has not been thoroughly studied. At the time this research was started, the only work on MFSK/DS spread spectrum multiple access systems is a paper by Yamauchi et al. translated from Japanese [16]. This paper shows that the multiple access efficiency of MFSK/DS SSMA systems improves when the spacing between MFSK symbol frequencies is greater than the symbol rate. The paper presents an analysis of the performance of an MFSK/DS SSMA system which references several sources available only in Japanese. Because of this, their analysis could not be verified easily.

The analysis presented in Chapter 3 is based on the paper by Yamauchi. The MFSK system with modified symbol frequency spacing that he presents, which is called "wideband MFSK" here, is used. The performance equations are completely rederived, with the mathematical details presented in appendices A and B, and do not agree with those in Yamauchi's paper. All the formulas used in this thesis are derived in this thesis.

In addition, the MFSK/DS SSMA system results are applied to satellite multiple access from small earth terminals. Two original SSMA systems based on the wideband MFSK/DS SSMA system are presented and analyzed. This analysis considers the power and interference constraints of practical satellite systems.

On-Board Processing

The practice of demodulating the uplink signals at the satellite and retransmitting them is known as "on-board processing". Simply demodulating the uplink signal and retransmitting it with the same modulation can give about a 3 dB improvement in C/N when the uplink C/N and downlink C/N are nearly equal.

Satellite Switched TDMA (SS-TDMA) is a technique that directs each TDMA burst to its particular destination through a narrow, high gain spot beam. The high gain downlink antenna significantly improves the downlink C/N. Since the downlink antenna no longer provides coverage of the entire service area, SS-TDMA requires the satellite to recognize the intended recipient of each uplink burst and direct it to the appropriate spot beam [17].

A processing transponder for multiple access of low data rate mobile users has been proposed [18]. This technique requires the transponder to compute a discrete Fourier transform of its bandwidth to demodulate MFSK uplink signals. Such a technique is said to be much more able to track the doppler shift of the mobile users' signals.

The analysis of satellite links that use processing transponders is easily accomplished by considering the uplink and downlink bit error rates separately [19]. Chapter 5 discusses various on-board processing systems which may improve the throughput of the systems analyzed in Chapter 3 and the conditions under which they may be used. An analysis of the Ku band example from Chapter 3 is performed to show the possible throughput improvement provided by a particular type of processing transponder.

Overlay Systems

Satellite signal overlay has not been widely studied or practiced. The only type of overlay signal known to be in use is in a system which overlays a DS signal on TDMA traffic for TDMA loop-back synchronization [20].

No analytic work on satellite overlay systems was found. One brief reference to a satellite television overlay experiment gives so few details of the system parameters that it is of no use [21]. The overlay analysis in Chapter 4 is intended to give a rough estimate of the performance of satellite signal overlay from small earth terminals. The possible overlay system performance of several spread spectrum overlay signals is compared. A general methodology for analyzing the overlay performance is presented and applied to three example systems. The methodology and anlaysis are original.

III. MFSK Spread Spectrum Multiple Access

Many spread spectrum multiple access (SSMA) systems have been studied. Unfortunately the efficiency, measured by the number of users accomodated in a given bandwidth, is usually low. This chapter analyzes two SSMA techniques which use a form of noncoherent M-ary FSK as the primary modulation to improve throughput. It includes a systems level description of the performance of these systems, while mathematical details are kept to a minimum. The following sections describe and analyze two practical SSMA systems. The analysis includes calculations of their bandwidth efficiency and link analyses to assess power and adjacent satellite interference limitations which may occur in practical systems.

Preliminaries

Several features are essential to keep the system as simple as possible and to reduce the equipment cost to a level appropriate to small earth terminals. First, noncoherent detection of the MFSK signal is assumed, simplifying the receiver. Also, all users transmit asynchronously, with no network synchronization. Synchronization of hundreds to thousands of transmitters, even at the millisecond level, would be extremely difficult. The analysis assumes that all users have the same power at the earth station receiver input. This assumption is valid for satellite communications since some form of power control at the transmitters is necessary to prevent power-hogging in the transponder.

Both of the SSMA systems to be analyzed are based on the system model shown in Figure 3. Information at a bit rate R_b is modulated into MFSK symbols at a rate R_s, where $R_s = R_b / k$ and $k = \log_2 M$. The spectrum of this MFSK signal is spread when mixed with a PN code at a code rate R_c. The j^{th} user's signal can be described by

$$s_j(t) = \sqrt{2C} \sum_{k=1}^{\infty} rect(t - kT_s) \cos(2\pi f_i t) \; PN_j(t) \tag{3.1}$$

where $PN_j(t)$ is a full period of a bipolar NRZ rectangular pseudonoise pulse sequence at a rate R_c, C is the signal power, and $T_s = 1/R_s$.

In a conventional MFSK system the signal is represented by M tones separated in frequency by R_s. This frequency spacing minimizes the total signal bandwidth while maintaing the orthogonality between the symbols. Minimizing the signal bandwidth is of no concern here since we intend to spread the signal bandwidth anyway. The modulation can be generalized to allow frequency spacing between MFSK symbols of

$$\Delta f = pR_s \tag{2.2}$$

where p is an integer. p = 1 corresponds to the conventional narrowband MFSK. When p > 1 the system will be referred to as *wideband* MFSK. It has been shown that using values of p > 1 increases the multiple-access efficiency by whitening the co-channel in-

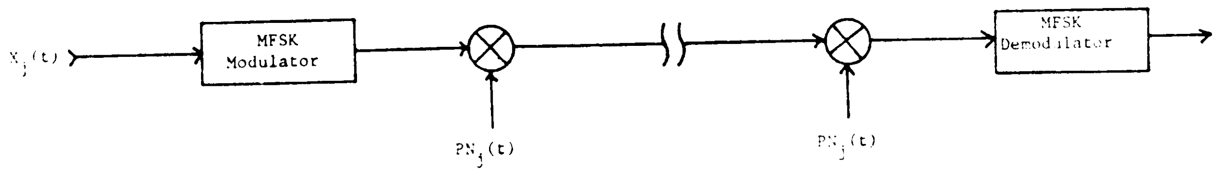

Figure 3. SSMA System Model

terference PSD at the receiver [22]. Since p is an integer, the symbols are still orthogonal and noncoherent detection is still possible.

Figure 4 depicts this system in a multiple-access context, with N one way transmissions. Each of the N transmitters spreads its signal with its own unique PN code, labelled PN_1 through PN_N. Transmitter j intends to communicate with receiver j. At the input to receiver j are N user signals plus thermal noise. When the receiver correlates the j^{th} transmitted signal with a properly synchronized version of the j^{th} PN code, the wideband MFSK signal s_j is recovered. Added to the recovered information signal is a co-channel interference signal which consists of the correlation of the j^{th} PN code with N-1 signals spread by N-1 different, unsynchronized PN codes.

Up to this point, nothing has been said about the type of PN spreading code to be used. Though it will not be discussed here, the co-channel interference caused by an asynchronous interfering user is dependent upon the partial cross-correlations between the two PN codes [23]. Therefore it is desirable to choose a family of codes with a low cross-correlation between any two members, such as the well known Gold or Kasami codes. Since the number of interfering users will be large, and they will all be transmitting asynchronously, a central-limit theorem argument can be used to model the co-channel user interference as a Gaussian process [24]. Doing so gives an ensemble average measure of the system performance. In practice some channels will exceed the average performance, and others will fare worse. Making this Gaussian assumption reduces the performance analysis of this system to that of wideband noncoherent MFSK in colored Gaussian noise.

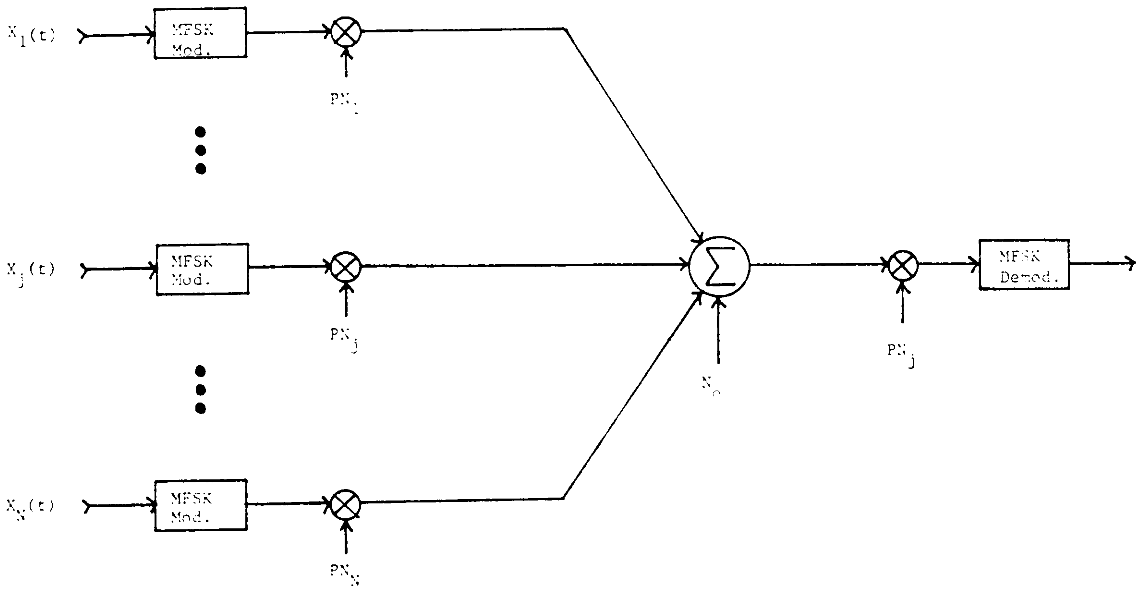

Figure 4. SSMA System Model - N Users

Performance Analysis

Assume that Gaussian noise exists with a PSD given by $I(f)$. The form of the MFSK signal is

$$\sqrt{2C} \sum_{j=1}^{\infty} rect(t - jT_s) \cos(2\pi f_i \, t) \qquad i \in [1,M] \tag{3.3}$$

Figure 5 shows the model of the MFSK receiver. Letting s_p denote that an MFSK symbol at frequency f_p was transmitted, the probability that the receiver incorrectly chooses symbol q given that symbol p was sent is given by [Appendix A]

$$\Pr(r_q > r_p \,|\, s_p) = \frac{N_q}{N_p + N_q} \exp\left[- \frac{E_s}{N_p + N_q} \right] \tag{3.4}$$

where E_s is the symbol energy ($= kCT_b$) and $N_p = I(f_p)$, $N_q = I(f_q)$. The probability that an error is not made in this decision is

$$\Pr(r_q < r_p \,|\, s_p) \;=\; 1 - \Pr(r_q > r_p \,|\, s_p) \tag{3.5}$$

The probability that no errors are made over all of the incorrect symbols is

$$\prod_{\substack{q=1 \\ q \neq p}}^{M} \left[1 - \Pr(r_q > r_p \,|\, s_p) \right] \tag{3.6}$$

Therefore the probability of a symbol error given symbol p is transmitted is

$$1 - \prod_{\substack{q=1 \\ q \neq p}}^{M} \left[1 - \Pr(r_q > r_p \,|\, s_p) \right] \tag{3.7}$$

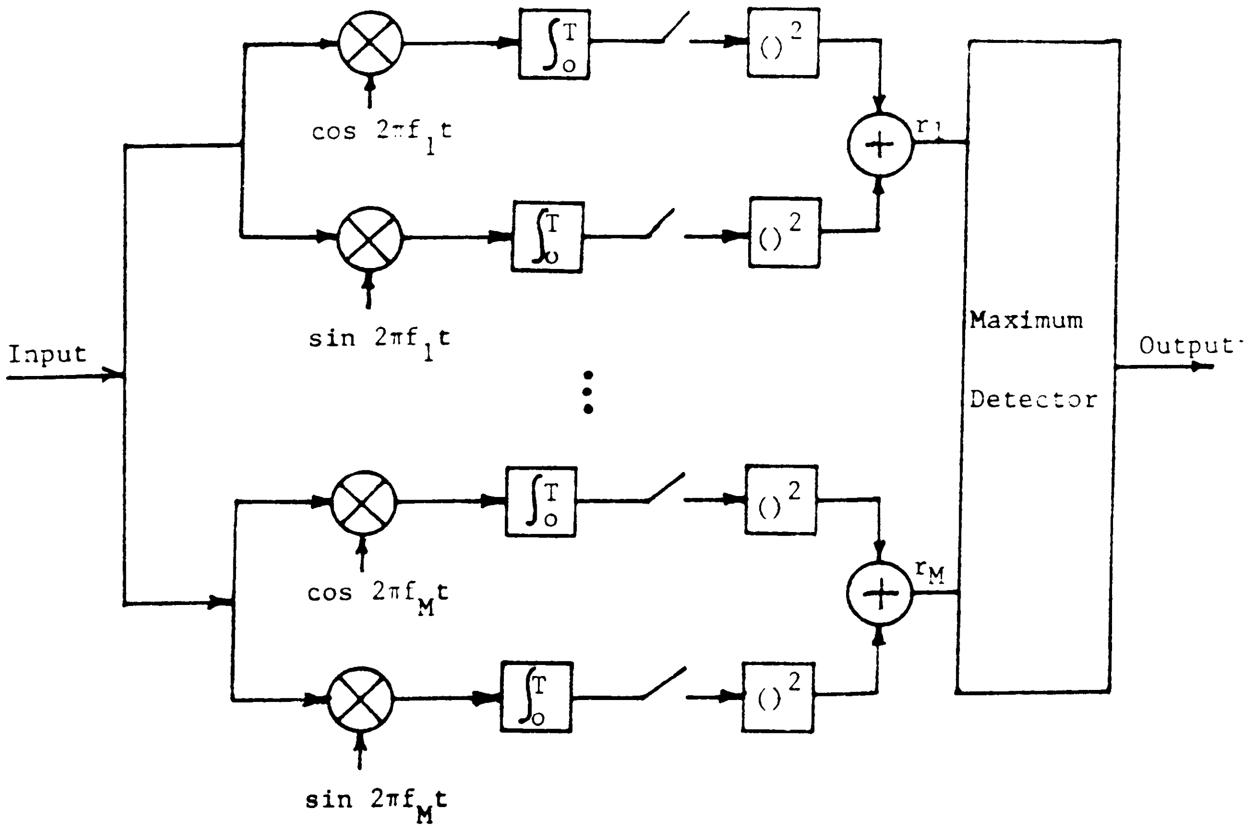

Figure 5. MFSK Receiver Model

Since the interference is not white, the probability of a symbol error is symbol dependent. The average symbol error rate is found by averaging over all of the symbols

$$P_{se} = \frac{1}{M}\sum_{p=1}^{M}\left[1 - \prod_{\substack{q=1\\ q\neq p}}^{M}[1 - \Pr(r_q > r_p | s_p)]\right] \tag{3.8}$$

The corresponding bit error probability can be approximated by using the relation

$$P_{be} = \frac{M/2}{M - 1} P_{se} \tag{3.9}$$

All that remains to be done is to find the form of the PSD of the interference, $I(f)$. An individual MFSK symbol from an interfering user is spread twice by two different asynchronous PN codes (Figure 6). The PSD of the resulting signal is centered at the symbol frequency f_p and has a shape determined by the convolution of the PSDs of the two PN codes. Using an envelope approximation to the PSD of a PN sequence, the resulting interference PSD can be approximated by [Appendix B]

$$I(f) = \frac{2CR_c}{4R_c^{\,2} + \pi^2(f - f_p)^2} \tag{3.10}$$

Since there are N-1 transmitters and each is transmitting any of the M symbols with equal probability, on average there are $(N - 1)/M$ users transmitting each symbol. Assuming all of the users' signals are uncorrelated and $R_s << R_c$, the powers add, and including thermal noise (N_o) the expression becomes

$$I(f) = N_o + \frac{(N - 1)C}{M}\sum_{j=1}^{M}\frac{2R_c}{4R_c^{\,2} + \pi^2(f - f_j)^2} \tag{3.11}$$

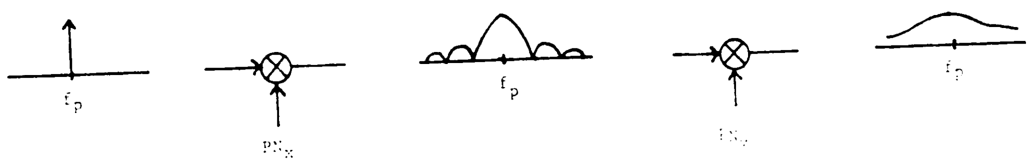

Figure 6. Interference PSD Model

With a frequency spacing between MFSK symbols of Δf, the interference at the i^{th} symbol frequency is

$$N_i = I(f_i) = N_0 + \frac{(N-1)C}{M} \sum_{j=1}^{M} \frac{2R_c}{4R_c^{\,2} + \pi^2 \Delta f^2 (i-j)^2} \tag{3.12}$$

Multiple Access Systems

Using the described system to spread the energy of a low data rate MFSK signal over the entire bandwidth of a satellite transponder is impractical for several reasons. First of all, the high chip-rate needed to spread the bandwidth to 36 MHz or more requires expensive hardware. A high chip-rate also greatly complicates the code synchronization problem over low chip-rate systems. Two alternate methods of spreading the bandwidth in the channel will be presented. In both cases part of the channel bandwidth must be allocated to a control channel. A simple control station can use this channel to limit the number of users to a preset maximum and to assign PN codes to users when they initiate communication.

System 1: MFSK/DS/FDM

One possible multiple access technique is to divide the available channel bandwidth into several "FDM" slots, each containing a separate MFSK/DS SSMA system. The approximate bandwidth of one slot is (Fig 7)

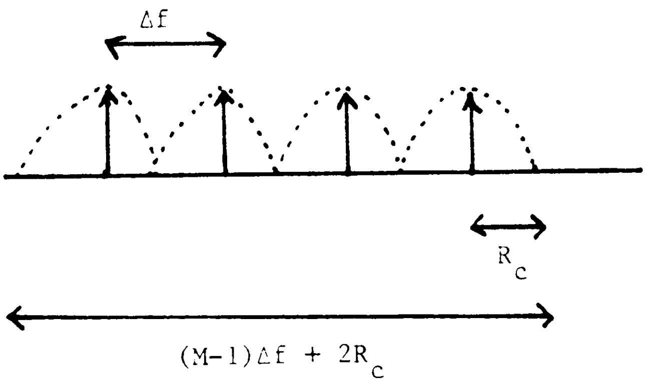

Figure 7. MFSK Slot Bandwidth

$$(M - 1)\,\Delta f + 2R_c \tag{3.13}$$

If the number of FDM "slots" that can fit in the channel bandwidth is denoted by Z, the number of allowable users is simply Z times the number of users able to use one slot as given by equation (3.9).

System 2: MFSK/DS/FH

Figure 8 shows a block diagram of hybrid SSMA transmitter and receiver which uses a frequency hopped carrier to spread an MFSK/DS signal over the transponder bandwidth.

Only slow hopping systems, with one frequency hop per symbol time will be considered. In a conventional slow-hop FHMA FSK system, if two (or more) users hop into the same FH slot simultaneously an error will occur (except for the case where all users are transmitting the same symbol). Fast-hopping (multiple hops per symbol) eliminates the certain occurence of a symbol error from a single collision. In a sense the hybrid SSMA system behaves like a fast-hop system, in that a single FH collision does not necessarily cause a symbol error. The PN codes provide the differentiation between intended and interfering users.

The performance of the hybrid system can be calculated by applying the total probability theorem:

$$P_{be} = \sum_{n=1}^{N} \Pr\left(\text{bit error} \mid n \text{ users colliding}\right)\ \Pr\left(n \text{ users colliding}\right) \tag{3.14}$$

where $N =$ the total number of users .

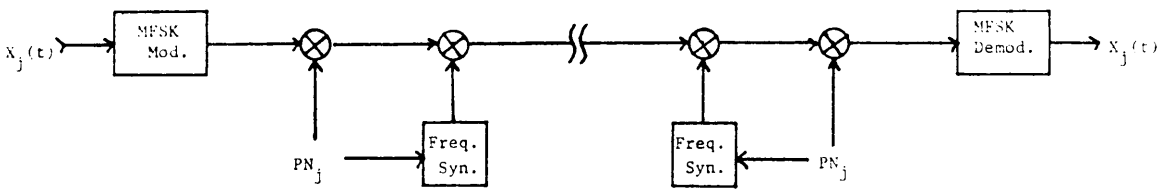

Figure 8. Hybrid MFSK/DS/FH SSMA System

If the user hops randomly among Z frequency slots, the probability that the user is in a given slot is $1/Z$, and the probability that n users out of N are using that slot is given by the Bernoulli trials formula

$$\Pr(n \text{ users colliding}) = \binom{N}{n} \left[\frac{1}{Z}\right]^n \left[1 - \frac{1}{Z}\right]^{N-n} \qquad (3.15)$$

The probability of a bit error given n interfering users is calculated using formula (2.14) with Pr (bit error | n users colliding) calculated using equation (3.9) with N replaced by n in the interference formula (3.12).

Numerical Examples

The following tables list the parameters of sample C and Ku band satellite SSMA systems. The tabulated parameters are:

M - the number of MFSK symbol frequencies ($= 2^k$)
R_s - the symbol rate ($= R_b / k$)
R_c - the PN code rate
Δf - the frequency spacing between symbol frequencies ($= p\, R_s$)
Z - the number of frequency hop slots in the FH system or the number of FDM slots in the FDM system

Example 1: C Band System

Transponder Bandwidth = 36 MHz
Data Rate (R_b) = 1200 bps
p = 46
BER = 10^{-6}
$R_c = 31\ R_s$

M	R_s	R_c	Δf	Z
2	1200	37,200	55,200	277
4	600	18,600	27,600	300
8	400	12,400	18,400	234
16	300	9,300	13,800	159

Example 2: Ku Band System

Transponder Bandwidth = 54 MHz
Data Rate (R_b) = 56 kbps
p = 22
BER = 10^{-6}
$R_c = 15\ R_s$
R_s, R_c, Δf are in kbps and kHz

M	R_s	R_c	Δf	Z
2	56	840	1,232	18
4	28	420	616	20
8	18.66	280	410.66	15
16	14	210	308	10

Figures 9-12 show the performance both multiple access systems for the C and Ku band examples. The choice of parameters is not optimized. Considerable flexibility exists in the choice of parameters and considerations such as hardware complexity and cost may dictate certain choices. The above examples serve only to illustrate the general behavior of the systems' performance. Δf is an integer multiple of R_s and is set to approximately 1.5 times R_c since this choice empirically gives good performance.

Sample Link Analyses

Below are link analyses for the C band and Ku band systems described previously with earth station parameters chosen to be those of the common small earth terminals. The network architecture is the "full mesh" type where direct communication between two small earth terminals via the satellite, as in Figure 13, is assumed.

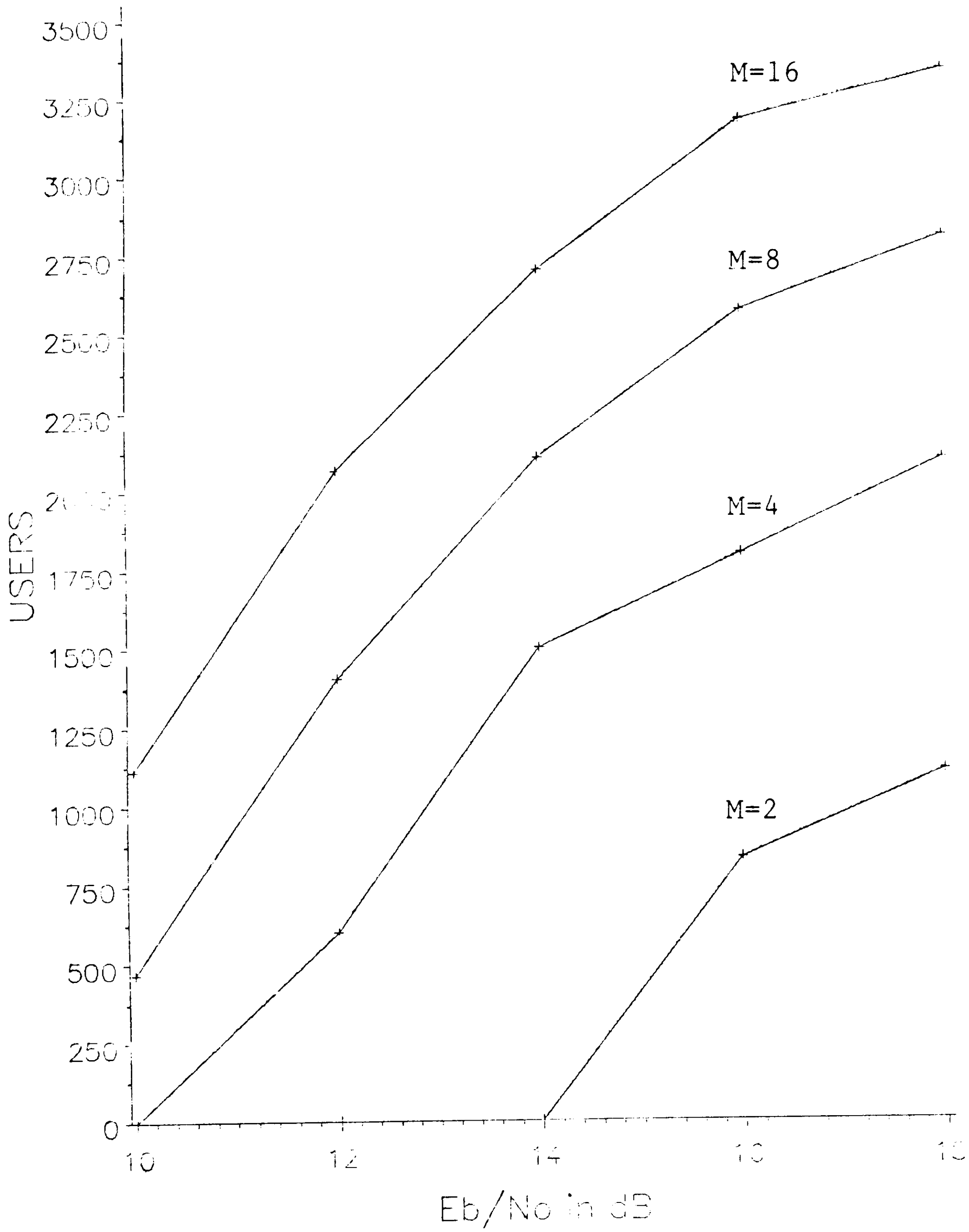

Figure 9. Performance of MFSK/DS/FDM Systems (C band)

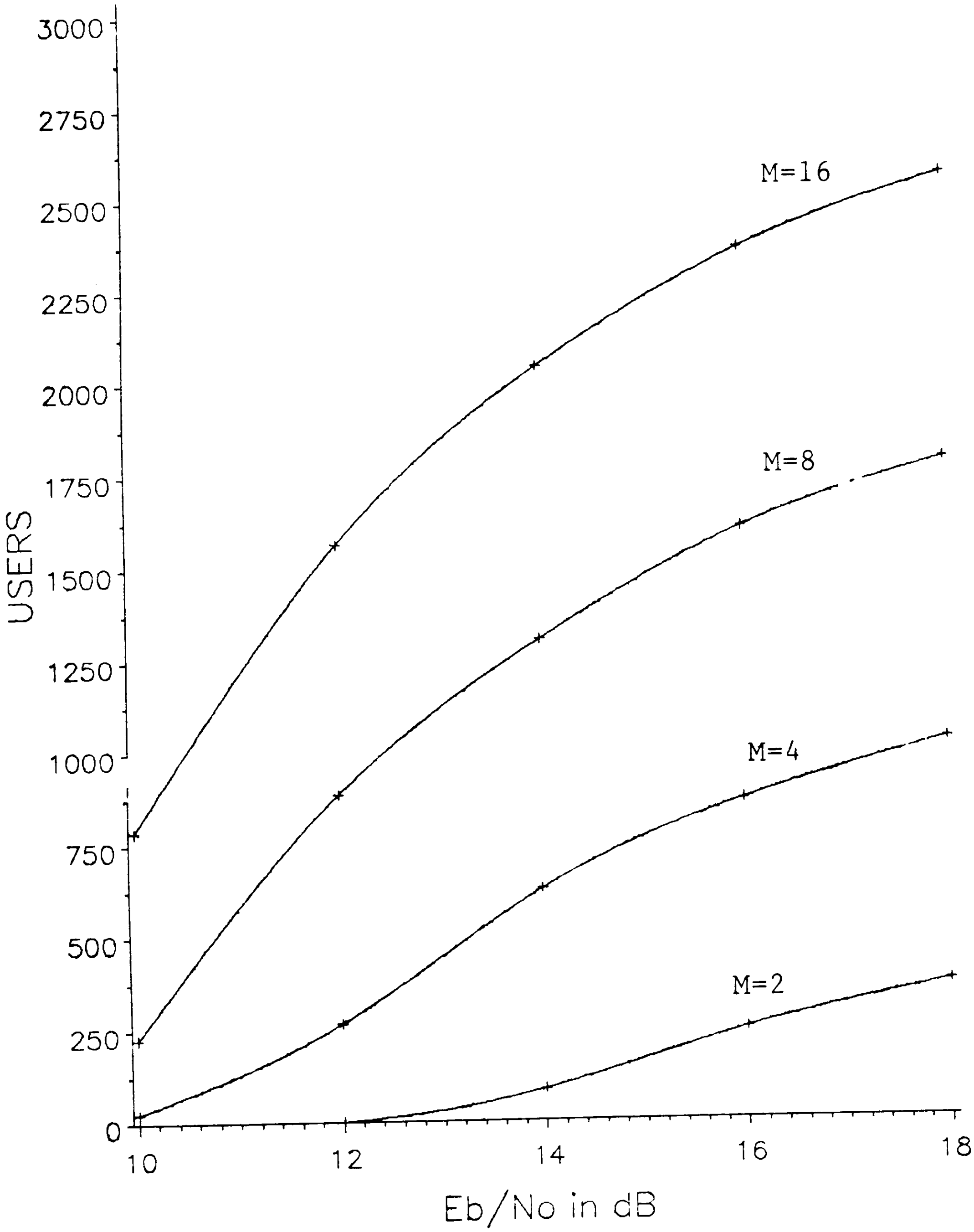

Figure 10. Performance of MFSK/DS/FH Systems (C band)

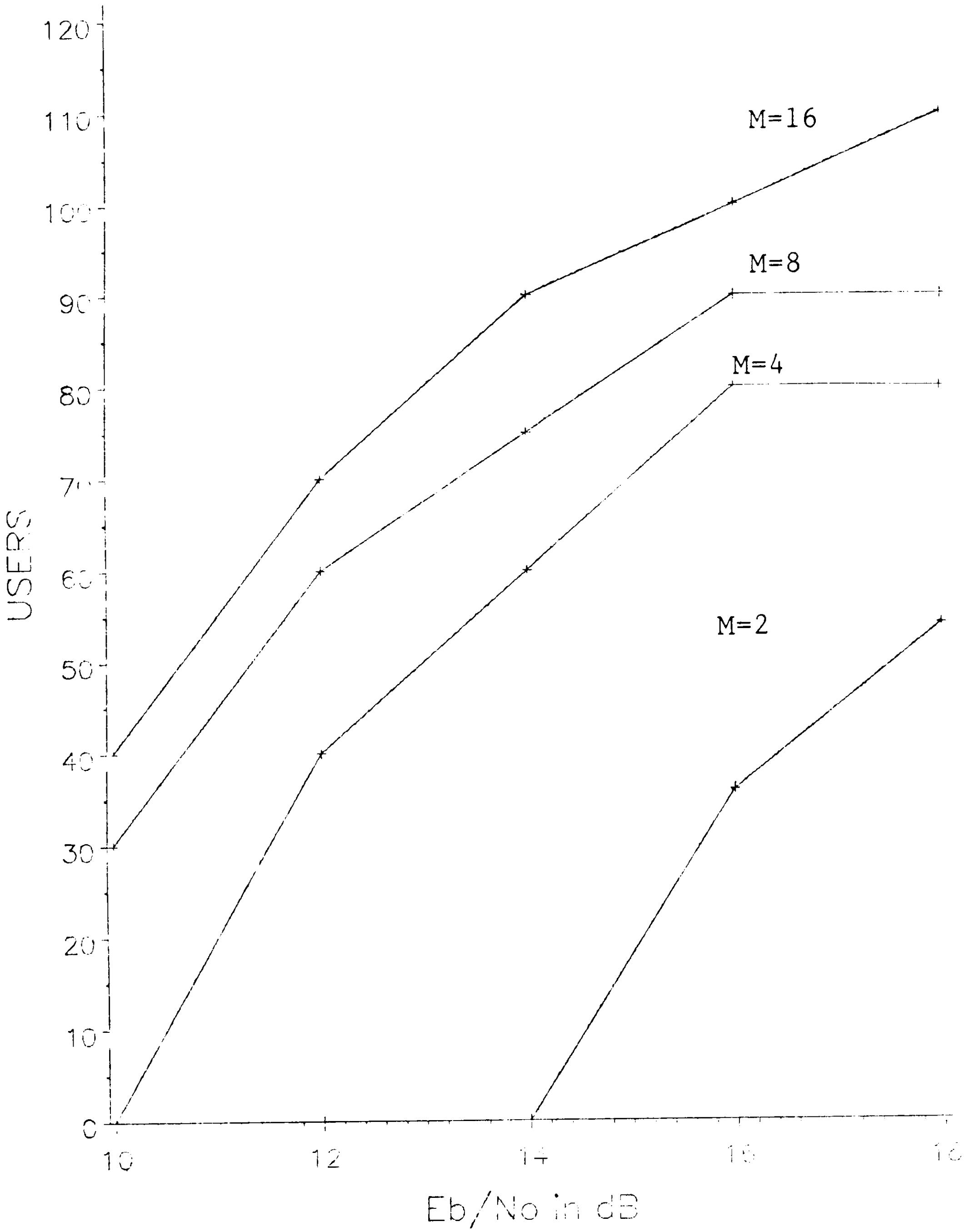

Figure 11. Performance of MFSK/DS/FDM Systems (Ku band)

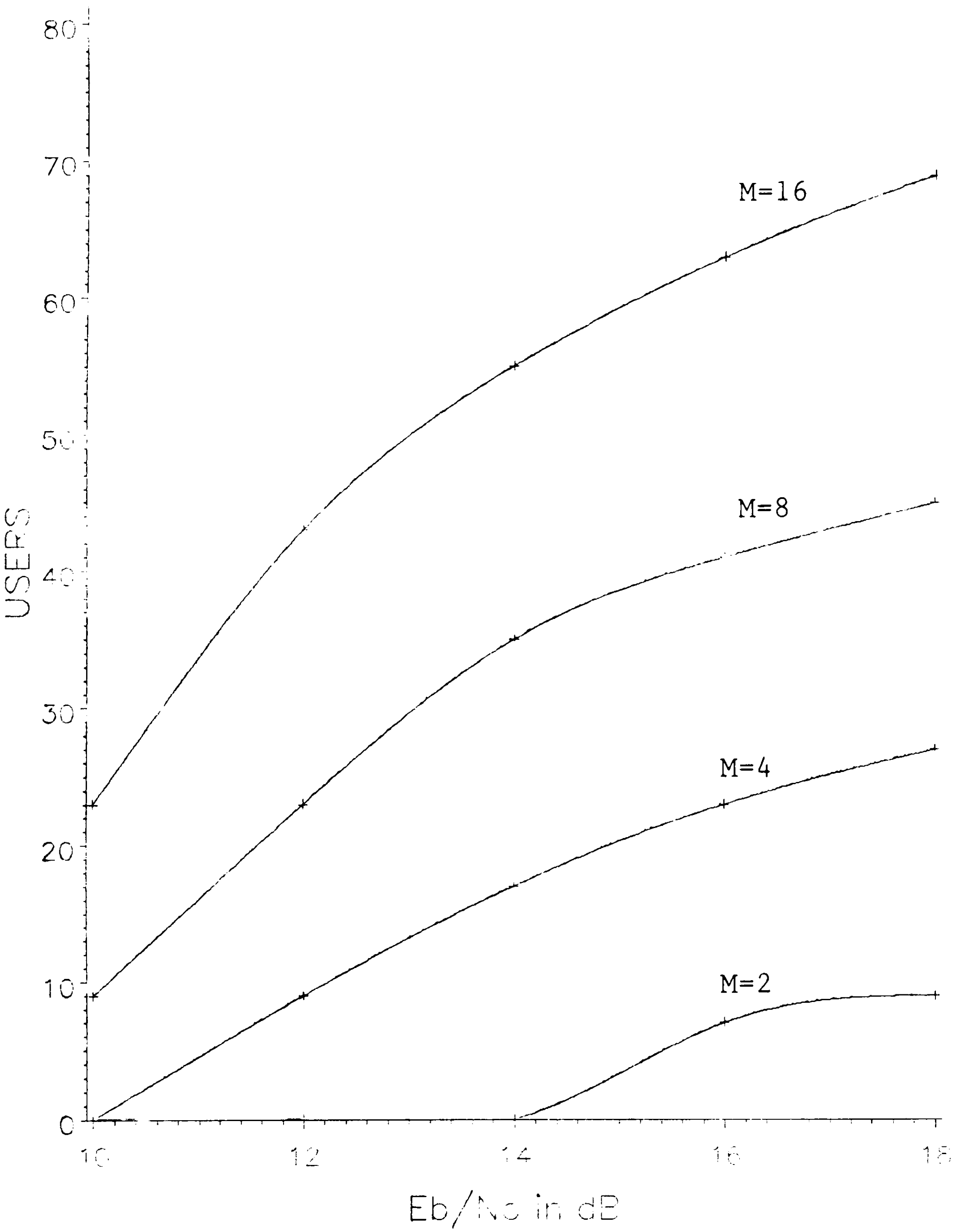

Figure 12. Performance of MFSK/DS/FH Systems (Ku band)

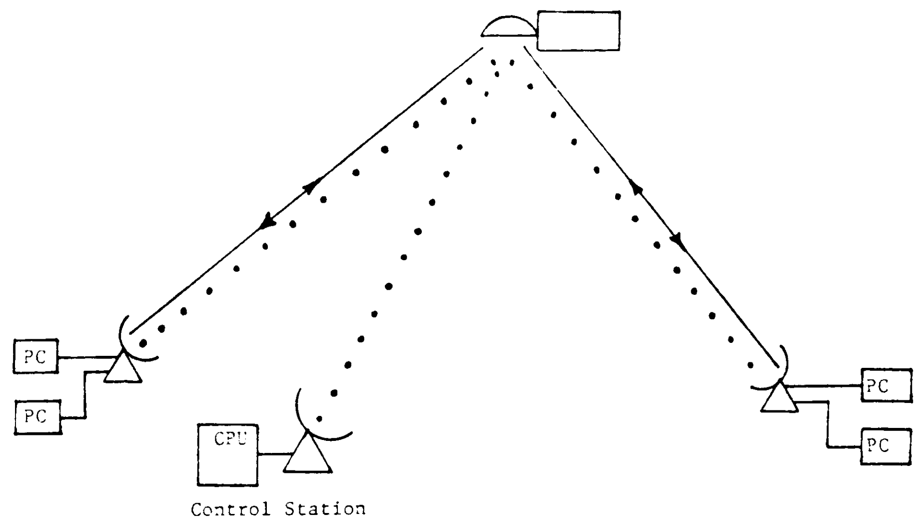

Figure 13. Full Mesh Network Architecture

C-band System - 968 users at 1.2 kbps

Satellite Parameters

EIRP	=	36 dBW
G/T	=	-3 dB/K
Bandwidth	=	36 MHz

Earth Station Parameters

Antenna Diameter	=	1.2 m
Aperture Efficiency	=	65%
Transmit Gain (6 GHz)	=	35.6 dB
Receive Gain (4 GHz)	=	32.2 dB
R_b	=	1200 bps
T_s	=	170 K

Downlink

Propagation and pointing loss	=	196.3 dB
Earth Station G/T	=	9.1 dB/K
$(C/N_o)_d$	=	45.0 dB-Hz

Uplink

Propagation and pointing loss	=	200.2 dB
Earth station power	=	3.65 dBW
$(C/N_o)_u$	=	64.7 dB-Hz

Overall Link

Carrier to Interference and Intermodulation Ratio	=	18 dB
Overall E_b/N_o	=	12.2 dB
BER	=	10^{-6}
Throughput	=	3.2%

Ku-band System - 57 users at 56 kbps

Satellite Parameters

EIRP	=	38.5 dBW
G/T	=	2 dB/K
Bandwidth	=	54 MHz

Earth Station Parameters

Antenna Diameter	=	1.8 m
Aperture Efficiency	=	65%
Transmit Gain (14 GHz)	=	46.6 dB
Receive Gain (11 GHz)	=	44.5 dB
R_b	=	56 kbps
T_s	=	370 K

Downlink

Propagation and pointing loss	=	206.8 dB
Earth Station G/T	=	18.78 dB/K
$(C/N_o)_d$	=	61.5 dB-Hz

Uplink

Propagation and pointing loss	=	208.5 dB
Earth station power	=	-3.0 dBW
$(C/N_o)_u$	=	65.7 dB-Hz

Overall Link

Carrier to Interference and Intermodulation Ratio	=	20 dB
Overall E_b/N_o	=	11.9 dB
BER	=	10^{-6}
Throughput	=	5.9%

The available downlink power limits the number of users to 968 for both the FDM and FH systems. The Ku band system, with its higher antenna gain, is power limited for the FDM system to 57 users, but is bandwidth limited for the FH system to approximately 43 users (Figure 11).

To determine the effect of such networks on adjacent satellites, the flux density they present to adjacent satellites will be compared to that produced by a typical large earth station with a 9 meter dish antenna (which meets the new FCC antenna gain specifications) transmitting 27 dBW. Such an earth station presents a flux density of approximately -112 dBW/m^2 to a satellite at 2° off axis. Assuming a uniform aperture illumination, at 6 GHz a 1.2 meter antenna's gain is down 6 dB relative to its maximum gain at 2° off axis. The flux density of the C band system (with 968 users transmitting simultaneously) at an adjacent satellite is approximately -100 dBW/m^2. Reducing the flux density to -112 dBW/m^2 limits the network to only 61 users. Alternatively, the diameter of the earth station antenna can be doubled to 2.4 meters. This bring the antenna gain down 17 dB at 2° off axis, reducing the interference flux density to -111 dBW/m^2 with no reduction in the number of users. At Ku band the adjacent satellite interference problem is much less severe. At 14 GHz, a 1.8 meter antenna's gain is down 24 dB at 2° off axis.

The wide beamwidth of these small antennas guarantees that signals from adjacent satellites will interfere with the network operation. In the link analysis, conservative carrier to interference ratio values are included for this reason. Spread spectrum systems, unlike other multiple access systems, have the ability to reject interfering signals due to their processing gain. This capability, and the relatively flat PSD presented to adjacent satellites as interference, are the major advantages of spread spectrum multiple access systems.

Conclusions

Both the MFSK/DS/FDM and MFSK/DS/FH SSMA systems provide reasonable multiple access performance. Considering bandwidth constraints only, the FDM SSMA system performs better than the FH SSMA system, providing bandwidth efficiencies of approximately 11% (0.11 bps/Hz) for the C band examples (1200 bps), and for the Ku band examples (56 kbps).

Downlink power limitations prevent the full capability of these systems from being realized in the satellite SSMA context. Considering both the power and bandwidth constraints present in the example systems presented, the C band system throughput was reduced to 3.2%, and the Ku band system to 5.9%. Since these systems are essentially power limited, coding could be used to trade power for bandwidth to increase system performance if the additional cost is tolerable. The link analyses show that a small earth terminal satellite network using wideband MFSK SSMA is feasible. Other types of multiple access systems are power limited but do not have the interference rejection capability and flat PSD of a SSMA system and may therefore become interference limited.

Because of its superior bandwidth efficiency and much simpler and faster synchronization, the FDM SSMA system is best suited for a practical SSMA small earth terminal network.

IV. Spread Spectrum Overlay Service

Overview

Overlay service is the practice of adding or *overlaying* a usually low rate data signal to an existing channel which is generally thought to be filled to capacity. This practice, a form of "frequency reuse", can further increase the capacity of satellite transponders and provide new services and functions to existing satellite users.

The primary consideration in the design overlay systems is that they do not interfere significantly with the operation of the signal which is already using the transponder. This will be called the "existing" signal. The existing signal can be any one of many types of satellite signals currently in use such as analog television, FDM/FM telephone traffic, or digital data. These signals already experience interference from adjacent satellites and terrestrial sources. The addition of the overlay signal to the transponder introduces another source of interference with which the existing signal must contend.

The performance degredation experienced by the existing signal can be kept to an arbitrarily low level by simply lowering the transmitted power of the overlay signal sufficiently. This obviously places severe limitations on the performance of the overlay link, lowering its carrier to noise density ratio C/N_o. Theoretically, any E_b/N_o can be achieved by the overlay link, for a fixed transmitted power C, if the data rate of the overlay signal is sufficiently low, since $E_b = C/R_b$. The relationship between the overlay signal power and data rate illustrates the general characteristics of overlay systems. The overlay signal will be a low data rate signal transmitted at a very low power relative to that of the existing signal. Just as the overlay signal interferes with the existing signal, the existing signal interferes with the overlay signal. The only difference is that the overlay signal must reject a relatively high level interferer. Spread spectrum signals, which have the ability to reject large interferers, are a natural choice for the overlay signal.

The performance of the overlay system is also highly dependent on the type of existing signal being used. This chapter compares the performance of several spread spectrum signals used as overlay signals for three types of existing signals: 1) analog television, 2) FDM/FM/FDMA telephone, and 3) digital SCPC signals. Link analyses are given to assess the feasibility of the overlay systems. The analysis includes calculations of the improvement from forward error correction.

Comparison of Spread Spectrum Overlay Systems

Frequency Hopped Spread Spectrum

In general, spread spectrum systems fall into two categories: 1) direct sequence systems, where the signal is spread by being mixed directly with a pseudo-noise sequence, and 2) frequency hopped systems, where the signal's carrier frequency is changed in a pseudo-random manner. Combinations of these two systems, such as the hybrid spread spectrum multiple access system presented in the previous chapter, also exist. Direct sequence systems are known as "noise averaging" systems, because their interference rejection, or processing gain, is achieved by spreading the interference signal power over a larger bandwidth, reducing its power spectral density. Frequency hopped systems are known as "avoidance" systems, because they achieve interference rejection by hopping their carrier into areas of the spectrum where there is no interference, thereby "avoiding" the interference. Since the existing signal occupies virtually the entire transponder bandwidth, it appears as wideband interference to the overlay signal. In essentially no portion of the transponder bandwidth will a frequency hopped signal avoid the existing signal. Therefore, pure frequency hopped overlay signals provide no rejection of the existing signal, and are not suitable for overlay service.

MFSK/DS Spread Spectrum Overlay

The MFSK/DS spread spectrum system proposed in Chapter 3 for multiple access has a direct sequence component, and therefore achieves interference rejection through noise averaging. Since the frequency hopping component of the hybrid system provides no interference rejection, the discussion will be confined to systems in which an MFSK signal is simply spread by multiplication with a pseudonoise sequence.

If a large number of MFSK tones are used, i.e. M is large, the energy of the signal will be spread fairly evenly over the transponder bandwidth. This relatively flat power spectral density is a desirable feature in overlay signals, since it is the peaks in the signal spectrum which would cause the most interference to the existing signal. Nevertheless, there are several disadvantages to an MFSK/DS system. First of all, noncoherent detection of the MFSK is required. The synchronization and general hardware complexity of a coherent MFSK/DS system would make this system expensive and complicated. Noncoherent detection schemes suffer a 3 dB penalty in signal to noise ratio relative to coherent detection schemes. Because the interference level is high, this penalty will have a strong effect on the overlay system BER. Also, if many MFSK tones are used to flatten the overlay signal PSD, then the spreading sequence bit rate must be reduced to keep the overlay signal power within the transponder bandwidth. Reducing the chip rate reduces the bandwidth the interference is spread over. This lowers the ability of the system to reject interference.

Direct Sequence Overlay

From the preliminary analysis of the MFSK/DS and frequency hopped overlay signals, it is evident that an ideal overlay signal would have a flat PSD, use coherent detection, and have as large a chip rate as possible. A pure direct sequence spread spectrum system comes as close to this ideal as any spread spectrum system can. Figure 14 illustrates this system.

Such a system achieves a high processing gain, using a chip rate up to half the transponder bandwidth, and can easily be detected coherently, providing a 3 dB advantage over noncoherent systems. While the PSD of the signal is not as flat as some other spread spectrum systems, the advantages just mentioned more than make up for this disadvantage. This system seems to have the most promise for overlay service, and will be analyzed exclusively.

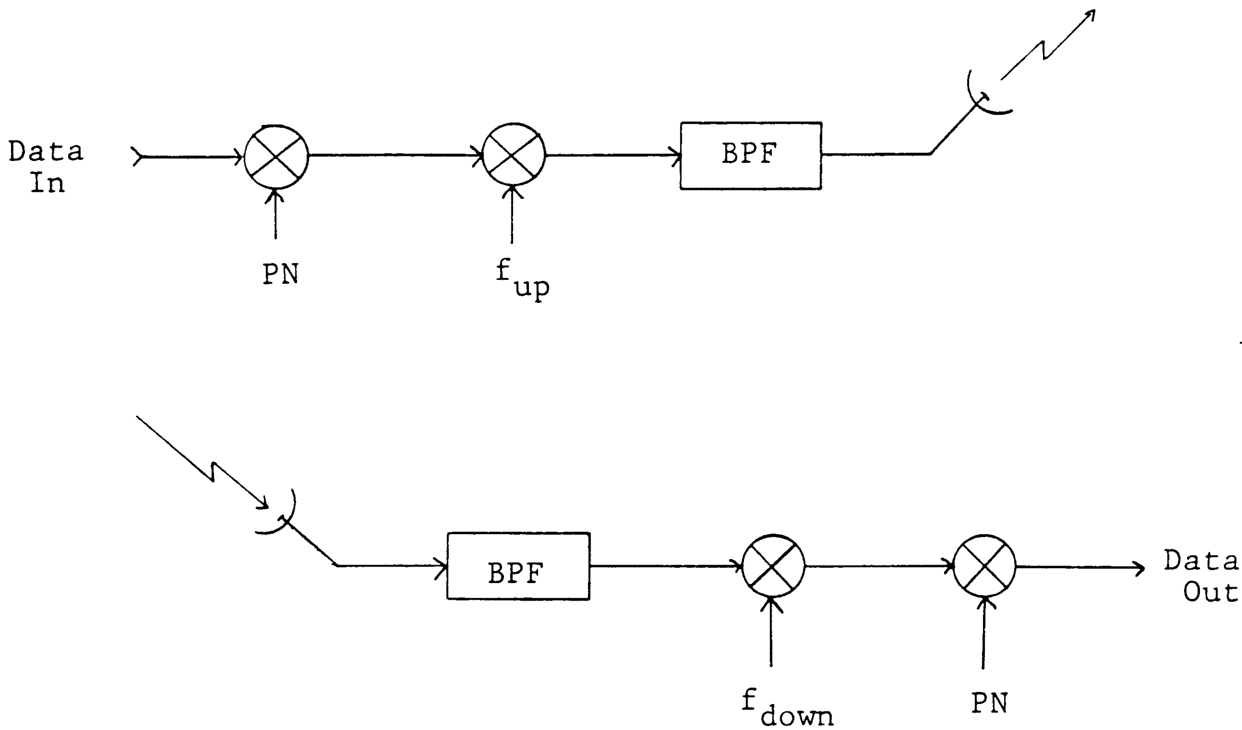

Figure 14. DS Overlay System

Interference Modeling

Appropriate statistical models of the interference that the overlay signal presents to the existing signal, and vice-versa, are an important part of the overlay system performance analysis. It will be shown that with a reasonable degree of certainty these interference sources are adequately represented as Gaussian noise. The following sections describe two results which are useful in justifying this treatment.

Modeling of Wideband Signals Passed Through Narrowband Filters

The statistics of an arbitrary signal passed through a filter with a bandwidth much narrower than the signal bandwidth approach a Gaussian distribution. This is a result of the central limit theorem and the related Berry-Esseen theorem [25,26]. In the overlay systems to be analyzed the interference bandwidth is often much greater than the a receiver's bandwidth. This result can then be used to model the interference in the receiver as a Gaussian process.

Modeling of Interference PSK Signals by Multiple PSK Interferers

In his classic paper V.K. Prabhu considers the error rate performance of a phase shift keyed signal in the presence of Gaussian noise and co-channel interference consisting of K identical phase shift keyed signals [27]. He shows that the error rate increases monotonically as K increases (with the total interference power constant and equally distributed among the K interferers). As K approaches infinity, the error rate reaches its maximum and is identical to the error rate calculated assuming the total interference was white Gaussian noise. The significance of this is that for the practical case, where K is finite, assuming that the interference is Gaussian noise is conservative: this assumption overestimates the bit error rate. This result is directly applicable to one of the cases to be analyzed, where the existing and overlay signals are phase shift keyed signals. One may argue that the worst kind of interference a signal may experience is from a signal of the same type, since the receiver detects this signal just as well as the intended signal. If using a white noise model overestimates the error rate in this case, as Prabhu has shown, it should also overestimate the error rate for a non-identical signal.

Overlay System Performance Analysis

Overview

The analysis of the performance of the overlay signals will be done in three steps. First the maximum overlay signal power that can be transmitted from a small earth terminal (transmitting a BPSK overlay signal) without causing significant interference to the existing signal will be determined. Next the bit error rate performance of the overlay link must be calculated. This is done by determining the PSD of the interference that the overlay signal receiver sees. Since the existing signal is spread at the overlay receiver, the PSD is found by numerically convolving the PSD of the existing signal with that of the spreading signal in the receiver. This PSD is used to calculate the overlay link carrier to interference density ratio. Finally a complete link analysis for the overlay signal is performed. It uses the transmitted power calculated in the first step, and the carrier to interference density ratio calculated in the second step. For a specified BER, a maximum data rate for the overlay signal can be calculated. This will be the measure of performance of the overlay system. The improvement provided by various forward error correction codes will also be calculated.

Description of Existing Signals

As mentioned previously, the overlay system performance depends on the type of traffic existing in the satellite transponder: the existing signal. Since all type of existing signals can not be considered, the analysis will be limited to the three signals described below.

1) An FDM/FM/FDMA telephone signal consisting of eight 4 MHz channels in an FDMA mode,

2) An SCPC system consisting of two hundred 64 kbps channels using QPSK modulation,

3) A single FM analog television signal occupying virtually an entire 36 MHz transponder.

All signals are assumed to be transmitted from a "typical" large earth station with a 9 meter diameter dish antenna, and approximately 200 watts of total power.

Overlay on FDM/FM/FDMA Telephone Traffic

Figure 15 shows the first existing signal to be considered. It consists of 8 FDMA channels with a bandwidth of 4 MHz each. An earth station with 9 meter diameter antenna transmits each FDMA channel with a power of 25 Watts.

Figure 16 shows the PSD of the overlays signal. It is a simple BPSK signal with a chip rate of 18 MHz. The overlay earth station has a two meter diameter dish antenna. The transmit power is to be determined. The analysis assumes a transponder bandwidth of 36 MHz and operation at C band.

The total bandwidth of the overlay signal is 36 MHz. Any one of the 8 FDM channels will receive only a portion of the overlay signal power. The bandwidth of one of these channels, 4 MHz, is only one ninth of the overlay signal bandwidth. The wideband overlay signal therefore passes through a relatively narrowband filter before being detected by the FM receiver. As discussed previously, when a wideband signal passes through such a filter the ouptut has Gaussian statistics. For this reason the interference to any one of the eight channels of the existing signal caused by the overlay signal will be modeled as Gaussian noise.

To calculate the maximum allowable transmitted power for the overlay signal, the power which causes the signal to interference ratio in the worst case channel to be 25 dB must be determined. Since the PSD of the overlay signal is at its highest in the center of the transponder, channels 4 and 5 in Figure 15 experience the most interference. The fraction of the overlay signal power contained in a 4 MHz band around its center is approximately 22%. For the signal to interference ratio at the transponder to be 25 dB in channel 4 or 5, the overlay signal power (again at the satellite) needs to be

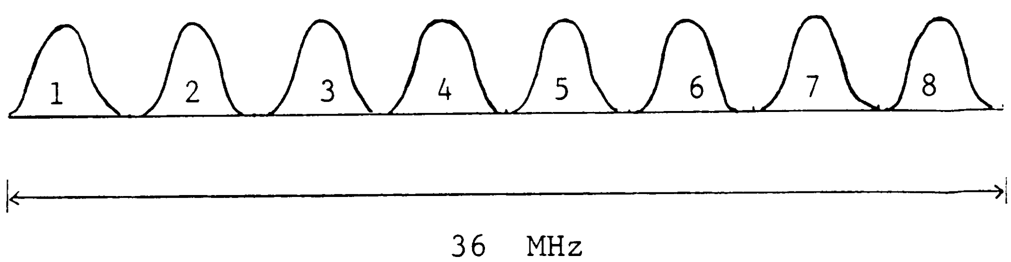

Figure 15. FDMA Existing Signal

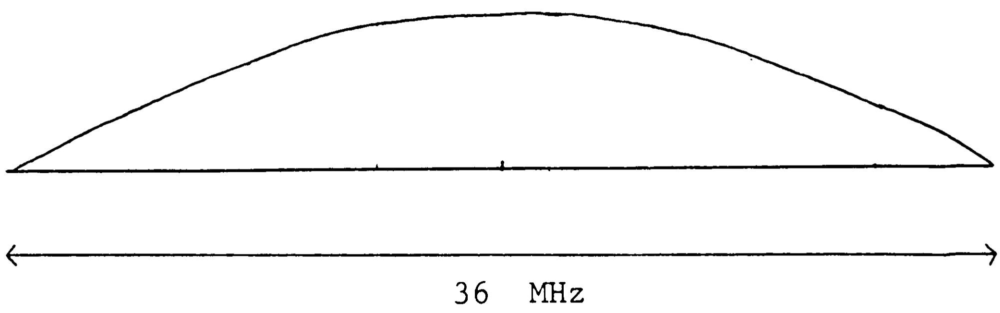

Figure 16. DS Overlay Signal

$$-25\,\mathrm{dB} - 10\log(.22) = -19\,\mathrm{dB}$$

The overlay signal power at the transponder must be 19 dB below the power of a single FDMA channel at the satellite. The FDMA signal has a transmitted power of 14 dBW (=25 watts) and its earth station antenna has a gain of 48.2 dB, giving it a total EIRP of 62.2 dBW. The overlay signal EIRP must be 19 dB below this, and since its 2 meter antenna has a gain of 40.1 dB, it must transmit 3 dBW, or 2 watts.

Now that a tranmitted power constraint has been placed on the overlay signal so that the performance of the FDMA telephone system is not degraded appreciably, the performance of the overlay link must be analyzed. The interference of the existing signal to the overlay signal must first be considered, then a conventional link analysis using the parameters of the overlay link and earth station can be performed.

As can be seen from Figure 14, the signal received by the overlay receiver is despread by mixing it with a replica of the spreading signal, an 18 MHz chip rate BPSK signal. To calculate the signal to interference ratio for the overlay link (the interference being the existing signal), the effect of this despreading must be calculated. This is done by convolving the PSD of the existing signal with that of the spreading signal, with the PSD of each FDM signal approximated by a Gaussian curve with a standard deviation of 546 kHz [28]. Figure 17 shows the result, with the power of a single FDMA signal normalized to 1.

The matched filter in the overlay receiver has a bandwidth approximately equal to the bit rate of the overlay signal. If the overlay signal data rate is on the order of several kilobits per second, and since the bandwidth of the interference is at least as large as the spreading signal bandwidth of 36 MHz, the statistics at the output of the matched filter are very nearly Gaussian. Since the overlay signal power is 19 dB below that of the FDM signal, or 12.6 mW normalized, and the noise spectral density at the center of the

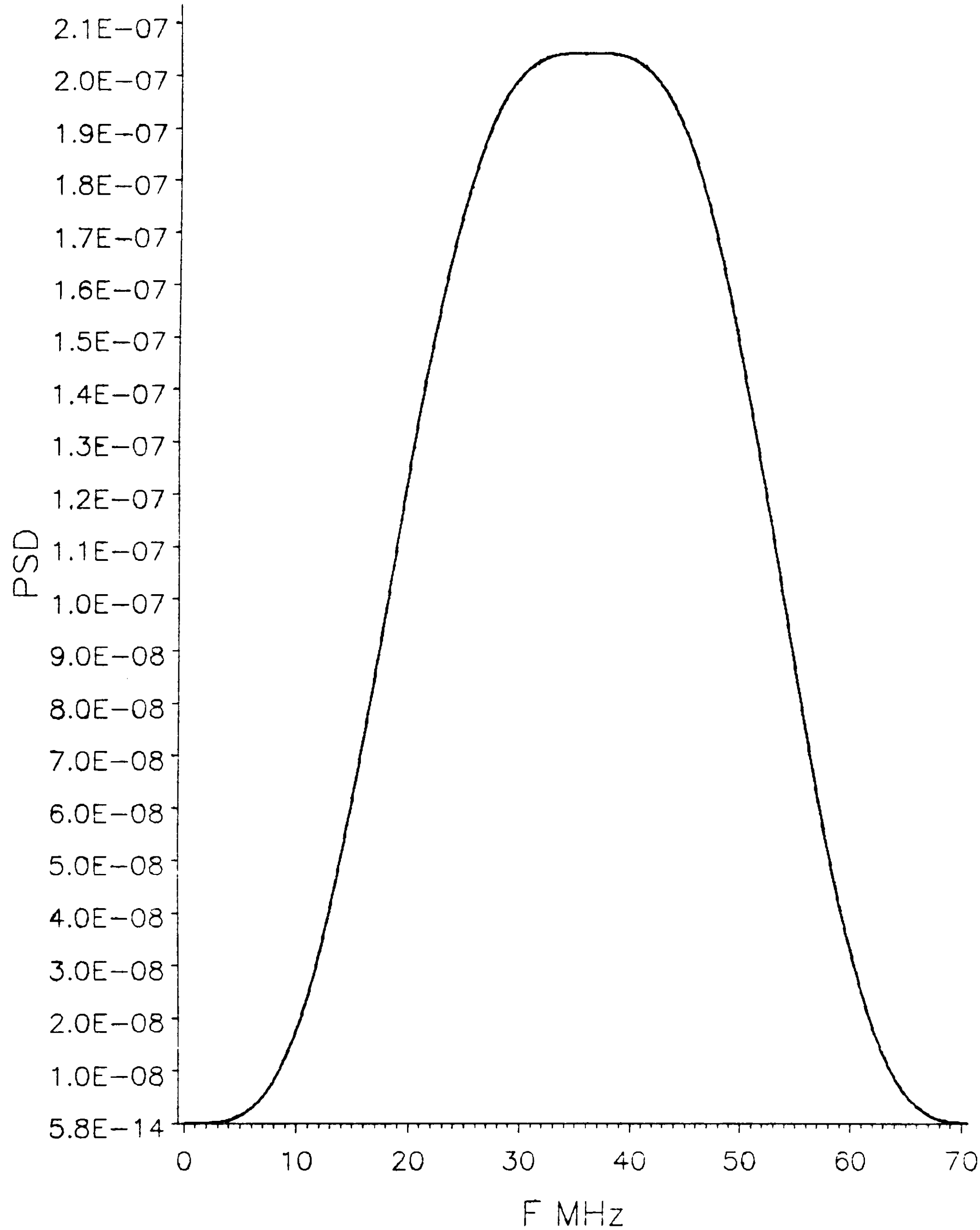

Figure 17. Interference PSD caused by the FDMA Signal

transponder bandwidth is 2×10^{-7} Watts/Hz, the carrier to interference density ratio at the overlay receiver is

$$\frac{.0126 \text{ W}}{2 \times 10^{-7} \text{ W/Hz}} \rightarrow 48.0 \text{ dB-Hz}$$

The following link analysis combines this carrier to interference density ratio with the carrier to noise density ratios of the uplink and downlink to determine the link E_b/N_o.

FDM Overlay System: C- Band

Satellite Parameters

EIRP	=	36 dBW
G/T	=	0 dB/K
Bandwidth	=	36 MHz

Earth Station Parameters

Antenna Diameter	=	2.0 m
Aperture Efficiency	=	65%
Transmit Gain (6 GHz)	=	40.1 dB
G/T	=	14 dB/K

Downlink

Propagation and pointing loss	=	196.3 dB
$(C/N_o)_d$	=	47.9 dB-Hz

Uplink

Propagation and pointing loss	=	200.2 dB
Earth station power	=	3.00 dBW
$(C/N_o)_u$	=	76.6 dB-Hz

Overall Link

Carrier to Interference Density Ratio	=	48.0 dB-Hz
Overall C/N_o	=	44.9 dB-Hz

With an overall link carrier to noise density ratio of 46.75 dB-Hz, and a E_b/N_o of 11 dB needed to achieve a 10^{-6} bit error rate, the maximum bit rate achievable is

$$44.9 \text{ dB-Hz} - 11 \text{ dB} = 33.9 \text{ dB-bps}$$

or

$$R_{b\,max} = 2475 \text{ bps}$$

While this data rate is quite low, it can be increased by using forward error correction. The chip rate can be held constant at 18 MHz regardless of the data rate by changing the length of the code. If the chip rate is held constant, all of the interference PSDs and link parameters mentioned previously are unchanged.

A rate 1/2, constraint length 7 Viterbi decoded convolutional code gives a 6 dB improvement in E_b/N_o at a bit error rate of 10^{-6} [29]. Therefore the achievable data rate is increased by 6 dB by using this coding scheme. With this coding:

$$R_{b\,\max} = 9855 \text{ bps}$$

Overlay of Digital SCPC System

Figure 18 illustrates the digital SCPC system to be considered. It consists of 200 64 kbps QPSK signals each transmitted at 1 Watt through a 9 meter diameter earth station, frequency division multiplexed in a 36 MHz transponder. The RF bandwidth of each of these signals with a 50% rolloff Nyquist filter is approximately 45 kHz. The overlay signal is unchanged from the previous section.

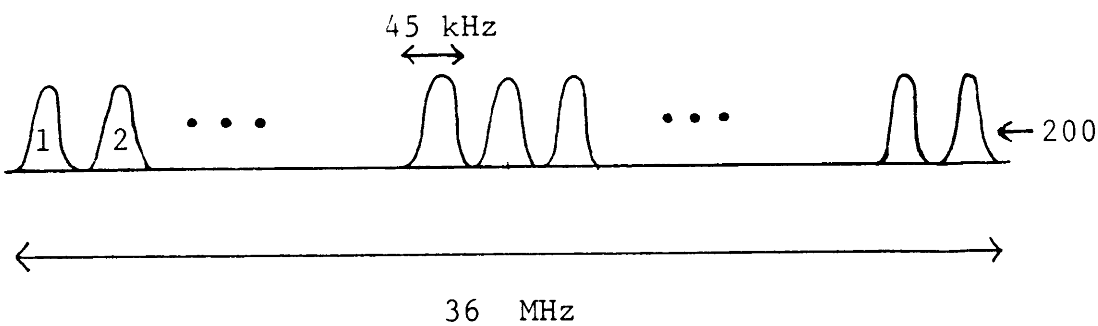

Figure 18. SCPC Existing signal

Using the same arguments as before, the statistics of the interference at the SCPC and overlay signal receivers will be treated as Gaussian. The 36 MHz bandwidth of the overlay signal is much wider than that of the SCPC receiver, causing the interference at the SCPC receiver to have Gaussian statistics. Furthermore, the multiplication of the 200 SCPC signals by the despreading signal in the overlay receiver creates an interference signal with a bandwidth much larger than 36 MHz, which is much larger than the bandwidth of the overlay receiver. Therefore the interference to the overlay system is also Gaussian.

The analysis of the overlay system performance is identical to that for the FDM system. The fraction of the overlay signal power contained in the bandwidth of any SCPC signal is less than 1%. One percent will be used as a conservative figure. Therefore for the signal to interference ratio in the bandwidth of one SCPC signal to be greater than 25 dB, the overlay signal power relative to the power of an SCPC signal (at the satellite) must be $-25 - 10 \log (.01) = -5$ dB. This gives a overlay signal tranmit power of 2 Watts. Performing a numerical convolution to determine the interference PSD at the overlay receiver, with the narrowband SCPC signals approximated by impulse functions in the frequency domain, gives an interference spectral density of 5.5×10^{-6} Watts/Hz (see Figure 19). This gives a carrier to interference density ratio of 47.60 dB-Hz. The complete link analysis follows.

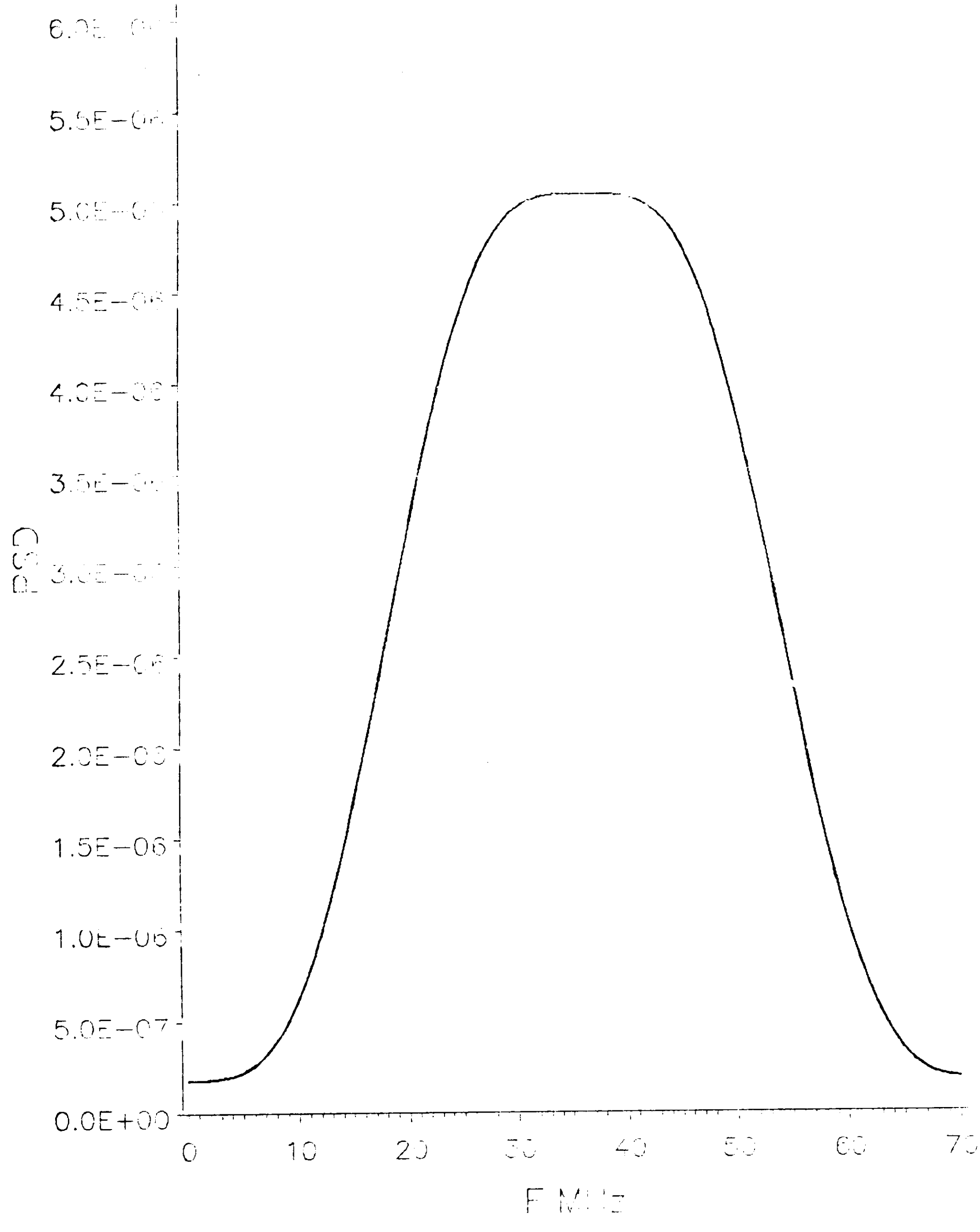

Figure 19. Interference PSD caused by the SCPC signal

SCPC Overlay System - C Band

Satellite Parameters

EIRP	=	36 dBW
G/T	=	0 dB/K
Bandwidth	=	36 MHz

Earth Station Parameters

Antenna Diameter	=	2.0 m
Aperture Efficiency	=	65%
Transmit Gain (6 GHz)	=	40.1 dB
G/T	=	14 dB/K

Downlink

Propagation and pointing loss	=	196.3 dB
$(C/N_o)_d$	=	54.3 dB-Hz

Uplink

Propagation and pointing loss	=	200.2 dB
Earth station power	=	3.1 dBW
$(C/N_o)_u$	=	76.6 dB-Hz

Overall Link

Carrier to Interference Density Ratio	=	47.6 dB-Hz
Overall C/N_o	=	46.75 dB-Hz

Again since an 11 dB E_b/N_o is needed to achieve a 10^{-6} BER, the maximum data rate of the overlay link is 3758 bps. Using a rate one-half convolutional code with a coding gain of 6 dB increases the data rate to approximately 15 kbps.

Analog Television Overlay

The overlay of data signals on analog television traffic presents some unique problems. First of all the spectrum of the television signal is not known with any degree of certainty. Its shape varies significantly with the type of image being shown. Secondly, in contrast to the FDM and SCPC cases, the television signal is a wideband signal. Essentially the entire overlay signal will be contained within the bandwidth of the television receiver, not only a small portion as is the case with the relatively narrowband FDM and SCPC recievers. Finally, the degree to which a interferer degrades the performance of a television signal is highly subjective, and cannot be quantified. Television is primarily a video signal. Even though an interferer may have a very low power relative to a television signal, if it has certain characteristics, it may produce objectionable images in the received television video. Furthermore, high level interferers with the right parameters may produce little noticeable interference. For these reasons, television interference research is best performed by experiment with human judges. Computer simulation may be useful, but will still fail to include the subjective measures of video quality that are an important part of the system design. This section presents estimates of the acceptable interference levels to provide a crude estimate of the feasibility of signal overlay on analog television signals.

In satellite television transmission, the baseband television signal, with a video bandwidth of approximately 4 MHz, is FM modulated so that its RF bandwidth fills an entire 36 MHz transponder. When the overlay signal, which is a BPSK signal with a data rate of 18 MHz, passes through an ideal FM demodulator, the output would appear as in Figure 20, an impulse at each bit transition. The impulses would be of random polarity and occur at a maximum rate of 18 MHz. The video receiver is essentially a 4 MHz wide filter. The fact that this wideband (> 18MHz) noiselike signal passes through a filter that has a relatively narrow bandwidth supports the assumption that the amplitude of this interference signal at the output of the video receiver has Gaussian statistics. For this reason it is assumed that the BPSK overlay signal should not produce especially objectional interference to the video signal. Since its distribution should be a nearly Gaussian function, it should not be more objectional than white noise of equal power.

Since the entire overlay signal power is within the television receiver bandwidth, to keep the signal to interference ratio at 25 dB the EIRP of the overlay transmitter should be 25 dB below that of the television transmitter. If we assume a television earth station with a 9 meter diameter antenna transmitting 200 Watts, the overlay transmit power from a 2 meter antenna should be approximately 4 Watts.

If we assume that the PSD of the television signal can be approximated by the following Gaussian curve [30]

$$\frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{(f - f_c)^2}{2\sigma^2} \right]$$

where σ = 7.6 MHz, then the numerical evaluation of the interference PSD at the overlay receiver is shown in Figure 21.

The carrier to interference density ratio is then 49.32 dB-Hz. The analysis of the overlay link is given below.

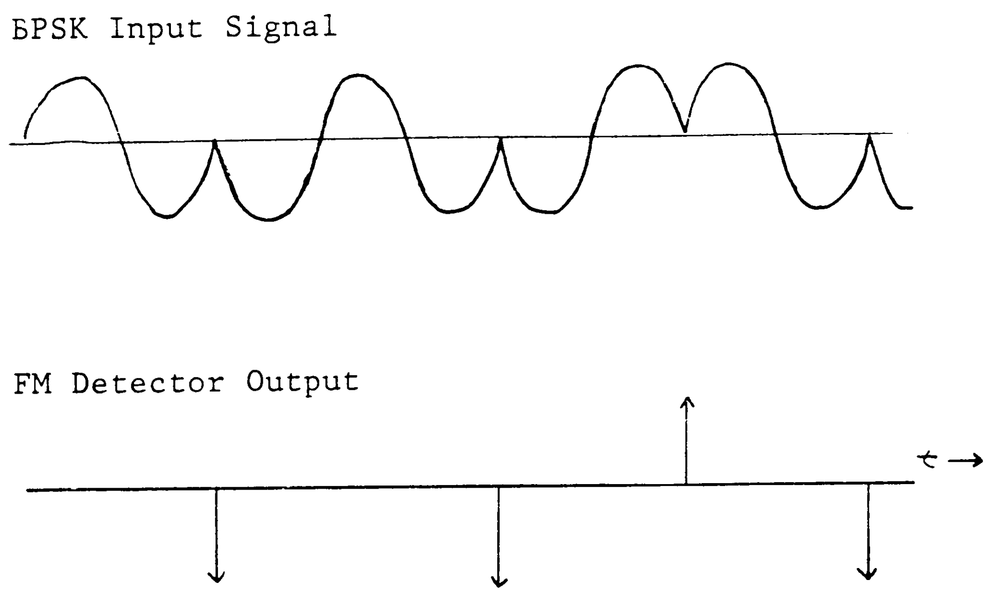

Figure 20. BPSK Signal Passed Through an FM Demodulator

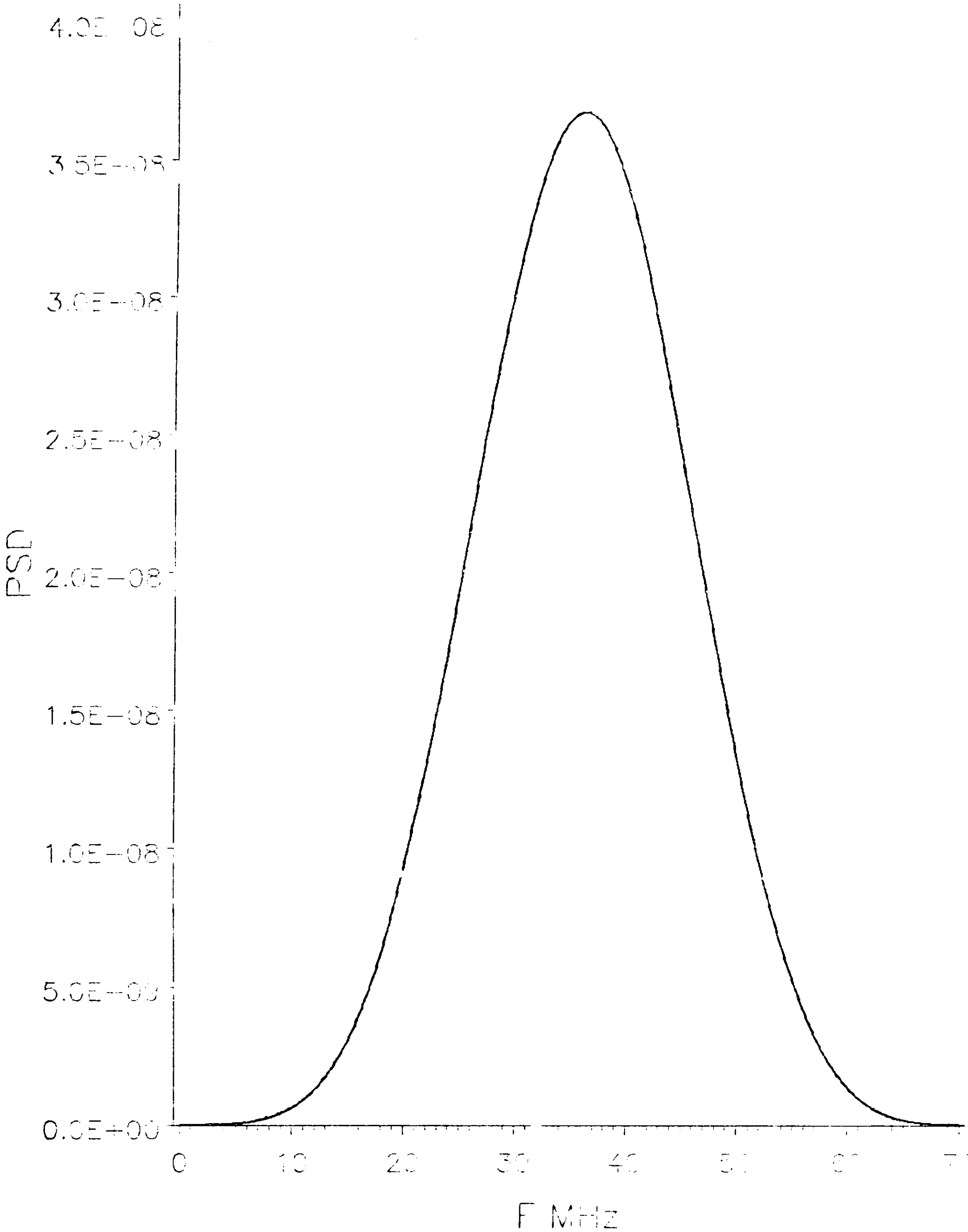

Figure 21. Interference PSD Caused by a TV Signal

Analog Television Overlay - C Band

Satellite Parameters

EIRP	=	36 dBW
G/T	=	0 dB/K
Bandwidth	=	36 MHz

Earth Station Parameters

Antenna Diameter	=	2.0 m
Aperture Efficiency	=	65%
Transmit Gain (6 GHz)	=	40.1 dB
G/T	=	14 dB/K

Downlink

Propagation and pointing loss	=	196.3 dB
$(C/N_o)_d$	=	57.6 dB-Hz

Uplink

Propagation and pointing loss	=	200.2 dB
Earth station power	=	6.1 dBW
$(C/N_o)_u$	=	74.6 dB-Hz

Overall Link

Carrier to Interference Density Ratio	=	49.3 dB-Hz
Overall C/N_o	=	48.7 dB-Hz

The overall link C/N_o of 48.69 dB-Hz implies a maximum overlay data rate of 5874 bps at a 10^{-6} BER. The 6 dB coding gain from a rate 1/2 convolutional code increases this data rate to approximately 23.5 kbps.

Extension to Multiple Overlay Signals

In the case where N simultaneous overlay signals are desired, the maximum data rate of each must be reduced by a factor of N. For example if the maximum allowable data rate for a single overlay signal is 10000 bps, then then two overlay signals of 5000 bps, or 4 signals of 2500 bps, etc., can be accomodated.

The reasoning for this is as follows. If the number of desired signals is N, then to keep the total interference power constant when N signals are used, the power of each must be reduced by a factor of N. This would lower the E_b/N_o of each signal by a factor of N. To compensate for this decrease to keep the BER at the same level, the data rate must also be reduced by a factor of N to keep E_b/N_o constant.

Conclusions

This chapter demonstrates that overlay of spread spectrum signals on existing satellite traffic is feasible. The most promising spread spectrum modulation for this purpose appears to be ordinary direct sequence spread spectrum. While this type of service is possible, the modest data rates it is able to support suggest that this service may be impractical. Data rates of less than 20 kbps are generally insufficient to accomodate a single voice channel, unless sophisticated bandwidth compression schemes are used. However, these data rates can support the operation of several low data rate computer terminals.

V. On Board Processing for Multiple Access Systems

Introduction

All of the systems considered so far and probably all commercial satellites in existence use what is known as a "classical transponder". The classical transponder amplifies the received signal and translates the uplink frequency to the appropriate downlink frequency (Figure 22). While this arrangement has proven itself to be extremely reliable, it has one disadvantage: the satellite retransmits the uplink noise along with the uplink signal increasing the noise received at the earth station. Satellites with "processing transponders" can decouple the effects of the uplink and downlink noise. All of these not only amplify the received signal, but detect it, regenerate the best estimate of the transmitted bit stream, and remodulate the data at the downlink frequency, as shown in Figure 23.

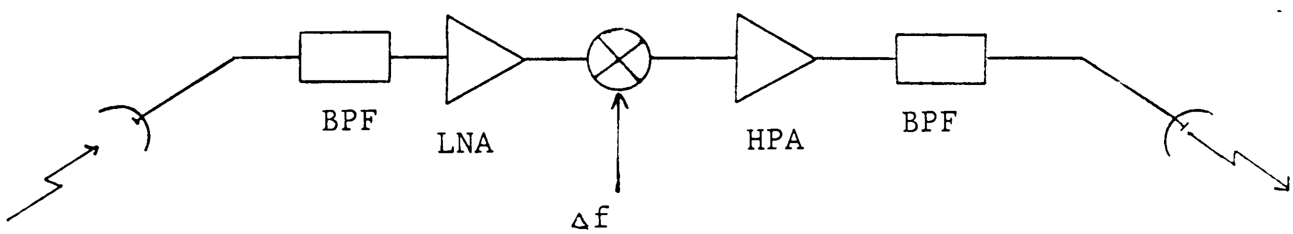

Figure 22. Classical Transponder

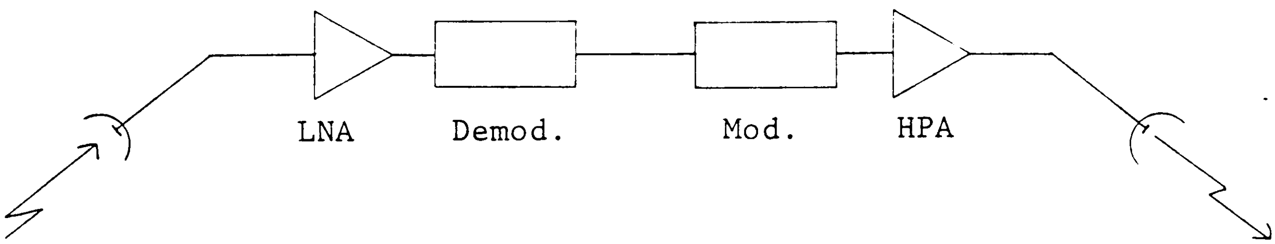

Figure 23. Processing Transponder

In systems where the uplink and downlink E_b/N_o are nearly equal, this type of system can provides about 3 dB gain. For instance, if the uplink and downlink E_b/N_o for a conventional system are each 10.6 dB, the overall link E_b/N_o determined from the formula

$$\left[\frac{E_b}{N_o}\right]^{-1} = \left[\frac{E_b}{N_o}\right]_{up}^{-1} + \left[\frac{E_b}{N_o}\right]_{down}^{-1} \tag{5.1}$$

is 7.6 dB. For small error rates, the following formula approximates the link bit error rate when a processing transponder is used [31]:

$$P_e = (P_e)_{up} + (P_e)_{down} \tag{5.2}$$

for small error rates. At an E_b/N_o of 10.6 dB, P_e for the uplink and downlink are each 10^{-6}, making the link BER approximately 2×10^{-6}. The link E_b/N_o necessary to achieve this BER without a processing transponder is approximately 10.3 dB. The bit error rate achieved by the processing transponder with an overall link E_b/N_o of 7.6 dB is identical to that achieved by a conventional transponder with a link E_b/N_o of 10.3 dB, a gain of 2.7 dB.

The previous example is not typical. In many applications the uplink and downlink E_b/N_o are very different, meaning that there is little contribution to the overall noise by either the uplink or downlink. In these cases the benefit of a processing transponder is slight.

Processing transponders need not transmit the downlink signal with the same type of modulation as the uplink. In some cases, changing the modulation can provide advantages such as lower interference, reduced hardware complexity, and a lower bit error rate, depending on the application. One commercial satellite system that may be used in the future has an FDMA uplink transformed by a processing transponder to a TDM downlink. This system retains the advantages of FDMA (no time synchronization between users and therefore simple equipment) while eliminating the need for any backoff of the satellite power amplifier since intermodulation interference is not a problem in TDM [32].

In the following sections, the techniques described here are applied to the multiple access problem described in Chapter 3 to determine if and what type of processing transponder would increase the throughput of multiple access from small earth terminals.

Simple Processing Transponder

As mentioned above, simply decoupling the uplink and downlink has little effect if their signal to noise ratios differ appreciably. Unfortunately this is the case for the spread spectrum multiple access systems considered in Chapter 3. Looking at the link analysis in Chapter 3 for the C band multiple access system with 968 users, the uplink C/N_o is 64.7 dB-Hz while the downlink C/N_o is 45.0 dB-Hz. The downlink noise determines the link performance. In effect, the difference in C/N_o , since it virtually negates the effect of the uplink on the link performance, has already decoupled the uplink and downlink. The same is true for the Ku band system. Both systems are downlink limited. The effect of a simple processing tranponder on the system performance would be minimal.

Dual Modulation Systems

While simply demodulating the received spread spectrum signals and retransmitting spread spectrum signals would provide little advantage, there are benefits in using non spread spectrum modulations for the downlink. Since the links are downlink limited, anything that would lower the downlink noise, and therefore increase the downlink C/N_o would increase the system performance significantly. One obvious source of noise that could be eliminated if a non spread spectrum modulation is used is the inter-user interference. Much of the downlink noise is simply the interference between different users, which are forced to share the same bandwidth at the same time.

Using a spread spectrum uplink is desirable to reduce adjacent satellite interference. On the uplink, the relatively flat PSD of a spread spectrum signal would interfere little with adjacent satellites. As explained in Chapter 1, this is desirable since the wide beamwidth of the small earth terminal's transmitting antenna would transmit significant power in the direction of adjacent satellites.

While interference to other users is not a problem for the downlink, since the antenna beamwidth is fixed by the desired coverage area on the earth, the use of non spread spectrum modulations would reduce the interference rejection capability of the small earth terminal receiver. Since the wide beamwidth of a small earth terminal's receiving antenna will receive signals from adjacent satellites, some form of rejection of these signals is necessary. Obviously the advantages of a transponder which changes the modulation of the downlink signal can only be realized when the means exist to reduce this interference to an acceptable level.

If the processing gain of a spread spectrum receiver is not available to reject interfering signals, the only means to reject these signals is with the directional gain of the antenna. This immediately excludes the use of non-spread spectrum downlink signals from C band full mesh VSAT networks. The gain of a small dish antenna at several degrees off axis is only reduced by 4 or 5 dB. Signals from adjacent satellites are therefore at a relatively high level, causing severe interference.

One exception to the use of such a system at C band is in multipoint to point networks, as shown in Figure 24. Here many small earth terminals communicate with a single large earth terminal, which may be connected to a central computer or telephone network. Because a narrow beamwidth (large diameter) antenna can be used for reception, signals from adjacent satellites are attenuated sufficiently.

Small earth terminal networks using spread spectrum uplinks and non spread spectrum downlinks are feasible at Ku band and above, where a small diameter antenna can provide significant attenuation of signals from adjacent satellites. One such system follows.

MFSK/TDM Processing Transponder System

The Ku band spread spectrum multiple access system presented in Chapter 3 is limited by the downlink carrier to noise ratio. To improve this ratio, which is influenced significantly by the co-channel interference that the users present to one another, an appropriate non-spread spectrum multliplexing scheme must be chosen. Any type of frequency division multipexing would require that the satellite's tranmitted power be backed-off to reduce intermodulation interference. Since the satellite demodulates all of the users' signals, the synchronization required in TDM systems can be done at the satellite. Since no synchronization between different transmitters is needed, a TDM downlink signal should give the best system performance.

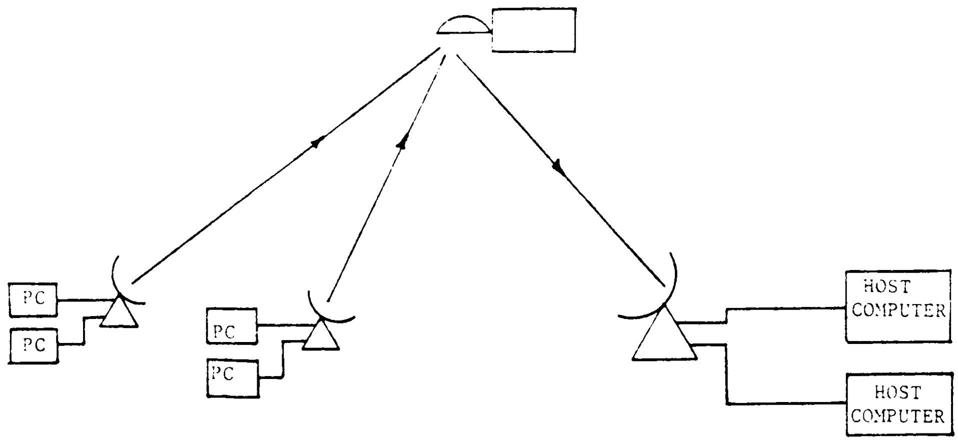

Figure 24. Multipoint to Point Network Architecture

Figure 25 shows the operation of the on-board processing system described. N parallel receivers demodulate the N MFSK/DS spread spectrum signals each with a data rate of R_b. Each synchronizes to one of the transmitted signals. A baseband digital multiplexer accepts the data from each of the receivers and forms a single data stream at a rate $N \times R_b$. This TDM data stream is then transmitted at the downlink frequency using BPSK modulation. The earth stations then demodulate the BPSK signal. At this point, all of the data signals from each transmitter are available at every receiver.

The analysis of the performance of this system is done separately for the uplink and downlink. The link bit error rate is given by equation 5.2.

Ku Band MFSK/DS - TDM System :110 users

Satellite Parameters

EIRP	=	41.0 dBW
G/T	=	2 dB/K
Bandwidth	=	54 MHz

Earth Station Parameters

Antenna diameter	=	2.0 m
Aperture Efficiency	=	65%
EIRP	=	46.6 dB
G/T	=	18.8 dB/K

Uplink Parameters

Propagation and Pointing Loss	=	208.5 dB
Uplink E_b/N_o	=	21.2 dB

Downlink Parameters

Propagationand pointing loss	=	206.8 dB
TDM bit rate	=	6.16 Mbps
Downlink E_b/N_o	=	13.7 dB

The link analysis confirms that this system can accomodate 110 56 kbps users versus 57 for the same system which uses a classical transponder. The throughput has been increased by 93% from .059 bps/Hz to .114 bps/Hz. The system is now limited by the uplink to 110 users assuming that $M=16$ and the MFSK/DS/FDM multiple access system (Figure 11) is used. The downlink E_b/N_o is 13.7 dB which gives a downlink BER of less than 10^{-8}. The MFSK/DS/FDM multiple access system can handle 110 users for $M=16$ at an E_b/N_o of 18 dB. Since the uplink E_b/N_o is 21.2 dB, its BER will also be much less than 10^{-6}, assuring that the system BER is less than 10^{-6}.

The throughput of the system is nearly doubled. The price for this increase in performance is an extremely complex and expensive satellite, more complicated than probably any in current commercial use.

VI. Conclusions

The analysis in the previous chapters demonstrates that spread spectrum multiple access is feasible, though still inefficient relative to non spread spectrum systems. The MFSK/DS systems proposed can achieve bandwidth efficiencies up to 11% for the Ku band example (56 kbps) and for the C band example (1200 bps). When the power and interference constraints of practical satellite systems are considered, the throughput is reduced to approximately 6% for the Ku band example and 3% for the C band example. The advantage of spread spectrum systems is that they make VSAT networks possible when operated at C band and when the angular satellite spacing is small, situations which make VSAT networks infeasible for other modulations. The construction of SSMA VSAT networks, because of their inefficient use of satellite bandwidth, is mainly a question of economics. If transponder leasing costs remain low, SSMA VSAT networks may proliferate. Presently, networks exist which are far less bandwidth efficient than the systems presented here but are still commercially successful [33].

Spread spectrum overlay will probably be implemented by a small number of satellite users that need an extra low data rate channel. The results of Chapter 4 predict that DS overlay signals with data rates of approximately 3000 bps can be superimposed on general satellite traffic. When convolutional coding is used, the data rate may be increased to 10 to 20 kbps. While these data rates are generally insufficient to accomodate even a single voice channel, they can accomodate several low rate terminals. Because of the overlay systems' limited performance, their commercial appeal will probably be limited.

On-board processing has the ability to dramatically increase the throughput of SSMA systems, as seen in the near doubling of the throughput in our example. The Ku band MFSK/DS multiple access system considered in Chapter 3 could accomodate 57 simultaneous users. The addition of a processing transponder which converts the MFSK/DS uplink to a TDM downlink increases the number of simultaneous users to 110. The future of on-board processing in the commercial market, however, is probably not bright. The complex on-board electronics required would make the satellite very expensive, and would probably decrease its reliability. More importantly, the transponder becomes dedicated to a certain type of service. The ability of the classical transponder to handle general signals allows it to be leased to many different users at different times. This makes its commercial success independent of the success of an individual company or specific system, an advantage that the dedicated processing transponders do not enjoy.

Bibliography

[1] Timothy Pratt and Charles W. Bostian, *Satellite Communications*, New York: Wiley, 1986 p. 225.

[2] S. Joseph Campanella, and John V. Harrington, "Satellite Communications Networks", Proceedings of the IEEE, November 1984, p. 1507.

[3] T.T. Ha, *Digital Satellite Communications.* New York: Macmillan, 1986. pp. 206-213.

[4] Pratt and Bostian, p. 235.

[5] Campanella and Harrington, p 1510.

[6] Robert C. Dixon, *Spread Spectrum Systems* , New York: Wiley, 1984, pp. 15-28.

[7] Dixon, pp. 28-42.

[8] Robert M. Gagliardi, *Satellite Communications* , Belmont, California: Lifetime Learning Publications, 1984, pp. 267-268.

[9] T.T. Ha, pp. 538-539.

[10] T.T. Ha, pp. 539-544.

[11] T.T. Ha, p. 543.

[12] T.T. Ha, pp. 544-546.

[13] M.B. Pursley and D.V. Sarwate, "Performance Evaluation for Phase-Coded Spread Spectrum Multiple Access Communication II. Code Sequence Analysis," IEEE Transactions on Communications, Vol. COM-25, No. 8, August 1977, pp. 800-803.

[14] Gagliardi, pp. 282-288.

[15] Rodger E. Ziemer and Roger L. Peterson, *Digital Communications and Spread Spectrum Systems*, New York: Macmillan, 1985, pp. 569,581,585.

[16] Y. Yamauchi, M. Sato, N. Morinaga, and T. Namekawa, "Improvement in Multiple ACcess Capability in M-ary-FSK/Direct Sequence SSMA," Electronics and Communications in Japan, Part 1, Vol. 69, No. 3, pp. 86-91, 1986.

[17] Pratt and Bostian, p. 274.

[18] Andrew J. Viterbi, "A Processing Satellite Transponder for Multiple Access by Low-Rate Mobile Users," Proceedings of the Fourth International Conference on Digital Satellite Communications, Montreal, Canada, October, 1978, pp. 166-174.

[19] T.T. Ha, pp. 560-561.

[20] Pratt and Bostian, p. 250.

[21] H.J. Kochevar, "Spread Spectrum Multiple Access Communications Experiment Through a Satellite," IEEE Transactions on Communications, Vol. COM-25, No. 8, August 1977, p. 855.

[22] Yamauchi, pp. 86-91.

[23] T.T. Ha, pp 544-546.

[24] K. Yao, "Error Probability of Asynchronous Spread Spectrum Multiple Access Communication Systems," IEEE Transactions on Communications, Vol. COM-25, No. 8, pp. 803-809, August 1977.

[25] George C. Clark, and J. Bibb Cain, *Error Correction Coding for Digital Communication* , New York: Plenum Press, 1982, p. 369.

[26] A. Papoulis, "Narrow Band Systems and Gaussianity", IEEE Transactions on Information Theory, January, 1972.

[27] V.K. Prabhu, "Error Rate Considerations for Coherent Phase-Shift Keyed Systems with Co-Channel Interference," The Bell System Techinical Journal, March 1969, pp.743-767.

[28] T.T. Ha, p 202.

[29] T.T. Ha, p. 538.

[30] T.T. Ha, pp. 150.

[31] T.T. Ha, pp. 561.

[32] Pratt and Bostian, p. 273.

[33] E.B. Parker, "Micro Earth Stations as Personal Computer Accessories," Proceedings of the IEEE, vol. 72, November 1984, pp. 1526-1531.

[34] T.T. Ha, pp. 428-433.

Appendix A. Performance of Noncoherent MFSK in Colored Noise

An MFSK modulator transmits M distinct symbols

$$s_1, s_2, \cdots, s_M$$

A noncoherent MFSK detector is composed of M parallel channels each containing a matched filter for one of the M symbols (Figure 5). The sampled outputs of these filters define a set of observation random variables

$$r_1, r_2, \cdots, r_M$$

The probability that symbol q is chosen in the receiver given symbol p was transmitted is denoted by

$$\Pr(r_q > r_p \mid s_p)$$

In the usual case where the interference is additive white Gaussian noise and the spacing between symbols satisfies the orthogonality condition, the output of a channel whose symbol has been transmitted is the envelope of a signal plus noise, and is described by a Rician probability density function. The outputs of the other channels are the envelopes of Gaussian noise, and are described by Rayleigh probability density functions.

For the case where the noise is Gaussian but colored and has a PSD described by the function $\Phi(f)$ the appropriate probability density functions are [34]

$$p\,(r_p \,|\, s_p) \;=\; \frac{2r_p}{E_s N_p}\,\exp\left[\,-\,\frac{r_p^{\,2} + E_s^{\,2}}{E_s N_p}\right]\, I_o\left[\frac{2r_p}{N_p}\right] \qquad (Rician) \qquad (A1)$$

$$p\,(r_q \,|\, s_p) \;=\; \frac{2r_q}{E_s N_q}\,\exp\left[\,-\,\frac{r_q^{\,2}}{E_s N_q}\right] \qquad (Rayleigh) \qquad (A2)$$

where $N_p = \Phi(f_p)$, $N_q = \Phi(f_q)$, I_o is the modified Bessel function of order zero, and E_s is the energy per symbol .

$$\Pr\,(r_q > r_p \,|\, s_p) \;=$$

$$= \int_0^{\infty} p(r_p \,|\, s_p) \int_{r_p}^{\infty} p(r_q \,|\, s_p)\, dr_q\, dr_p$$

$$= \int_0^{\infty} p(r_p \,|\, s_p)\, \exp\left[\,-\,\frac{r_p^{\,2}}{E_s N_q}\right] dr_p$$

$$= \frac{2}{E_s N_p} \int_0^\infty r_p \exp\left[- \frac{r_p^{\,2} + E_s^2 \dfrac{N_q}{N_p + N_q}}{\dfrac{E_s N_p N_q}{N_p + N_q}} \right] I_o \left[\frac{2 r_p}{N_p} \right] dr_p$$

Now making the substitution

$$z^2 = \frac{r_p^{\,2} N_q}{N_p + N_q}$$

$$= \frac{N_q}{N_p + N_q} \int_0^\infty \frac{2z}{E_s N_p} \exp\left[- \frac{z^2 + E_s^2}{E_s N_p} \right] I_o \left[\frac{2z \dfrac{\sqrt{N_q}}{\sqrt{N_p + N_q}}}{N_p} \right] dz$$

Multiplying by

$$\exp\left[\frac{E_s}{N_p + N_q} \right]$$

inside the integral and compensating outside the integral gives:

$$= \frac{N_q}{N_p + N_q} \exp\left[- \frac{E_s}{N_p + N_q} \right] \int_0^\infty \frac{2z}{E_s N_p} \exp\left[- \frac{z^2 + E_s^2 \dfrac{N_q}{N_p + N_q}}{E_s N_p} \right] I_o \left[\frac{2z \dfrac{\sqrt{N_q}}{\sqrt{N_p + N_q}}}{N_p} \right] dz$$

now let

$$A^2 = \frac{E_s^2 N_q}{N_p + N_q}$$

and

$$\sigma^2 = \frac{E_s N_p}{2}$$

and the expression becomes

$$\frac{N_q}{N_p + N_q} \exp\left[-\frac{E_s}{N_p + N_q} \right] \int_0^\infty \frac{z}{\sigma^2} \exp\left[-\frac{z^2 + A^2}{2\sigma^2} \right] I_o\left[\frac{Az}{\sigma^2} \right] dz$$

Since the function inside the integral is a Rician pdf, the integral = 1, giving the final result:

$$\Pr(r_q > r_p \mid s_p) = \frac{N_q}{N_p + N_q} \exp\left[-\frac{E_s}{N_p + N_q} \right] \qquad (A3)$$

When the noise power spectral density is flat, $N_p = N_q$ and this equation is identical to that for the probability of error for noncoherent binary FSK in white noise.

Appendix B. Derivation of Interference PSD

The power spectral density (PSD) of a pseudo-noise (PN) sequence is of the form

$$\left[\frac{\sin(af)}{af} \right]^2 \tag{B1}$$

The envelope of this function can be approximated by

$$\frac{1}{1 + a^2 f^2} \tag{B2}$$

The power spectral density $I(f)$ of an FSK tone spread twice by being multiplied by two uncorrelated PN codes can therefore be approximated by a convolution of the approximating function above with itself

$$\frac{1}{1 + a^2 f^2} * \frac{1}{1 + a^2 f^2} \tag{B3}$$

$$I(f) = \int_{-\infty}^{\infty} \frac{1}{1 + a^2k^2} \times \frac{1}{1 + a^2(f - k)^2}\, dk$$

$$= \int_{-\infty}^{\infty} \frac{1}{1 + a^2k^2} \times \frac{1}{k^2a^2 - 2a^2fk + f^2a^2 + 1}\, dk \qquad (B4)$$

$$= \int_{-\infty}^{\infty} \frac{lk + n}{1 + a^2k^2}\, dk + \int_{-\infty}^{\infty} \frac{mk + p}{k^2a^2 - 2a^2kf + f^2a^2 + 1}\, dk$$

where l, n, m, and p are partial fraction expansion coefficients which satisfy

$$(lk + n)(k^2a^2 - 2a^2kf + f^2a^2 + 1) + (mk + p)(1 + a^2k^2) = 1 \qquad (B5)$$

Equating like coefficients of powers of k and solving gives

$$p = \frac{3}{4 + a^2f^2}$$

$$m = \frac{-2}{x(4 + a^2f^2)}$$

$$l = \frac{2}{x(4 + a^2f^2)}$$

$$n = \frac{1}{4 + a^2f^2}$$

EVALUATE INTEGRALS:

$$\int_{-\infty}^{\infty} \frac{lk + n}{1 + a^2k^2}\, dk \;=\; \int_{-\infty}^{\infty} \frac{lk}{1 + a^2k^2}\, dk \;+\; \int_{-\infty}^{\infty} \frac{n}{1 + a^2k^2}\, dk$$

$$= \quad 0 \quad + \frac{n}{a}\Big[\ \tan^{-1}(ak)\ \Big]_{-\infty}^{\infty}$$

$$= \frac{n\pi}{a}$$

$$\int_{-\infty}^{\infty} \frac{mk}{k^2a^2 - 2a^2kf + f^2a^2 + 1}\, dk \quad =$$

$$= \int_{-\infty}^{\infty} \frac{mk}{k^2a^2 - 2a^2kf + f^2a^2 + 1}\, dk \;+\; \int_{-\infty}^{\infty} \frac{p}{k^2a^2 - 2a^2kf + f^2a^2 + 1}\, dk$$

$$= \frac{m}{2a^2}\ \ln(a^2k^2 - 2a^2kf + a^2f^2 + 1)\ \Big]_{-\infty}^{\infty} \;+\; mx\int_{-\infty}^{\infty} \frac{dk}{a^2k^2 - 2a^2kf + f^2a^2 + 1}$$

$$+ \int_{-\infty}^{\infty} \frac{p}{a^2k^2 - 2a^2kf + f^2a^2 + 1}\, dk$$

$$= 0 \;+\; \frac{m\pi x}{a} \;+\; \frac{p\pi}{a}$$

Combining terms gives

$$I(f) = \frac{n\pi}{a} + \frac{m\pi f}{a} + \frac{p\pi}{a} \qquad (B6)$$

Substituting the values for n, m, and p gives

$$I(f) = \frac{\frac{2\pi}{a}}{4 + a^2 f^2} \qquad (B7)$$

Normalizing the function to have an area of 1 by multiplying by a constant c

$$c\frac{2\pi}{a}\int_{-\infty}^{\infty}\frac{df}{4 + a^2 f^2} = c\frac{\pi}{2a}\frac{2\pi}{a} \equiv 1$$

$$c = \frac{a^2}{\pi^2}$$

which gives a normalized interference PSD function of

$$I(f) = \frac{2a}{\pi(4 + a^2 f^2)} \qquad (B8)$$

For a PN code with a code rate of R_c , $a = \frac{\pi}{R_c}$

Substituting this into equation (B8) above gives a normalized interference PSD function of

$$I(f) = \frac{2R_c}{4R_c^2 + \pi^2 f^2} \qquad (B9)$$

Appendix C. MFSK/DS/FDM Performance Analysis Program

```
C     THIS PROGRAM EVALUATES THE BER FOR A DS/MFSK MULTIPLE ACCESS
C     SYSTEM. THE PROGRAM CALCULATES THE ALLOWABLE NUMBER OF USERS
C     IN A MFSK/DS SSMA SYSTEM FOR A GIVEN SYSTEM BIT ERROR RATE AND
C     VALUES OF EB/N0 FROM 10 TO 18 DB.
C
C
C     INPUT PARAMETERS:
C        RC   - THE CODE (OR CHIP RATE) OF THE SPREADING CODE
C               IN BPS
C        DELF - THE FREQUENCY SPACING BETWEEN MFSK FREQUENCIES
C               IN HZ
C        M    - THE NUMBER OF MFSK FREQUENCIES
C        K    - LOG BASE TWO OF M
C        TB   - THE BIT DURATION OF THE DATA SIGNAL = 1/RB
C        BER  - THE DESIRED SYSTEM BIT ERROR RATE
C        N0   - THE NOISE POWER SPECTRAL DENSITY (ALWAYS NORMALIZED
C               TO 1)
C
C     OUTPUT PARAMETERS:
C        N    - THE NUMBER OF USERS
C
C      PROGRAM OPERATION:
C         A VALUE OF EB/N0 (=10) IS SELECTED.  THE BER IS CALCULATED
C         FOR INCREASING VALUES OF N UNTIL THE BER IS GREATER THAN OR
C         EQUAL TO THE DESIRED SYSTEM BER.  THIS VALUE OF N IS THEN
C         OUTPUT AND THE PROCESS IN REPEATED FOR THE NEXT EB/N0.
C
C
```

```
C       APPLICATION TO MFSK/DS/FDM SYSTEM PERFORMANCE
C         THIS PROGRAM IS USED TO CALCULATE THE NUMBER OF USERS THAT
C         CAN BE ACCOMODATED IN AN FDM SLOT.  TO FIND THE TOTAL NUMBER
C         OF SYSTEM USERS, THIS PROGRAM'S OUTPUT MUST BE MULTIPLIED
C         BY Z, THE NUMBER OF FDM SLOTS.
C
C
C
      COMMON RC,C,DELF,N,M,K,TB,N0
       RC=210000.00
       DELF=308000.00
       M=16
       K=4
       TB=1/56000.0
       BER= 1.E-06
       N0=1
         DO 200 J=6,10
           C=10.**((J-1)/5.)/TB
         DO 100 N=1,500
             Y=E(N)
          IF (Y.GE.BER) THEN
            WRITE(6,*) C,N
            GO TO 200
          ENDIF
 100     CONTINUE
 200     CONTINUE
      STOP
       END
C
C
C
C
       FUNCTION PHI(I)
C       FUNCTION TO EVALUATE THE INTERFERENCE POWER FUCTION
C         EVALUATES EQUATION NUMBER 2.12 IN CHAPTER 2
C
C
       COMMON RC,C,DELF,N,M,K,TB,N0
C
       PI=3.141592654
       PHI=0.0
         DO 100 J=1,M
           PHI=PHI+1.0/(4.*RC**2+(PI*(I-J)*DELF)**2)
 100     CONTINUE
C
       PHI=2.*RC*C*(N-1)/M*PHI+N0
       RETURN
       END
C
C
C
```

```
C
C
C
      FUNCTION E(N)
C         EVALUATES THE BER OF THE SSMA SYSTEM AS A FUNCTION OF THE
C         NUMBER OF USERS IN THE SYSTEM USING EQUATION 2.9
C
C
C
        REAL*16 V1,V2,PROD,SUM,ONE
C        FUNCTION EVALUATES THE PROB OF BIT ERROR FOR DS/MFSK
C
      INTEGER P,Q
      COMMON RC,C,DELF,N1,M,K,TB,N0
      SUM=0.0
C
      DO 200 P=1,M
        PROD=1.0
        TP=PHI(P)
             ONE=1.0
          DO 100 Q=1,M
            IF(Q.EQ.P) GOTO 100
              TQ=PHI(Q)
              V0=-C*TB*K/(TP+TQ)
              V1=EXP(V0)
              V2=ONE-TQ/(TQ+TP)*V1
              PROD=PROD*V2
 100        CONTINUE
        SUM=SUM+(1.D0-PROD)
 200  CONTINUE
C
      E=SUM/(2.*(M-1))
      RETURN
      END
```

Appendix D. MFSK/DS/FH Performance Analysis Program

```
C     THIS PROGRAM EVALUATES THE BER FOR A FH/DS/MFSK MULTIPLE ACCESS
C     SYSTEM.
C
C     THE INPUT PARAMETERS ARE INDENTICAL TO THOSE OF THE MFSK/DS
C     PROGRAM AND ARE READ FROM UNIT NUMBER 4.
C
C     Z IS THE NUMBER OF FH SLOTS IN THE SYSTEM BANDWIDTH
C     NMIN - THE START VALUE OF THE NUMBER OF USERS IN THE ITERATIVE
C            CALCULATION OF THE NUMBER OF USERS
C     INC  - THE INCREMENT APPLIED TO THE NUMBER OF USERS
C
C
C     PROGRAM OPERATION:
C        THE PROGRAM STARTS WITH THE NUMBER OF USERS N=NMIN.
C        IT THEN COMPUTES THE BER FOR THIS N.  IF THE BER IS LESS
C        THAN THE DESIRED SYSTEM BER THEN N IS INCREMENTED BY INC
C        AND THE CALCULATION IS PERFORMED AGAIN, UNTIL THE BER IS
C        GREATER THAN OR EQUAL TO THE DESIRED BER.  THIS VALUE OF N
C        IS OUTPUT AND THE PROCESS IS REPEATED FOR A NEW EB/N0.
C
C
C
      REAL N0
      COMMON RC,C,DELF,M,K,TB,N0
       READ(4,10) RC,C,DELF,M,K,RB,N0,BER,Z
 10    FORMAT(F20.5,/,F20.5,/,F20.5,/,I20,/,I20,/,F20.5,/,F20.5,
     $ /,F20.5,/,F20.5)
C
```

```
      BER=1.E-06
      WRITE(7,12) RC,DELF,M,K,RB,N0,BER,Z
 12   FORMAT(1X,'HYBRID FH/DS/MFSK SSMA PERFORMANCE',//,3X,
     $ 'CODE RATE  = ',F15.2,/,3X,
     $ 'DELTA F    = ',F15.2,/,3X,
     $ 'M          = ',I6,/,3X,
     $ 'K          = ',I6,/,3X,
     $ 'RB         = ',F15.2,/,3X,
     $ 'N0         = ',F15.2,/,3X,
     $ 'BER        = ',E15.2,/,3X,
     $ 'FH SLOTS   = ',F15.2,//, 6X,'EB/N0',18X,'N')
C
       TB=1/RB
       INC=2
C
           NMIN=5
        DO 300 J= 6,10
            EBNO=(J-1)*2.
          C=10.**((J-1)/5.)/TB
         DO 200 N=NMIN,5000,INC
             PBE=0.0
           DO 100 I=1,N
               PBE=PBE+W(N,I,Z)
 100         CONTINUE
C               IF(N.GE.100) INC=15
C               IF(N.GE.250) INC=75
C               IF(N.GE.1000) INC=200
            IF(PBE.GE.BER) THEN
              WRITE(7,*) EBNO,N
              NMIN=N
              GOTO 300
            ENDIF
C
 200       CONTINUE
 300      CONTINUE
C
     STOP
      END
C
C
C
C
C
C
C
C
      FUNCTION PHI(I,N)
C      FUNCTION TO EVALUATE THE INTERFERENCE POWER FUCTION EQ 2.12
      REAL N0
      COMMON RC,C,DELF,M,K,TB,N0
C
```

```
      PI=3.141592654
      PHI=0.0
        DO 100 J=1,M
          PHI=PHI+1.0/(4.*RC**2+(PI*(I-J)*DELF)**2)
 100    CONTINUE
C
      PHI=2.*RC*C*(N-1)/M*PHI+N0
      RETURN
      END
C
C
C
C
C
C
C
C
C
C
      FUNCTION E(N)
C         EVALUATES THE MFSK/DS BER AS A FUNCTION OF THE NUMBER OF
C         USERS
C
        REAL*16 V1,V2,PROD,SUM,ONE
        REAL N0
C        FUNCTION EVALUATES THE PROB OF BIT ERROR FOR DS/MFSK
C
      INTEGER P,Q
      COMMON RC,C,DELF,M,K,TB,N0
      SUM=0.0
      ONE=1.0
C
      DO 200 P=1,M
        PROD=1.0
        TP=PHI(P,N)
          DO 100 Q=1,M
            IF(Q.EQ.P) GOTO 100
              TQ=PHI(Q,N)
              V0=-C*TB*K/(TP+TQ)
              V1=EXP(V0)
              V2=ONE-TQ/(TQ+TP)*V1
              PROD=PROD*V2
 100        CONTINUE
        SUM=SUM+(ONE-PROD)
 200  CONTINUE
C
      E=SUM/(2.*(M-1))
      RETURN
      END
C
C
```

```
C
C
C
C
C
C
C
C
C
      FUNCTION COMB(N,K)
C       FINDS THE NUMBER OF COMBINATIONS OF N OBJECTS TAKEN K AT A TIME
C
C
        REAL*16 PROD
        INTEGER DENOM
C
         IF(N-K.GT.K) THEN
              JMIN=N-K+1
              DENOM=K+1
           ELSE
              JMIN=K+1
              DENOM=N-K+1
          ENDIF
C
         PROD=1.0
           DO 100 J=JMIN,N
             DENOM=DENOM-1
             PROD=PROD*J/DENOM
 100         CONTINUE
C
          COMB=PROD
      RETURN
      END
C
C
C
C
        FUNCTION W(N,K,Z)
C           EVALUATES THE BERNOULLI TRIALS FORMULA
C             COMB(N,K)*P**K*Q**(N-K) WHERE P AND Q ARE DEFINED BELOW
C             USES LOGARITHMS IF THE VALUES OF THIS FUNCTION ARE
C             SUFFICIENTLY SMALL TO CAUSE UNDERFLOW IN THE COMPUTER
C
          P=1./Z
          Q=1.-1./Z
               IF (N.LE.200) THEN
                    R=ALOG10(COMB(N,K))
                ELSE
                   D0=FACLOG(N)
                       IF(K.LE.50) THEN
                          D1=ALOG10(FACT(K))
```

```
                  ELSE
                    D1=FACLOG(K)
                  ENDIF
C
                 IF(N-K.LE.50) THEN
                    D2=ALOG10(FACT(N-K))
                  ELSE
                    D2=FACLOG(N-K)
                 ENDIF
               R=D0-D1-D2
            ENDIF
               X=E(K)
                 IF(X.LE.0.0) THEN
                  U=-50
                  ELSE
                  U=ALOG10(X)
                 ENDIF
         W=U+K*ALOG10(P)+(N-K)*ALOG10(Q)+R
         IF(W.LT.-60.) THEN
           W=0.0
           RETURN
         ELSE
           W=10.**W
           RETURN
         ENDIF
       END
C
C
C
      FUNCTION FACT(K)
C        COMPUTES K FACTORIAL
C
         FACT=1.
          DO 10 J=2,K
           FACT=FACT*J
 10       CONTINUE
       RETURN
       END
C
C
C
      FUNCTION FACLOG(K)
C
C        THIS FUNCTION COMPUTES THE COMMON LOG OF
C        STIRLING'S APPROXIMATION TO K
C
        PI=3.1415926536
        E=2.7182818284
         FACLOG=K*ALOG10(K/E)+0.5*ALOG10(2.*PI*K)
        RETURN
        END
```

The vita has been removed from the scanned document