Performance Analysis of VSAT Networks

by

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(ABSTRACT)

Very small aperture terminal (VSAT) networks offer a solution to the increasing demand for low-density voice and data communications. Spread spectrum and single-channel-per-carrier (SCPC) transmission techniques work well for multiple access purposes while allowing the earth station antennas to remain small. Direct sequence code division multiple access (DS-CDMA) is the simplest spread spectrum technique to use in a VSAT network, since a frequency synthesizer is not required for each terminal.

This thesis examines DS-CDMA and SCPC Ku-band VSAT satellite systems for low-density (64 kbps or less) communications. It develops methods for calculating PN coding crosscorrelation interference losses and satellite transponder effects, and it includes these losses in a performance analysis of 50 channel full mesh and star network architectures. It demonstrates selection of operating conditions producing optimum performance.

The thief comes only to steal, and kill, and destroy; I came that they might have life, and might have it abundantly.

John 10:10

The New American Standard Bible

And the witness is this, that God has given us eternal life, and this life is in His Son. He who has the Son has the life; he who does not have the Son of God does not have the life.

I John 5:11-12

The New American Standard Bible

Dedication

TO MY PARENTS,

who love me with a love that never changes,

never fails, and never seeks its own.

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I. INTRODUCTION

1.1 Purpose of Thesis

Many applications exist for satellite networks carrying low-density traffic, as evidenced by the present popularity of very small aperture terminal (VSAT) networks. Low-density traffic typically consists of 1 or 2 voice or data links, with a total bit rate of less than 100 kbps [1, p.451]. With the maturing of Ku-band (11 to 14 GHz) technology, small antenna sizes have increased the practicality of low-density satellite networks and greatly broadened the range of potential applications by lowering the cost of earth stations. Previously, low-density communication networks were only practical for expensive earth stations having medium or large antennas, due to operation at C-band (4 to 6 GHz); and with the possible exception of military applications, the large earth station cost effectively prevented construction of low-density satellite systems.

VSAT earth stations have antennas less than 2.4m in diameter and high power amplifiers (HPA) normally limited to a transmitting power of no more than 2.0 W. The low antenna gain and the low transmitting power render a VSAT earth station incapable of producing the full flux density required at the satellite receiver. As a result, VSAT satellite networks typically use transmission techniques which allow many terminals to use the satellite transponder simultaneously, thus obtaining the desired satellite input flux density from the combined signals. Spread spectrum (SS) and single-channel-per-carrier (SCPC) systems are favored.

The first purpose of this thesis is to develop a highly accurate link analysis for direct sequence code division multiple access (DS-CDMA) spread spectrum satellite communication. In a DS-CDMA system, a set of pseudo-noise (PN) codes defines the signal channels, one code per channel. In addition to the basic link analysis, a DS-CDMA system suffers a receiver correlation loss resulting from crosscorrelation interference within the set of codes. This loss quantifies the receiver's difficulty in distinguishing one code from another. Whenever multiple signals share a satellite transponder, a further loss results from suppression of small signals by large signals. This suppression loss is usually estimated instead of calculated, and the estimate is often no more than a guess. This thesis includes suppression effects and PN coding loss in the link analysis for DS-CDMA signals, thus yielding results with greater accuracy than normally obtained.

The second purpose of this thesis is to examine the performance of a DS-CDMA VSAT Ku-band satellite system for different network architectures, comparing it to the performance of several SCPC systems. The performance analysis includes receiver correlation losses and suppression effects, and it illustrates the effects that bit rate, antenna size, HPA power, and the length of the PN code have on the quality of the satellite link. Further, the performance analysis demonstrates system optimization by showing the implementation margin for given operating conditions.

1.2 Description of a DS-CDMA System

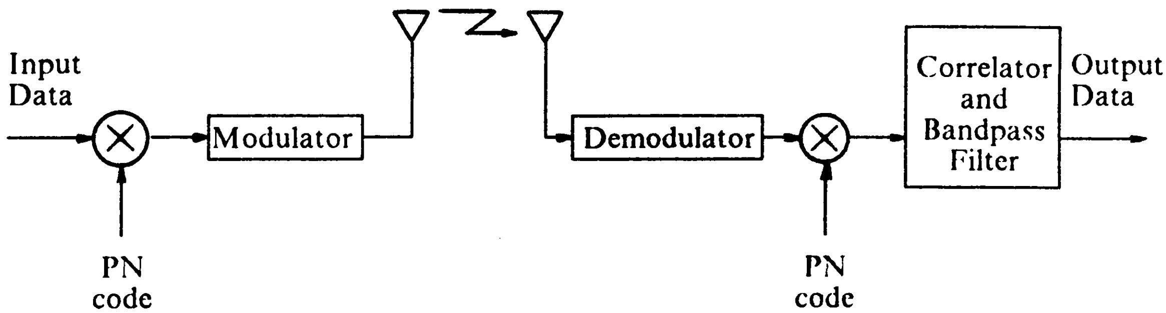
The central idea in direct sequence spread spectrum communication is to spread the original signal over a much larger bandwidth by multiplying the signal with a PN code sequence, also called a spread code; and this spread signal is then transmitted. At the receiver, the same multiplication process using the same PN code, synchronized to the transmitted code, causes the spread signal to collapse to its original bandwidth. The two multiplications effectively cancel out each other.

The bit rate of the PN code sequence, called the chip rate (R_c), greatly exceeds the bit rate of the data (R_b). Since R_c exceeds R_b, many bits of the PN code sequence are multiplied by the same bit of data; the output bit stream is at the chip rate; and each of these output bits are called chips. Thus, a data bit is transmitted as a series of chips. Since R_c is much greater than R_b, the required transmission bandwidth is much greater than the bandwidth of the original data signal. Although a long PN code may be used to spread a series of data bits before the PN code begins to repeat, this thesis uses the entire code to spread one data bit. As a result, the code repeats for each data bit, and R_c equals R_b multiplied by the length of the PN code.

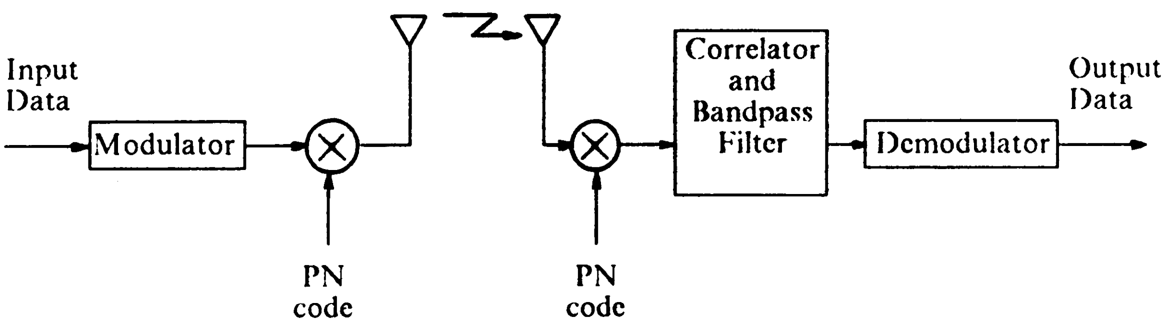
There are two ways of implementing the multiplication process within the transmitter and receiver: data in digital form and the PN code may be multiplied before the data are modulated, provided the digital data and the PN code are {1,-1} valued sequences; or the modulated data signal may be multiplied by a PN function (a signal which has been modulated by the PN code) [2, 3]. Figure 1.2-1 shows a simple block diagram of each system. Just as the transmitter spreads the original signal, the receiver spreads any interfering signals to a large bandwidth, and the bandpass filter eliminates most of the energy contributed by the interfering signals. This dramatically decreases the effect of the interfering signals within the bandwidth of the desired signal.

In a DS-CDMA system, each channel in the network has its own PN code. The correlator selects the desired spread spectrum signal from the set of all received signals. Although oversimplified, Figure 1.2-2 illustrates this concept. For {1,-1} valued sequences, Figure 1.2-2 (a) and (b) show the output chip streams resulting from two different spread codes multiplied by an input data bit of value 1. These are the chip streams which would be modulated and then transmitted by the system of Figure 1.2-1 (a). Figure 1.2-2 (c) and (d) show these two output chip streams as they arrive at the receiver corresponding to the spread code used in Figure 1.2-2 (a). As is shown in Figure 1.2-2 (c), the receiver uses the same spread code as the transmitter (Figure 1.2-2 (a)), and the chips of the desired signal collapse to the desired bit, a value of 1 at the rate R_b, and thus to the original bandwidth. The unwanted series of chips, corresponding to an unwanted spread spectrum signal (Figure 1.2-2 (d)), remains at the chip rate, R_c.

The task of the correlator is now clearly seen: it must lock onto the desired signal, as shown in Figure 1.2-2 (c), and separate it from many interfering signals similar to the ouput in Figure 1.2-2 (d). The bandpass filter decreases the effects of the unwanted signals; but if the spread codes are very similar and have a high amount of crosscorrelation, the unwanted spread spectrum signals will collapse to bandwidths



(a)



(b)

Figure 1.2-1. Direct sequence spread spectrum system using (a) multiplication of bit streams and (b) multiplication of modulated waveforms.

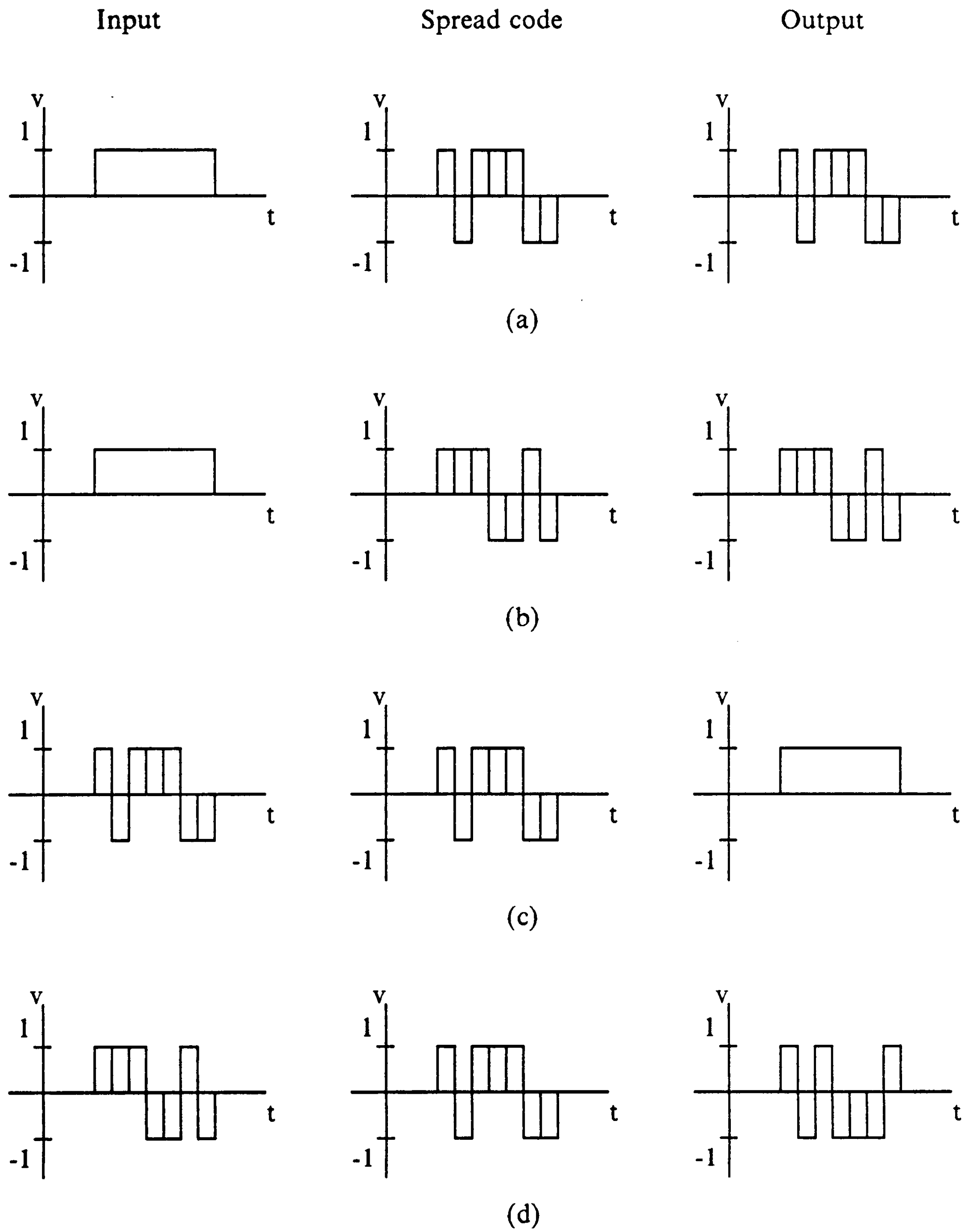


Figure 1.2-2. A simplified multiplication example for DS-CDMA: (a) and (b) at the transmitter, using two different spread codes; (c) and (d) at the receiver, using the output of (a) and (b), respectively, and the spread code of (a).

nearer to the desired bandwidth, thus increasing the interference. This interference between coded signals produces the PN coding loss mentioned earlier.

As a final note, practical DS-CDMA systems use PN codes much longer than the 7 bits shown in Figure 1.2-2. The examples in this thesis use Gold codes with lengths of 511 and 1023 bits to spread the data bits. The number of codes having reasonably low crosscorrelation properties limits the number of channels in the system. This motivates using long codes, because the longer code length increases the number of code choices within a given set of codes. In addition, longer codes produce more chips per bit, and the resulting decrease in coding interference improves the correlator performance. On the other hand, longer codes require more time for synchronization, hence increasing the acquisition time. Further, the length of the codes influences the cost of equipment, which increases as code length increases. For commercial systems, the choice of code length has a large bearing on the feasibility of the system.

1.3 Review of Previous Work

Spread spectrum communication techniques date back at least forty to fifty years; the first systems were built in the 1940's, and much literature exists on the subject. The military has heavily used spread spectrum for its inherent anti-jamming and security advantages over other transmission methods. The basic types of spread spectrum are direct sequence, frequency hopping, time hopping, and chirp. Dixon gives an introductory discussion of these methods and a general examination of spread spectrum

[4]. Scholtz and Price give an excellent history of spread spectrum's development and use [5, 6, 7].

Most previous spread spectrum work has been in the areas of radar, guidance, and terrestrial communications. Application of spread spectrum to satellite communications is relatively new, and the work published in this area is primarily confined to interference rejection and PN coding losses. This is seen in [8], which is probably the most comprehensive collection of recent spread spectrum work. Other papers in the area of direct sequence spread spectrum address rapid acquisition techniques, narrow-band interference rejection, and random access [9-13].

In the area of system analysis of practical DS-CDMA satellite networks, the literature is nearly nonexistent. Geraniotis presents a performance analysis comparing noncoherent modulation and demodulation techniques [14], but his analysis focuses on receiver and PN coding aspects and does not include link analysis or network configuration. Furthermore, his analysis is not for QPSK (quadrature phase shift keying) modulation or VSAT networks, both of which are central to this thesis. Also, Geraniotis' system is of no practical value, having only 3 users and a 31 bit spreading code. Mangulis has discussed the potential of spread spectrum for VSAT networks but has not presented a system analysis [15]. Hamamoto and Masamura present results for a C-band VSAT spread spectrum network, but they give no method for including PN code and suppression losses [16]. Several authors have discussed low-density communications [17, 18, 19]. Of these, only [19] discusses VSAT Ku-band systems; and that discussion is limited to SCPC transmission.

Thus, no literature has been found concerning DS-CDMA VSAT Ku-band satellite networks. Further, no performance analysis is available for any VSAT network or any

DS-CDMA network having a detailed correction for PN coding losses and suppression effects. As a result, further reference to the literature will be limited to those papers upon which this thesis builds directly.

As stated earlier, spread spectrum is not new, although its application to satellite communications is. In the 1970's, Pursley and others determined the effect of PN coding crosscorrelation interference upon the system's performance [20, 21, 22]. This thesis applies Pursley's method to the link analysis. The effect of suppression within the satellite transponder is also not new. Shaft derived a suppression equation in the 1960's, Ramanan has since extended it, and Baer has verified its applicability to DS-CDMA signals [23, 24, 25]. This thesis applies Shaft's and Ramanan's results to VSAT networks for the first time. Chapters 2 and 3 detail the application of PN coding loss and suppression effects to the performance analysis. Finally, the optimum design performance analysis for VSAT networks is new, both for DS-CDMA and SCPC transmission.

1.4 Overview of Thesis

The remainder of this thesis is divided into two main sections. The first section, chapters 2 and 3, describes the analysis corrections required to account for PN coding and suppression losses. The second section, chapters 4, 5, and 6, uses these results in a performance analysis of several VSAT network configurations, resulting in a comparison of some of the more promising methods of low-density satellite communications for commercial applications.

Chapter 2 describes the selection of Gold codes for use in the DS-CDMA system analysis. It includes the generation of Gold codes from shift registers, the selection of optimum codes, and the calculation of coding interference and its effect on the signal-to-noise ratio (SNR). Chapter 3 presents a suppression effect correction method, based on the results of prior satellite transponder suppression studies. Chapter 4 examines the performance of DS-CDMA systems for two network architectures: a full mesh configuration, in which each terminal may communicate with any of the others; and a star network comprising one hub terminal and a number of remote terminals, in which the hub communicates with all of the remotes while the remotes communicate only with the hub. Chapter 5 analyzes SCPC systems using the full mesh and star configurations and a partial mesh architecture, which is a modified star configuration having multiple hub terminals. Chapter 6 finishes with conclusions and recommendations.

The author's contributions to this work correspond to the two main sections of this thesis. First, the effects of satellite transponder suppression and coding interference losses were researched in the literature. Computer programs were written to verify previous data from the coding crosscorrelation interference equations, and this technique was extended to codes of more practical value in actual spread spectrum systems. The calculated effect of suppression was resurrected from the literature and a method was developed to include it in the link analysis. Second, these techniques were incorporated into the system analysis and used to demonstrate the feasibility of DS-CDMA VSAT networks. A performance analysis was developed to optimize system performance, graphically illustrating the optimum high power amplifier power levels, the quality of transmission, and the resulting implementation margin.

II. GOLD CODE ANALYSIS AND SELECTION

2.1 Introduction

In this chapter a set of 50 Gold codes is determined for a spread spectrum multiple access (SSMA) network. In determining the set, the following characteristics are desired for the set:

- code length of $N = 511$ bits
- the set of 50 codes is composed of 2 m-sequences of 511 bits and of 48 Gold codes of 511 bits (Section 2.2 discusses m-sequences and Gold codes)
- the 2 m-sequences meet the minimum crosscorrelation bound (for $N = 511$ the bound is 33) determined by Gold [26].
- the 48 Gold codes are generated from the 2 m-sequences
- shift register generators of length $n = 9$ are used to generate the 2 m-sequences
- each code is in its optimum phase, either the auto-optimal with least sidelobe energy (AO/LSE) phase or the least sidelobe energy auto-optimal (LSE/AO) phase (Section 2.3 defines these phases).

Achieving these goals involves two stages. The first stage generates the codes; and this consists primarily of finding the proper tap connections for the shift register generators. The second stage determines the optimum phase of each code; and this consists primarily of number crunching on a computer, cycling through each phase of each code until the optimum phase is found. These two stages form two sections of this chapter. Two other sections are included in this chapter: one illustrates the method used to arrive at signal-to-noise ratio (SNR) values for a network using spread spectrum, independent of the type of codes used (the codes do not have to be Gold codes); and the other presents the final set of Gold codes, with $N = 1023$, to be used in the DS-CDMA performance analysis of Chapter 4.

2.2 Code Generation

For specific feedback configurations, a linear feedback shift register of length n generates a maximal length m-sequence of length and period N. For a maximal length m-sequence,

$$N = 2^n - 1. \qquad (2.2-1)$$

The shift register and its feedback taps may be represented by a polynomial of degree n of the form

$$h(x) = h_0 x^n + h_1 x^{n-1} + \cdots + h_{n-1} x + h_n \qquad (2.2-2)$$

where $h_0 = 1$ and the remaining coefficients in the polynomial equal 1 or 0 depending on the arrangement of the feedback taps. Except for h_0, each coefficient represents an element in the shift register, and the coefficient equals 1 if there is a feedback tap from that particular element. The coefficient equals 0 if there is not a feedback tap from that element [22].

For example, Figure 2.2-1 shows two shift register generators of length 5, $n = 5$. The output of element 5 forms the code that is being generated. In Figure 2.2-1 (a), there are feedback taps from elements 5 and 2, and thus coefficients h_5 and h_2 are both 1. Coefficients h_1, h_3, and h_4 are 0, because elements 1, 3, and 4 are not used in the feedback logic. Thus, the polynomial representing the shift register generator of Figure 2.2-1 (a) is $h(x) = x^5 + x^3 + 1$. Figure 2.2-1 (b) is an example for the same shift register but with different feedback taps. Modulo 2 addition is used in the feedback, and the allowable values in the registers are 0 and 1. However, the {1,0} valued codes must be converted to {1,-1} valued codes before performing the optimization and crosscorrelation calculations of Sections 2.3 and 2.4 or the spreading multiplication of Figure 1.2-1 (a).

A set of N Gold codes, each code of length N, may be generated from two m-sequences of length N by simply using modulo 2 addition to add each bit of one m-sequence to each bit of the second m-sequence. This is illustrated in Figure 2.2-1 by the addition of code 1 to code 2, producing code 3. If code 1 and code 2 are maximal length m-sequences, then code 3 is one of the Gold codes in the set of N codes. After code 1 has been generated, shifting code 1 by one bit to a new phase and repeating the same addition process produces a second Gold code. As code 1 has N phases (since it is N bits long), this process of adding each phase of code 1 to the unshifted code 2 generates N different Gold codes [4, pp. 72-75].

As an example, if code 1 is generated by the shift register of Figure 2.2-1 (a) having initial conditions (1,2,3,4,5) = 1 0 1 0 1, meaning that elements 1, 3, and 5 contain a 1,

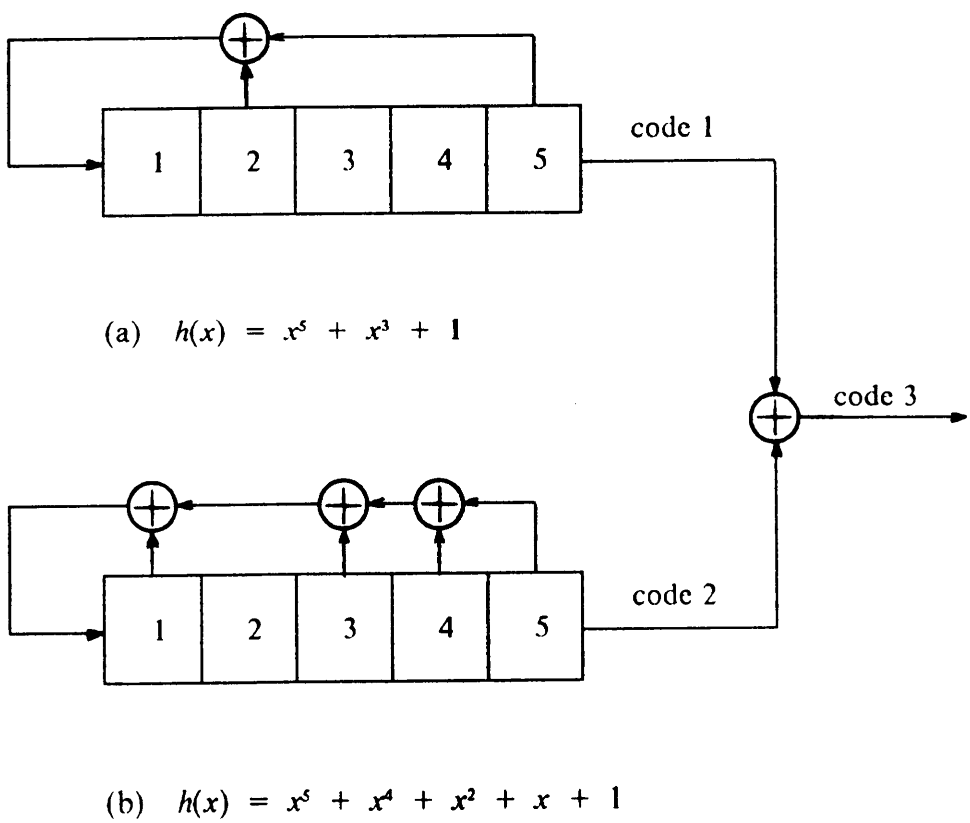


Figure 2.2-1. Code generation using linear feedback shift registers, where (a) and (b) show different feedback configurations and the resulting polynomial representations. Codes 1 and 2 are 31 bit m-sequences, and code 3 is a 31 bit Gold code.

and elements 2 and 4 contain a 0, and if code 2 is generated by the shift register of Figure 2.2-1 (b) having initial conditions (1,2,3,4,5) = 0 1 1 1 1, then Table 2.2-1 lists the first ten values of codes 1, 2, and 3. If code 1 is shifted by one bit so that its first 9 bits are 0 1 0 1 1 1 0 1 1, then the first 9 bits of code 3 (which is a different Gold code from the one listed in Table 2.2-1) are 1 0 1 0 1 0 0 1 1.

Since the 2 m-sequences are different from the codes in the set of N Gold codes, yet are also of length N, including them in the set gives a total of $N+2$ codes. For {1,-1} valued codes, the crosscorrelation of sequences u and v is

$$\theta(l) = \sum_{j=0}^{N-1} u(j)\, v(j+l)\,, \quad 0 \leq l \leq N-1. \qquad (2.2-3)$$

The crosscorrelation bound for a set of codes is the largest crosscorrelation value obtained by any combination of two codes within the set. The minimum crosscorrelation bound is the smallest possible crosscorrelation bound for a given type of code of length N bits. Thus, the minimum crosscorrelation bound differs from one type of code to another. However, Gold has shown that if the two m-sequences meet the m-sequence minimum crosscorrelation bound,

$$\begin{aligned} |\theta(l)| &\leq 2^{(n+1)/2} + 1\,, \quad \text{for } n \text{ odd} \\ |\theta(l)| &\leq 2^{(n+2)/2} + 1\,, \quad \text{for } n \text{ even} \end{aligned} \qquad (2.2-4)$$

then all the Gold codes generated by those two m-sequences meet the same minimum crosscorrelation bound. In other words, all the Gold codes have a crosscorrelation value less than or equal to the bound, and using these codes minimizes the coding interference loss (to be discussed in Section 2.4). Thus, if m-sequences are chosen which meet the

Table 2.2-1. Example of m-sequence and Gold code generation from the shift registers of Figure 2.2-1. Only the first 10 bits of the 31 bit codes are shown.

Register (a)	Register (b)	code 1	code 2	code 3
1 0 1 0 1	0 1 1 1 1	1	1	0
1 1 0 1 0	1 0 1 1 1	0	1	1
1 1 1 0 1	0 1 0 1 1	1	1	0
0 1 1 1 0	0 0 1 0 1	0	1	1
1 0 1 1 1	0 0 0 1 0	1	0	1
1 1 0 1 1	1 0 0 0 1	1	1	0
0 1 1 0 1	0 1 0 0 0	1	0	1
0 0 1 1 0	0 0 1 0 0	0	0	0
0 0 0 1 1	1 0 0 1 0	1	0	1
1 0 0 0 1	0 1 0 0 1	1	1	0

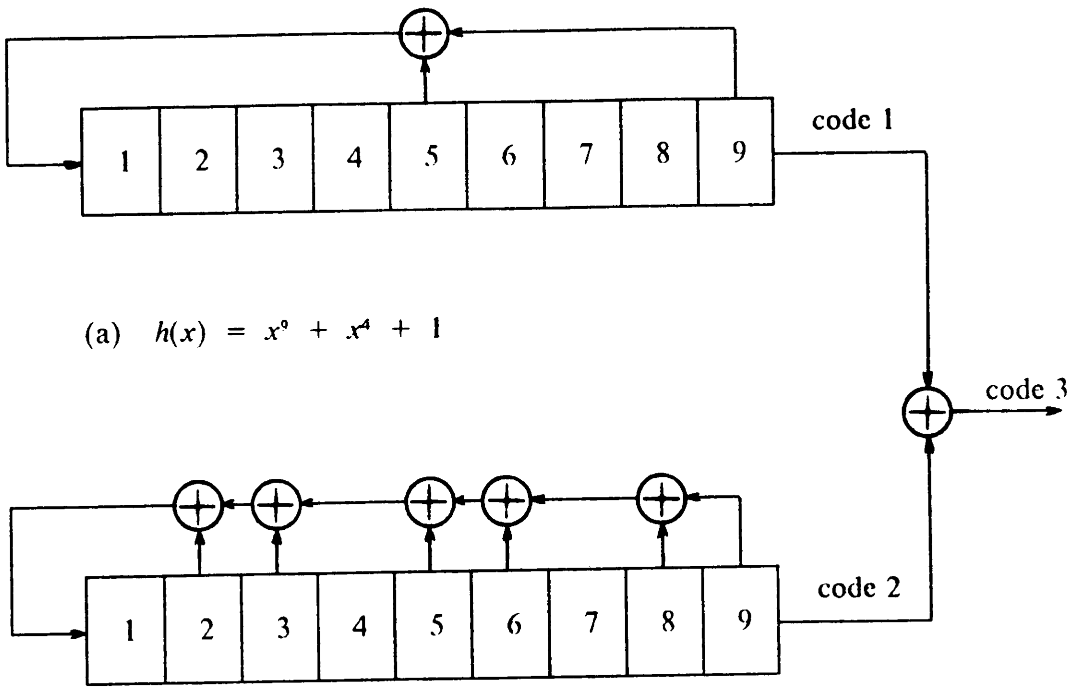
bound given in Equation 2.2-4, then all of the codes in the resulting set of $N+2$ codes meet the bound [27].

In [26], Gold gives the feedback tap connections for two $n = 9$, $N = 511$, m-sequences which meet the minimum crosscorrelation bound of 33. He gives the connections in an octal representation of the coefficients in the $h(x)$ polynomial expression. The numbers Gold gives are 1021 and 1333, in octal, and these translate to the polynomials

$$h(x) = x^9 + x^4 + 1 \qquad (2.2-5)$$

$$h(x) = x^9 + x^7 + x^6 + x^4 + x^3 + x + 1. \qquad (2.2-6)$$

Figure 2.2-2 shows the resulting shift registers which are used to generate the desired set of 50 Gold codes. For notation purposes, the two m-sequences are codes 49 and 50 in the 50 code set, and the 48 Gold codes are the first 48 Gold codes resulting from the first 48 phases (one-bit shifts) of code number 50.



(a) $h(x) = x^9 + x^4 + 1$

(b) $h(x) = x^9 + x^7 + x^6 + x^4 + x^3 + x + 1$

Figure 2.2-2. Shift registers of $n = 9$ used to generate a set of $N = 511$ bit Gold codes meeting the minimum crosscorrelation bound of 33.

2.3 AO|LSE and LSE|AO Phase Determination

In [22], Pursley and Roefs describe the determination of the auto-optimal with least sidelobe energy (AO/LSE) phase of a given sequence. The method involves the parameters defined below.

For {1,-1} valued sequences, the aperiodic autocorrelation function for u is

$$C_u(l) = \begin{cases} \sum_{j=0}^{N-1-l} u_j u_{j+l}, & 0 \le l \le N-1 \\ \sum_{j=0}^{N-1+l} u_{j-l} u_j, & 1-N \le l < 0 \\ 0, & |l| \ge N. \end{cases} \qquad (2.3-1)$$

The odd autocorrelation function of sequence u is

$$\hat{\theta}_u(l) = C_u(l) - C_u(l-N), \; 0 \le l \le N-1. \qquad (2.3-2)$$

The maximum absolute value of the odd autocorrelation function is

$$\hat{M}(u) \triangleq \max\{|\hat{\theta}_u(l)|: 1 \le l \le N-1\}. \qquad (2.3-3)$$

The number of times the above maximum occurs is defined as $\hat{L}(u)$. The sidelobe energy of sequence u is

$$S(u) = \sum_{l=1}^{N-1} C_u^2(l). \qquad (2.3-4)$$

All of these equations are given and discussed in [22].

The method essentially consists of finding the phase which has the minimum value of $\hat{M}(u)$. If more than one phase of the sequence has this value of $\hat{M}(u)$, then the phase is chosen in which $\hat{M}(u)$ occurs the least number of times; that is, the phase having the minimum value of $\hat{L}(u)$. This phase is an auto-optimal phase. Since there may sometimes be more than one auto-optimal phase, the phase with the minimum value of $S(u)$ is chosen. This AO/LSE phase is unique.

Thus, finding the AO/LSE phase of a sequence consists of finding the phase which has the smallest maximum odd autocorrelation; in other words, the aim is to minimize the maximum odd autocorrelation. The number of times the maximum occurs in a given phase of the sequence, $\hat{L}(u)$, and the sidelobe energy, $S(u)$, of a given phase of the sequence are both used to break ties between phases.

For example, code 50 in the set of 50 Gold codes is the m-sequence generated from Equation 2.2-6, corresponding to code 2 in Figure 2.2-2. It has a minimum odd autocorrelation of 39. Thus, $\hat{M}(u) = 39$. This occurs for 6 of the 511 phases of this code, and those six phases are listed in Table 2.3-1, along with the values of $\hat{L}(u)$ and $S(u)$ for each phase. Each phase is identified by the first 9 values of the sequence when in that phase, and each phase may be reproduced by the shift register of Figure 2.2-2 (b) by letting these 9 values be the initial conditions of the shift register. The auto-optimal phase is defined as the phase having the minimum value of $\hat{M}(u)$ and the least occurrences of that minimum value, which is the minimum value of $\hat{L}(u)$. Thus, only the third, fourth, and fifth phases listed in Table 2.3-1 are auto-optimal, for the other three phases have $\hat{L}(u) > 2$. The three-way tie is broken by finding the minimum value of $S(u)$ among the auto-optimal phases, and that value is $S(u) = 36231$; so the fourth phase listed in Table 2.3-1 is the unique AO/LSE phase for code 50.

Table 2.3-1. An example illustrating the selection of the AO/LSE phase of a code. This is for code 50 in the set of Gold codes of length $N = 511$ bits.

First 9 values of the phase	$\hat{M}(u)$ Maximum absolute value of odd autocorrelation	$\hat{L}(u)$ Number of occurences of $M(u)$	$S(u)$ Sidelobe energy
-1 -1 -1 -1 1 -1 1 1 1	39	10	38843
-1 -1 -1 1 -1 1 1 1 1	39	10	38259
1 -1 1 1 1 1 1 1 1	39	2	37595
-1 1 1 1 1 1 1 1 1	39	2	36231
1 1 1 -1 -1 1 -1 1 -1	39	2	37543
-1 -1 1 -1 1 -1 1 -1 1	39	8	37771

Table 2.3-2. AO/LSE phases of the 50 Gold codes, $N = 511$.

CODE #	FIRST 9 VALUES OF THE CODE	Maximum absolute value of odd autocorrelation $\hat{M}(u)$	Number of occurences of $\hat{M}(u)$ $\hat{L}(u)$	Sidelobe energy $S(u)$	SHIFT VALUES
1	-1 -1 -1 1 1 1 -1 -1 1	51	4	121479	178
2	-1 -1 1 1 1 1 1 -1 1	47	2	129051	247
3	-1 1 1 -1 -1 -1 1 1 1	47	6	125551	206
4	-1 -1 -1 -1 1 1 -1 -1 1	47	4	124571	34
5	1 -1 1 1 -1 -1 1 1 1	47	2	112843	49
6	1 1 1 -1 1 1 1 1 1	51	4	121067	17
7	1 1 -1 -1 -1 -1 -1 -1 1	47	4	121563	246
8	1 1 1 1 1 1 -1 1 1	49	6	128027	325
9	1 1 -1 1 -1 -1 -1 1 1	49	4	135711	321
10	-1 1 -1 -1 1 1 1 1 1	51	12	132619	152
11	1 -1 1 1 1 1 -1 -1 1	51	2	123779	341
12	1 -1 1 1 -1 -1 1 1 -1	47	6	132215	22
13	1 -1 -1 1 -1 -1 1 -1 1	45	10	125751	374
14	-1 1 1 1 1 1 1 -1 1	53	2	130855	175
15	-1 -1 -1 -1 1 -1 -1 -1 1	53	6	130015	33
16	-1 -1 -1 -1 1 -1 1 1 -1	47	4	113695	394
17	-1 1 -1 -1 1 1 -1 -1 -1	51	2	113779	276
18	1 -1 1 -1 1 1 1 1 1	51	2	123999	29
19	-1 1 -1 1 1 1 1 -1 -1	49	2	118419	297
20	1 1 -1 1 1 1 -1 -1 -1	51	2	120719	83
21	-1 1 1 1 1 1 1 -1 -1	51	2	120855	256
22	-1 1 1 1 1 1 1 1 1	53	2	115595	351
23	-1 1 1 -1 1 1 1 1 1	49	6	116499	327
24	1 -1 1 -1 -1 1 1 1 1	49	4	125239	146
25	-1 1 -1 1 1 -1 -1 1 1	49	2	120563	403
26	-1 -1 1 1 1 -1 -1 1 -1	51	4	132131	384
27	-1 1 1 1 1 -1 1 1 1	51	2	126063	107
28	1 1 1 -1 1 -1 1 1 -1	49	4	123451	278
29	-1 -1 -1 -1 1 -1 -1 -1 -1	47	4	117339	313
30	1 -1 -1 -1 1 1 1 -1 1	51	4	124535	165
31	1 1 -1 1 -1 -1 1 -1 1	51	4	130063	488
32	-1 -1 -1 1 1 -1 1 1 -1	47	4	115315	213
33	1 1 -1 -1 -1 1 1 -1 -1	51	2	125491	421
34	1 1 -1 -1 1 1 1 -1 1	53	2	115455	342
35	-1 1 1 1 1 1 1 -1 -1	51	4	134207	84
36	1 1 1 1 -1 1 1 1 -1	47	4	109607	305
37	-1 -1 -1 -1 1 1 1 -1 1	55	6	124355	329
38	1 1 -1 -1 -1 -1 1 -1 -1	51	2	121487	167
39	1 -1 1 1 -1 1 -1 -1 1	49	4	121647	188
40	-1 1 1 -1 -1 1 1 1 1	49	6	119203	49
41	-1 1 -1 -1 -1 -1 1 -1 1	55	2	126207	20
42	-1 1 1 1 -1 -1 1 -1 -1	49	2	114359	329
43	1 -1 -1 1 1 1 1 1 -1	51	6	122395	434
44	1 1 -1 1 1 -1 1 -1 1	47	4	116027	71
45	-1 -1 1 1 -1 1 1 1 -1	53	6	137567	155
46	1 -1 1 -1 -1 -1 -1 1 1	47	2	124771	500
47	1 1 -1 1 1 -1 1 1 -1	47	4	120375	416
48	-1 -1 -1 1 1 -1 1 -1 1	51	2	128975	152
49	1 1 -1 -1 -1 -1 1 1 -1	41	2	43071	0
50	-1 1 1 1 1 1 1 1 1	39	2	36231	0

Table 2.3-2 lists the results for the set of 50 Gold codes under consideration. By using a value of 1 as the initial condition in each element of both registers of Figure 2.2-2, two m-sequences were generated; the AO/LSE phase of each m-sequence was found, and these two optimal phase codes are codes 49 and 50 in the set of codes; these two AO/LSE codes were then used to generate 48 Gold codes using the shift registers of Figure 2.2-2 as discussed in the previous section. The first 9 values of each code are given in Table 2.3-2. These are the first 9 values of the code when the code is in its AO/LSE phase. Also, the column entitled "SHIFT VALUES" gives the amount of shift required to convert each code from its initial phase, as it is generated from Figure 2.2-2, to its AO/LSE phase. For instance, for code 1 the shift value is 178. This means that the value in position 179 of the original phase is the first value of the AO/LSE phase, the value in position 180 is the second value of the AO/LSE phase, etc. If j is the shift value, $S1$ is the sequence in its original phase, and $S0$ is the sequence in its AO/LSE phase, then for $0 \leq i \leq N$ and $0 \leq j \leq N - 1$,

$$\begin{aligned} S0(i) &= S1(i + j) , \quad i + j \leq N \\ S0(i) &= S1(i + j - N) , \quad i + j > N \end{aligned} \qquad (2.3 - 5)$$

where $S(k)$ represents the value in position k of sequence S . Thus, the first 9 values of the AO/LSE phase identify the phase, and the shift values provide a way of placing each code in its AO/LSE phase without having to recalculate the AO/LSE phase. For codes 511 bits long, the AO/LSE phase determination requires approximately 100 times as many calculations as does the Gold code generation and the PN coding loss analysis (Section 2.4) combined. On the VPI&SU VM1 computer system, the program which determined the AO/LSE phases required 104 minutes of mainframe computer time. Obviously, repetition of this calculation should be avoided, if at all possible.

There are two other items to note about the column of shift values in Table 2.3-2. The first is that codes 49 and 50 have a shift value of 0. This is because the computer program which generated the set of codes was originally tested by determining the AO/LSE phase of the two m-sequences, which are codes 49 and 50. Since the AO/LSE phases were then known for these two codes, the first 9 values of each code's AO/LSE phase were used as the initial conditions for the two shift registers of Figure 2.2-2. The result was that codes 49 and 50 were generated in their AO/LSE phases. The shift value of 0 for each code thus correctly serves as a check of the computer program which generated Table 2.3-2.

The second item to note is that the program used to generate Table 2.3-2 was set up to list multiple shift values for each code. This situation would have occurred if the AO/LSE phase was not unique. If there were three AO/LSE phases of code 3, for example, then 3 different shift values would have been listed in the line for code 3. Since each code has only one shift value listed, each code in the set has an unique AO/LSE phase.

As a final note to this section, a unique phase can also be found from the LSE/AO phase of a given sequence. This simply means changing the criteria for the code; now, $S(u)$ is minimized first, then $\hat{M}(u)$, and finally $\hat{L}(u)$. Sometimes this will produce a better set of codes for certain applications. Table 2.3-3 lists the LSE/AO phases of the same set of Gold codes. The codes were generated using the AO/LSE phases of codes 49 and 50, which is why codes 49 and 50 have nonzero shift values.

Table 2.3-3. LSE/AO phases of the 50 Gold codes, $N = 511$.

CODE #	FIRST 9 VALUES OF THE CODE	Maximum absolute value of odd autocorrelation $\hat{M}(u)$	Number of occurences of $\hat{M}(u)$ $\hat{L}(u)$	Sidelobe energy $S(u)$	SHIFT VALUES
1	-1 -1 1 -1 1 -1 -1 1 -1	59	2	118987	184
2	1 -1 1 -1 1 1 1 1 1	59	4	121871	358
3	1 -1 -1 -1 -1 1 1 1 -1	55	2	112775	426
4	1 1 1 1 -1 -1 1 -1 -1	63	2	115515	446
5	1 1 1 1 -1 -1 -1 -1 1	63	2	110095	278
6	-1 -1 -1 1 1 1 1 1 -1	67	2	115691	488
7	-1 1 -1 1 1 -1 1 -1 -1	51	4	119043	204
8	-1 -1 -1 -1 1 -1 1 -1 1	61	2	125915	310
9	-1 -1 -1 -1 1 1 -1 -1 -1	61	2	123347	48
10	-1 -1 1 1 -1 1 -1 -1 1	63	2	117051	445
11	-1 -1 1 -1 -1 -1 -1 -1 1	57	2	120983	93
12	1 1 -1 1 1 1 -1 -1 -1	77	2	128799	64
13	-1 -1 1 1 -1 -1 1 -1 -1	57	2	125543	368
14	1 1 1 -1 1 -1 -1 -1 -1	73	4	129835	62
15	-1 -1 1 1 -1 1 -1 -1 -1	63	2	117051	245
16	1 1 -1 -1 1 1 1 1 -1	53	2	111819	400
17	1 -1 1 -1 -1 -1 1 1 1	57	2	112587	249
18	-1 1 1 -1 -1 -1 1 -1 -1	55	2	115115	159
19	1 1 1 1 -1 -1 1 -1 1	59	2	117535	456
20	1 1 1 1 -1 -1 1 -1 1	63	2	114031	286
21	1 -1 1 1 1 1 -1 1 -1	51	4	117975	265
22	1 -1 -1 -1 1 -1 -1 1 1	61	2	113135	334
23	1 1 -1 -1 1 -1 1 1 1	63	2	113159	347
24	1 -1 1 1 1 -1 1 1 -1	57	4	122111	122
25	1 1 -1 1 -1 1 1 -1 -1	75	2	117095	81
26	-1 -1 1 1 -1 -1 -1 -1 1	65	2	129271	491
27	1 -1 1 1 1 1 -1 1 1	57	2	122163	111
28	-1 -1 1 -1 -1 -1 -1 -1 -1	61	2	116959	243
29	-1 -1 -1 -1 -1 1 1 -1 -1	59	4	116463	275
30	1 1 -1 1 -1 1 1 1 1	59	2	121315	174
31	-1 -1 1 -1 -1 1 1 -1 1	57	2	119675	170
32	-1 -1 1 1 -1 -1 1 -1 1	57	2	114771	189
33	1 -1 1 1 1 1 -1 1 1	67	2	119127	130
34	-1 -1 1 1 -1 -1 -1 1 1	67	2	114551	358
35	1 -1 1 -1 -1 -1 1 1 -1	69	2	122595	32
36	-1 1 1 1 -1 -1 -1 1 1	51	2	107751	309
37	1 1 1 1 -1 -1 -1 -1 1	65	2	122163	71
38	-1 1 1 1 1 -1 1 1 1	53	2	116027	491
39	-1 -1 -1 1 -1 1 1 -1 1	49	6	120687	185
40	-1 1 -1 1 -1 1 1 -1 -1	55	2	112863	314
41	1 -1 1 1 1 1 -1 1 1	67	2	122803	26
42	-1 1 -1 -1 1 1 1 1 1	61	2	111339	379
43	1 1 -1 1 -1 -1 -1 -1 1	65	2	112195	343
44	-1 1 -1 1 -1 1 1 1 -1	59	2	113303	78
45	1 1 1 -1 -1 1 -1 -1 -1	77	2	124835	15
46	1 -1 -1 -1 -1 1 -1 1 1	65	2	120603	350
47	-1 -1 1 -1 -1 -1 -1 1 -1	57	2	116475	405
48	-1 -1 -1 1 1 1 -1 -1 1	59	2	122571	297
49	-1 1 -1 -1 -1 1 1 -1 1	43	2	38859	110
50	-1 -1 -1 1 1 -1 -1 1 1	47	2	34851	181

2.4 SNR Calculation

Two equations are required to calculate the signal-to-noise ratio, SNR, of a given signal in a set of signals which are using a set of codes and spread spectrum techniques. The interfering codes are assumed to be noiselike. The first equation, derived by Pursley and Sarwate [21], gives the so-called average interference parameter for {1,-1} valued codes u and v of period N:

$$r_{u,v} \;=\; r(u,v) \;=\; 2N^2 + 4\sum_{l=1}^{N-1} C_u(l)\,C_v(l) + \sum_{l=1-N}^{N-1} C_u(l)\,C_v(l+1) \qquad (2.4-1)$$

The second equation, derived by Pursley [20], determines the rms signal voltage-to-rms noise ratio (VNR) for a given signal, j , from the bit energy to noise density ratio (E_b/N_0) and from the sum of the average interference parameters for signal j paired with each of the other signals in the set:

$$VNR_j \;=\; \left[\frac{1.0}{2E_b/N_0} + \left(\frac{1.0}{6N^3}\right)\sum_{\substack{k=1\\k\neq j}}^{K} r_{j,k}\right]^{-1/2} \qquad (2.4-2)$$

where K is the number of codes in the set (which is also the number of carriers in the satellite transponder and the number of simultaneously active users in the system), and $r_{j,k}$ is the average interference parameter for codes j and k, as given in Equation 2.4-1. The corresponding signal-to-noise power ratio, SNR, is obtained from Equation 2.4-2 as follows:

$$SNR_j \;=\; \frac{1}{2}\,VNR_j^2 \;=\; 0.5\left[\frac{1.0}{2E_b/N_0} + \left(\frac{1.0}{6N^3}\right)\sum_{\substack{k=1\\k\neq j}}^{K} r_{j,k}\right]^{-1} \qquad (2.4-3)$$

Thus, the signal-to-noise power ratio in dB is

$$SNR_j = 10.0 log_{10}\left[0.5 \left[\frac{1.0}{2E_b/N_0} + \left(\frac{1.0}{6N^3} \right) \sum_{\substack{k=1 \\ k \neq j}}^{K} r_{j,k} \right]^{-1} \right] \qquad (2.4-4)$$

Equation 2.4-3 yields the correct SNR for substitution into the bit error probability (P_b) equation for PSK and QPSK signals [28, 29], which is equivalent to the bit error rate (BER):

$$BER = P_b = Q\left(\sqrt{2\,SNR_j}\right) \qquad (2.4-5)$$

where

$$Q(x) = \frac{1.0}{\sqrt{2\pi}} \int_x^{\infty} e^{-u^2/2}\, du.$$

For $K = 1$ channel there is no coding interference loss and Equation 2.4-5 correctly reduces to

$$BER = P_b = Q\left(\sqrt{2(E_b/N_0)}\right)$$

Equation 2.4-4 shows that the E_b/N_0, which is determined by link analysis, is independent of the coding interference. Thus, once the code analysis has been performed, tabulating the average interference parameters for each code allows future SNR calculations to be separated from further PN code analysis. If $ISUM$ is the sum of the average interference parameters for a given code,

$$ISUM_j = \sum_{\substack{k=1 \\ k \neq j}}^{K} r_{j,k} \qquad (2.4-6)$$

then Equation 2.4-4 becomes

$$SNR_j = 10.0log_{10}\left[0.5\left[\frac{1.0}{2E_b/N_0} + \left(\frac{1.0}{6N^3}\right)ISUM_j\right]^{-1}\right] \qquad (2.4-7)$$

The procedure for finding the *SNR* is now stated. For a given set of codes composed of {1,-1} valued sequences of period *N*, Equation 2.3-1 is used to determine the aperiodic autocorrelation function for each code. From these values, Equation 2.4-1 is used to determine the average interference parameter for each pair of codes. Then, Equation 2.4-6 yields the sum of the average interference parameters for each code. Finally, Equation 2.4-7 is used to find the *SNR* for the signal corresponding to each code. Pursley and Roefs use this procedure in [22] to generate *SNR* values for several sample code sets. Table 2.4-1 lists the *ISUM* values for the set of 50 Gold codes used here. The computer program which generated Table 2.4-1 has also been used to verify Pursley and Roefs' examples [22, pp. 1603-1604].

Future link analysis calculations using this set of 50 Gold codes require no further code analysis. The *ISUM* values given in Table 2.4-1 are all that are needed. From the link analysis, a value for E_b/N_0 may be found, and then Equation 2.4-7 will yield the *SNR*.

Table 2.4-1. Code analysis data for the set of 50 Gold codes, $N = 511$, for both the AO/LSE and LSE/AO phases.

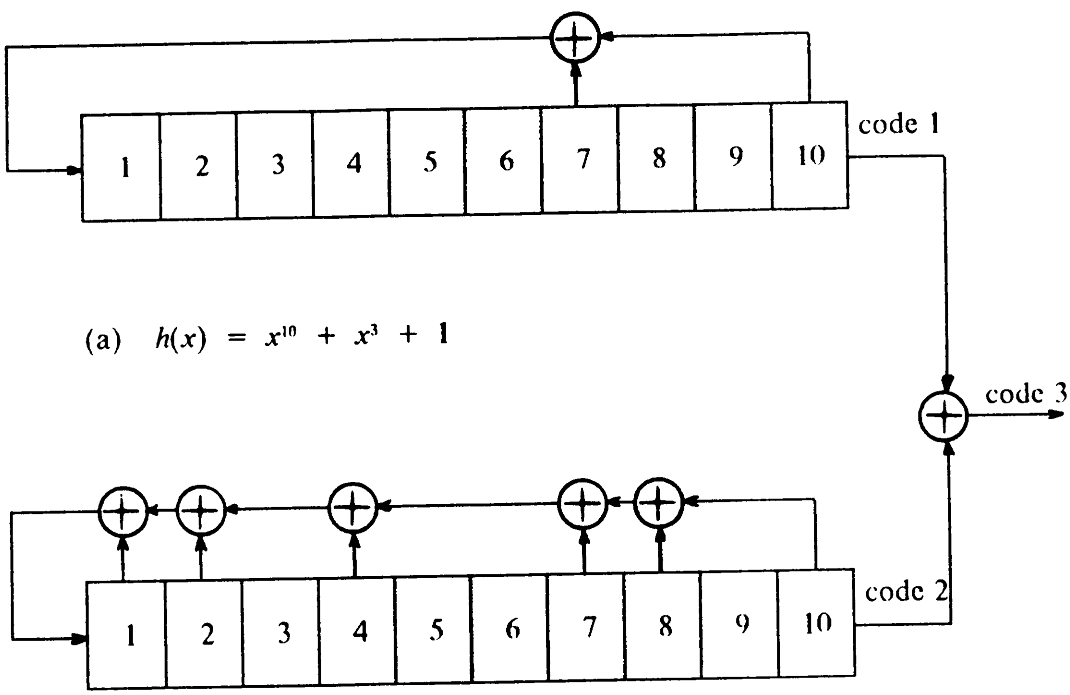
CODE #	Sum of the average interference parameters for each code ISUM (AO/LSE)	ISUM (LSE/AO)
1	26495754	26481302
2	25450098	25401134
3	25489938	25661230
4	26229618	26442078
5	25529258	25354086
6	25473922	25533918
7	25500666	25478574
8	24573442	24614062
9	24488050	24579230
10	26264938	26490950
11	25639610	25523606
12	26495874	26418198
13	25744338	25856102
14	24786058	24803102
15	25159194	25299054
16	26406810	26440974
17	26147506	26055302
18	25407778	25524070
19	26286522	26432062
20	26524794	26639278
21	25525850	25756366
22	25513858	25514102
23	25531082	25460350
24	25066818	24787038
25	26289890	26280886
26	26303834	26142558
27	25588218	25449094
28	25521290	25415606
29	25637874	25605334
30	26492970	26499830
31	25846018	25612278
32	25670082	25617926
33	24828410	24805518
34	25693906	25585518
35	24851114	24820094
36	25661178	25679710
37	26366858	26302606
38	25772674	25522750
39	25673218	25499766
40	25580386	25691382
41	26275618	26333542
42	24724994	24743942
43	25643298	25471726
44	24763242	24827262
45	24841514	24843246
46	25651826	25629758
47	25534954	25748214
48	26308810	26458958
49	25517154	25637598
50	25779378	25546710

2.5 Final Code Selection

Examining the effect of code length on the coding interference loss requires a set of Gold codes having a different length than the sets previously discussed. For $n = 10$, Gold gives 2011 and 3515 as the octal representations of the feedback connections of two shift registers which yield m-sequences meeting the minimum crosscorrelation bound of 65 [26]. The shift registers and the corresponding polynomial expressions are shown in Figure 2.5-1. These shift registers produce a set of Gold codes having a length of 1023 bits. Table 2.5-1 lists the *ISUM* values resulting from the code analysis for sets of 50 and 25 codes.

As was mentioned earlier, choosing the optimum phase of a code requires much more computer time than does the combined process of generating the code and calculating the *ISUM* values. Generating fifty 511 bit Gold codes and calculating the *ISUM* values takes 51 seconds of computer time on the VPI&SU VM1 mainframe; but finding the AO/LSE phases of the 50 codes takes 104 minutes. Similarly, without phase optimization, the calculations require 77 seconds of computer time for fifty 1023 bit Gold codes, and it is estimated that it will require approximately 316 minutes to include the AO/LSE phase determination. Because computer resources are limited, this has not been done. Therefore, the codes corresponding to Table 2.5-1 were generated by using a value of 1 as the initial condition of each element of the registers in Figure 2.5-1.

Choosing an E_b/N_0 value and carrying out the *SNR* calculations provides the basis for comparing the different sets of codes. Table 2.5-2 lists the *SNR* values resulting from



(a) $h(x) = x^{10} + x^3 + 1$

(b) $h(x) = x^{10} + x^9 + x^8 + x^6 + x^3 + x^2 + 1$

Figure 2.5-1. Shift registers of $n = 10$ used to generate a set of $N = 1023$ bit Gold codes meeting the minimum crosscorrelation bound of 65.

Table 2.5-1. Code analysis data for sets of 50 and 25 Gold codes, $N = 1023$; code phase optimization has not been done.

CODE #	Sum of the average interference parameters for each code *ISUM* (50 codes)	*ISUM* (25 codes)
1	102656558	50047780
2	107102462	51883056
3	103310542	50802300
4	103282342	50832712
5	103466358	50810860
6	103163206	50184904
7	102591966	50366932
8	101842630	49594704
9	102286838	49582860
10	102525582	49926896
11	103783814	50568720
12	102905078	50323036
13	98452526	48535072
14	104481950	51696720
15	102098270	49532080
16	102519014	49980560
17	102998358	50514368
18	102265766	50067704
19	105466350	51320832
20	102354126	50051276
21	103293670	50639436
22	103259086	50527396
23	99296886	49034264
24	99537726	48400312
25	102165462	50033284
26	102445934	
27	103075582	
28	99524582	
29	102746542	
30	101763398	
31	106199326	
32	104805294	
33	102281318	
34	102635158	
35	103012502	
36	106641374	
37	103255358	
38	102485038	
39	102651598	
40	102899878	
41	101811822	
42	103412414	
43	102601350	
44	102584062	
45	103912262	
46	104259838	
47	106636318	
48	102817518	
49	103194102	
50	103187518	

Table 2.5-2 Signal-to-noise ratio (SNR) values (in dB) for E_b/N_0 = 13 dB for four sets of codes.

CODE #	SNR N = 511 (AO/LSE)	SNR N = 511 (LSE/AO)	SNR N = 1023 (50 codes)	SNR N = 1023 (25 codes)
1	9.35	9.35	10.86	11.83
2	9.45	9.45	10.79	11.79
3	9.44	9.43	10.85	11.82
4	9.37	9.35	10.85	11.82
5	9.44	9.46	10.85	11.82
6	9.44	9.44	10.86	11.83
7	9.44	9.44	10.86	11.83
8	9.53	9.53	10.88	11.84
9	9.54	9.53	10.87	11.84
10	9.37	9.35	10.87	11.83
11	9.43	9.44	10.85	11.82
12	9.35	9.36	10.86	11.83
13	9.42	9.41	10.93	11.86
14	9.51	9.51	10.83	11.80
15	9.47	9.46	10.87	11.84
16	9.36	9.35	10.87	11.83
17	9.38	9.39	10.86	11.82
18	9.45	9.44	10.87	11.83
19	9.37	9.35	10.82	11.81
20	9.35	9.33	10.87	11.83
21	9.44	9.42	10.85	11.82
22	9.44	9.44	10.85	11.82
23	9.44	9.45	10.92	11.85
24	9.48	9.51	10.92	11.87
25	9.37	9.37	10.87	11.83
26	9.37	9.38	10.87	
27	9.43	9.45	10.86	
28	9.44	9.45	10.92	
29	9.43	9.43	10.86	
30	9.35	9.35	10.88	
31	9.41	9.43	10.81	
32	9.43	9.43	10.83	
33	9.51	9.51	10.87	
34	9.42	9.43	10.86	
35	9.50	9.51	10.86	
36	9.43	9.43	10.80	
37	9.36	9.37	10.85	
38	9.42	9.44	10.87	
39	9.43	9.44	10.86	
40	9.43	9.42	10.86	
41	9.37	9.36	10.88	
42	9.52	9.52	10.85	
43	9.43	9.45	10.86	
44	9.51	9.51	10.87	
45	9.51	9.51	10.84	
46	9.43	9.43	10.84	
47	9.44	9.42	10.80	
48	9.37	9.35	10.86	
49	9.44	9.43	10.85	
50	9.42	9.44	10.86	
LOW SNR (dB)	9.3456	9.3349	10.7911	11.7944
HIGH SNR (dB)	9.5399	9.5311	10.9338	11.8662
AVERAGE SNR (dB)	9.4282	9.4286	10.8589	11.8288

an E_b/N_0 of 20 (13 dB) for each of the four sets of codes. At the bottom, Table 2.5-2 lists the low, high, and average *SNR* for each set. Two conclusions are obvious:

- as stated in Chapter 1, longer codes produce lower coding interference losses, resulting in higher *SNR* values

- smaller code sets yield higher *SNR* values, due to the decreased coding interference loss; but smaller code sets reduce the number of simultaneous users, yielding a lower system throughput.

The performance difference between the AO/LSE and LSE/AO codes for $N = 511$ is insignificant; one must go to the fourth decimal place to see a difference in the average *SNR* . Due to its slightly better average *SNR*, the LSE/AO set is used in Figure 2.5-2, as is the 50 code set for $N = 1023$. However, the AO/LSE set could have been selected based on its better low and high *SNR* values. Its low *SNR* value would yield a slightly better result in a worse channel analysis.

Figure 2.5-2 illustrates the E_b/N_0 degradation resulting from coding crosscorrelation interference for 1023 and 511 bit Gold codes, using the two sets selected above. The straight, solid line is the E_b/N_0 line ($SNR = E_b/N_0$) , representing the ideal case of zero crosscorrelation interference. The three curves clustered together are the high, average, and low *SNR* curves for the set of fifty 1023 bit codes. Obviously, the low *SNR* curve is the worse case for this set of codes. As expected, the curve for the set of fifty 511 bit codes shows the poorest performance.

The best curve in Figure 2.5-2 is the effective low *SNR* curve with 3 dB forward error correction (FEC) coding, for the 1023 bit codes. As Figure 2.5-2 shows, 3 dB FEC

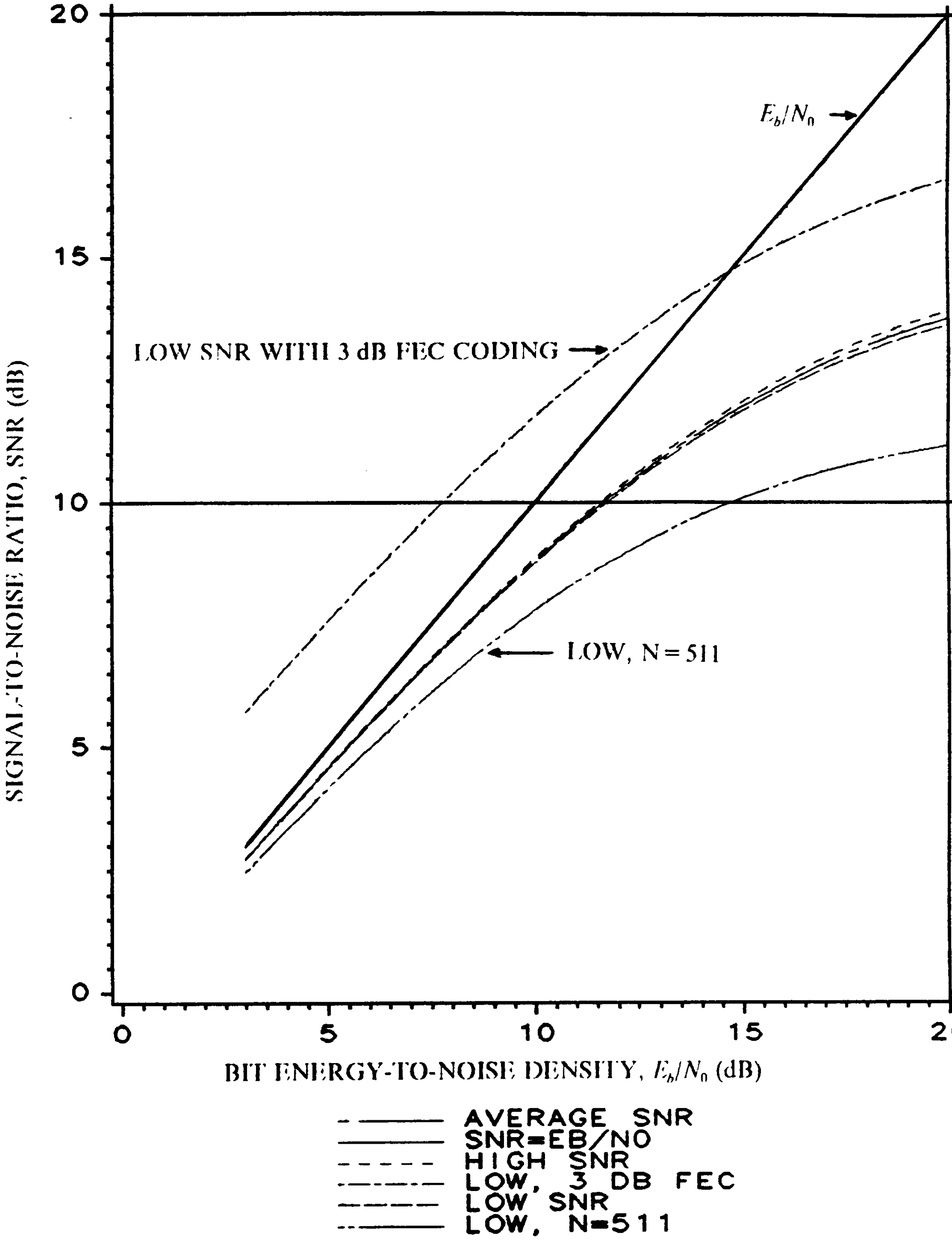


Figure 2.5-2. Coding interference effects on E_b/N_0 for a 50 code set. All curves are for N = 1023 except for the bottom curve, which is for N = 511.

coding more than offsets the crosscorrelation interference up to an E_b/N_0 of approximately 14.8 dB, at which point the crosscorrelation interference dominates.

The curves of Figure 2.5-2 lead to two observations. First, coding interference causes a considerable loss, at least for these two sets of codes. At an E_b/N_0 of 10 dB, coding causes a 1.2 dB loss for the 1023 bit codes and a 2.2 dB loss for the 511 bit codes. The use of longer codes would significantly decrease this loss. The set of fifty 1023 bit Gold codes will be used in the DS-CDMA analysis in Chapter 4. Second, the coding loss increases as the E_b/N_0 increases. This indicates that there is a point where over-design of a system becomes fruitless. At the higher E_b/N_0 values, the large change in E_b/N_0 required to produce a small change in *SNR* may not be worth the increased equipment cost.

III. SUPPRESSION EFFECTS

3.1 Overview

Several authors have modeled and analyzed the suppression of one signal by another signal as both pass through a satellite transponder. Generally, the transponder is modeled by a hard limiter, simulating either saturation of the travelling wave tube amplifier (TWTA) or an actual limiter built into the system. With minor corrections, the results often extend to soft limiting [23]. It is assumed that the hard limiting results apply here.

Signal suppression results from signals competing for the TWTA's limited output power. Large signals tend to rob power from small signals, thus capturing a larger percentage of output power than the percentage of input power which they supplied. However, the suppression effect is highly dependent on the signal sizes and especially the number of large signals. As an example, one large signal sharing the transponder with several small signals produces a 5 to 6 dB suppression effect for high signal-to-noise and signal-to-signal ratios. In contrast, if there are two large signals of equal amplitude sharing the transponder with several small signals, then the large signals destructively interfere with each other and allow the weaker signals to pass through; in fact, this effect increases as the signal-to-noise ratio of the large signals increases, so that the stronger the large signals are at the input the stronger the small signals become at the output—the small signals rob power from the large signals. Also, when all of the signals occupying the transponder are equal in amplitude, the suppression is equal for all signals, which means that there is essentially no suppression and all signals have the same percentage of output power as they supplied to the input [23, 24].

Shaft has derived the following equation giving the normalized magnitudes (MAG) of signals and their crossproducts at the output of a hard limiter [23].

$$MAG_{m_1 m_2 m_3 \ldots m_k} = \int_0^{\infty} \exp\left[\frac{-\alpha^2 x^2}{2}\right]^2 J_{m_1}(A_1 x) J_{m_2}(A_2 x) \ldots J_{m_k}(A_k x) \frac{dx}{x} \qquad (3.1-1)$$

where $J_{m_i}(A_i x)$ = m_ith order Bessel function of the first kind

A_i = amplitude (voltage) of the ith signal

α^2 = noise power

m_i = an integer constant; 1 for power in signal m_i, 2 for power at the second harmonic of signal m_i, etc.; $|m_1| + |m_2| + \cdots + |m_k| = \text{odd}$

k = total number of signals.

Equation 3.1-1 gives the magnitude of the output power for each signal. For example, $MAG_{00100\ldots0}$ gives the power at the fundamental frequency of signal three, and signal four is given by $MAG_{00010\ldots0}$. Shaft and Ramanan give a detailed discussion of Equation 3.1-1 and its results for several signal combinations [23, 24].

For large k, Equation 3.1-1 is extremely complicated and unwieldy, and no evaluation is available for direct application to a 50 code system, as is needed here. Figure 3.1-1 is for the 5 signal analysis, 1 large signal and 4 small signals, performed by Ramanan [24]. Fortunately, Figure 3.1-1 and 3 and 4 signal analyses performed by Shaft [23] reveal that, for one large signal and the rest small signals, suppression decreases as the number of signals increases. For instance, the $S_1/N = 10$ dB curve (S_1/N is the strong signal-to-noise ratio) has the following values corresponding to a strong signal-to-weak signal ratio of 10 dB ($S_1/S_5 = 10$ on Figure 3.1-1):

4.3 dB suppression for 1 large signal and 2 small signals
3.6 dB suppression for 1 large signal and 3 small signals
3.2 dB suppression for 1 large signal and 4 small signals
(this last value comes from Figure 3.1-1).

Therefore, the curves of Figure 3.1-1 bound the true values for the case of 1 large signal and 50 small signals, the situation in Chapter 4. This is reasonable, since one would intuitively expect an increasing number of small signals to dilute the effect of the large signal. Furthermore, a decreasing number of small signals approaches the case of 1 large signal and 1 small signal, which has a theoretical suppression limit of 6 dB [30]. That case is opposite of the case at hand, so the suppression is expected to decrease rather than approach the theoretical limit.

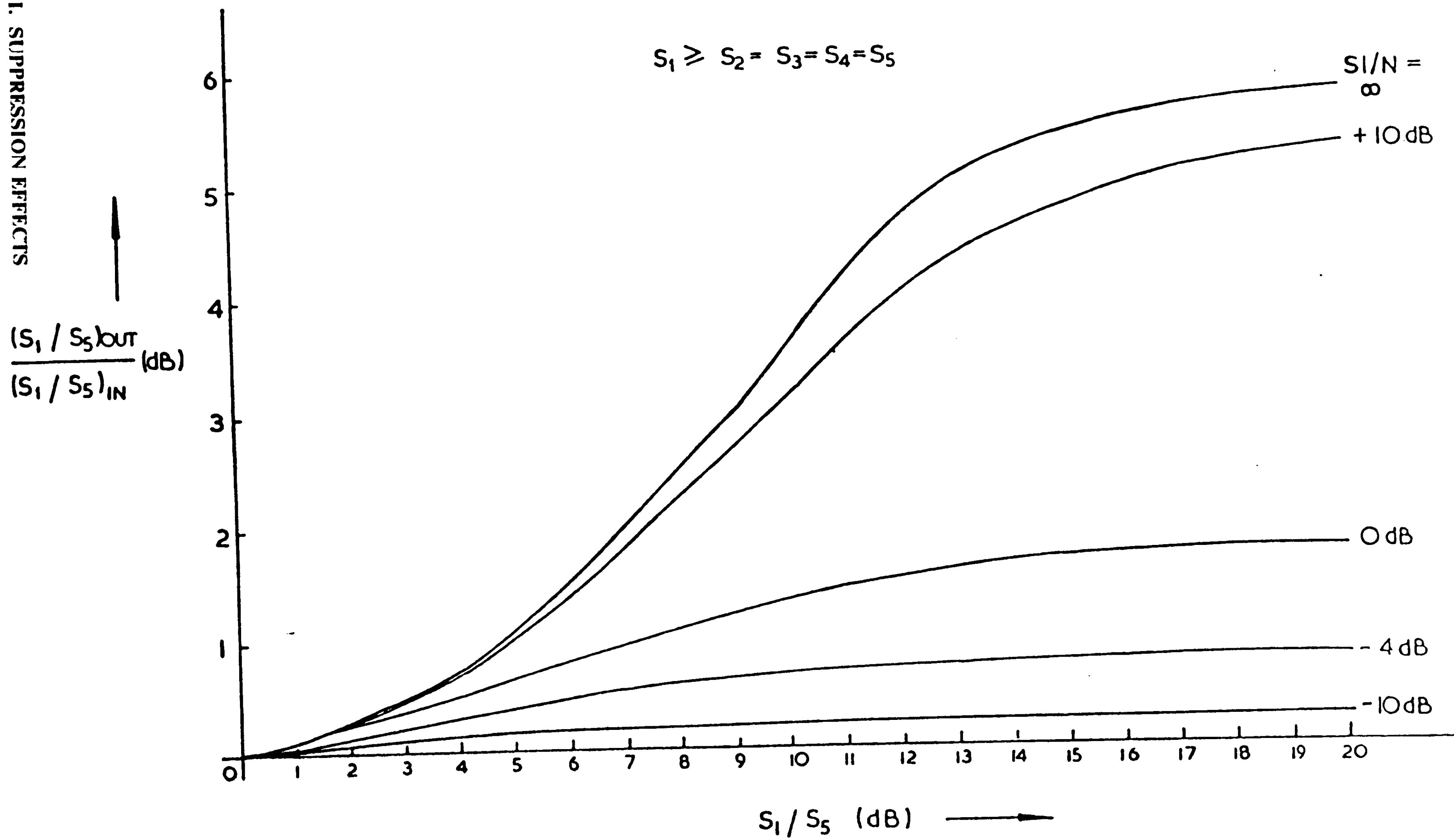


Figure 3.1-1. Suppression, the ratio of $(S_1/S_5)_{OUT}$ to $(S_1/S_5)_{IN}$, as a function of S_1/S_5 and S_1/N at the input; one large signal and 4 small signals. From Ramanan [24, Figure 5.25 (a)]

3.2 Incorporating Suppression in the Link Analysis

The previous section yields two conclusions. First, when all signals in a system have the same amplitude, suppression effects are negligible and the output power per signal is simply the total output power (including any backoff) divided by the number of signals using the transponder. Second, Figure 3.1-1 gives the data needed to include suppression effects for systems having 1 large signal and 4 or more small signals, since this case bounds the situation for an increasing number of small signals. For the system of Chapter 4, having 50 small signals, the curves of Figure 3.1-1 will yield conservative values for suppression. Thus, it is assured that suppression will be no greater than the values shown in Figure 3.1-1.

Including the suppression effects in the link analysis requires some equation manipulation. If S is the suppression value in dB from Figure 3.1-1, then

$$S = \frac{(S_1/S_5)_{OUT}}{(S_1/S_5)_{IN}} = \frac{(S_{1,o}/S_{5,o})}{(S_{1,i}/S_{5,i})} \qquad (3.2-1)$$

where $o = OUT$ and $i = IN$. Converting to ratios and solving for $S_{1,o}$ gives

$$S_{1,o} = \frac{S_{1,i}S_{5,o}S}{S_{5,i}}. \qquad (3.2-2)$$

Given that, after any output backoff, $EIRP_{1,o}$ is the satellite output EIRP (ratio) corresponding to signal 1, $EIRP_{5,o}$ is the satellite output EIRP (ratio) corresponding to signal 5, and G_s is the satellite antenna gain (ratio), then Equation 3.2-2 becomes

$$\frac{EIRP_{1,o}}{G_s} = \frac{S_{1,i}EIRP_{5,o}S}{S_{5,i}G_s}$$

which reduces to

$$EIRP_{1,o} = \frac{S_{1,i}EIRP_{5,o}S}{S_{5,i}} \qquad (3.2-3)$$

The EIRP is the effective isotropically radiated power and is equal to the antenna gain multiplied by the transmitted power. If *EIRP* is the total satellite output EIRP (ratio) after backoff and *K* is the number of small signals, then

$$EIRP = EIRP_{1,o} + K(EIRP_{5,o}) \qquad (3.2-4)$$

Solving Equations 3.2-3 and 3.2-4 for $EIRP_{1,o}$ and $EIRP_{5,o}$ produces the following two equations:

$$EIRP_{5,o} = \frac{EIRP}{\left[\frac{S_{1,i}S}{S_{5,i}} + K\right]} \qquad (3.2-5)$$

$$EIRP_{1,o} = EIRP - K(EIRP_{5,o}) \qquad (3.2-6)$$

The right hand sides of Equations 3.2-5 and 3.2-6 contain only terms which are either known or can be calculated. The *EIRP* and *K* values are known system parameters, and $S_{1,i}$ and $S_{5,i}$ can be calculated during the uplink analysis. Then, S_1/S_5 is known, and S_1/N can also be determined in the uplink analysis. Next, *S* can be found from Figure 3.3-1; and using ratios, Equations 3.2-5 and 3.2-6 give the satellite output EIRP values per signal, so the downlink can be analyzed.

IV. DS-CDMA PERFORMANCE ANALYSIS FOR VSAT NETWORKS

4.1 Introduction

This chapter examines the performance of a DS-CDMA VSAT Ku-band satellite system for two network architectures. The architectures are described as follows:

1. A full mesh configuration---

   - 50 identical VSAT terminals
   - one channel per terminal
   - any terminal may communicate with any other terminal
   - 50 simultaneous spread spectrum (SS) signals occupy the satellite transponder at peak capacity.

2. A star configuration---

   - 50 identical VSAT remote terminals

- one hub terminal, 5.5m diameter antenna
- one SS signal transmitted by each remote terminal, and 50 channels carried by one time division multiplexing (TDM) signal transmitted by the hub terminal
- the hub terminal may communicate simultaneously with all remote terminals, but each remote terminal may only communicate with the hub terminal---remote terminals cannot communicate with each other via a single hop
- one TDM and 50 spread spectrum signals simultaneously occupy the satellite transponder at peak capacity.

The performance analysis for both networks includes the receiver correlation loss resulting from crosscorrelation interference within the set of codes. The star network analysis also includes the suppression effects resulting from the large TDM signal and the small SS signals occupying the same transponder. The link analysis section includes these effects.

4.2 Link Analysis

The equations for the satellite link analysis are as follows. For both the uplink and the downlink, the carrier-to-noise density (C/N_0) equation, in dB, is

$$C/N_0 = EIRP + G/T - L - k \qquad (4.2-1)$$

where *EIRP* = the EIRP per carrier (dBW), where EIRP represents the effective isotropically radiated power and equals the antenna gain multiplied by the transmitted power

G/T = the antenna gain to system noise temperature ratio (figure of merit for an earth station) (dB/K)

L = total propagation and pointing losses (path loss, atmospheric loss, tracking loss) (dB)

k = Boltzmann's constant, -228.6 dBW/K-Hz.

All of the signals are identical in magnitude in the full mesh configuration; suppression is negligible and power sharing results. For the uplink, the EIRP per carrier is given by

$$EIRP = FS - BO_i + L_u + 2(R) - K + 11 \qquad (4.2-2)$$

where FS = satellite input saturation flux density (dBW/m^2)

BO_i = satellite input backoff (dB)

L_u = uplink atmospheric and pointing losses (dB)

R = slant range (dBmeters)

K = number of carriers in the satellite transponder (dB)

11 = $10\log_{10}(4\pi)$.

For the downlink, the EIRP per carrier is given by

$$EIRP = EIRP_s - BO_o - K \qquad (4.2-3)$$

where $EIRP_s$ = satellite EIRP (dBW)

BO_o = satellite output backoff (dB).

In the star configuration, unequal signals share the transponder. A parameter such as the remote terminal HPA power (P_r) or the hub terminal HPA power (P_h) or a ratio of the hub terminal EIRP ($EIRP_{TDM,u}$) to the remote terminal EIRP ($EIRP_{SS,u}$) must be specified in order to perform the uplink calculations. Choosing P_r, the uplink $EIRP_{SS,u}$ and the total uplink EIRP ($EIRP_{t,u}$) are given in dBW by

$$EIRP_{SS,u} = P_r + G_r \qquad (4.2-4)$$

$$EIRP_{t,u} = FS - BO_i + L_u + 2(R) + 11 \qquad (4.2-5)$$

where P_r is the remote terminal HPA power (dBW) and G_r is the remote terminal antenna gain (dB). The uplink $EIRP_{TDM,u}$ (ratio) is given by

$$EIRP_{TDM,u} = EIRP_{t,u} - K\,EIRP_{SS,u} \qquad (4.2-6)$$

Note that Equation 4.2-6 is in ratio, not dB.

In the star configuration the large TDM signal suppresses the small SS signals. Equations 3.2-5 and 3.2-6 account for the suppression, but the signal power of the TDM and SS signals must be calculated at the satellite input in order to find the suppression value from Figure 3.3-1. Letting S_{TDM} be the TDM signal power and S_{SS} be the DS-CDMA spread spectrum signal power, then at the satellite input

$$S_{TDM} = P_h + G_h - L \text{ (dBW)} \qquad (4.2-7)$$

$$S_{SS} = P_r + G_r - L \text{ (dBW)} \qquad (4.2-8)$$

where P_h = hub terminal HPA output power (dBW)

G_h = hub terminal antenna gain (dB).

The antenna gain is normally known, and the HPA power for the hub terminal may be found from $P = EIRP - G$ (in dB) and Equation 4.2-6. Assuming L is the same for each path, the parameters needed are

$$S_1/S_5 = S_{TDM}/S_{SS} = P_h + G_h - P_r - G_r \text{ (dB)} \qquad (4.2-9)$$

$$S_1/N = S_{TDM}/N = S_{TDM} + (G/T)_{sat} - B_{TDM} - k \text{ (dB)} \qquad (4.2-10)$$

$$S_1/N = S_{TDM}/N = S_{TDM} + (G/T)_{sat} - B_{TDM} - k \text{ (dB)} \qquad (4.2-10)$$

where $(G/T)_{sat}$ = satellite input G/T (dB/K)

B_{TDM} = the TDM signal bandwidth (dBHz).

If L is not the same for each path, Equation 4.2-9 is easily modified from Equations 4.2-7 and 4.2-8. For a given bit rate, the maximum bandwidth (assuming peak capacity operation) for QPSK modulation using a raised cosine filter with a roll-off factor of 0.4 is

$$B_{TDM} = 0.7\, K\, R_b \text{ (Hz)} \qquad (4.2-11)$$

$$B_{SS} = 0.7\, N\, R_b \text{ (Hz)} \qquad (4.2-12)$$

where R_b = bit rate per channel (bits per second, bps)

N = the period (or length) of the Gold codes.

Equations 4.2-9 and 4.2-10 yield values for S_1/S_5 and S_1/N, and Figure 3.3-1 yields the suppression value, S. Substituting the TDM and SS subscripts for the 1 and 5 subscripts in Equations 3.2-5 and 3.2-6, and substituting $EIRP = EIRP_s/BO_o$ (ratio), the downlink EIRP per channel (ratio), after adjustment for suppression, is given by

$$EIRP_{SS,d} = \frac{EIRP_s/BO_o}{\left[\frac{S_{TDM,i}\,S}{S_{SS,i}} + K\right]} \text{ (Watts)} \qquad (4.2-13)$$

$$EIRP_{TDM,d} = EIRP - K(EIRP_{SS,d}) \text{ (Watts)} \qquad (4.2-14)$$

Thus, Equations 4.2-1 through 4.2-3 give the uplink and downlink C/N_0 for the full mesh network. For the star network, Equation 4.2-1 and Equations 4.2-4 through 4.2-14 and Figure 3.3-1 must be used to perform the uplink and downlink C/N_0 calculations. Note that the $EIRP_{SS,d}$ and $EIRP_{TDM,d}$ values must be converted to dBW before being substituted into Equation 4.2-1.

The interference carrier-to-noise power ratio, $(C/N)_i$, which includes both adjacent satellite interference and intermodulation interference, is normally given for a satellite link. For QPSK modulation using a raised cosine filter with a roll-off factor of 0.4, the intermodulation carrier-to-noise density ratio, $(C/N_0)_i$, is given by

$$(C/N_0)_I \;=\; (C/N)_I \;+\; 10.0 log_{10}(0.7 R_b) \quad (\text{dB}). \qquad (4.2-15)$$

The total C/N_0 for the link, where each parameter is a ratio (not in dB), is given by

$$(C/N_0)_t \;=\; \frac{1.0}{\dfrac{1.0}{(C/N_0)_u} + \dfrac{1.0}{(C/N_0)_d} + \dfrac{1.0}{(C/N_0)_i}} \qquad (4.2-16)$$

where t = total

u = uplink

d = downlink

i = intermodulation.

Finally, the bit energy per noise density (E_b/N_0, in dB) is given by

$$E_b/N_0 \;=\; (C/N_0)_t \;-\; 10 log_{10}(R_b) \qquad (4.2-17)$$

where $(C/N_0)_t$ has been converted to dB.

To include the loss due to PN coding interference, Equation 2.4-7 is repeated here:

$$SNR_j = 10.0 log\left[0.5 \left[\frac{1.0}{2E_b/N_0} + \left(\frac{1.0}{6N^3}\right) ISUM_j \right]^{-1} \right] \quad (4.2-18)$$

where $ISUM_j$ = the sum of the average interference parameters, as given by Equation 2.4-6 and listed for several Gold code sets in Tables 2.4-1 and 2.5-1.

4.3 Full Mesh Network

As defined in Section 4.1, the full mesh network consists of 50 VSAT terminals, each of which transmits a DS-CDMA spread spectrum signal. Each terminal may communicate with all other terminals. Table 4.3-1 lists parameters for a VSAT Ku-band system. Table 4.3-2 lists a power budget for a system using the set of fifty 1023 bit Gold codes whose *ISUM* values are listed in Table 2.5-1. The power budget includes 3 dB forward error correction (FEC) coding.

For a system using a set of fifty 1023 bit Gold codes, Figure 4.3-1 illustrates the results of the link analysis of Equations 4.2-1 through 4.2-3 and 4.2-15 through 4.2-18. The four curves result from antenna diameters of 1.8m and 1.2m and bit rates of 32 kbps and 64 kbps. The curves show the 3 dB FEC coded E_b/N_0 (the lowest *SNR* value given by Equation 4.2-18) produced by a given earth station HPA transmitting power. The bandwidths required are 22.92 MHz and 45.83 MHz for the 32 kbps and 64 kbps cases, respectively.

Table 4.3-1. VSAT Ku-band system parameters, full mesh network.

slant range (R) = 75.73 dBmeters
satellite input G/T = -3.0 dB/K
downlink frequency = 11.7 GHz
uplink frequency = 14.0 GHz

input backoff (BO_i) = 8.2 dB
output backoff (BO_o) = 3.5 dB
length of spread code (N) = 1023 bits
number of carriers (K) = 50

antenna efficiency = 0.60
uplink atmospheric and pointing loss (L_u) = 1.0 dB
satellite output EIRP ($EIRP_s$) = 42.0 dBW
uplink propagation and pointing loss (L) = 207.8 dB
downlink propagation and pointing loss (L) = 206.3 dB
satellite input saturation flux density (FS) = -90 dBW/m^2
interference carrier-to-noise ratio, $(C/N)_i$ = 18.5 dB
earth station system noise temperature = 370.0 K
satellite transponder bandwidth = 54 MHz.

Table 4.3-2. A sample power budget for the full mesh network using a set of fifty 1023 bit Gold codes (Equations 4.2-1 through 4.2-3 and 4.2-15 through 4.2-18).

bit rate per carrier (R_b) = 32 kbps
uplink antenna gain = 46.21 dB
spread spectrum bandwidth (B_{SS}) = 22.92 MHz
remote terminal transmitted power (P_r) = 1.6 W
sum of the average interference parameters for code 1, $ISUM_1$, (from Table 2.5-1) = 102656558

antenna diameter = 1.8m
downlink antenna gain = 44.65 dB

	Uplink	Downlink
effective isotropically radiated power, $EIRP$ (dBW)	48.26	21.51
propagation and pointing loss, L (dB)	207.8	206.3
receiver antenna gain to noise temperature, G/T (dB/K)	-3.0	18.97
Boltzmann's constant, k (dBW/K-Hz)	-228.6	-228.6
carrier-to-noise density ratio, C/N_0 (dB-Hz)	66.06	62.78
interference C/N_0, $(C/N_0)_i$ (dB-Hz)	62.00	
total C/N_0, $(C/N_0)_t$ (dB-Hz)	58.52	
bit energy-to-noise density ratio, E_b/N_0 (dB)	13.47	
signal-to-noise ratio of signal 1, SNR_1 (dB)	11.14	
3 dB FEC coded SNR required for $10^{-7}BER$ (dB)	8.33	
Rain and implementation margin (dB)	2.81	

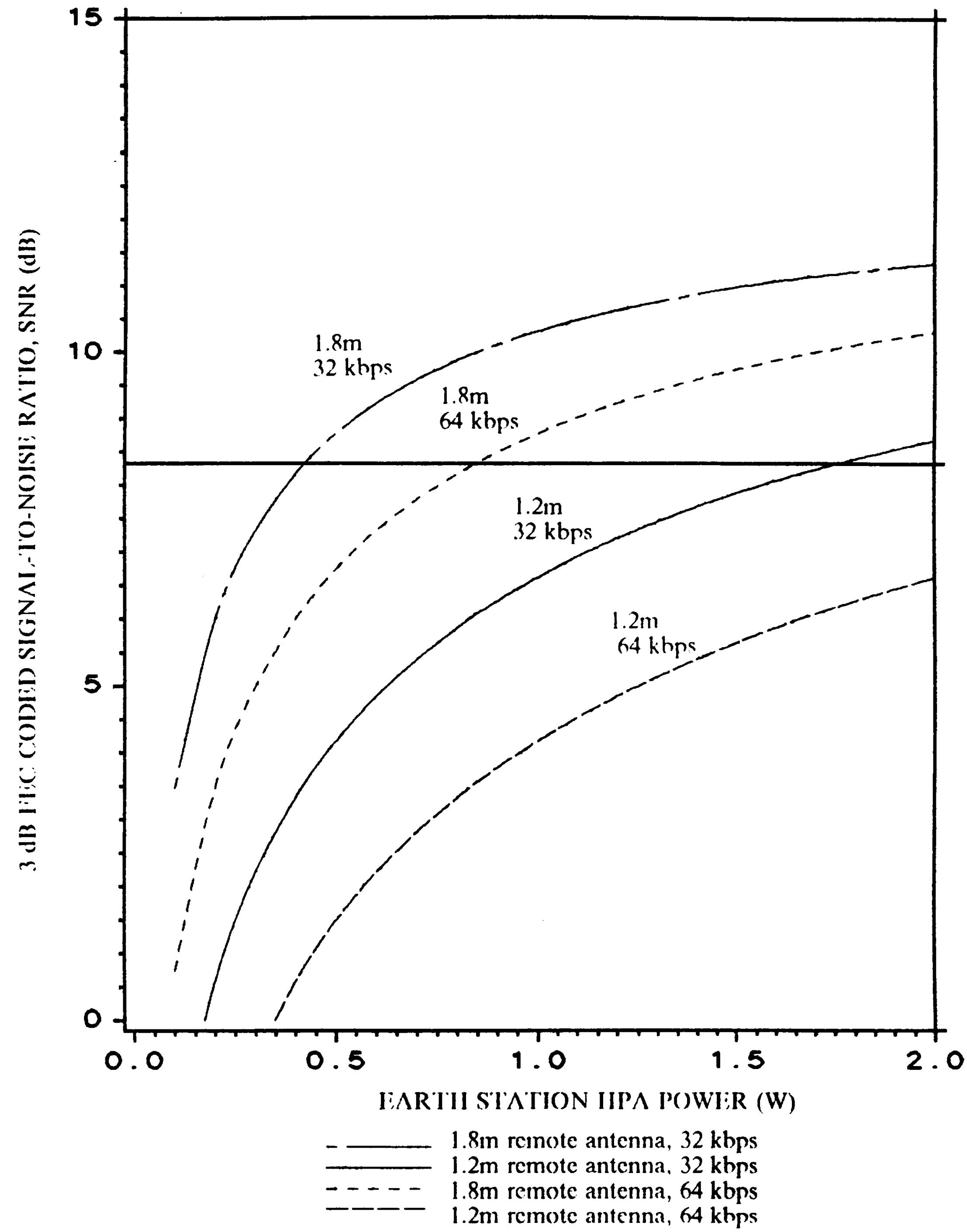


Figure 4.3-1. E_b/N_0 vs. HPA power for a DS-CDMA full mesh network using a set of fifty 1023 bit Gold codes.

There is one thing to note before drawing conclusions from Figure 4.3-1. The link analysis assumes that the required satellite input flux density is met. Although demand access will allow many terminals to use the system, for a system having a set of 50 codes, only 50 terminals may transmit signals at the same time. Assuming all the terminals operate at identical HPA power levels, a terminal with a 1.8m antenna requires an HPA power level of 1.6 W. Table 4.3-3 lists the required number of terminals, and thus the required number of codes, for various HPA power levels and a 1.8m antenna.

A power level less than 1.6 W requires an increase in the number of codes, which will increase the coding crosscorrelation interference. Depending on the size of the set of codes, this may force an increase in the length of the codes in order to lessen the crosscorrelation interference. An alternative to increasing the code length is to provide a separate signal to meet the satellite's input flux density requirement, but signal suppression effects must then be considered.

The curves of Figure 4.3-1 lead to the following observations.

- The E_b/N_0 increases as the HPA power increases. However, the system is not uplink limited, but rather downlink limited. The satellite output EIRP per carrier (downlink *EIRP*) is dependent upon the percentage of the satellite input flux density supplied by that particular carrier. Thus, as the HPA power increases, the downlink *EIRP* increases, and this downlink improvement is responsible for the E_b/N_0 improvement.

- The E_b/N_0 is smaller for smaller antenna diameters.

- The E_b/N_0 decreases as the bit rate increases.

Table 4.3-3. Number of terminals required for various HPA power levels

HPA Power (Watts)	Terminals Required	HPA Power (Watts)	Terminals Required
0.2	400	1.2	66
0.4	200	1.4	57
0.6	133	1.6	50
0.8	100	1.8	44
1.0	80	2.0	40

- At the HPA power operating point of 1.6 W for a terminal with a 1.8m antenna, the coded E_b/N_0 is 11.1 dB for a bit rate of 32 kbps and is 9.9 dB for a bit rate of 64 kbps. The horizontal line at an E_b/N_0 of 8.33 dB marks the point corresponding to a *BER* of 10^{-7}, the acceptable *BER* for a data link. Thus, the implementation and rain margin (hereafter referred to simply as implementation margin) for the system under each situation can be read from Figure 4.3-1. Figure 4.3-1 shows clearly that a 1.2m antenna cannot be used and that the implementation margin is only marginal for the 1.8m, 64 kbps case. The implementation margin for the 1.8m, 32 kbps case is approximately 2.8 dB.

4.4 Star Network

The star network consists of a hub terminal with a 5.5m antenna and fifty remote terminals with either 1.8m or 1.2m antennas. The remote terminals transmit DS-CDMA spread spectrum signals to the hub terminal, and the hub terminal transmits a TDM signal to the remote terminals. The TDM and spread spectrum signals share the same transponder. Table 4.4-1 lists parameters for the star network; the primary differences between these parameters and those of Table 4.3-1 are the addition of the $(C/N)_i$ value of 22.0 dB for the TDM link and the hub terminal system noise temperature of 260 K. Table 4.4-2 lists a power budget for the star configuration.

The large TDM signal alleviates the earlier concern with providing the desired satellite input flux density, since the TDM signal can be adjusted to maintain the proper flux density as the remote terminal HPA power level changes. However, as mentioned

Table 4.4-1. VSAT Ku-band system parameters, star network.

slant range (R) = 75.73 dBmeters
satellite input G/T = -3.0 dB/K
downlink frequency = 11.7 GHz
uplink frequency = 14.0 GHz
antenna efficiency = 0.60

input backoff (BO_i) = 8.2 dB
output backoff (BO_o) = 3.5 dB
length of spread code (N) = 1023 bits
number of carriers (K) = 50
satellite EIRP ($EIRP_s$) = 42.0 dBW

uplink atmospheric and pointing loss (L_u) = 1.0 dB
uplink propagation and pointing loss (L) = 207.8 dB
downlink propagation and pointing loss (L) = 206.3 dB
satellite input saturation flux density (FS) = -90 dBW/m^2
spread spectrum interference carrier-to-noise ratio, $(C/N)_{SS,i}$ = 18.5 dB
TDM interference carrier-to-noise ratio, $(C/N)_{TDM,i}$ = 22.0 dB
remote terminal system noise temperature = 370.0 K
hub terminal system noise temperature = 260 K
satellite transponder bandwidth = 54 MHz.

Table 4.4-2. A sample power budget for the star network using a set of fifty 1023 bit Gold codes (Equations 4.2-1 and 4.2-4 through 4.2-18); subscripts r, h, u, and d stand for remote, hub, uplink, and downlink, respectively.

bit rate per carrier (R_b) = 32 kbps
$ISUM_1$(from Table 2.5-1) = 102656558
TDM bandwidth (B_{TDM}) = 1.12 MHz
spread spectrum bandwidth (B_{SS}) = 22.92 MHz
remote antenna diameter = 1.8m
hub antenna diameter = 5.5m

P_r = 1.00 W $G_{r,u}$ = 46.21 dB $G_{r,d}$ = 44.65 db
P_h = 3.23 W $G_{h,u}$ = 55.91 dB $G_{h,d}$ = 54.35 dB
S_{TDM}/S_{SS} = 14.79 dB S_{TDM}/N = 18.29 dB   suppression (S) = 4.95 dB

	Hub-to-remote		Remote-to-hub	
	Uplink	Downlink	Uplink	Downlink
$EIRP$ (dBW)	61.03	36.65	46.21	17.1
propagation and pointing loss, L (dB)	207.8	206.3	207.8	206.3
G/T (dB/K)	-3.0	18.97	-3.0	30.20
Boltzmann's constant, k (dBW/K-Hz)	-228.6	-228.6	-228.6	-228.6
carrier-to-noise density ratio, C/N_0 (dB-Hz)	78.83	77.92	64.01	69.60
interference C/N_0, $(C/N_0)_i$ (dB-Hz)	82.49		62.00	
total C/N_0, $(C/N_0)_t$ (dB-Hz)	74.58		59.44	
bit energy-to-noise density ratio, E_b/N_0 (dB)	12.53		14.39	
signal-to-noise ratio of signal 1, SNR_1 (dB)	---		11.65	
FEC coded SNR required for $10^{-7}BER$ (dB)	8.33		8.33	
Rain and implementation margin (dB)	4.20		3.32	

previously, the large TDM signal causes suppression of the SS signals in the satellite transponder. The TDM signal robs power from the SS signals, resulting in a larger than normal downlink *EIRP* for the TDM signal and a smaller than normal downlink *EIRP* for the SS signals.

After accounting for suppression, the link analysis of Equation 4.2-1 and Equations 4.2-4 through 4.2-18 produces the results displayed in Figures 4.4-1 and 4.4-2. Both figures show the effect of the remote terminal HPA power on the 3 dB FEC coded E_b/N_0. In both figures R-T-H stands for the remote-to-hub link, and H-T-R stands for the hub-to-remote link. For a given system, the optimum operating point occurs where the R-T-H curve intersects the H-T-R curve. The curves of Figure 4.4-1 are for a system with a bit rate of 32 kbps and antenna diameters of 1.8m and 1.2m. The curves of Figure 4.4-2 are for a system with a 1.8m antenna and bit rates of 32 kbps and 64 kbps. In Figure 4.4-1, the 2 dashed lines are for the 1.2m antenna case, and in Figure 4.4-2, the 2 dashed lines are for the 64 kbps case. The required bandwidths are 24.04 MHz and 48.07 MHz for the 32 kbps and 64 kbps cases, respectively. Some observations follow.

- As the remote terminal HPA power increases, the downlink *EIRP* increases for the SS signals, and the R-T-H link improves.

- As the remote terminal HPA power increases, the downlink *EIRP* decreases for the TDM signal, and the H-T-R link degrades.

- Since all links are downlink limited, the 5.5m hub antenna greatly strengthens the R-T-H link, because the 5.5m antenna is the downlink antenna in the R-T-H link. The difference is obvious when the R-T-H curves of Figures 4.4-1 and 4.4-2 are compared to the curves of Figure 4.3-1.

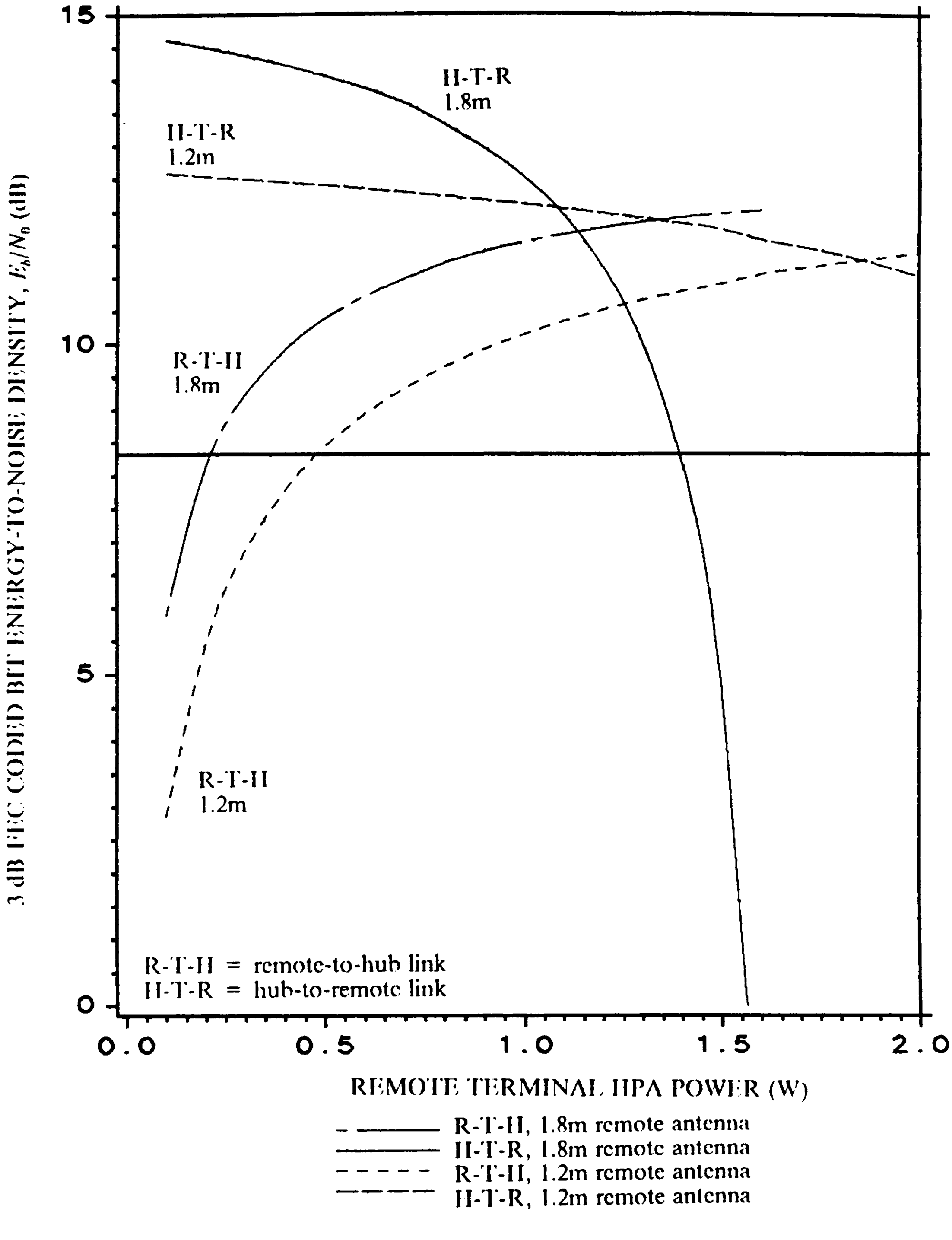


Figure 4.4-1. E_b/N_0 vs. remote terminal HPA power for the star network using a set of fifty 1023 bit Gold codes, R_b = 32 kbps.

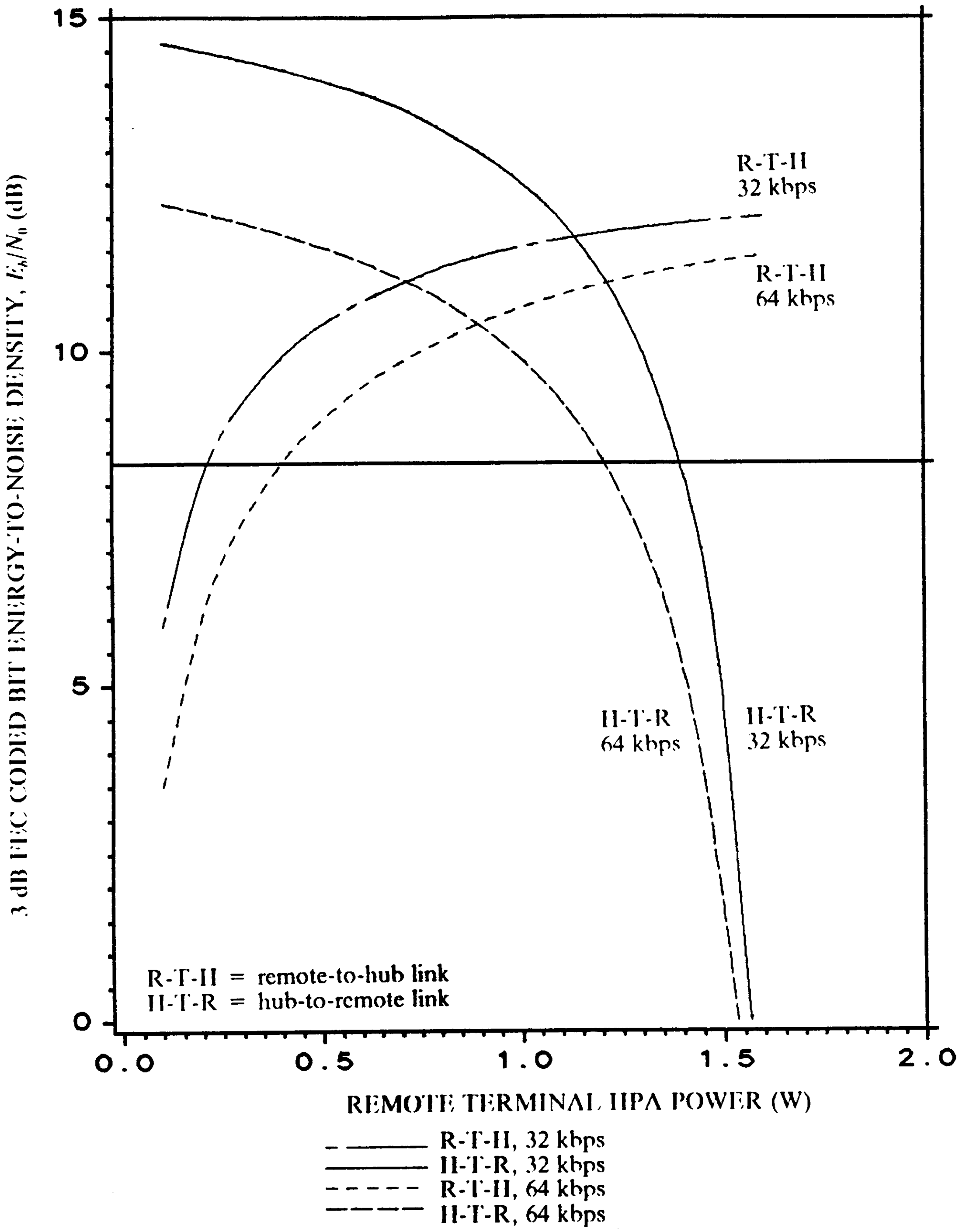


Figure 4.4-2. E_b/N_0 vs. remote terminal HPA power for the star network using a set of fifty 1023 bit Gold codes, VSAT antenna diameter = 1.8m.

- Six of the eight curves in Figures 4.4-1 and 4.4-2 end near a remote terminal HPA power of 1.6 W. This happens for all systems using VSAT antennas of diameter 1.8m because 1.6 W is the point where the fifty remote terminals provide all of the satellite input flux density, the TDM signal power reduces to zero, the H-T-R link is lost, and the R-T-H link peaks due to the limit on the HPA power.

- For the 1.8m antennas, the optimum operating point occurs for a remote terminal HPA power of 1.14 W for the 32 kbps case and 0.9 W for the 64 kbps case. The corresponding implementation margins are 3.4 dB and 2.1 dB. Although not shown on Figures 4.4-1 and 4.4-2, the corresponding optimum operating points for the hub terminal HPA are 2.48 W and 3.77 W, respectively (see Figure 4.4-3).

- For the 1.2m antennas, the optimum operating point occurs for a remote terminal HPA power of 1.85 W for the 32 kbps case. The implementation margin is 2.9 dB. Although not shown on Figure 4.4-1, the optimum operating point for the hub terminal HPA is 4.18 W (see Figure 4.4-3).

Figure 4.4-3 shows the hub terminal HPA power corresponding to a given remote terminal HPA power. Curves are shown for remote terminal diameters of 1.8m and 1.2m. The two curves converge as the remote terminal HPA power approaches zero because the hub terminal begins to supply nearly all of the satellite input flux density. The limiting value is 8.61 W, at which point the SS signals are no longer transmitted.

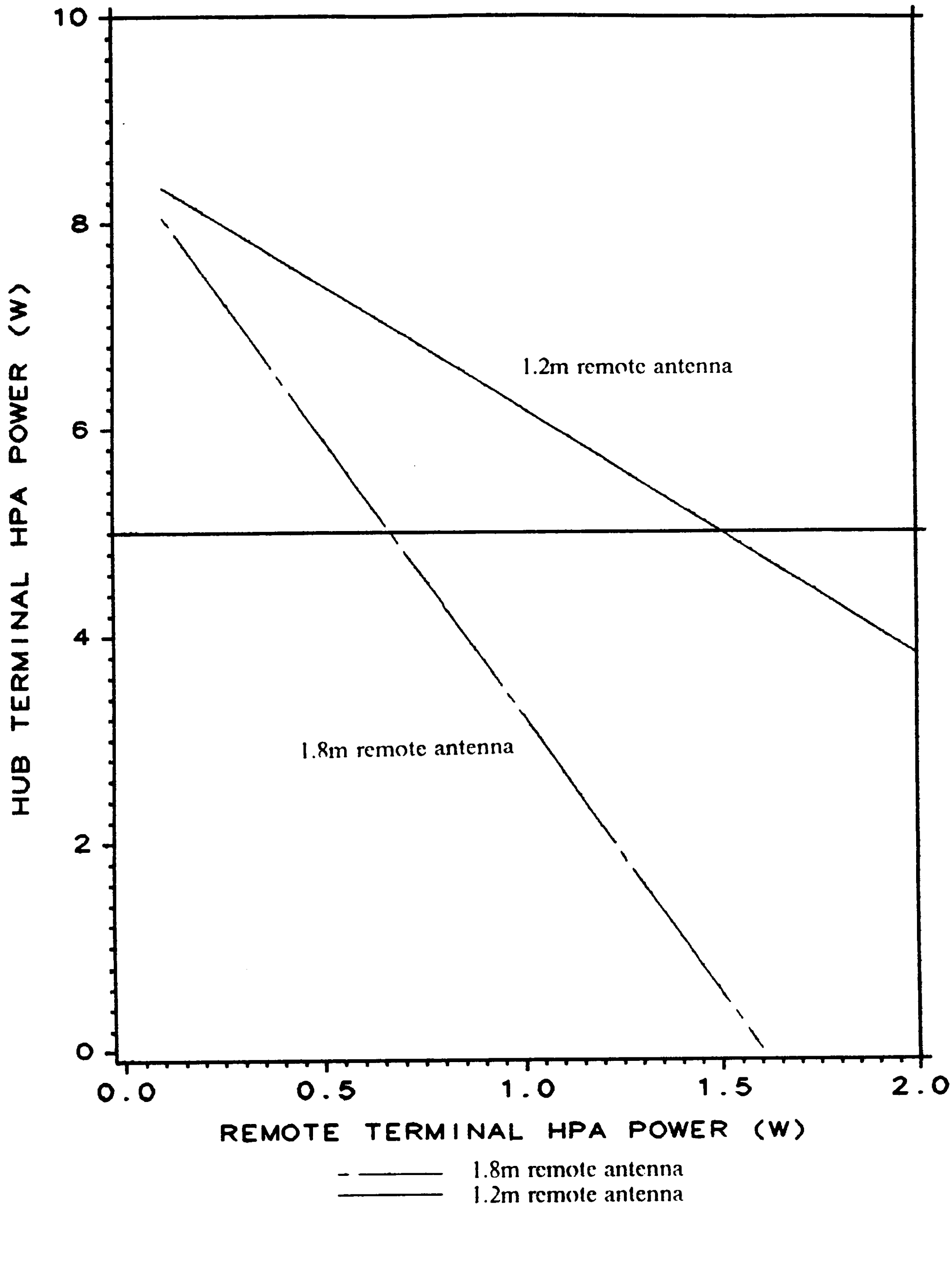


Figure 4.4-3. Hub terminal HPA power vs. remote terminal HPA power for the star configuration, using a hub antenna of 5.5m and remote antennas of 1.8m and 1.2m.

V. SCPC PERFORMANCE ANALYSIS AND COMPARISON TO DS-CDMA

5.1 SCPC Performance Analysis for Full Mesh and Star Architectures

The work of Chapter 4 renders the performance analysis of the full mesh and star architectures a simple task. Section 4.1 described the two architectures, and Sections 4.2 through 4.4 presented the link analysis and illustrated the performance analysis. The link analysis of Section 4.2 is easily adapted to SCPC calculations by leaving out the PN coding interference loss calculations. The link itself, including the suppression effects in the star network, is identical for both SCPC and DS-CDMA until the signals enter the correlator---then the PN coding interference degrades the DS-CDMA performance.

For SCPC calculations, Equations 4.2-1 through 4.2-17 apply. Equation 4.2-18 converted the calculated E_b/N_0 into a corrected E_b/N_0 , which was called SNR_j, reflecting the effect of PN coding interference. The E_b/N_0 of Equation 4.2-17 is the correct value for SCPC. As a result, no power budgets will be given, since the power budgets of Tables 4.3-2 and 4.4-2 give the correct SCPC E_b/N_0 values, for those particular cases. Figure 5.1-1 shows the results for the full mesh architecture, comparable to Figure 4.3-1 for DS-CDMA; and Figures 5.1-2 and 5.1-3 illustrate the results of the analysis for the star configuration, comparable to Figures 4.4-1 and 4.4-2 for DS-CDMA. Figure 4.4-3 remains accuarate for SCPC in determining the hub terminal HPA power based upon the remote terminal HPA power.

Figure 5.1-1 shows that 1.2m antennas do not provide sufficient implementation margin in the full mesh network, similar to the result for DS-CDMA. Unlike DS-CDMA, however, a network using 1.8m antennas can feasibly operate at a 64 kbps data rate. Figure 5.1-1 shows an implementation margin of 3.2 dB for this case at the operating point of 1.6 W, and the 1.8m 32 kbps case has a 5.1 dB margin, compared to the 2.8 dB for DS-CDMA.

From Figures 5.1-2 and 5.1-3, the 1.8m VSAT network has implementation margins and optimum remote terminal HPA power points of 5.3 dB and 0.73 W for 32 kbps, and 2.9 dB and 0.64 W for 64 kbps. The 1.2m VSAT network has values of 3.7 dB and 1.03 W for 32 kbps. Thus, SCPC attains better implementation margins at a lower remote terminal HPA power than does DS-CDMA.

Section 5.3 presents further comparison of SCPC and DS-CDMA for these two network architectures. However, it is clear that SCPC will outperform DS-CDMA in both networks. This advantage of SCPC, however, may often be offset by less expensive

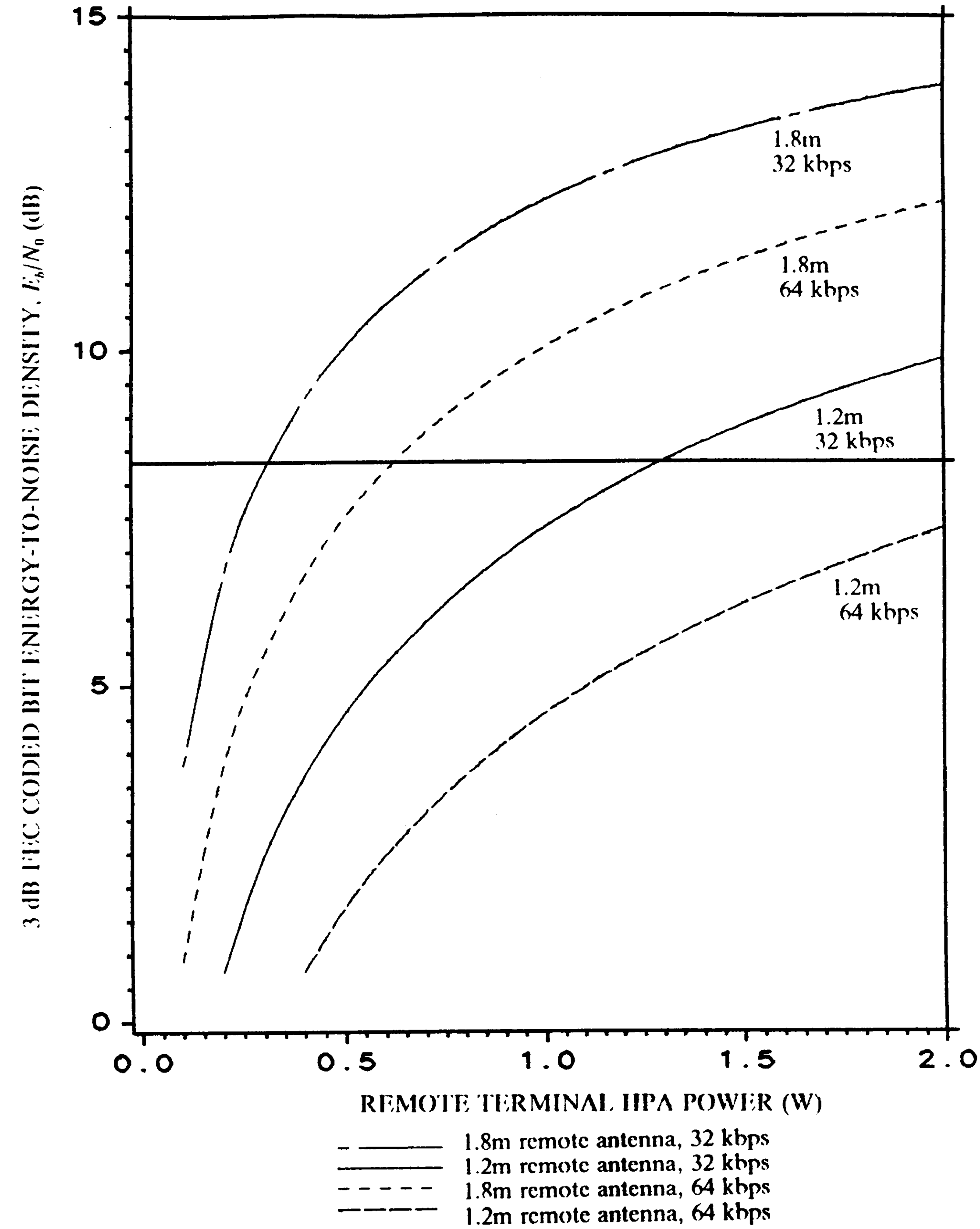


Figure 5.1-1. E_b/N_0 vs. HPA power for the SCPC full mesh network.

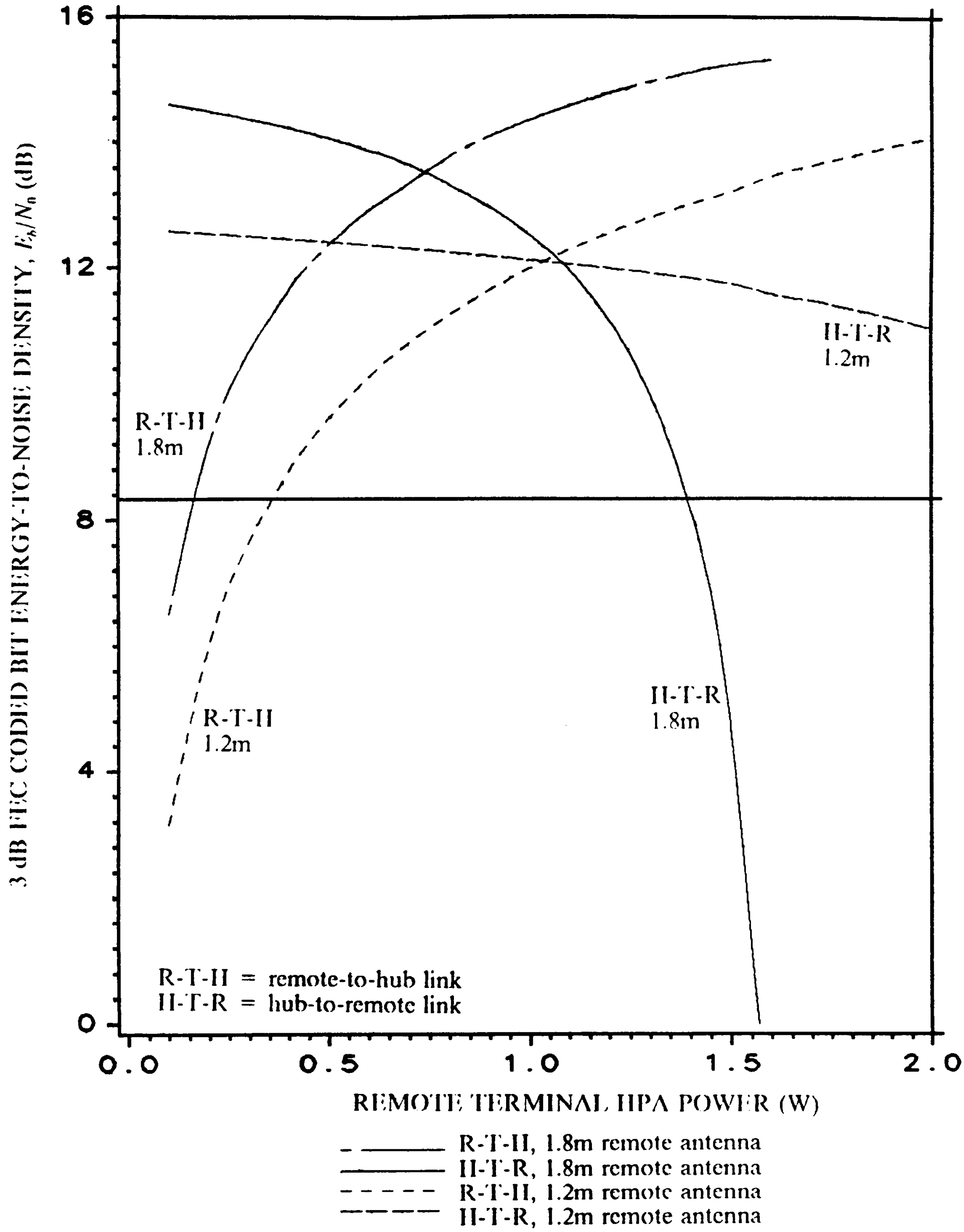


Figure 5.1-2. E_b/N_0 vs. remote terminal HPA power for the SCPC star network, R_b = 32 kbps.

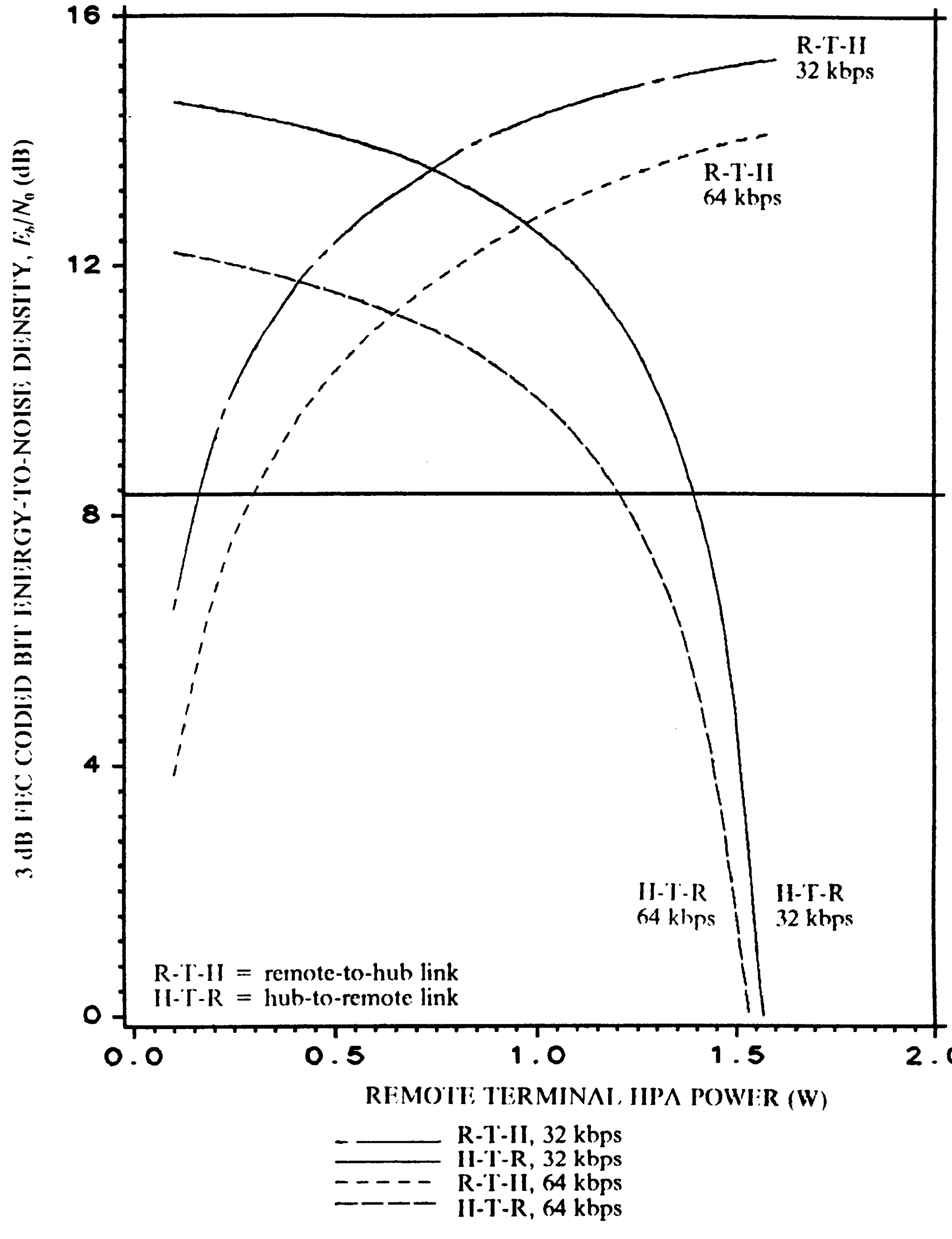


Figure 5.1-3. E_b/N_0 vs. remote terminal HPA power for the SCPC star network, VSAT antenna diameter = 1.8m.

equipment in the DS-CDMA network. For instance, the full mesh system will require each SCPC terminal to have a frequency synthesizer. Such tradeoffs between performance and cost may be worthwhile in networks where the level of DS-CDMA performance is already acceptable.

5.2 An SCPC Partial Mesh System

Some low-density communication networks require considerably more than 50 channels, and this puts DS-CDMA at a severe disadvantage. To reduce crosscorrelation losses, a large set of codes requires longer codes than have been considered here, but longer codes require more expensive equipment. Such problems do not exist in applying SCPC to larger systems. However, as the number of channels increases, individual links become increasingly downlink limited, due to the decreasing downlink *EIRP* available per carrier. A full mesh VSAT system especially suffers from this problem since VSAT antennas are on each end of the link. One possible solution is to allow VSAT terminals to communicate only with medium or large terminals. The following partial mesh system is included as an example of such an SCPC application to a larger network.

During a preliminary design of a regional satellite system for the Virginia Polytechnic Institute and State University (VPI&SU) Agricultural Extension Service, Table 5.2-1 and Equations 4.2-1, 4.2-2, 4.2-3, 4.2-16, and 4.2-17 were used in the link analysis of a system having 300 channels. For a 32 kbps voice link between two medium earth stations, each having 4.0m diameter antennas (uplink gain of 53.1 dB, downlink gain of 51.6 dB), the power budget of Table 5.2-2 results.

Table 5.2-1. Ku-band system parameters.

slant range (R) = 75.98 dBmeters
satellite input G/T = -3.0 dB/K
input backoff (BO_i) = 9.2 dB
downlink frequency = 11.7 GHz
antenna efficiency = 0.60
satellite EIRP ($EIRP_s$) = 42.0 dBW
output backoff (BO_o) = 4.65 dB
uplink frequency = 14.0 GHz

uplink atmospheric and pointing loss (L_u) = 1.0 dB
uplink propagation and pointing loss (L) = 208.3 dB
downlink propagation and pointing loss (L) = 206.8 dB
satellite input saturation flux density (FS) = -90 dBW/m^2
interference carrier-to-noise density ratio, $(C/N_0)_i$ = 66.1 dB
earth station system noise temperature = 240.0 K.

Table 5.2-2. Power budget for 300 channel system, with 4.0m antennas at each end of the link.

	Uplink	Downlink
$EIRP$ per carrier (dBW)	40.0	12.6
propagatio and pointing loss, L (dB)	208.3	206.8
G/T (dB/K)	-3.0	27.8
Boltzmann's constant, k (dBW/K-Hz)	-228.6	-228.6
C/N_0 (dB-Hz)	57.3	62.2

total C/N_0, $(C/N_0)_t$ = 55.6 dB-Hz
bit energy-to-noise density ratio, E_b/N_0 = 10.6 dB.

The acceptable bit error rate (*BER*) for a data link is 10^{-7}; an ADPCM voice link requires a *BER* of 10^{-6} or better. The E_b/N_0 value given above corresponds to a *BER* of 8.2×10^{-7}. If 3 dB forward error correction (FEC) coding is used, then the coded E_b/N_0 required for a *BER* of 10^{-7} is 8.33 dB. The coded $E_b/N_0 = 10.6$ dB gives a implementation margin of 2.3 dB.

Rain causes a degradation in the link's performance due to additional atmospheric attenuation and an increase in the earth station's system noise temperature. For a 99.8% availability, rain attenuation may be included in the downlink equation by adding 2.0 dB to the downlink value of L and raising the earth station system noise temperature to 420 K. For the above example, the link analysis yields a 3 dB FEC coded E_b/N_0 of 9.2 dB, which corresponds to a BER of 6×10^{-9}. The implementation margin has dropped to 0.9 dB due to the rain.

Equations 4.2-1, 4.2-2, 4.2-3, 4.2-16, and 4.2-17 have been used to generate Figures 5.2-1, 5.2-2, and 5.2-3. Figure 5.2-1 illustrates the effect of antenna diameter on the *BER* of the received signal. This is for a system composed of 300 carriers transmitted through the satellite transponder, each carrier carrying 32 kbps. Results are shown for both clear sky and rain conditions (99.8% availability). Note that the rain causes more than an order of magnitude change in the *BER*. Figure 5.2-1 shows that the data channel requirement of $BER = 10^{-7}$ is not met for the antenna diameters shown, 1.0m to 5.0m. However, the horizontal line at a *BER* of 1.1×10^{-4} is the approximate point where 3 dB FEC coding would produce a *BER* of 10^{-7} or better. Thus, if 3 dB FEC coding is used, a system using 1.95m or larger antennas would be sufficient for clear sky conditions, and antennas of 3.3m or larger would be sufficient for rain conditions.

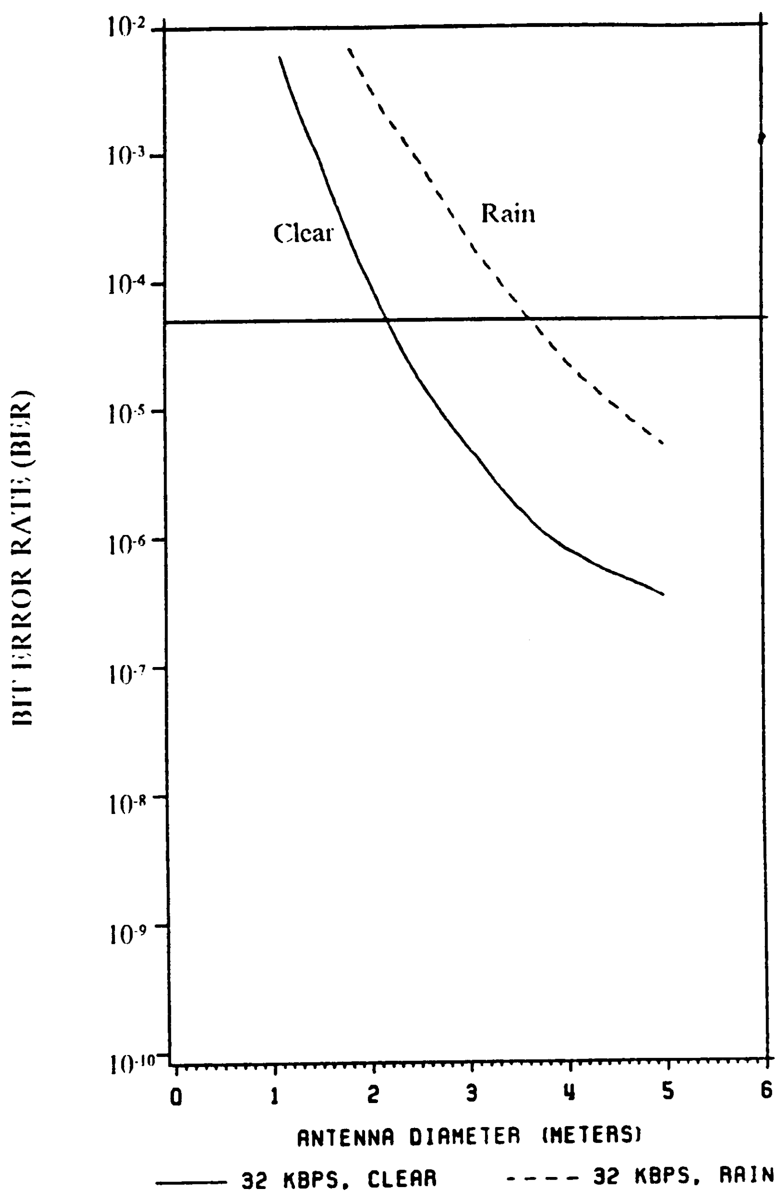


Figure 5.2-1. *BER* vs. antenna diamcter, including rain effects, 300 channels.

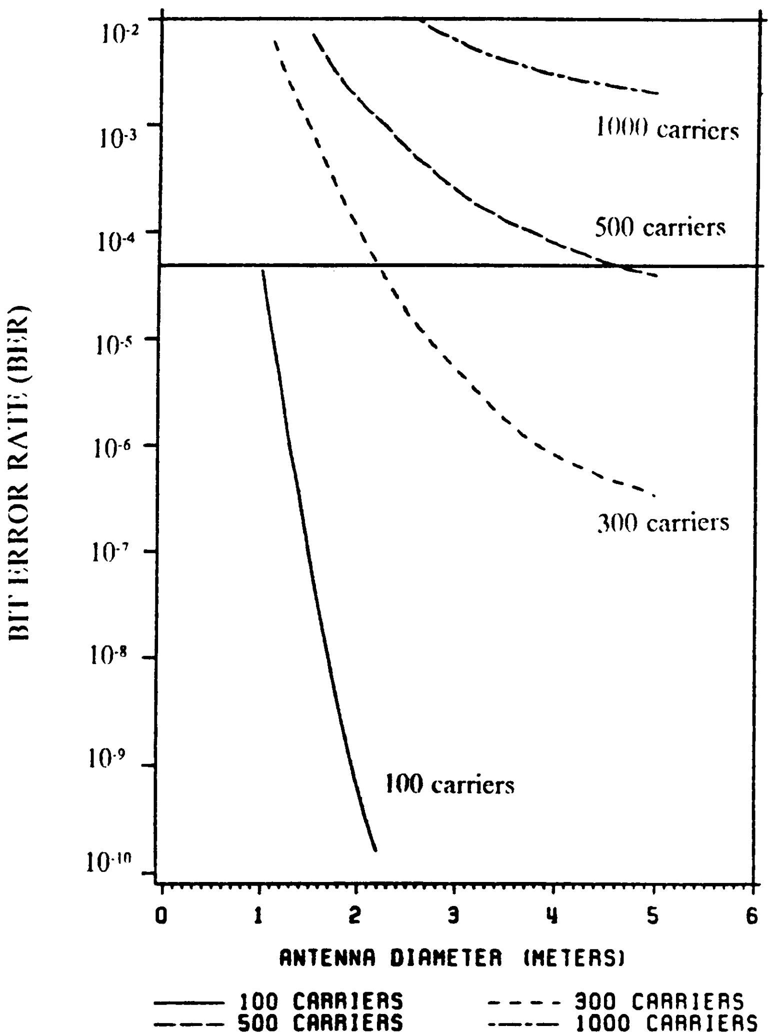


Figure 5.2-2. *BER* vs. antenna diameter; 32 kbps, clear sky.

Figure 5.2-2 shows the effect of varying the number of carriers through the satellite transponder. Each carrier is still carrying a single 32 kbps channel. The 300 carrier curve is the same as the solid curve in Figure 5.2-1. Obviously, increasing the number of carriers increases the bit error rate. This is because the system is downlink limited, so when the number of carriers increases, the available satellite output power per carrier decreases (since the total satellite output power is normally fixed) and causes the downlink C/N_0 to decrease, which reduces the performance of the system.

Thus far, a satellite flux density (*FS*) of -90 dBW/m^2 and a satellite G/T (GTS, on Figure 5.2-3) of -3.0 dB/K have been used. Some satellites operate at FS = -80 dBW/m^2 and G/T = 3.0 dB/K, which greatly improves the *BER*. Figure 5.2-3 illustrates this improvement for the 300 carrier clear sky curve. The performance will fall between the curves of Figure 5.2-3 if the satellite has *FS* and G/T values between those mentioned above.

Traffic estimates indicate that approximately 18 of the VPI&SU Extension offices require 5 voice and/or data channels, whereas the remaining offices require only 2 voice and/or data channels. Further, these remaining offices communicate primarily with VPI&SU and with the 18 larger offices, not with one another. For these reasons a partial mesh system was designed in which VPI&SU and the larger offices communicate with all offices, but the smaller offices only communicate with VPI&SU and the larger offices (communication between smaller offices will remain on the existing long-distance service).

The result is that smaller antennas, 2.4m (uplink gain of 48.7 dB, downlink gain of 47.2 dB) and 1.8m (uplink gain of 46.2 dB, downlink gain of 44.7 dB), may be used for the majority of the extension offices. Figure 5.2-1 shows 2.4m antennas to be unacceptable

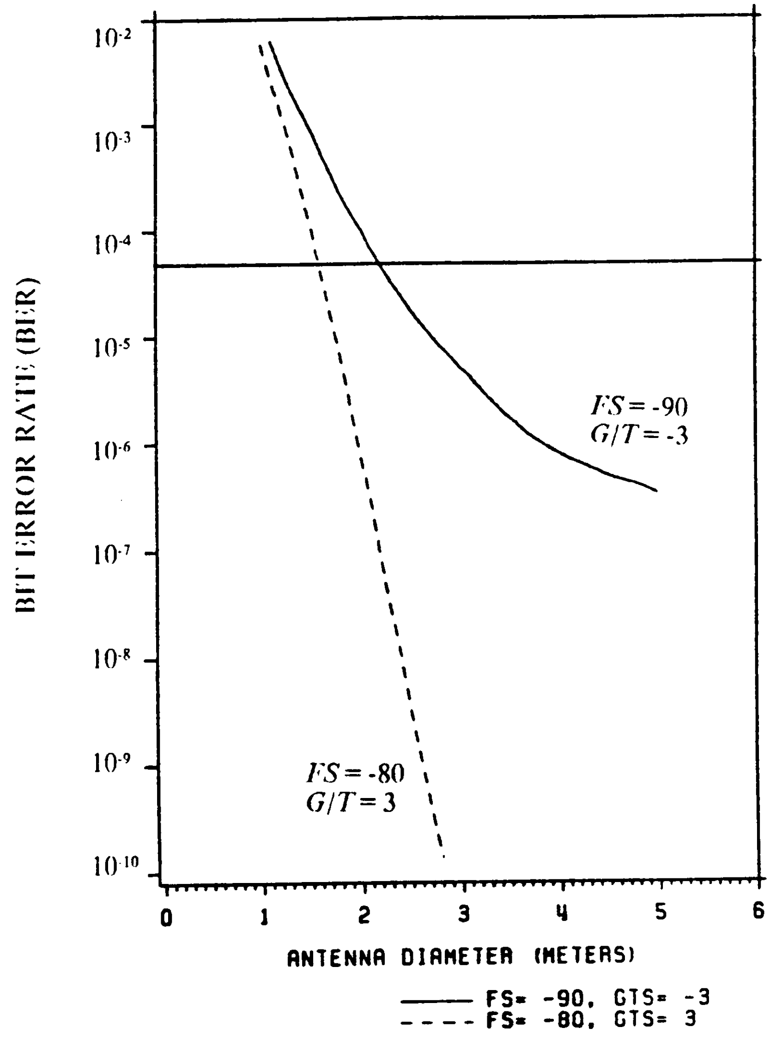


Figure 5.2-3. *BER* vs. antenna diameter; 300 channels, 32 kbps, clear sky.

under rain conditions, and the 1.8m antennas to be unacceptable under both rain and clear sky conditions; however, that analysis was for uplink and downlink antennas of identical size. A partial mesh system, in which earth stations with smaller antennas only have access to those having larger antennas, improves the performance.

A partial mesh system is defined below.

Medium stations:	4.0m antennas
	5 voice or data channels, maximum
	(1 channel = 32 kbps)
	communication with all stations
Small stations:	2.4m or 1.8m antennas
	2 voice or data channels, maximum
	(1 channel = 32 kbps)
	communication with medium stations.

Choosing new satellite parameters, FS = -88 dBW/m^2 and G/T = 2.0 dB/K, and N = 300 channels, the link analysis produces the results in Table 5.2-3. The BER values are for 3 dB FEC coded E_b/N_0 values.

For the 2.4m antenna, the performance is acceptable at all times for voice channels; but for the 2.4m downlink case under rain conditions, the performance is only marginal for data channels. The BER does not quite meet the desired value of 10^{-7}. The same situation occurs for the 1.8m antenna, except that for the downlink case the BER is completely intolerable under rain conditions. Both voice and data links would be lost in a heavy rain. Thus, the small antennas should not be less than 2.4m in diameter. The system appears to work for 2.4m antennas, with a slight deterioration on data links

Table 5.2-3. Bit energy-to-noise density ratio (E_b/N_0) and bit error rate (*BER*) values for different antenna combinations; partial mesh system, 300 channels.

		Clear Air		Rain	
Uplink antenna (m)	Downlink antenna (m)	Coded E_b/N_0 (dB)	*BER*	Coded E_b/N_0 (dB)	*BER*
4.0	2.4	11.3	$< 10^{-10}$	7.7	4.5×10^{-7}
2.4	4.0	14.1	$< 10^{-10}$	11.3	$< 10^{-10}$
4.0	1.8	9.4	3.5×10^{-9}	5.5	8×10^{-5}
1.8	4.0	14.1	$< 10^{-10}$	11.3	$< 10^{-10}$

during a heavy rain. However, the implementation margin is insufficient under rain conditions, so the link would probably be lost even with 2.4m antennas.

As a possible solution, the data links are primarily used for accounting purposes and do not really need a 32 kbps bit rate. If a 9.6 kbps bit rate is used for data links, the E_b/N_0 increases dramatically (see Equation 4.2-17). For this situation, the $(C/N_0)_i$ decreases to 60.8 dB, and for the 4.0m uplink-1.8m downlink case under rain conditions, the coded E_b/N_0 increases to 10.4 dB, which corresponds to a BER $< 10^{-10}$ and a 2.1 dB implementation margin. Therefore, if voice links are 32 kbps and data links are 9.6 kbps, the system will perform with high quality under all situations, using small station antennas only 1.8m in diameter.

This example illustrates the tradeoff between bit rate and the number of channels in a VSAT system. Since the antennas are small and do not have a large gain, the system is severely downlink limited. To improve the downlink, either the bit rate or the number of channels must be made relatively small.

5.3 Comparison of DS-CDMA and SCPC

This section contains a series of curves illustrating the effects of DS-CDMA transmission, SCPC transmission, suppression loss, and PN coding interference loss. For the sake of comparison, all curves are for the star configuration with 1.8m diameter remote terminal antennas and a bit rate per channel of 32 kbps. The hub terminal has a 5.5m antenna. The variables are the type of transmission, whether or not suppression is included, whether or not coding interference is included in the DS-CDMA signals, and whether or not suppression and coding interference are simultaneously included.

Figure 5.3-1 compares DS-CDMA and SCPC directly. The curves are identical to those shown earlier for the 1.8m antenna and 32 kbps case, in Figures 4.4-1 and 4.4-2 for DS-CDMA and in Figures 5.1-2 and 5.1-3 for SCPC. As noted in Section 5.1, SCPC performs better at a lower remote terminal HPA power than does DS-CDMA. Figure 5.3-1 shows that the optimum operating points are 0.73 W for SCPC and 1.14 W for DS-CDMA. The corresponding implementation margins are 5.3 dB for SCPC and 3.4 dB for DS-CDMA. Note that the hub-to-remote curve is identical for both transmission techniques. The hub is transmitting the same TDM signal in both systems, it is not affected by coding interference problems, and suppression affects it equally for SCPC and DS-CDMA signals in the transponder.

Since the SCPC link analysis differs from the DS-CDMA link analysis only in regard to coding interference losses, Figure 5.3-1 shows the amount of error present in a DS-CDMA analysis which does not include coding crosscorrelation effects. Such an analysis would lead to the conclusion that the optimum remote terminal operating point is at 0.73 W. However, as Figure 5.3-1 indicates, that operating point would cause the hub-to-remote link to operate at an E_b/N_0 of 13.6 dB while the remote-to-hub link operates at 11 dB. Thus, the remote-to-hub link has an implementation margin of 2.7 dB instead of the expected 5.3 dB. For a system without such large implementation margins, the difference might be crucial.

Figure 5.3-2 demonstrates the effect of signal suppression within the satellite transponder. The pair of short dashed lines are without suppression, and the pair of solid lines include suppression. The curves are for a star network using DS-CDMA, so

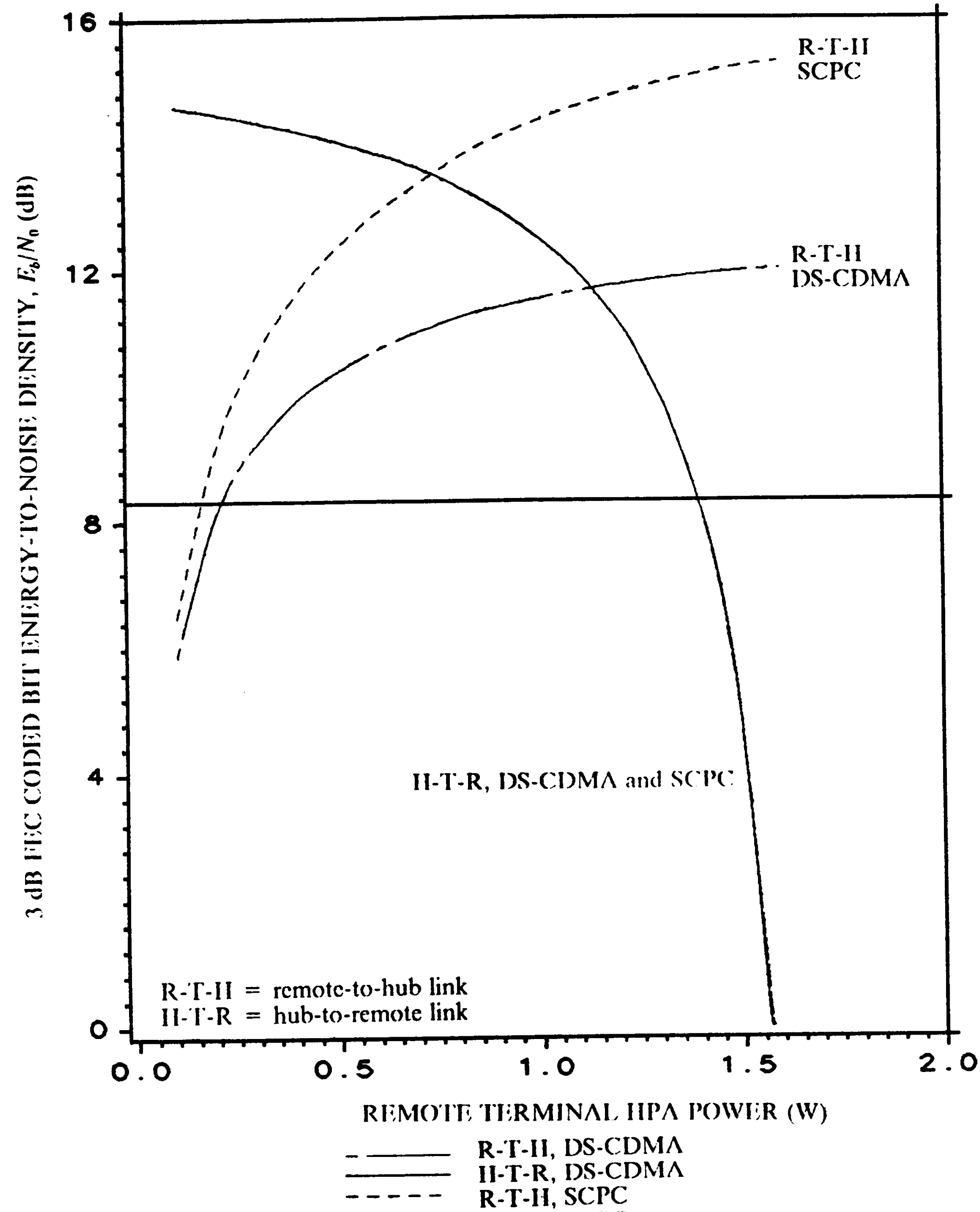


Figure 5.3-1. Comparison of SCPC and DS-CDMA signals in the star network for 1.8m remote antennas and 32kbps per channel (50 channels).

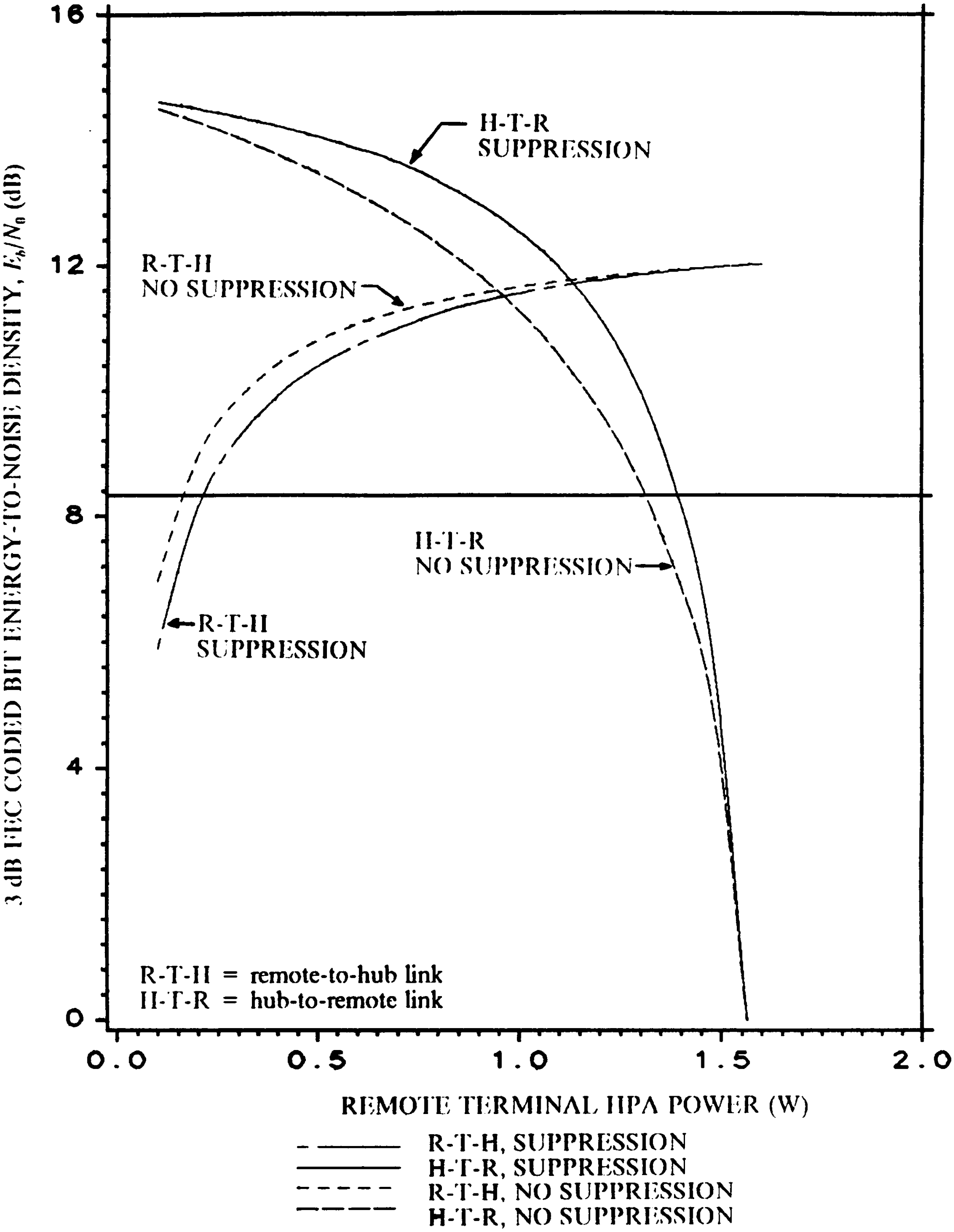


Figure 5.3-2. Comparison of performance in the star network with and without suppression for DS-CDMA signals (1.8m, 32 kbps).

coding interference is included in both remote-to-hub curves. Suppression does not have near as great an impact on system performance as PN coding losses do, as shown in Figure 5.3-1. Nonetheless, suppression does cause a shift in the optimum operating point, from 0.93 W to 1.14 W, and from an implementation margin of 3.27 db to 3.4 dB.

Although the increase in implementation margin is small and almost negligible, it is interesting that suppression causes the system to operate at a higher E_b/N_0 value. Figure 5.3-2 clearly shows why this happens: suppression boosts the TDM signal much more than it suppresses the DS-CDMA signal. The two remote-to-hub curves are never quite 1 dB apart in value, and they are much closer for most remote terminal HPA values. However, the two hub-to-remote curves differ by as much as 1.5 dB, especially in the middle of Figure 5.3-2 where the optimum operating points occur. The 50 DS-CDMA signals tend to dissipate the power robbing of the TDM signal, particularly as the DS-CDMA signals increase in strength. Thus, the TDM signal increases more than any one DS-CDMA signal decreases. As the operating point is shifted toward higher HPA values, the net result is a slight gain in the system implementation margin. Figure 5.3-3 shows the same thing for SCPC signals. Suppression actually increases the optimum system implementation margin.

In Figure 5.3-4, the pair of dashed lines are for a DS-CDMA star network with both PN coding losses and suppression effects omitted from the analysis. The other pair of lines are the ones which have been the model throughout this section, a DS-CDMA star network with PN coding losses and suppression effects included. The uncorrected curves have an optimum operating point of 0.55 W with an implementation margin of 5 dB. However, the correct operating point is at 1.14 W with an implementation margin of 3.4 dB. If the system operates at the 0.55 W point, then the remote-to-hub link has an

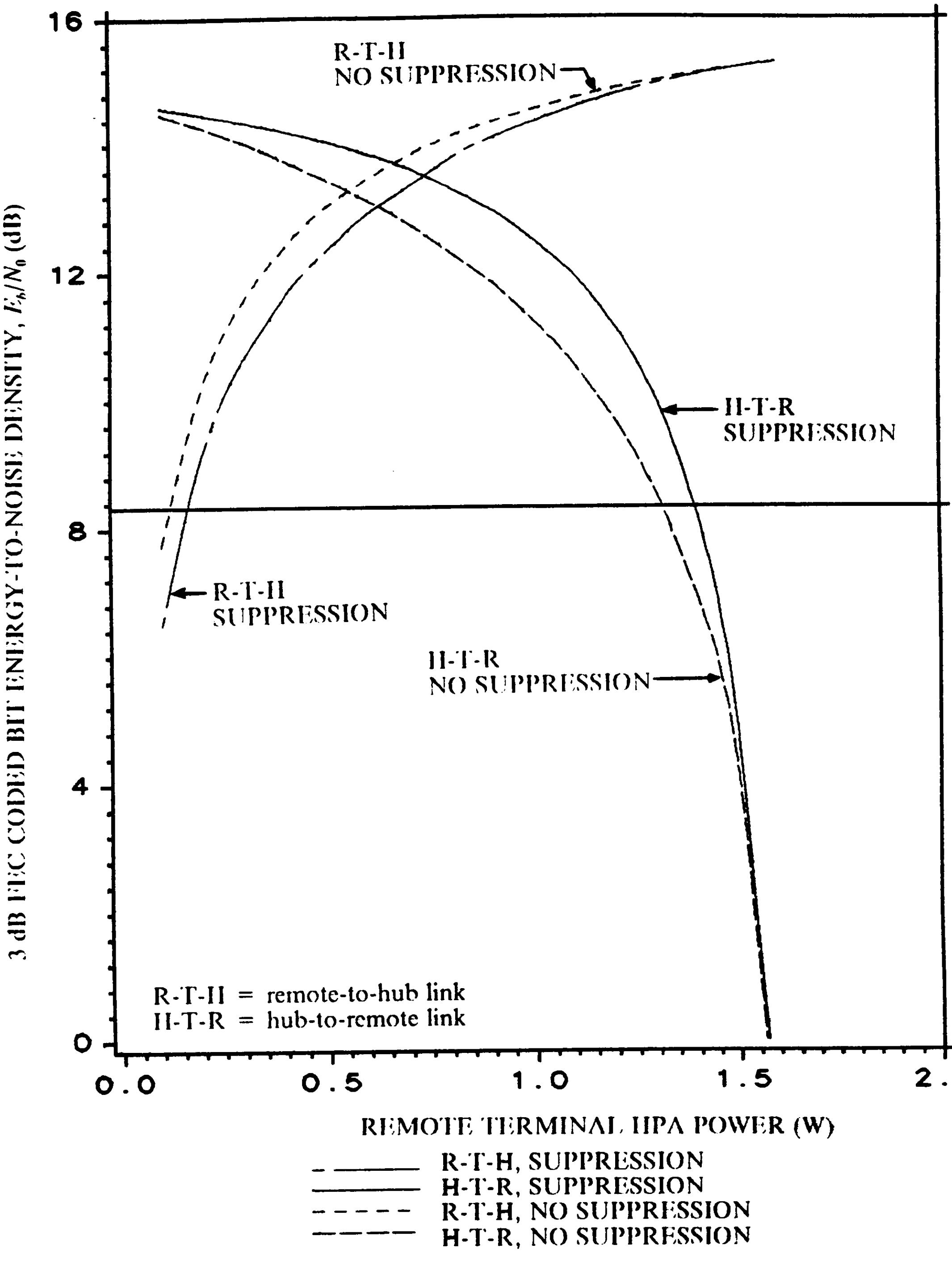


Figure 5.3-3. Comparison of performance in the star network with and without suppression for SCPC signals (1.8m, 32 kbps).

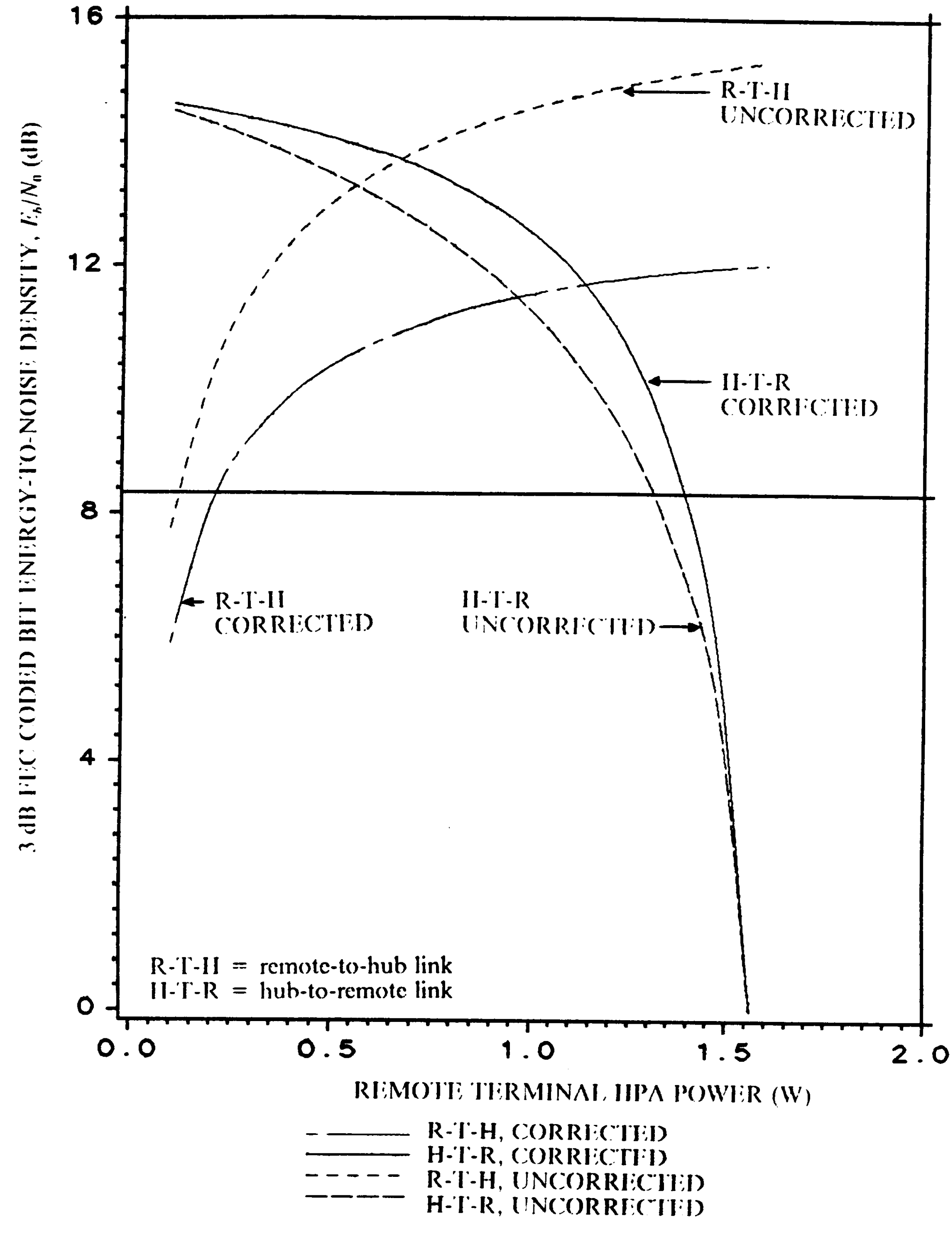


Figure 5.3-4. Comparison of DS-CDMA star network performance with and without correction for PN coding loss and suppression effects.

actual implementation margin of only 2.2 dB, and the system becomes more susceptable to rain fadeouts and equipment irregularities.

VI. CONCLUSIONS AND RECOMMENDATIONS

This thesis has presented the performance analysis of DS-CDMA and SCPC satellite networks for low-density communication. Full mesh and star network architectures have been examined for both techniques, and a partial mesh system was examined for SCPC. The analysis included satellite transponder suppression effects and PN coding crosscorrelation interference losses. Several conclusions follow.

1. DS-CDMA is feasible for VSAT networks. However, the technique is limited to some degree by the network configuration. For a full mesh system, DS-CDMA performs satsifactorily for 1.8m antennas and a 32 kbps bit rate; but the performance is marginal for a 64 kbps bit rate and unacceptable for either bit rate when 1.2m antennas are used. These limitations are not as severe for a star configuration; in fact, of the four combinations of antenna diameter and bit rate,

only the 1.2m antenna and 64 kbps bit rate combination has a marginally low implementation margin.

2. The loss due to PN coding crosscorrelation interference is significant in DS-CDMA systems. For the fifty 1023 bit Gold code set used in the analysis, the coding interference forced the VSAT terminals to operate at a higher HPA power and reduced the implementation margin by 1 to 2.5 dB, depending on the operating point. As a result, SCPC outperforms DS-CDMA for each network architecture.

3. Suppression effects shift a system's optimum operating point to higher VSAT HPA power levels. However, the shift is small, on the order of 0.1 to 0.3 W. The surprising result is that the system's optimum implementation margin does not suffer. In fact, it improves, although not significantly.

4. The star architecture outperforms the full mesh architecture for both types of transmission. Since the hub terminal in the star network is a medium antenna and not a VSAT terminal, its large antenna gain strengthens the remote-to-hub link. As all links are downlink limited, the hub-to-remote link does not improve appreciably; but the remote-to-hub link's improvement is significant and increases the system's implementation margin at the optimum operating point.

There are a few modifications to the analysis which would increase its accuracy. One is to find the optimal phases of the 1023 bit Gold codes. That task will offer only minor changes to the end result but will require a large amount of computer time to accomplish. Of greater value, Shaft's suppression equation should be directly incorporated into the computer program which performs the link analysis, so that values do not have to be read from the curve of Figure 3.1-1. Further, evaluating Shaft's equation for 1 strong signal and 50 weak signals may show a significant decrease in the transponder suppression compared to the case of 4 weak signals, which Ramanan evaluated and which was used in this thesis. These modifications to the analysis were not done due to limited computer resources.

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Appendix A. MESH2 FORTRAN

MESH2 is a FORTRAN computer program written to perform all DS-CDMA and SCPC link analysis calculations for the full mesh configuration. Internal DO loops (labeled 400, 410, 420, 430, and 440) control system parameters such as bit rate, antenna diameter, HPA power, and whether or not PN coding and suppression losses are included in the analysis. The program can feasibly be used for C-band analysis as well as Ku-band analysis, which is why it is not as streamlined as it could be.

```
C     PROGRAM MESH2
C
C     DAVID P. HAYES
C     JANUARY 1987
C
C*****THIS PROGRAM IS MODIFIED (A MAJOR MODIFICATION) FROM *****
C*****PROGRAM STAR1 --- DECEMBER 30, 1986.
C
C     THIS PROGRAM PERFORMS LINK ANALYSIS FOR C AND KU BANDS FOR THE
C     MESH NETWORK.  THE NETWORK CONSISTS OF N REMOTE
C     TERMINALS (N IS NORMALLY 50, BUT MAY BE CHANGED IN THE PROGRAM).
C     SPREAD SPECTRUM (SS) IS THE TRANSMISSION TECHNIQUE USED FOR THE
C     LINKS.  FOR A GIVEN HPA OUTPUT POWER, THE PROGRAM CALCULATES THE
C     NUMBER OF TERMINALS REQUIRED TO SATURATE THE TRANSPONDER (MINUS
C     INPUT BACKOFF).
C
C     FILEDEF 2 IS THE INPUT DATA FILE CONTAINING THE SET OF SPREAD
C     SPECTRUM AVERAGE INTERFERENCE PARAMETER SUMS (ISUM) FOR 511 BIT
C     GOLD CODES.  FILEDEF 3 IS SIMILAR BUT FOR 1023 BIT GOLD CODES.
C     FILEDEF 4 IS THE TERMINAL, FOR USER INPUT.
C     FILEDEF 7 IS THE OUTPUT FILE.
C
C     THE INPUT PARAMETERS ARE DEFINED IN THE FOLLOWING SECTION.
C     THE OUTPUT PARAMETERS ARE DEFINED AS THEY ARE CALCULATED IN THE
C     PROGRAM.
C
C     QPSK MODULATION IS USED.
C
C***********************************************************************
C
      REAL KEP,K,K1,LU,LD,LPD,LPU,LAU,LAD,LTU,LTD,LN,LR,LATE,LATS
     &,LONE,LONS
      DIMENSION ISUM(50),ISUMX(50),ISUMY(50)
      COMMON CNI,DU,DD,EIRP,GTS,I1,I2,RB,NGC,N,FS,PR,IXP
C
C     INPUT PARAMETERS---CONSTANTS
C
C     KEP = KEPPLER'S CONSTANT  (M**3/S**2)
C     ER = EARTH'S RADIUS  (M)
C     C = SPEED OF LIGHT  (M/S)
C     PI = PI  (CLEVER, HUH?)
C     K = BOLTZMANN'S CONSTANT  (W*S/K)
C
      KEP=0.398613E 15
      ER=0.637800E 07
      C=0.3E 09
      PI=3.1415927
      K=0.138E-22
C
C     INPUT PARAMETERS---VARIABLES
C
C     SUFFIXES U AND D, WHERE THEY APPEAR, DESIGNATE THE QUANTITY FOR
C     EITHER UPLINK OR DOWNLINK.
C
C     BOI = TWTA INPUT BACKOFF (DB)
C     BOO = TWTA OUTPUT BACKOFF (DB)
C     CNI = INTERMODULATION CARRIER TO NOISE (DB)
C     EFF = RECEIVING EARTH STATION'S ANTENNA EFFICIENCY (0<EFF<1)
C     EL = ELEVATION ANGLE OF EARTH STATION'S ANTENNA (DEGREES)
C     K1 = BANDWIDTH TO SYMBOL RATE PROPORTIONALITY CONSTANT
C        (FOR QPSK, K1 = 1.4)
C     T = ORBITAL PERIOD (SECONDS)
C     TE = RECEIVING EARTH STATION'S EQUIVALENT NOISE TEMPERATURE (K)
```

```
C
      PR=1.0
      IXP=0
      NGC2=0
      NGC3=0
      I3=0
      I4=0
      IDUMP=1
    2 KJI=0
      IF(I4.EQ.1)GO TO 20
    3 BOI=8.2
      BOO=3.5
      IF(I3.EQ.0)CNI=18.5
      EFF=0.60
      EL=20.0
      K1=1.4
      T=86400.00
      TE=370.0
C
C      D = ANTENNA DIAMETER (METERS)
C      EIRP = DOWNLINK EIRP (DBW)
C      FD = DOWNLINK CARRIER FREQUENCY (GHZ)
C      FU = UPLINK CARRIER FREQUENCY (GHZ)
C      FS = SATELLITE INPUT SATURATION FLUX DENSITY (DBW/M**2)
C      GTS = SATELLITE G OVER T; FIGURE OF MERIT (DB/K)
C      LAD = DOWNLINK ATMOSPHERIC LOSSES (DB)
C      LAU = UPLINK ATMOSPHERIC LOSSES (DB)
C      LATE = EARTH STATION LATITUDE (DEGREES)
C      LATS = SATELLITE LATITUDE (DEGREES)
C      LONE = EARTH STATION LONGITUDE (DEGREES)
C      LONS = SATELLITE LONGITUDE (DEGREES)
C      LR = RAIN ATTENUATION LOSSES (DB)
C      LTD = DOWNLINK ANTENNA TRACKING ERROR LOSSES (DB)
C      LTU = UPLINK ANTENNA TRACKING ERROR LOSSES (DB)
C      RB = DATA RATE (KBPS)
C      NGC = THE LENGTH OF THE GOLD CODES (BITS)
C      N = THE NUMBER OF REMOTE TERMINALS
C
      IF(I3.EQ.0)DU=1.8
      IF(I3.EQ.0)DD=1.8
      EIRP=34.0
      FD=4.0
      FU=6.0
      FS=-80.0
      GTS=-7.0
      LAD=0.5
      LAU=0.5
      LATE=37.20833
      LATS=0.0
      LONE=80.41667
      LONS=74.0
      LR=0.0
      LTD=0.5
      LTU=0.5
      IF(I3.EQ.0)RB=32.0
      IF(I3.EQ.0)NGC=1023
      IF(I3.EQ.0)N=50
C
C      I1 SPECIFIES C OR KU BAND:  0 = C BAND, 1 = KU BAND
C      I2 SPECIFIES CLEAR SKY OR RAIN:  0 = CLEAR SKY, 1 = RAIN
C
      IF(KJI.EQ.1)GO TO 14
      I1=1
```

```
      I2=0
C
   14 IF(I1.NE.1)GO TO 15
C     RESET VALUES TO PROPER VALUES FOR KU-BAND
C
      EIRP=42.0
      FD=11.7
      FU=14.0
      FS=-90.0
      GTS=-3.0
      TE=370.0
C
   15 IF(I2.NE.1)GO TO 20
C
      IF(I1.EQ.1)LR=2.0
      TE=480.0
C
C     I3 SPECIFIES POWER BUDGET.
C
   20 IF(KJI.EQ.0)WRITE(4,22)
   22 FORMAT(/'POWER BUDGET?  (0) NO  (1) YES')
      IF(KJI.EQ.0)READ(4,*)I3
      I3=0
      IF(I3.EQ.1)CALL DATACK(KJI)
      IF(KJI.EQ.1)GO TO 3
C
      DO 440 JA4=2,2
C
C     JA2=1 MEANS CODING LOSS IS INCLUDED IN THE CALCULATION; JA2=2
C     MEANS CODING LOSS IS NOT INCLUDED.  THE DIFFERENCE IS THAT THE
C     EBN0 IS USED INSTEAD OF THE SNRLO; THIS APPLIES ONLY TO THE
C     DATA FILE OUTPUT, NOT THE LISTING FILE OUTPUT
C
      DO 430 JA3=1,2
      RB=32.0
      IF(JA3.EQ.2)RB=64.0
C
      DO 420 JA2=1,2
      DU=1.8
      DD=1.8
      IF(JA2.EQ.2)DU=1.2
      IF(JA2.EQ.2)DD=1.2
C
      DO 410 JA1=2,2
      I3=1
      IF(JA1.EQ.2)I3=0
      IF(I3.EQ.1)PR=1.0
C
      IF(NGC2.EQ.1.AND.NGC3.EQ.1)GO TO 35
      DO 30 I=1,N
      IF(NGC.EQ.1023.AND.NGC3.EQ.0)READ(3,*)IJK,ISUMY(I)
      IF(NGC.EQ.511.AND.NGC2.EQ.0)READ(2,*)IJK,ISUMX(I)
   30 CONTINUE
      IF(NGC.EQ.1023)NGC3=1
      IF(NGC.EQ.511)NGC2=1
C
   35 DO 37 I=1,N
      IF(NGC.EQ.1023)ISUM(I)=ISUMY(I)
      IF(NGC.EQ.511)ISUM(I)=ISUMX(I)
   37 CONTINUE
C
C*******************************************************************
C
```

```
C   MATH SECTION
C
C
C   A = SEMIMAJOR AXIS OF SATELLITE'S ORBIT (METERS)
C   R = SLANT RANGE, DISTANCE FROM EARTH STATION TO SATELLITE (M)
C   GAMMA = THE CENTRAL ANGLE BETWEEN THE EARTH STATION AND THE
C        SATELLITE (DEGREES)
C
    X=1.0/3.0
    A=(T**2*KEP/(4.0*PI**2))**X
    X=PI/180.0
    GAMMA=ARCOS(COS(LATE*X)*COS(LATS*X)*COS((LONS-LONE)*X)+SIN(LATE*X)
   &*SIN(LATS*X))/X
    R=A*SQRT(1.0+(ER/A)**2-2.0*(ER/A)*COS(GAMMA*X))
    EL=ARCOS(A*SIN(GAMMA*X)/R)/X
C
C   WD = DOWNLINK WAVELENGTH (M)
C   WU = UPLINK WAVELENGTH (M)
C   LPD = DOWNLINK FREE-SPACE PATH LOSS (RATIO)
C   LPU = UPLINK FREE-SPACE PATH LOSS (RATIO)
C
    WD=C/(FD*0.1E 10)
    WU=C/(FU*0.1E 10)
    LPD=(4.0*PI*R/WD)**2
    LPU=(4.0*PI*R/WU)**2
C
C   LD = ADDITIONAL DOWNLINK LOSSES, INCLUDING BACKOFF  (DB)
C   LU = ADDITIONAL UPLINK LOSSES, INCLUDING BACKOFF  (DB)
C
    LD=LAD+LTD+LR
    LU=LAU+LTU
C
C   B = BIT RATE (MBPS)
C   BW = BANDWIDTH (MHZ)
C   FOR QPSK, BW = 0.5 * K1 * B
C
    B=NGC*RB/1000.0
    BW=0.5*K1*B
C
C   THE CNI VALUE IS CONVERTED TO NOISE DENSITY (DB).
C
    CI0=CNI+DB(0.5*K1*RB*1000.0)
C
C   G = GAIN OF THE REMOTE TERMINAL ANTENNA (RATIO)
C   GTE = G/T RATIO FOR THE EARTH STATION (RATIO)
C   U AND D ON THE END OF THE VARIABLES' NAMES STAND FOR UPLINK AND
C   DOWNLINK, RESPECTIVELY.
C
C
    GU=EFF*(PI*DU/WU)**2
    GD=EFF*(PI*DD/WD)**2
    GTE=GD/TE
C
C
    IF(I3.EQ.1)GO TO 65
    DO 400 J=1,20
    PR=0.10*J
C
C
C
C   POWER AND SUPPRESSION CALCULATIONS.
C
C   THE EIRP AND POWER VALUES ARE IN WATTS. THE LAST 2 LETTERS ON
```

```
C    THE VARIABLES' NAMES STAND FOR THE FOLLOWING:
C          T = TOTAL EIRP AFTER BO IS SUBTRACTED
C          R = GENERATED BY ONE REMOTE TERMINAL'S TRANSMISSION
C             SIGNAL, WHICH IS SS
C          D = DOWNLINK
C          U = UPLINK.
C
C    EXAMPLE:  EIRPRU = UPLINK EIRP (IN WATTS) PRODUCED BY ONE REMOTE
C                  TERMINAL (SS TRANSMISSION).
C
   65 EIRPTU=RATIO(FS-BOI+LU)*4.0*PI*R**2
      CHAN=N
      IF(IXP.EQ.1)GO TO 70
      EIRPRU=PR*GU
      CHAN=EIRPTU/EIRPRU
      EIRPU=N*EIRPRU
      GO TO 73
   70 EIRPRU=EIRPTU/N
      PR=EIRPRU/GRU
      EIRPU=N*EIRPRU
   73 EIRPTD=RATIO(EIRP-BOO)
      EIRPRD=EIRPTD/CHAN
C
C    NOW THE LINK ANALYSIS IS PEFORMED.
C
C
C    CNT  =  TOTAL CARRIER TO NOISE DENSITY  (RATIO)
C    CNU  =  UPLINK CARRIER TO NOISE DENSITY  (RATIO)
C    CND  =  DOWNLINK CARRIER TO NOISE DENSITY  (RATIO)
C    EBN0  =  ENERGY PER BIT / NOISE DENSITY (DB)
C    BER  =  BIT ERROR RATE
C
      CNU=EIRPRU*RATIO(GTS-LU)/(LPU*K)
      CND=EIRPRD*GTE/(LPD*K*RATIO(LD))
      CNT=1.0/(1.0/CNU+1.0/CND+1.0/RATIO(CI0))
      EBN0=DB(CNT/(RB*1000.0))
      BER=PRBERR(EBN0)
C
      X1=1.0/(6.0*NGC**3)
      X2=1.0/(2.0*RATIO(EBN0))
      SNRLO=100000.0
      SNRHI=-100000.0
      SNRAVG=0.0
      JLO=100000
      JHI=-100000
C
      DO 80 I=1,N
C
      SNR=DB(0.5/(ISUM(I)*X1+X2))
      IF(SNR.LE.SNRHI)GO TO 77
      SNRHI=SNR
      JHI=I
   77 IF(SNR.GE.SNRLO)GO TO 78
      SNRLO=SNR
      JLO=I
   78 SNRAVG=SNRAVG+SNR
C
   80 CONTINUE
C
      SNRAVG=SNRAVG/N
      BERAVG=PRBERR(SNRAVG+3.0)
      BERLO=PRBERR(SNRLO+3.0)
      BERHI=PRBERR(SNRHI+3.0)
```

```
C
C*****************************************************************
C
C    OUTPUT SECTION
C
     GO TO 100
  95 WRITE(7,96)PR,DB(N*EIRPRU),DB(EIRPTU)
  96 FORMAT(T4,'REMOTE TERMINAL HPA OUTPUT POWER (',F6.2,' WATTS) IS T'
    &,'OO HIGH.'/T4,'TOTAL SS EIRP = ',F4.1,' DBW EXCEEDS THE MAX. EIR'
    &,'P = ',F4.1,' DBW.'/)
     IF(I3.EQ.1)GO TO 500
     IF(I3.EQ.0)GO TO 400
C
C    THIS SECTION PERFORMS A DATA DUMP OF MOST OF THE DATA.  IT IS
C    ACTIVE WHEN IDUMP = 1 AND A POWER BUDGET HAS BEEN REQUESTED (I3=1)
C
 100 IF(IDUMP.NE.1.OR.I3.NE.1)GO TO 300
C
C
     WRITE(7,102)
 102 FORMAT('1'////T10,'INPUT PARAMETERS'//)
C
     IF(I1.EQ.0.AND.I2.EQ.0)WRITE(7,104)
     IF(I1.EQ.0.AND.I2.EQ.1)WRITE(7,106)
     IF(I1.EQ.1.AND.I2.EQ.0)WRITE(7,108)
     IF(I1.EQ.1.AND.I2.EQ.1)WRITE(7,110)
C
 104 FORMAT(T10,'C-BAND, CLEAR SKY'//)
 106 FORMAT(T10,'C-BAND, RAIN'//)
 108 FORMAT(T10,'KU-BAND, CLEAR SKY'//)
 110 FORMAT(T10,'KU-BAND, RAIN'//)
C
     WRITE(7,120)DU,BOI,DD,BOO,EIRP,CNI,FS,T,GTS,EFF,RB,
    &K1,NGC,TE,N,FU,LAD,FD,LAU,LATE,LTD,LATS,LTU,LONE,
    &LR,LONS
 120 FORMAT(T2,'DU  =',T10,E15.7,T30,'METERS',T45,'BOI  =',T53,E15.7,T73
    &,'DB'/
    &T2,'DD  =',T10,E15.7,T30,'METERS',T45,'BOO  =',T53,E15.7,T73,'DB'/
    &T2,'EIRP  =',T10,E15.7,T30,'DBW',T45,'CNI  =',T53,E15.7,T73,'DB'/
    &T2,'FS  =',T10,E15.7,T30,'DBW/M**2',T45,'T  =',T53,E15.7,T73,'SEC'/
    &T2,'GTS  =',T10,E15.7,T30,'DB/K',T45,'EFF  =',T53,E15.7/
    &T2,'RB  =',T10,E15.7,T30,'KBPS',T45,'K1  =',T53,E15.7/
    &T2,'NGC  =',T10,I6,T30,'BITS',T45,'TE  =',T53,E15.7,T73,'K'/
    &T2,'N  =',T10,I4,T30,'CODES',T45/
    &T2,'FU  =',T10,E15.7,T30,'GHZ',T45,'LAD  =',T53,E15.7,T73,'DB'/
    &T2,'FD  =',T10,E15.7,T30,'GHZ',T45,'LAU  =',T53,E15.7,T73,'DB'/
    &T2,'LATE  =',T10,E15.7,T30,'DEGREES N',T45,'LTD  =',T53,E15.7,T73,'D
    &B'/T2,'LATS  =',T10,E15.7,T30,'DEGREES N',T45,'LTU  =',T53,E15.7,T73
    &,'DB'/T2,'LONE  =',T10,E15.7,T30,'DEGREES W',T45,'LR  =',T53,E15.7
    &,T73,'DB'/T2,'LONS  =',T10,E15.7,T30,'DEGREES W'///)
C
     WRITE(7,125)
 125 FORMAT(//T10,'OUTPUT PARAMETERS'///)
C
     WRITE(7,130)A,R,GAMMA,EL,WU,WD,DB(LPU),DB(LPD),LU,LD,B,
    &BW,DB(GU),DB(GD),DB(GTE),PR
     WRITE(7,135)DB(EIRPTU),DB(EIRPRU),DB(EIRPU),CHAN,
    &DB(EIRPTD),DB(EIRPRD),DB(CNU),DB(CND),SNRLO,BERLO,JLO,CI0,DB(CNT),
    &SNRHI,BERHI,JHI,EBN0,BER,SNRAVG,BERAVG
 130 FORMAT(T2,'A  =',T10,E15.7,T30,'METERS',T45,'R  =',T53,E15.7,T73,'ME
    &TERS'/
    &T2,'GAMMA  =',T10,E15.7,T30,'DEGREES',T45,'EL  =',T53,E15.7,T73,'DEG
    &REES'/
```

```
   &T2,'WU  =',T10,E15.7,T30,'METERS',T45,'WD  =',T53,E15.7,T73,'METERS'
   &/T2,'LPU  =',T10,E15.7,T30,'DB',T45,'LPD  =',T53,E15.7,T73,'DB'/
   &T2,'LU  =',T10,E15.7,T30,'DB',T45,'LD  =',T53,E15.7,T73,'DB'/
   &T2,'B  =',T10,E15.7,T30,'MBPS',T45,'BW  =',T53,E15.7,T73,'MHZ'/
   &T2,'GU  =',T10,E15.7,T30,'DB',T45,'GD  =',T53,E15.7,T73,'DB',T85,
   &'SPREAD SPECTRUM ANALYSIS'/
   &T2,'GTE  =',T10,E15.7,T30,'DB/K',T45,'PR  =',T53,E15.7,T73,'WATTS',
   &T90,'CODED')
 135 FORMAT(T2,'EIRPTU  =',T10,E15.7,T30,'DBW',T45,'EIRPRU  =',T53,E15.7,
   &T73,'DBW',T90,'SNR (DB)',T102,'BER',T110,'CODE'/
   &T2,'EIRPU  =',T10,E15.7,T30,'DBW',T45,'CHAN  =',T53,E15.7/
   &T2,'EIRPTD  =',T10,E15.7,T30,'DBW',T45,'EIRPRD  =',T53,E15.7,T73,'DB
   7  =',T10,E15.7,T30,'DB',T45,'CND  =',T53,E15.7,T73,'DB',
   &T85,'LOW',T90,F6.2,T98,1PE11.3,T110,I3/
   &T2,'CI0  =',T10,0PE15.7,T30,'DB',T45,'CNT  =  ',E15.7,T73,'DB',
   &T85,'HIGH',T90,F6.2,T98,1PE11.3,T110,I3/
   &T2,'EBN0  =',T10,0PE15.7,T30,'DB',T45,'BER  =',T53,1PE11.3,
   &T85,'AVG.',T90,0PF6.2,T98,1PE11.3)
C
C   THIS SECTION PRINTS A POWER BUDGET WHEN I3 = 1.
C
 150 IF(I3.NE.1)GO TO 300
   IF(I3.EQ.1) GO TO 410
C
   WRITE(7,160)
 160 FORMAT('1'//////T10,'POWER BUDGET FOR THE STAR NETWORK'///)
   IF(I1.EQ.0.AND.I2.EQ.0)WRITE(7,162)
   IF(I1.EQ.0.AND.I2.EQ.1)WRITE(7,164)
   IF(I1.EQ.1.AND.I2.EQ.0)WRITE(7,166)
   IF(I1.EQ.1.AND.I2.EQ.1)WRITE(7,168)
C
 162 FORMAT(T4,'C-BAND, CLEAR SKY'//)
 164 FORMAT(T4,'C-BAND, RAIN'//)
 166 FORMAT(T4,'KU-BAND, CLEAR SKY'//)
 168 FORMAT(T4,'KU-BAND, RAIN'//)
C
 300 IF(J.NE.1)GO TO 330
   WRITE(7,305)
 305 FORMAT('1'//////T10,'MESH NETWORK ANALYSIS'//)
C
   IF(I1.EQ.0.AND.I2.EQ.0)WRITE(7,310)
   IF(I1.EQ.0.AND.I2.EQ.1)WRITE(7,312)
   IF(I1.EQ.1.AND.I2.EQ.0)WRITE(7,314)
   IF(I1.EQ.1.AND.I2.EQ.1)WRITE(7,316)
C
 310 FORMAT(T4,'C-BAND, CLEAR SKY'/)
 312 FORMAT(T4,'C-BAND, RAIN'/)
 314 FORMAT(T4,'KU-BAND, CLEAR SKY'/)
 316 FORMAT(T4,'KU-BAND, RAIN'/)
C
   WRITE(7,320)
 320 FORMAT(T10,'SATELLITE PARAMETERS',T35,'SS TERMINAL',T51,'REQUIRED'
   &,T61,'SS LINK'
   &//T2,'FLUX DENSITY',T15,'G/T',T25,'OUTPUT',T35,'D',T44,'HPA',
   &T54,'N',T61,'BIT RATE',T74,'CODED',T85,'BER'/
   &T2,'(SATURATED)',T15,'(DB/K)',T25,'EIRP',T33,'(METERS)',
   &T42,'(WATTS)',T61,'(DATA RATE)',T74,'SNRLO'/
   &T2,'(DBW/M**2)',T25,'(DBW)',T61,'(MBPS)',T74,'(DB)'//)
C
 330 WRITE(7,335)FS,GTS,EIRP,DD,PR,INT(CHAN),B,SNRLO,BERLO,(RB/1000.0)
 335 FORMAT(T4,F6.1,T15,F4.1,T25,F4.1,T35,F4.1,T42,F6.2,T53,I3,T61,
   &F6.3,T74,F4.1,T82,1PE11.3/T60,'(',0PF6.3,')')
C
```

```
      IF(JA4.EQ.1)WRITE(5,*)PR,SNRLO
      IF(JA4.EQ.2)WRITE(5,*)PR,EBN0
C
  400 CONTINUE
  410 CONTINUE
  420 CONTINUE
  430 CONTINUE
  440 CONTINUE
C
  500 WRITE(4,505)
  505 FORMAT(' SELECT:',T10,'(0)  PERFORM ANOTHER LINK ANALYSIS'/T10,
     &'(1)  QUIT'/)
      READ(4,*)IAGAIN
C
      I4=1
      IF(IAGAIN.EQ.0)GO TO 2
C
      STOP
      END
C
C**********************************************************************
C
C     THE FOLLOWING TWO FUNCTIONS CONVERT RATIOS TO DB AND
C     DB TO RATIOS.
C
      FUNCTION DB(XX)
      DB=10.0*ALOG10(XX)
      RETURN
      END
C
      FUNCTION RATIO(YY)
      ZZ=YY/10.0
      RATIO=10.0**ZZ
      RETURN
      END
C
C**********************************************************************
C
C     THIS SUBROUTINE ALLOWS THE USER TO INTERACTIVELY CHECK AND
C     CHANGE SOME OF THE DATA INPUT PARAMETERS WHEN IN THE POWER
C     BUDGET MODE (I3=1).
C
      SUBROUTINE DATACK(KJI)
C
      REAL KRBTDM
      COMMON CNI,DU,DD,EIRP,GTS,I1,I2,RB,NGC,N,FS,PR,IXP
C
    5 N2=0
      KJI=0
      IF(I1.EQ.0)WRITE(4,10)I1
      IF(I1.EQ.1)WRITE(4,12)I1
   10 FORMAT(///' (1) I1 = ',I1,' C BAND')
   12 FORMAT(///' (1) I1 = ',I1,' KU BAND')
      IF(I2.EQ.0)WRITE(4,14)I2
      IF(I2.EQ.1)WRITE(4,16)I2
   14 FORMAT(' (2) I2 = ',I1,' CLEAR SKY')
   16 FORMAT(' (2) I2 = ',I1,' RAIN')
      WRITE(4,20)DU,DD,EIRP,GTS,CNI,RB,NGC,N,FS,PR,IXP
   20 FORMAT(' (3) DU = ',F6.2,T26,'(4) DD = ',F6.2/
     &' (5) EIRP = ',F6.2,T26,'(6) GTS = ',F6.2/
     &' (7) CNI = ',F6.2,T26,'(8) RB = ',F6.2/
     &' (9) NGC = ',I5,T25,'(10) N = ',I3,T50,'(11) FS = ',F6.2/
     &'(12) PR = ',F6.2,T25,'(13) IXP = ',I1)
```

```
C
      WRITE(4,22)
   22 FORMAT('ENTER THE NUMBER OF THE PARAMETER TO BE CHANGED.'
     &/'ENTER 0 WHEN FINISHED OR IF NO CHANGES ARE DESIRED.')
   24 READ(4,*)N1
C
      IF(N1.EQ.0.AND.N2.EQ.0)GO TO 100
      IF(N1.EQ.0.AND.N2.EQ.1)GO TO 5
      WRITE(4,25)
   25 FORMAT('ENTER THE NEW VALUE')
      IF(N1.NE.1.AND.N1.NE.2)GO TO 30
      IF(N1.EQ.1)READ(4,*)I1
      IF(N1.EQ.2)READ(4,*)I2
      KJI=1
      GO TO 100
C
   30 IF(N1.EQ.3)READ(4,*)DU
      IF(N1.EQ.4)READ(4,*)DD
      IF(N1.EQ.5)READ(4,*)EIRP
      IF(N1.EQ.6)READ(4,*)GTS
      IF(N1.EQ.7)READ(4,*)CNI
      IF(N1.EQ.8)READ(4,*)RB
      IF(N1.EQ.9)READ(4,*)NGC
      IF(N1.EQ.10)READ(4,*)N
      IF(N1.EQ.11)READ(4,*)FS
      IF(N1.EQ.12)READ(4,*)PR
      IF(N1.EQ.13)READ(4,*)IXP
      IF(N1.EQ.0)GO TO 5
      N2=1
      GO TO 24
C
  100 RETURN
      END
C
C*********************************************************************
C
C     THIS SUBROUTINE DETERMINES AN APPROXIMATE SUPPRESSION VALUE
C     BASED ON V. RAMANAN, "AN ASYNCHRONOUS MULTIPLE ACCESS SCHEME
C     FOR SATELLITE COMMUNICATIONS", (A THESIS FOR DR. PRATT, VPI&SU
C     AND UNIVERSITY OF BIRMINGHAM), 1983, PP. 92-95, SPECIFICALLY
C     FIGURE 5.25 (A).
C
C     S1S5 = S1/S5 (DB)
C     S1N = S1/N (DB)
C     SP = SUPPRESSION VALUE READ FROM RAMANAN'S CURVES (DB)
C
      SUBROUTINE SUPRES(S1S5,S1N,SP)
C
      IF(S1S5.LE.4.0.OR.S1N.LT.5.0)GO TO 100
C
      IF(S1N.LT.20.0)GO TO 10
      IF(S1S5.GT.17.0)SP=6.0
      IF(S1S5.LE.17.0.AND.S1S5.GT.14.0)SP=5.5
      IF(S1S5.LE.14.0.AND.S1S5.GT.12.0)SP=5.0
      IF(S1S5.LE.12.0.AND.S1S5.GT.4.0)SP=0.5*S1S5-1.4
      IF(S1S5.LE.4.0)GO TO 100
      GO TO 200
C
   10 IF(S1N.LT.12.0)GO TO 20
      IF(S1S5.GT.17.0)SP=5.5
      IF(S1S5.LE.17.0.AND.S1S5.GT.13.0)SP=0.25*S1S5+1.25
      IF(S1S5.LE.13.0.AND.S1S5.GT.4.0)SP=0.41667*S1S5-0.91667
      IF(S1S5.LE.4.0)GO TO 100
```

```
      GO TO 200
C
   20 IF(S1N.LT.8.0)GO TO 30
      IF(S1S5.GT.22.0)SP=5.5
      IF(S1S5.LE.22.0.AND.S1S5.GT.15.0)SP=0.07143*S1S5+3.92857
      IF(S1S5.LE.15.0.AND.S1S5.GT.12.0)SP=0.3*S1S5+0.5
      IF(S1S5.LE.12.0.AND.S1S5.GT.5.0)SP=0.45714*S1S5-1.38571
      IF(S1S5.LE.5.0)GO TO 100
      GO TO 200
C
   30 IF(S1N.LT.5.0)GO TO 100
      IF(S1S5.GT.20.0)SP=4.75
      IF(S1S5.LE.20.0.AND.S1S5.GT.13.0)SP=0.14286*S1S5+1.89286
      IF(S1S5.LE.13.0.AND.S1S5.GT.5.0)SP=0.375*S1S5-1.125
      IF(S1S5.LE.5.0)GO TO 100
      GO TO 200
C
  100 IF(S1N.LT.5.0.AND.S1S5.GT.3.0)WRITE(4,105)S1S5,S1N
  105 FORMAT('S1S5 = ',F7.2.5X,'S1N = ',F7.2,5X,'ENTER S (IN DB)')
      IF(S1N.LT.5.0.AND.S1S5.GT.3.0)READ(4,*)SP
      IF(S1N.GE.5.0.AND.S1S5.LE.5.0)SP=0.2*S1S5
C
  200 RETURN
      END
C
C*********************************************************************
C
C     THIS FUNCTION USES INTERPOLATION AND EXTRAPOLATION
C     (WHICH ONE IS USED DEPENDS ON THE LOCATION OF THE
C     EB/N0 VALUE) TO DETERMINE THE
C     BER (BIT ERROR RATE). THE DATA POINTS IN ARRAYS XA AND YA ARE
C     FROM THE CURVE ON PAGE 159 OF DR. KAMILO FEHER'S BOOK 'DIGITAL
C     COMMUNICATIONS: SATELLITE/EARTH STATION ENGINEERING'.
C
C     THE PARAMETER AA SENT FROM THE CALLING ROUTINE SHOULD
C     BE THE EBN0 IN DB.
C
      FUNCTION PRBERR(AA)
      DIMENSION XA(14),YA(14)
      DATA (XA(NXA),NXA=1,14,1)/4.4,6.0,6.8,7.5,8.0,8.4,8.9,9.6,10.0,
     &10.5,10.9,11.3,12.0,12.6/
      DATA (YA(NYA),NYA=1,14,1)/0.1E-01,0.215E-02,0.1E-02,0.4E-03,0.18E-
     &03,0.1E-03,0.4E-04,0.1E-04,0.42E-05,0.1E-05,0.4E-06,0.1E-06,0.1E-0
     &7,0.1E-08/
C
      SLP1=-0.9606982
      YINT1=0.6851635
      SLP2=-3.837641
      YINT2=0.1E 13
C
      IF(AA.LT.XA(1))GO TO 10
      IF(AA.GT.XA(14))GO TO 20
C
      DO 5 ILOOP=1,14
      JLOOP=ILOOP-1
      IF(AA.GT.XA(ILOOP))GO TO 5
      SLPM=ALOG(YA(ILOOP)/YA(JLOOP))/(XA(ILOOP)-XA(JLOOP))
      YINTB=YA(JLOOP)/EXP(SLPM*XA(JLOOP))
      PRBERR=YINTB*EXP(SLPM*AA)
      GO TO 50
    5 CONTINUE
C
   10 PRBERR=YINT1*EXP(SLP1*AA)
```

```
      GO TO 50
C
   20 PRBERR=YINT2*EXP(SLP2*AA)
C
   50 RETURN
      END
```

Appendix B. STAR2 FORTRAN

STAR2 is a FORTRAN computer program written to perform all DS-CDMA and SCPC link analysis calculations for the star configuration. Internal DO loops (labeled 400, 410, 420, 430, 440, and 450) control system parameters such as bit rate, Gold code length, antenna diameter, HPA power, and whether or not PN coding and suppression losses are included in the analysis. The program can feasibly be used for C-band analysis as well as Ku-band analysis, which is why it is not as streamlined as it could be.

```
C   PROGRAM STAR2
C
C   DAVID P. HAYES
C   JANUARY 1987
C
C   THIS PROGRAM PERFORMS LINK ANALYSIS FOR C AND KU BANDS FOR THE
C   STAR NETWORK.  THE NETWORK CONSISTS OF ONE HUB AND N REMOTE
C   TERMINALS (N IS NORMALLY 50, BUT MAY BE CHANGED IN THE PROGRAM).
C   THE LINK BETWEEN THE HUB AND THE REMOTE TERMINALS IS A TDM
C   (TIME DIVISION MULTIPLEXING) LINK.  THE RETURN LINK BETWEEN THE
C   REMOTE TERMINALS AND THE HUB IS A SS (SPREAD SPECTRUM) LINK.
C
C   FILEDEF 2 IS THE INPUT DATA FILE CONTAINING THE SET OF SPREAD
C   SPECTRUM AVERAGE INTERFERENCE PARAMETER SUMS (ISUM) FOR 511 BIT
C   GOLD CODES.  FILEDEF 3 IS SIMILAR BUT FOR 1023 BIT GOLD CODES.
C   FILEDEF 4 IS THE TERMINAL, FOR USER INPUT.
C   OTHER FILEDEF VALUES ARE FOR OUTPUT.
C
C   THE INPUT PARAMETERS ARE DEFINED IN THE FOLLOWING SECTION.
C   THE OUTPUT PARAMETERS ARE DEFINED AS THEY ARE CALCULATED IN THE
C   PROGRAM.
C
C   QPSK MODULATION IS USED.
C
C***********************************************************************
C
      REAL KEP,K,K1,KRBTDM,LU,LD,LPD,LPU,LAU,LAD,LTU,LTD,LN,LR,LATE,LATS
     &,LONE,LONS
      DIMENSION ISUM(50),ISUMX(50),ISUMY(50)
      COMMON CNISS,CNITDM,DSS,DTDM,EIRP,GTS,I1,I2,KRBTDM,RBSS,NGC,N,FS,
     &PR,XP,IXP
C
C   INPUT PARAMETERS---CONSTANTS
C
C   KEP = KEPPLER'S CONSTANT  (M**3/S**2)
C   ER = EARTH'S RADIUS  (M)
C   C = SPEED OF LIGHT  (M/S)
C   PI = PI  (CLEVER, HUH?)
C   K = BOLTZMANN'S CONSTANT  (W*S/K)
C
      KEP=0.398613E 15
      ER=0.637800E 07
      C=0.3E 09
      PI=3.1415927
      K=0.138E-22
C
C   INPUT PARAMETERS---VARIABLES
C
C   SUFFIXES TDM AND SS, WHERE THEY APPEAR, DESIGNATE THE QUANTITY FOR
C   EITHER THE HUB TERMINAL (TDM) OR THE REMOTE TERMINALS (SS), BASED
C   UPON THE TRANSMISSION TECHNIQUE OF THE TERMINAL.
C
C   BOI = TWTA INPUT BACKOFF (DB)
C   BOO = TWTA OUTPUT BACKOFF (DB)
C   CNI = INTERMODULATION CARRIER TO NOISE (DB)
C   EFF = RECEIVING EARTH STATION'S ANTENNA EFFICIENCY (0 < EFF < 1)
C   EL = ELEVATION ANGLE OF EARTH STATION'S ANTENNA (DEGREES)
C   K1 = BANDWIDTH TO SYMBOL RATE PROPORTIONALITY CONSTANT
C       (FOR QPSK, K1 = 1.4)
C   T = ORBITAL PERIOD (SECONDS)
C   TE = RECEIVING EARTH STATION'S EQUIVALENT NOISE TEMPERATURE (K)
C
      PR=1.0
```

```
      XP=0.376
      IXP=0
      NGC2=0
      NGC3=0
      I3=0
      I4=0
      IDUMP=1
    2 KJI=0
      IF(I4.EQ.1)GO TO 20
    3 BOI=8.2
      BOO=3.5
      IF(I3.EQ.0)CNISS=18.5
      IF(I3.EQ.0)CNITDM=22.0
      EFF=0.60
      EL=20.0
      K1=1.4
      T=86400.00
      TETDM=120.0
      TESS=370.0
C
C      D = ANTENNA DIAMETER (METERS)
C      EIRP = DOWNLINK EIRP (DBW)
C      FD = DOWNLINK CARRIER FREQUENCY (GHZ)
C      FU = UPLINK CARRIER FREQUENCY (GHZ)
C      FS = SATELLITE INPUT SATURATION FLUX DENSITY (DBW/M**2)
C      GTS = SATELLITE G OVER T; FIGURE OF MERIT (DB/K)
C      LAD = DOWNLINK ATMOSPHERIC LOSSES (DB)
C      LAU = UPLINK ATMOSPHERIC LOSSES (DB)
C      LATE = EARTH STATION LATITUDE (DEGREES)
C      LATS = SATELLITE LATITUDE (DEGREES)
C      LONE = EARTH STATION LONGITUDE (DEGREES)
C      LONS = SATELLITE LONGITUDE (DEGREES)
C      LR = RAIN ATTENUATION LOSSES (DB)
C      LTD = DOWNLINK ANTENNA TRACKING ERROR LOSSES (DB)
C      LTU = UPLINK ANTENNA TRACKING ERROR LOSSES (DB)
C      RB = DATA RATE (KBPS)
C      KRB = BIT RATE FACTOR FOR FEC CODING
C      NGC = THE LENGTH OF THE GOLD CODES (BITS)
C      N = THE NUMBER OF REMOTE TERMINALS
C
      IF(I3.EQ.0)DSS=1.8
      IF(I3.EQ.0)DTDM=5.5
      EIRP=34.0
      FD=4.0
      FU=6.0
      FS=-80.0
      GTS=-7.0
      LAD=0.5
      LAU=0.5
      LATE=37.20833
      LATS=0.0
      LONE=80.41667
      LONS=74.0
      LR=0.0
      LTD=0.5
      LTU=0.5
      IF(I3.EQ.0)RBSS=32.0
      IF(I3.EQ.0)KRBTDM=1.0
      IF(I3.EQ.0)NGC=1023
      IF(I3.EQ.0)N=50
C
C      I1 SPECIFIES C OR KU BAND:  0 = C BAND, 1 = KU BAND
C      I2 SPECIFIES CLEAR SKY OR RAIN:  0 = CLEAR SKY, 1 = RAIN
```

```
C
      IF(KJI.EQ.1)GO TO 14
      I1=1
      I2=0
C
   14 IF(I1.NE.1)GO TO 15
C     RESET VALUES TO PROPER VALUES FOR KU-BAND
C
      EIRP=42.0
      FD=11.7
      FU=14.0
      FS=-90.0
      GTS=-3.0
      TETDM=260.0
      TESS=370.0
C
   15 IF(I2.NE.1)GO TO 20
C
      IF(I1.EQ.1)LR=2.0
      TETDM=370.0
C
C     I3 SPECIFIES POWER BUDGET.
C
   20 IF(KJI.EQ.0)WRITE(4,22)
   22 FORMAT(/'POWER BUDGET?  (0) NO  (1) YES')
      IF(KJI.EQ.0)READ(4,*)I3
      I3=0
      IF(I3.EQ.1)CALL DATACK(KJI)
      IF(KJI.EQ.1)GO TO 3
C
      DO 450 JA5=2,2
C
C     JA5=1 MEANS CODING AND SUPPRESSION ARE INCLUDED; JA5=2 MEANS
C     CODING LOSS IS OMITTED; J15=3 MEANS SUPPRESSION EFFECTS ARE
C     OMITTED; JA5=4 MEANS BOTH ARE OMITTED.
C     THE SUPPRESSION OMISSION APPLIES TO ALL OUTPUT; THE CODING
C     OMISSION APPLIES ONLY TO THE DATA FILE OUTPUT, NOT THE LISTING
C     FILE OUTPUT.  THE EBNOR VALUE IN THE DATA DUMP IS ALWAYS BEFORE
C     CODING EFFECTS HAVE BEEN INCLUDED.
C
      DO 440 JA4=1,1
      NGC=1023
      IF(JA4.EQ.2)NGC=511
C
      DO 430 JA3=1,2
      RBSS=32.0
      IF(JA3.EQ.2)RBSS=64.0
C
      DO 420 JA2=1,1
      DSS=1.8
      DTDM=5.5
      IF(JA2.EQ.2)DSS=1.2
C
      DO 410 JA1=2,2
      I3=1
      IF(JA1.EQ.2)I3=0
      IF(I3.EQ.1)PR=1.0
C
      IF(NGC2.EQ.1.AND.NGC3.EQ.1)GO TO 35
      DO 30 I=1,N
      IF(NGC.EQ.1023.AND.NGC3.EQ.0)READ(3,*)IJK,ISUMY(I)
      IF(NGC.EQ.511.AND.NGC2.EQ.0)READ(2,*)IJK,ISUMX(I)
   30 CONTINUE
```

```
      IF(NGC.EQ.1023)NGC3=1
      IF(NGC.EQ.511)NGC2=1
C
   35 DO 37 I=1,N
      IF(NGC.EQ.1023)ISUM(I)=ISUMY(I)
      IF(NGC.EQ.511)ISUM(I)=ISUMX(I)
   37 CONTINUE
C
C*******************************************************************
C
C     MATH SECTION
C
C
C     A = SEMIMAJOR AXIS OF SATELLITE'S ORBIT (METERS)
C     R = SLANT RANGE, DISTANCE FROM EARTH STATION TO SATELLITE (M)
C     GAMMA = THE CENTRAL ANGLE BETWEEN THE EARTH STATION AND THE
C           SATELLITE (DEGREES)
C
      X=1.0/3.0
      A=(T**2*KEP/(4.0*PI**2))**X
      X=PI/180.0
      GAMMA=ARCOS(COS(LATE*X)*COS(LATS*X)*COS((LONS-LONE)*X)+SIN(LATE*X)
     &*SIN(LATS*X))/X
      R=A*SQRT(1.0+(ER/A)**2-2.0*(ER/A)*COS(GAMMA*X))
      EL=ARCOS(A*SIN(GAMMA*X)/R)/X
C
C     WD = DOWNLINK WAVELENGTH (M)
C     WU = UPLINK WAVELENGTH (M)
C     LPD = DOWNLINK FREE-SPACE PATH LOSS (RATIO)
C     LPU = UPLINK FREE-SPACE PATH LOSS (RATIO)
C
      WD=C/(FD*0.1E 10)
      WU=C/(FU*0.1E 10)
      LPD=(4.0*PI*R/WD)**2
      LPU=(4.0*PI*R/WU)**2
C
C     LD = ADDITIONAL DOWNLINK LOSSES, INCLUDING BACKOFF  (DB)
C     LU = ADDITIONAL UPLINK LOSSES, INCLUDING BACKOFF  (DB)
C
      LD=LAD+LTD+LR
      LU=LAU+LTU
C
C     B = BIT RATE (MBPS)
C     BW = BANDWIDTH (MHZ)
C     FOR QPSK, BW = 0.5 * K1 * B
C
      BSS=NGC*RBSS/1000.0
      BTDM=KRBTDM*N*RBSS/1000.0
      BWSS=0.5*K1*BSS
      BWTDM=0.5*K1*BTDM
      BWTOT=BWSS+BWTDM
C
C     THE CNI VALUES ARE CONVERTED TO NOISE DENSITY (DB).
C
      CI0SS=CNISS+DB(0.5*K1*RBSS*1000.0)
      CI0TDM=CNITDM+DB(BWTDM*0.1E 07)
C
C     GR = GAIN OF THE REMOTE TERMINAL ANTENNA (RATIO)
C     GH = GAIN OF THE HUB TERMINAL ANTENNA (RATIO)
C     GTE = G/T RATIO FOR THE EARTH STATION (RATIO)
C     U AND D ON THE END OF THE VARIABLES' NAMES STAND FOR UPLINK AND
C     DOWNLINK, RESPECTIVELY.
C
```

```
C
      GRU=EFF*(PI*DSS/WU)**2
      GHU=EFF*(PI*DTDM/WU)**2
      GRD=EFF*(PI*DSS/WD)**2
      GHD=EFF*(PI*DTDM/WD)**2
      GTR=GRD/TESS
      GTH=GHD/TETDM
C
C
      IF(I3.EQ.1)GO TO 65
      DO 400 J=1,20
      PR=0.10*J
C
C
C
C      POWER AND SUPPRESSION CALCULATIONS.
C
C      THE EIRP AND POWER VALUES ARE IN WATTS.  THE LAST 2 LETTERS ON
C      THE VARIABLES' NAMES STAND FOR THE FOLLOWING:
C            T = TOTAL EIRP AFTER BO IS SUBTRACTED
C            H = GENERATED BY THE HUB'S TRANSMISSION SIGNAL, WHICH IS
C                TDM
C            R = GENERATED BY ONE REMOTE TERMINAL'S TRANSMISSION
C                SIGNAL, WHICH IS SS
C            D = DOWNLINK
C            U = UPLINK.
C
C      EXAMPLE:  EIRPRU = UPLINK EIRP (IN WATTS) PRODUCED BY ONE REMOTE
C                   TERMINAL (SS TRANSMISSION).
C
   65 EIRPTU=RATIO(FS-BOI+LU)*4.0*PI*R**2
      IF(IXP.EQ.1)GO TO 70
      EIRPRU=PR*GRU
      XP=1.0-(N*EIRPRU/EIRPTU)
      IF(XP.LT.0.0)GO TO 95
      GO TO 73
   70 EIRPRU=(1.0-XP)*EIRPTU/N
      PR=EIRPRU/GRU
   73 EIRPHU=XP*EIRPTU
      PH=EIRPHU/GHU
C
C      THE CARRIER POWER RECEIVED AT THE SATELLITE IS FOUND FOR HUB AND
C      REMOTE TERMINAL SIGNALS.  C IS THE CARRIER POWER (WATTS)
C
      CH=EIRPHU/(LPU*RATIO(LU))
      CR=EIRPRU/(LPU*RATIO(LU))
      CHCR=DB(CH/CR)
      CHN=DB(CH/(K*BWTDM*0.1E 07))+GTS
C
C      SP IS THE SUPPRESSION (IN DB) RESULTING FROM THE HUB ROBBING POWER
C      FROM THE REMOTE SIGNALS.
C
      CALL SUPRES(CHCR,CHN,SP)
      S=RATIO(SP)
      EIRPTD=RATIO(EIRP-BOO)
      EIRPRD=EIRPTD/(N+S*CH/CR)
      EIRPHD=EIRPTD-N*EIRPRD
C
      IF(JA5.EQ.1.OR.JA5.EQ.2)GO TO 75
      EIRPHD=XP*EIRPTD
      EIRPRD=(EIRPTD-EIRPHD)/N
C
C      NOW THE LINK ANALYSIS IS PEFORMED.
```

```
C
C
C    CNT = TOTAL CARRIER TO NOISE DENSITY  (RATIO)
C    CNU = UPLINK CARRIER TO NOISE DENSITY  (RATIO)
C    CND = DOWNLINK CARRIER TO NOISE DENSITY  (RATIO)
C    EBN0 = ENERGY PER BIT / NOISE DENSITY (DB)
C    BER = BIT ERROR RATE
C
C    THE LETTERS H AND R AT THE END OF THESE NAMES STAND FOR THE HUB-TO
C    -REMOTE LINK AND THE REMOTE-TO-HUB LINK, RESPECTIVELY.
C
   75 CNUH=EIRPHU*RATIO(GTS-LU)/(LPU*K)
      CNDH=EIRPHD*GTR/(LPD*K*RATIO(LD))
      CNTH=1.0/(1.0/CNUH+1.0/CNDH+1.0/RATIO(CI0TDM))
      EBN0H=DB(CNTH/(N*RBSS*1000.0))
      BERH=PRBERR(EBN0H+3.0)
C
      CNUR=EIRPRU*RATIO(GTS-LU)/(LPU*K)
      CNDR=EIRPRD*GTH/(LPD*K*RATIO(LD))
      CNTR=1.0/(1.0/CNUR+1.0/CNDR+1.0/RATIO(CI0SS))
      EBN0R=DB(CNTR/(RBSS*1000.0))
      BERR=PRBERR(EBN0R+3.0)
C
      X1=1.0/(6.0*NGC**3)
      X2=1.0/(2.0*RATIO(EBN0R))
      SNRLO=100000.0
      SNRHI=-100000.0
      SNRAVG=0.0
      JLO=100000
      JHI=-100000
C
      DO 80 I=1,N
C
      SNR=DB(0.5/(ISUM(I)*X1+X2))
      IF(SNR.LE.SNRHI)GO TO 77
      SNRHI=SNR
      JHI=I
   77 IF(SNR.GE.SNRLO)GO TO 78
      SNRLO=SNR
      JLO=I
   78 SNRAVG=SNRAVG+SNR
C
   80 CONTINUE
C
      SNRAVG=SNRAVG/N
      BERAVG=PRBERR(SNRAVG+3.0)
      BERLO=PRBERR(SNRLO+3.0)
      BERHI=PRBERR(SNRHI+3.0)
C
C*********************************************************************
C
C    OUTPUT SECTION
C
      GO TO 100
   95 IF(I3.EQ.0)GO TO 400
      WRITE(7,96)PR,DB(N*EIRPU),DB(N*EIRPTU)
   96 FORMAT(T4,'REMOTE TERMINAL HPA OUTPUT POWER (',F6.2,' WATTS) IS T'
     &,'OO HIGH.'/T4,'TOTAL SS EIRP = ',F4.1,' DBW EXCEEDS THE MAX. EIR'
     &,'P = ',F4.1,' DBW.'/)
      IF(I3.EQ.1)GO TO 410
      IF(I3.EQ.0)GO TO 410
C
C    THIS SECTION PERFORMS A DATA DUMP OF MOST OF THE DATA.  IT IS
```

```
C   ACTIVE WHEN IDUMP = 1 AND A POWER BUDGET HAS BEEN REQUESTED (I3=1)
C
 100 IF(IDUMP.NE.1.OR.I3.NE.1)GO TO 300
C
C
    WRITE(7,102)
 102 FORMAT('1'/////T10,'INPUT PARAMETERS'//)
C
    IF(I1.EQ.0.AND.I2.EQ.0)WRITE(7,104)
    IF(I1.EQ.0.AND.I2.EQ.1)WRITE(7,106)
    IF(I1.EQ.1.AND.I2.EQ.0)WRITE(7,108)
    IF(I1.EQ.1.AND.I2.EQ.1)WRITE(7,110)
C
 104 FORMAT(T10,'C-BAND, CLEAR SKY'//)
 106 FORMAT(T10,'C-BAND, RAIN'//)
 108 FORMAT(T10,'KU-BAND, CLEAR SKY'//)
 110 FORMAT(T10,'KU-BAND, RAIN'//)
C
    WRITE(7,120)DSS,BOI,DTDM,BOO,EIRP,CNISS,FS,CNITDM,GTS,EFF,RBSS,
   &K1,KRBTDM,T,NGC,TESS,N,TETDM,FU,LAD,FD,LAU,LATE,LTD,LATS,LTU,LONE,
   &LR,LONS
 120 FORMAT(T2,'DSS =',T10,E15.7,T30,'METERS',T45,'BOI =',T53,E15.7,T73
   &,'DB'/
   &T2,'DTDM =',T10,E15.7,T30,'METERS',T45,'BOO =',T53,E15.7,T73,'DB'/
   &T2,'EIRP =',T10,E15.7,T30,'DBW',T45,'CNISS =',T53,E15.7,T73,'DB'/
   &T2,'FS =',T10,E15.7,T30,'DBW/M**2',T45,'CNITDM =',T53,E15.7,T73,
   &'DB'/T2,'GTS =',T10,E15.7,T30,'DB/K',T45,'EFF =',T53,E15.7/
   &T2,'RBSS =',T10,E15.7,T30,'KBPS',T45,'K1 =',T53,E15.7/
   &T2,'KRBTDM =',T10,E15.7,T45,'T =',T53,E15.7,T73,'SEC'/
   &T2,'NGC =',T10,I6,T30,'BITS',T45,'TESS =',T53,E15.7,T73,'K'/
   &T2,'N =',T10,I4,T30,'CODES',T45,'TETDM =',T53,E15.7,T73,'K'/
   &T2,'FU =',T10,E15.7,T30,'GHZ',T45,'LAD =',T53,E15.7,T73,'DB'/
   &T2,'FD =',T10,E15.7,T30,'GHZ',T45,'LAU =',T53,E15.7,T73,'DB'/
   &T2,'LATE =',T10,E15.7,T30,'DEGREES N',T45,'LTD =',T53,E15.7,T73,'D
   &B'/T2,'LATS =',T10,E15.7,T30,'DEGREES N',T45,'LTU =',T53,E15.7,T73
   &,'DB'/T2,'LONE =',T10,E15.7,T30,'DEGREES W',T45,'LR =',T53,E15.7
   &,T73,'DB'/T2,'LONS =',T10,E15.7,T30,'DEGREES W'///)
C
    WRITE(7,125)
 125 FORMAT(//T10,'OUTPUT PARAMETERS'///)
C
    WRITE(7,130)A,R,GAMMA,EL,WU,WD,DB(LPU),DB(LPD),LU,LD,BTDM,BSS,
   &BWTDM,BWSS,BWTOT,DB(GHU),DB(GRU),DB(GHD),DB(GRD),DB(GTH),DB(GTR)
    WRITE(7,135)DB(EIRPTU),XP,DB(EIRPHU),DB(EIRPRU),PH,PR,DB(CH),DB(C
   &R)
    WRITE(7,137)CHCR,CHN,
   &SP,DB(EIRPTD),DB(EIRPHD),DB(EIRPRD),DB(CNUH),DB(CNUR),DB(CNDH),
   &DB(CNDR),SNRLO,BERLO,JLO,CI0TDM,CI0SS,SNRHI,BERHI,JHI,
   &DB(CNTH),DB(CNTR),SNRAVG,BERAVG,EBN0H,EBN0R,BERH,BERR
 130 FORMAT(T2,'A =',T10,E15.7,T30,'METERS',T45,'R =',T53,E15.7,T73,'ME
   &TERS'/
   &T2,'GAMMA =',T10,E15.7,T30,'DEGREES',T45,'EL =',T53,E15.7,T73,'DEG
   &REES'/
   &T2,'WU =',T10,E15.7,T30,'METERS',T45,'WD =',T53,E15.7,T73,'METERS'
   &/T2,'LPU =',T10,E15.7,T30,'DB',T45,'LPD =',T53,E15.7,T73,'DB'/
   &T2,'LU =',T10,E15.7,T30,'DB',T45,'LD =',T53,E15.7,T73,'DB'/
   &T2,'BTDM =',T10,E15.7,T30,'MBPS',T45,'BSS =',T53,E15.7,T73,'MBPS'/
   &T2,'BWTDM =',T10,E15.7,T30,'MHZ',T45,'BWSS =',T53,E15.7,T73,'MHZ'/
   &T2,'BWTOT =',T10,E15.7,T30,'MHZ'/
   &T2,'GHU =',T10,E15.7,T30,'DB',T45,'GRU =',T53,E15.7,T73,'DB'/
   &T2,'GHD =',T10,E15.7,T30,'DB',T45,'GRD =',T53,E15.7,T73,'DB'/
   &T2,'GTH =',T10,E15.7,T30,'DB/K',T45,'GTR =',T53,E15.7,T73,'DB/K')
 135 FORMAT(T2,'EIRPTU =',T10,E15.7,T30,'DBW',T45,'XP =',T53,E15.7/
```

```
     &T2,'EIRPHU =',T10,E15.7,T30,'DBW',T45,'EIRPRU =',T53,E15.7,T73,'DB
     6 =',T10,E15.7,T30,'WATTS',T45,'PR =',T53,E15.7,T73,'WATTS
     &'/T2,'CH =',T10,E15.7,T30,'DBW',T45,'CR =',T53,E15.7,T73,'DBW')
  137 FORMAT(T2,'CHCR =',T10,E15.7,T30,'DB',T45,'CHN =',T53,E15.7,T73,'D
     &B',T85,'SPREAD SPECTRUM ANALYSIS'/
     &T2,'S =',T10,E15.7,T30,'DB',T45,'EIRPTD =',T53,E15.7,T73,'DBW',
     &T90,'CODED'/
     &T2,'EIRPHD =',T10,E15.7,T30,'DBW',T45,'EIRPRD =',T53,E15.7,T73,'DB
     8 (DB)',T102,'BER',T110,'CODE'/
     &T2,'CNUH =',T10,E15.7,T30,'DB',T45,'CNUR =',T53,E15.7,T73,'DB'/
     &T2,'CNDH =',T10,E15.7,T30,'DB',T45,'CNDR =',T53,E15.7,T73,'DB',
     &T85,'LOW',T90,F6.2,T98,1PE11.3,T110,I3/
     &T2,'CI0TDM =',0PE15.7,T30,'DB',T45,'CI0SS = ',E15.7,T73,'DB',
     &T85,'HIGH',T90,F6.2,T98,1PE11.3,T110,I3/
     &T2,'CNTH =',T10,0PE15.7,T30,'DB',T45,'CNTR =',T53,E15.7,T73,'DB',
     &T85,'AVG.',T90,F6.2,T98,1PE11.3/
     &T2,'EBN0H =',T10,0PE15.7,T30,'DB',T45,'EBN0R =',T53,E15.7,T73,'DB'
     &/T2,'BERH =',T10,1PE11.3,T45,'BERR =',T53,1PE11.3)
C
C   THIS SECTION PRINTS A POWER BUDGET WHEN I3 = 1.
C
  150 IF(I3.NE.1)GO TO 300
      IF(I3.EQ.1) GO TO 410
C
      WRITE(7,160)
  160 FORMAT('1'//////T10,'POWER BUDGET FOR THE STAR NETWORK'///)
      IF(I1.EQ.0.AND.I2.EQ.0)WRITE(7,162)
      IF(I1.EQ.0.AND.I2.EQ.1)WRITE(7,164)
      IF(I1.EQ.1.AND.I2.EQ.0)WRITE(7,166)
      IF(I1.EQ.1.AND.I2.EQ.1)WRITE(7,168)
C
  162 FORMAT(T4,'C-BAND, CLEAR SKY'//)
  164 FORMAT(T4,'C-BAND, RAIN'//)
  166 FORMAT(T4,'KU-BAND, CLEAR SKY'//)
  168 FORMAT(T4,'KU-BAND, RAIN'//)
C
  300 IF(J.NE.1)GO TO 330
      WRITE(7,305)
  305 FORMAT('1'//////T10,'STAR NETWORK ANALYSIS'//)
C
      IF(I1.EQ.0.AND.I2.EQ.0)WRITE(7,310)
      IF(I1.EQ.0.AND.I2.EQ.1)WRITE(7,312)
      IF(I1.EQ.1.AND.I2.EQ.0)WRITE(7,314)(N*RBSS/1000.0),RBSS,BSS,BWTOT
      IF(I1.EQ.1.AND.I2.EQ.1)WRITE(7,316)
C
  310 FORMAT(T4,'C-BAND, CLEAR SKY'/)
  312 FORMAT(T4,'C-BAND, RAIN'/)
  314 FORMAT(T4,'KU-BAND, CLEAR SKY',', TDM BIT RATE = ',F6.3,' MBPS'
     &,', SS BIT RATE = ',F6.3,' KBPS',', SS CHIP RATE = ',F6.3,
     &' MBPS'/T4,'BWTOT = ',F6.3,' MHZ'/)
  316 FORMAT(T4,'KU-BAND, RAIN'/)
C
      WRITE(7,320)
  320 FORMAT(T10,'SATELLITE PARAMETERS',T44,'HUB TERMINAL',T59,'REMOTE '
     &,'TERMINAL',T82,'HUB-TO-REMOTE',T105,'REMOTE-TO-HUB '//T2
     &,'FLUX DENSITY',T15,'G/T',T25,'OUTPUT',T35,'X',T44,'D',T53,'HPA',
     &T61,'D',T70,'HPA',T79,'CODED',T90,'BER',T102,'CODED',T112,
     &'BER'/T2,'(SATURATED)',T15,'(DB/K)',T25,'EIRP',T42,'(METERS)',
     &T51,'(WATTS)',T59,'(METERS)',T68,'(WATTS)',T79,'EB/N0',
     &T102,'SNRLO'/T2,'(DBW/M**2)',T25,'(DBW)',T79,'(DB)',T102,'(DB)'//)
C
  330 WRITE(7,335)FS,GTS,EIRP,XP,DTDM,PH,DSS,PR,EBN0H,BERH,SNRLO,BERLO
  335 FORMAT(T4,F6.1,T15,F4.1,T25,F4.1,T35,F5.3,T44,F4.1,T51,F6.2,T61,
```

```
     &F3.1,T68,F6.2,T79,F4.1,T87,1PE11.3,T102,0PF4.1,T110,1PE11.3/)
C
      IF(JA1.NE.2)GO TO 400
      IF(JA5.EQ.2.OR.JA5.EQ.4)WRITE(5,*)PR,EBN0R
      IF(JA5.EQ.3)WRITE(5,*)PR,SNRLO
      WRITE(6,*)PR,EBN0H
C
  400 CONTINUE
  410 CONTINUE
  420 CONTINUE
  430 CONTINUE
  440 CONTINUE
  450 CONTINUE
C
  500 WRITE(4,505)
  505 FORMAT(' SELECT:',T10,'(0)  PERFORM ANOTHER LINK ANALYSIS'/T10,
     &'(1)  QUIT'/)
      READ(4,*)IAGAIN
C
      I4=1
      IF(IAGAIN.EQ.0)GO TO 2
C
      STOP
      END
C
C*********************************************************************
C
C     THE FOLLOWING TWO FUNCTIONS CONVERT RATIOS TO DB AND DB TO
C     RATIOS.
C
      FUNCTION DB(XX)
      DB=10.0*ALOG10(XX)
      RETURN
      END
C
      FUNCTION RATIO(YY)
      ZZ=YY/10.0
      RATIO=10.0**ZZ
      RETURN
      END
C
C*********************************************************************
C
C     THIS SUBROUTINE ALLOWS THE USER TO INTERACTIVELY CHECK AND
C     CHANGE SOME OF THE DATA INPUT PARAMETERS WHEN IN THE POWER
C     BUDGET MODE (I3=1).
C
      SUBROUTINE DATACK(KJI)
C
      REAL KRBTDM
      COMMON CNISS,CNITDM,DSS,DTDM,EIRP,GTS,I1,I2,KRBTDM,RBSS,NGC,N,FS,
     &PR,XP,IXP
C
    5 N2=0
      KJI=0
      IF(I1.EQ.0)WRITE(4,10)I1
      IF(I1.EQ.1)WRITE(4,12)I1
   10 FORMAT(///' (1) I1  =  ',I1,' C BAND')
   12 FORMAT(///' (1) I1  =  ',I1,' KU BAND')
      IF(I2.EQ.0)WRITE(4,14)I2
      IF(I2.EQ.1)WRITE(4,16)I2
   14 FORMAT(' (2) I2  =  ',I1,' CLEAR SKY')
   16 FORMAT(' (2) I2  =  ',I1,' RAIN')
```

```
      WRITE(4,20)DSS,DTDM,EIRP,GTS,CNISS,CNITDM,KRBTDM,RBSS,NGC,N,FS,
     &PR,XP,IXP
   20 FORMAT(' (3) DSS = ',F6.2,T26,'(4) DTDM = ',F6.2/
     &' (5) EIRP = ',F6.2,T26,'(6) GTS = ',F6.2/
     &' (7) CNISS = ',F6.2,T26,'(8) CNITDM = ',F6.2/
     &' (9) KRBTDM = ',F6.2,T25,'(10) RBSS = ',F6.2/
     &'(11) NGC = ',I5,T25,'(12) N = ',I3,T50,'(13) FS = ',F6.2/
     &'(14) PR = ',F6.2,T25,'(15) XP = ',F6.4,T50,'(16) IXP = ',I1)
C
      WRITE(4,22)
   22 FORMAT('ENTER THE NUMBER OF THE PARAMETER TO BE CHANGED.'/'ENTER '
     &'0 WHEN FINISHED OR IF NO CHANGES ARE DESIRED.')
   24 READ(4,*)N1
C
      IF(N1.EQ.0.AND.N2.EQ.0)GO TO 100
      IF(N1.EQ.0.AND.N2.EQ.1)GO TO 5
      WRITE(4,25)
   25 FORMAT('ENTER THE NEW VALUE')
      IF(N1.NE.1.AND.N1.NE.2)GO TO 30
      IF(N1.EQ.1)READ(4,*)I1
      IF(N1.EQ.2)READ(4,*)I2
      KJI=1
      GO TO 100
C
   30 IF(N1.EQ.3)READ(4,*)DSS
      IF(N1.EQ.4)READ(4,*)DTDM
      IF(N1.EQ.5)READ(4,*)EIRP
      IF(N1.EQ.6)READ(4,*)GTS
      IF(N1.EQ.7)READ(4,*)CNISS
      IF(N1.EQ.8)READ(4,*)CNITDM
      IF(N1.EQ.9)READ(4,*)KRBTDM
      IF(N1.EQ.10)READ(4,*)RBSS
      IF(N1.EQ.11)READ(4,*)NGC
      IF(N1.EQ.12)READ(4,*)N
      IF(N1.EQ.13)READ(4,*)FS
      IF(N1.EQ.14)READ(4,*)PR
      IF(N1.EQ.15)READ(4,*)XP
      IF(N1.EQ.16)READ(4,*)IXP
      IF(N1.EQ.0)GO TO 5
      N2=1
      GO TO 24
C
  100 RETURN
      END
C
C********************************************************************
C
C     THIS SUBROUTINE DETERMINES AN APPROXIMATE SUPPRESSION VALUE
C     BASED ON V. RAMANAN, "AN ASYNCHRONOUS MULTIPLE ACCESS SCHEME
C     FOR SATELLITE COMMUNICATIONS", (A THESIS FOR DR. PRATT, VPI&SU
C     AND UNIVERSITY OF BIRMINGHAM), 1983, PP. 92-95, SPECIFICALLY
C     FIGURE 5.25 (A).
C
C     S1S5 = S1/S5 (DB)
C     S1N = S1/N (DB)
C     SP = SUPPRESSION VALUE READ FROM RAMANAN'S CURVES (DB)
C
      SUBROUTINE SUPRES(S1S5,S1N,SP)
C
      IF(S1S5.LE.4.0.OR.S1N.LT.5.0)GO TO 100
C
      IF(S1N.LT.20.0)GO TO 10
      IF(S1S5.GT.17.0)SP=6.0
```

```
      IF(S1S5.LE.17.0.AND.S1S5.GT.14.0)SP=5.5
      IF(S1S5.LE.14.0.AND.S1S5.GT.12.0)SP=5.0
      IF(S1S5.LE.12.0.AND.S1S5.GT.4.0)SP=0.5*S1S5-1.4
      IF(S1S5.LE.4.0)GO TO 100
      GO TO 200
C
   10 IF(S1N.LT.12.0)GO TO 20
      IF(S1S5.GT.17.0)SP=5.5
      IF(S1S5.LE.17.0.AND.S1S5.GT.13.0)SP=0.25*S1S5+1.25
      IF(S1S5.LE.13.0.AND.S1S5.GT.4.0)SP=0.41667*S1S5-0.91667
      IF(S1S5.LE.4.0)GO TO 100
      GO TO 200
C
   20 IF(S1N.LT.8.0)GO TO 30
      IF(S1S5.GT.22.0)SP=5.5
      IF(S1S5.LE.22.0.AND.S1S5.GT.15.0)SP=0.07143*S1S5+3.92857
      IF(S1S5.LE.15.0.AND.S1S5.GT.12.0)SP=0.3*S1S5+0.5
      IF(S1S5.LE.12.0.AND.S1S5.GT.5.0)SP=0.45714*S1S5-1.38571
      IF(S1S5.LE.5.0)GO TO 100
      GO TO 200
C
   30 IF(S1N.LT.5.0)GO TO 100
      IF(S1S5.GT.20.0)SP=4.75
      IF(S1S5.LE.20.0.AND.S1S5.GT.13.0)SP=0.14286*S1S5+1.89286
      IF(S1S5.LE.13.0.AND.S1S5.GT.5.0)SP=0.375*S1S5-1.125
      IF(S1S5.LE.5.0)GO TO 100
      GO TO 200
C
  100 IF(S1N.LT.5.0.AND.S1S5.GT.3.0)WRITE(4,105)S1S5,S1N
  105 FORMAT('S1S5 = ',F7.2,5X,'S1N = ',F7.2,5X,'ENTER S (IN DB)')
      IF(S1N.LT.5.0.AND.S1S5.GT.3.0)READ(4,*)SP
      IF(S1N.GE.5.0.AND.S1S5.LE.5.0)SP=0.2*S1S5
C
  200 RETURN
      END
C
C*********************************************************************
C
C     THIS FUNCTION USES INTERPOLATION AND EXTRAPOLATION (WHICH ONE IS
C     USED DEPENDS ON THE LOCATION OF THE EB/N0 VALUE) TO DETERMINE THE
C     BER (BIT ERROR RATE).  THE DATA POINTS IN ARRAYS XA AND YA ARE
C     FROM THE CURVE ON PAGE 159 OF DR. KAMILO FEHER'S BOOK 'DIGITAL
C     COMMUNICATIONS:  SATELLITE/EARTH STATION ENGINEERING'.
C
C     THE PARAMETER AA SENT FROM THE CALLING ROUTINE SHOULD
C     BE THE EBN0 IN DB.
C
      FUNCTION PRBERR(AA)
      DIMENSION XA(14),YA(14)
      DATA (XA(NXA),NXA=1,14,1)/4.4,6.0,6.8,7.5,8.0,8.4,8.9,9.6,10.0,
     &10.5,10.9,11.3,12.0,12.6/
      DATA (YA(NYA),NYA=1,14,1)/0.1E-01,0.215E-02,0.1E-02,0.4E-03,0.18E-
     &03,0.1E-03,0.4E-04,0.1E-04,0.42E-05,0.1E-05,0.4E-06,0.1E-06,0.1E-0
     &7,0.1E-08/
C
      SLP1=-0.9606982
      YINT1=0.6851635
      SLP2=-3.837641
      YINT2=0.1E 13
C
      IF(AA.LT.XA(1))GO TO 10
      IF(AA.GT.XA(14))GO TO 20
C
```

```
      DO 5 ILOOP=1,14
      JLOOP=ILOOP-1
      IF(AA.GT.XA(ILOOP))GO TO 5
      SLPM=ALOG(YA(ILOOP)/YA(JLOOP))/(XA(ILOOP)-XA(JLOOP))
      YINTB=YA(JLOOP)/EXP(SLPM*XA(JLOOP))
      PRBERR=YINTB*EXP(SLPM*AA)
      GO TO 50
    5 CONTINUE
C
   10 PRBERR=YINT1*EXP(SLP1*AA)
      GO TO 50
C
   20 PRBERR=YINT2*EXP(SLP2*AA)
C
   50 RETURN
      END
```

The vita has been removed from
the scanned document