N92-24130

Performance of Random Multiple Access Transmission System

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ABSTRACT

This paper determines the performance of the RMA technique applied to direct terminal-to-terminal link with large number of potential users. The average signal-to-noise (SNR) is derived. Under Gaussian assumption, the approximation of the probability of error is given. The analysis shows that the system performance is affected by the sequence length, the number of simultaneous users, and the number of cochannel symbols, but is not sensitive to the thermal noise. The performance of using very small aperture antenna for both transmitting and receiving without a hub station is given.

INTRODUCTION

Most satellite networks, at present, use earth stations as shared nodes or involve a number of small terminals in a star network interacting with a central master station, or hub station. Random Multiple Access (RMA) technique will allow very small aperture terminals (VSAT) to be installed directly on end-user premises (fixed or mobile terminals) and have a mesh configuration. The reason for mesh configuration is to avoid double-hop of messages through the gateway or hub stations, thus, allowing small terminal to small terminal interconnectivity.

Within a satellite antenna coverage area, all terminals potentially can directly communicate with any other terminal. For n terminals, the number of possible terminal-to-terminal link is n(n-1)/2. If the system consists of five thousand terminals or more, then the potential number of connection is over 12,497,500 different links. Under such conditions, frequency division multiple access (FDMA), or time division multiple access (TDMA), or any other orthogonal access system are not likely to be feasible. The direct sequence spread spectrum (DS-SS) is also not shown for applications of such large number of user links. Therefore, it appears that RMA is an attractive solution to provide access for large number of VSAT.

The basic transmission scheme of a RMA system is the transformation of each binary bit into a set of time-frequency (TF) symbols. These symbols form a code sequence which is uniquely assigned to a particular user. The receiver of the system, then, performs the inverse transformation from a sequence of symbols back to the corresponding binary bit.

The procedures for RMA code sequence generation, which utilizing Euclidean Geometry (EG) Difference Set {De} and Projective Geometry (PG) Difference Set {Dp}, were presented in [1] [2] [4]. In this paper only the system performance results based on the derivation from {De} are presented.

Section Two describes the system model and defines the notations. Section Three addresses the issue of average signal to noise ratio. Section Four relates signal to noise ratio to the probability of error with sequence parameters. Numerical examples are given in Section Five.

SYSTEM MODEL

Our model for a RMA transmission system presented in Figure 1 is taken from [1]. The L active users simultaneously transmit through the satellite transponder to L receivers. Each RMA transmitter contains a set of frequency generators (FG), a set of delay units, biphase modulators, and assembler. Assume that each transmitter has the same power and there is only one overlapping symbol between any two sequences.

The #k user's data signal b_k (t) is a sequence of unit amplitude, positive and negative, rectangular pulse of duration T. The #k user is assigned a RMA code sequence, which contains M symbols, to represent each of it's binary information bit. Each FG generates a carrier frequency with proper delay by the delay unit to represent a symbol in the code sequence. The biphase modulator phase modulates the data signal b_k (t) of the #k user onto the carrier. The number of such FG and delay units depends on the number of symbols/sequence (M). After passing through the assembler, the corresponding code sequence S_k (t) is formed for transmission. The remaining (L-1) transmitters are identical to the #k transmitter except that different FG and delay units are used to generate different code sequence for each of the transmitters.

A the receiving end, the corresponding FG and delay units, and correlation detections are used to reverse the encoding process from the received signal W(t). The total output from all M correlation receivers of any #k user (C_k) will include the desired signal b_k (t), channel noise n(t), and multiple-access interference (MAI) signals. The recovery of the data bit b_k is done by the threshold comparator which provides at T interval a +1 or -1 output state, depending on whether C_k is larger or smaller than zero.

The analysis of the interaction between RMA signals in a multiple access transmission environment is presented in [1] [3]. The analysis shows that SNR depends on the number of simultaneous users (c) the number of energy per data bit, and the design of TF matrix.

Because the statistic of the simultaneous users is time varying, the exact evaluations of SNR and error rate Pe are difficult. Instead, an approximation will be used, based on the assumption that all noise is additive white Gaussian noise and large number of users are involved. The system is operating in the environment where there are strong interfering signals, hence, the system performance is not sensitive to the variation in the thermal noise. Consequently, allowing the use of very large number of small aperture terminals for both transmission and reception.

APPROXIMATION OF THE AVERAGE SIGNAL-TO-NOISE RATIO

We have shown in [1] [3] that the output from each correlation receiver includes the desired signal, channel noise, and the multiple-access interference (MAI). This MAI is caused by all simultaneous users whose sequence symbols are represented by the same carrier frequencies as the desired symbols. The total number of cochannel symbols for each carrier is simply the number of time-delay units in the TF matrix, or T_d.

The precise value of MAI can be calculated only when the statistic of the simultaneous users are known at a particular time for a particular system determined by the corresponding TF matrix. Therefore, the average value of multiple access interference and consequently the signal-to-noise ratio, which is useful for preliminary system design where the statistic of each user is not available but the sequence parameters and TF matrix are known, will be determined. The

SNR at the input of the threshold comparator can be expressed as [1].

$$\overline{SNR} = \left[\frac{M}{\frac{\overline{U}}{3M} + \frac{N_o}{2E_b}}\right]^{1/2} \tag{1}$$

$$\text{where } \overline{U} = \bar{a} + c\bar{d} = \frac{\overline{U}}{3M} \tag{2}$$

The parameters $\bar{a}$ and $\bar{d}$ are the part of MAI of any user, which is caused by his own transmitter, and any other simultaneous user accordingly.

$\bar{a}$ = average number of designated cochannel symbols ($0 \le a \le M$)
$\bar{d}$ = average number of cochannel symbols between designated user and any other user ($0 \le d \le M$)
c = total number of simultaneous users ($0 \le c < L$)

Both $\bar{a}$ and $\bar{d}$ can be expressed in term of sequence length, as followed:

$$\bar{a} = yM \quad \text{where } 0 \le y \le 1 \tag{3}$$

$$\bar{d} = \frac{\max.\ (U) - yM}{\max.\ (c)} \tag{4}$$

Parameter y is a user's cochannel symbols-to-sequence symbols ratio, or

$$\bar{y} = \frac{\left[\text{average number of cochannel symbols in a sequence}\right]}{\left[\text{total number of symbols in that sequence}\right]}$$

When all users are activated simultaneously, we have

$$\max.\ (c) = L - 1 \tag{5}$$

$$\text{where } L = L_e = M(M+1) \tag{6}$$

The maximum value of parameter U are given by [1]

$$\max.\ (U) = M[(M+1)T_d - 1] \tag{7}$$

Substituting (7) and (6) into (4)

$$d = \frac{M[(M+1)T_d - 1] - yM}{M(M+1) - 1} \tag{8}$$

Since M>>1, (8) reduce to

$$d \approx T_d \tag{9}$$

From (2), (3) and (9), we have

$$\overline{U} = yM + cT_d \tag{10}$$

Finally substituting $\overline{U}$ into (1), we have

$$\overline{SNR} = \left[\frac{M}{\frac{1}{3M}[\bar{y}M + cT_d] + \frac{N_o}{2E_b}}\right]^{1/2} \tag{11}$$

In terms of energy per data bit, (11) can be expressed as

$$\overline{SNR} = \left[\frac{M}{\frac{1}{(E_b/N_o)_{MAI}} + \frac{1}{(E_b/N_o)_{th.}}}\right]^{1/2} \tag{12}$$

where $\left(\frac{E_b}{N_o}\right)_{th.}$ = energy -per-bit/channel thermal noise density ratio

$$\left(\frac{E_b}{N_o}\right)_{MAI} = \frac{3M}{\bar{y}M + cT_d} \tag{13}$$

or $\left(\frac{E_b}{N_o}\right)_{MAI}$ = energy-per-bit/multiple-access-interference density ratio

PROBABILITY OF ERROR

In this case of a communication system with additive white Gaussion noise (AWGN), which includes multiple access interference noise and channel noise, a data bit error occurs at the threshold comparator output when the integrated amplitude of the noise is larger than the integrated amplitude of the desired signal in the opposite direction.

The threshold comparator provides, at T intervals, a +1 or -1 output state, depending on whether C is larger or smaller than zero, respectively. Thus, the probability of error is given by

$$Pe = P[C_i>0/b_i = -1]\ P[b_i = -1] + P[C_i<0/b_i = +1\ P[b_i = +1] \quad (14)$$

where $P[C_i>0/b_i = -1]$ = probability of having sampled C_i larger than zero, given that a -1 (b_i) is being transmitted

For equa-probable signaling, (14) becomes

$$Pe = 0.5\{P[C_i>0/b_i = -1] + P[C_i<0/b_i = +1]\}$$

or Pe = 0.5 P[(total noise at the sampling instant) > (total desired signals at the sampling instant)]

The probability of error can be approximated by

$$Pe \approx Q[\overline{SNR}] \quad (15)$$

From (11) and (15), we can conclude that the probability of error of the RMA system depends on the following parameters:

- sequence length (M)
- user's cochannel symbols-to-sequence symbols ratio (y)
- number of simultaneous users (c)
- number of time-delay in the TF matrix or number of cochannel symbols (T_d)
- energy-per-bit/channel-thermal-noise density ratio $(E_b/N_o)_{th.}$

Note that the parameters M, y and T_d depend on the structure of the sequence and the size of the TF matrix, but the $(E_b/N_o)_{th.}$ can be calculated from the link budget parameters, such as transmitted carrier power, bit rate, etc. It is of interest to know how the system will perform when the number of simultaneous users are varying, as this is the only parameter which can not be predetermined or fixed due to the random access nature of the system. Thus, the graphs in Figures 2 - 5 are of Pe versus C for different values of M, y, T_d and $(E_b/N_o)_{th.}$

Our objective is to keep the value of $(E_b/N_o)_{th.}$ to a minimum; as the higher $(E_b/N_o)_{th.}$ may result in higher uplink carrier power, or larger antenna at the received station or a reduced data rate. We assume that all stations have the same power, thus, any increase in energy per data bit from the desired user also means an increase in the MAI. Therefore, $(E_b/N_o)_{th.}$ has little effect on the Pe as we can observe in Figure 3. The Pe is also not sensitive to the change of parameter y as shown in the plot in Figure 4. On the contrary Figures 2 and 5 demonstrate that the sequence length and the number of cochannel symbols in the TF matrix greatly affect the probability of error, especially when the number of simultaneous users are relatively very small compared to the total number of users.

Plots in all figures are for sequences of length 59, 97, 107, 127, and 169 which can be constructed from EG sets. The corresponding number of users are calculated from (6) as followed:

Table 1. Total Number of Users For Each Sequence

Sequence Length (M)	Total No. of Users (L_e)
59	3,450
97	9,560
107	11,556
127	16,256
169	28,730
289	83,810

For preliminary system design it is useful to be able to carry out a tradeoff between the parameters M, T_d, and c as they all have significant effect on Pe. Such a tradeoff can be obtained from (11) and (15) as:

$$Pe - Q\left[\frac{M}{\frac{1}{3}\,[y + \frac{cT_d}{M}] + \frac{N_o}{2E_b}}\right]^{1/2} \quad (16)$$

Given y = 0.2, E_b/N_o = 0.2 dB, (16) becomes

$$Pe - Q\left[\frac{M}{\frac{1}{3}[0.2 + \frac{cT_d}{M}] + 0.477}\right]^{1/2} \quad (17)$$

The effects of these three parameters can be summarized as followed:

1) For a fixed number of simultaneous users, we have to increase the sequence length in order to improve the system performance. An example is shown in Table 2

Table 2. Pe for Different Sequence Length When Number of Simultaneous Users is Fixed (c = 25), and T_d = M

M	Pe
289	5.95E-09
169	6.71E-06
127	8.00E-05
107	2.65E-04
97	4.72E-04
59	4.90E-03

2) If a certain percentage of users is expected to transmit simultaneously, we'll find that smaller size system will have a better performance than the bigger one. This can be observed from the Table 3.

Table 3 Pe for Different System Size When c is a Fixed Percentage of Total Users (c = 0.001% of L), and T_d = M

Total users	c = 0.001% of Total users	Pe
83,810	84	7.4E-04
28,730	29	2.5E-05
16,256	16	1.7E-06
11,556	12	6.3E-07
9,506	10	2.9E-07
3,540	4	1.0E-08

3) Since the noise in this RMA system is dominated by cochannel interference, we can improve the system performance by reducing the number of cochannel symbols. In other words,

we have to reduce T_d while increasing F accordingly, so that the total number of symbols ($V = T_d*F$) can remain constant.

Table 4 and Figure 5 show how we can significantly reduce the probability of error by increasing the carrier frequency. In this specific example, the sequences are derived from a EG set, hence, $T_d*F=M^2$. When the TF matrix is a square matrix, we have $F = T_d = M$. If we reduce the cochannel symbols by half, the TF matrix becomes a rectangular matrix and F = 2M.

Table 4. Pe for Different Cochannel Symbols (T_d) (M = 169)

c (users)	$T_d = M$	$T_d = 0.5M$
14	4.48E-09	3.38E-15
16	3.45E-08	1.03E-13
18	1.64E-07	1.45E-12
20	5.84E-07	1.29E-11
22	1.68E-06	8.12E-11
24	4.12E-06	3.89E-10
26	8.87E-06	1.50E-09
28	1.72E-05	4.88E-09
30	3.0E-05	1.38E-08

4) If the system is designed to provide a fixed nominal bit error rate performance, the number of simultaneous users can not exceed a certain limit. An example is shown in Table 5.

Table 5. Maximum Number of Simultaneous Users for Different Sequence Length When $Pe = 10^{-7}$ and $T_d = M$

M	Maximum c	Max. c as % of Total Users
289	31	0.037%
169	16	0.056%
127	13	0.08%
107	11	0.095%
97	10	0.1%
59	5	0.14%

EXAMPLES OF LINK BUDGET FOR VERY SMALL APERTURE ANTENNAS

In this section some link budgets are presented to illustrate that the proposed RMA technique is of use to a system with very small aperture terminals (VSAT).

We have demonstrated in the previous section that the $(E_b/N_o)_{th.}$ has some contribution to the system performance (Pe) but it will require a big increase in $(E_b/N_o)_{th.}$ to have any noticeable effect on Pe. In addition, the carrier power varies with $(E_b/N_o)_{th.}$, thus, it is important to keep the value of this parameter at some minimum level. Since the lowest level of $(E_b/N_o)_{th.}$ assumed in this section is 2.0 dB, we will use this same value for conveniently relating the link budgets to the PE already calculated. The link budgets are designed for the system which the transmit and receive stations are the same size.

	14/11 GHz			6/4
Antenna Diameter (m).	1.2	1	0.8	1
Antenna Gain (dB)	42.3	40.8	38.8	35.0
HPA (dB/carrier)	-24.1	-21.6	-16.9	-1.4
EIRP/carrier (dBW)	18.2	19.2	21.9	33.6
Satellite G/T (dB/K)	1.7	1.7	1.7	-2.0
Up Link (C/T) thermal (dBW/K)	-188.1	-186.4	-184.4	-169.1
Antenna Gain 1 m^2 (dB-m^2)	44.0	44.0	44.0	37.0
Saturation Flux Density (dBW/m^2)	-90.5	-90.5	-90.5	-81.0
Input Backoff/ carrier (dB)	-53.6	-51.9	-49.9	-51.1
Output Backoff/ carrier (dB)	-48.1	-46.4	-44.4	-46.6
EIRP Downlink (dBW)	-7.1	-5.4	-3.4	-10.6
Earth Station G/T (dB/K)	15.5	13.8	11.8	10.0

At Ku-band the EIRP is assumed as 41.0 dB, downlink (C/T) is -197.6 dBW/K which is almost the same as the total (C/T). At C-band the EIRP is 36.0 dB and the total (C/T) or (C/No) is the same as that of Ku-band.

In order to increase the speed of information bit, we have to increase the transmitted EIRP or increase G/T of the earth terminal. Table 6 shows bit rate versus (E_b/N_o)th..

Table 6. $(C/N_o)_{th.}$ Required for Different Bit Rate

R_b bit/sec.	R_b dB	Total $(C/N_o)_{th.}$ dBW/Hz
1200	30.8	31
2400	33.8	34
4800	36.8	37
9600	39.8	40

As an example, if we increase the information bit rate of 1200 bit/sec. to 4800 bit/sec., we have to increase the EIRP proportionally. That is to raise the uplink EIRP level up to 6 dB. Another alternative is to introduce error coding in order to increase the G/T by 6 dB.

CONCLUSION

The expressions for approximation of the signal-to-noise ratio and the probability of error of the RMA system has been obtained, based on the Gaussian interference assumption. It is assumed that the system consists of a large number of users, thus, long sequence are required.

The evaluations of the error probability are presented. The results show that the sequence length, the number of cochannel symbols in the TF matrix and the number of simultaneous users, which all contribute to the multiple access interference (MAI) parameters, affect the bit error rate. On the contrary, the system is not sensitive to the changes in the energy-per-bit/channel thermal noise density ratio $(E_b/N_o)_{th.}$, thus, allowing the use of very small aperture terminals (VSAT) for both transmission and reception without a larger hub station. The examples of link budget for VSAT are given for illustration.

However, the system performance will degrade rapidly as the number of simultaneous users is increasing. Therefore, this access technique is suitable for systems with large number of users and light traffic. This technique can be applied to emergency network, military network, thin route commercial network, and mobile satellite communication for aeronautical, land or maritime.

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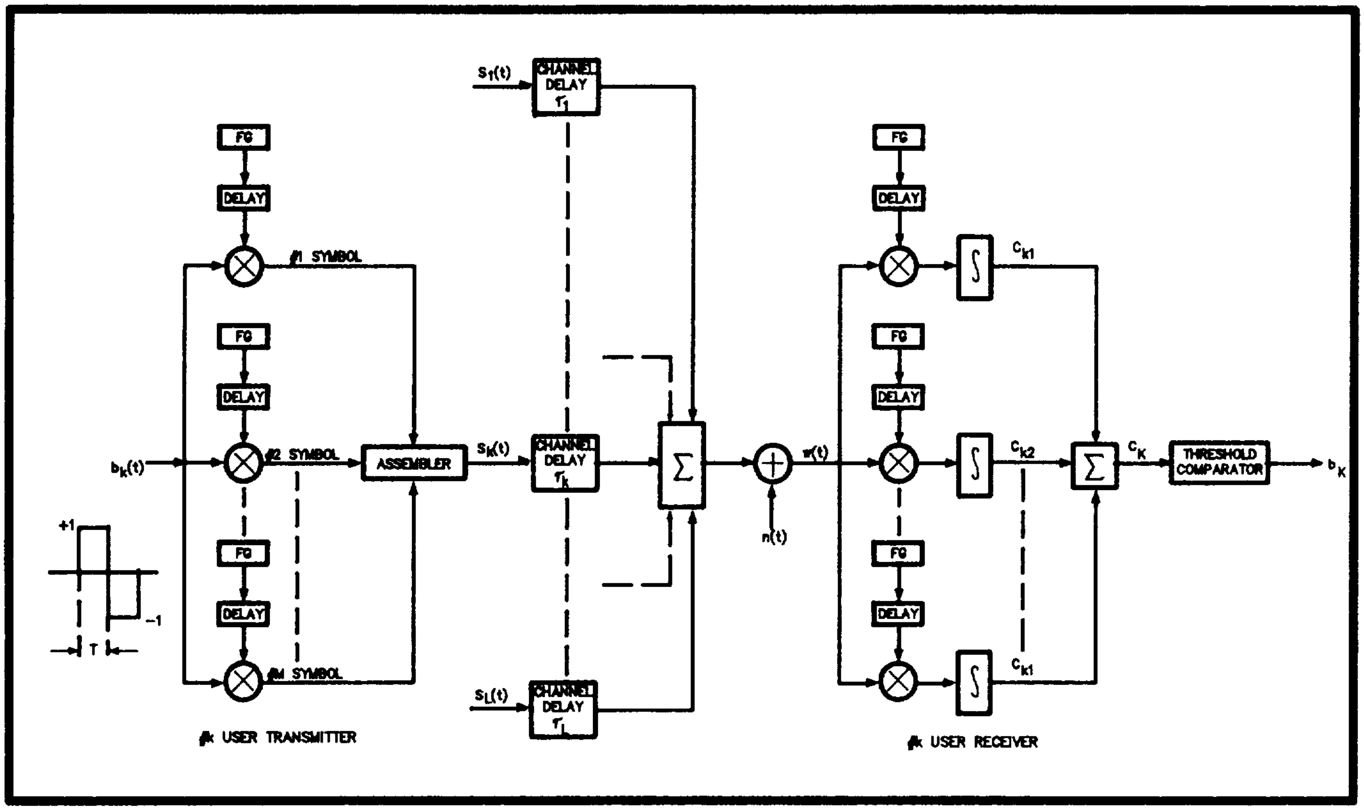

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FIGURE 1: RMA SYSTEM MODEL

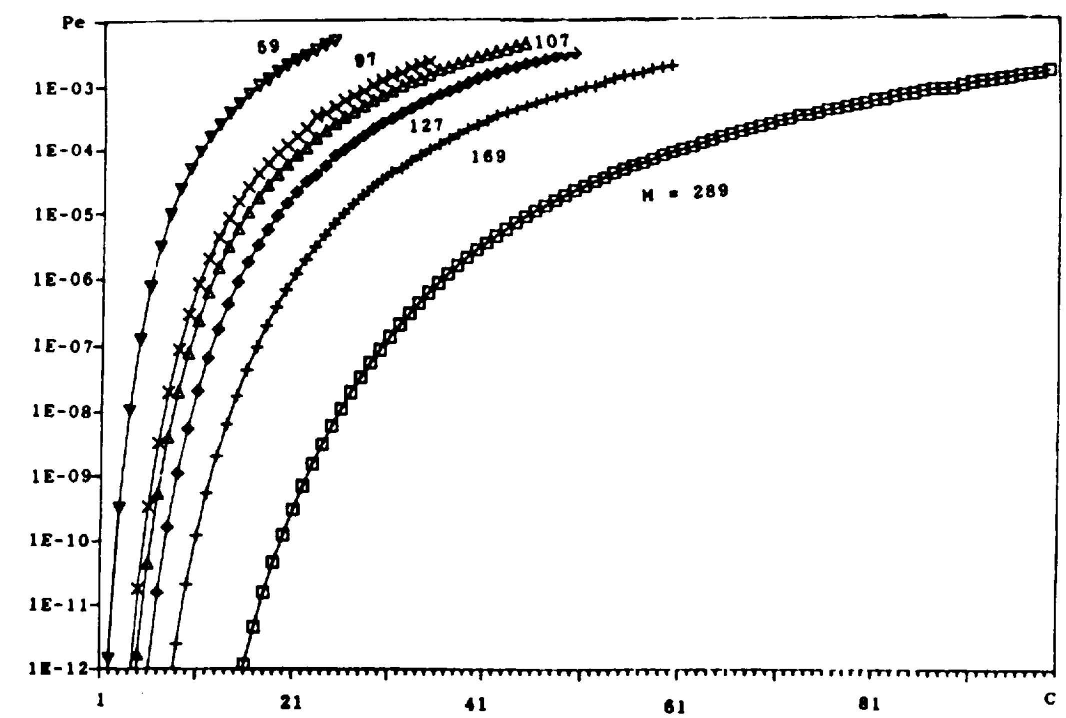

FIGURE 2: Pe AS A FUNCTION OF c FOR DIFFERENT M
($(E_b/N_o)_{th.}$ =0.2 dB, y=0.2, T_d=M)

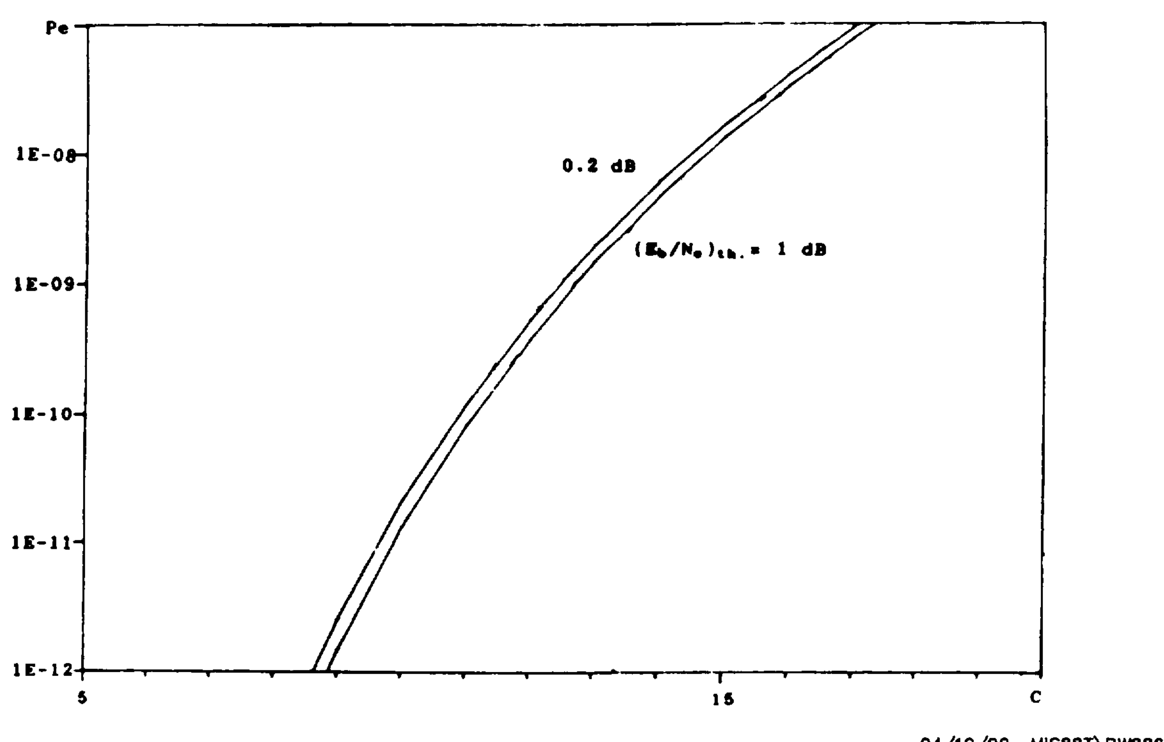

FIGURE 3: Pe AS A FUNCTION OF c FOR DIFFERENT $(E_b/N_o)_{th.}$ (y=0.2, M=169, T_d=M)

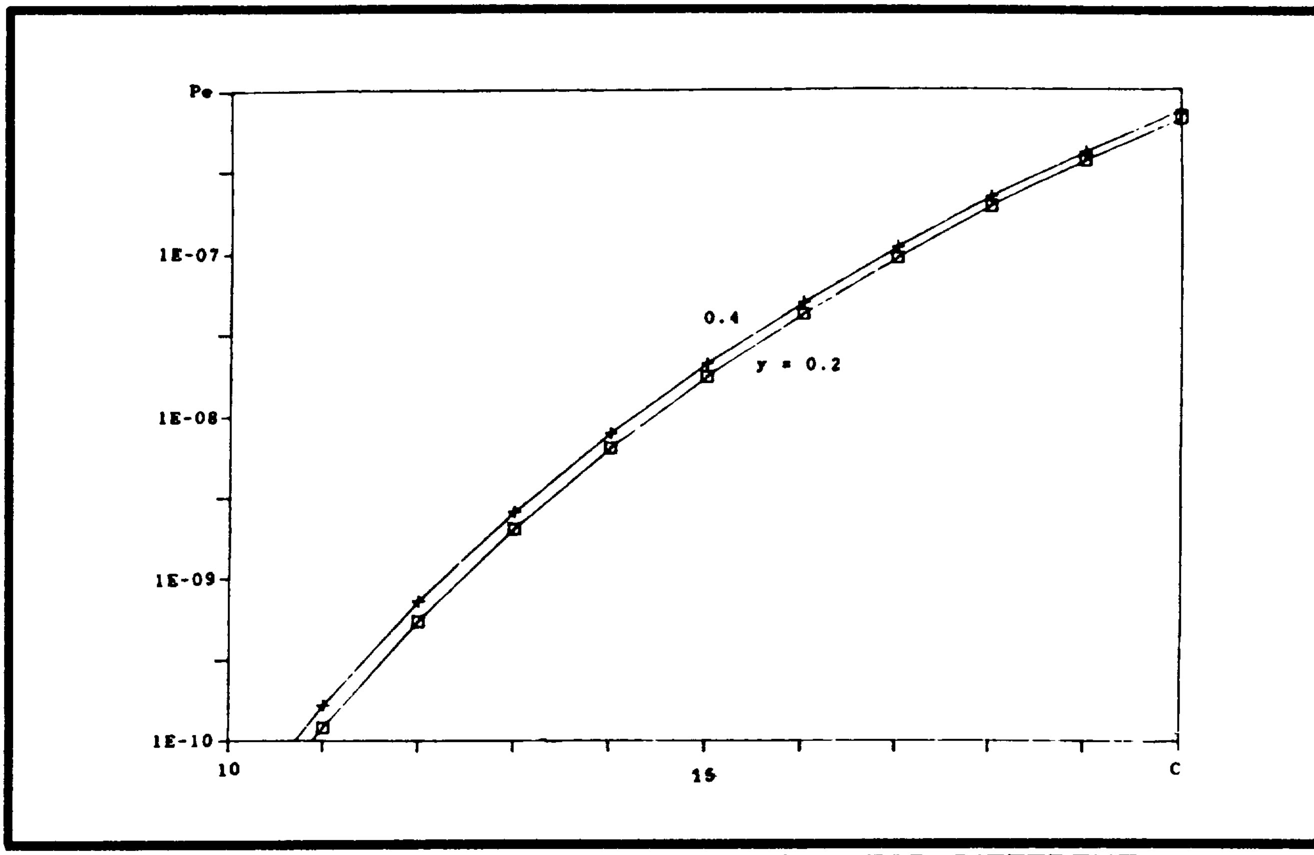

FIGURE 4: Pe AS A FUNCTION OF c FOR DIFFERENT y
$(E_b/N_o)_{th.}$ =0.2 dB, T_d=M, M=169

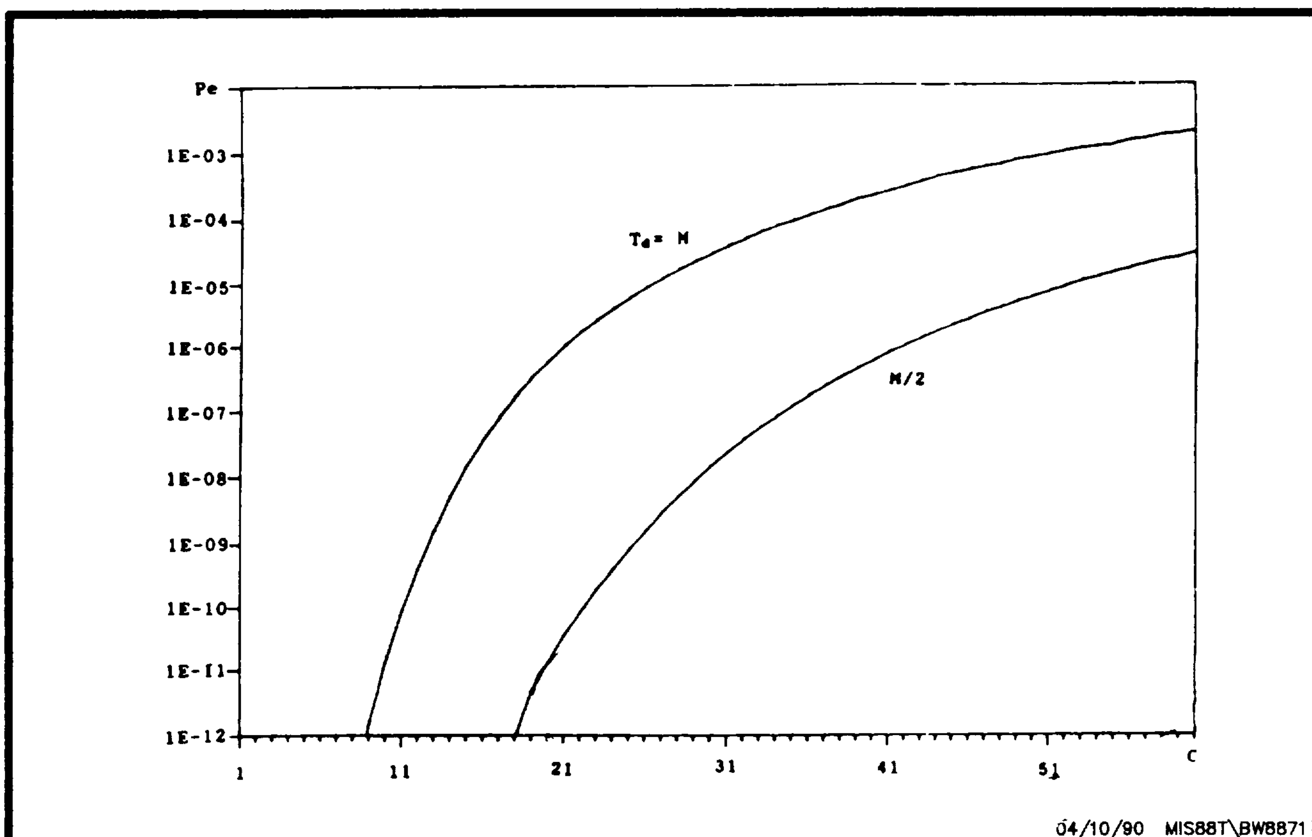

FIGURE 5: Pe AS A FUNCTION OF c FOR DIFFERENT T_d
y=0.2, M=169, $(E_b/N_o)_{th.}$ =1 dB