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EFFECTS OF AMPLIFIER NONLINEARITIES ON MULTILEVEL PAM SCHEMES.

by

HATZINAKOS DIMITRIOS

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ABSTRACT

The effects of amplitude and phase nonlinearities on the transmission of multilevel Pulse-Amplitude-Modulated (PAM) signals are investigated. Specific AM-AM and AM-PM characteristics have been chosen and used for 2,4,8,16 and 32 level PAM schemes. Computer simulation methods and baseband measurements have been used to calculate the degradation in the error performance, when the operation point is changed from the linear region of the characteristics towards saturation. The results obtained for the spectral regrowth due to the nonlinear amplification and adjacent channel interference problems have been explained.

The experimental and the computer simulation results match very closely. For the measurements a 4-PAM encoder-decoder has been designed and the generated signal has been applied to a low frequency power amplifier, which exhibits AM-AM nonlinearity.

Methods for reducing the nonlinear distortion have also been investigated. Predistortion linearization techniques have been used and suboptimum baseband linearizers have been proposed. A baseband AM-AM linearizer has been designed in order to compare simulation results with measurements. Improvements in the performance have been obtained by adjusting the conventional thresholds during the decoding. In combination with the linearization process, led to significant improvements.

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Special thanks must also go to Mr T.Tzakis for his friendship and the many forms of support provided to me.

Finally I wish to thank my family for encouraging and inspiring my career.

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LIST OF ABBREVIATIONS

BER - bit error rate.

C/N - signal to noise power ratio.

D/A - digital to analog conversion.

FFT - fast Fourier transform

IF - intermediate Frequency

ISI - intersymbol interference

MSK - minimum shift keying.

OBE - out of band emission

OBO - output Backoff

PAM - pulse amplitude modulation.

QAM - quadrature amplitude modulation.

QPRS - quadrature partial response signalling.

QPSK - quadrature phase shift keying.

RF - radio Frequency.

S/N - signal to noise power ratio

TWT - travelling wave tube

LIST OF SYMBOLS

$$\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2}\, dt$$

f_b - bit rate.

f_s - symbol rate.

$P_s(e)$ - symbol error probability.

$P(e)$ - bit error probability.

T_s - symbol interval.

CONTENTS

Chapter I

INTRODUCTION

A bandlimited signal when transmitted via radio channels is distorted due to the presence of nonlinear elements such as power amplifiers (TWT or GaAs FET). These exhibit nonlinear distortions in both amplitude (AM-AM conversion) and phase (AM-PM conversion). [10,11]

For efficient use the power amplifiers must be operated close to the saturation. On the other hand the need for more efficient use of the available spectrum, suggest use of spectrally efficient signals such as multilevel schemes. However the sensitivity of these schemes to the impairments of the nonlinear channel increases rapidly with the number of levels.

The amount of distortion and the degradation in the system performance are dependent upon the nature of the amplifier characteristics and the shape of the transmit filter. Due to the significant envelope fluctuation of the filtered multilevel signals, spectral regrowth effects are also observed at the output of the amplifier.

Significant work has been made so far on the study of the nonlinear channel effects and methods to compensate for them. First, various models for representation of the channel nonlinearities have been proposed and techniques for their study have been developed. Thus a nonlinear element can be classified as memoryless, effectively memoryless

or with memory [12]. The Volterra series ,Heiter's model or the simplified Quadrature model can be used to represent a nonlinear system [4,9,13]. Bessel functions,odd and even order polynomials and two or three parameter formulas have been proposed to express the characteristics of the nonlinear elements [1,3,9,14].

The probability of error performance and spectral properties of various constant envelope modulation schemes like QPSK or MSK in a nonlinear environment,have been investigated by many authors in depth. These schemes are not so sensitive to the channel nonlinearities.Methods to reduce the nonlinear distortion by predistorting or postdistorting the transmitted signal,so that the overall system response becomes more linear have been investigated and applied [3 to 9].

Recently,the performance and sensitivity of non-constant envelope multilevel schemes have attracted the attention. This is due to the high spectral efficiency of these schemes. PAM,QAM or QPRS schemes are involved in the investigation [2,13,15,16, 17,18]. However,the effects of the nonlinear channel on these schemes have not been studied in great detail. Most of the research has been limited to low level schemes and only a few publications have been available on the study of the high level schemes. The increasing need for more efficient use of the available spectrum ,makes the investigation of the behaviour of higher schemes in a nonlinear environment indispensable.

Among the most popular investigated systems are the QAM systems. A QAM signal consists of two phase-quadrature carriers,each modulated by a PAM signal [11,22]. This means that a PAM system is the equiva-

lent baseband of a linearly modulated QAM system. In our investigation 2,4,8,16 and 32 level PAM schemes were chosen, for reasons of simplicity. These are the baseband equivalent schemes of 4,16,64,256 and 1024 QAM modulated systems.

The objectives of this study are:

i) To examine the effects of amplitude and phase nonlinearities on multilevel PAM schemes by computing their probability of error performance and their spectral properties.

ii) To apply methods in order to reduce the nonlinear distortion and improve the system performance.

iii) To compare the sensitivity and behaviour of different PAM schemes to the nonlinear channel impairments.

Specific AM-AM and AM-PM characteristics have been chosen for this purpose. These are assumed to be frequency independent, effectively memoryless nonlinearities. Computer simulation methods and baseband measurements have been used. The organization of the Thesis is as follows.

In Chapter II the amplitude and phase characteristics used in our study are given and various models for their representation are described. The representation is needed for the calculation of the computer simulation results. A comparison between the different models is made. According to the nature of the application, in later Chapters a different model is chosen.

The computer simulation and measurement set ups are described in Chapter III. Computer simulation results on the probability of error performance and spectral regrowth of 2,4,8,16 and 32 PAM schemes, distorted by the nonlinearities of Chapter II are presented. The measurements made for a 4-PAM signal justify the simulated results. The dependence of the distortion on the nature of the nonlinearities, the filter shape and the number of signal levels is shown.

In Chapter IV a brief analysis of the predistortion linearization techniques applied in our study is made. The characteristics of suboptimum linearizers are drawn and their coefficients for the different representation models are computed. The overall predistorter- amplifier characteristics are much more linear and exhibit low phase rotation. According to them baseband linearizers are proposed. An amplitude linearizer for the LM-380 characteristic is designed and implemented.

The improvement in the performance obtained by the linearization, is calculated in Chapter V again for 2,4,8,16 and 32 PAM schemes. Experimental results for a 4-PAM signal, using the implemented linearizer justify the simulated ones. Comparisons with the performance of the conventional system are made. The reduction of the spectral regrowth and thus of the adjacent and cochannel channel interference is explained. Improvements in the performance are obtained by adjusting the conventional thresholds during the decoding. The total improvement in the system performance is very significant.

The summary of our conclusions based on the obtained results is given in Chapter VI.

The designed circuits diagrams as well as the used computer programs are given analytically in Appendix A to D.

Chapter II

MODELS AND CHARACTERISTICS USED

In this chapter the amplitude and phase characteristics used in our study are given. A brief description of various existing models for the representation of the characteristics is presented. The coefficients required for the representation are calculated. A comparison between the different models is made.

2.1 MEASUREMENT OF THE AM-AM CHARACTERISTIC

The set up for the measurement of the AM-AM characteristic used in our study is given in Figure 2.1. The amplification stage consists of the LM-380 audio power amplifier ,impendance matching and DC offset components (see Appendix B). The measured AM-AM characteristic is that of the amplification stage. Since the source of the nonlinear distortions is the LM-380 amplifier, in the next chapters we refer to it as the LM-380 characteristic for simplicity.

For the measurements,a sinusoidal signal was used as input to the amplification stage. The input and output power were measured with a spectrum analyzer. The measured characteristic is drawn in Figure 2.2 (a). We note the nonlinear nature of the characteristic near saturation.

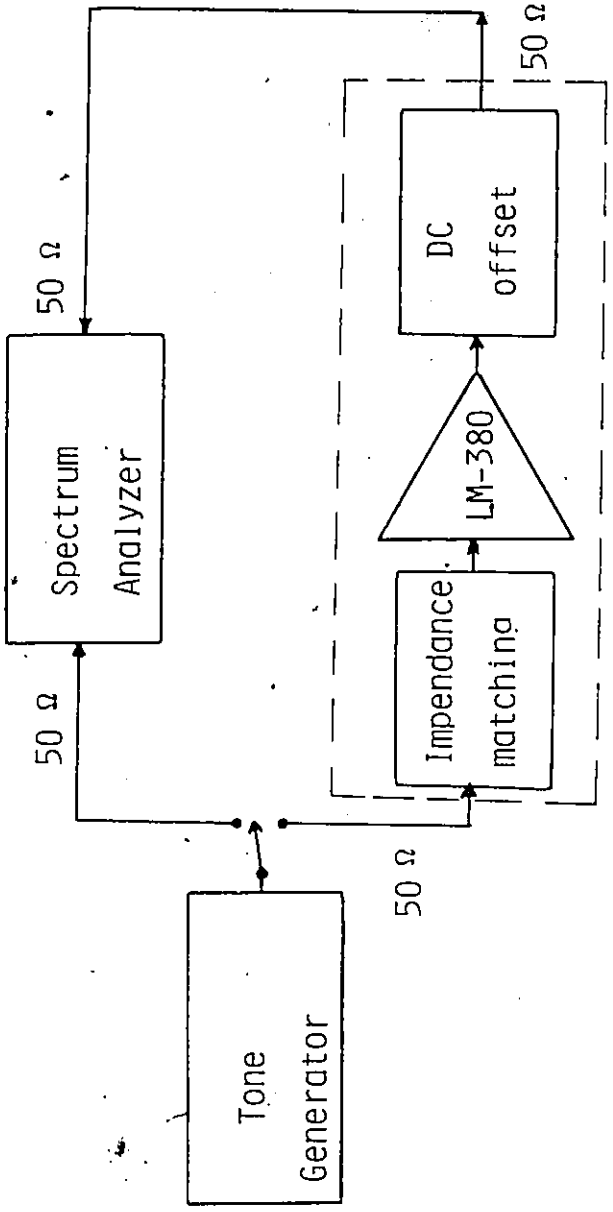


Figure 2.1 . Measurement set-up for the AM-AM characteristic.

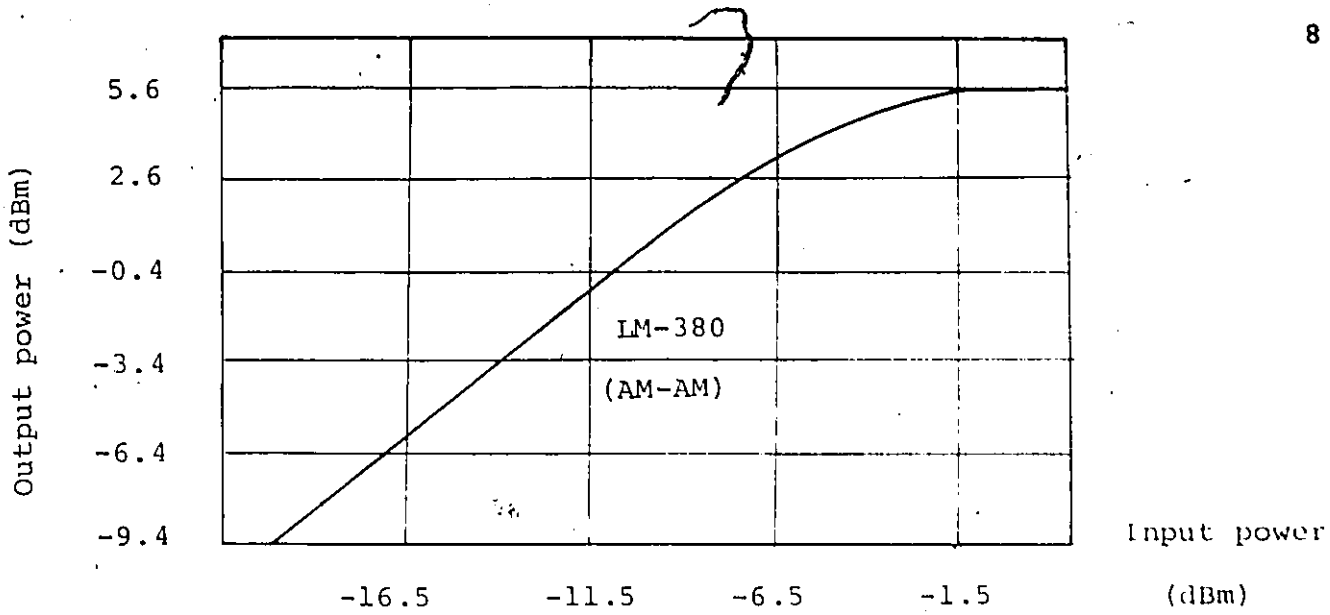


Figure 2.2 (a). The single tone measured AM-AM power characteristic of the LM-380 power amplifier.

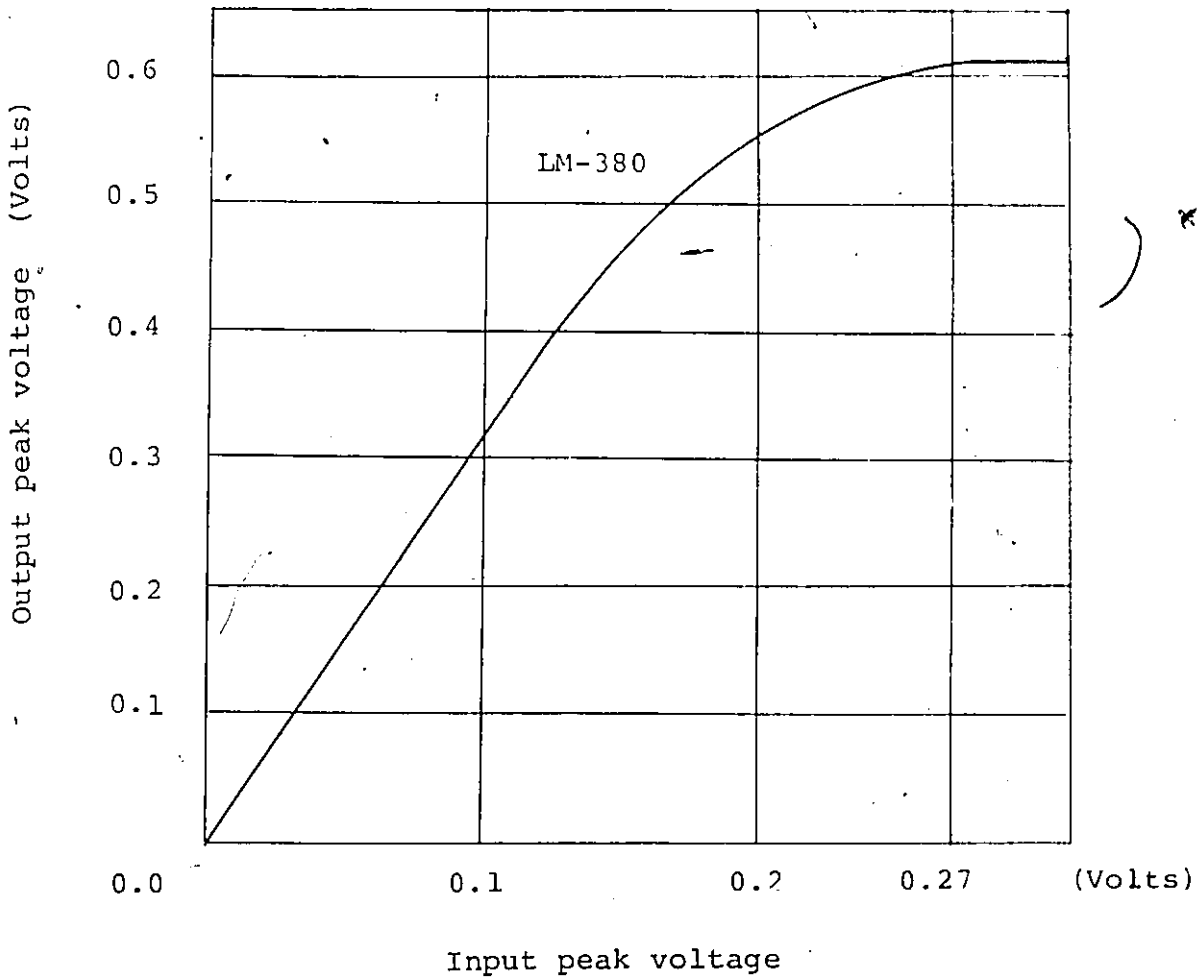


Figure 2.2 (b). Instantaneous amplitude characteristic derived from the measured curve of Fig. 2.2 (a) using the equation 2.1.

The relation between the average envelope power and the instantaneous envelope amplitude, refering to a 50 Ohm resistance is given by the equation :

$$P_{dBm} = 10 \cdot \log (P_{watts} / 1mW) = 10 \cdot \log (V^2/2/50) / 10^{-3} \qquad 2.1$$

Using equation 2.1 , the instantaneous amplitude characteristic can easily be obtained from the measured power characteristic. It is drawn for positive input values in Figure 2.2 (b).

2.2 NORMALIZED AM-AM AND AM-PM CHARACTERISTICS

It is usual to express the AM-AM and AM-PM characteristics in terms of Backoff power from saturation [11]. The normalized power characteristic of the LM-380 amplifier, is drawn in Figure 2.3 (a). In the same Figure AM-PM normalized characteristics similar to those of the H-261 and Intelsat-V TWT amplifiers are also drawn.

The corresponding normalized instantaneous envelope-amplitude characteristics are calculated using the equation [9]:

$$V = \pm\sqrt{2} \cdot 10^{-\frac{B}{20}} \qquad 2.2$$

where B is the Backoff power in dB, and are drawn (for positive only input values) in Figure 2.3 (b).

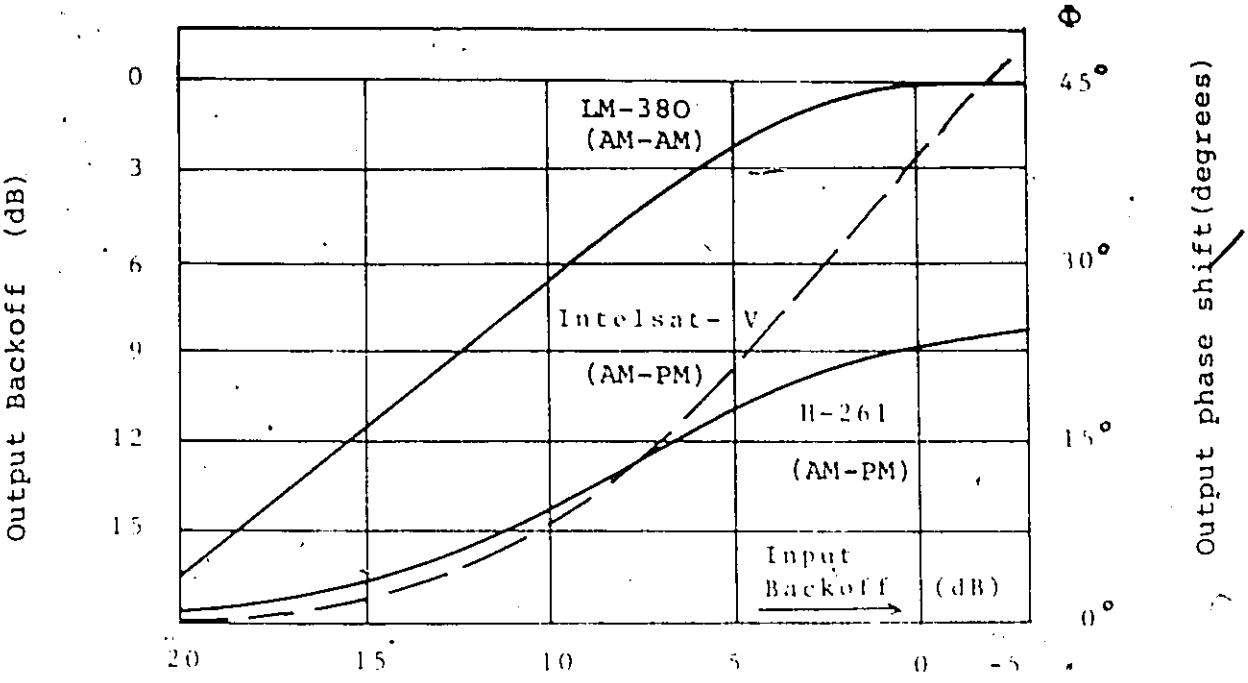


Figure 2.3 (a). The normalized power characteristics with respect the saturation power of the LM-380 power amplifier.

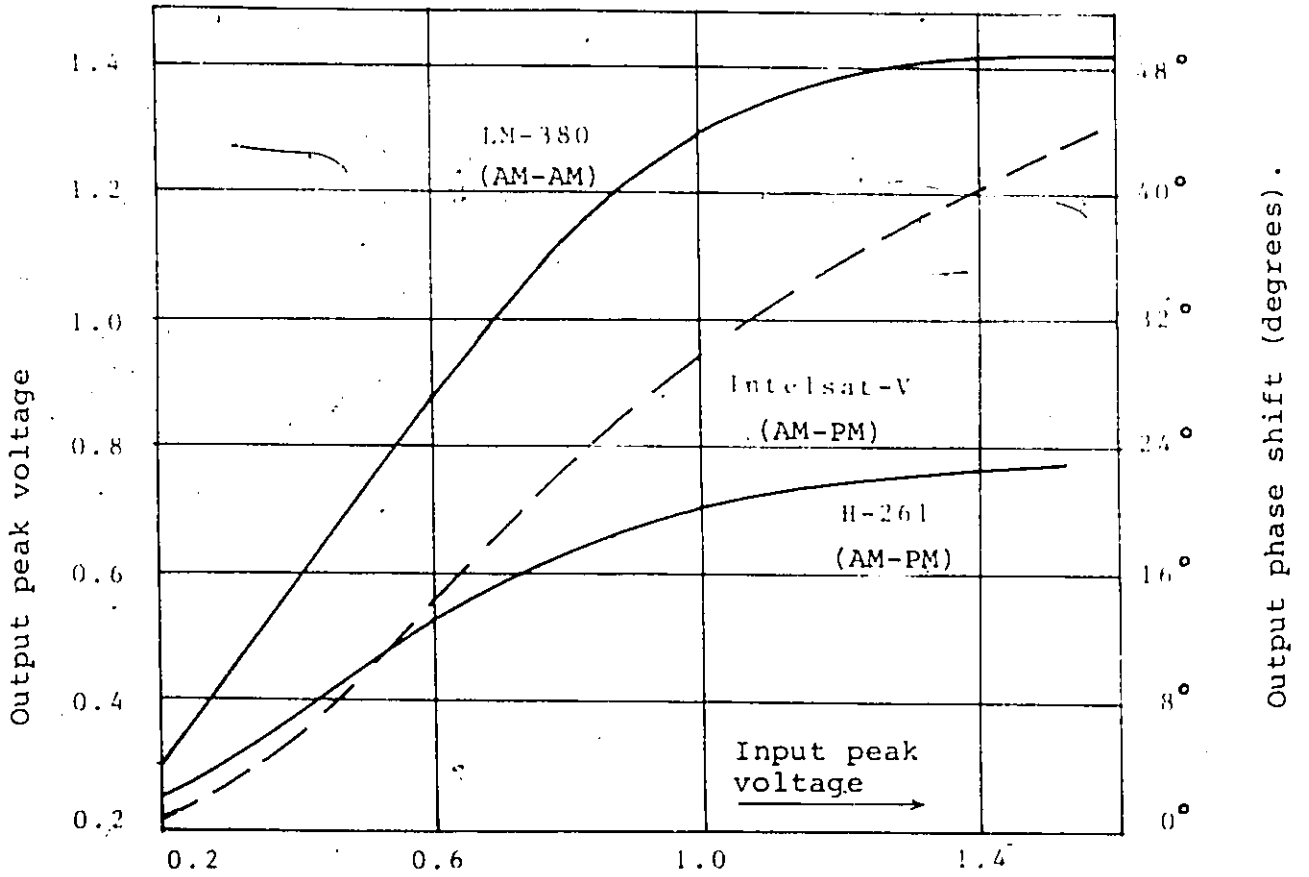


Figure 2.3 (b). Instantaneous amplitude characteristics derived from the curves of Fig. 2.3 (a) using the equation 2.2.

2.3 THE QUADRATURE MODEL

The quadrature model is a model used for representation of bandpass nonlinearities [9]. According to this, if the input to an amplifier is a narrowband radio signal given by the equation:

$$X(t)=R(t)\cos(\quad t+\quad (t))$$

the output of the amplifier is given by the equation:

$$Y(t)=g(t)\cos(\quad t+\quad (t)+\quad (t))$$

where $R(t)$ is the lowpass envelope of the signal, is the carrier frequency and $g(t)=g(R(t))$ and $(t)=(R(t))$ are the AM-AM and AM-PM envelope dependent transfer characteristics of the amplifier. The amplifier is assumed to be an effectively memoryless nonlinear element [12]. The equation 2.4 can be written as:

$$Y(t)=P(t)\cos(\quad t+\quad (t))-Q(t)\sin(\quad t+\quad (t))$$

where

$$P(t)=g(R(t))\cos(\quad (R(t)))$$

and

$$Q(t)=g(R(t))\sin(\quad (R(t)))$$

The inphase and quadrature components $P(t)$ and $Q(t)$, represent only amplitude characteristics. In other words, a phase and an amplitude bandpass nonlinearities can be described (or replaced) by two amplitude nonlinearities. This is the principle of the quadrature model [9], which is shown in Figure 2.4 .

A baseband expression of the quadrature model can be derived as follows. Assuming the baseband input to the amplifier is:

$$X(t) = R(t) \qquad 2.8$$

the output is given by the equation:

$$Y(t) = G(t) \exp(j\Phi(t)) \qquad 2.9$$

where $G(t)=G(R(t))$ and $\Phi(t)=\Phi(R(t))$ are baseband AM-AM and AM-PM nonlinearities similar to the bandpass ones. The equation 2.9 can be written as:

$$Y(t) = G_p(t) + j\, G_q(t) \qquad 2.10$$

where

$$G_p(t) = G(R(t)) \cos(\Phi(R(t))) \qquad 2.11$$

and

$$G_q(t) = G(R(t)) \sin(\Phi(R(t))) \qquad 2.12$$

As before $G_p(t)$ and $G_q(t)$ represent only amplitude nonlinearities. It is easy to see from equations 2.9, 2.11 and 2.12 that:

$$G(R) = \sqrt{G_p^2(R) + G_q^2(R)}$$

and $\qquad 2.13$

$$\tan \Phi(R) = (G_q(R)/G_p(R))$$

Using equations 2.11 and 2.12 the characteristics of Figure 2.3(b) are converted to the corresponding ones of the Ouadrature model, drawn in Figure 2.5. The baseband model will be used in the next Chapters for the representation of the chosen nonlinearities. The reason we chose

this model is the similarity of the equations 2.11,2.12 and 2.6,2.7. Due to this similarity $G_p(t)$ and $G_q(t)$ of the baseband model will be also called the inphase and quadrature components respectively. The derived baseband results of Chapters III and V and the approach used in Chapter IV, can be applied to bandpass systems as well.

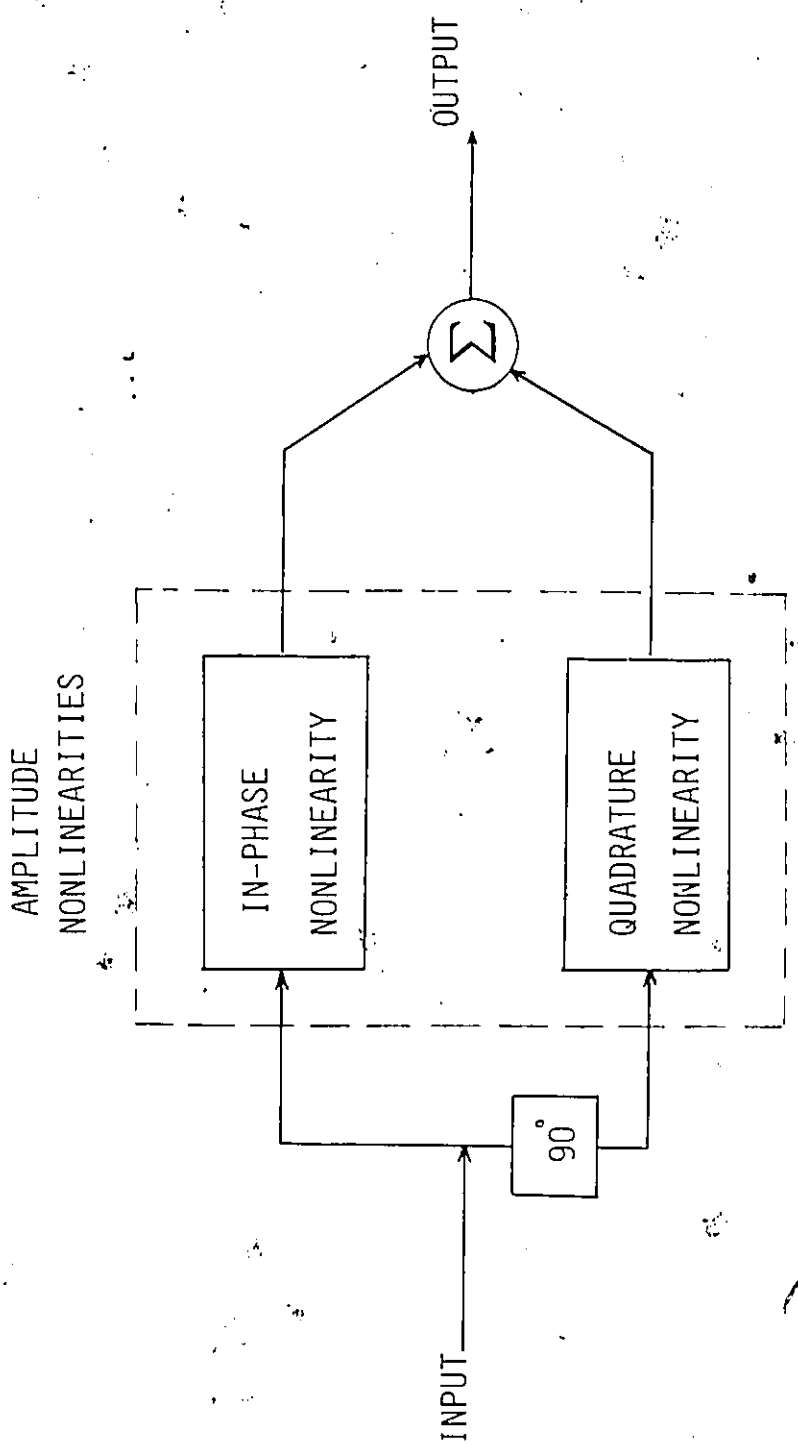


FIGURE 2.4. QUADRATURE MODEL

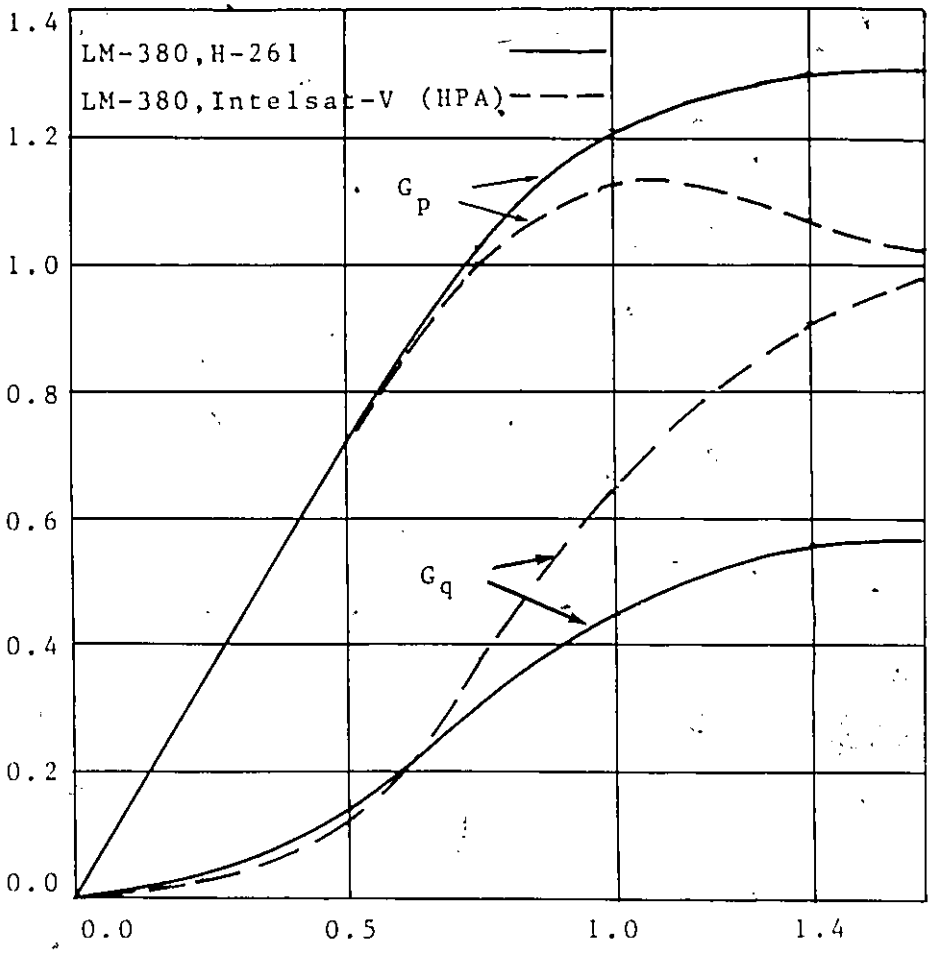


FIGURE 2.5. Amplitude characteristics of the quadrature model, derived from the characteristics of Fig. 2.3 using the equations 2.11 and 2.12.

2.4 MODELS FOR CHARACTERISTIC REPRESENTATION

To calculate the effects of the various nonlinearities we must represent them by proper envelope functions. There are many models proposed [1,3,9,13]. In this section three of these models used in our study are presented.

2.4.1 The polynomial model

This model proposed by Eric [9] uses odd order polynomials for the representation of amplitude nonlinearities and even order polynomials for phase nonlinearities. More analytically, an instantaneous envelope- amplitude characteristic G(R)=G(R(t)) can be written as:

$$G(R)=\sum_{n=0}^{N} C_{2n+1}\cdot R^{2n+1} \quad , \quad -R_1/2 \le R \le R_1/2 \qquad 2.14$$

while a corresponding phase characteristic $\Phi(R) = \Phi(R(t))$ as:

$$\Phi(R)=\sum_{n=1}^{M} D_{2n}\cdot R^{2n} \quad , \quad -R_2/2 \le R \le R_2/2 \qquad 2.15$$

We note that the amplitude characteristic G(R) is an odd function of R while the phase characteristic $\Phi(R)$ is an even function of R. Using the equations 2.11,2.12,2.14,2.15 and the series expansions of $\cos\Phi(R)$, $\sin\Phi(R)$, the amplitude characteristics $G_p(R), G_q(R)$ of the quadrature model can be represented by two odd order polynomials of R, with linear and cubic leading terms respectively:

$$G_p(R)=\sum_{i=0}^{N} A_{2i+1}\cdot R^{2i+1} \quad , \quad -R_3/2 \le R \le R_3/2 \qquad 2.16$$

and

$$G_q(R)=\sum_{i=1}^{M} B_{2i+1}\cdot R^{2i+1} \quad , \quad -R_4/2 \le R \le R_4/2 \qquad 2.17$$

For small values of R these polynomials are proportional to R and R^3 respectively. The high order terms become significant for large values of R.

The polynomial representation is very accurate, but it requires many terms to fit a characteristic in a long range. It needs many coefficients to be optimized and introduces calculation difficulties due to the high order of the used polynomials. That is the reason simpler models with few coefficients have been proposed.

2.4.2 Hetrakul and Taylor model

This model uses two parameter formulas involving modified Bessel functions of the first kind, in combination with linear and exponential terms [3]. The amplitude characteristics $G_p(R), G_q(R)$ of the quadrature model can be represented by the following equations:

$$G_p(R)=C_1 R\cdot\exp(-C_2R^2)\cdot I_0(C_2R^2) \qquad 2.18$$

$$G_q(R)=S_1 R\cdot\exp(-S_2R^2)\cdot I_1(S_2R^2) \qquad 2.19$$

where the parameters C_1, C_2 and S_1, S_2 have to be determined.

We see that this model uses only two parameters for each function but it is still a complicated expression.

2.4.3 Saleh model

Saleh proposed the representation of nonlinearity characteristics by two parameter formulas [1]. An AM-AM characteristic G(R) and an AM-PM characteristic $\Phi(R)$ can be represented as:

$$G(R) = a \cdot R / (1 + b \cdot R^2) \qquad 2.20$$

and

$$\Phi(R) = c \cdot R^2 / (1 + d \cdot R^2) \qquad 2.21$$

while the amplitude characteristics $G_p(R), G_q(R)$ of the quadrature model can be represented as:

$$G_p(R) = a_1 \cdot R / (1 + b_1 \cdot R^2) \qquad 2.22$$

and

$$G_q(R) = c_1 \cdot R^3 / (1 + d_1 \cdot R^2)^2 \qquad 2.23$$

We notice that for small values of R equations 2.20 and 2.22 are proportional to R. For large values of R the equations 2.20, 2.22 and 2.23 become proportional to 1/R while the equation 2.21 is almost constant. The parameters a,b,c,d can be calculated using optimization procedures [1],(Appendix D).

Compared with the previous models, Saleh model is simpler but not necessarily more accurate, as we found during our study.

2.4.4 Representation of the used characteristics

In this section the models used for the representation of the characteristics of Figures 2.2 to 2.5 and their coefficients are given. A particular characteristic is represented by more than one models. In our study, depending on the nature of application the more suitable model is chosen (chapters III, IV). The coefficients were calculated using optimization subroutines and are given in tables 2.1 to 2.7. The absolute RMS error was also calculated according to the equation:

$$E_{rms} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(a_i - d_i)^2}$$

where a_i and d_i are the derived and estimated values respectively.

MODEL	LM-380.	ERROR	RANGE
Polynomial	C1 = 1.4621649 C3 = -0.0998297 C5 = 0.5981663 C7 = -0.8914303 C9 = -0.8178380 C11= 2.0430622 C13= -1.2413568 C15= 0.2490590	0.00731	$\|R\| \leq 1.35$
Hetrakul Taylor	C1 = 1.6446420 C2 = 0.2892350	0.05750	$\|R\| \leq 1.5$

TABLE 2.1 . The coefficients of the normalized LM-380 AM-AM characteristic of Figure 2.3 (b) .

MODEL	LM-380	ERROR	RANGE
Hetrakul Taylor	C1 = 3.590262 C2 = 7.462000	0.01437	$\|R\| \leq 0.4$

TABLE 2.2 . The coefficients of the LM-380 AM-AM characteristic of Figure 2.2 (b) .

MODEL	H-261	ERROR	RANGE
Polynomial	D2 = 1.032361 D4 = -1.202852 D6 = 0.164144 D8 = 1.191000 D10= -1.267618 D12= 0.503055 D14= -0.059495 D16= -0.004849	0.00219	$\|R\| \leq 1.4$
Saleh	c = 1.390587 d = 2.988430	0.02670	$\|R\| \leq 1.5$

TABLE 2.3 . The coefficients of the normalized H-261 AM-PM characteristic of Figure 2.3 (b).

MODEL	LM-380, H-261	ERROR	RANGE
Polynomial	A1 = 1.4630000 A3 = -0.1424000 A5 = 0.6573800 A7 = -2.5463552 A9 = 3.9320452 A11= -1.9768057 A13= 0.5927067 A15= -0.0695557	0.00209	$\|R\| \leq 1.35$
Hetrakul Taylor	C1 = 1.6013820 C2 = 0.3257130	0.02259	$\|R\| \leq 1.35$

TABLE 2.4 . The coefficients of the inphase nonlinearity $G_p(R)$ derived from the LM-380 and H-261 characteristics (Figure 2.5).

MODEL	LM-380, H-261	ERROR	RANGE
Polynomial	B3 = 1.1649265 B5 = 0.0535739 B7 = -4.4133043 B9 = 7.7314234 B11= -6.0660324 B13= 2.2945530 B15= -0.3384920	0.02426	$\|R\| \leq 1.4$
Saleh	c1 = 1.6446420 d1 = 0.2892350	0.01113	$\|R\| \leq 1.4$

TABLE 2.5. The coefficients of the quadrature nonlinearity $G_q(R)$ derived from the LM-380 and H-261 characteristics (Figure 2.5).

MODEL	LM-380, INTEL.-V	ERROR	RANGE
Polynomial	A1 = 1.4619360 A3 = -0.0975490 A5 = 0.4134734 A7 = -2.3335270 A9 = 2.9813547 A11= -1.7313000 A13= 0.4804000 A15= -0.0510523	0.00385	$\|R\| \leq 1.4$

TABLE 2.6. The coefficients of the inphase nonlinearity $G_p(R)$ derived from the LM-380 and Intelsat-V characteristics (Figure 2.5).

MODEL	LM-380, INTEL.-V	ERROR	RANGE
Polynomial	B3 = 0.1769764 B5 = 6.0393476 B7 =-16.5881000 B9 = 20.5560000 B11=-13.4176200 B13= 4.4521000 B15= -0.5910000	0.01792	$\|R\| \leq 1.5$

TABLE 2.7. The coefficients of the quadrature nonlinearity $G_q(R)$ derived from the LM-380 and Intelsat-V characteristics (Figure 2.5).

Chapter III

EFFECTS OF AMPLITUDE AND PHASE NONLINEARITIES ON PAM SIGNALS

In this Chapter, the computer simulation and experimental set-ups used in our study are described. The effects caused by amplifier nonlinearities on PAM schemes are presented. The degradation in the error performance and the spectral regrowth of various PAM schemes, with the nonlinearities given in chapter II are computed. The optimum operating points for all the schemes are found.

3.1 COMPUTER SIMULATION SET-UP.

The computer simulation model we used, is shown in Figure 3.1. A brief explanation of the model follows, while all the simulation programs we used are given in details in Appendix D.

Binary data are generated by a Random Generator. A PAM encoder translates them to a multilevel stream, long enough to contain all the possible combinations of the generated levels. For an M-ary PAM scheme these levels are given by the formula [22]:

$$A_m = 2m-1-M \quad , \quad m=1,2,\ldots,M$$

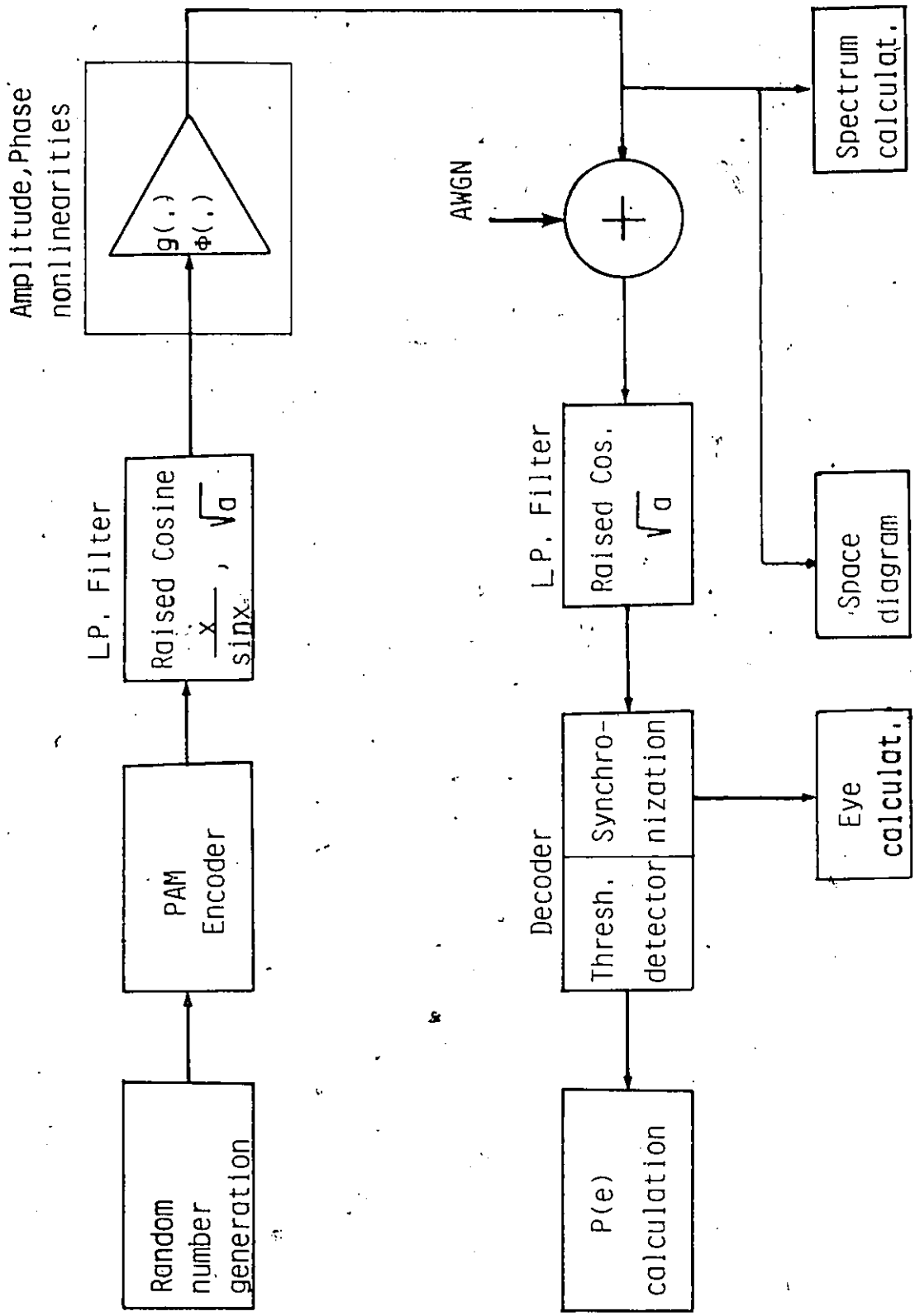


Figure 3.1. Computer simulation set up.

The transmit and receive filters are ideal square root of raised cosine filters, having a roll-off factor α . The transmit filter is x/sinx amplitude equalized so that the overall system satisfies the Nyquist first criterion.

The channel impairments assumed are ,distortions due to the amplitude and phase nonlinearities given in Chapter II and Additive White Gaussian Noise (AWGN).

The different levels of the distorted signal, are detected by comparing them to suitable thresholds ($T_k = 2k-M$, $k=1,\ldots,M-1$). The error probability of the i-th received symbol is computed using the equations [21]:

$$P_s^i(e) = \begin{cases} 1/2 \cdot \operatorname{erfc}\left(\dfrac{\operatorname{abs}(A_m^i - T_k^i)}{\sqrt{2N_o}}\right) & , \quad m=1,M \quad , \quad k=1,M-1 \\ 1/2 \cdot \left[\operatorname{erfc}\dfrac{\operatorname{abs}(A_m^i - T_k^i)}{\sqrt{2N_o}} + \operatorname{erfc}\dfrac{\operatorname{abs}(T_{k-1}^i - A_m^i)}{\sqrt{2N_o}}\right] & \end{cases}$$

$$k=2,..,M-2 \quad , \quad m=2,..,M-1 \qquad 3.1$$

where A_m^i is the magnitude of the optimum sample of the i-th received symbol, T_k^i and T_{k-1}^i are the lower and upper corresponding thresholds and N_0 is the equivalent to the receiving Nyquist filter noise power. Assuming Gray coding for the PAM scheme, the total bit error probability for a sequence of N symbols is calculated as:

$$P(e) = 1/\log_2 M \cdot (1/N \sum_{i=1}^{N} P_s^i) \qquad 3.2$$

The eye and space diagrams as well as the spectrum of the signal are calculated at the points shown in Figure 3.1. The filtering of the signal is performed using FFT algorithms.

Assuming ideal carrier and timing recovery, the baseband simulation model of Figure 3.1 is equivalent to a bandpass one with similar nonlinearities (the AM-AM, AM-PM characteristics we used are assumed to be frequency independent) [11]. In all the simulation results given in this and the following chapters the S/N and C/N ratios are equivalent.

3.2 MEASUREMENT SET-UP.

Measured results on the performance of a 4-PAM signal with the LM-380 amplifier were also obtained in order to justify the computer simulation results. The used baseband measurement set-up is drawn in Figure 3.2 . A description of the set-up follows.

An HP-1647 Data error analyzer was used for the generation of a 413.3 kb/s binary stream. This is actually a pseudorandom periodic data stream that it is considered random if it is long.

A 4-PAM encoder-decoder was implemented for the translation of binary stream to a 4 level stream. The diagram and the performance of this circuit are explained in detail in Appendix A. The generated 4-PAM signal has a rate of 206.66 kBaud.

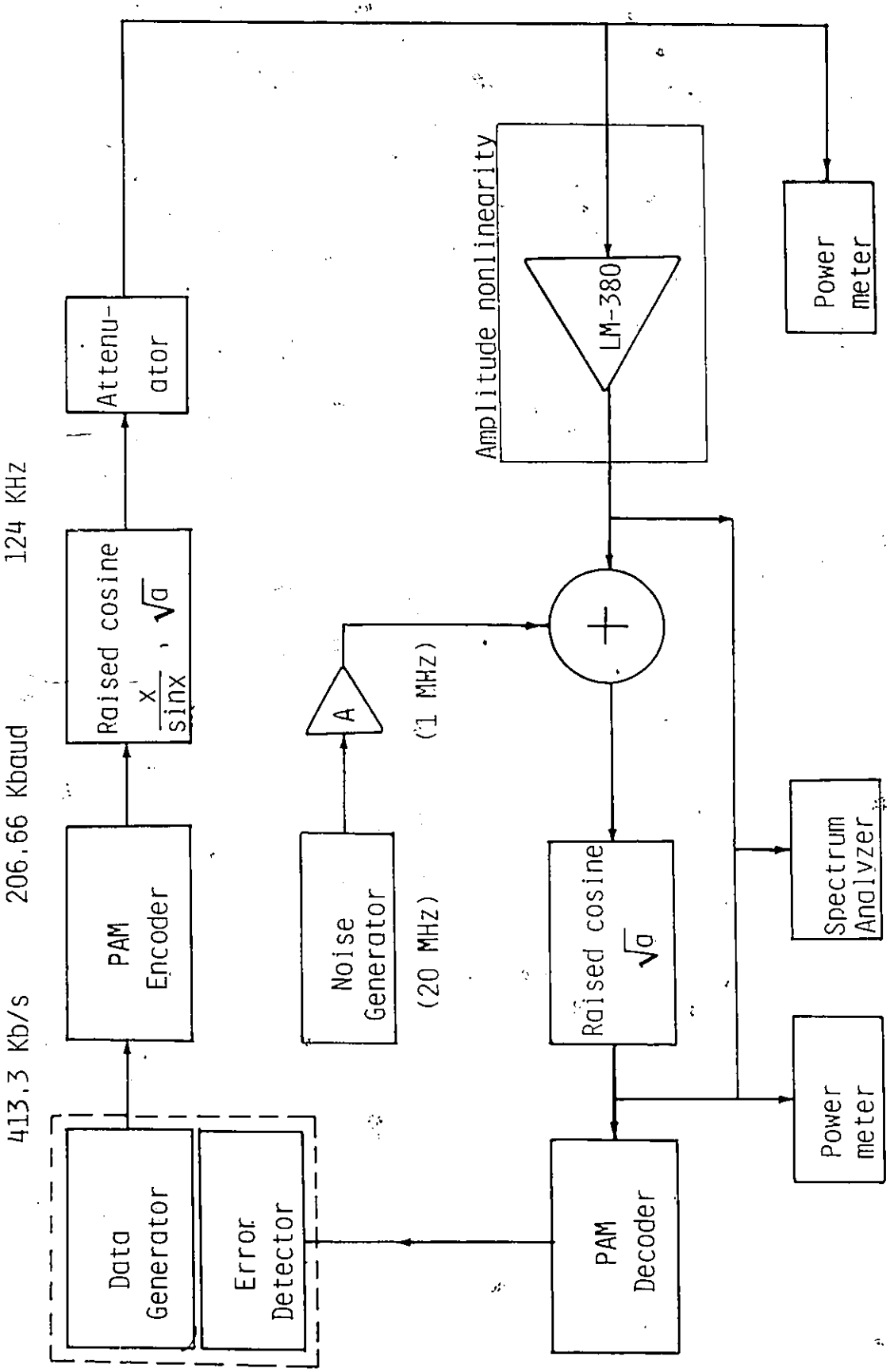


Figure 3.2. Measurement set-up.

The transmit and receive filters are square root of raised cosine filters with a roll-off factor $\alpha = 0.2$. The transmit filter is x/sinx amplitude equalized and the overall system satisfies the Nyquist first criterion. The filter is manufactured by Karkar Electronics Inc. and has a Nyquist Frequency of 103.3 kHz and an out of band rejection of 50 dB at 124 kHz. The receiver filter is also used for the noise limitation.

The signal is distorted by the LM-380 amplifier. The distortion depends on the input power level which is controlled by a variable attenuator. The operation point is changed from the linear region of the amplifier to the saturation. The signal power at the output of the amplifier is measured by a true RMS power meter.

Additive Gaussian noise is added to the signal. The noise is amplified and bandlimited before the addition. The final noise bandwidth is wide enough (1 MHz), compared to the signal bandwidth and thus the noise is considered white.

The error probability is measured with the HP-1647 Data error analyzer. The decoded signal plus noise is compared with the stored in memory transmitted signal and the errors are counted. The S/N ratio is measured by a true RMS power meter (HP-3400 A) at the output of the receiver filter. We must mention here that different values of the S/N ratio are measured by changing the noise power, while the signal power is kept constant.

3.3 EFFECTS ON THE SIGNAL PERFORMANCE.

The impact of the nonlinear channel impairments on the error performance of PAM schemes is explained in this section. .

3.3.1 Analysis of the effects.

A baseband PAM scheme is characterized by the equation [22]:

$$R(t)=\sum_{k=0}^{\infty} A_k \cdot u(t-kT_s) \qquad 3.3$$

where A_k takes the M discrete values (levels)

$$A_m = 2m-1-M \quad , \quad m=1,2,\ldots,M$$

for a given M. T_s is the signal rate and u(t) the signal pulse. In our study u(t) is a Nyquist shape pulse, given ideally by the equation [11]:

$$u(t)=\frac{\sin(\pi t/T_s)}{\pi t/T_s} \cdot \left[\frac{\cos(\alpha t/T_s)}{1-4\alpha^2 t^2/T_s^2}\right] \qquad 3.4$$

where α is the channel roll-off factor.

A signal like that of equation 3.1 is distorted due to the AM-AM envelope dependent response of the power amplifiers . If we operate close to or into the nonlinear region of the amplifier AM-AM characteristic, we notice that the envelope dependent amplification causes suppression of the higher signal levels compared to the lower levels. On the other hand, the interaction of the envelope depended response with the enve-

lope fluctuations due to the filtering of the transmitted signal, give rise to intersymbol interference. Both effects are shown in Figures 3.3 to 3.5 for a 4-PAM signal with the LM-380 AM-AM characteristic. We notice that the distortion becomes more severe as the operation point is changed from the linear region of the characteristic to saturation.

The above effects cause significant degradation in the error performance of the transmitted signal as it is shown in the next section. The major contribution to the degradation comes from the higher level. We call amplitude margin the percentage of the higher level suppression that causes system failure (fig. 3.6). As it is shown in Table 3.1 the amplitude margin decreases when we move to higher schemes.

No of levels	Amplitude margin
2	100 %
4	33 %
8	14.3 %
16	6.7 %
32	3.2 %

TABLE 3.1 Amplitude margin of PAM schemes.

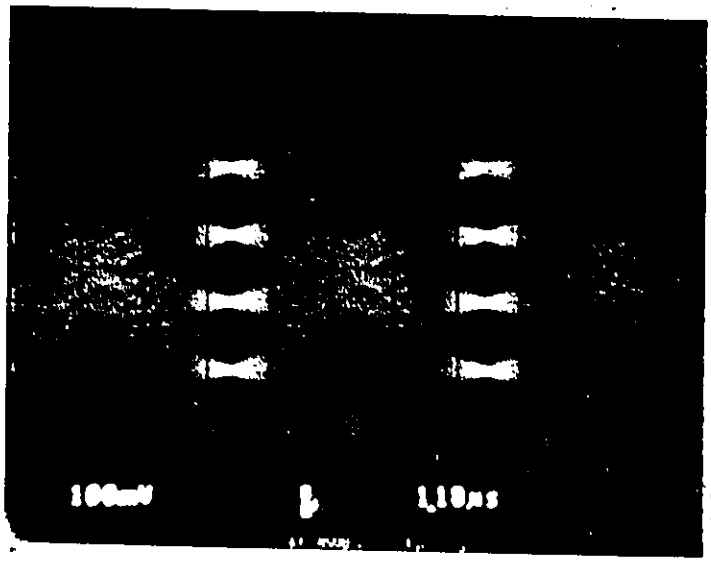


Figure 3.3. Measured eye diagram of a 4-PAM signal with the LM-380 amplifier. Linear region. Nyquist filters with α=0.2 are used. The signal rate is 413.3 kb/s.

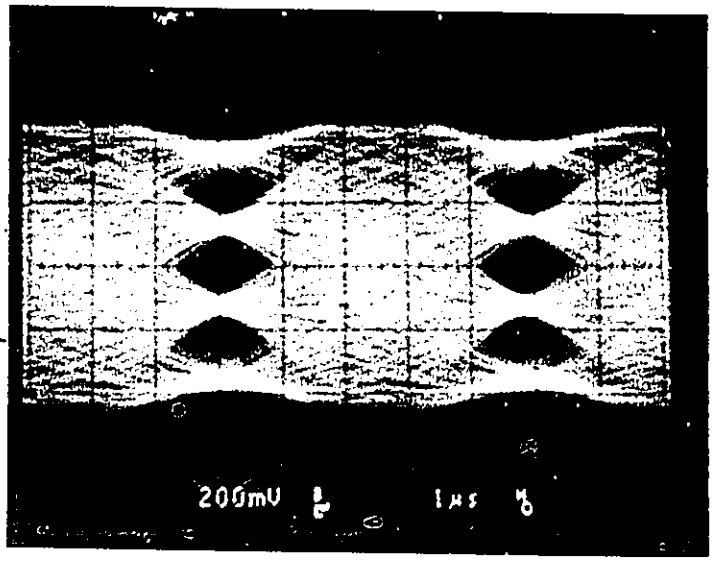


Figure 3.4. Measured eye diagram of a 4-PAM signal with the LM-380 amplifier (3 dB Output Backoff). Nyquist filters with α=0.2 are used. The signal rate is 413.3 kb/s.

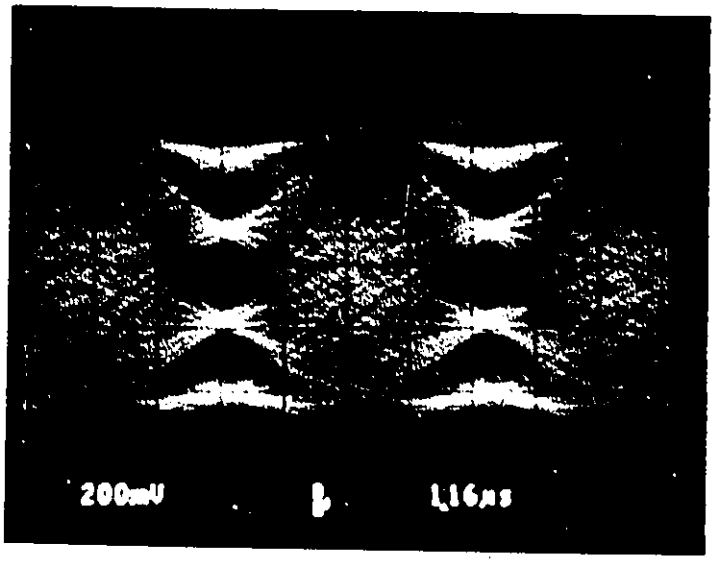
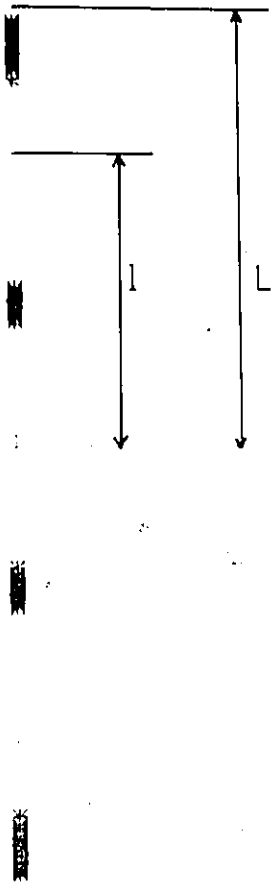


Figure 3.5. Measured eye diagram of a 4-PAM signal with the LM-380 amplifier (2 dB Output Backoff). Nyquist filters with α=0.2 are used. The signal rate is 413.3 kb/s.

4 dB Out.Backoff



Amplitude margin=

$$= \frac{L-l}{L} \cdot \%$$

Figure 3.6. Space diagram of a 4-PAM scheme with the LM-380 characteristic. Computer simulation results with α=0.2 Nyquist filters.The initial transmitted levels were $\pm 1, \pm 3$. The gain of the LM-380 amplifier has been removed.

A phase nonlinearity (AM-PM conversion) causes envelope dependent phase rotation of the incoming signal levels with the following results.

Assuming only AM-PM conversion, the output of the amplifier can be written as (equation 2.9):

$$Y(t)= R(t)\ \exp(j\Phi(t)) = R_p(t) + j\ R_q(t) \qquad 3.5$$

where

$$R_p(t)= R(t)\ \cos(\Phi(t))= R(t)\ \cos(\Phi(R(t))) \qquad 3.6$$

and

$$R_q(t)= R(t)\ \sin(\Phi(t))= R(t)\ \sin(\Phi(R(t))) \qquad 3.7$$

We note that the original one dimensional signal, is expressed as a two dimensional signal according to the equation 3.5 (see also Figure 3.7). Since our decoding system is one dimensional, only the in-phase component R_p will remain after demodulation. The result is a level dependent suppression according to the $\cos(\Phi(R(t)))$. Additional inter-symbol interference is also expected.

The above effects degrade the error performance of the system. Once more, the major contribution to the degradation comes from the higher level. We call phase margin the amount of rotation of the higher level that causes system failure (Fig 3.7). In Table 3.2 we note that the phase margin decreases as we move to higher schemes.

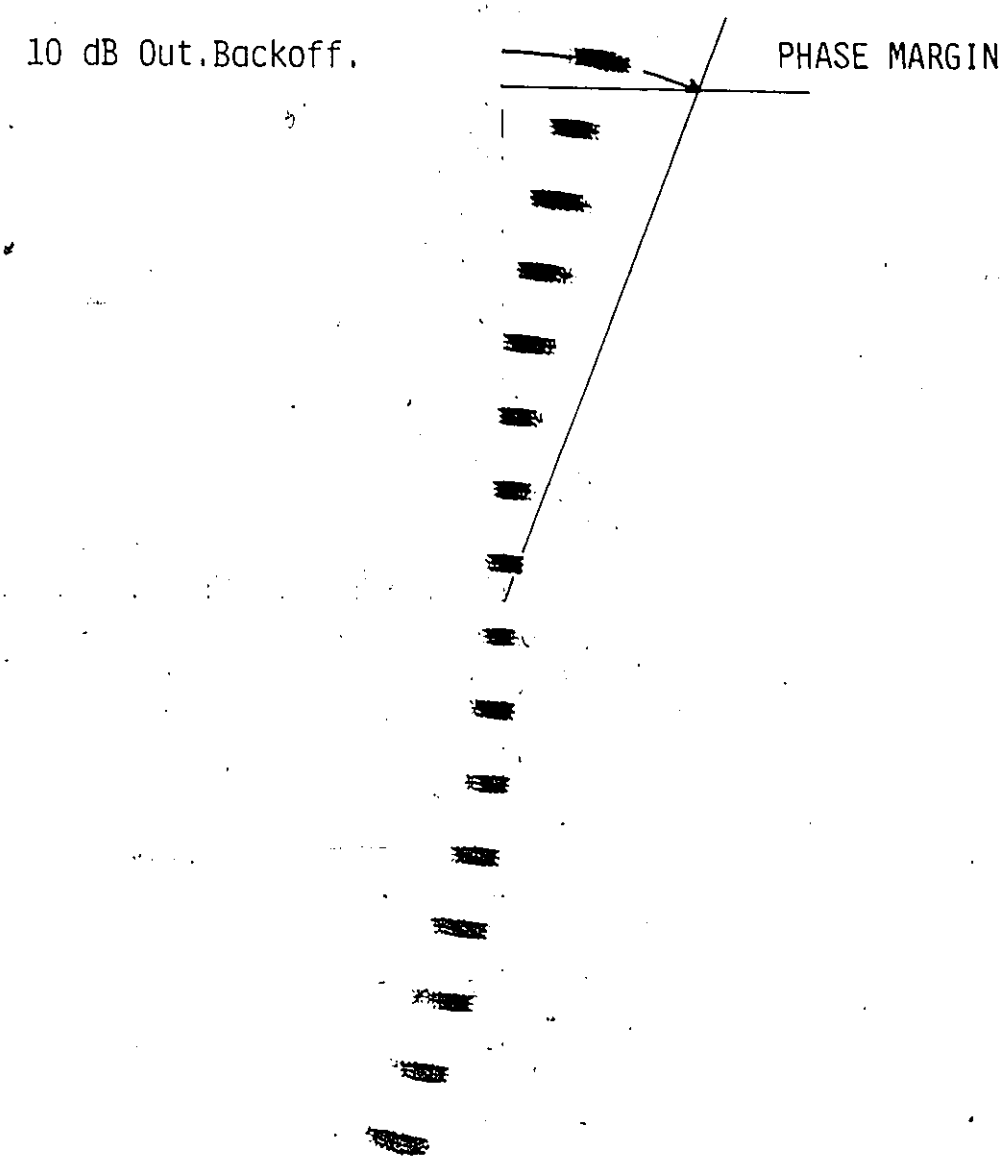


Figure 3.7. Space diagram of a 16-PAM scheme with the H-261 AM-PM characteristic.Computer simulation results with a=0.2 Nyquist filters. The Out.Backoff refers to the LM-380 characteristic. The initial transmitted levels were ±1,±3,±5,±7,±9,±11,±13,±15.

No of levels	Phase margin (degrees)
2	90
4	48
8	31
16	21
32	14.6

TABLE 3.2 . Phase margin of PAM schemes.

The signal distortion due to the combined AM-AM and AM-PM effects is much more severe than the distortion of each effect. The signal levels are suppressed and rotated simultaneously. The distortion is more severe for the higher levels. This is shown clearly in Figures 3.8 and 3.9 for an 8-PAM signal with the LM-380 and H-261 nonlinearities. We notice that the higher transmitted levels ($\pm$ 7), have almost reach their corresponding decoding thresholds, which means that the system has almost failed.

At this point, we must make a remark about the simulated space diagrams and eye diagram of Figures 3.6 to 3.9. We should expect the received signal power to be higher than the power of the transmitted signal. We should also expect the received signal power to increase as Backoff is decreased. However this does not seem so. This happens because in our simulations we remove the gain of the amplifier. Thus in the above Figures we see only the effects of the amplifier nonlinearities.

We mentioned in the precenting analysis, that the higher schemes are more sensitive to the effects of the channel nonlinearities and that their error performance is expected to be worst than that of the lower schemes. The advantage of using schemes with high number of levels is to accomplish spectral efficiency. The bandwidth requirements for transmitting PAM signals can be found by the formula [22]:

$$W = R / (2 \log_2 M)$$

where W is the baseband signal bandwidth, R the signal rate in b/s and M the number of signal levels. The bandwidth efficiency for PAM as measured by the ratio R/W in bits per second per Hertz is given in Table 3.3.

No of levels	Bandwidth efficiency b/s/Hz
2	2
4	4
8	6
16	8
32	10

TABLE 3.3 . Bandwidth Efficiency of PAM signals.

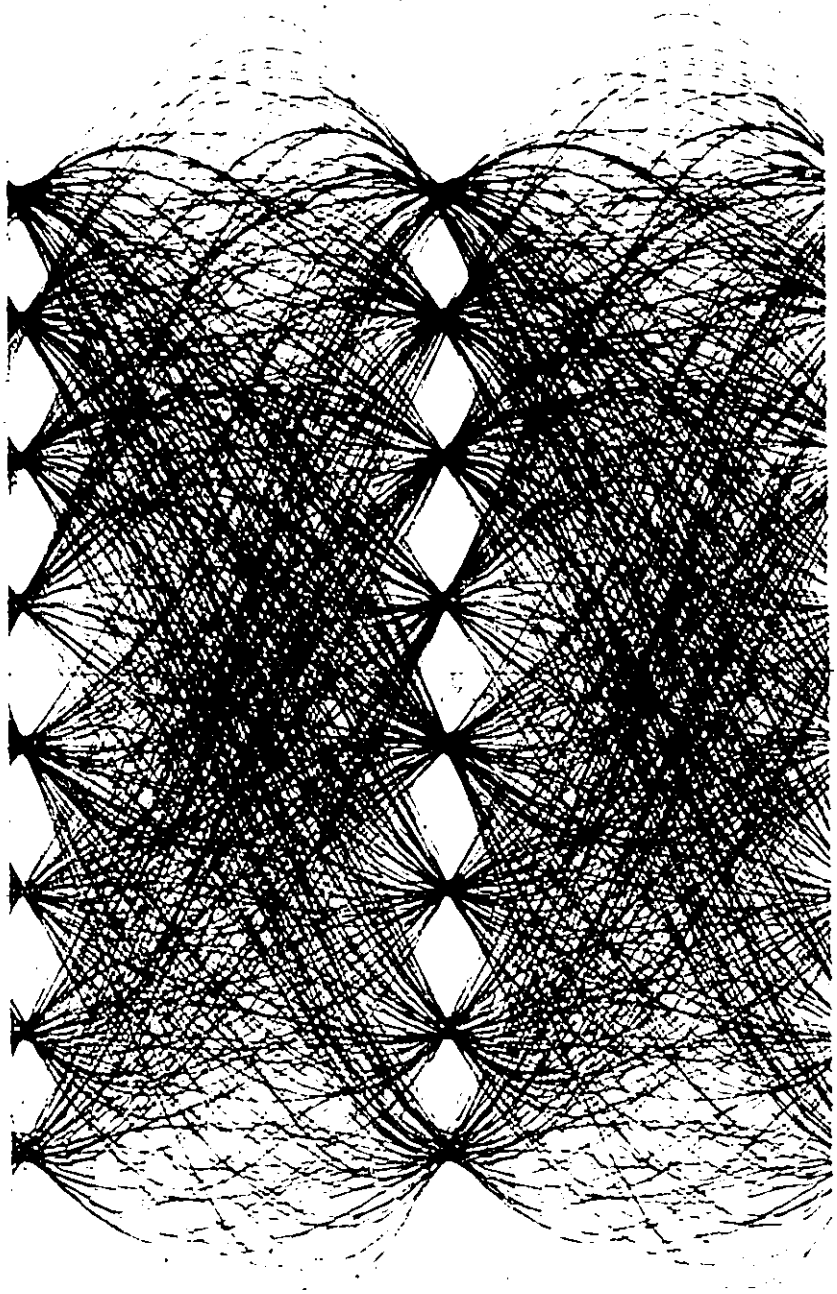


Figure 3.8. Eye diagram of an 8-PAM scheme with the LM-380, H-261 characteristics (6 dB Out.Backoff). Computer simulation results with α=0.2 Nyquist filters. The initial transmitted levels were ±1,±3, ±5,±7. The gain of the LM-380 amplifier has been removed.

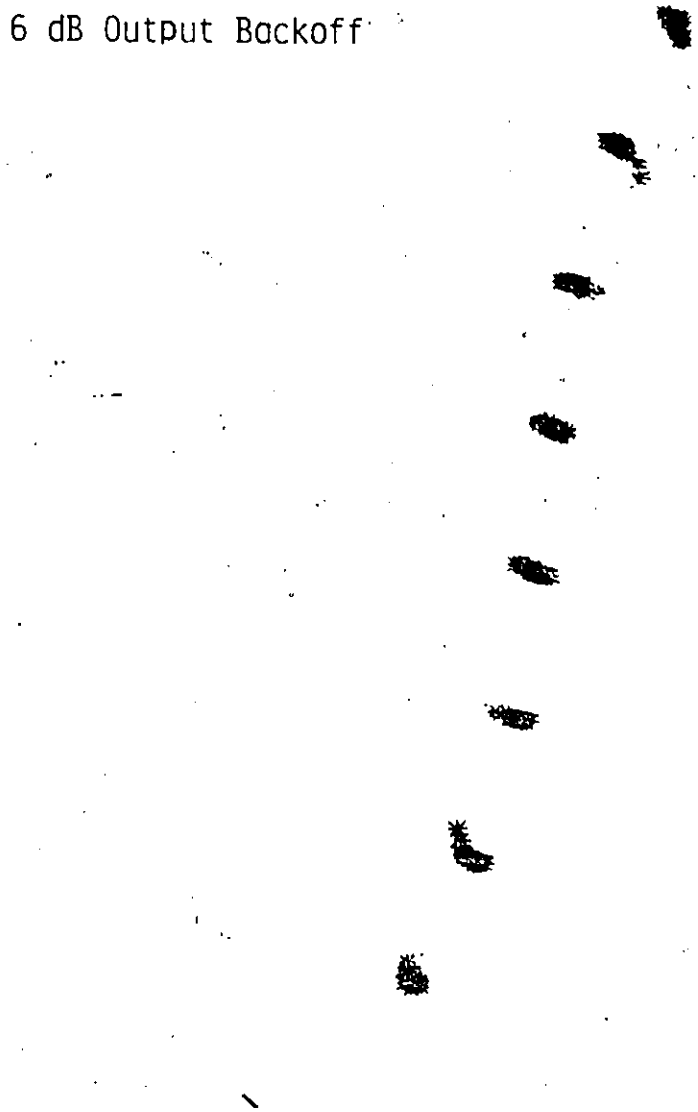


Figure 3.9. Space diagram of an 8-PAM scheme with the LM-380,H-261 characteristics. Computer simulation results with α=0.2 Nyquist filters. The initial transmitted levels were $\pm1,\pm3,\pm5,\pm7$. The gain of the LM-380 amplifier has been removed.

3.3.2 Calculation of the error performance.

Using the described simulation set-up, the probability of error P(e) was calculated for 2,4,8,16 and 32 PAM schemes and for different operating points of the nonlinear characteristics. For better accuracy the polynomial representation was prefered (see Tables 2.1 to 2.7). The quadrature model with the characteristics of Figure 2.5 was used for the AM-AM and AM-PM nonlinearities.

In Figure 3.10, the error performance of a 4-PAM signal with the LM-380 AM-AM characteristic is shown. The different operating points are expressed as Output Backoff. We notice that the performance degrades when the Backoff is decreasing. In order to obtain a good performance the power amplifiers must be operated at average power levels which are significantly below saturation. This makes the system less power efficient. The same observations are made when the AM-PM and the AM-AM, AM-PM combined effects are considered (Figures 3.11,3.12).

The observed degradation in the error performance is due to the nonlinear distortions of the signal, explained in Section 3.3.1. The vertical eye openings (see Figures 3.3 to 3.9), decrease due to the envelope dependent suppression and rotation of the signal levels. In other words, the distances $A_m - T_k$ ($m = 1,..,M$, $k=1,..,M-1$) of the equations 3.1 become smaller, resulting in higher probability of error (erfc(x) increases when x decreases). The degradation of the performance increases when the operation point is changed towards saturation, because the nonlinear distortions become more severe.

The measured Probability of bit error for a 4-PAM signal and for various operating points of the LM-380 characteristic is shown in Figure 3.13. To measure the S/N ratio for a particular operating point (Output Backoff), we changed the noise power while the signal power was kept constant. Comparing the measured results with those of computer simulation (Fig. 3.10) we observe that:

i) For $P(e)=10^{-4}$ and without the amplifier (linear channel), there is a 0.6 dB degradation in the S/N ratio from the simulated performance. This is due to Hardware imperfections of the 4-PAM circuit, impendance mismatching and filter Group delay (see Appendix A). These impairments generate Intersymbol Interference.

ii) For $P(e)=10^{-4}$ and with the LM-380 amplifier operating in the "linear" region there is an additional 0.4 dB degradation in the S/N ratio. This is due to a basic difference between the simulation and the measurement models. In the simulation model the LM-380 amplifier is assumed to be phase equalized. In Appendix B we show that the above degradation is mainly due to the phase of the LM-380 amplifier which is drawn in Figure B.2 .

iii) The effects of the above imperfections become more severe when we operate closer to saturation, due to the very small vertical opening of the signal outer eyes.

As we see in Figure 3.14, the difference between computer simulation and measured results for $P(e)=10^{-4}$ is between 1 to 1.5 dB. Considering the above remarks we can say that the measured results justify the simulated ones.

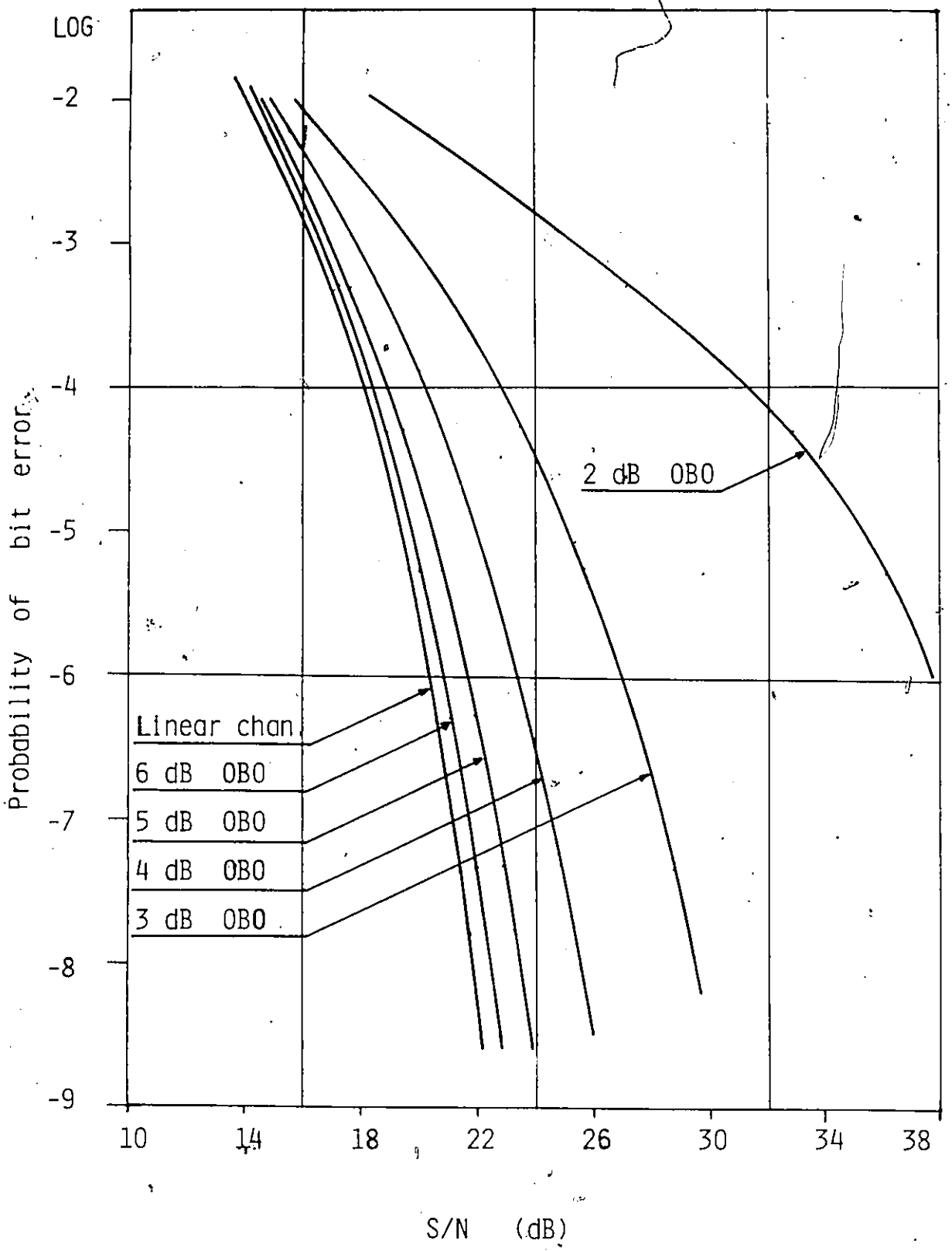


Figure 3.10. Performance of a 4-PAM signal with the LM-380 AM-AM characteristic. Computer simulation results with α=0.2 Filters. The S/N ratio is measured in the Nyquist bandwidth at the output of the receiver LPF.

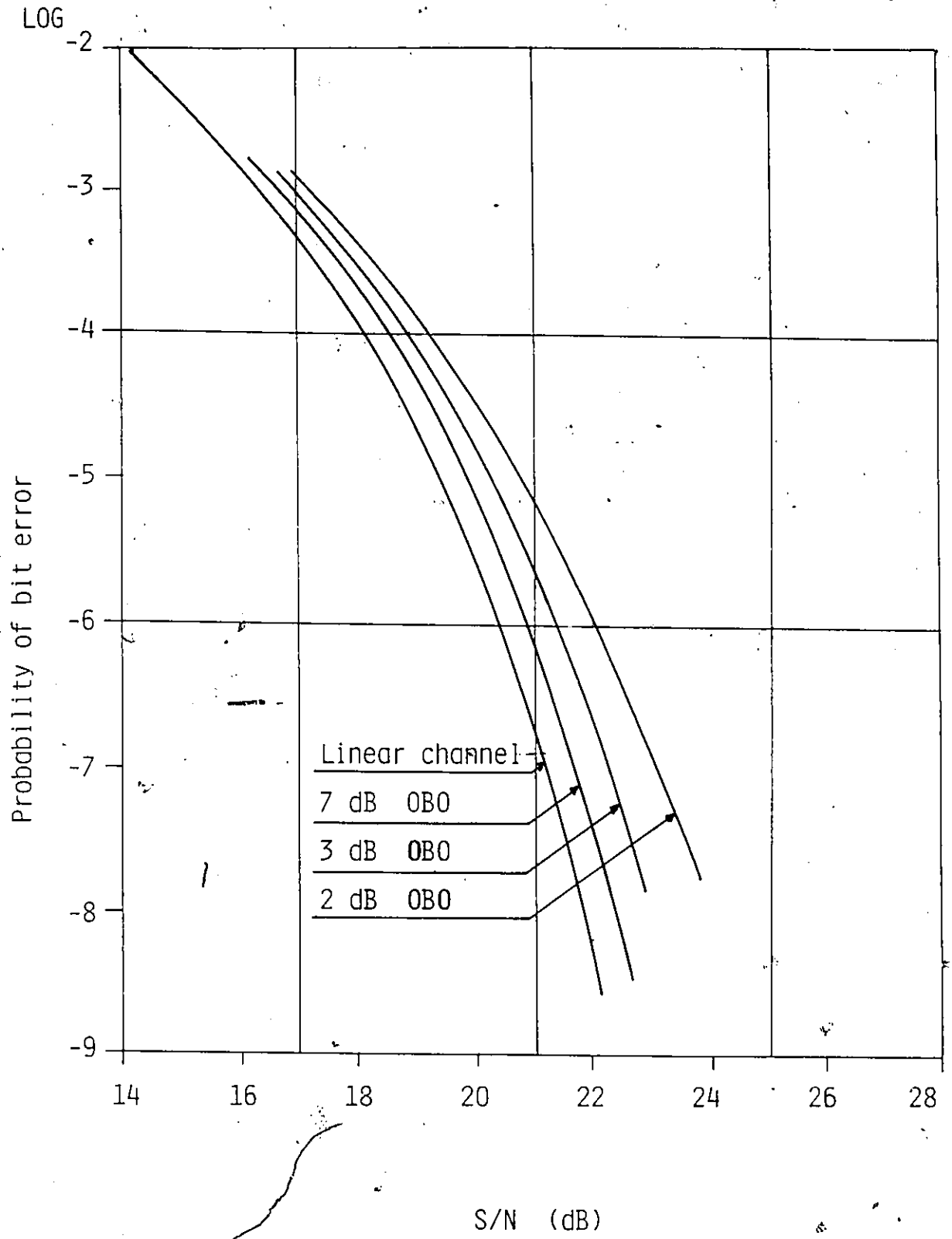


Figure 3.11. Performance of a 4-PAM signal with the H-261 AM-PM characteristic. Computer simulation results with α=0.2 Filters. The S/N ratio is measured in the Nyquist bandwidth at the output of the receiver LPF. The Output Backoff refers to the LM-380 characteristic.

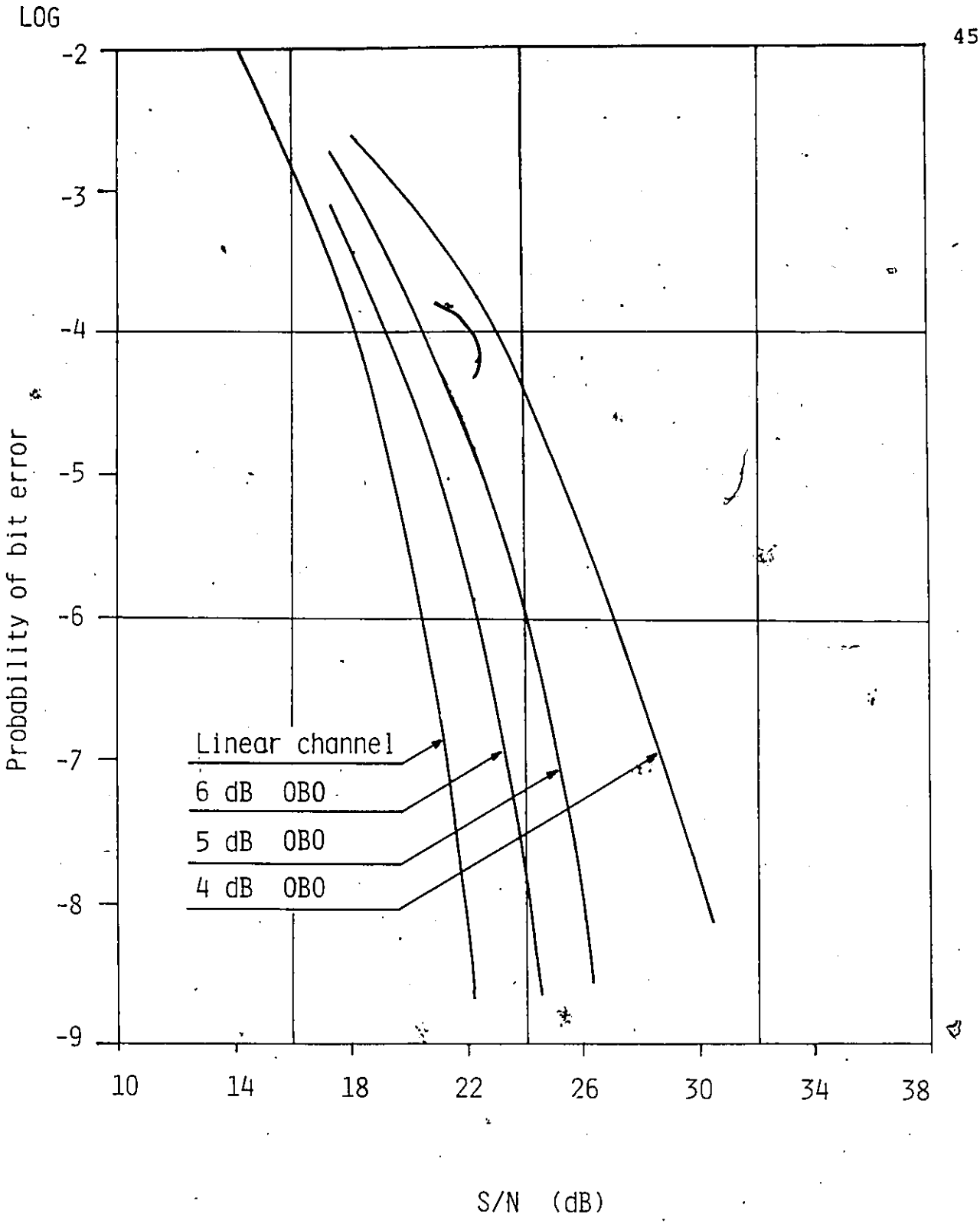


Figure 3.12: Performance of a 4-PAM signal with the LM-380 and H-261 characteristics. Computer simulation results with α=0.2 Filters. The S/N ratio is measured in the Nyquist bandwidth at the output of the receiver LPF.

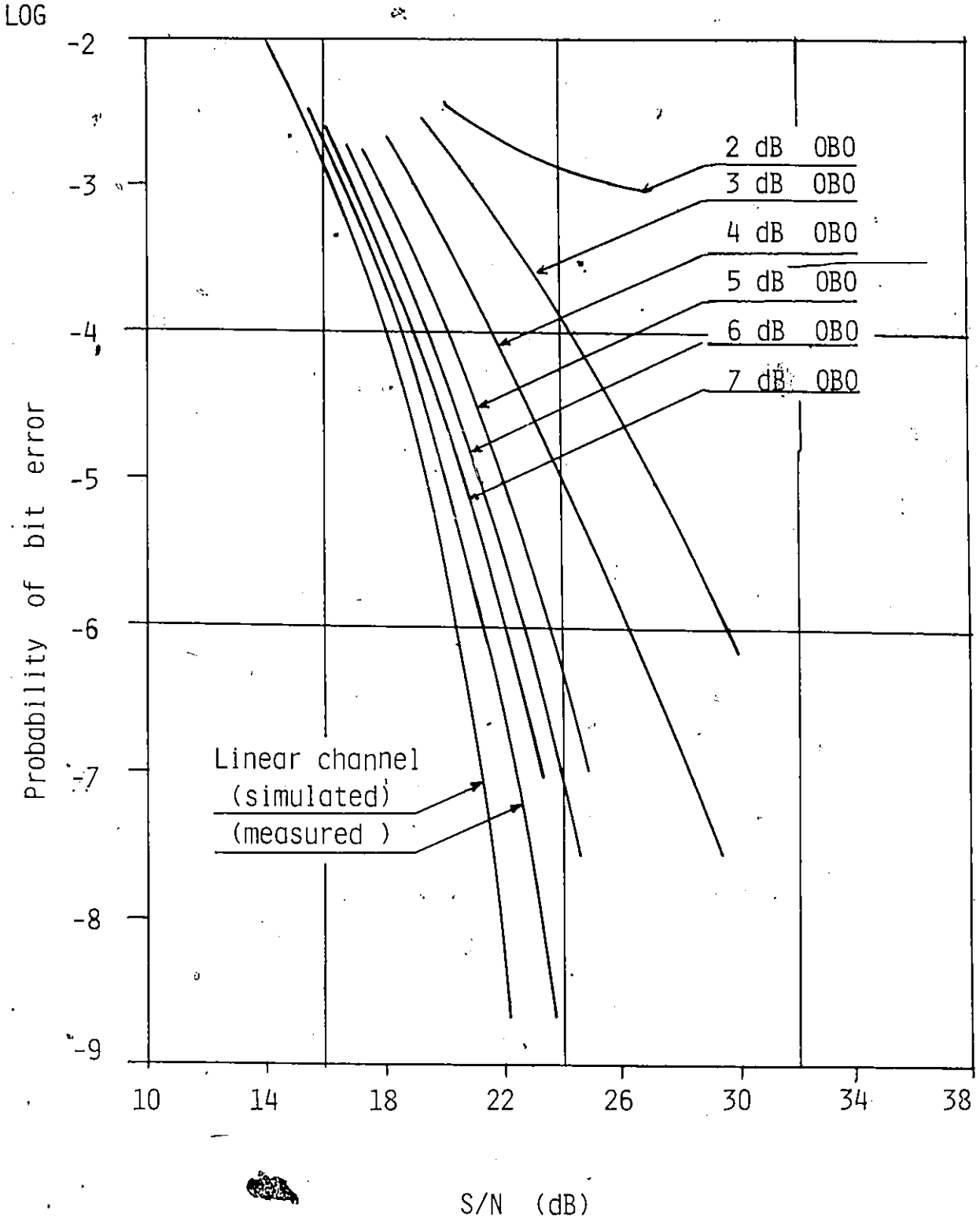


Figure 3.13. Performance of a 4-PAM signal with the LM-380 AM-AM characteristic. Measured results with α=0.2 Filters. The S/N ratio is measured in the Nyquist bandwidth at the output of the receiver LPF.

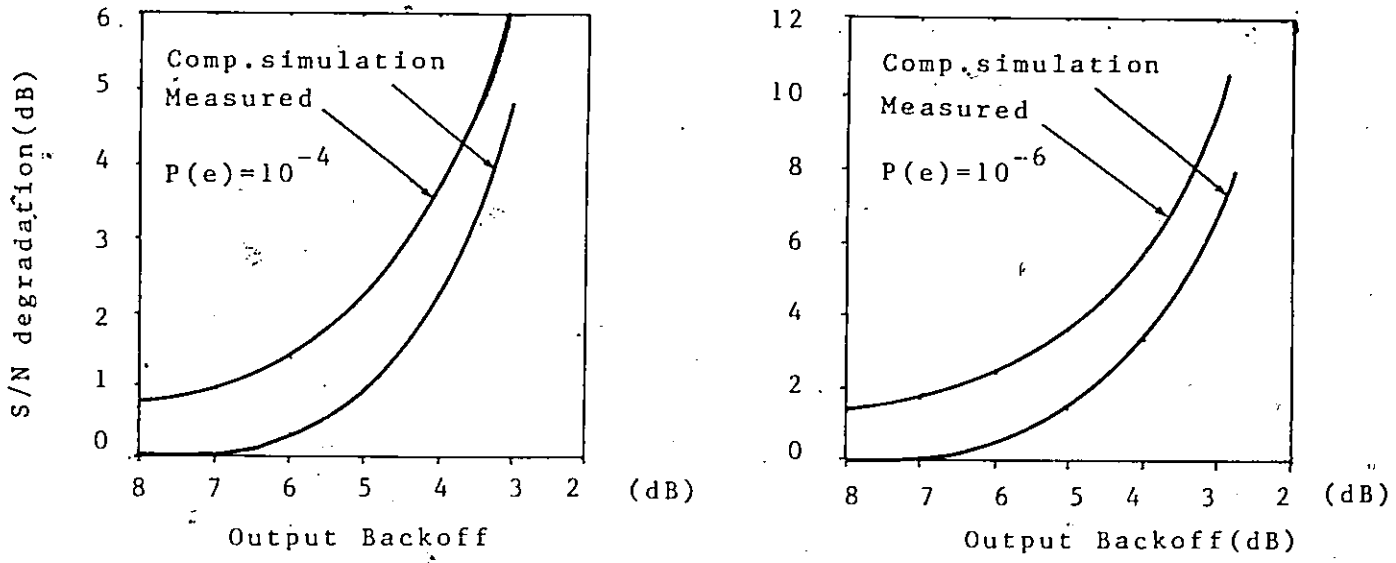


FIGURE 3.14. C/N DEGRADATION OF A 4-PAM SIGNAL WITH THE LM-380 AM-AM CHARACTERISTIC.COMPUTER SIMULATION AND MEASURED RESULTS WITH α=0.2. NYQUIST FILTER.

The degradation in the error performance for various PAM schemes has also been computed. The sum of the S/N degradation (dB) and Output Backoff (dB) versus Output Backoff, for $P(e)=10^{-6}$ is drawn in Figures 3.15 to 3.17. This is done because in a communication link, in order to find the best operating point both the S/N degradation and the Output Backoff must be considered. According to these Figures the following conclusions are made:

i) The closer to saturation we operate the greater the degradation is. As we explained before, this happens because the nonlinear distortions become more severe.

ii) The higher the scheme the more sensitive is to the nonlinear effects. This is due to the significantly lower amplitude and phase margins of the higher schemes (see Tables 3.1, 3.2). In Figure 3.15 we see that for an acceptable performance, and with an 8-PAM signal we must operate more than 5 dB Output Backoff while with a 32 PAM signal we must operate more than 12 dB Output Backoff.

iii) There is a small dependance of the nonlinear distortion on the shape of the transmit filter. The performance for roll-off factors =0.2 and =0.5 is drawn in Figures 3.15 and 3.17. We note that the degradation increases as the roll-off factor decreases. This is expected since the smaller the roll-off factor, the greater the envelope fluctuation of the signal and therefore the greater the distortions caused by the envelope dependent nonlinearities. We also observe that the higher schemes are less sensitive to the filter shape. This is because they exhibit high envelope fluctuations even before filtering.

iv)The severity of the degradation depends also on the nature of the amplifier characteristics. The H-261 characteristic allows less Back-off than the Intelsat V characteristic ,since it exhibits lower phase shifts (Figure 3.17).

v)Comparing Figures 3.15 and 3.16,we observe that the degradation due to the AM-PM conversion is for the higher schemes more critical than the degradation due to AM-AM conversion. For these schemes the phase margin is comparable to the phase rotation caused by the chosen AM-PM characteristics. However,generally there is no consistent explanation to identify whether the major cause of performance degradation is due to the AM-AM or the AM-PM characteristic of the amplifier [2,13].

vi)The degradation caused by the combined AM-AM,AM-PM effects is greater than the sum of the degradation of each effect. This is due to the interaction of the envelope dependent suppression and rotation of the signal levels.

From the obtained results we can find the optimum operating points when both the S/N degradation and the Output Backoff are considered. They are given in table 3.4 and they justify the conclusions we made.

OPTIMUM OPERATING POINTS (Out.Backoff,dB). $P(e)=10^{-6}$

scheme / nonlin.	2 PAM	4 PAM	8 PAM	16 PAM	32 PAM
LM-380	0	5	7	9	11
H-261	0	0	3	11	13
Intel.-V	0	5	/	/	/
LM-380 H-261	0	6	9	12	14
LM-380 Intel.-V	0	7.5	/	/	/

TABLE 3.4

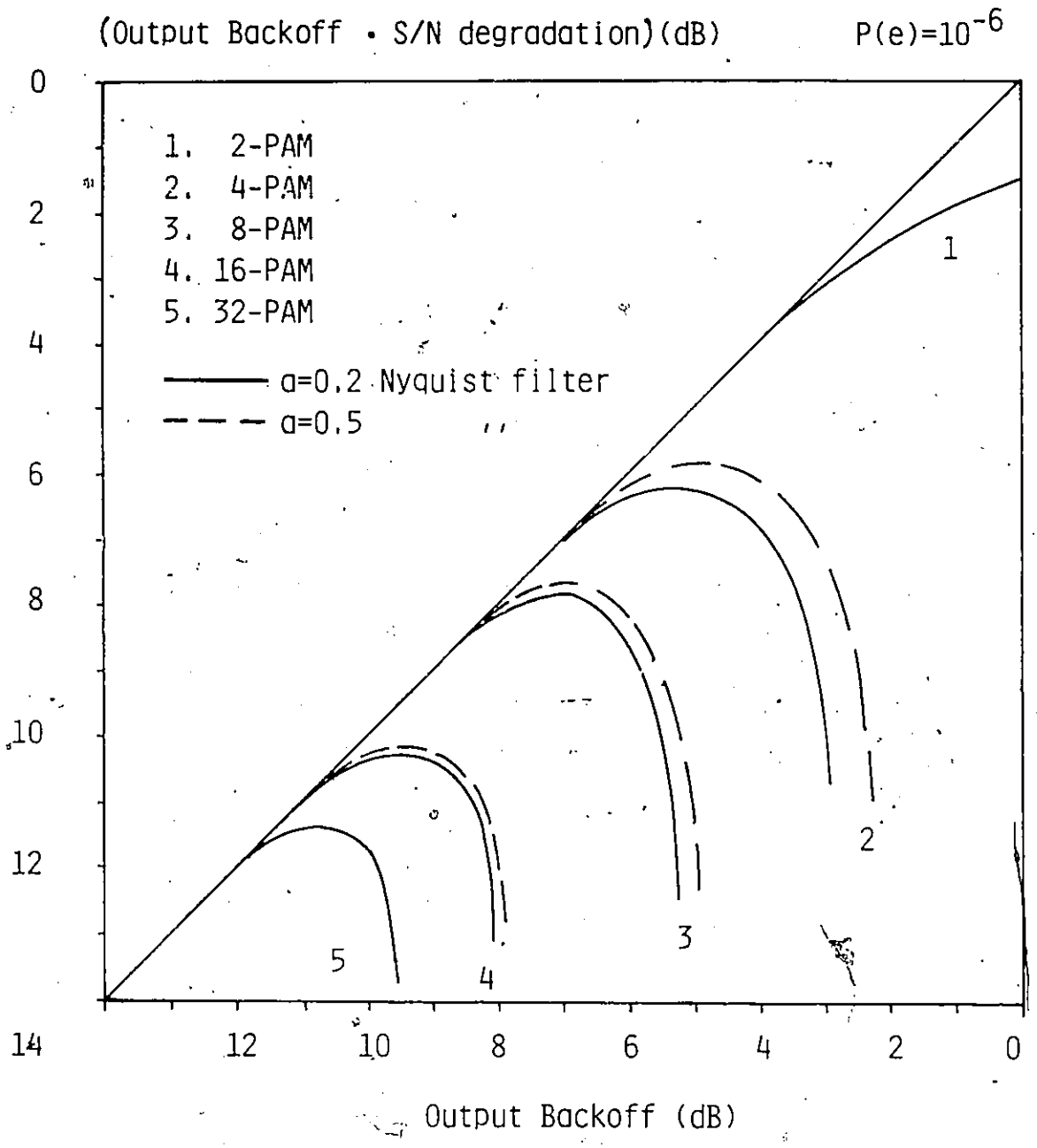


Figure 3.15 Degradation due to Amplitude conversion (LM-380 characteristic). Computer simulation results.

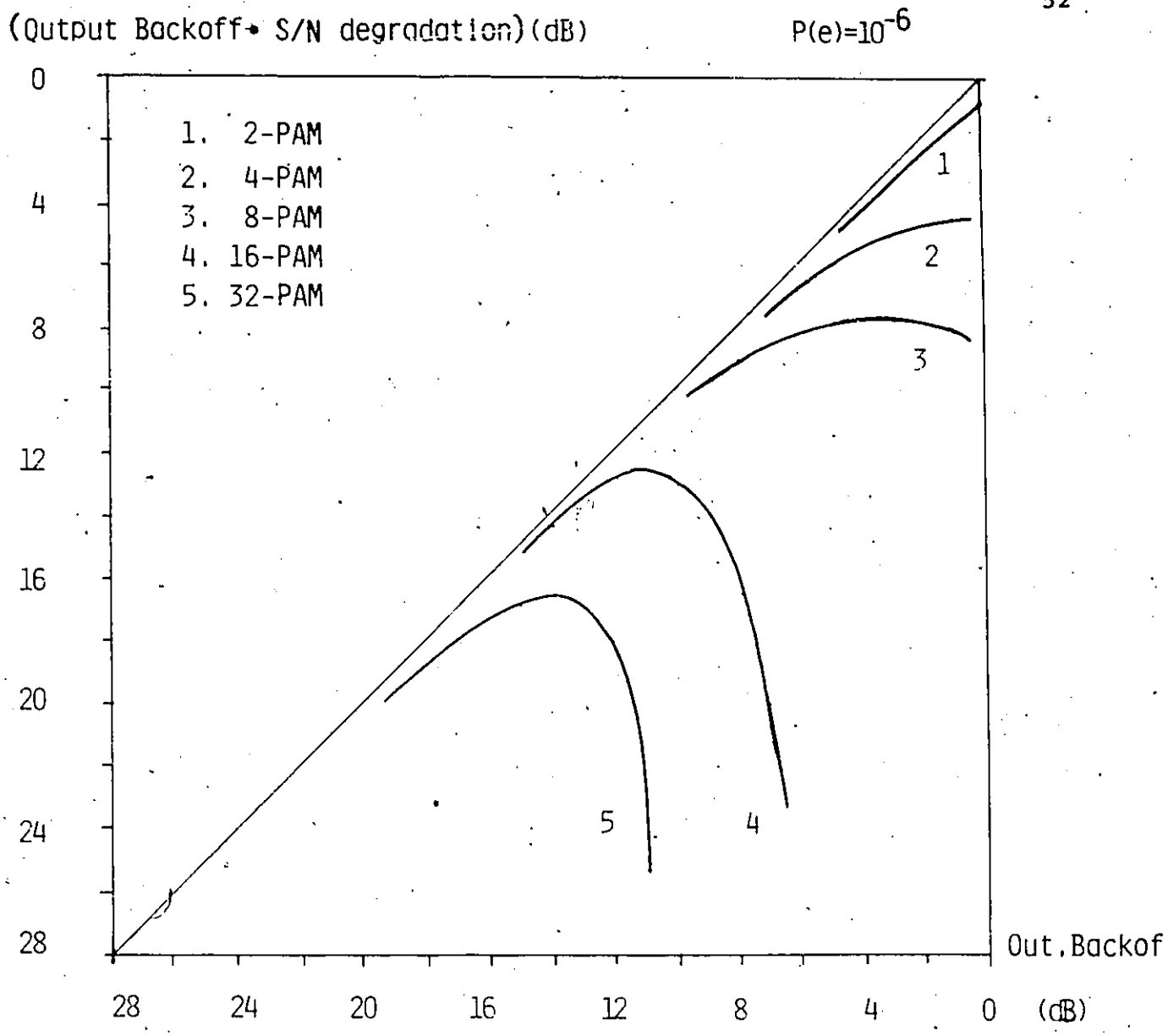


Figure 3.16. Degradation due to AM-PM conversion (H-261 characteristic). The Output Backoff refers to the LM-380 characteristic. Computer simulation results with α=0.2 Nyquist filters. The S/N ratio is measured in the Nyquist bandwidth at the output of the receiver LPF.

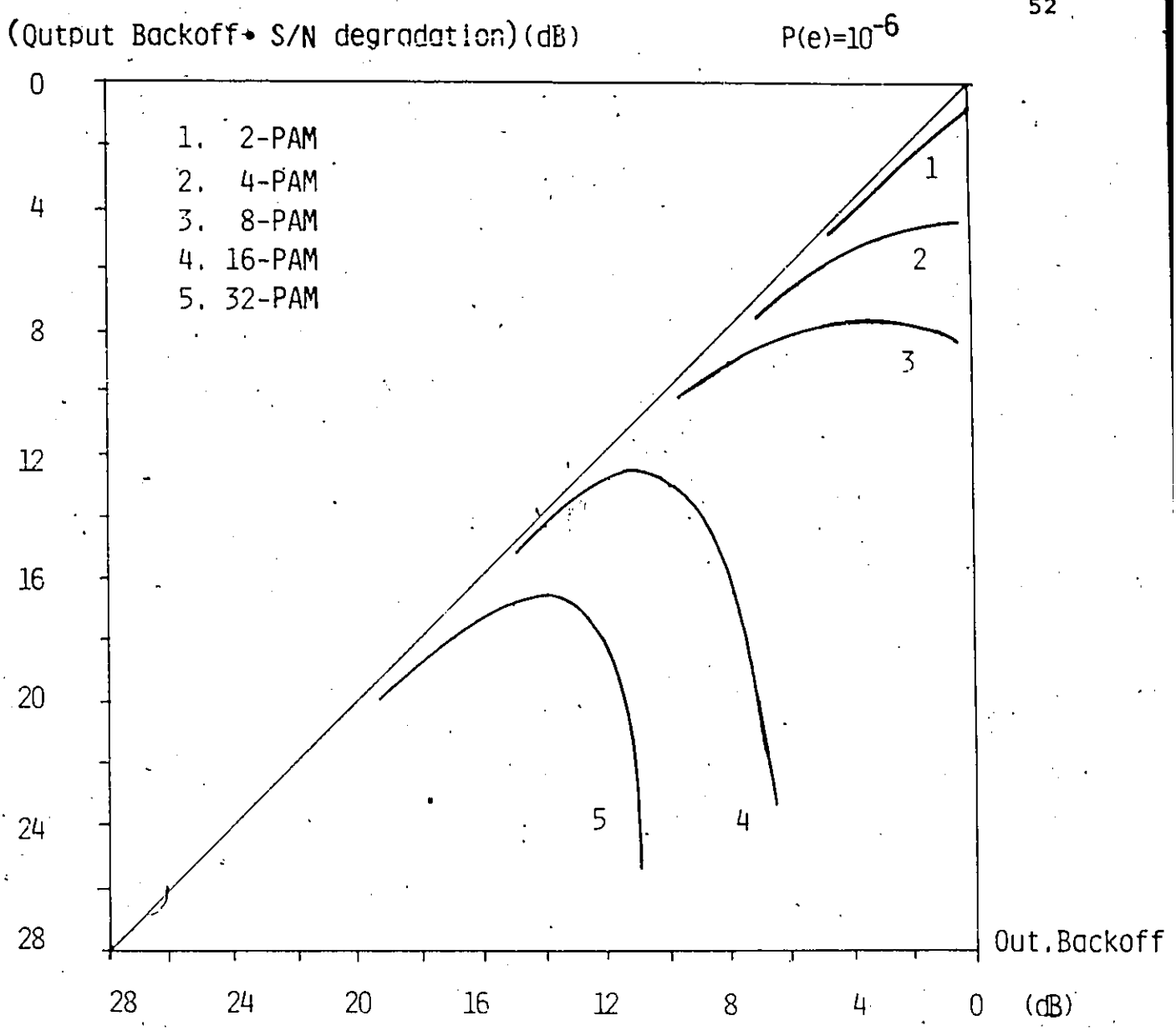


Figure 3.16. Degradation due to AM-PM conversion (H-261 characteristic). The Output Backoff refers to the LM-380 characteristic. Computer simulation results with α=0.2 Nyquist filters. The S/N ratio is measured in the Nyquist bandwidth at the output of the receiver LPF.

3.3.3 Spectral regrowth

Spectral regrowth is another severe problem caused by power amplifier nonlinearities. In spite of the bandwidth limitation of the transmitted signal by the transmit filter, spectral sidelobe regrowth is observed at the output of the amplifier (usually the filter is prior to the amplifier). This is due to the increase of the signal envelope fluctuations, caused by the amplitude and phase nonlinearities. The amount of the OBE is dependent upon the operating Backoff of the amplifier and the amount of envelope fluctuation of the incoming signal.

The measured spectral regrowth for a 4-PAM scheme due to the LM-380 amplifier is shown in Figures 3.18 (a),(b). We note that for operation in the "linear" region of the amplifier (8 dB Out. Backoff), there is some spectral regrowth. This is consistent with the obtained degradation in the error performance which is shown in Figure 3.13 and is due to the phase of the LM-380 amplifier (Appendix B).

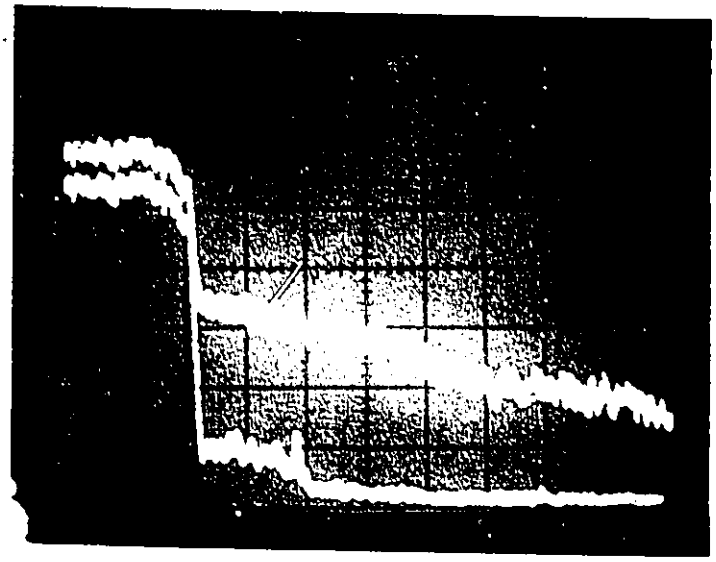
For the combined AM-AM, AM-PM effect we computed the spectral regrowth of the inphase and quadrature components (Equation 3.4). They are shown in Figure 3.19 (a),(b).

The following conclusions can be made:

i) For operation far below saturation the AM-PM conversion has the major contribution to the spectral regrowth (compare the In-phase and Quadrature spectrum). However, this is generally dependent on the nature of the nonlinear characteristics.

ii)As the operation point is changed towards saturation, the spectral regrowth increases. This is expected since, due to the severity of the nonlinear distortions close to saturation, the signal envelope fluctuations become more significant. We also note that the AM-AM conversion becomes the major contributor.

The spectral regrowth can become a cause for adjacent and cochannel channel interference. That is why we usually want to suppress it. In chapter VI we will show that the spectral regrowth can be reduced by using linearization techniques.

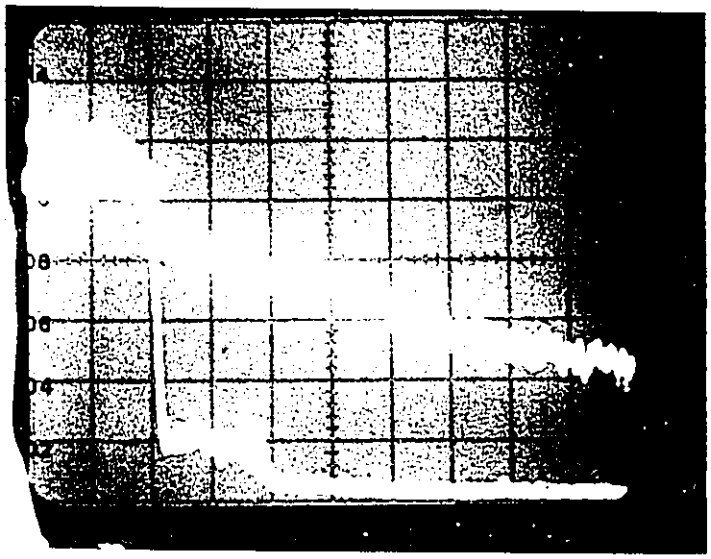


Vert. 10 dB/div.
Horiz. 50KHz/div.
Up.ref.lev. 0 dBm

4 dB Out.Backoff.

8 dB Out.Backoff.

(a)



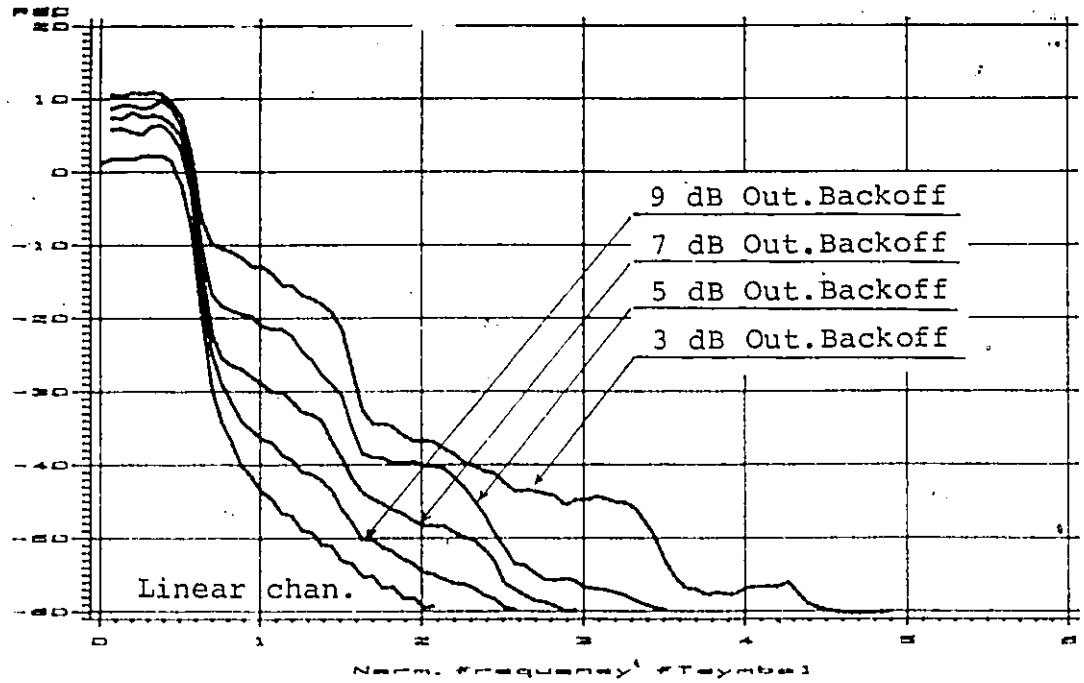
Vert. 10 dB/div.
Horiz. 50KHz/div.
Up.ref.lev. 0 dBm

2 dB Out.Backoff.

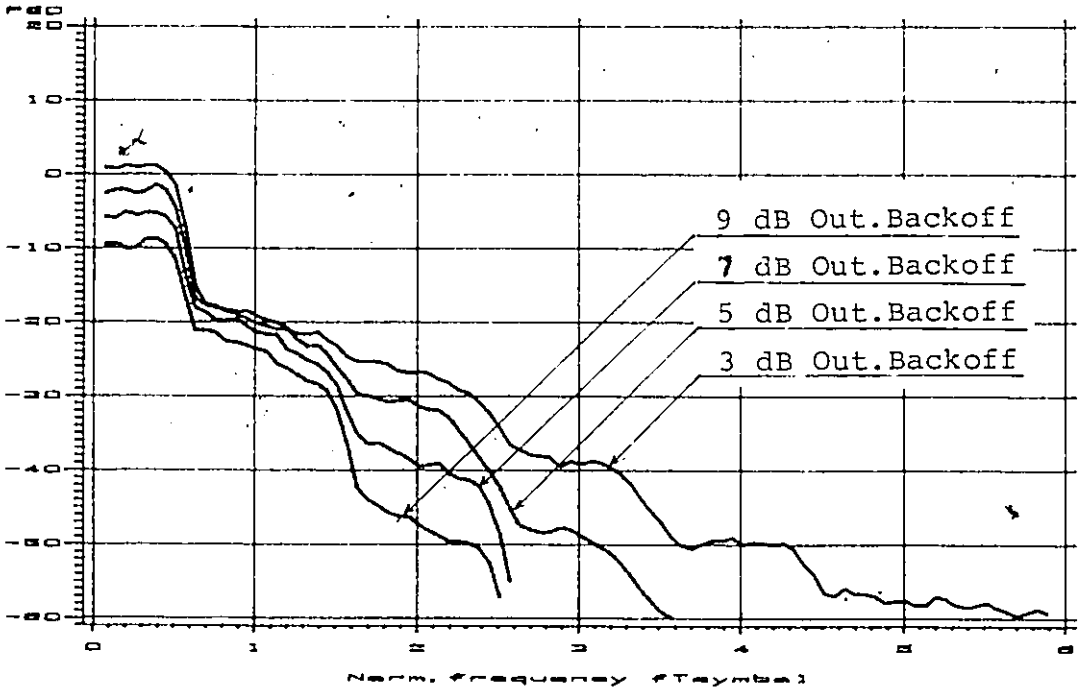
8 dB Out.Backoff.

(b)

Figure 3.18. Measured spectrum diagrams of a 4-PAM signal with the LM-380 amplifier. The signal rate is 413.3 Kb/s. Nyquist filters with a=0.2 were used.



(a) Inphase component spectrum.



(b) Quadrature component spectrum.

Figure 3.19. Spectral regrowth of a 4-PAM signal due to the LM-380 and H-261 nonlinearities. Computer simulation results with α =0.2 Nyquist filters.

Chapter IV

LINEARIZATION OF THE AMPLIFIER CHARACTERISTICS

The characteristics of predistortion linearizers for the amplifier nonlinearities used in chapter IV are calculated. The overall linearizer-amplifier characteristic is more linear and exhibits low phase shifts. Baseband linearization models are proposed and a baseband linearizer for the LM-380 amplifier is implemented.

4.1 GENERAL

The reduction of the distortion due to amplifier nonlinearities, is approached here by the introduction of a source of complementary nonlinear distortion in the signal path (linearizer),so that the overall transfer characteristic becomes more linear. For microwave transmitters in Microwave or Satellite links,predistortion linearization is prefered (Fig. 4.1), for the following reasons [4,6].

i)Because of the high microwave power at the output of the power amplifiers predistortion applications are less costly. The predistorter is not required to handle as much power and thus it is easier to be implemented.

ii)It is possible to apply predistortion in the RF,IF or baseband sections of the transmitter.

A drawback of predistortion linearization is that for perfect compensation, all the significant frequencies produced by the predistorter should be applied without shaping to the input of the power amplifier. This is difficult to be satisfied in practice.

The above considerations affect the decision on where to introduce the predistorter. In RF, IF or baseband. RF predistorters have the advantage of operating at smaller fractional bandwidths and thus achieving minimum frequency shaping. Baseband and IF predistorters on the other hand, are more flexible in signal processing and less costly [4].

The predistorter considered in our study is such that the overall predistorter-amplifier amplitude characteristic approaches that of a soft limiter and the overall phase characteristic is almost zero. These characteristics although suboptimal [3], yield significant performance improvements.

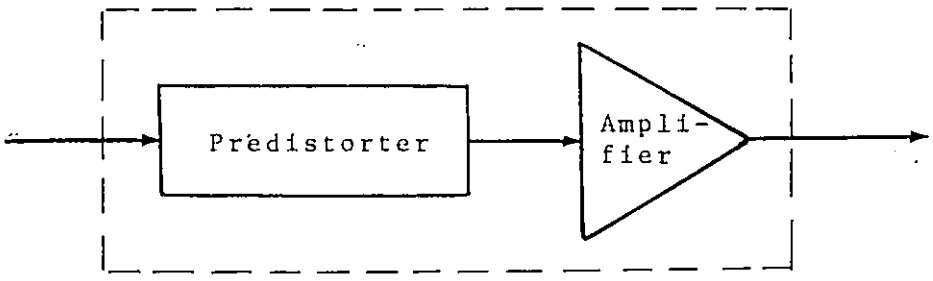


Figure 4.1. Predistortion linearization.

4.2 LINERIZATION OF THE LM-380 AM-AM CHARACTERISTIC

Here the phase rotation is considered zero. The LM-380 characteristic (Fig.2.2 (b)) is represented by the Hetrakul-Taylor model (Table 2.2) given by the equation:

$$Z(R)=3.590262\cdot R\cdot\exp(-7.462\ R^2)\cdot I_0(7.462\cdot R^2) \qquad 4.1$$

where R is the input to the power amplifier. The reason for using this model instead of the more accurate polynomial model is explained later.

The predistorter linearizer is modeled as a 2m-1 order polynomial:

$$G(R)=\sum_{i=1}^{m} a_{2i-1}\ R^{2i-1} \qquad 4.2$$

where the coefficients a_k are to be determined. In Figure 4.2 the cascade combination of the linearizer and the LM-380 amplifier is shown. We want the overall characteristic to be:

$$Z(G(R))=\begin{cases} V_0\ R/R_i & ,\ 0\le |R|\le R_i \\ V_0 & ,\ |R|\ge R_i \end{cases} \qquad 4.3$$

where V_0 is the saturation voltage and R_i the minimum voltage corresponding to the saturation of the soft limiter (Fig. 4.2). From equations 4.1, 4.2 and 4.3 we get:

$$Z(G(R))=3.590262\cdot\Big(\sum_{i=1}^{m}a_{2i-1}\cdot R^{2i-1}\Big)\cdot\exp\Big(-7.462\cdot\Big(\sum_{i=1}^{m}a_{2i-1}\cdot R^{2i-1}\Big)^2\Big)$$

$$\cdot I_0\Big(7.462\cdot\Big(\sum_{i=1}^{m}a_{2i-1}\cdot R^{2i-1}\Big)^2\Big) = \begin{cases} V_0\cdot R/R_i & ,\ 0\le|R|\le R_i \\ V_0 & |R|\ge R_i \end{cases} \qquad 4.4$$

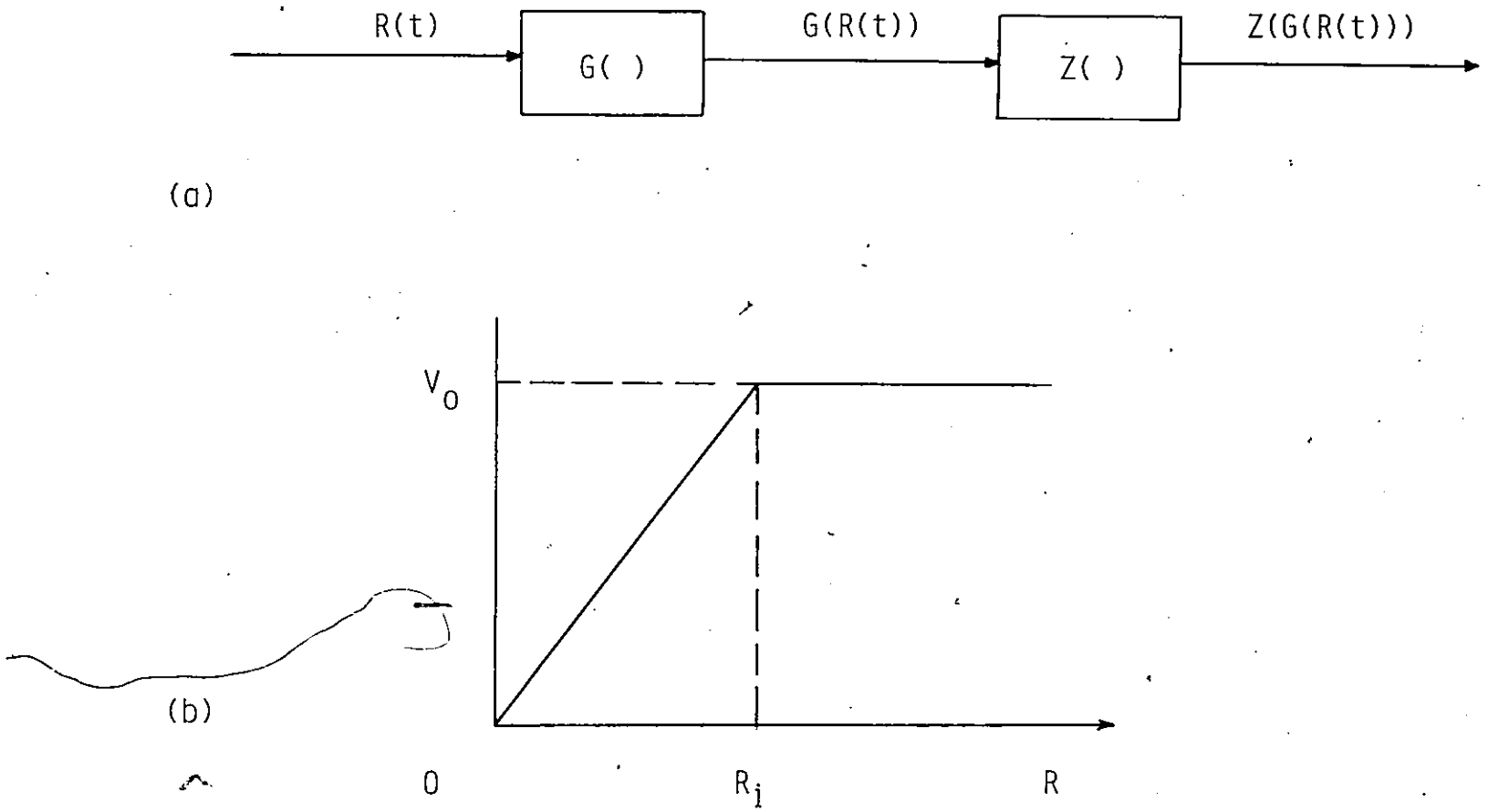


Figure 4.2. (a) Predistortion linearization of AM-AM nonlinearity.
(b) Required overall characteristic.

From the equations 4.3 and 4.4, we see that in order to calculate the predistorter coefficients, the polynomial G(R) must be inserted into the equation 4.1. If the polynomial representation were chosen for the Z(R), the resulting polynomial Z(G(R)) would have terms of very high order. These terms may cause overflow or underflow in the simulation. That is the reason we chose the Hetrakul-Taylor model which has lower power terms. This model was found more accurate than the Saleh model.

Using a conventional curve fitting optimization subroutine (Appendix D) the coefficients a_k were determined for different values of m. Their values for m=2,3 and 4 and R_i=0.183, V_0=0.6063 are given in table 4.1.

a_k \ m	2	3	4
a_1	0.991	0.98102	0.98520
a_3	4.663	3.80665	3.78135
a_5		104.19950	101.53210
a_7			-205.13100

TABLE 4.1 . Coefficients of the LM-380 predistorter.

In Figure 4.3 the linearizer and linearized characteristics are drawn for m=2,3. For m=3,4 the characteristics are almost the same and much more linear than m=2. In the next chapter the case for m=3 is considered.

A baseband linearizer was implemented for the LM-380 amplifier. A diode wave shaping circuit was considered [19,20]. The single-tone measured characteristic of the linearizer is a piece-wise linear approximation of the simulated one and is drawn in Figure 4.4. The analytical circuit of the linearizer is given and explained in Appendix C.

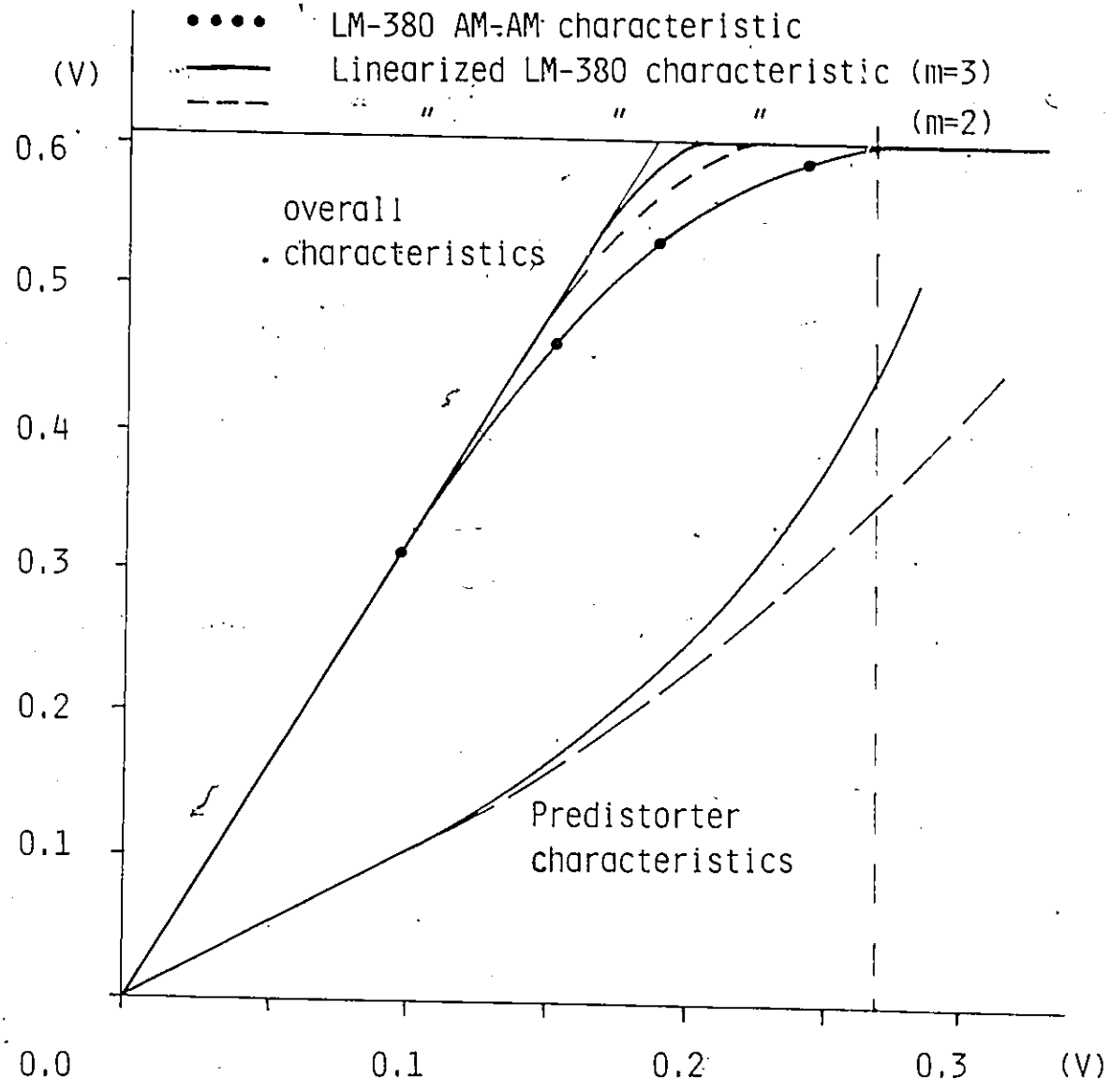


Figure 4.3. Linearization of the LM-380 AM-AM characteristic.

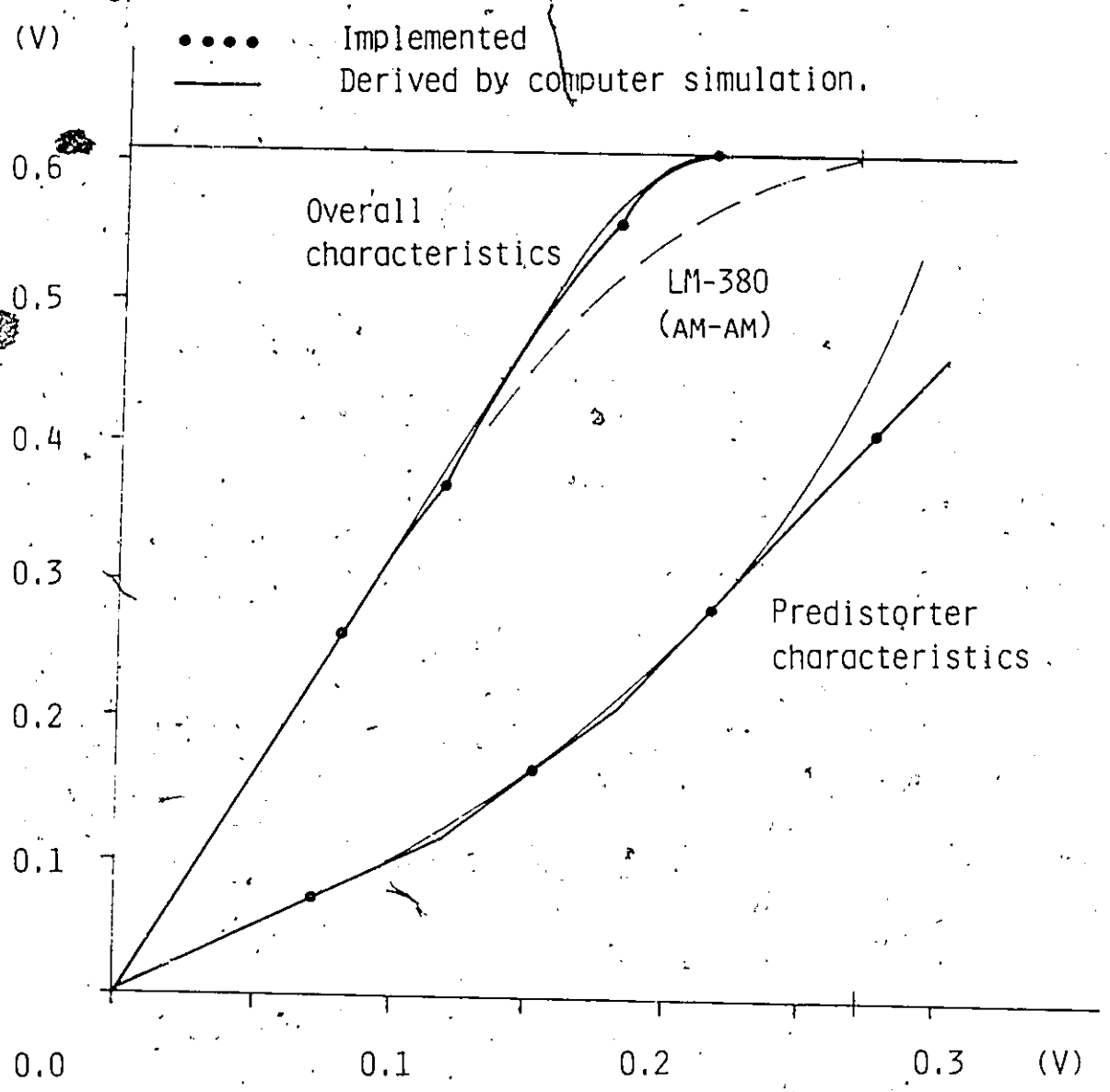


Figure 4.4 . Implemented piece-wise linear approximation Of the LM-380 predistorter characteristic.

4.3 COMPENSATION OF THE LM-380 AND H-261 CHARACTERISTICS.

We want the overall predistorter-amplifier AM-AM characteristic to approach that of a soft limiter and the overall AM-PM characteristic to be zero. We use the quadrature model of the normalized LM-380 and H-261 characteristics. The corresponding inphase and quadrature envelope nonlinearities are represented as (see Tables 2.4,2.5):

$$Z_p(R)=1.60138\ \exp(-0.325713\ R^2)\cdot I_0(0.325713\cdot R^2)$$

$$Z_q(R)=1.887482\ R^3/(1+1.063857\cdot R^2)^2 \qquad 4.5$$

These models were chosen for the same reason explained in Section 4.2. The Hetrakul-Taylor model was found more accurate for the representation of the $Z_p(R)$, while the Saleh model was found more accurate for the representation of the $Z_q(R)$. The predistorter is modeled as a second quadrature nonlinearity having the inphase and quadrature envelope nonlinearities $G_p(R), G_q(R)$ represented by two odd order polynomials:

$$G_p(R)=\sum_{i=1}^{m} a_{2i-1}\ R^{2i-1}$$

$$G_q(R)=\sum_{i=1}^{n} a_{2i+1}\ R^{2i+1} \qquad 4.6$$

A block diagram of the overall predistortion model is shown in Figure 4.5 . According to this we get for the overall amplitude and phase characteristics:

$$G(R)=\sqrt{G_p^2(R) + G_q^2(R)} \qquad Z(R)=\sqrt{Z_p^2(G) + Z_q^2(G)}$$

$$\Theta(R)= \tan^{-1} \frac{G_q(R)}{G_p(R)} \qquad \Phi(R)= \tan^{-1} \frac{Z_q(G)}{Z_p(G)}$$

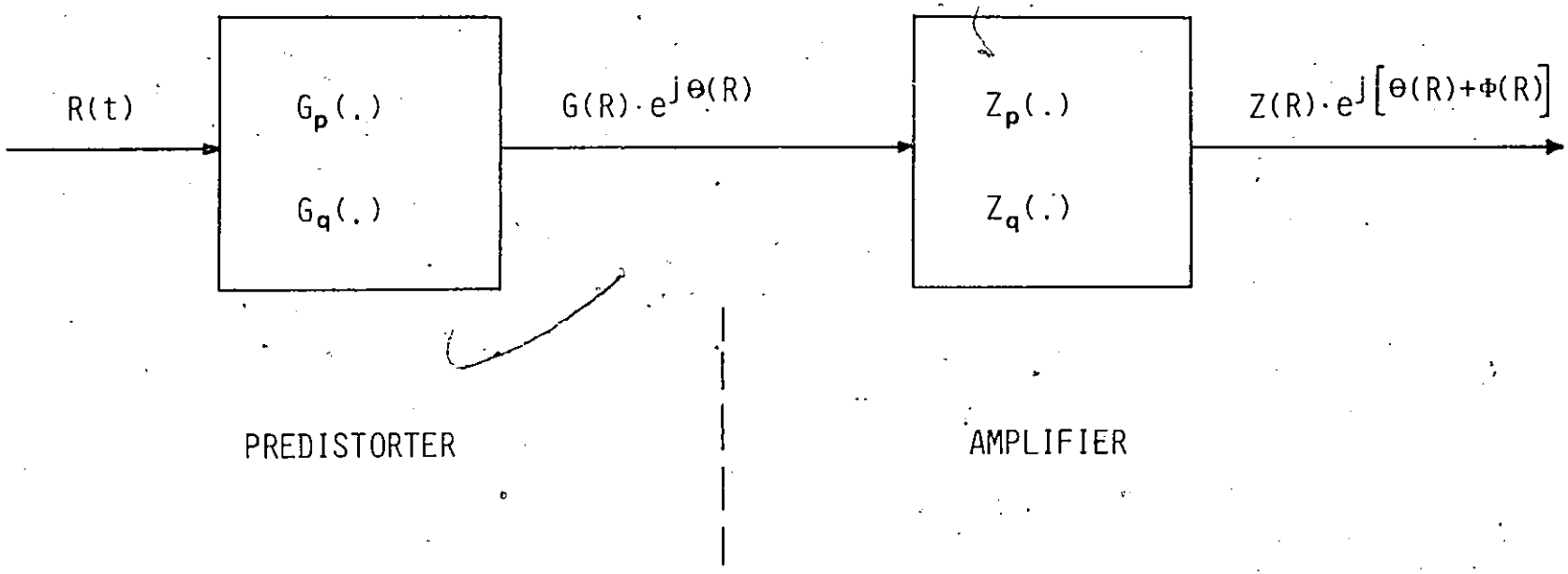


Figure 4.5. Predistortion compensation for AM-AM and AM-PM nonlinearities.

$$Z(R)=\sqrt{Z_p^2(R) + Z_q^2(R)} =$$

$$\sqrt{Z_p^2\left(\sqrt{G_p^2(R) + G_q^2(R)}\right) + Z_q^2\left(\sqrt{G_p^2(R) + G_q^2(R)}\right)} =$$

$$= \begin{cases} V_0 \cdot R/R_i & 0 \le |R| \le R_i \\ V_0 & |R| \ge R_i \end{cases} \qquad 4.7$$

and

$$\theta(R) + \Phi(G(R)) = \tan^{-1}\left(G_q(R)/G_p(R)\right) +$$

$$+ \tan^{-1}\left(Z_q\left(\sqrt{G_p^2(R) + G_q^2(R)}\right)\Big/ Z_p\left(\sqrt{G_p^2(R) + G_q^2(R)}\right)\right) = 0 \qquad 4.8$$

where $R_i = 0.966$ and $V_0 = 1.414$. Using equations 4.5 to 4.8 and an optimization subroutine (Appendix D) the coefficients of the predistorter characteristics were computed . They are given in table 4.2 .

The compensated overall AM-AM and AM-PM characteristics for the above coefficients are drawn in Figure 4.6.

A baseband implementation of a predistorter with characteristics similar to the $G_p(R), G_q(R)$ could be the one shown in Figure 4.7 [7]. The circuit is a hardware realization of the equation:

$$G(R)\exp(j\cdot\theta(R)) = G(R)\cdot\cos(\theta(R)) +$$

$$j\, G(R)\cdot\sin(\theta(R)) = G_p(R) + j\, G_q(R) \qquad 4.9$$

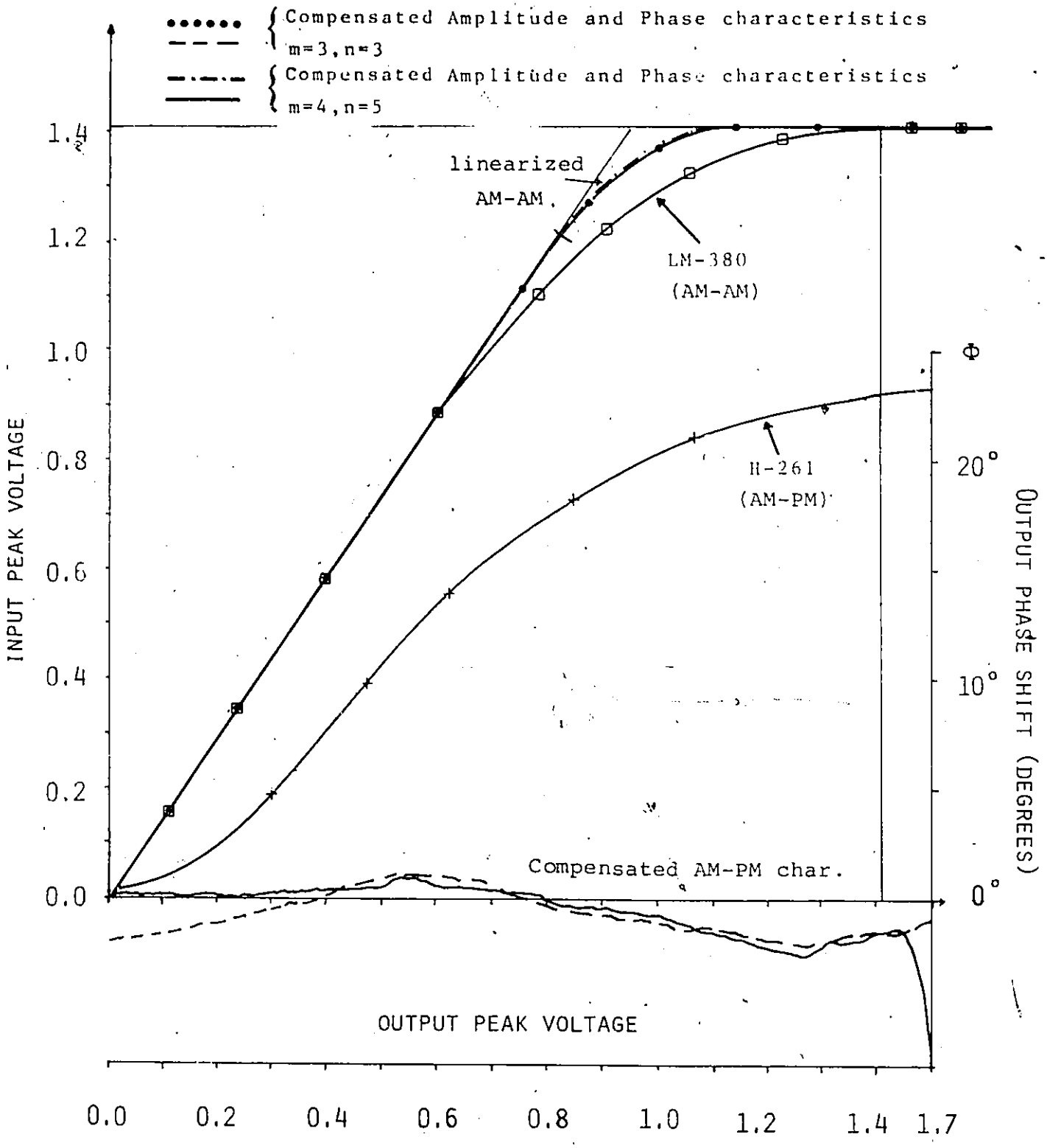


Figure 4.6. Compensation of the normalized LM-380,H-261 characteristics.

k	a_k	b_k
1	1.024364	
3	-0.215228	-0.525770
4	0.287643	0.151374
7		-0.038831
1	1.020762	
3	-0.201460	-0.879726
5	0.274770	1.138574
7	0.003371	-1.135015
9		0.522154
11		-0.089051

TABLE 4.2 . Coefficients of equations 4.6.

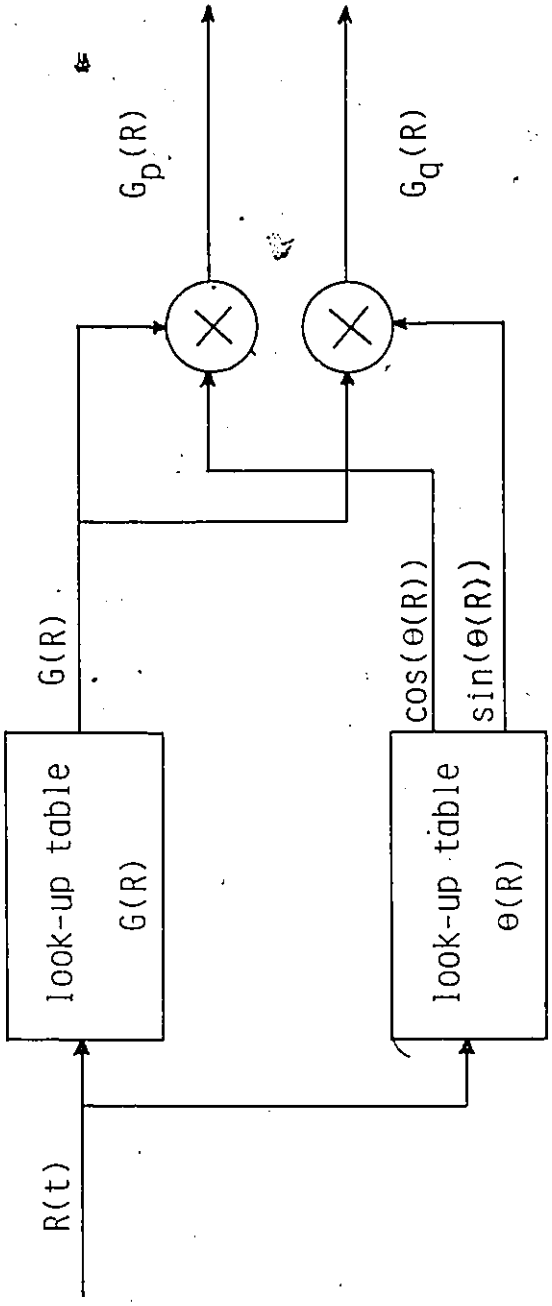


Figure 4.7. Baseband predistorter for AM-AM,AM-PM nonlinearities.

4.4 AMPLITUDE COMPENSATION FOR THE LM-380 AND H-261 CHARACTERISTICS

This time we use only amplitude predistortion for both the LM-380 and H-261 nonlinearities. Our objective is the overall amplitude characteristic to approach that of a soft limiter and the overall phase characteristic to be better than that of the H-261. Since the H-261 characteristic is envelope dependent, the smaller the gain of the predistorter the lower the overall phase response will be. We chose gain equal to one ($V_0 = R_i = 1.414$). The predistorter is modeled again as an odd order polynomial:

$$G(R) = \sum_{i=1}^{m} a_{2i-1} R^{2i-1} \qquad 4.10$$

The block diagram of the predistorter-amplifier is drawn in Figure 4.8. According to this we get for the overall AM-AM and AM-PM characteristics.

$$Z(R) = \sqrt{Z_p^2(G(R)) + Z_q^2(G(R))} =$$

$$= \begin{cases} R & , \quad 0 \le |R| \le 1.414 \\ 1.414 & , \quad |R| \ge 1.414 \end{cases} \qquad 4.11$$

$$\Phi(G(R)) = \tan^{-1}\left[Z_q(G(R))/Z_p(G(R))\right] \qquad 4.12$$

Using equations 4.5, 4.10, 4.11 with an optimization subroutine the coefficients of the predistorter characteristic were computed (Table 4.3). The procedure is that of section 4.3 with $G_q(R) = 0$.

$$Z(R)=\sqrt{Z_p^2(G(R))+Z_q^2(G(R))}$$

$$\Phi(R)=\tan^{-1}\frac{Z_q(G(R))}{Z_q(G(R))}$$

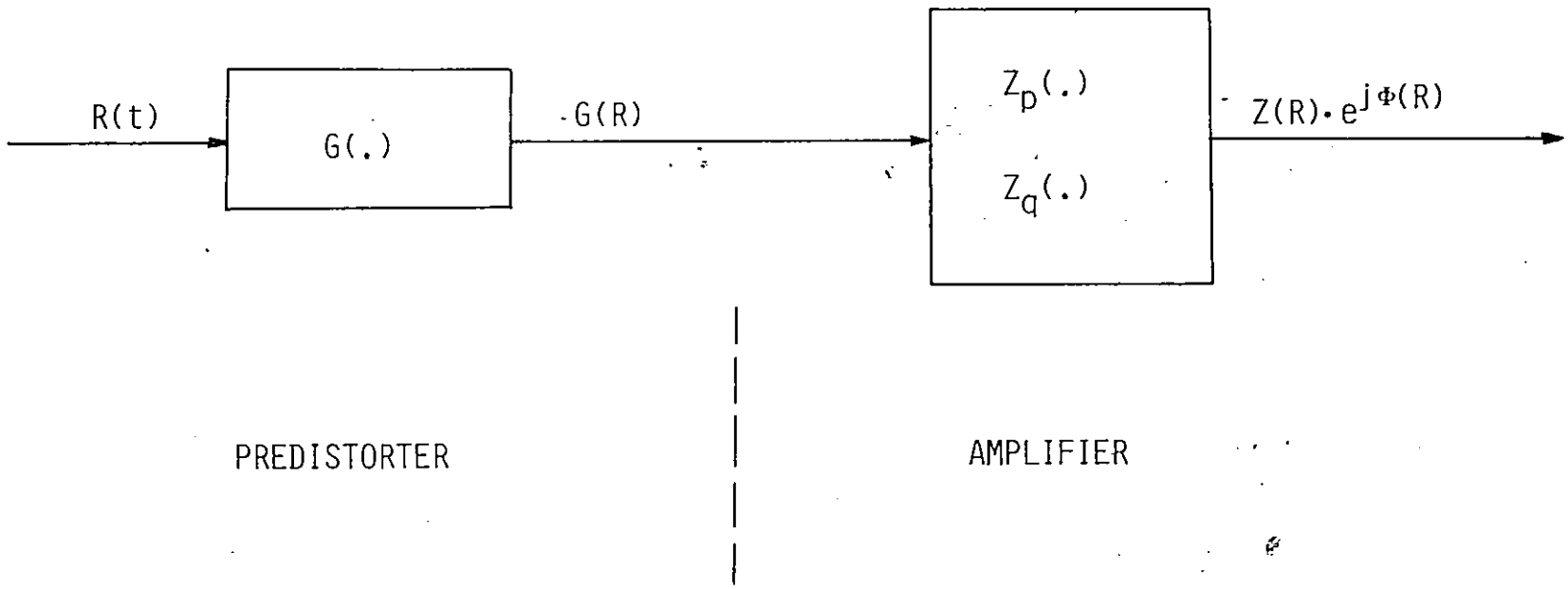


Figure 4.8. AM-AM predistortion compensation for AM-AM, AM-PM nonlinearities.

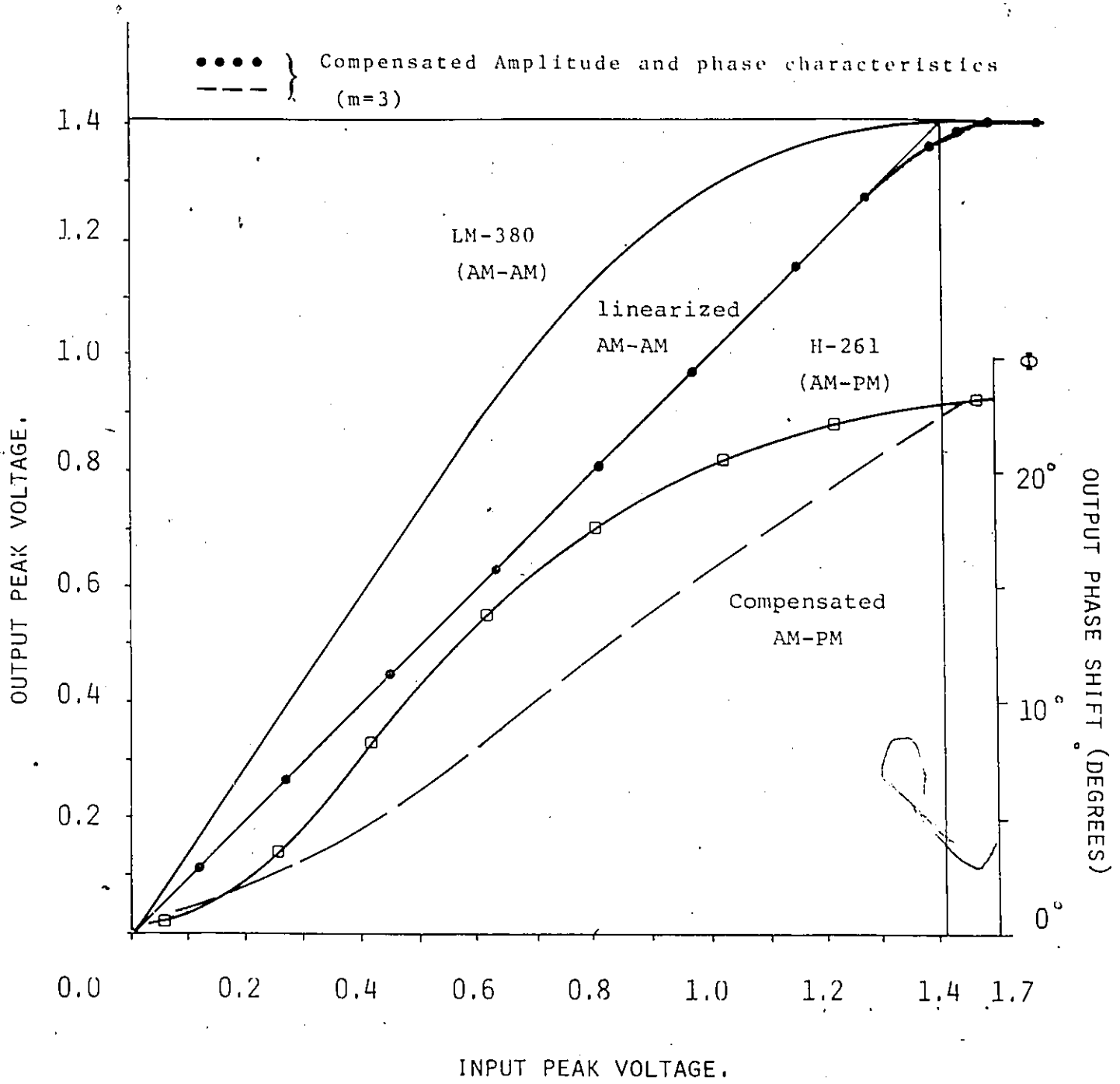


Figure 4.9. AM-AM compensation of the LM-380,H-261 characteristics.

k	a_k
1	0.693974
3	-0.065900
5	0.067550

TABLE 4.3. Coefficients of equation 4.8 .

The corresponding overall AM-AM and AM-PM characteristics are drawn in Figure 4.9. We note that a small improvement in the AM-PM response is also accomplished.

Chapter V

LINEARIZATION RESULTS.-IMPROVEMENTS IN THE ERROR PERFORMANCE BY ADJUSTING THE DECODING THRESHOLDS.

The performance of the linearized systems in combination with threshold adjustment is investigated. The obtained results are compared with those of the conventional system.

5.1 PERFORMANCE WITH THE LINEARIZED LM-380 CHARACTERISTIC AND THRESHOLD ADJUSTMENT.

The error performance of a 4-PAM scheme with the linearized LM-380 characteristic and with or without threshold adjustment is shown in Figures 5.1 to 5.4. For the linearization results the equation 4.4 with the coefficients of Table 4.1 (m=3) were used. For the threshold adjustment an optimization procedure was used in order to set the decoding thresholds at the middle of each eye. This is done because after the suppression of the higher levels due to the nonlinearity effects (see section 3.3), the conventional decoding thresholds are not optimum any more (Figure 5.4).

For the results,the computer simulation and measurement set-ups described in Sections 3.1 and 3.2 were used. In the simulation model the LM-380 characteristic was replaced by the linearized LM-380 characteristic. In the measurements the LM-380 amplifier was replaced by the cascade combination of the implemented linearizer (see section 4.2) and the LM-380 amplifier.

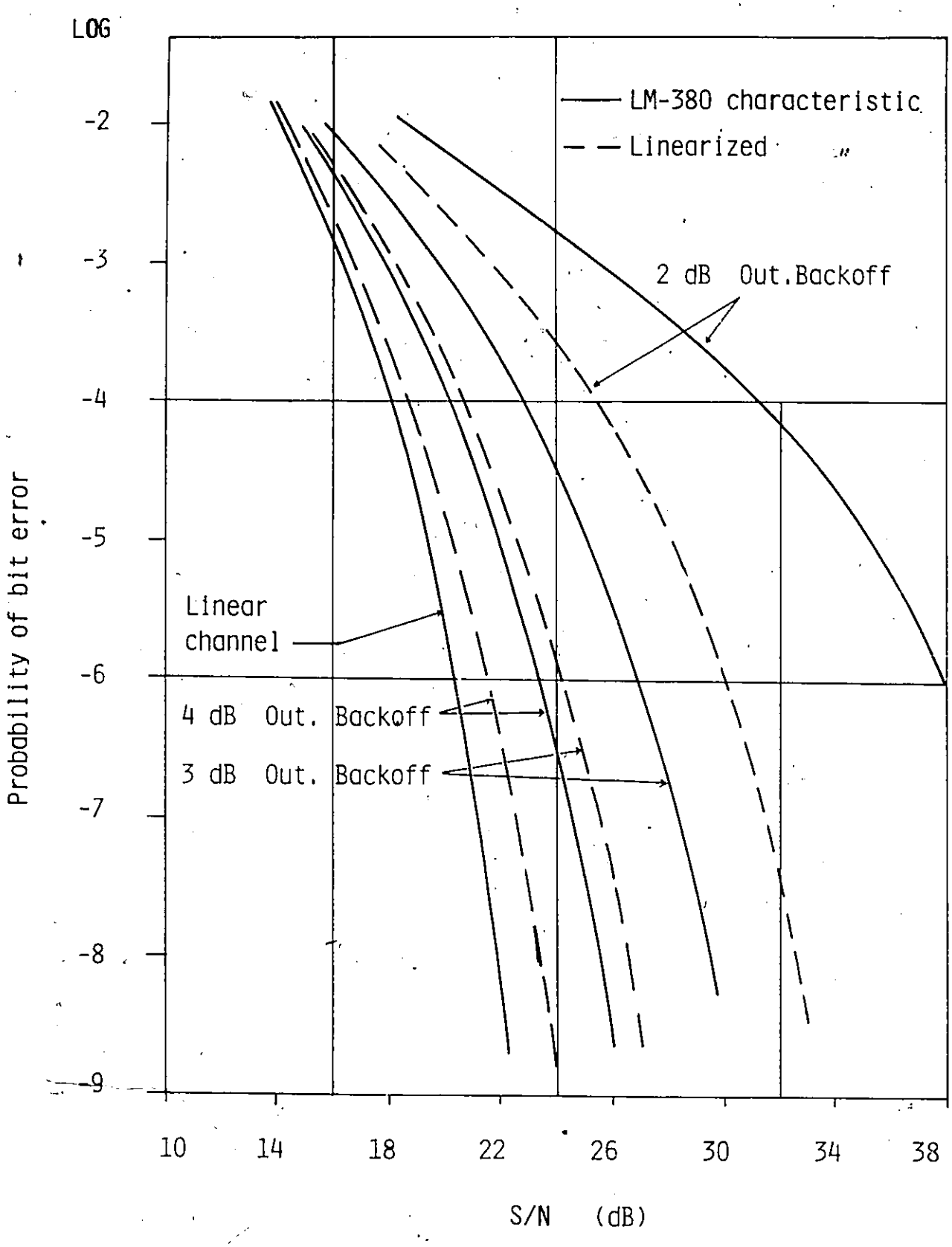


Figure 5.1 . Improvement in the error performance of a 4-PAM signal obtained by linearizing the LM-380 characteristic. Computer simulation results with a=0.2 Nyquist filter.

Once more we mension that the S/N ratio was measured at the output of the receiver filter, by changing the noise power while the signal power was kept constant. The procedure was repeated for various operating points (Output Backoff).

The following remarks can be made for the obtained results.

i)The total improvement obtained in the error performance using the above techniques is significant. The best operating point (where the sum of the S/N degradation and Out.Backoff is minimum) is moved about 2 dB closer to saturation.

ii)Considering the remarks of section 3.3.2 we conclude that the measured results of Figure 5.2 when only threshold adjustment is considered, are satisfactory. For the measured results when both linearization and threshold adjustment are considered, we note an additional degradation of 0.3 dB (for $P(e)=10^{-6}$) which is due to the piece-wise linear nature and Hardware imperfections of the implemented predistorter.

The improvement obtained by linearizing the LM-380 characteristic, is due to the reduction of the nonlinear distortion. This means that the envelope dependent suppression of the signal levels and the generated ISI (see Section 3.3), become less significant. The vertical opening of the signal eyes increases, resulting in better system performance. In Figure 5.5 measured eye diagrams of a 4-PAM signal before and after linearization are given. We note that the outer eyes of the signal have opened slightly and the ISI has been reduced. On the other hand, by

adjusting the decoding thresholds we increase the distances of the received signal levels from their corresponding lower thresholds (see Section 3.1 and Figure 5.4). This results in an additional improvement in the error performance.

The spectral regrowth reduction accomplished by linearizing the LM-380 characteristic, is shown clearly in Figure 5.6. It is due to the reduction of the signal envelope fluctuation. The reduction of the spectral regrowth is important since it also reduces the adjacent channel interference.

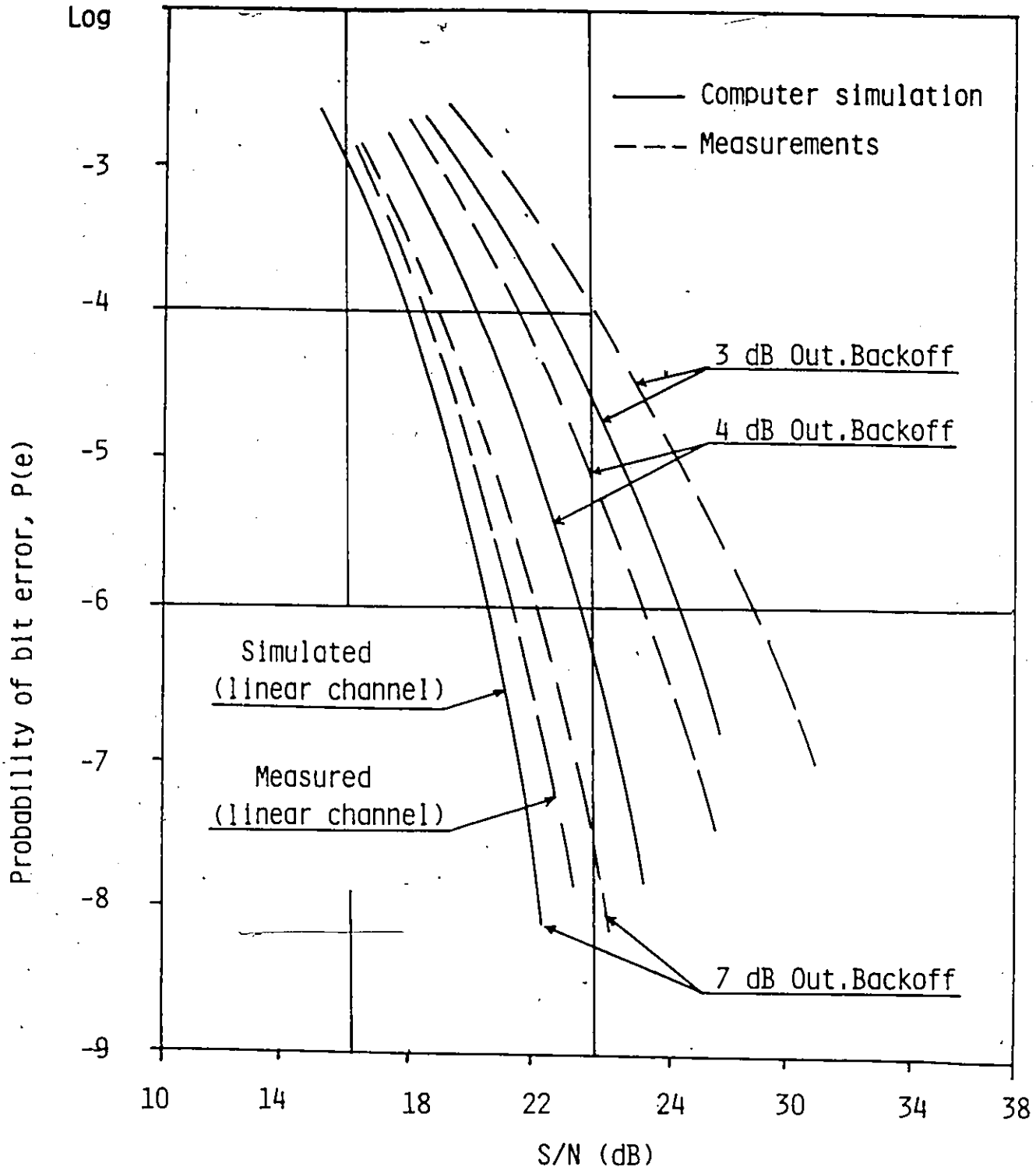


FIGURE 5.2 Performance of a 4-PAM signal distorted by the LM-380 amplitude characteristic. The signal rate is 413.3 kb/s. Filters with a=0.2 are used. The S/N ratio is defined in the Nyquist bandwidth at the output of the receiver LPF.

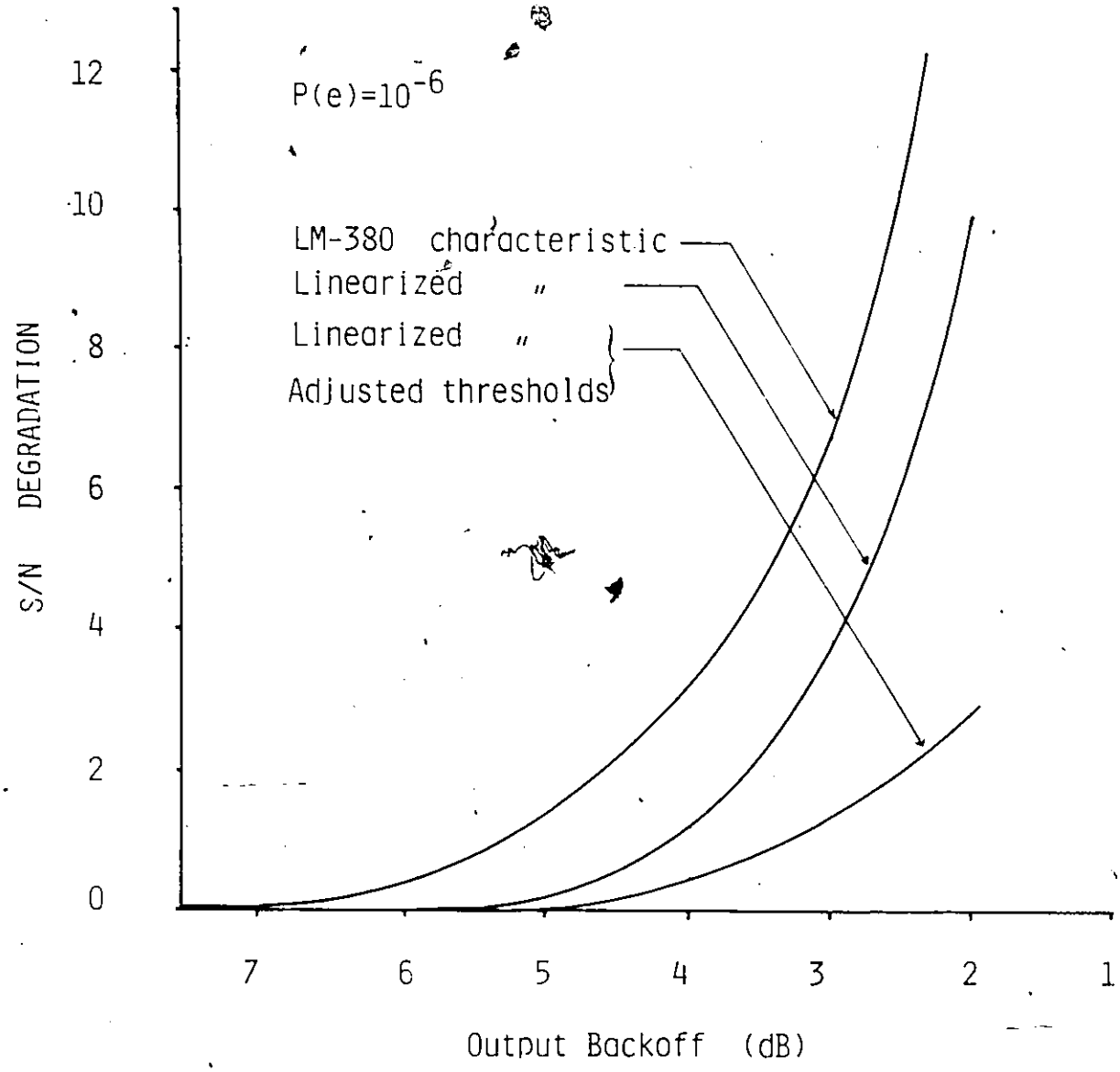
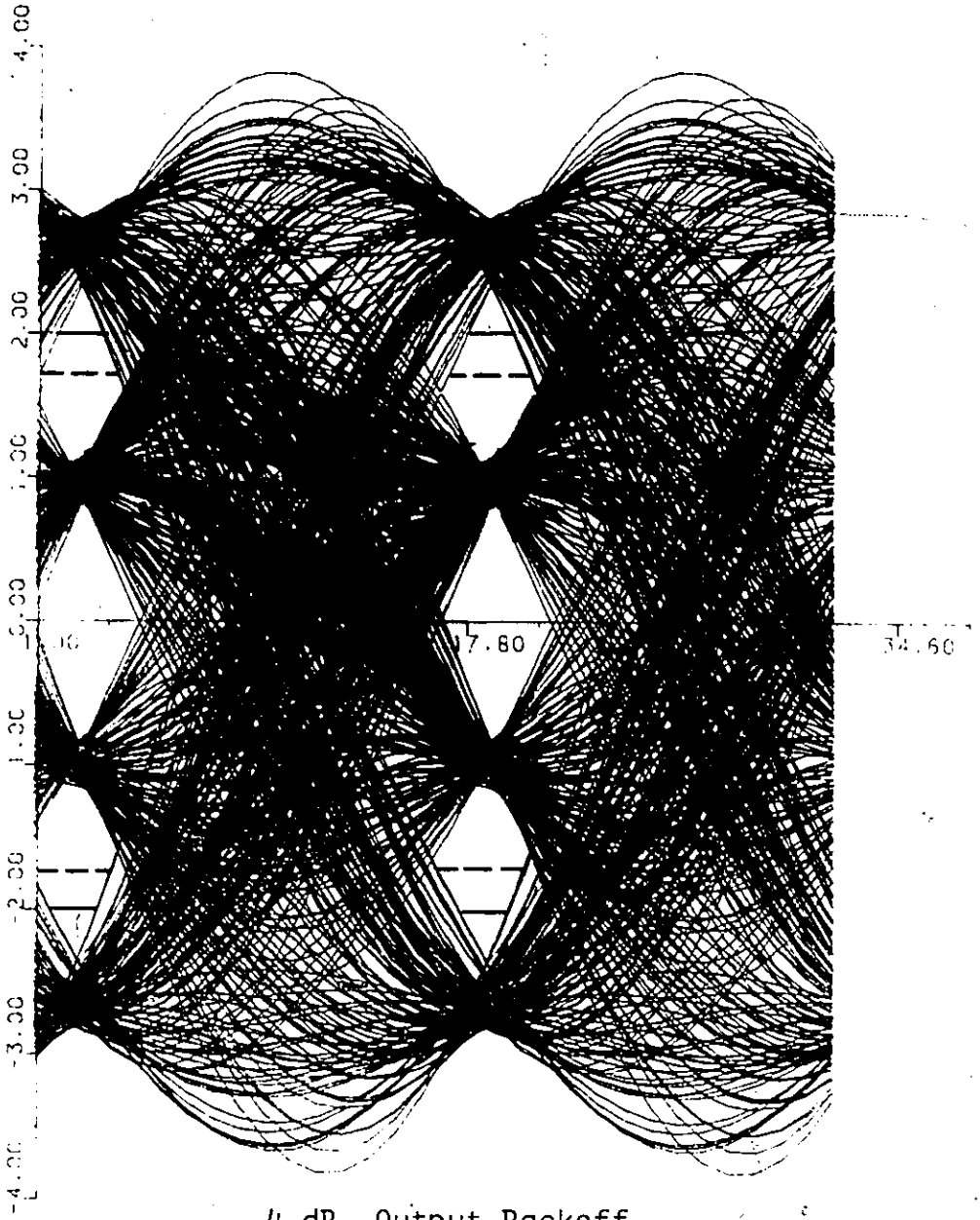


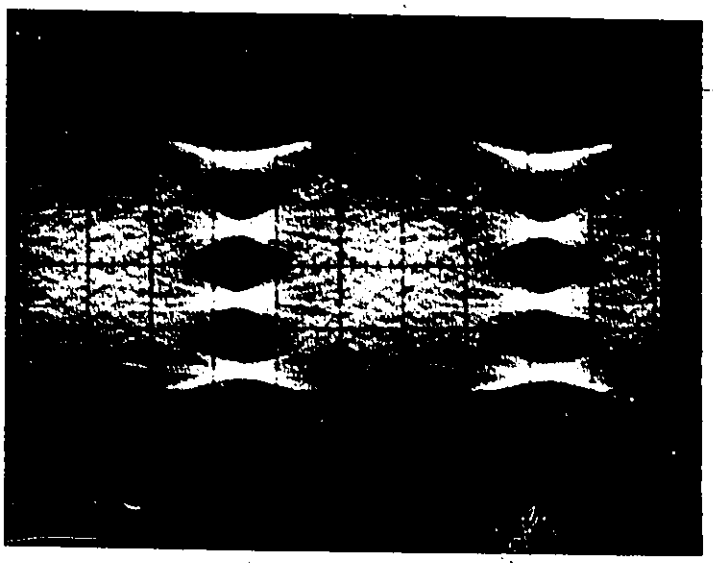
Figure 5.3 . Improvements in the S/N ratio degradation of a 4-PAM signal, obtained by linearizing the LM-380 characteristic and by adjusting the decoding thresholds.



4 dB Output Backoff

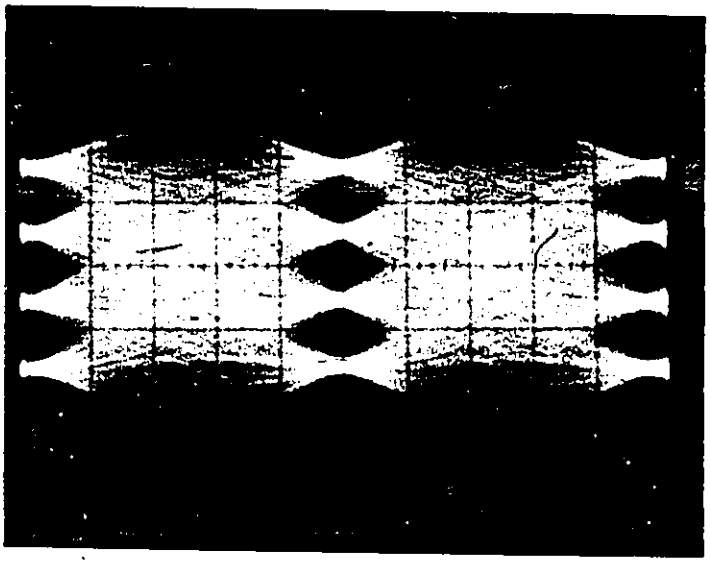
——— Conventional thresholds
— — — Adjusted thresholds

Figure 5.4. Eye diagram of a 4-PAM signal with the LM-380 amplifier. Computer simulation results with α=0.2 Nyquist filters. The initial transmitted levels were $\pm 1, \pm 3$. The gain of the amplifier has been removed.



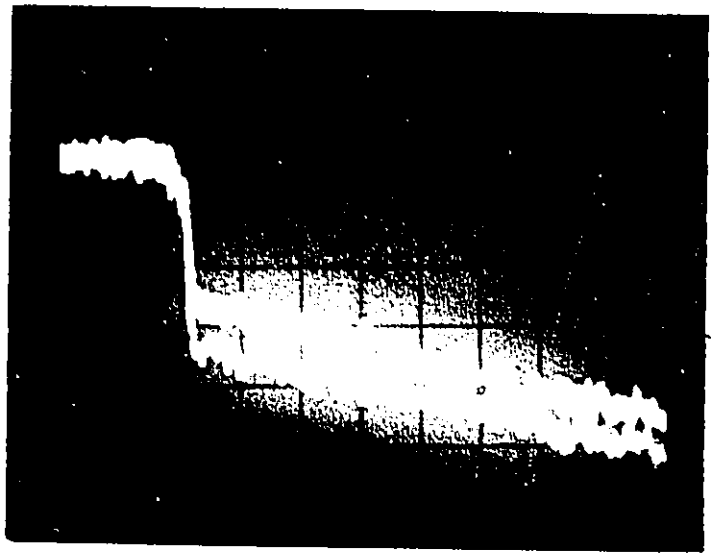
Horiz. 1 μs/div.
Vert. 200 mV/div.
f_b= 413.3 kb/sec.
4 dB Out.Backoff.

Fig. 5.5(a). Measured eye diagram of a 4-PAM signal with the LM-380 amplifier. Filters with α=0.2 were used.



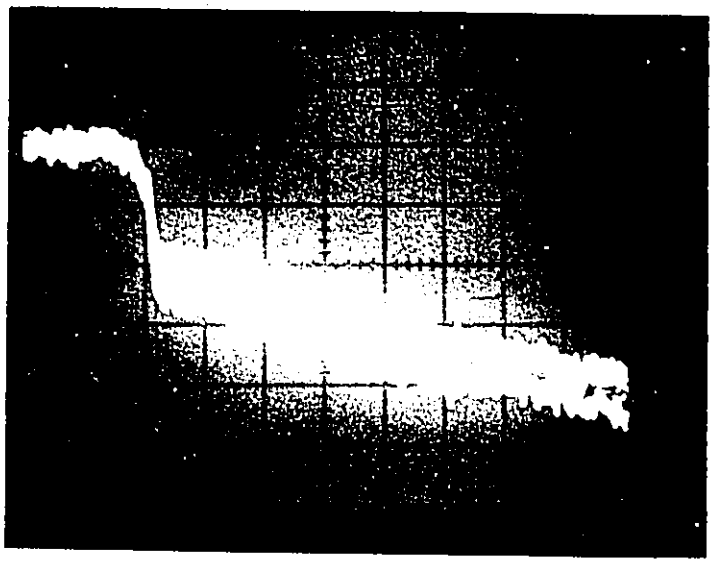
Horiz. 1 μs/div.
Vert. 200 mV/div.
f_b= 413.3 kb/sec.
4 dB Out.Backoff.

Fig. 5.5(b). Measured eye diagram of a 4-PAM signal with the linearized LM-380 amplifier. Filters with α=0.2 were used.



Vert. 10 dB/div.
Horiz. 50 KHz/div.
Up.ref.lev. 0 dBm.

4 dB Out.Backoff



Vert. 10 dB/div.
Horiz. 50 KHz/div.
Up.ref.lev. 0 dBm.

2 dB Out.Backoff

Figure 5.6. Reduction of the spectral regrowth of a 4-PAM signal by linearizing the LM-380 AM-AM characteristic. The signal rate is 413.3 Kb/s.Nyquist filter with α=0.2 is used.

5.2 PERFORMANCE WITH THE COMPENSATED LM-380 , H-261 CHARACTERISTICS AND THRESHOLD ADJUSTMENT.

5.2.1 Error performance

The error performance of various PAM schemes with the LM-380,H-261 and the compensated LM-380,H-261 characteristics,was computed using equations 4.7. The coefficients of Table 4.2. with m=3 and n=3 were used.The error performance of the various PAM schemes when both threshold adjustment and linearization are considered was also computed. The obtained results which are drawn in Figures 5.7 and 5.8 show that:

i)The total improvement obtained in the error performance is very significant. The best operating point (where the sum of S/N ratio and Output Backoff is minimum) is moved closer to saturation,3 dB for a 4-PAM scheme and more than 5 dB for a 32 PAM scheme. This increases the power utilization efficiency of the system. The reasons which led to the performance improvement were explained in the previous Section.

ii)The improvement obtained by linearization (compensation) is more significant for the higher schemes,while the improvement obtained by adjusting the decoding thresholds is more significant for the lower schemes. The reasons are the following. As we mentioned before,the nonlinear distortions affect the opening of the signal eyes. The size of the eyes of the higher schemes are sufficiently smaller than that of the lower schemes (assuming the same transmitted power for all schemes),which makes them more sensitive to the nonlinear distortions. Thus it should be expected that the reduction of the distortion obtained

by linearization will affect more the higher schemes. On the other hand, the threshold adjustment can be more significant in large size eyes and thus it will affect more the lower schemes.

iii) For each scheme the improvement obtained by adjusting the thresholds becomes negligible over a particular operating point. This happens because the outer eyes of the signal are almost closed due to the nonlinear effects and the system has almost failed.

5.2.2 Spectral regrowth reduction

The spectral regrowth reduction due to the compensation of the LM-380 and H-261 characteristics is shown in Figures 5.9 (a) and (b), where the inphase and quadrature spectrum for a 4-PAM scheme are drawn. It is due to the reduction of the signal envelope fluctuations. We notice that the improvement obtained in the spectrum of the inphase component for operation at 7 dB Out. Backoff is about 8 dB. The improvement obtained in the spectrum of the quadrature component is even more significant. This is expected, since due to the low phase rotations of the compensated system the quadrature component is not significant. In the compensated system the AM-AM conversion has the major contribution to the spectral regrowth.

Due to the spectral regrowth reduction the adjacent and cochannel channel interference are also reduced.

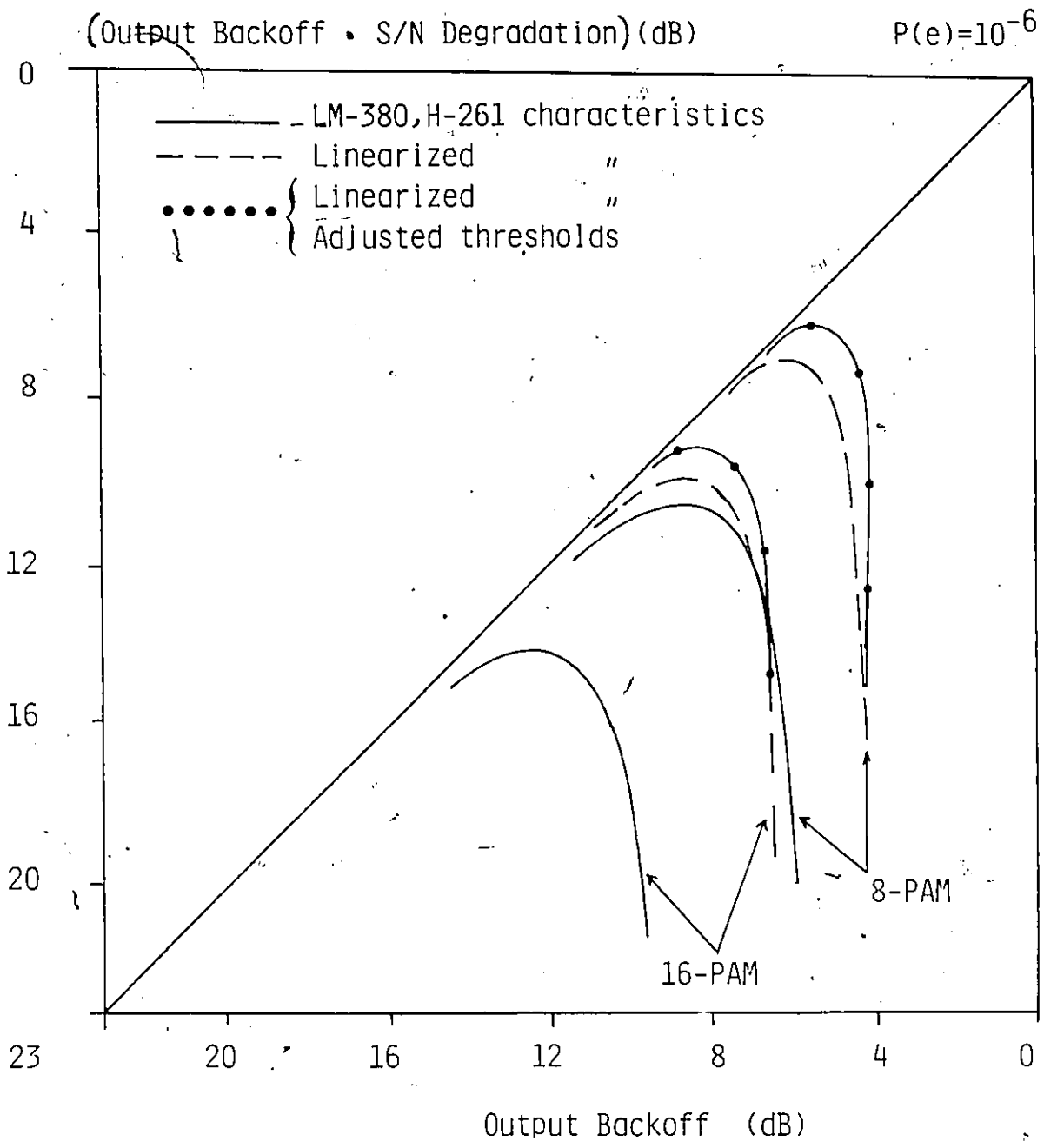


Figure 5.7. Improvements in the performance of 8 and 16 PAM signals obtained by linearizing the LM-380,H-261 characteristics and by adjusting the decoding thresholds. Computer simulation results with $\alpha=0.2$ Nyquist filter. Both signals have the same symbol rate.

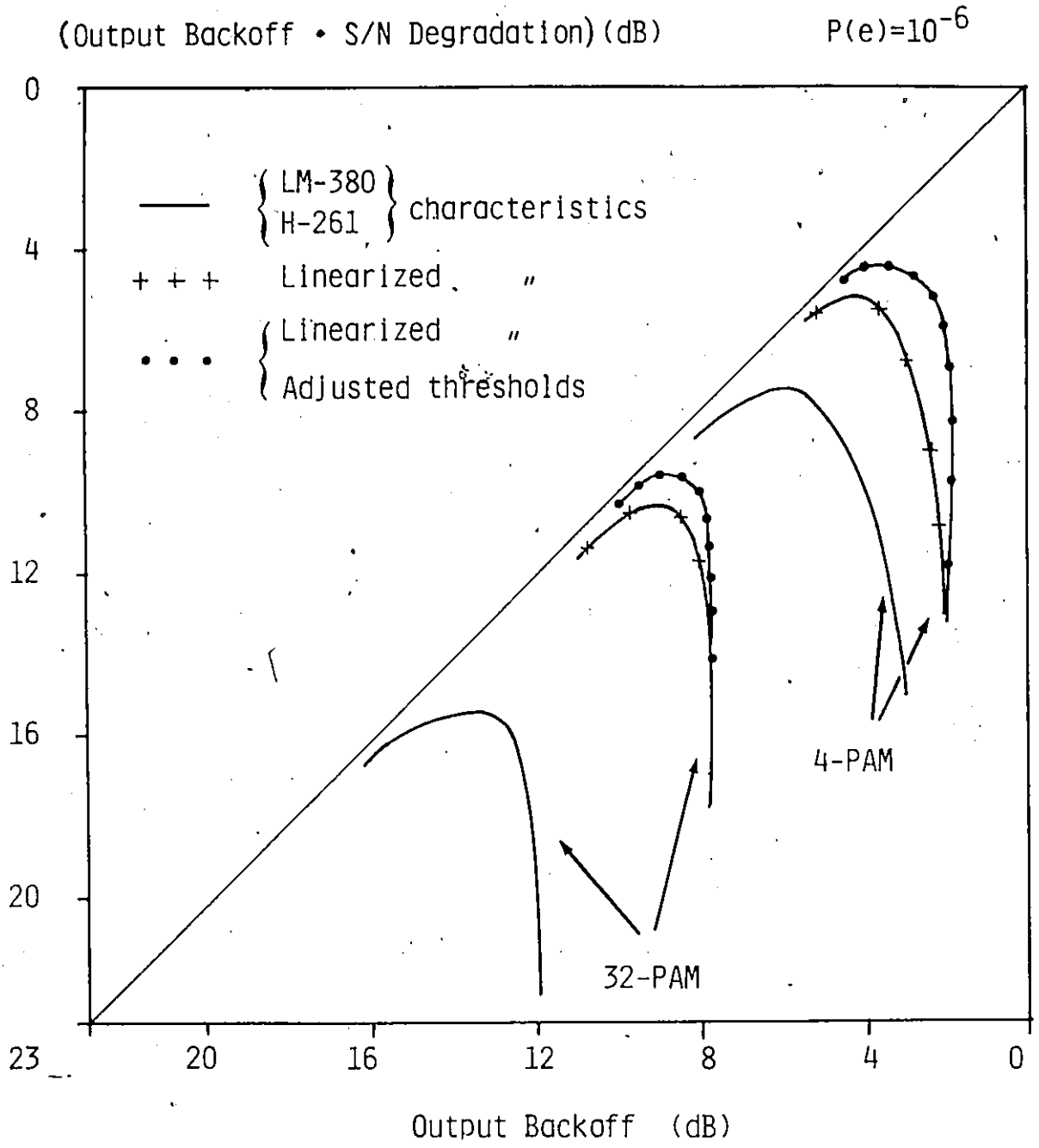
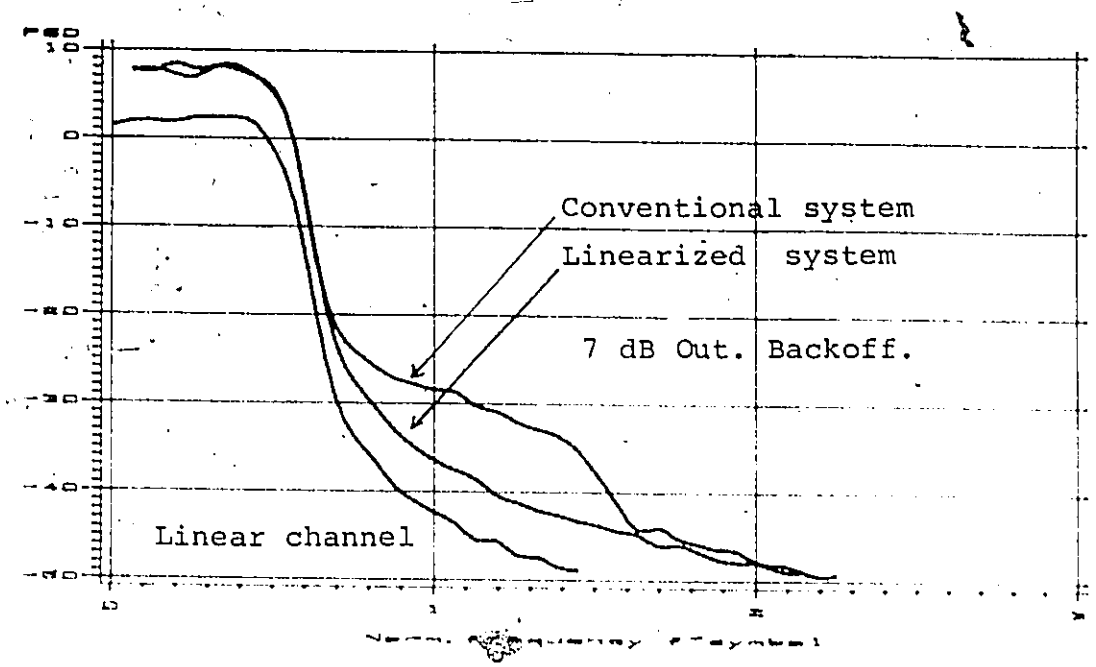
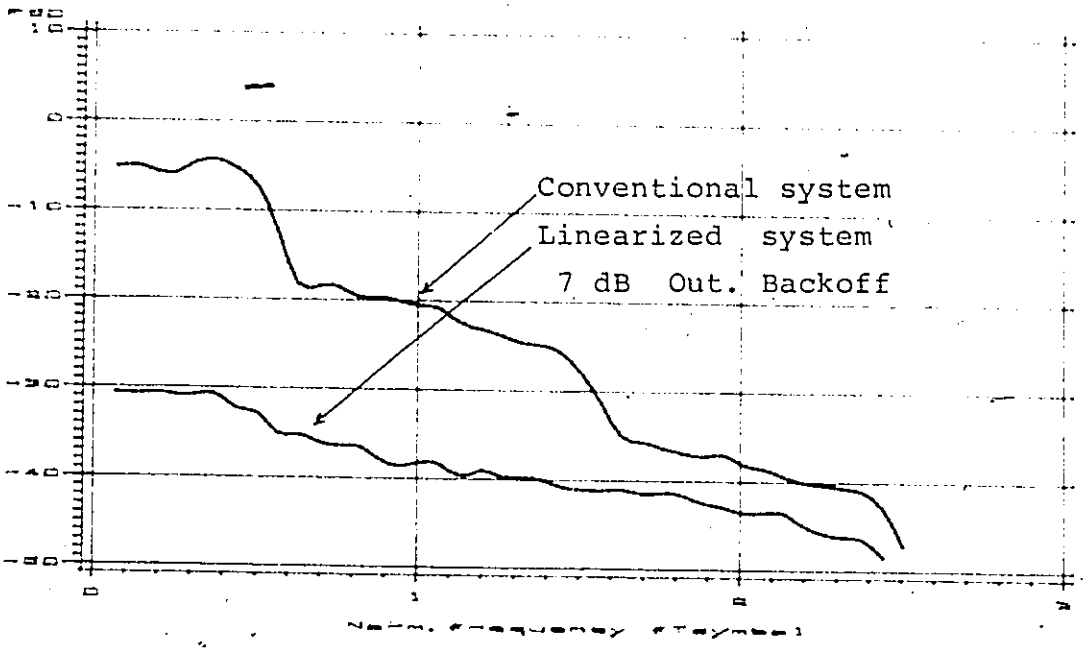


Figure 5.8. Improvements in the performance of 4 and 32 PAM signals obtained by linearizing the LM-380,H-261 characteristics and by adjusting the decoding thresholds. Computer simulation results with α=0.2 Nyquist filter.Both signals have the same symbol rate.



(a) Inphase component spectrum.



(b) Quadrature component spectrum.

Figure 5.9. Reduction in the spectral regrowth of a 4-PAM signal obtained by linearizing the LM-380 and H-261 characteristics. Computer simulation results with α =0.2 Nyquist filters.

5.3 PERFORMANCE WHEN ONLY AMPLITUDE OR PHASE COMPENSATION FOR AM-AM AND AM-PM NONLINEARITIES IS CONSIDERED.

Following the analysis of section 4.1.4 we computed ,the improvement in the S/N degradation,when only Amplitude linearization or Phase compensation is considered for the combined AM-AM and AM-PM effect. From the results drawn in Figure 5.10 we conclude that:

i)The improvement obtained when only amplitude linearization is considered is not significant compared to the improvement obtained when both amplitude and phase linearization are employed.

ii)The improvement obtained when only phase compensation is considered is more significant than the amplitude linearization. However,generally this depends on the nature of the AM-AM and AM-PM characteristics.

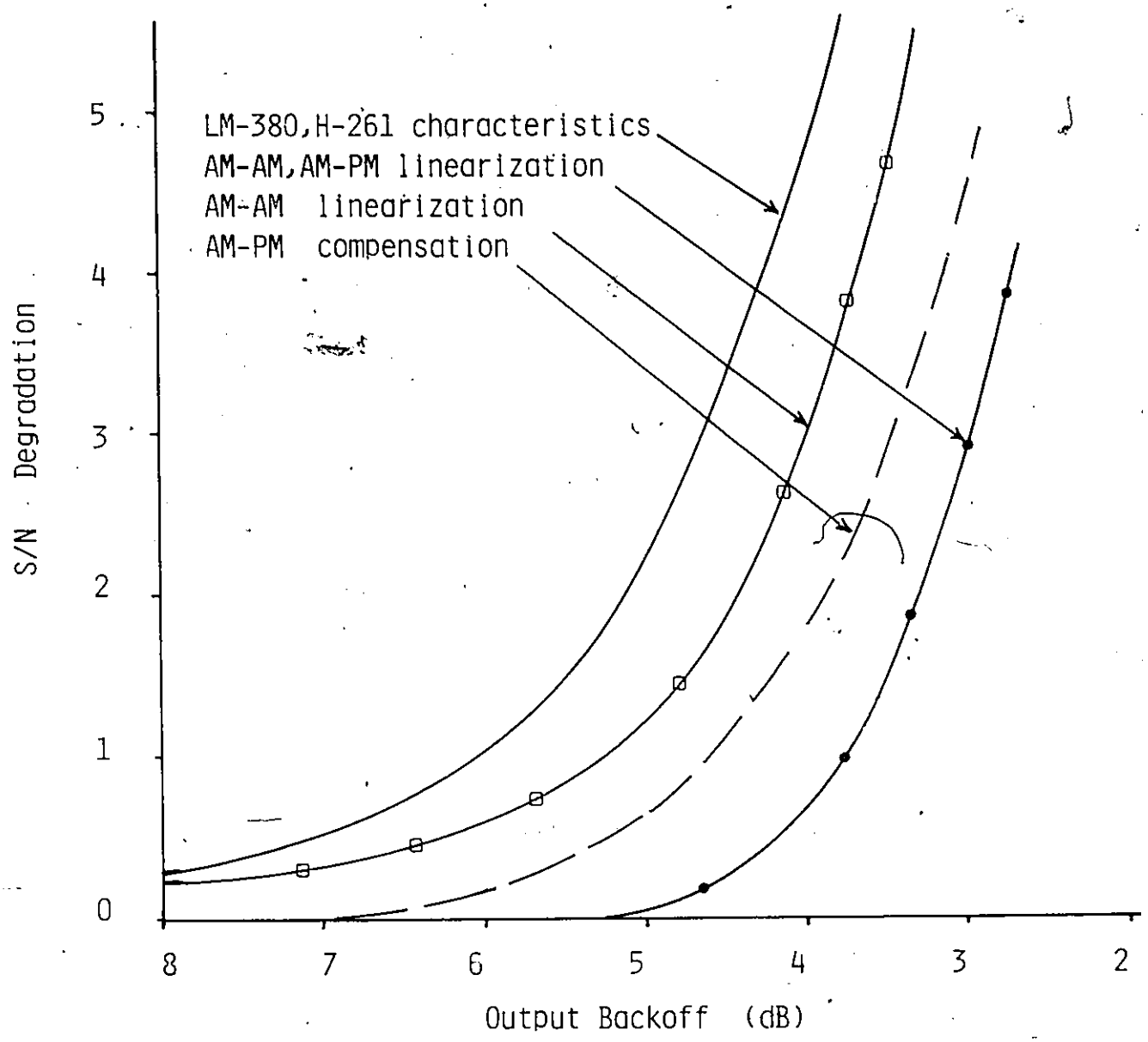


Figure 5.10. Improvements in the S/N degradation of a 4-PAM signal obtained by linearizing (compensated) the LM-380 and H-261 characteristics. Computer simulation results with α=0.2 Nyquist filter.

Chapter VI

CONCLUSION

In this chapter the most important results of our study are summarized.

The effects of amplitude and phase nonlinearities on multilevel PAM signals were investigated. Specific AM-AM and AM-PM amplifier characteristics were used. The conclusions that can be made by analyzing the obtained simulation and experimental results are the following.

i) The degradation in the system performance, is dependent on the nature of the channel nonlinearities, the number of the signal levels and the transmit filter shape. The sensitivity of the signal to the nonlinearities increases rapidly with the number of levels. The degradation increases significantly, when the operation point is changed from the linear region of the amplifier characteristic towards saturation.

ii) The interaction of envelope fluctuations due to filtering, with the nonlinear distortions caused by the power amplifiers, give rise to spectral regrowth effects which cause adjacent and cochannel channel interference.

iii) It is found that for the higher schemes, the major cause of performance degradation is due to the AM-PM conversion. However, generally this depends on the nature of the AM-AM and AM-PM characteristics.

iv)The means to limit signal distortions,are either to operate the power amplifiers at average power levels which are significantly below the output saturation power,or to predistort the signal before amplification so as to make the overall system more linear. Predistortion linearization increases the power utilization efficiency and reduces the spectral regrowth. The improvements obtained are very significant especially for the higher schemes.

v)Significant improvement in the error performance was obtained by adjusting the conventional decoding thresholds. The improvement is more significant for the lower schemes.

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Appendix A

IMPLEMENTATION AND PERFORMANCE EVALUATION OF A 4-PAM SYSTEM

A.1 DESCRIPTION OF THE HARDWARE IMPLEMENTATION.

A photograph of the implemented 4-PAM encoder-decoder circuit is shown in Figure A.1. We explain the system operation in the following paragraphs.

A.1.1 Description of the Encoder circuit.

The following description refers to circuit diagram of the 4-PAM encoder drawn in Figure A.2 . The symbol rate clock (clock-2),is derived through 3B by dividing the bit rate clock (clock-1) by two. The incoming binary data stream consisting of 1 ad 0 which are represented by 5V and 0V respectively,is serial to parallel converted by 2A and 4B. The D/A converter (3A) converts the input parallel binary signals (Q1 and Q2) to a 4 level (i.e. 0,1,2,3) waveform according to Table A.1.

Q1	Q2	A
1	1	3
1	0	2
0	1	1
0	0	0

Table A.1. Encoding table with reference to Figure A.2.

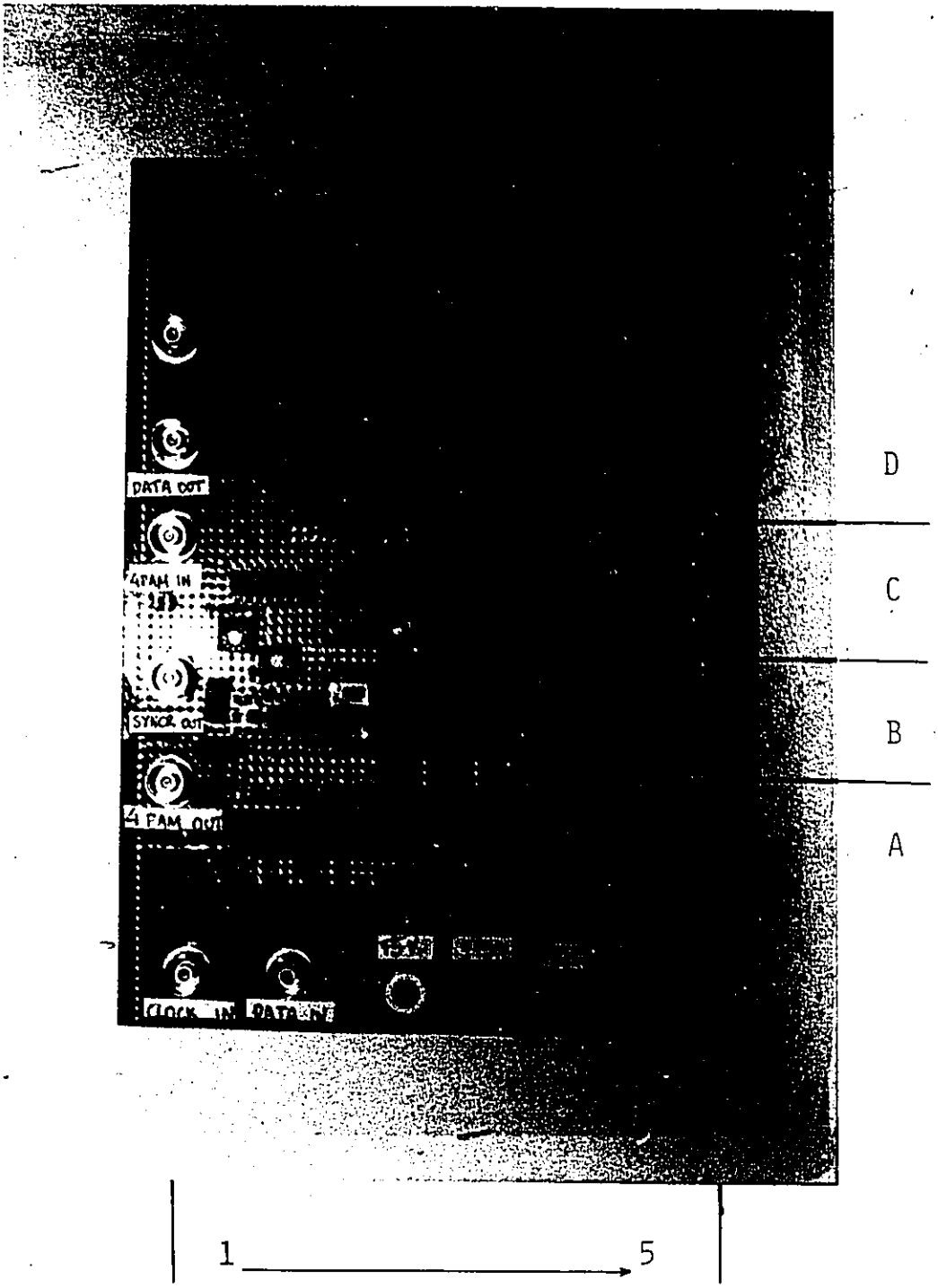


Figure A.1. Photograph of the implemented 4-PAM encoder-decoder.

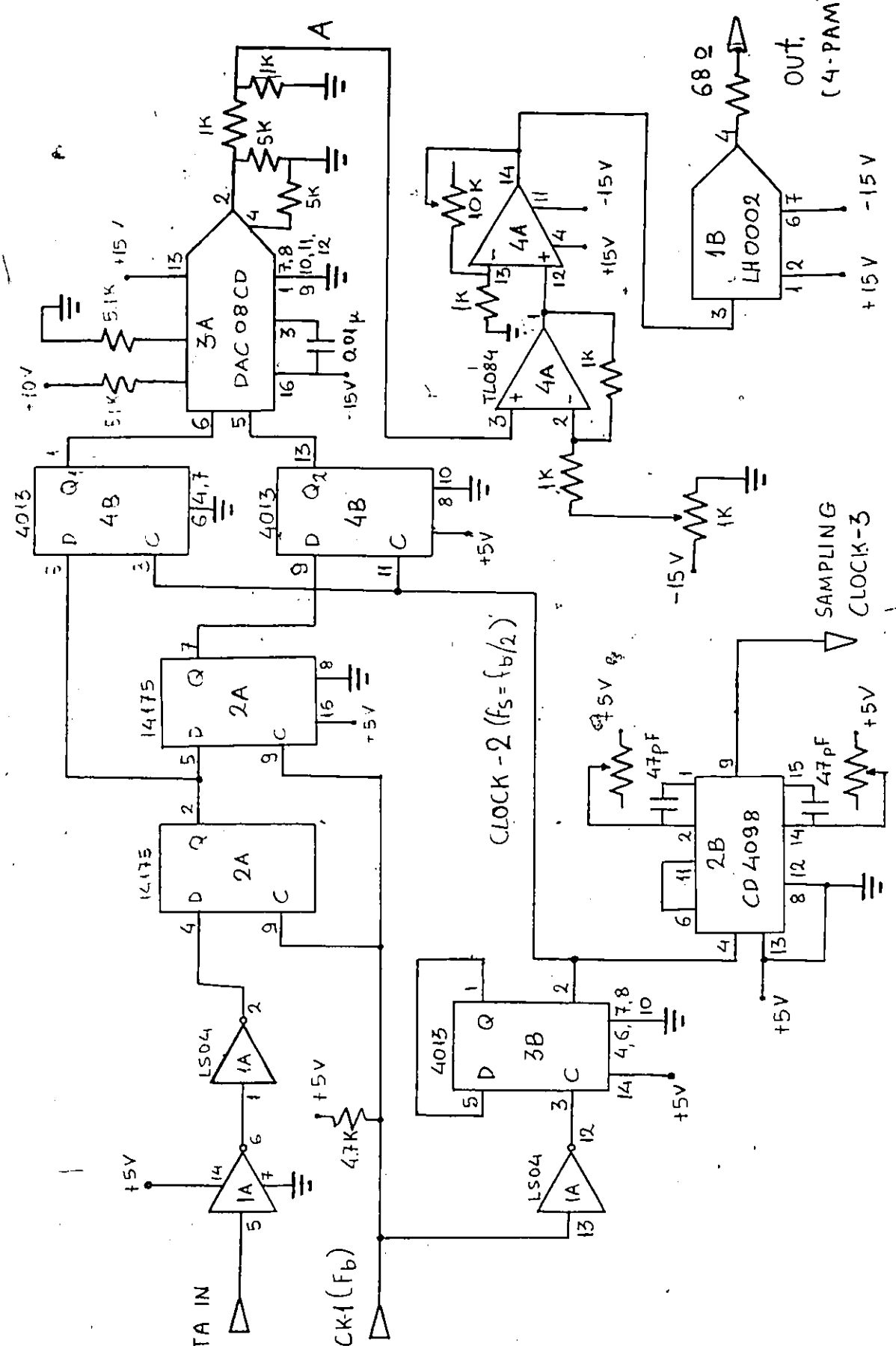


FIGURE A.2. Implemented 4-PAM Encoder.

A dc balancing adjustment and level magnitude control is provided by 4A. A current amplifier (1B) is used to drive a 75 Ohm load which is the input impendance of the used raised cosine filter. The wideband generated signal will be bandlimited by the filter to achieve spectral efficiency.

The symbol rate clock triggers a set of two one-shot multivibrators (2B) to generate the required sampling clock (clock-3) which will be wired to the decoder. The delay and pulse width of the sampling clock is adjusted by two potensiometers.

A.1.2 Description of the Decoder circuit.

Refering to Figure A.3 the received signal r(t) is first amplified by 1C. After the amplification the signal is passed through a 4-level quantizer consisting of three voltage comparators (2C-4C) and three D flip-flops (5C). The threshold voltages V1,V2,V3 are set properly in the middle of each eye of the eye diagram. We define as r_k the sampled value of r(t) at $t=kT+\tau$, i.e,

$$r_k = r(t)\Big|_{t=kt+\tau}$$

where k is an integer and τ is the sampler's phase which is to be adjusted to the optimum sampling instants. The output of 5C depends on the location of r_k, as illustrated by Table A.1.

Finally the two parallel bits (A,B outputs) are converted to a serial bit stream (1D to 4D). This completes the description of the circuit operation.

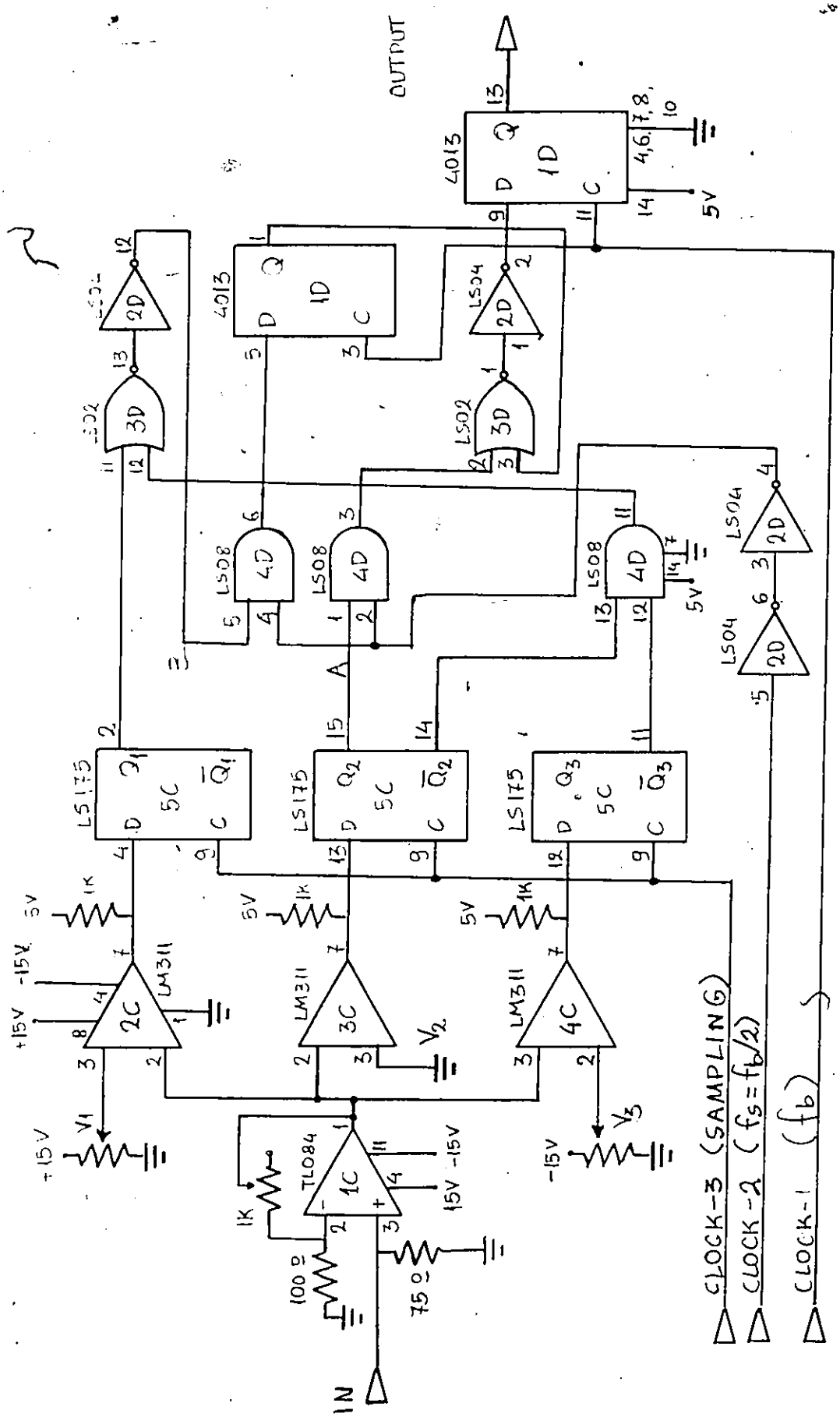


FIGURE A.3 • Implemented 4-PAM Decoder.

Range	74174			7408	
	Q1	Q2	Q3	A	B
$V1 \leq r_k$	1	1	0	1	1
$V2 \leq r_k \leq V1$	0	1	0	1	0
$V3 \leq r_k \leq V2$	0	0	0	0	1
$r_k \leq V4$	0	0	1	0	0

Table A.2. Decoding table with reference to Figure A.3.

A.2 EXPERIMENTAL RESULTS AND DISCUSSIONS.

The data pattern and the corresponding spectrum of the generated wideband 4-PAM signal are shown in Figure A.4 while the eye diagram and spectrum of the bandlimited received signal are shown in Figure A.5. Raised cosine filters with α =0.2 were used. The transmit filter is x/sinx amplitude equalized. The filter bandwidth is 124 KHz (given by the designer). The 3 dB cutoff frequency is:

$$f_{3dB} = 124/(1+\alpha) = 124/1.2 = 103.33 \text{ kHz}.$$

Thus the filter is designed for transmitting data at a symbol rate of:

$$f_s = 2 \cdot f_{3dB} = 206.66 \text{ kBaud}$$

For the 4-level PAM the nominal bit rate is

$$f_b = 2 \cdot 206.66 = 413.3 \text{ kb/sec}$$

The BER performance versus S/N was measured for the described system. The signal and noise powers were measured at the output of the lowpass filter just before the threshold detectors. The results are

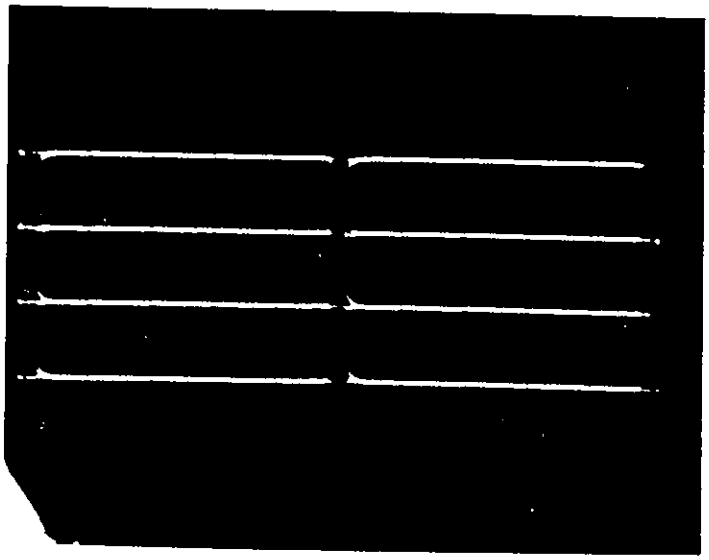
shown in Figure A.6. As we note for $P(e)=10^{-6}$ the difference between measured and simulated results is about 1 dB. This is due to the following.

i) Hardware imperfections of the implemented circuit and impendance mismatching.

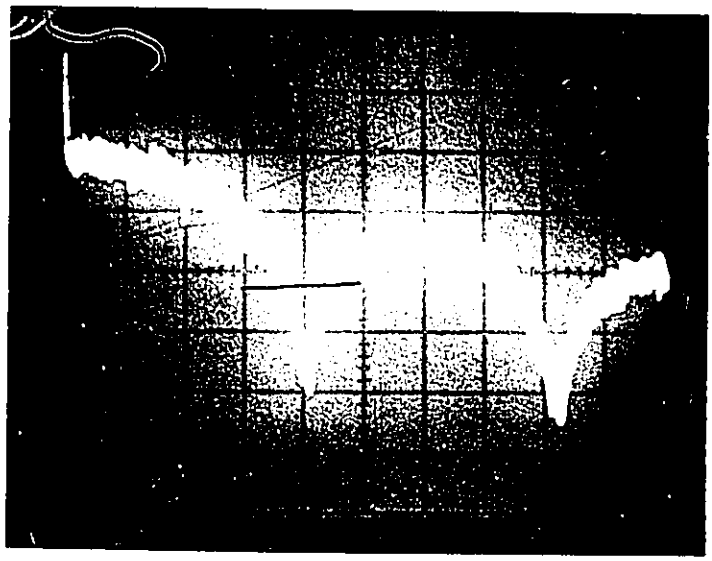
ii) Filter group delay which is not considered in the computer simulation .

iii) In the simulation Gray encoding of the 4-PAM signal is assumed while the generated 4-PAM signal is not Gray encoded.

The measurement set up is shown in Figure A.7.

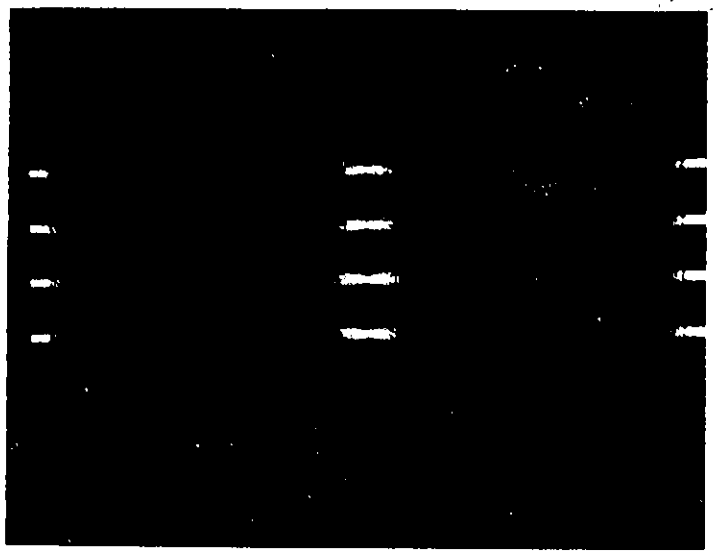


Horiz. 890ns/div.
Vert. 500mV/div.

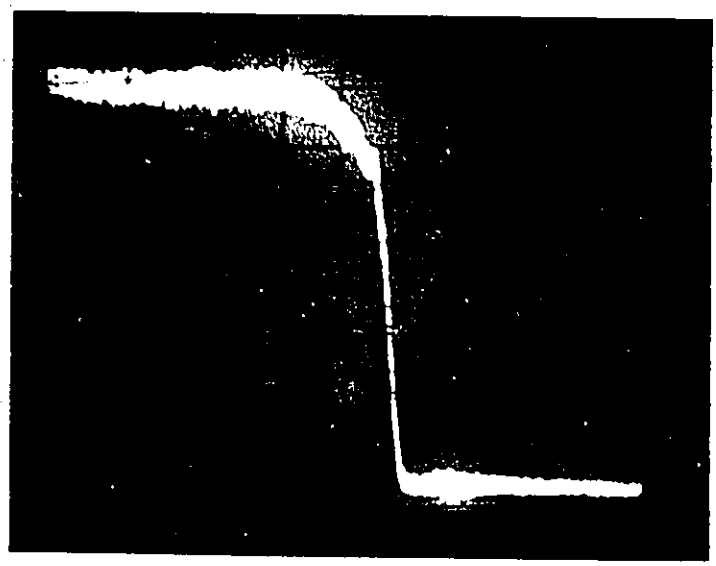


Horiz. 50 KHz/div.
Vert. 10 dB/div.

FIGURE A.4. Measured eye and spectrum diagrams of the wideband 4-PAM signal generated by the circuit of Fig. A.2. The signal rate is 206.66 kBaud.



Horiz. 890ns/div.
Vert. 200mV/div.



Horiz. 20 KHz/div.
Vert. 10 dB/div.

FIGURE A.5 . Measured eye and spectrum diagrams of the 4-PAM signal generated by the circuit of Figure A.2. Nyquist filters with α =0.2 were used. The signal rate is 206.66 kBaud.

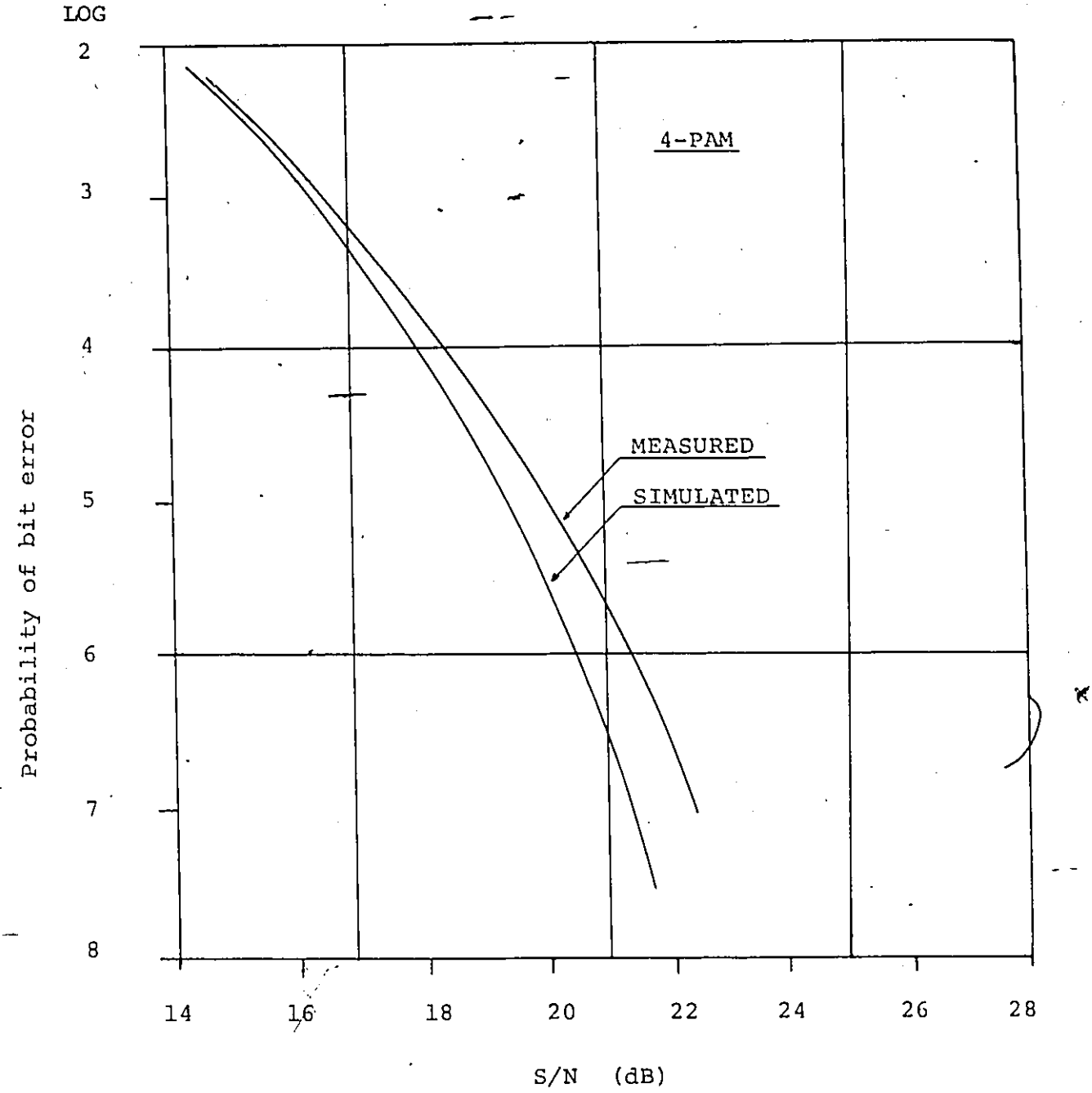


FIGURE A.6. Error performance of the 4-PAM signal generated by the implemented circuit. Nyquist filters with α =0.2 were used.

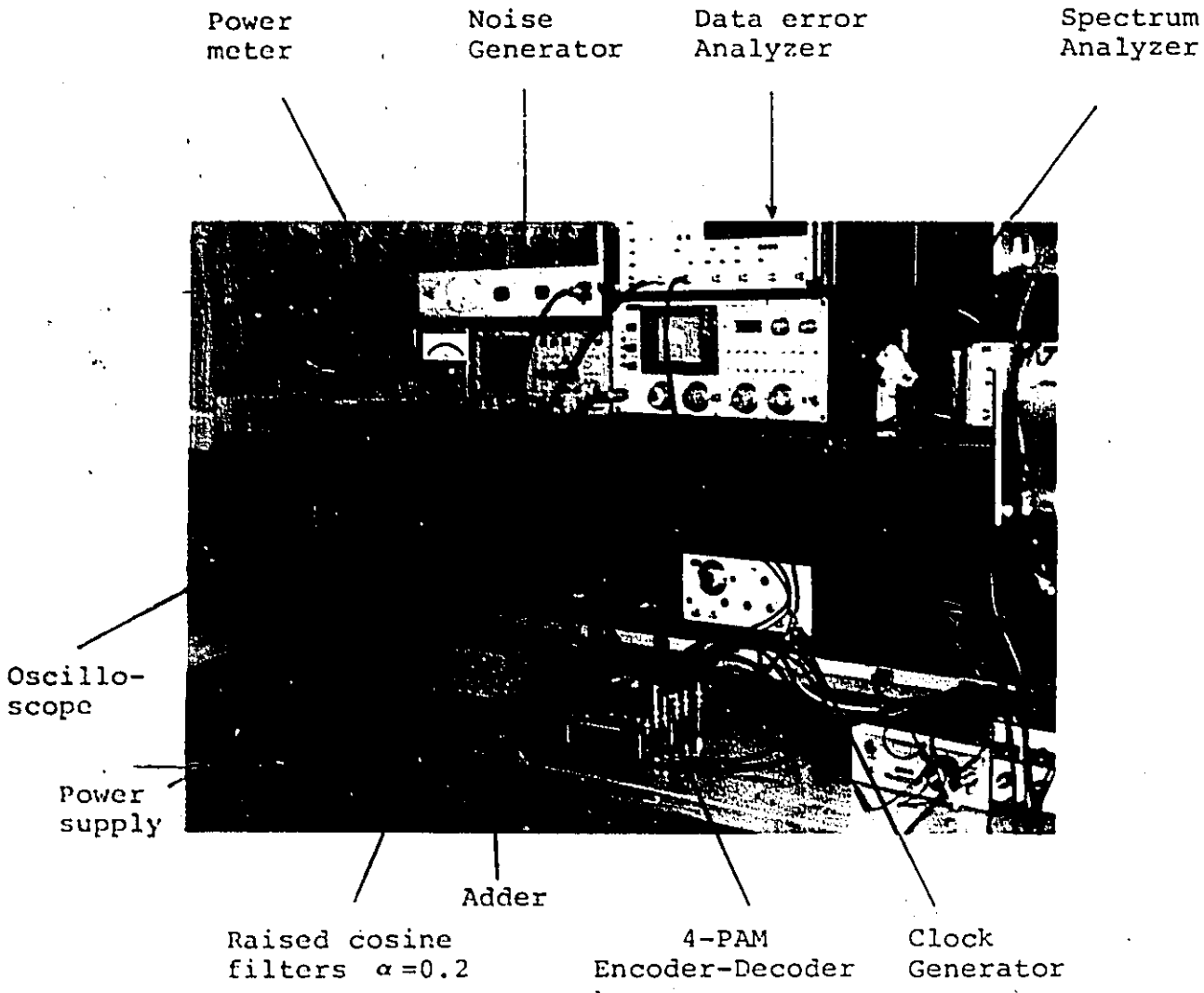


FIGURE A.7. Photograph of the experimental set-up in the Digital Communications Laboratory, Department of Electrical Engineering , University of Ottawa.

Appendix B

AMPLIFICATION STAGE CIRCUIT DESCRIPTION

The circuit of the amplification stage is shown in Figure B.1.It consists of the following parts.

In the input an operational amplifier (TL-084) is used for input impendance matching and buffering. The input impendance of the amplification stage is 50 Ohm in order to match with the signal sourses (sinusoidal generator or Nyquist transmit filter).

The LM-380 audio power amplifier amplifies the incoming signal. In order to cause nonlinear distortions to the signal,it is operated in full input range from low input power levels to saturation. The output of the amplifier is set automatically at one-half of the supply voltage.

The second operational amplifier is used for the DC offset of the amplifier output and for output impendance matching which is 50 Ohm.

The amplitude response of the stage (AM-AM characteristic) was measured using a single tone input and is given in section 2.1. The power bandwidth of the amplification stage was also measured and it is shown in Figure B.2. We note that the gain is constant over sufficient range for the used bandlimited 4-PAM signal which has a bandwidth of 124 KHz. In the same Figure,the phase of the LM-380 amplifier (as it is given by the designer) is also drawn. As we see in Figure B.3 the

phase contributes to additional degradation in the error performance of the 4-PAM signal.

In this point we must mention that in the computer simulation model the LM-380 amplifier is assumed phase equalized. For the simulated results of chapters III and V only distortions due to the LM-380 AM-AM characteristic are considered.

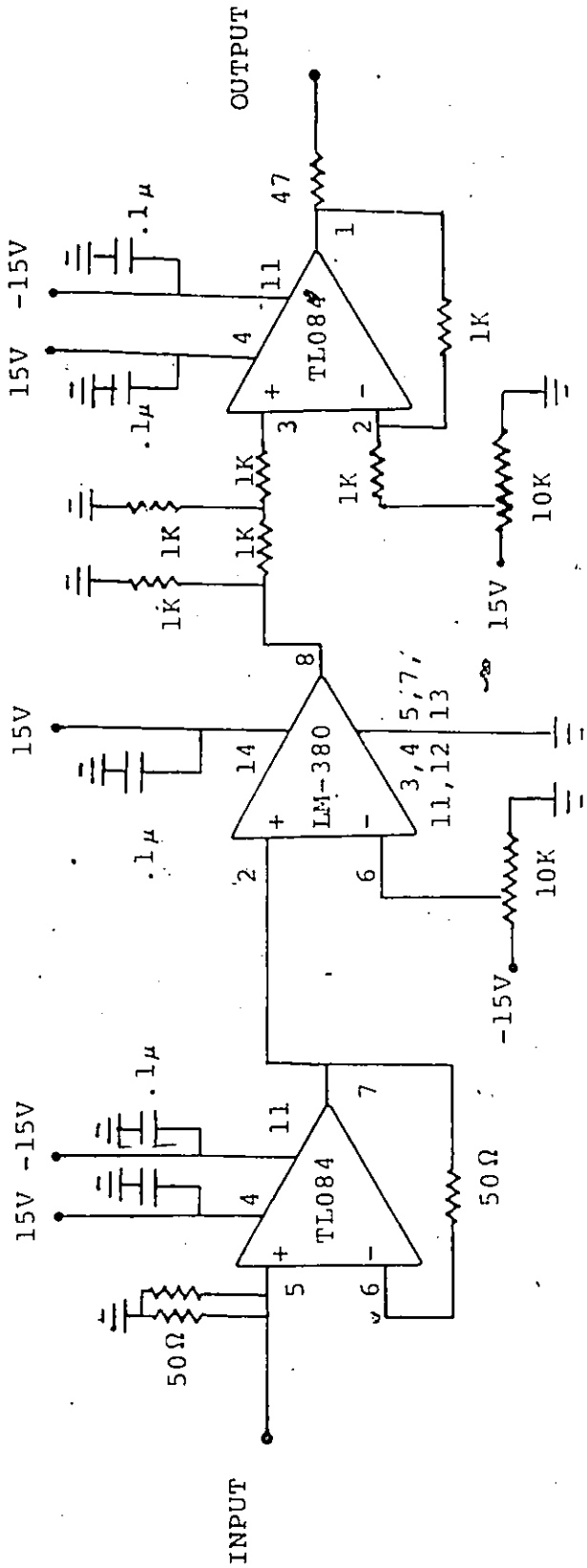


Figure B.1. Amplification stage circuit diagram.

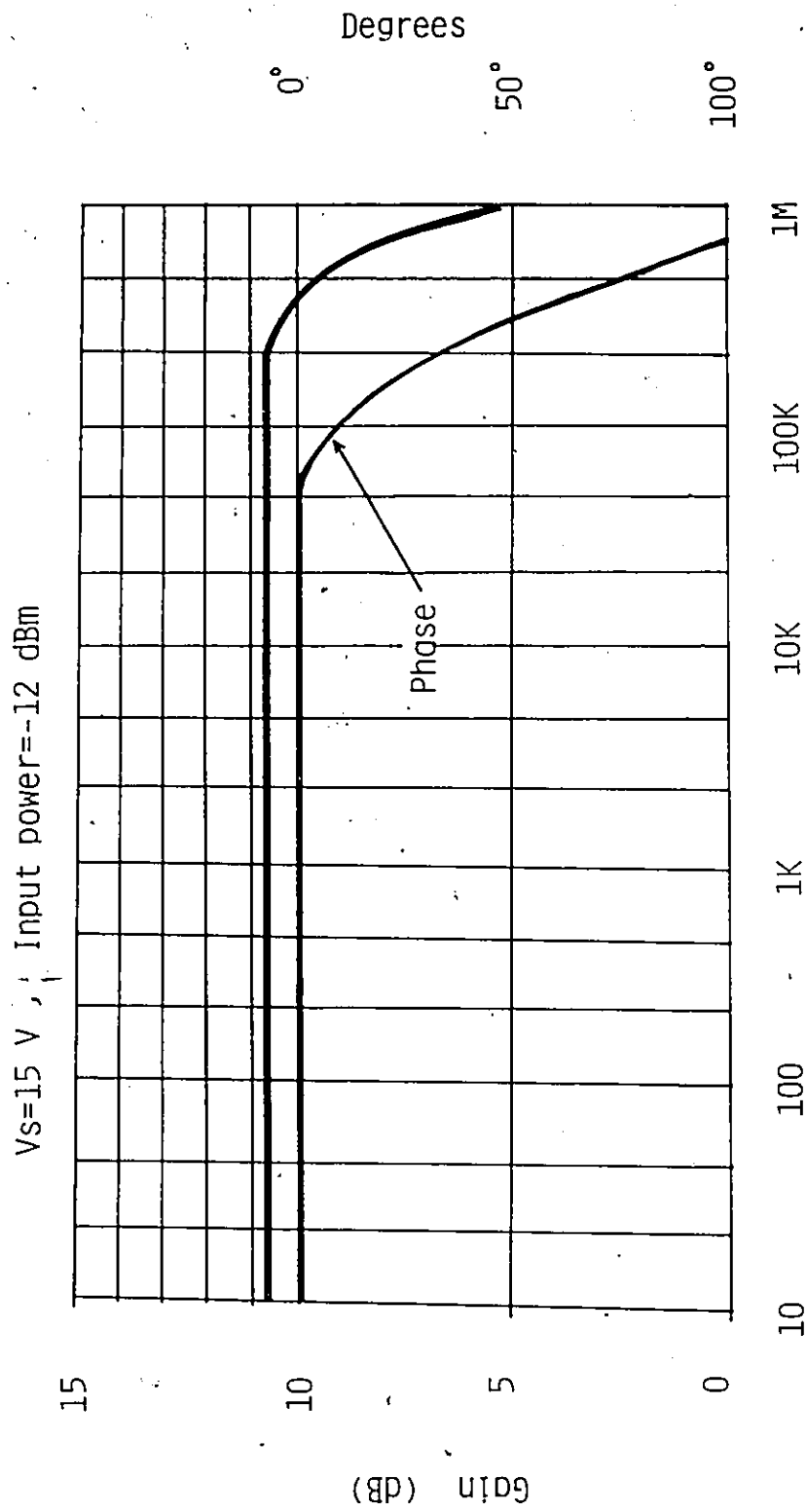


Figure B.2. Output power gain versus frequency of the LM-380 amplification stage .

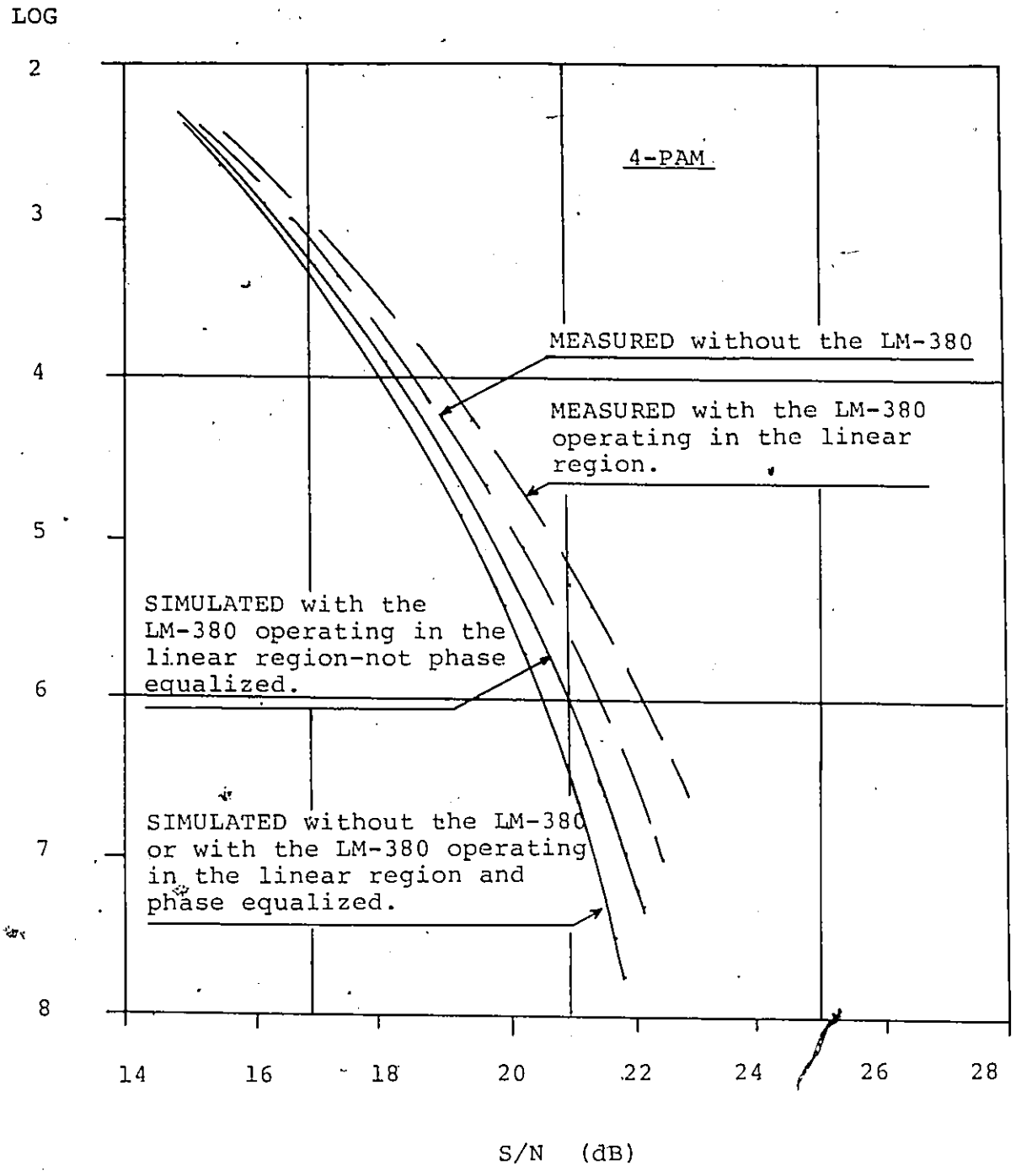


FIGURE B.3 . Error performance of the 4-PAM signal of Appendix A with the LM-380 amplification stage. Nyquist filters with $\alpha = 0.2$ were used.

Appendix C

IMPLEMENTATION AND PERFORMANCE EVALUATION OF A PREDISTORTER LINEARIZER FOR THE LM-380 AMPLIFICATION STAGE.

C.1 DESCRIPTION OF THE CIRCUIT.

A photograph of the implemented predistorter is shown in Figure C.1. The following description refers to the circuit of Figure C.2 . As we see the predistorter is a diode based circuit. Although semiconductor diodes available today are close to "ideal" devices they have severe limitations in low level applications. Thus ,due to the low level of the required signals (see Figure 4.4) the input to the predistorter is first amplified (1A). The degree of amplification is such that we operate in the "linear" region of the diodes. Two half wave rectifiers with dc balancing adjustment (1B), separate the negative and positive parts of the signal. This is necessary because of the two quadrant type (one polarity signals) of the following waveshaping stages (1C) [20].

The diodes D1-D4 of the waveshaping stages have a threshold which depends on the value of the voltages V1-V4. When the outputs of the operational amplifiers overcome the diodes thresholds,the corresponding branches are conducting and the resistances R1 to R4 are placed in parallel with the resistance R. This changes the gain of the operational amplifier resulting in a piece wise linear response [20].

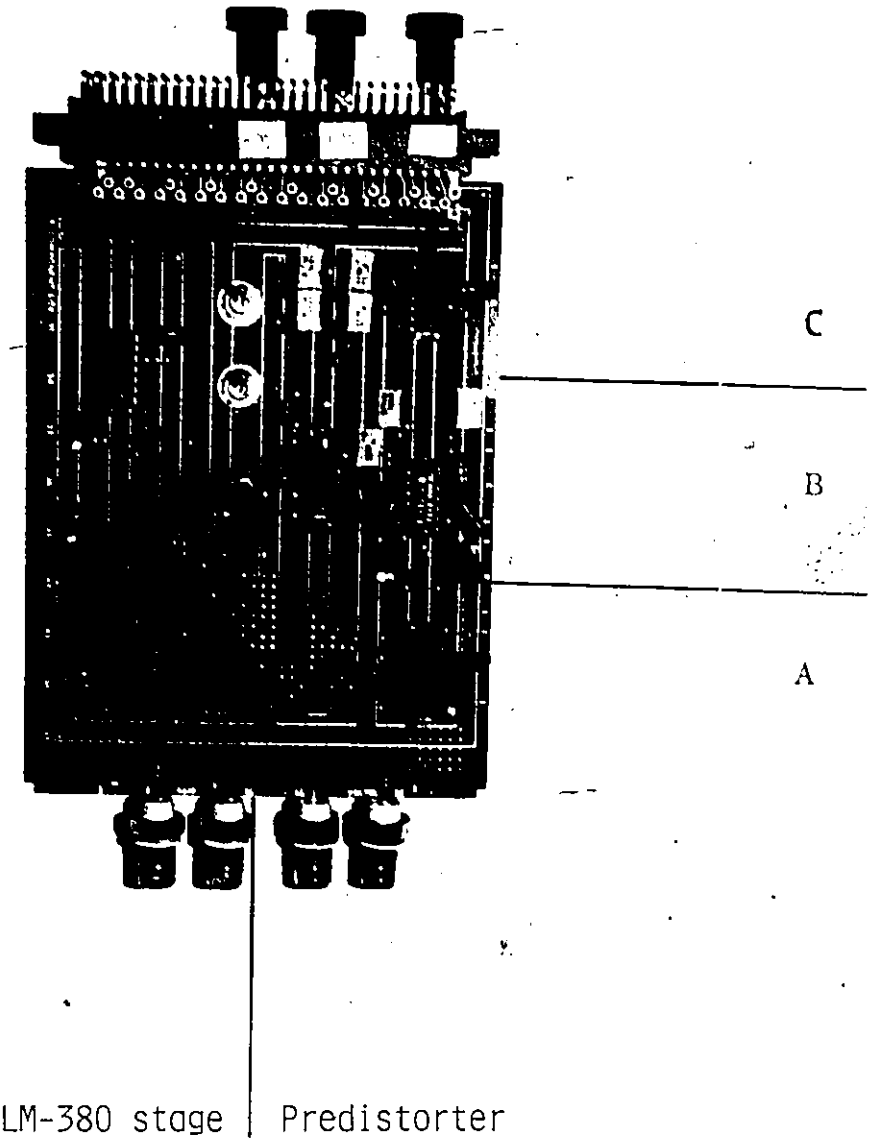


Figure C.1. Photograph of the implemented predistorter linearizer for the LM-380 amplification stage.

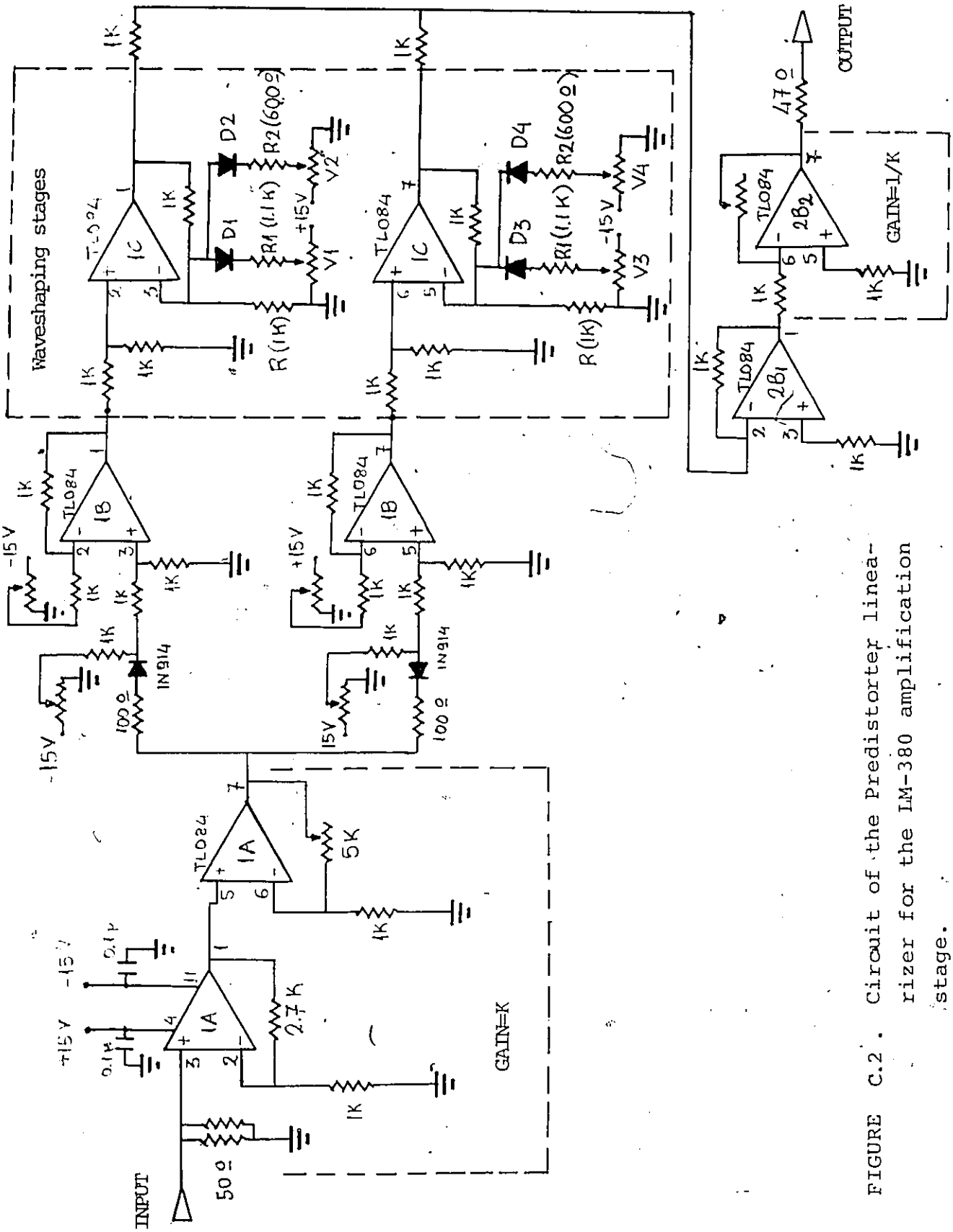


FIGURE C.2. Circuit of the Predistorter linearizer for the LM-380 amplification stage.

Finally the two signal parts are added (2B1) and the resulting signal is amplified (2B2) so that the overall predistorter gain becomes one. The input and output impendance of the predistorter are 50 Ohm.

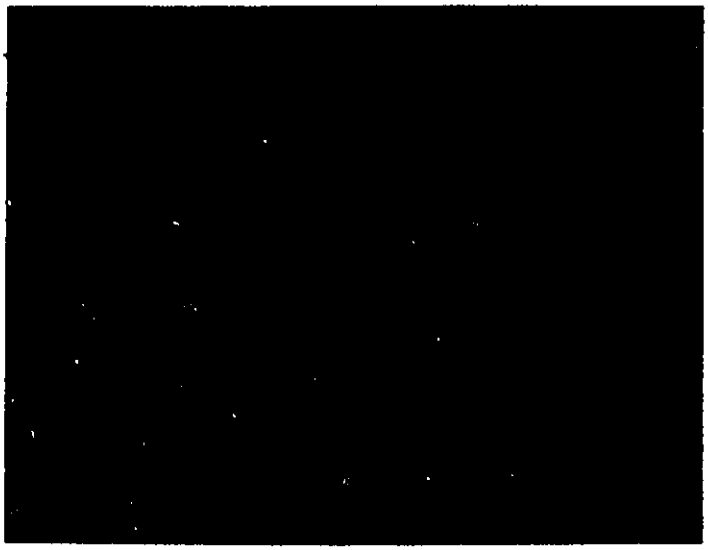
C.2 PERFORMANCE OF THE PREDISTORTER.

The single tone measured piece-wise linear transfer characteristic of the predistorter was given in Figure 4.4. As we see the slope of the characteristic is changing as it is shown in Table C.1:

Input range	Gain
$\|R\| \leq 0.12$	1.0
$0.12 \leq \|R\| \leq 0.1825$	1.45
$0.1825 \leq \|R\|$	2.3

Table C.1. Gain of the predistorter.

The effect of the predistorter on the 4-PAM signal generated by the encoder of Appendix B, is shown in Figure C.3. Considering the saturation power of the LM-380 amplification stage the operating point is 4 dB Output Backoff. Only the transmit raised cosine filter is used. We note that the higher levels of the signal are amplified more than the lower ones. The effect is the inverse of that of the LM-380 nonlinearity. Thus the overall response of the cascaded combination of the predistorter and the LM-380 stage becomes more linear (Figure 4.4, section 5.1).

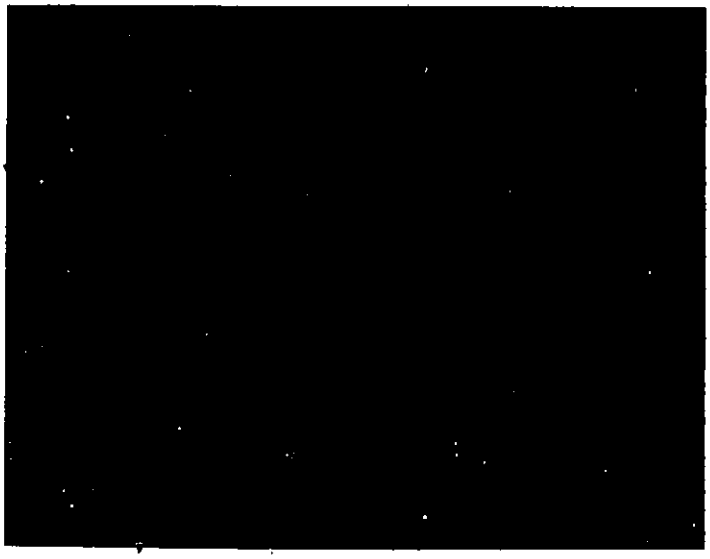


(a)

Horiz. 1 μs/div.

Vert. 50 mV/div.

4 dB Out.Backoff.



(b)

Horiz. 1 μs/div.

Vert. 50 mV/div.

4 dB Out.Backoff.

FIGURE C.3. .Measured eye diagrams of a 4-PAM signal at the (a) input, (b) output of the LM-380 predistorter. Only the transmit raised cosine filter with α=0.2 is used.

Appendix D

COMPUTER SIMULATION PROGRAMS.

The simulation programs listed in the first part of this appendix were used to simulate various performances of PAM systems, such as the performance in nonlinear channels and the performance in the linearized channels, with or without threshold adjustment. The programs listed in the second part, were used to fit the various AM-AM and AM-PM characteristics with suitable models and to optimize the coefficients of the equations which we used in the linearization process.

The author of this thesis used, modified and extended numerous subroutines and programs which were developed by the Digital Communications Research Group, Department of Electrical Engineering, University of Ottawa.

FILE: PAM FORTRAN A UNIV D'/OF OTTAWA

```
C*************************************************************************      PAM00010
C     PROGRAM FOR SIMULATION OF  PAM SCHEMES IN NONLINEAR CHANNEL.             PAM00020
C     FILE NAME: PAM                                                           PAM00030
C                                                                              PAM00040
C*************************************************************************      PAM00050
      COMPLEX DATA(262144),TF(262144)                                          PAM00060
      DIMENSION PE1(64),EBNO(64),NI(16384),NQ(16384),PE(64)                    PAM00070
      DIMENSION XARRAY(68),YARRAY(68),P(64)                                    PAM00080
      REAL SS(262144),P                                                        PAM00090
C                                                                              PAM00100
C     INITIALIZE PROGRAM.                                                      PAM00110
C                                                                              PAM00120
      COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,LSAMPL                                PAM00130
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                           PAM00140
      ALPHA=0.20                                                               PAM00150
C     ALPHA=0.50                                                               PAM00160
      CF=4.                                                                    PAM00170
      LDIM=262144                                                              PAM00180
      IOFF=0                                                                   PAM00190
      LSAMPL=16                                                                PAM00200
      OFF=FLOAT(IOFF)/FLOAT(LSAMPL)                                            PAM00210
      NSNR=64                                                                  PAM00220
      NSYMB=16384                                                              PAM00230
      BAUD=200                                                                 PAM00240
      FBW=100                                                                  PAM00250
      FFB=FBW*(1.+ALPHA)                                                       PAM00260
      WRITE(6,23) FBW,ALPHA,OFF                                                PAM00270
   23 FORMAT(5X,11H 16QAM FBW=,F10.6,5X,7H ALPHA=,F6.3,5X,5H OFF=,F6.3)        PAM00280
      ISIN=1                                                                   PAM00290
      NFILTR=2                                                                 PAM00300
      NRUNS=4                                                                  PAM00310
      LMAX=31                                                                  PAM00320
      ID=1.                                                                    PAM00330
C                                                                              PAM00340
C     END OF INITIALIZATIONS.                                                  PAM00350
C------------------------------------------------------------                  PAM00360
C                                                                              PAM00370
C     START OF COMPUTATIONS.                                                   PAM00380
      DO 100 NR=1,NRUNS                                                        PAM00390
      DSEED=135791.D0                                                          PAM00400
      CALL RAND (NI,NSYMB,DSEED)                                               PAM00410
      DSEED=780956.D0                                                          PAM00420
      CALL RAND (NQ,NSYMB,DSEED)                                               PAM00430
      CALL SIGNAL(DATA,NI,NQ)                                                  PAM00440
      CALL RCOSTX(TF)                                                          PAM00450
      CALL FILTER(DATA,TF)                                                     PAM00460
      CALL POWER(DATA,MP,PF)                                                   PAM00470
      GO TO (1,2,3,4,5,6,7,8),NR                                               PAM00480
    1 GO TO 20                                                                 PAM00490
    2 BAKOFF=15.4                                                              PAM00500
      GO TO 21                                                                 PAM00510
    3 BAKOFF=13.4                                                              PAM00520
      GO TO 31                                                                 PAM00530
    4 BAKOFF=12.4                                                              PAM00540
      GO TO 11                                                                 PAM00550
```

FILE: PAM FORTRAN A UNIV D'/OF OTTAWA

```
 5     BAKOFF=11.4                                                    PAM00560
       GO TO 51                                                       PAM00570
 6     BAKOFF=0.0                                                     PAM00580
       GO TO 21                                                       PAM00590
 7     BAKOFF=4.9                                                     PAM00600
       GO TO 21                                                       PAM00610
 8     BAKOFF=3.2                                                     PAM00620
       GO TO 21                                                       PAM00630
 71    CALL TWT(DATA,BAKOFF,PSHIFT)                                   PAM00640
       CALL AMPH(TF)                                                  PAM00650
       CALL FILTER(DATA,TF)                                           PAM00660
       GO TO 20                                                       PAM00670
 11    CALL TWT(DATA,BAKOFF,PSHIFT)                                   PAM00680
       GO TO 20                                                       PAM00690
 21    CALL TWT1(DATA,BAKOFF,PSHIFT)                                  PAM00700
       GO TO 20                                                       PAM00710
 41    CALL TWT2(DATA,BAKOFF,PSHIFT)                                  PAM00720
       GO TO 20                                                       PAM00730
 31    CALL TWT3(DATA,BAKOFF,PSHIFT)                                  PAM00740
       GO TO 20                                                       PAM00750
 51    CALL TWT4(DATA,BAKOFF,PSHIFT)                                  PAM00760
       GO TO 20                                                       PAM00770
 61    CALL TWT5(DATA,BAKOFF,PSHIFT)                                  PAM00780
 20     CALL ENERGY(DATA,ES)                                          PAM00790
C                                                                     PAM00800
C      END OF TRANSMITTER                                             PAM00810
C                                                                     PAM00820
C      CALL SPECT(DATA,PO,NR)                                         PAM00830
       CALL PFOBP(PO,NR,NRUNS)                                        PAM00840
       CALL RCOSRX(TF)                                                PAM00850
       CALL HHGG(TF,PNOISE)                                           PAM00860
       CALL FILTER(DATA,TF)                                           PAM00870
       CALL SYNCRO(DATA,PNOISE,NI,NQ,MI,MQ,ES,LMAX)                   PAM00880
C      CALL PSPACE(DATA,NR,NRUNS,MI)                                  PAM00890
       CALL DETECT(NERROR,DATA,PNOISE,MI,MQ,NI,NQ,EBNO,PE,ES,LMAX)    PAM00900
       CALL DECOD1(NERROR,DATA,PNOISE,MI,NI,EBNO,P,PE,ES,BAKOFF,NR)   PAM00910
C                                                                     PAM00920
C      CALL THE DRAWING ROUTINE                                       PAM00930
C                                                                     PAM00940
       DO 99 I=1,NSNR                                                 PAM00950
       XARRAY(I)=EBNO(I)                                              PAM00960
  99   YARRAY(I)=PE(I)                                                PAM00970
       CALL DRAWCN(ID,XARRAY,YARRAY,NR,NRUNS)                         PAM00980
C      CALL THE EYE DIAGRAM ROUTINE                                   PAM00990
C      CALL EYEQ(DATA,NR,NRUNS)                                       PAM01000
 100   CONTINUE                                                       PAM01010
       STOP                                                           PAM01020
       END                                                            PAM01030
                                                                      PAM01040
C*********************************************************************PAM01050
C     THIS SUBROUTINE GENERATES RANDOM NUMBERS FOR PRODUCING RANDOM DATA.PAM01060
C*********************************************************************PAM01070
       SUBROUTINE RAND(IR,N,DSEED)                                    PAM01080
       INTEGER IR(1)                                                  PAM01090
       DOUBLE PRECISION DSEED                                         PAM01100
```

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      DO 3000 I=1,N                                                     PAM01110
      R=GGUBFS(DSEED)                                                   PAM01120
      IR(I)=IFIX(R)                                                     PAM01130
      IF( R.LE.0.031) IR(I)=-31                                         PAM01140
      IF((R.GT.0.031).AND. (R.LE.0.062))IR(I)=-29                       PAM01150
      IF((R.GT.0.062).AND. (R.LE.0.093))IR(I)=-27                       PAM01160
      IF((R.GT.0.093).AND. (R.LE.0.124))IR(I)=-25                       PAM01170
      IF((R.GT.0.124).AND. (R.LE.0.155))IR(I)=-23                       PAM01180
      IF((R.GT.0.155).AND. (R.LE.0.186))IR(I)=-21                       PAM01190
      IF((R.GT.0.186).AND. (R.LE.0.217))IR(I)=-19                       PAM01200
      IF((R.GT.0.217).AND. (R.LE.0.248))IR(I)=-17                       PAM01210
      IF((R.GT.0.248).AND. (R.LE.0.279))IR(I)=-15                       PAM01220
      IF((R.GT.0.279).AND. (R.LE.0.31)) IR(I)=-13                       PAM01230
      IF((R.GT.0.31) .AND. (R.LE.0.341))IR(I)=-11                       PAM01240
      IF((R.GT.0.341).AND. (R.LE.0.372))IR(I)=-9                        PAM01250
      IF((R.GT.0.372).AND. (R.LE.0.403))IR(I)=-7                        PAM01260
      IF((R.GT.0.403).AND. (R.LE.0.434))IR(I)=-5                        PAM01270
      IF((R.GT.0.434).AND. (R.LE.0.465))IR(I)=-3                        PAM01280
      IF((R.GT.0.465).AND. (R.LE.0.496))IR(I)=-1                        PAM01290
      IF((R.GT.0.496).AND. (R.LE.0.527))IR(I)=1                         PAM01300
      IF((R.GT.0.527).AND. (R.LE.0.558))IR(I)=3                         PAM01310
      IF((R.GT.0.558).AND. (R.LE.0.589))IR(I)=5                         PAM01320
      IF((R.GT.0.589).AND. (R.LE.0.62)) IR(I)=7                         PAM01330
      IF((R.GT.0.624) .AND. (R.LE.0.651))IR(I)=9                        PAM01340
      IF((R.GT.0.651).AND. (R.LE.0.682))IR(I)=11                        PAM01350
      IF((R.GT.0.682).AND. (R.LE.0.713))IR(I)=13                        PAM01360
      IF((R.GT.0.713).AND. (R.LE.0.744))IR(I)=15                        PAM01370
      IF((R.GT.0.744).AND. (R.LE.0.775))IR(I)=17                        PAM01380
      IF((R.GT.0.775).AND. (R.LE.0.806))IR(I)=19                        PAM01390
      IF((R.GT.0.806).AND. (R.LE.0.837))IR(I)=21                        PAM01400
      IF((R.GT.0.837).AND. (R.LE.0.868))IR(I)=23                        PAM01410
      IF((R.GT.0.868).AND. (R.LE.0.899))IR(I)=25                        PAM01420
      IF((R.GT.0.899).AND. (R.LE.0.930))IR(I)=27                        PAM01430
      IF((R.GT.0.930).AND. (R.LE.0.961))IR(I)=29                        PAM01440
      IF((R.GT.0.961).AND. (R.LE.0.996))IR(I)=31                        PAM01450
      IF (R.GT.0.996) IR(I)=-31                                         PAM01460
 3000 CONTINUE                                                          PAM01470
      RETURN                                                            PAM01480
      END                                                               PAM01490
C*****************************************************************     PAM01500
C     THIS FORMS COMPLEX BASEBAND SIGNAL                                PAM01510
C     NI : I-CHANNEL SEQ                                                PAM01520
C     NQ : Q-CHANNEL SEQ                                                PAM01530
C     DATA : OUTPUT SIGNAL                                              PAM01540
C*****************************************************************     PAM01550
      SUBROUTINE SIGNAL (DATA,NI,NQ)                                    PAM01560
      COMPLEX DATA(1)                                                   PAM01570
      DIMENSION NI(1), NQ(1)                                            PAM01580
      COMMON /NUMB1/ FBW,ALPHA,LDEM,IOFF,LSAMPL                         PAM01590
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                    PAM01600
      DO 2 I=1,NSYMB                                                    PAM01610
C     LOAD INTO SAMPLE ARRAY , LSAMPLES PER SYMBOL                      PAM01620
      J1=(I-1)*LSAMPL+1                                                 PAM01630
      J2=I*LSAMPL                                                       PAM01640
      DO 3 J3=J1,J2                                                     PAM01650
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    3   DATA(J3)=CMPLX(FLOAT(NI(I)),0.0)                                    PAM01660
    2   CONTINUE                                                            PAM01670
        RETURN                                                              PAM01680
        END                                                                 PAM01690
                                                                            PAM01700
                                                                            PAM01710
C*******************************************************************       PAM01720
C     RAISED COSINE FILTER WITH ARBITRARY ALPHA AND X/SINX                  PAM01730
C*******************************************************************       PAM01740
      SUBROUTINE RCOSTX(TF)                                                 PAM01750
       COMPLEX TF(1)                                                        PAM01760
      COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,ISAMPL                            PAM01770
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                        PAM01780
      SBANDW=BAUD*ISAMPL                                                    PAM01790
      NO=LDIM/2                                                             PAM01800
      NO1=NO+1                                                              PAM01810
       IF (ALPHA.EQ.0) ALPHA=0.0001                                         PAM01820
      FN=LDIM*(FBW/SBANDW)                                                  PAM01830
      F1=(1.-ALPHA)*FN                                                      PAM01840
      F2=(1.+ALPHA)*FN                                                      PAM01850
      IFN=IFIX(FN)                                                          PAM01860
      IF1=IFIX(F1)+1                                                        PAM01870
      IF2=IFIX(F2)+1                                                        PAM01880
C                                                                           PAM01890
C     THE AMPLITUDE CHARACTERISTICS                                         PAM01900
C                                                                           PAM01910
       A1=3.1415926/(2.*FLOAT(IFN))                                         PAM01920
       DO 8 I=2,IF1                                                         PAM01930
      TF(I)=CMPLX(1.0,0.0)                                                  PAM01940
       J=I-1                                                                PAM01950
C                                                                           PAM01960
C     X/SIN(X) EQUALIZATION                                                 PAM01970
C                                                                           PAM01980
       A2=(FLOAT(J)*A1)/(SIN(FLOAT(J)*A1))                                  PAM01990
      TF(I)=CMPLX(A2,0.0)                                                   PAM02000
    8 CONTINUE                                                              PAM02010
      JK=IF1+1                                                              PAM02020
      DO 9 J=JK,IF2                                                         PAM02030
       I=J-1                                                                PAM02040
C                                                                           PAM02050
C     ROOT OF RAISED COSINE                                                 PAM02060
C                                                                           PAM02070
      A3=(FLOAT(I)*A1)/(SIN(FLOAT(I)*A1))                                   PAM02080
      A=(3.1415926/(2.0*ALPHA))*((FLOAT(I)/FLOAT(IFN))-1.)                  PAM02090
      TF(J)=CMPLX(SQRT(0.5*(1.0-SIN(A)))*0.0)                               PAM02100
      TF(J)=TF(J)*CMPLX(A3,0.0)                                             PAM02110
    9 CONTINUE                                                              PAM02120
      JH=IF2+1                                                              PAM02130
      DO 10 I=JH,NO1                                                        PAM02140
      TF(I)=CMPLX(0.0,0.0)                                                  PAM02150
   10 CONTINUE                                                              PAM02160
      NO2=NO1+1                                                             PAM02170
      DO 5 I=NO2,LDIM                                                       PAM02180
      TF(I)=CONJG(TF(LDIM+2-I))                                             PAM02190
    5 CONTINUE                                                              PAM02200
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      RETURN                                                            PAM02210
      END                                                               PAM02220
C*****************************************************************    PAM02230
C     RAISED COSINE FILTER WITH ARBITRARY ALPHA                         PAM02240
C*****************************************************************    PAM02250
      SUBROUTINE RCOSRX(TF)                                             PAM02260
       COMPLEX TF(1)                                                    PAM02270
      COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,LSAMPL                         PAM02280
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                    PAM02290
      SBANDW=BAUD*LSAMPL                                                PAM02300
      NO=LDIM/2                                                         PAM02310
      NO1=NO+1                                                          PAM02320
       IF (ALPHA.EQ.0) ALPHA=0.0001                                     PAM02330
      FN=LDIM*(FBW/SBANDW)                                              PAM02340
      F1=(1.-ALPHA)*FN                                                  PAM02350
      F2=(1.+ALPHA)*FN                                                  PAM02360
      IFN=IFIX(FN)                                                      PAM02370
      IF1=IFIX(F1)+1                                                    PAM02380
      IF2=IFIX(F2)+1                                                    PAM02390
C                                                                       PAM02400
C     AMPLITUDE CHARACTERISTIC                                          PAM02410
C                                                                       PAM02420
       A1=3.141592/(2.*FLOAT(IFN))                                      PAM02430
       DO 8 I=2,IF1                                                     PAM02440
      TF(1)=CMPLX(1.0,0.0)                                              PAM02450
       J=I-1                                                            PAM02460
      TF(I)=CMPLX(1.,0.0)                                               PAM02470
    8 CONTINUE                                                          PAM02480
      JK=IF1+1                                                          PAM02490
      DO 9 J=JK,IF2                                                     PAM02500
       I=J-1                                                            PAM02510
C                                                                       PAM02520
C     ROOT OF RAISED COSINE                                             PAM02530
C                                                                       PAM02540
      A=(3.141592/(2.0*ALPHA))*((FLOAT(I)/FLOAT(IFN))-1.)               PAM02550
      TF(J)=CMPLX(SQRT(0.5*(1.0-SIN(A))),0.0)                           PAM02560
    9 CONTINUE                                                          PAM02570
      JH=IF2+1                                                          PAM02580
      DO 10 I=JH,NO1                                                    PAM02590
      TF(I)=CMPLX(0.0,0.0)                                              PAM02600
   10 CONTINUE                                                          PAM02610
         NO2=NO1+1                                                      PAM02620
      DO 5 I=NO2,LDIM                                                   PAM02630
      TF(I)=CONJG(TF(LDIM+2-I))                                         PAM02640
    5 CONTINUE                                                          PAM02650
      RETURN                                                            PAM02660
      END                                                               PAM02670
                                                                        PAM02680
                                                                        PAM02690
C*****************************************************************    PAM02700
C     THE FOLLOWING SUBROUTINE PERFORMS THE FILTERING                   PAM02710
C     PROCESS ON THE DATA SEQUENCE.                                     PAM02720
C*****************************************************************    PAM02730
C                                                                       PAM02740
      SUBROUTINE FILTER(DATA,TF)                                        PAM02750
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```
      COMPLEX DATA(1),TF(1)                                          PAM02760
      DIMENSION IWK(19)                                              PAM02770
      COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,LSAMPL                      PAM02780
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                 PAM02790
      CALL FFT2C(DATA,18,IWK)                                        PAM02800
      DO 1 I=1,LDIM                                                  PAM02810
    1 DATA(I)=CONJG(DATA(I)*TF(I))                                   PAM02820
      CALL FFT2C(DATA,18,IWK)                                        PAM02830
      DO 2 I=1,LDIM                                                  PAM02840
    2 DATA(I)=CONJG(DATA(I))/FLOAT(LDIM)                             PAM02850
      RETURN                                                         PAM02860
      END                                                            PAM02870
C*****************************************************************  PAM02880
C     THIS SUBROUTINE COMPUTES THE EFFECTIVE NOISE (PNOISE)          PAM02890
C     AT THE OUTPUT OF THE RECEIVE FILTER                            PAM02900
C*****************************************************************  PAM02910
C                                                                    PAM02920
      SUBROUTINE HHGG(TF,PNOISE)                                     PAM02930
      COMPLEX TF(1)                                                  PAM02940
      COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,LSAMPL                      PAM02950
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                 PAM02960
      SUM=0.0                                                        PAM02970
      SBANDW=BAUD*LSAMPL                                             PAM02980
      DO 1 L=1,LDIM                                                  PAM02990
      HH=(CABS(TF(L)))**2                                            PAM03000
    1 SUM=SUM+HH                                                     PAM03010
      PNOISE=SUM*SBANDW/FLOAT(LDIM)/2.                               PAM03020
      WRITE (6,2) PNOISE                                             PAM03030
    2 FORMAT(5X,'PNOISE=',E7.3,/)                                    PAM03040
      RETURN                                                         PAM03050
      END                                                            PAM03060
C*****************************************************************  PAM03070
C CALCULATE ENERGY (ES)                                              PAM03080
C *****************************************************************  PAM03090
          SUBROUTINE ENERGY(DATA,ES)                                 PAM03100
          COMPLEX DATA(1)                                            PAM03110
          COMMON /NUMB2/ NSNR,NSYMB,BAUD                             PAM03120
          COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,LSAMPL                  PAM03130
          WATTS=0.                                                   PAM03140
          DO 1 I=1,LDIM                                              PAM03150
          WATTS=WATTS+((CABS(DATA(I)))**2.)                          PAM03160
    1     CONTINUE                                                   PAM03170
          WATTS=WATTS/(FLOAT(LDIM))                                  PAM03180
          ES=WATTS/BAUD                                              PAM03190
          WRITE (6,40) WATTS,ES                                      PAM03200
   40     FORMAT(5X,E15.8,5X,E15.8)                                  PAM03210
          RETURN                                                     PAM03220
          END                                                        PAM03230
                                                                     PAM03240
                                                                     PAM03250
C*****************************************************************  PAM03260
C     THIS SUBROUTINE DRAWS PROBABILITY OF ERROR CURVES              PAM03270
C*****************************************************************  PAM03280
      SUBROUTINE DRAWCN(ID,XARRAY,YARRAY,JCURV,JLAST)                PAM03290
      DIMENSION XARRAY(68),YARRAY(68),X(64),Y(64)                    PAM03300
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```
      COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,LSAMPL                          PAM03310
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                     PAM03320
      CF=2.0                                                             PAM03330
      M=NSNR                                                             PAM03340
      NNSNR=NSNR                                                         PAM03350
      DO 1 K=1,NNSNR                                                     PAM03360
      XARRAY(K)=XARRAY(K)+10.*ALOG10(CF)                                 PAM03370
      IF(YARRAY(K).GE.1.0) YARRAY(K)=1.0                                 PAM03380
      IF(YARRAY(K).LE.1.0E-9) GOTO 3                                     PAM03390
      GOTO 1                                                             PAM03400
    3 M=K-1                                                              PAM03410
      GOTO 4                                                             PAM03420
    1 CONTINUE                                                           PAM03430
    4 CONTINUE                                                           PAM03440
      I=M+1                                                              PAM03450
      II=I+1                                                             PAM03460
      XARRAY(I)=4.0                                                      PAM03470
      XARRAY(II)=3.0                                                     PAM03480
      YARRAY(I)=1.E-9                                                    PAM03490
      YARRAY(II)=0.4                                                     PAM03500
      IF(JCURV.GT.1) GOTO 2                                              PAM03510
C                                                                        PAM03520
C     ESTABLISH THE SURFACE AREA.                                        PAM03530
C                                                                        PAM03540
      CALL PLOTS(30.0,27.5)                                              PAM03550
      CALL FACTOR(0.85)                                                  PAM03560
C                                                                        PAM03570
C     ESTABLISH THE ORIGIN.                                              PAM03580
C                                                                        PAM03590
      CALL PLOT(3.0,1.5,-3)                                              PAM03600
C                                                                        PAM03610
C     DRAW THE LOGARITHMIC Y-AXIS.                                       PAM03620
C                                                                        PAM03630
      CALL LGAXS(0.0,0.0,29HPROBABILITY OF A SYMBOL ERROR,29.25.,        PAM03640
     +90.,1.0E-9,.4)                                                     PAM03650
C                                                                        PAM03660
C     DRAW THE LINEAR X-AXIS.                                            PAM03670
C                                                                        PAM03680
      CALL AXIS(0.0,0.0,11H C/N  IN DB,-11,                              PAM03690
     +27.0,0.0,4.0,3.0)                                                  PAM03700
      CALL LGLIN(XARRAY,YARRAY,M,1,2,JCURV,1)                            PAM03710
      IF(JCURV.EQ.JLAST) CALL PLOT(0.0,0.0,999)                          PAM03720
      RETURN                                                             PAM03730
      END                                                                PAM03740
                                                                         PAM03750
                                                                         PAM03760
C*************************************************************         PAM03770
C     THIS SUBROUTINE DRAWS THE EYE DIAGRAM FOR TWO                      PAM03780
C     SYMBOL DURATION.                                                   PAM03790
C*************************************************************         PAM03800
      SUBROUTINE EYEQ(DATA,NR,NRUNS)                                     PAM03810
      DIMENSION DATA2(66),DATA3(66)                                      PAM03820
      COMPLEX DATA(1)                                                    PAM03830
      REAL XLEN,YLEN                                                     PAM03840
      INTEGER NR,NRUNS                                                   PAM03850
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```
      COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,LSAMPL                          PAM03860
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                     PAM03870
C     ESTABLISH THE SURFACE AREA.                                        PAM03880
      IF (NR.NE.1) GO TO 15                                              PAM03890
      XLEN=40.0*FLOAT(NRUNS)                                             PAM03900
      YLEN=27.5                                                          PAM03910
      CALL PLOTS(XLEN,YLEN)                                              PAM03920
C     ESTABLISH THE ORIGIN.                                              PAM03930
      CALL PLOT(3.0,13.0,-3)                                             PAM03940
      GO TO 110                                                          PAM03950
 15   CALL PLOT(40.0,0.0,-3)                                             PAM03960
C     WRITE THE TITLE OF THE GRAPH.                                      PAM03970
110     CALL SYMBOL(10.0,12.0,0.49,17HL-PAM EYE DIAGRAM,0.0,17)          PAM03980
C     DRAW THE TIME AXIS.                                                PAM03990
      CALL AXIS(0.0,0.0,1H ,-1,32.,0.0,1.0,1.0)                          PAM04000
C     DRAW THE AMPLITUDE AXIS.                                           PAM04010
      CALL AXIS(0.0,-8.00,1H ,1,16.0,90.0,-32.,4.0)                      PAM04020
C     PLOT THE DATA.                                                     PAM04030
      JJ=2*LSAMPL                                                        PAM04040
      DATA2(JJ+1)=0.0                                                    PAM04050
      DATA2(JJ+2)=4.0                                                    PAM04060
      DATA3(JJ+1)=1.0                                                    PAM04070
      DATA3(JJ+2)=1.0                                                    PAM04080
      M2=750                                                             PAM04090
      DO 40 KK=1,M2                                                      PAM04100
      DO 20 I=1,JJ                                                       PAM04110
      II=(KK-1)*LSAMPL+I                                                 PAM04120
      IF (II.GT.LDIM) II=II-LDIM                                         PAM04130
      DATA2(I)=REAL(DATA(II))                                            PAM04140
   20  DATA3(I)=FLOAT(I)                                                 PAM04150
      CALL LINE(DATA3,DATA2,JJ,1,0,0)                                    PAM04160
   40   CONTINUE                                                         PAM04170
      IF (NR.NE.NRUNS) GO TO 10                                          PAM04180
      CALL PLOT(0.0,0.0,999)                                             PAM04190
10     RETURN                                                           PAM04200
      END                                                                PAM04210
                                                                         PAM04220
                                                                         PAM04230
C*************************************************************************PAM04240
C     THIS SUBROUTINE SIMULATES THE BASEBAND  AM-AM                      PAM04250
C     NONLINEARITY OF THE LM-380 AMPLIFIER                               PAM04260
C*************************************************************************PAM04270
      SUBROUTINE TWT(DATA,BAKOFF,PSHIFT)                                 PAM04280
      COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,LSAMPL                          PAM04290
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                     PAM04300
      COMPLEX DATA(1)                                                    PAM04310
      REAL MP,C(80),D(80),G(80),E(80)                                    PAM04320
      DATA ZPMAX,ZOMAX,VMAX,VO/1.414,0.000,1.350,1.414/                  PAM04330
      DATA A1,A3,A5,A7,A9,A11,A13,A15,A17/1.4621649,-0.0998297,0.59917, PAM04340
     &-0.8914303,-0.817838,2.0430622,-1.2413568,0.2490589,0.0/           PAM04350
      DATA B1,B3,B5,B7,B9,B11,B13,B15,B17/0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,PAM04360
     #0.0,0.0/                                                           PAM04370
      P(X)=((((((A17*X**2+A15)*X**2+A13)*X**2+A11)*X**2+A9)*            PAM04380
     #X**2+A7)*X**2+A5)*X**2+A3)*X**2+A1                                 PAM04390
      ZP(X)=P(X)*X                                                       PAM04400
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      Q(X)=((((((B17*X**2+B15)*X**2+B13)*X**2+B11)*X**2+B9)*
     #X**2+B7)*X**2+B5)*X**2+B3,)*X**2+B1                              PAM04410
      ZQ(X)=Q(X)*X                                                     PAM04420
      Z(X)=SQRT(ZP(X)**2+ZQ(X)**2)                                     PAM04430
      TWTIN=V0*10.**(-BAKOFF/20.)                                      PAM04440
      PPP=ZQ(TWTIN)/ZP(TWTIN)                                          PAM04450
      PSHIFT=ATAN(PPP)                                                 PAM04460
      WRITE (6,2) BAKOFF,PSHIFT,TWTIN                                  PAM04470
    2 FORMAT(5X,'TWTA INPUT BACKOFF:',F4.1,' DB',                      PAM04480
     #'   OUTPUT PHASE SHIFT:',F7.3,1X,'TWTIN:',F5.3,/)                PAM04490
      MP=0.0                                                           PAM04500
      DO 15 K=1,LDIM                                                   PAM04510
      MP=MP+((CABS(DATA(K)))**2.)                                      PAM04520
   15 CONTINUE                                                         PAM04530
      MP=MP/LDIM                                                       PAM04540
      WRITE(6,20) MP                                                   PAM04550
   20 FORMAT(5X,'MEAN POWER:',F8.4)                                    PAM04560
      FNORMI=TWTIN/SQRT(MP)                                            PAM04570
      WRITE (6,22) FNORMI                                              PAM04580
   22 FORMAT(5X,'FNORMI:',F8.4)                                        PAM04590
      DO 11 I=1,LDIM                                                   PAM04600
      DATA(I)=DATA(I)*FNORMI                                           PAM04610
   11 CONTINUE                                                         PAM04620
      DO 10 I=1,LDIM                                                   PAM04630
      X=REAL(DATA(I))                                                  PAM04640
      Y=0.0                                                            PAM04650
      R=SQRT(X**2+Y**2)                                                PAM04660
      IF(R.GT.VMAX) GOTO 12                                            PAM04670
      DATA(I)=CMPLX(P(R)*X-Q(R)*Y,P(R)*Y+Q(R)*X)                       PAM04680
      GO TO 10                                                         PAM04690
   12 DATA(I)=CMPLX(ZPMAX*X-ZQMAX*Y,ZQMAX*X+ZPMAX*Y)/R                 PAM04700
   10 CONTINUE                                                         PAM04710
      DO 16 I=1,LDIM                                                   PAM04720
      DATA(I)=DATA(I)/FNORMI/A1                                        PAM04730
   16 CONTINUE                                                         PAM04740
      RETURN                                                           PAM04750
      END                                                              PAM04760
                                                                       PAM04770
                                                                       PAM04780
C ***************************************************************     PAM04790
C     THIS SUBROUTINE DRAWS SPACE DIAGRAM                              PAM04800
C ***************************************************************     PAM04810
      SUBROUTINE PSPACE (DATA,NR,NRUNS,MI)                             PAM04820
      COMPLEX DATA(1)                                                  PAM04830
      REAL XLEN,YLEN                                                   PAM04840
      REAL X(2000),Y(2000)                                             PAM04850
      INTEGER NR,NRUNS                                                 PAM04860
      COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,LSAMPL                        PAM04870
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                   PAM04880
C     ESTABLISH THE SURFACE AREA.                                      PAM04890
      IF(NR.NE.1) GO TO 2                                              PAM04900
      XLEN=40.0*FLOAT(NRUNS)                                           PAM04910
      YLEN=27.5                                                        PAM04920
      CALL PLOTS(XLEN,YLEN)                                            PAM04930
C     ESTABLISH THE ORIGIN.                                            PAM04940
                                                                       PAM04950
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FILE: PAM       FORTRAN  A1  UNIV D'/OF OTTAWA

      CALL PLOT(20.0,12.5,-3)                                                  PAM04960
      GO TO 3                                                                  PAM04970
    2 CALL PLOT(40.0,0.0,-3)                                                   PAM04980
C     TITLE                                                                    PAM04990
    3 CALL SYMBOL(-6.0,12.5,0.49,13HSPACE DIAGRAM,0.0,13)                      PAM05000
C     DRAW AXES                                                                PAM05010
      CALL AXIS(-16.,0.0,10.,1,32.0,0.0,-32.0,2.0)                             PAM05020
      CALL AXIS(0.0,-8.0,10.,1,16.0,90.0,-16.0,2.0)                            PAM05030
C     PLOT THE DATA.                                                           PAM05040
      X(1999)=0.0                                                              PAM05050
      X(2000)=2.0                                                              PAM05060
      Y(2000)=0.0                                                              PAM05070
      Y(2000)=2.0                                                              PAM05080
      L=MI                                                                     PAM05090
        DO 4 I=1,1997                                                          PAM05100
      K=LSAMPL*I+L                                                             PAM05110
      IF (K.GT.LDIM) K=K-LDIM                                                  PAM05120
      Y(I)=(AIMAG(DATA(K))+AIMAG(DATA(K+1)))/2.                                PAM05130
      X(I)=(REAL(DATA(K))+REAL(DATA(K+1)))/2.                                  PAM05140
    4 CONTINUE                                                                 PAM05150
      X(1998)=X(1)                                                             PAM05160
      Y(1998)=Y(1)                                                             PAM05170
      CALL LINE (X,Y,1998,1,-1,11)                                             PAM05180
      IF(NR.EQ.NRUNS) CALL PLOT(0.0,0.0,999)                                   PAM05190
      WRITE(6,61)                                                              PAM05200
   61 FORMAT(5X,'---SPACE DIAGRAM IS REQUESTED ---')                           PAM05210
      RETURN                                                                   PAM05220
      END                                                                      PAM05230
C*****************************************************                       PAM05240
C     COMPUTATION OF MEAN POWER                                                PAM05250
C*****************************************************                       PAM05260
      SUBROUTINE POWER(DATA,MP,PF)                                             PAM05270
      COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,LSAMPL                                PAM05280
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                           PAM05290
      COMPLEX DATA(1)                                                          PAM05300
      REAL MP,PF,XX(65536),NP                                                  PAM05310
      MP=0.0                                                                   PAM05320
      PF=0.0                                                                   PAM05330
      DO 10 I=1,LDIM                                                           PAM05340
      MP=MP+((CABS(DATA(I)))**2.)                                              PAM05350
      IF(PF.LT.CABS(DATA(I))) PF=CABS(DATA(I))                                 PAM05360
   10 CONTINUE                                                                 PAM05370
      WRITE(6,11) PF                                                           PAM05380
   11 FORMAT(5X,'PEAK VALUE:',E5.2)                                            PAM05390
      NP=MP/FLOAT(LDIM)                                                        PAM05400
      PF=PF**2./NP                                                             PAM05410
      GO TO 15                                                                 PAM05420
   15 PF=10.*ALOG10(PF)                                                        PAM05430
      WRITE(6,20) PF,NP                                                        PAM05440
   20 FORMAT(5X,'PEAK FACTOR:',F8.4,' DB ',1X,'MEAN POWER:',E9.3,/)            PAM05450
      RETURN                                                                   PAM05460
      END                                                                      PAM05470
                                                                               PAM05480
C     ***************************************************************************PAM05490
                                                                               PAM05500
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FILE: PAM      FORTRAN  A1  UNIV D'/OF OTTAWA

C      THIS SUBROUTINE DECODES THE RECEIVED SIGNAL.                          PAM05510
C    ************************************************************************ PAM05520
       SUBROUTINE DECOD1(NERROR,DATA,PNOISE,MI,NI,EBNO,P,PE,ES,BAKOFF,       PAM05530
      &NR)                                                                   PAM05540
       COMPLEX*DATA(1),AMP                                                   PAM05550
       REAL P(1),PE(1)                                                       PAM05560
       INTEGER L,MI                                                          PAM05570
       DIMENSION EBNO(1),NI(1)                                               PAM05580
       COMMON /NUMB1/FBW,ALPHA,LDIM,IOFF,LSAMPL,CF                           PAM05590
       COMMON /NUMB2/NSNR,NSYMB,BAUD                                         PAM05600
       NERROR=0                                                              PAM05610
       DO 1 I=1,NSNR                                                         PAM05620
       P(I)=0.                                                               PAM05630
    1  PE(I)=0.                                                              PAM05640
       DO 2 K=1,NSYMB                                                        PAM05650
       J1=(K-1)*LSAMPL+MI                                                    PAM05660
       AXBAR=(REAL(DATA(J1))+REAL(DATA(J1+1)))/2.                            PAM05670
       SS=FLOAT(NI(K))*AXBAR                                                 PAM05680
       IF (SS.LT.0.) GO TO 153                                               PAM05690
       AMPX=ABS(AXBAR)                                                       PAM05700
       AMPI=ABS(FLOAT(NI(K)))                                                PAM05710
       DO 4 M=1,NSNR                                                         PAM05720
       VARIAN=PNOISE*ES*(10.**(-0.1*FLOAT(M)))                               PAM05730
       SIGMA=SQRT(VARIAN)                                                    PAM05740
C*******************************                                            PAM05750
       IF(AMPI.EQ.31.) GO TO 30                                              PAM05760
       IF(AMPI.EQ.0.0) GO TO 40                                              PAM05770
       IF(AMPI.EQ.1.0) GO TO 50                                              PAM05780
       THR1I=AMPI-WL                                                         PAM05790
       THR2I=AMPI+2.-WH                                                      PAM05800
       D1=ABS(AMPX-THR1I)                                                    PAM05810
       ARG=D1/(SIGMA*SQRT(2.))                                               PAM05820
       IF (ARG.GT.13.) ARG=13.                                               PAM05830
       PEI=ERFC(ARG)/2.                                                      PAM05840
       D2=ABS(THR2I-AMPX)                                                    PAM05850
       ARG=D2/(SIGMA*SQRT(2.))                                               PAM05860
       IF (ARG.GT.13.) ARG=13.                                               PAM05870
       PEI=PEI+ERFC(ARG)/2.                                                  PAM05880
       GO TO 100                                                             PAM05890
   30  THR1I=AMPI-WL                                                         PAM05900
       D1=ABS(AMPX-THR1I)                                                    PAM05910
       ARG=D1/(SIGMA*SQRT(2.))                                               PAM05920
       IF (ARG.GT.13.) ARG=13.                                               PAM05930
       PEI=ERFC(ARG)/2.                                                      PAM05940
       GO TO 100                                                             PAM05950
   40  THR1I=AMPI+2.0-WH                                                     PAM05960
       D1=ABS(AMPX-THR1I)                                                    PAM05970
       ARG=D1/(SIGMA*SQRT(2.))                                               PAM05980
       IF (ARG.GT.13.) ARG=13.                                               PAM05990
       PEI=ERFC(ARG)/2.                                                      PAM06000
       GO TO 100                                                             PAM06010
   50  D1=ABS(AMPX)                                                          PAM06020
       ARG=D1/(SIGMA*SQRT(2.))                                               PAM06030
       PEI=ERFC(ARG)/2.                                                      PAM06040
  100  IF (PEI.LT.1.E-15) PEI=0.0                                            PAM06050
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FILE: PAM      FORTRAN  A1  UNIV D'/OF OTTAWA

    4   PE(M)=PE(M)+PEI                                                  PAM06060
    2   CONTINUE                                                         PAM06070
        DO 6 I=1,NSNR                                                    PAM06080
    6   PE(I)=PE(I)/FLOAT(NSYMB)                                         PAM06090
        DO 7 I=1,NSNR                                                    PAM06100
        P(I)=PE(I)                                                       PAM06110
    7   CONTINUE                                                         PAM06120
  101   DO 8 I=1,NSNR                                                    PAM06130
    8   EBNO(I)=FLOAT(I)                                                 PAM06140
        PRINT 150                                                        PAM06150
  150   FORMAT(5X,'ES/NO',10X,'PROB. OF ERROR',/)                        PAM06160
        WRITE(6,151) (EBNO(I),P(I),I=1,NSNR)                             PAM06170
  151   FORMAT(5X,F5.2,10X,E15.6)                                        PAM06180
        GO TO 155                                                        PAM06190
  153   PRINT 154                                                        PAM06200
  154   FORMAT(10X,'SYMBOL WAS IN ERROR, RUN WAS TERMINATED',/)          PAM06210
  155   CONTINUE                                                         PAM06220
        RETURN                                                           PAM06230
        END                                                              PAM06240
                                                                         PAM06250
C ********************************************************             PAM06260
C     THIS SUBROUTINE SIMULATES THE LINEARIZED                           PAM06270
C     LM-380  CHARACTERISTIC.                                            PAM06280
C ********************************************************             PAM06290
        SUBROUTINE TWT1(DATA,BAKOFF,PSHIFT)                              PAM06300
        COMMON/NUMB1/FBW,ALPHA,LDIM,IOFF,LSAMPL                          PAM06310
        COMMON/NUMP2/NSNR,NSYMB,BAUD                                     PAM06320
        COMPLEX DATA(1)                                                  PAM06330
        REAL MP,R,Q,OI,ZP                                                PAM06340
        DATA A1,A2,A3/0.98102,3.80665,104.1995/                          PAM06350
        P(X)=A1*X+A2*X**3+A3*X**5                                        PAM06360
        MP=0.0                                                           PAM06370
        DO 15 K=1,LDIM                                                   PAM06380
        MP=MP+((CABS(DATA(K)))**2.)                                      PAM06390
   15   CONTINUE                                                         PAM06400
        MP=MP/LDIM                                                       PAM06410
        WRITE(6,20) MP,BAKOFF                                            PAM06420
   20   FORMAT(5X,'MEAN POWER:',F8.4,3X,'OPER.POINT:',F8.4,'V',/)        PAM06430
        FNORM=BAKOFF/SQRT(MP)                                            PAM06440
        DO 11 I=1,LDIM                                                   PAM06450
        DATA(I)=DATA(I)*FNORM                                            PAM06460
   11   CONTINUE                                                         PAM06470
        DO 10 I=1,LDIM                                                   PAM06480
        R=REAL(DATA(I))                                                  PAM06490
        Y=AIMAG(DATA(I))                                                 PAM06500
        S=ABS(R)                                                         PAM06510
        IF(S.LT.0.1) GO TO 35                                            PAM06520
        Q=7.462*(P(R)**2)                                                PAM06530
        OI=1.0+0.25*Q**2+0.015625*Q**4+0.000434*Q**6                     PAM06540
        ZP=3.590262*P(R)*EXP(-Q)*OI                                      PAM06550
        GO TO 45                                                         PAM06560
   35   ZP=3.311*R                                                       PAM06570
   45   DATA(I)=CMPLX(ZP,Y)                                              PAM06580
        DATA(I)=DATA(I)/FNORM/3.311                                      PAM06590
                                                                         PAM06600
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FILE: PAM      FORTRAN  A1  UNIV D'/OF OTTAWA

   10  CONTINUE                                                          PAM06610
       RETURN                                                            PAM06620
       END                                                               PAM06630
                                                                         PAM06640
                                                                         PAM06650
C   ***************************************************************     PAM06660
C     THIS SUBROUTINE SIMULATES THE COMPENSATION OF THE                 PAM06670
C     AM-AM(LM-380),AM-PM(HUNGES-261) NONLINEARITIES                    PAM06680
C   ***************************************************************     PAM06690
      SUBROUTINE TWT3(DATA,BAKOFF,PSHIFT)                               PAM06700
      COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,LSAMPL                         PAM06710
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                    PAM06720
      COMPLEX DATA(1)                                                   PAM06730
      REAL MP                                                           PAM06740
      DATA ZPMAX,ZQMAX,VMAX,V0/1.3,0.55,1.400,1.414/                    PAM06750
      DATA A1,A3,A5,A7,A9,A11,A13,A15,A17/1.463,-0.1424,0.65738,        PAM06760
     #-2.5463552,3.2320452,-1.9768057,0.5927067,-0.0695537,0.0/         PAM06770
      DATA B3,B5,B7,B9,B11,B13,B15,B17/1.1649265,                       PAM06780
     &0.053574,-4.4133043,7.7314234,-6.0660324,2.294553,-0.3385,0.0/    PAM06790
      ZP(X)=(((((((A17*X**2+A15)*X**2+A13)*X**2+A11)*X**2+A9)*          PAM06800
     #X**2+A7)*X**2+A5)*X**2+A3)*X**2+A1)*X                             PAM06810
      ZQ(X)=((((((B17*X**2+B15)*X**2+B13)*X**2+B11)*X**2+B9)*           PAM06820
     #X**2+B7)*X**2+B5)*X**2+B3)*X                                      PAM06830
      TWTIN=V0*10.**(-BAKOFF/20.)                                       PAM06840
      MP=0.0                                                            PAM06850
      DO 15 K=1,LDIM                                                    PAM06860
      MP=MP+((CABS(DATA(K)))**2.)                                       PAM06870
   15 CONTINUE                                                          PAM06880
      MP=MP/LDIM                                                        PAM06890
      WRITE(6,20) MP                                                    PAM06900
   20 FORMAT(5X,'MEAN POWER:',F8.4)                                     PAM06910
      FNORMI=TWTIN/SQRT(MP)                                             PAM06920
      WRITE (6,22) FNORMI                                               PAM06930
   22 FORMAT(5X,'FNORMI:',F8.4)                                         PAM06940
      DO 11 I=1,LDIM                                                    PAM06950
      DATA(I)=DATA(I)*FNORMI                                            PAM06960
   11 CONTINUE                                                          PAM06970
      DO 10 I=1,LDIM                                                    PAM06980
      R=REAL(DATA(I))                                                   PAM06990
      GP=1.024364*R-0.215228*R**3+0.287643*R**5                         PAM07000
      GQ=-0.52577*R**3+0.151374*R**5-0.038831*R**7                      PAM07010
      B=SQRT(GP**2+GQ**2)                                               PAM07020
      IF(B.GT.1.414)GO TO 12                                            PAM07030
      ZZ=SQRT((ZP(B)**2)+(ZQ(B)**2))                                    PAM07040
      IF(R.LT.0.0) ZZ=-ZZ                                               PAM07050
      PPP=ATAN(GQ/GP)+ATAN(ZQ(B)/ZP(B))                                 PAM07060
      DATA(I)=CMPLX(ZZ*COS(PPP),ZZ*SIN(PPP))                            PAM07070
      GO TO 10                                                          PAM07080
   12 ZZ=SQRT(1.3**2+0.55**2)                                           PAM07090
      IF(R.LT.0.0) ZZ=-ZZ                                               PAM07100
      PPP=ATAN(GQ/GP)+ATAN(0.55/1.3)                                    PAM07110
      DATA(I)=CMPLX(ZZ*COS(PPP),ZZ*SIN(PPP))                            PAM07120
   10 CONTINUE                                                          PAM07130
      WRITE (6,2) BAKOFF,PSHIFT,TWTIN                                   PAM07140
    2 FORMAT(5X,'TWTA INPUT BACKOFF:',F4.1,' DB',                       PAM07150
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     #'   OUTPUT PHASE SHIFT:',F9.4,1X,'TWTIN:',F5.3,/)                    PAM07160
      DO 16 I=1,LDIM                                                       PAM07170
      DATA(I)=DATA(I)/FNORM1/A1                                            PAM07180
   16 CONTINUE                                                             PAM07190
      RETURN                                                               PAM07200
      END                                                                  PAM07210
C                                                                          PAM07220
C ***********************************************************************  PAM07230
C      THIS SUBROUTINE SIMULATES THE AM-AM COMPENSATION OF THE             PAM07240
C      AM-AM(LM-380),AM-PM(HUNGES-261) CHARACTERISTICS.                    PAM07250
C ***********************************************************************  PAM07260
      SUBROUTINE TWTA(DATA,BAKOFF,PSHIFT)                                  PAM07270
      COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,LSAMPL                            PAM07280
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                       PAM07290
      COMPLEX DATA(1)                                                      PAM07300
      REAL MP                                                              PAM07310
      DATA ZPMAX,ZQMAX,VMAX,VO/1.3,0.55,1.414,1.414/                       PAM07320
      DATA A1,A3,A5,A7,A9,A11,A13,A15,A17/1.463,-0.1428,0.65738,           PAM07330
     #-2.5463552,3.2320452,-1.9768057,0.5927067,-0.0695537,0.0/            PAM07340
      DATA B3,B5,B7,B9,B11,B13,B15,B17/1.1649265,                          PAM07350
     &0.053574,-4.4133043,7.7314234,-6.0660324,2.294553,-0.3385,0.0/       PAM07360
      ZP(X)=((((((((A17*X**2+A15)*X**2+A13)*X**2+A11)*X**2+A9)*            PAM07370
     #X**2+A7)*X**2+A5)*X**2+A3)*X**2+A1)*X                                PAM07380
      ZQ(X)=((((((B17*X**2+B15)*X**2+B13)*X**2+B11)*X**2+B9)*              PAM07390
     #X**2+B7)*X**2+B5)*X**2+B3)*X                                         PAM07400
      TWTIN=VO*10.**(-BAKOFF/20.)                                          PAM07410
      MP=0.0                                                               PAM07420
      DO 15 K=1,LDIM                                                       PAM07430
      MP=MP+((CABS(DATA(K)))**2.)                                          PAM07440
   15 CONTINUE                                                             PAM07450
      MP=MP/LDIM                                                           PAM07460
      WRITE(6,20) MP                                                       PAM07470
   20 FORMAT(5X,'MEAN POWER:',F8.4)                                        PAM07480
      FNORM1=TWTIN/SQRT(MP)                                                PAM07490
      WRITE (6,22) FNORM1                                                  PAM07500
   22 FORMAT(5X,'FNORM1:',F8.4)                                            PAM07510
      DO 11 I=1,LDIM                                                       PAM07520
      DATA(I)=DATA(I)*FNORM1                                               PAM07530
   11 CONTINUE                                                             PAM07540
      DO 10 I=1,LDIM                                                       PAM07550
      R=REAL(DATA(I))                                                      PAM07560
      GP=0.693974*R-0.0659*R**3+0.00755*R**5                               PAM07570
      GQ=0.0                                                               PAM07580
      B=SQRT(GP**2+GQ**2)                                                  PAM07590
      IF(B.GT.1.414)GO TO 12                                               PAM07600
      ZZ=SQRT((ZP(B)**2)+(ZQ(B)**2))                                       PAM07610
      IF(R.LT.0.0) ZZ=-ZZ                                                  PAM07620
      PPP=ATAN(GQ/GP)+ATAN(ZQ(B)/ZP(B))                                    PAM07630
      DATA(I)=CMPLX(ZZ*COS(PPP),ZZ*SIN(PPP))                               PAM07640
      GO TO 10                                                             PAM07650
   12 ZZ=SQRT(1.3**2+0.55**2)                                              PAM07660
      IF(R.LT.0.0) ZZ=-ZZ                                                  PAM07670
      PPP=ATAN(GQ/GP)+ATAN(0.55/1.3)                                       PAM07680
      DATA(I)=CMPLX(ZZ*COS(PPP),ZZ*SIN(PPP))                               PAM07690
                                                                           PAM07700
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   10  CONTINUE                                                          PAM07710
       WRITE (6,2) BAKOFF,PSHIFT,TWTIN                                   PAM07720
    2  FORMAT(5X,'TWTA INPUT BACKOFF:',F4.1,' DB',                       PAM07730
      #'   OUTPUT PHASE SHIFT:',F9.4,1X,'TWTIN:',F5.3,/)                 PAM07740
       DO 16 I=1,LDIM                                                    PAM07750
       DATA(I)=DATA(I)/FNORMI                                            PAM07760
    16 CONTINUE                                                          PAM07770
       RETURN                                                            PAM07780
       END                                                               PAM07790
                                                                         PAM07800
                                                                         PAM07810
C ***********************************************************           PAM07820
C   THIS SUBROUTINE SIMULATES THE CHARACTERISTICS OF THE                 PAM07830
C   AM-AM (LM-380), AM-PM (HUNGES-261) OR THE                            PAM07840
C   AM-AM (LM-380), AM-PM (INTELSAT-V) NONLINEARITIES                    PAM07850
C***********************************************************           PAM07860
      SUBROUTINE TWT5(DATA,BAKOFF,PSHIFT)                                PAM07870
      COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,LSAMPL                          PAM07880
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                     PAM07890
      COMPLEX DATA(1)                                                    PAM07900
      REAL MP,C(80),D(80),G(80),E(80)                                    PAM07910
      DATA ZPMAX,ZQMAX,VMAX,VO/1.300,0.550,1.400,1.414/                  PAM07920
      DATA A1,A3,A5,A7,A9,A11,A13,A15,A17/1.463,-0.1424,0.65738,         PAM07930
     #-2.5463552,3.2320452,-1.9768057,0.5927067,-0.0695537,0.0/          PAM07940
      DATA B3,B5,B7,B9,B11,B13,B15,B17/1.1649265,                        PAM07950
     &0.053574,-4.4133043,7.7314234,-6.0660324,2.294553,-0.3385,0.0/     PAM07960
C     DATA A1,A3,A5,A7,A9,A11,A13,A15,A17/1.461936,-0.0975490,0.413473,  PAM07970
C    &-2.333527,2.9813547,-1.7313,0.4804,-0.0510523,0.0/                 PAM07980
C     DATA B3,B5,B7,B9,B11,B13,B15/0.1769764,6.0393476,-16.5881,20.556,  PAM07990
C    &-13.41762,4.4521,-0.591,0.0/                                       PAM08000
      P(X)=((((((A17*X**2+A15)*X**2+A13)*X**2+A11)*X**2+A9)*             PAM08010
     #X**2+A7)*X**2+A5)*X**2+A3)*X**2+A1                                 PAM08020
      ZP(X)=P(X)*X                                                       PAM08030
      Q(X)=((((((B17*X**2+B15)*X**2+B13)*X**2+B11)*X**2+B9)*             PAM08040
     #X**2+B7)*X**2+B5)*X**2+B3                                          PAM08050
      ZQ(X)=Q(X)*X                                                       PAM08060
      Z(X)=SQRT(ZP(X)**2+ZQ(X)**2)                                       PAM08070
      TWTIN=VO*10.**(-BAKOFF/20.)                                        PAM08080
      PPP=ZQ(TWTIN)/ZP(TWTIN)                                            PAM08090
      PSHIFT=ATAN(PPP)                                                   PAM08100
      WRITE (6,2) BAKOFF,PSHIFT,TWTIN                                    PAM08110
    2 FORMAT(5X,'TWTA INPUT BACKOFF:',F4.1,' DB',                        PAM08120
     #'   OUTPUT PHASE SHIFT:',F9.4,1X,'TWTIN:',F5.3,/)                 PAM08130
      MP=0.0                                                             PAM08140
      DO 15 K=1,LDIM                                                     PAM08150
      MP=MP+((CABS(DATA(K)))**2.)                                        PAM08160
   15 CONTINUE                                                           PAM08170
      MP=MP/LDIM                                                         PAM08180
      WRITE(6,20) MP                                                     PAM08190
   20 FORMAT(5X,'MEAN POWER:',F8.4)                                      PAM08200
      FNORMI=TWTIN/SQRT(MP)                                              PAM08210
      WRITE (6,22) FNORMI                                                PAM08220
   22 FORMAT(5X,'FNORMI:',F8.4)                                          PAM08230
      DO 11 I=1,LDIM                                                     PAM08240
      DATA(I)=DATA(I)*FNORMI                                             PAM08250
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  11  CONTINUE                                                          PAM08260
C     DO 31 M=1,80                                                      PAM08270
C     D(M)=REAL(DATA(M))                                                PAM08280
C 31  CONTINUE                                                          PAM08290
      DO 10 I=1,LDIM                                                    PAM08300
      X=REAL(DATA(I))                                                   PAM08310
      Y=0.0                                                             PAM08320
C     Y=AIMAG(DATA(I))                                                  PAM08330
      R=SQRT(X**2+Y**2)                                                 PAM08340
      IF(R.GT.VMAX) GOTO 12                                             PAM08350
      DATA(I)=CMPLX(P(R)*X-Q(R)*Y,P(R)*Y+Q(R)*X)                        PAM08360
      GO TO 10                                                          PAM08370
  12  DATA(I)=CMPLX(ZPMAX*X-ZQMAX*Y,ZQMAX*X+ZPMAX*Y)/R                  PAM08380
  10  CONTINUE                                                          PAM08390
C     DO 32 K=1,80                                                      PAM08400
C     G(K)=REAL(DATA(K))                                                PAM08410
C 32  CONTINUE                                                          PAM08420
      DO 16 I=1,LDIM                                                    PAM08430
      DATA(I)=DATA(I)/FNORMI/A1                                         PAM08440
   16 CONTINUE                                                          PAM08450
      RETURN                                                            PAM08460
      END                                                               PAM08470
                                                                        PAM08480
                                                                        PAM08490
C ***************************************************************       PAM08500
C   THIS SUBROUTINE SIMULATE THE EQUIVALENT BASEBAND CHARACTERISTIC     PAM08510
C   OF THE AM-PM (HUNGES-261)  NONLINEARITY                             PAM08520
C***************************************************************       PAM08530
      SUBROUTINE TWT2(DATA,BAKOFF,PSHIFT)                               PAM08540
      COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,LSAMPL                         PAM08550
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                    PAM08560
      COMPLEX EPS,DATA(1)                                               PAM08570
      REAL MP                                                           PAM08580
      DATA A2,A4,A6,A8,A10,A12,A14,A16/1.032361,-1.202852,0.164144,     PAM08590
     #1.191,-1.267618,0.503055,-0.59495;-0.0048490/                     PAM08600
      P(X)=((((((A16*X**2+A14)*X**2+A12)*X**2+A10)*X**2+A8)*            PAM08610
     #X**2+A6)*X**2+A4)*X**2+A2                                         PAM08620
      TWTIN=V0*10.**(-BAKOFF/20.)                                       PAM08630
      WRITE (6,2) BAKOFF,TWTIN                                          PAM08640
    2 FORMAT(5X,'TWTA INPUT BACKOFF:',F4.1,' DB',                       PAM08650
     #1X,'TWTIN:',F5.3,/)                                               PAM08660
      MP=0.0                                                            PAM08670
      DO 15 K=1,LDIM                                                    PAM08680
      MP=MP+((CABS(DATA(K)))**2.)                                       PAM08690
   15 CONTINUE                                                          PAM08700
      MP=MP/LDIM                                                        PAM08710
      WRITE(6,20) MP                                                    PAM08720
   20 FORMAT(5X,'MEAN POWER:',F8.4)                                     PAM08730
      FNORMI=TWTIN/SQRT(MP)                                             PAM08740
      WRITE (6,22) FNORMI                                               PAM08750
   22 FORMAT(5X,'FNORMI:',F8.4)                                         PAM08760
      DO 11 I=1,LDIM                                                    PAM08770
      DATA(I)=DATA(I)*FNORMI                                            PAM08780
   11 CONTINUE                                                          PAM08790
      DO 10 I=1,LDIM                                                    PAM08800
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      EPS=CMPLX(COS(P(X)),-SIN(P(X)))                                   PAM08810
      DATA(I)=DATA(I)*EPS                                               PAM08820
   10 CONTINUE                                                          PAM08830
      DO 16 I=1,LDIM                                                    PAM08840
      DATA(I)=DATA(I)/ENORM1                                            PAM08850
   16 CONTINUE                                                          PAM08860
      RETURN                                                            PAM08870
      END                                                               PAM08880
                                                                        PAM08890
                                                                        PAM08900
C ***************************************************************     PAM08910
C     THE FOLLOWING SUBROUTINE SYNCHRONIZES THE RECEIVED DATA.          PAM08920
C***************************************************************      PAM08930
C                                                                       PAM08940
      SUBROUTINE SYNCRO(DATA,PNOISE,NI,NQ,MI,MQ,EB,LMAX)                PAM08950
      INTEGER Q7FLAG                                                    PAM08960
      COMPLEX DATA(1),AMP                                               PAM08970
      DIMENSION NI(1),NQ(1)                                             PAM08980
      COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,LSAMPL                         PAM08990
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                    PAM09000
      NERROR=0                                                          PAM09010
      AMAX=0.0                                                          PAM09020
      S=FLOAT(LSAMPL)/2.                                                PAM09030
      DO 1 J=1,NSYMB                                                    PAM09040
      J1=(J-1)*LSAMPL+S                                                 PAM09050
      XX1=(REAL(DATA(J1))+REAL(DATA(J1+1)))/2.                          PAM09060
      XX1=ABS(XX1)                                                      PAM09070
      IF(AMAX.LT.XX1) AMAX=XX1                                          PAM09080
    1 CONTINUE                                                          PAM09090
      YY=AMAX/FLOAT(LMAX)                                               PAM09100
      IF (IOFF.EQ.0) GO TO 111                                          PAM09110
      DO 6 K=1,IOFF                                                     PAM09120
      XX=AIMAG(DATA(LDIM))                                              PAM09130
      LL=LDIM-1                                                         PAM09140
      DO 7 KK=1,LL                                                      PAM09150
      LDKK=LDIM+1-KK                                                    PAM09160
    7 DATA(LDKK)=CMPLX(REAL(DATA(LDKK)),AIMAG(DATA(LDKK-1)))            PAM09170
    6 DATA(1)=CMPLX(REAL(DATA(1)),XX)                                   PAM09180
C                                                                       PAM09190
C     SYNCHRONIZE THE RECEIVED DATA                                     PAM09200
C                                                                       PAM09210
  111 NOLD=0                                                            PAM09220
      NOF=0                                                             PAM09230
      K=1                                                               PAM09240
  300 CONTINUE                                                          PAM09250
      NEW=0                                                             PAM09260
      DO 200 J=1,NSYMB                                                  PAM09270
      J1=K+(J-1)*LSAMPL                                                 PAM09280
      IF(J1.GT.LDIM) J1=J1-LDIM                                         PAM09290
      AXBAR=(REAL(DATA(J1))+REAL(DATA(J1+1)))/2.                        PAM09300
      AYBAR=(AIMAG(DATA(J1))+AIMAG(DATA(J1+1)))/2.                      PAM09310
      SS=AXBAR*NI(J)                                                    PAM09320
      IF (SS .GT. 0.) NEW=NEW+1                                         PAM09330
      SS=AYBAR*NQ(J)                                                    PAM09340
      IF (SS .GT. 0.) NEW=NEW+1                                         PAM09350
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  200  CONTINUE                                                          PAM09360
       IF(NOLD.GE.NEW) GO TO 399                                         PAM09370
       NOLD=NEW                                                          PAM09380
       NOF=K                                                             PAM09390
  399  K=K+1                                                             PAM09400
       LEU=2*NSYMB                                                       PAM09410
C                                                                        PAM09420
C      SHIFT RECEIVED DATA LEFT UNTIL ALL SYMBOLS ARE LINED UP           PAM09430
C                                                                        PAM09440
C======================================================================  PAM09450
       NSFT=LSAMPL*3                                                     PAM09460
       IF (NOLD.LT.LEU.AND.K.LE.NSFT) GO TO 300                          PAM09470
       NOF=NOF-1                                                         PAM09480
       WRITE(6,56) NOLD,K                                                PAM09490
    56 FORMAT(1X,'NO OF CORRECT SYMBOLS = ',I6,1X,'NO OF                 PAM09500
      *SHIFT = ',I6,/)                                                   PAM09510
       IF (NOF.EQ.0) GO TO 230                                           PAM09520
       LO=LDIM-1                                                         PAM09530
       DO 250 I=1,NOF                                                    PAM09540
       AMP=DATA(1)                                                       PAM09550
       DO 240 J=1,LO                                                     PAM09560
       DATA(J)=DATA(J+1)                                                 PAM09570
  240  CONTINUE                                                          PAM09580
       DATA(LDIM)=AMP                                                    PAM09590
  250  CONTINUE                                                          PAM09600
C                                                                        PAM09610
C       OPTIMIZE THE SAMPLING INSTANT                                    PAM09620
C                                                                        PAM09630
  230 MI=1                                                               PAM09640
       MQ=1                                                              PAM09650
       EOI=FLOAT(NSYMB) + 1.                                             PAM09660
       EOQ=FLOAT(NSYMB) + 1.                                             PAM09670
       M=22                                                              PAM09680
       VARIAN=PNOISE*EB*(10.**(-0.1*FLOAT(M)))                          PAM09690
       SIGMA=SQRT(VARIAN)                                                PAM09700
       DO 80 J=1,LSAMPL                                                  PAM09710
       EI=0.                                                             PAM09720
       EQ=0.                                                             PAM09730
       DO 70 K=1,NSYMB                                                   PAM09740
C      VERIFY THAT NO SAMPLED SYMBOL IS IN ERROR                         PAM09750
       J1=(K-1)*LSAMPL+J                                                 PAM09760
       AXBAR=(REAL(DATA(J1))+REAL(DATA(J1+1)))/2.                        PAM09770
       AXBAR=(AIMAG(DATA(J1))+AIMAG(DATA(J1+1)))/2.                      PAM09780
       INDEXI=0                                                          PAM09790
       SS=FLOAT(NI(K))*AXBAR                                             PAM09800
       IF (SS .LT. 0.) INDEXI=1                                          PAM09810
       AMPX=ABS(AXBAR)                                                   PAM09820
       AMPI=ABS(FLOAT(NI(K)))                                            PAM09830
       THR1I=AMPI - 1.0                                                  PAM09840
       THR2I=AMPI + 1.0                                                  PAM09850
       THR1I=THR1I*YY                                                    PAM09860
       THR2I=THR2I*YY                                                    PAM09870
       IFLAG=0                                                           PAM09880
       IF (AMPI.EQ.31.) GO TO 30                                         PAM09890
       IF ((AMPX.GE.THR2I).OR.(AMPX.LE.THR1I)) INDEXI=1                  PAM09900
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      GO TO 40                                                          PAM09910
   30 IF(AMPX.LE.THR1I) INDEXI=1                                        PAM09920
      I7FLAG=1                                                          PAM09930
   40 CONTINUE                                                          PAM09940
      INDEXQ=0                                                          PAM09950
      SS=FLOAT(NQ(K))*AYBAR                                             PAM09960
      IF(SS .LT. 0.) INDEXQ=1                                           PAM09970
      AMPY=ABS(AYBAR)                                                   PAM09980
      AMPQ=ABS(FLOAT(NQ(K)))                                            PAM09990
      THR1Q=AMPQ - 1.0                                                  PAM10000
      THR2Q=AMPQ + 1.0                                                  PAM10010
      THR1Q=THR1Q*YY                                                    PAM10020
      THR2Q=THR2Q*YY                                                    PAM10030
      Q7FLAG=0                                                          PAM10040
      IF (AMPQ.EQ. 3.) GO TO 50                                         PAM10050
      IF (( AMPY.GE.THR2Q).OR.(AMPY.LE.THR1Q)) INDEXQ=1                 PAM10060
      GO TO 60                                                          PAM10070
   50 IF(AMPY.LE.THR1Q) INDEXQ=1                                        PAM10080
      Q7FLAG=1                                                          PAM10090
   60 CONTINUE                                                          PAM10100
      IF(INDEXI.EQ.1) EI=EI + 1.                                        PAM10110
      IF(INDEXQ.EQ.1) EQ= EQ + 1.                                       PAM10120
C                                                                       PAM10130
C     COMPUTE THE PROBABILITY OF ERROR FOR THIS SYMBOL AT EB/NO=22dB.   PAM10140
C                                                                       PAM10150
      D1=ABS(AMPX-THR1I)                                                PAM10160
      ARG=D1/(SIGMA*SQRT(2.))                                           PAM10170
C     CHECK IF ARG IS LARGE IN WHICH CASE PE IS INSIGNIFICANT           PAM10180
C                                                                       PAM10190
      IF (ARG.GT.12.) ARG=12.                                           PAM10200
      EI=EI + ERFC(ARG)/2.                                              PAM10210
      IF (I7FLAG .EQ. 1) GO TO 65                                       PAM10220
      D2=ABS(THR2I-AMPX)                                                PAM10230
      ARG=D2/(SIGMA*SQRT(2.))                                           PAM10240
      IF (ARG.GT.12.) ARG=12.                                           PAM10250
      EI=EI + ERFC(ARG)/2.                                              PAM10260
   65 D1=ABS(AMPY-THR1Q)                                                PAM10270
      ARG=D1/(SIGMA*SQRT(2.))                                           PAM10280
      IF (ARG.GT.12.) ARG=12.                                           PAM10290
      EQ=EQ + ERFC(ARG)/2.                                              PAM10300
      IF (Q7FLAG .EQ. 1) GO TO 70                                       PAM10310
      D2=ABS(THR2Q-AMPY)                                                PAM10320
      ARG=D2/(SIGMA*SQRT(2.))                                           PAM10330
      IF (ARG.GT.12.) ARG=12.                                           PAM10340
      EQ=EQ + ERFC(ARG)/2.                                              PAM10350
   70 CONTINUE                                                          PAM10360
      IF(EOI.LE.EI) GO TO 75                                            PAM10370
      EOI=EI                                                            PAM10380
      MI=J                                                              PAM10390
   75 CONTINUE                                                          PAM10400
      IF (EOQ.LE.EQ) GO TO 80                                           PAM10410
      EOQ=EQ                                                            PAM10420
      MQ=J                                                              PAM10430
   80 MOFF=IABS(MI-MQ)                                                  PAM10440
      IF(MOFF.NE.0) WRITE(6,90) MOFF                                    PAM10450
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      OFF=(FLOAT(MI) + FLOAT(NOF))/FLOAT(LSAMPL)                        PAM10460
   90 FORMAT(5X,'SAMPLING POINTS FOR I AND Q CHANNELS DIFFER BY',       PAM10470
     #I2,'  SIXTEENTHS OF THE SYMBOL INTERVAL',/)                       PAM10480
      WRITE(6,95) OFF                                                   PAM10490
   95 FORMAT(5X,'RECEIVED DATA IS DELAYED BY ',F7.3,' SYMBOLS',/)       PAM10500
      RETURN                                                            PAM10510
      END                                                               PAM10520
                                                                        PAM10530
C*****************************************************************     PAM10540
C     THE FOLLOWING SUBROUTINE DECODES THE RECEIVED DATA                PAM10550
C     BY ADJUSTING THE CONVENTIONAL DECODING THRESHOLDS.                PAM10560
C*****************************************************************     PAM10570
C                                                                       PAM10580
      SUBROUTINE DETECT(NERROR,DATA,PNOISE,MI,MQ,NI,NQ,EBNO,PE,FB,LMAX) PAM10590
      COMPLEX DATA(1),AMP                                               PAM10600
      INTEGER JJ                                                        PAM10610
      DIMENSION EBNO(1),PE(1),NI(1),NQ(1)                               PAM10620
      DIMENSION REG(31,2),THRI(31),THRQ(31),ISLICE(31),AA(31),BB(31)    PAM10630
      COMMON /NUMB1/ FBW,ALPHA,IDIM,IOFF,LSAMPL                         PAM10640
      COMMON /NUMB2/ NSNR,NSYMB,BAUD                                    PAM10650
      NERROR=0                                                          PAM10660
      DO 1 I=1,NSNR                                                     PAM10670
    1 PE(I)=0.                                                          PAM10680
C     OBTAIN THE OPTIMUM THRESHOLDS                                     PAM10690
      AMAX1=0.0                                                         PAM10700
      AMAX2=0.0                                                         PAM10710
C   NUMBER OF POSITIVE THRESHOLDS IS NI (FOR LMAX=1)                    PAM10720
      NI=(LMAX-1)/2                                                     PAM10730
      DO 7 J=1,NSYMB                                                    PAM10740
      J1=(J-1)*LSAMPL+MI                                                PAM10750
      XX1=(REAL(DATA(J1))+REAL(DATA(J1+1)))/2.                          PAM10760
      XX1=ABS(XX1)                                                      PAM10770
      IF(AMAX1.LT.XX1) AMAX1=XX1                                        PAM10780
      XX2=(AMAX1-1)/NI                                                  PAM10790
    7 CONTINUE                                                          PAM10800
      WRITE(6,555) XX2                                                  PAM10810
  555   FORMAT(5X,'XX2=',F6.3)                                          PAM10820
        CC=XX2                                                          PAM10830
C  FIX CRUDE THRESHOLDS INTIALLY                                        PAM10840
      DO 10 K=1,LMAX,2                                                  PAM10850
      THRI(K)=(FLOAT(K-1)/2.)*XX2                                       PAM10860
   10 CONTINUE                                                          PAM10870
C   NOW REFINE THE THRESHOLDS                                           PAM10880
      REG(1,1)=1.01                                                     PAM10890
      REG(1,2)=0.99                                                     PAM10900
      DO 21 J=3,LMAX,2                                                  PAM10910
      REG(J,1)=REG(1,1)+(FLOAT(J-1))*AMAX1/FLOAT(LMAX)                  PAM10920
      REG(J,2)=REG(1,2)+(FLOAT(J-1))*AMAX1/FLOAT(LMAX)                  PAM10930
   21 CONTINUE                                                          PAM10940
      DO 2 K=1,NSYMB                                                    PAM10950
      J1=(K-1)*LSAMPL+MI                                                PAM10960
      XX1=(REAL(DATA(J1))+REAL(DATA(J1+1)))/2.                          PAM10970
      INDEX1=0                                                          PAM10980
      SS=FLOAT(NI(K))*XX1                                               PAM10990
                                                                        PAM11000
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      IF(SS.LT.0.) INDEX1=1                                              PAM11010
      XX1=ABS(XX1)                                                       PAM11020
       DO 11 J=1,LMAX,2                                                  PAM11030
      IF((XX1.GT.THRI(J)).AND.(XX1.LE.(THRI(J)+XX2))) GO TO 15           PAM11040
   11 CONTINUE                                                           PAM11050
   15  IF ((REG(J,1).GT.XX1).AND.(REG(J,2).GT.XX1)) REG(J,2)=XX1         PAM11060
       IF ((REG(J,1).LE.XX1).AND.(REG(J,2).LE.XX1)) REG(J,1)=XX1         PAM11070
       IF(J.EQ.1) GO TO 100                                              PAM11080
       THRI(J)=(REG((J-2),1)+REG(J,2))/2.                                PAM11090
        GO TO 63                                                         PAM11100
  100   THRI(1)=0.                                                       PAM11110
   63   CONTINUE                                                         PAM11120
       IF (INDEX1.EQ.1.) NERROR=NERROR+1                                 PAM11130
 2      CONTINUE                                                         PAM11140
       IF (NERROR.GT.1) GO TO 400                                        PAM11150
       WRITE(6,3) (THRI(I),I=1,31,2)                                     PAM11160
 3     FORMAT(5X,'THRI=',F6.3)                                           PAM11170
C                                                                        PAM11180
C     COMPUTE THE PROBABILITY OF ERROR FOR EACH SYMBOL.                  PAM11190
C     THE VARIABLES ARE AS FOLLOWS: M IS EB/NO IN dB; PNOISE IS          PAM11200
C     1/2*INTEGRAL (  H(F)**2  DF); AND VARIAN = NO*PNOISE.              PAM11210
C     FOR THE END POINTS THE PE=1/2*ERFC(D1/(SIGMA*SQRT(2)))             PAM11220
C     AND FOR THE INNER POINTS THE PE=1/2*ERFC(D1/(SIGMA*SQRT(2))) +     PAM11230
C     1/2*ERFC(D2/(SIGMA*SQRT(2))).                                      PAM11240
C                                                                        PAM11250
      DO 202 K=1,NSYMB                                                   PAM11260
      J1=(K-1)*LSAMPL+M1                                                 PAM11270
      XX1=(REAL(DATA(J1))+REAL(DATA(J1+1)))/2.                           PAM11280
      XX1=ABS(XX1)                                                       PAM11290
       DO 22 J=1,LMAX,2                                                  PAM11300
      IF((XX1.GT.THRI(J)).AND.(XX1.LE.(THRI(J)+CC)))  GO TO 34           PAM11310
   22 CONTINUE                                                           PAM11320
   34 AA(J)=THRI(J)                                                      PAM11330
      DO 4 M=1,NSNR                                                      PAM11340
      VARIAN=PNOISE*EB*(10.**(-0.1*FLOAT(M)))                            PAM11350
      SIGMA=SQRT(VARIAN)                                                 PAM11360
      D1=ABS(XX1-AA(J))                                                  PAM11370
      ARG=D1/(SIGMA*SQRT(2.))                                            PAM11380
C     CHECK IF ARG IS LARGE IN WHICH CASE PE IS INSIGNIFICANT            PAM11390
C                                                                        PAM11400
      IF (ARG.GT.12.) ARG=12.                                            PAM11410
      PE1=ERFC(ARG)/2.                                                   PAM11420
      IF (J.EQ.LMAX)  GO TO 54                                           PAM11430
      D2=ABS(AA(J+2)-XX1)                                                PAM11440
      ARG=D2/(SIGMA*SQRT(2.))                                            PAM11450
      IF (ARG.GT.12.) ARG=12.                                            PAM11460
      PE1=PE1 + ERFC(ARG)/2.                                             PAM11470
   54 IF(PE1.LT.1.E-15) PE1=0.                                           PAM11480
    4 PE(M)=PE(M)+PE1                                                    PAM11490
  202 CONTINUE                                                           PAM11500
      DO 5 I=1,NSNR                                                      PAM11510
      PE(I)=PE(I)/FLOAT(NSYMB)                                           PAM11520
    5 EBNO(I)=FLOAT(I)                                                   PAM11530
      GO TO 220                                                          PAM11540
  400 WRITE(6,420) NERROR                                                PAM11550
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 420   FORMAT(5X,'ERRORS=',I5)                                          PAM11560
       PRINT 440                                                        PAM11570
 440   FORMAT(5X,'SYMBOL WAS IN ERROR, RUN WAS TERMINATED',/)           PAM11580
 220   CONTINUE                                                         PAM11590
       PRINT 150                                                        PAM11600
 150   FORMAT(5X,'ES/NO',10X,'PROB. OF ERROR',/)                        PAM11610
       WRITE(6,151) (EBNO(I),PE(I),I=1,NSNR)                            PAM11620
 151   FORMAT(5X,F5.2,10X,E15.6)                                        PAM11630
       RETURN                                                           PAM11640
       END                                                              PAM11650
C*****************************************************************    PAM11660
C     THIS SUBROUTINE SIMULATES THE PHASE OF THE                       PAM11670
C     LM-380 AMPLIFLER                                                 PAM11680
C*****************************************************************    PAM11690
       SUBROUTINE AMPH(TF)                                              PAM11700
       COMPLEX TF(1)                                                    PAM11710
       COMMON /NUMB1/ FBW,ALPHA,LDIM,IOFF,LSAMPL                        PAM11720
       COMMON /NUMB2/ NSNR,NSYMB,BAUD                                   PAM11730
       SBANDW=BAUD*LSAMPL                                               PAM11740
       NO=LDIM/2                                                        PAM11750
       NO1=NO+1                                                         PAM11760
       FN=LDIM*(FBW/SBANDW)                                             PAM11770
       F1=0.7*FN                                                        PAM11780
       IF1=IFIX(F1)+1                                                   PAM11790
       DO 8 I=2,IF1                                                     PAM11800
       TF(1)=CMPLX(1.0,0.0)                                             PAM11810
       TF(I)=CMPLX(1.,0.0)                                              PAM11820
     8 CONTINUE                                                         PAM11830
       JK=IF1+1                                                         PAM11840
       DO 9 J=JK,NO1                                                    PAM11850
       PHI=-0.8167+0.00114*J                                            PAM11860
       TF(J)=CMPLX(COS(PHI),SIN(PHI))                                   PAM11870
     9 CONTINUE                                                         PAM11880
       NO2=NO1+1                                                        PAM11890
       DO 5 I=NO2,LDIM                                                  PAM11900
       TF(I)=CONJG(TF(LDIM+2-I))                                        PAM11910
     5 CONTINUE                                                         PAM11920
       RETURN                                                           PAM11930
       END                                                              PAM11940
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C*************************************************************************      FIT00010
C     THIS PROGRAM IS USED TO SOLVE A MATRIX EQUATION.                         FIT00020
C     USED FOR FINDING  THE COEFFICIENTS OF AM/AM                              FIT00030
C     OR AM-PM CHARACTERISTICS                                                 FIT00040
C*************************************************************************      FIT00050
      INTEGER IJOB,N,IA,IER                                                    FIT00060
      N 6                                                                      FIT00070
      REAL  C(6,6),D1,D2,WKAREA(12),B(6),A(6)                                  FIT00080
      DATA A(1),A(2),A(3),A(4),A(5),A(6)/                                      FIT00090
     &0.16,0.17,0.18,0.19,0.195,0.205/                                         FIT00100
      DO 55 J=1,N                                                              FIT00110
      DO 56 I=1,N                                                              FIT00120
      L=(2*J)-1                                                                FIT00130
  56  C(L,J)=(A(I))**L                                                         FIT00140
  55  CONTINUE                                                                 FIT00150
      DATA B(1),B(2),B(3),B(4),B(5),B(6)/                                      FIT00160
     &0.52976,0.555,0.575,0.59,0.595,0.6025/                                   FIT00170
      IA=6                                                                     FIT00180
      IJOB=3                                                                   FIT00190
      D1=-1.0                                                                  FIT00200
       CALL LINV3F (C,B,IJOB,N,IA,D1,D2,WKAREA,IER)                            FIT00210
      WRITE(6,20) B                                                            FIT00220
  20  FORMAT(5X,F18.7)                                                         FIT00230
      WRITE(6,30) IER                                                          FIT00240
  30  FORMAT(5X,I4)                                                            FIT00250
      X=0.0                                                                    FIT00260
      DO 44 I=1,35                                                             FIT00270
      X=X+0.01                                                                 FIT00280
      F=B(1)*X+B(2)*X**3+B(3)*X**5+B(4)*X**7+B(5)*X**9+B(6)*X**11              FIT00290
      WRITE(6,45) X,F                                                          FIT00300
  45  FORMAT(5X,F4.2,5X,F18.7)                                                 FIT00310
  44  CONTINUE                                                                 FIT00320
      END                                                                      FIT00330
C     ************************************************************           FIT00340
C      EVALUATION OF A,B PARAMETERS FOR CURVE FITTING WITH SALEH MODEL.        FIT00350
C     ************************************************************           FIT00360
      DIMENSION R(14),Z(14)                                                    FIT00370
      REAL A,B,RAT,SQ,R2,R4,W,WR2                                              FIT00380
      DATA R(1),R(2),R(3),R(4),R(5),R(6),R(7),R(8),R(9),R(10),R(11),           FIT00390
     &R(12),R(13),R(14)/                                                       FIT00400
     &0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1.0,1.1,1.2,1.3,1.4,1.5/                 FIT00410
      DATA Z(1),Z(2),Z(3),Z(4),Z(5),Z(6),Z(7),Z(8),Z(9),Z(10),Z(11),           FIT00420
     &Z(12),Z(13),Z(14)/                                                       FIT00430
     &0.0408057,0.0734502,0.1305782,0.179551,0.668512,0.2693176,0.302,         FIT00440
     &0.330526,0.351,0.36725,0.3754124,0.3835735,0.3917347,0.4/                FIT00450
      M=13                                                                     FIT00460
      F=1.0                                                                    FIT00470
      R2=0.0                                                                   FIT00480
      R4=0.0                                                                   FIT00490
      W=0.0                                                                    FIT00500
      WR2=0.0                                                                  FIT00510
      N=M                                                                      FIT00520
      DO 1 I=1,N                                                               FIT00530
      SQ=R(I)**2.                                                              FIT00540
      R2=R2+SQ                                                                 FIT00550
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      R4=R4+(SQ**2.)                                                    FIT00560
      RAT=(R(I)**2)/Z(I)                                                FIT00570
      W=W+RAT                                                           FIT00580
      WR2=WR2+RAT*SQ                                                    FIT00590
    1 CONTINUE                                                          FIT00600
      ARA=R2**2.-M*R4                                                   FIT00610
      PARA=R2*WR2-R4*W                                                  FIT00620
      ARB=R2*W-M*WR2                                                    FIT00630
      PARB=R2*WR2-R4*W                                                  FIT00640
      C=ARA/PARA                                                        FIT00650
      A=C**.5                                                           FIT00660
      B=ARB/PARB                                                        FIT00670
      WRITE(6,2) A,B                                                    FIT00680
    2 FORMAT(5X,'A=',F10.6,6X,'B=',F10.6)                               FIT00690
      STOP                                                              FIT00700
      END                                                               FIT00710
C     ****************************************************************  FIT00720
C      THIS PROGRAMME OPTIMIZES N UNKNOWN PARAMETERS OF A               FIT00730
C      GIVEN FUNCTION (FOR THE LM-380,H-261 PREDISTORTER)               FIT00740
C     ****************************************************************  FIT00750
      EXTERNAL FUNCT                                                    FIT00760
      INTEGER N NSIG,MAXFN,IOPT                                         FIT00770
      REAL X(6),H(21),G(6),W(18),F                                      FIT00780
      N=6                                                               FIT00790
      NSIG=3                                                            FIT00800
      MAXFN=500                                                         FIT00810
      IOPT=0                                                            FIT00820
      X(1)=3.3                                                          FIT00830
      X(2)=1.0                                                          FIT00840
      X(3)=-1.0                                                         FIT00850
      X(4)=1.5                                                          FIT00860
      X(5)=-2.0                                                         FIT00870
      X(6)=3.0                                                          FIT00880
      CALL ZXMIN(FUNCT,N,NSIG,MAXFN,IOPT,X,H,G,F,W,IER)                 FIT00890
      WRITE(6,5)(X(N),N=1,6)                                            FIT00900
    5 FORMAT(3X,F11.6)                                                  FIT00910
      WRITE(6,9) F                                                      FIT00920
    9 FORMAT(3X,F13.8)                                                  FIT00930
      STOP                                                              FIT00940
      END                                                               FIT00950
C     ******** SUBROUTINE FUNCT ***********************************     FIT00960
      SUBROUTINE FUNCT(N,X,F)                                           FIT00970
      INTEGER N                                                         FIT00980
      REAL X(N),F,SUM                                                   FIT00990
      ZP(Y)=1.60138*Y*EXP(-0.325713*(Y**2))*(1.0+0.25*((0.325713*Y**2)  FIT01000
     &**2)+0.045625*((0.325713*Y**2)**4)+0.000634*((0.325713*Y**2)**6)) FIT01010
      ZQ(Y)=1.887482*(Y**3)/((1.+1.063857*(Y**2))**2)                   FIT01020
      SUM=0.                                                            FIT01030
      R=0.0                                                             FIT01040
      DO 20 I=1,150                                                     FIT01050
      R=R+0.01                                                          FIT01060
      GP=X(1)*R+X(2)*R**3+X(3)*R**5                                     FIT01070
      GQ=X(4)*R**3+X(5)*R**5+X(6)*R**7                                  FIT01080
      E=GP**2+GQ**2                                                     FIT01090
      B=SQRT(E)                                                         FIT01100
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      IF(B.GT.1.35) GO TO 23                                            FIT01110
      Q=ZQ(B)                                                           FIT01120
      U=ZP(B)                                                           FIT01130
      IF(Q.LT.1.0E-09) Q=0.0                                            FIT01140
      IF(U.LT.1.0E-09) U=0.0                                            FIT01150
      C=(GP**2)*((U**2+Q**2)/(U**2))                                    FIT01160
      GO TO 22                                                          FIT01170
   23 C=(GP**2)*((0.56**2+1.3**2)/1.3**2)                               FIT01180
   22 CONTINUE                                                          FIT01190
      D=SQRT(C)                                                         FIT01200
      IF(D.GT.1.35) GO TO 33                                            FIT01210
      Q=ZP(D)                                                           FIT01220
      U=ZQ(D)                                                           FIT01230
      IF(U.LT.1.0E-09) U=0.0                                            FIT01240
      IF(Q.LT.1.0E-09) Q=0.0                                            FIT01250
      ZZ=Q**2+U**2                                                      FIT01260
      GO TO 32                                                          FIT01270
   33 ZZ=0.56**2+1.3**2                                                 FIT01280
   32 CONTINUE                                                          FIT01290
      PZ=SQRT(ZZ)                                                       FIT01300
      IF(R.GT.0.968) GO TO 10                                           FIT01310
      SUM=SUM+(U-1.463*R)**2                                            FIT01320
      GO TO 20                                                          FIT01330
   10 SUM=SUM+(PZ-1.414)**2                                             FIT01340
   20 CONTINUE                                                          FIT01350
      F=SUM                                                             FIT01360
      RETURN                                                            FIT01370
      END                                                               FIT01380
                                                                        FIT01390
                                                                        FIT01400
C     ****************************************************************  FIT01410
C      THIS PROGRAMME OPTIMIZES N UNKNOWN PARAMETERS OF A               FIT01420
C      GIVEN FUNCTION (LINEARIZATION OF THE LM-380 CHARACTERISTIC).     FIT01430
C     ****************************************************************  FIT01440
      EXTERNAL FUNCT                                                    FIT01450
      INTEGER N NSIG,MAXFN,IOPT                                         FIT01460
      REAL X(3),H(6),G(3),W(9),F                                        FIT01470
      N=3                                                               FIT01480
      NSIG=3                                                            FIT01490
      MAXFN=500                                                         FIT01500
      IOPT=0                                                            FIT01510
      X(1)=3.3                                                          FIT01520
      X(2)=1.0                                                          FIT01530
      X(3)=-1.0                                                         FIT01540
      CALL ZXMIN(FUNCT,N,NSIG,MAXFN,IOPT,X,H,G,F,W,IER)                 FIT01550
      WRITE(6,5)(X(N),N=1,3)                                            FIT01560
    5 FORMAT(3X,F11.6)                                                  FIT01570
      WRITE(6,9) F                                                      FIT01580
    9 FORMAT(3X,F13.8)                                                  FIT01590
C***************SUBROUTINE FUNCTION*********************************  FIT01600
      SUBROUTINE FUNCT(N,X,F)                                           FIT01610
      INTEGER N                                                         FIT01620
      REAL X(N),F,SUM                                                   FIT01630
      ZP(Y)=3.5902620*EXP(7.462*(Y**2))*(1.0+0.25*((-7.462*Y**2)        FIT01640
     &**2)+0.015625*((-7.462*Y**2)**4)+0.000434*((-7.462*Y**2)**6))     FIT01650
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```
      SUM=0.                                                        FIT01660
      R=0.0                                                         FIT01670
      DO 20 I=1,150                                                 FIT01680
      R=R+0.01                                                      FIT01690
      GP=X(1)*Q+X(2)*Q**3+X(3)*Q**5                                 FIT01700
      IF(GP.GT.1.414) GO TO 23                                      FIT01710
      U=ZZ(GP)                                                      FIT01720
      GO TO 22                                                      FIT01730
23    U=1.414                                                       FIT01740
22    CONTINUE                                                      FIT01750
      IF(R.GT.0.968) GO TO 10                                       FIT01760
      SUM=SUM+(ZZ-1.463*R)**2                                       FIT01770
      GO TO 20                                                      FIT01780
10    SUM=SUM+(ZZ-1.4140)**2                                        FIT01790
20    CONTINUE                                                      FIT01800
      F=SUM                                                         FIT01810
      RETURN                                                        FIT01820
      END                                                           FIT01830
```