DIGITAL DATA TRANSMISSION IN A PAM COMMUNICATION SYSTEM

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Summary. This paper presents the results of an experimental evaluation of the effectiveness of digital data transmission in a pulse-amplitude modulation (PAM) communication system. A PAM communication system was simulated and equipment was developed to obtain experimental results indicative of PAM's effectiveness in transmission of digital data. The results consist of word, channel, and bit error probability curves for different numbers of digital bits per PAM channel. The digital bits were converted to analog voltage levels which amplitude-modulated selected PAM channels. After decommutation the digital bits were recovered from the analog voltage levels by an analog to digital conversion.

The data indicates that the number of bits per channel should be 4 or less depending upon the digital data quality requirements. The error probability curves can be used to determine whether or not a PAM communication system can telemeter digital data within given constraints. In addition, the results provide guidelines for the implementation of digital data in a PAM system.

Introduction. The development of Navy missiles containing minicomputers for control and data processing has resulted in PAM telemetry being required to accommodate various amounts of digital data. Since many Navy telemetry systems involve PAM, and if these systems are to be used in support of missiles with digital data, then it is necessary to know the digital data transmission characteristics of a PAM system This paper is aimed at determining those characterisitics and their ramifications on the effectiveness of PAM with digital data. The problem was one of determining to what degree an existing PAM system could support digital data. This does not imply PAM is a replacement for PCM. Rather, given an existing PAM system and a small digital data requirement, it suggests that PAM can possibly be used effectively to transmit all data requirements thus avoiding a major investment into a new telemetry system.

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PAM System Errors. The following discussion on PAM system errors is required to understand the generation of digital bit errors for digital data in PAM. The amplitudes of the channels of a PAM frame after receiver demodulation are biased by nonlinearities of preceding system components; in addition, superimposed on the amplitudes are receiver noise (i.e. demodulated incidental frequency modulation (FM) noise, additive noise, subtractive noise), circuit noise, and crosstalk. The decommutator's low-pass filter tends to average out any high frequency mean-value-zero noise, but any noise that is not mean-value-zero cannot be averaged out and causes futher biasing of the channel amplitudes. Noise below the low-pass filter cutoff is passed along with the PAM sequence to the decommutator's integrator.

The integration and sample/hold process in the decommutator acts to average the noise and crosstalk remaining on the biased amplitudes of the channels. Because of the nature of noise and crosstalk, and because of the decommutator's own nonlinearities, the averaging process generally results in further biasing of the amplitudes. Therefore, the decommutator output voltage level is usually not an absolutely accurate representation of the sampled signal. The degree to which the decommutator output amplitude may differ in value from the actual signal amplitude at the time of sampling depends upon the radio frequency (RF) signal power level and the degree of nonlinearities, crosstalk, circuit noise, incidental frequency modulation (FM), and demodulator noise present at any given time in the system.

The bias of a channel at the decommutator output due to nonlinearities and crosstalk depends upon the modulation level of the channel and the modulation level of the preceding channel, respectively. Neglecting time and temperature variations, the net channel bias for nonlinearities and crosstalk at any given pair of modulation levels, is a static error. Since both demodulator noise (of which transmitter incidental FM will be considered a part) and circuit noise are random, the biases they cause on the decommutated channel amplitude are random. This random bias will hereafter be called decommutator noise. Consequently, the decommutated channel output voltage is randomly distributed about the true amplitude of the commutator sample and is characterized by a probability density function (PDF). The mean of the PDF distribution is shifted by the biases of nonlinearities and crosstalk such that the mean of the PDF may not be the amplitude of the actual sample (see figure 1). The distribution in general is dependent upon channel modulation levels, system nonlinearities, crosstalk, circuit noise and demodulator noise.

The PDF distribution is also dependent upon the power level of the RF signal (via its effect on demodulator noise). At high RF signal levels, the PDF distribution at the decommutator output is that of the basic system noise floor and is primarily determined by nonlinearities, crosstalk, circuit noise, and incidental FM. These factors determine the best accuracy obtainable at the decommutator output. As the RF level decreases, the demodulator noise increases and the decommutated channel output distribution widens. Accordingly, the overall accuracy at the decommutator output decreases with the RF level. Because of the rapid degradation of the video signal by subtractive noise, FM threshold should have a significant effect upon the decommutator output distribution and PAM data accuracy. Figure 1 shows PDF distributions at one modulation level for two intermediate frequency (i-f) signal-to-noise ratios (SNR). Subtractive noise causes the PDF distribution to become lopsided toward band center modulation.

Digital Data Considerations in a PAM System. Digital data can be handled by a PAM communication system if the digital data is first converted to analog voltage levels by means of a digital-to-analog (D/A) conversion. Once converted, the data can be sampled by the system commutator and transmitted with other data to a receiving station. The received analog voltage levels are separated from other data in the decommutator and reconverted to digital data by an analog-to-digital (A/D) conversion.

When N bits of digital data are converted to an analog voltage level and this level is sampled by the commutator, transmitted, received, and decommutated, the analog voltage level out of the decommutator will, in general, not be exactly the same as that sampled by the commutator. The difference between the sampled value and the recovered value will be a randomly distributed variable as previously described. Since recovery of the digital data requires an A/D conversion, an accurate recovery of the N bits requires that the difference between sampled and recovered values be smaller than 1/2 the voltage representative of the least significant bit (LSB), otherwise the conversion will be in error.

If the PDF distribution curve’s end points lie within ±1/2 LSB of the code’s correct voltage level, then there will essentially be no digital recovery errors. If the distribution curve’s end points exceed ±1/2 LSB, there will exist some probability that the decommutator output voltage will cause an A/D conversion error (see figure 1). The probability of error is proportional to the area under those parts of the distribution curve exceeding ±1/2 LSB. Since the distribution of the decommutator output error is variable with RF power, the probability of a digital recovery error will also be variable. Digital errors can be reduced by increasing the size of the LSB. This increase is accomplished by decreasing N, the number of bits per channel. Obviously, the quality and quantity of recovered digital data on PAM are inversely proportional to one another. For a fixed RF signal power level, the quantity of digital data per PAM channel decreases as the quality requirement becomes more stringent; or, for a given quality requirement, the quantity of digital data per channel decreases as the RF power decreases.

If quality constraints require N bits per channel and $N<M$ (where M is the number of bits per word) then the word must be divided into segments and each segment converted and

sampled in order to transmit the word. The word must be reconstructed when the segments are recovered. Each of the N bits per channel has different error probabilities because they are not equally weighted in the D/A and A/D conversions. Consequently, consideration must be given to the arrangement and packing of the M bits in the channels so as to maximize final data quality.

Description of Experiment. The measure of effectiveness used in evaluating digital data transmission in a PAM system was quantity and quality of recovered digital data. Accordingly, the experiment was designed to produce data relevant to this measure. The experiment examined the digital data quality (bit, channel and word error probabilities) as a function of receiver i-f signal-to-noise ratio for a given quantity of bits, N, per channel for three modes of the system. The three modes are shown in Table 1. Mode 1 was selected for most of the experimentation. The other two modes were examined to determine the effects of a change in IF filter bandwidth and sampling rate.

A bit error for any of the recovered N bits per channel was defined to be the occurrence of a digital “1” (“0”) level when the correct digital level was a “0” (“1”). A channel error was defined to be the occurrence of one or more bit errors within the N bits of a channel. A word error was defined to be the occurrence of one or more bit errors within the M bits of a word or one or more channel errors within the K channels of a word. M was fixed at 12 for the experiment.

The experiment required the simulation of a PAM communication system and the development of a digital signal generator; a D/A converter-interface; an A/D interface-converter; and a bit, channel, and word error detector. The digital source was a pseudo-random 2047 bit generator capable of supplying up to six bits in parallel to the D/A converter-interface and the error detector.

The A/D interface-converter was coupled to the decommutator’s integrator output for digital data recovery. The error detector compared the A/D interface-converter output with the original signal from the pseudo-random generator. The detector operated in three modes: bit error, channel error, and word error detection.

The PAM simulation was made up of standard telemetry components. The transmitting end consisted of a commutator with selectable sample rate and premodulation filter, and an FM signal generator operating at 1483 MHz. The transmission medium was simulated with RF coaxial cable and 1- and 10-decibel (dB) step attenuators. The receiving end consisted of an L-band receiver with selectable i-f filter and demodulator bandwidths, and a decommutator with selectable sample rate and video filter bandwidth. A diagram of the experiment is shown in figure 2.

Listed in table 2 are the PAM frame channel assignments. Channels 60 through 64 comprise the decommutator frame synchronization code. Every fourth channel from 3 to 59 was reserved for digital information. Every fourth channel from 2 to 58 was modulated with a low frequency (1 kilohertz (kHz) at a 25 kilosamples per second PAM rate and 2 kHz at a 100 kilosamples per second PAM rate) sine wave to introduce crosstalk distortion in the digital information channels. Every eighth and ninth channel from 8 to 56 was tied to full-scale high and low modulation levels, respectively, to ensure enough channel voltage transitions to maintain decommutator timing. All other channels were grounded.

For control of nonlinearities, the D/A output voltage levels were aligned through the system to approximately halfway between the A/D decision points. The nonlinearity at the decommutator output was held to approximately ±1/2 percent of full scale.

Experimental Results. The experimental error probabilities are presented in figures 3 through 8. The graphs illustrate how word error probability (WEP), channel error probability (CEP), and bit error probability (BEP) vary with i-f SNR. They are an indication of the degradation of digital data quality with degradation in SNR.

Observations indicated that subtractive noise was becoming significant around 11 dB i-f SNR for modes I and II. However, no significant change in the error probability curves appeared. Some of the errors that should have been caused by subtractive noise were suppressed by decommutator calibrator operation. Comparison of subtractive-noise-suppressed calibration channels with internal calibration levels resulted in amplification of the PAM signal. The amplification offset the suppression and resulted in fewer digital errors than might otherwise be expected. Subtractive noise never really became a factor in mode III operation. Most of the data quality degradation was caused by the wider baseband filter before subtractive noise appeared. The decommutator began dropping out of synchronization below 8 dB i-f SNR in modes I and II. Therefore, experimental data below 8 dB are not reliable.

Figure 3 shows the improvement in the word error probability as N is decreased and the improvement in word error probability obtained by placing the bits of the word in only the most significant bit (MSB) locations of the channel. To distinguish between WEP curves, the notation WEP_{XN} was used. X is the number of the most significant channel bit locations used out of the N bits of the channel. This notation was also used to distinguish between CEP curves. The bits of the word were always placed in the X most significant bit positions of the channel. The other N-X bit locations of the channel were filled with pseudorandom bits. The pairs of curves for each value of N in figure 3 represent experimental maximum and minimum WEP possible for a given N.

All of the WEP_{1N} curves were calculated from their respective MSB error probability curves of figure 6. Measurement of WEP_{1N} was not feasible due to the length of measurement time. The calculation was based upon the MSB errors being binomially distributed for a fixed IF SNR. The probability of a word error for X = 1 was calculated from the formula shown below for a 12-bit word:

$$WEP_{1N} = 1-(1-P_{msb)})^{12}$$

where P_{msb} is the MSB error probability. This formula and subsequent ones were derived on the basis of errors being binomially distributed for a given SNR. A chi-squared test postulating a binomial distribution verified a distribution of this nature. Derivation of WEP_{1N} was as follows:

$$WEP_{1N} = 1\text{- Prob (no word error)}$$

$$\text{Prob (no word error)} = \text{Prob (no MSB errors)} = (1-P_{msb})^{12}$$

The improvement between WEP_{1N} and,WEP_{NN} results from the analog weighting of the bits in the D/A and A/D conversion process. For example, for N = 4, no matter what four word bits are placed on a channel, a word error will occur any time the decommutator noise exceeds ±1/2 the LSB voltage of the A/D. On the other hand, for word bits placed only in the MSB locations of the channels, a word error will occur only when the decommutator noise exceeds the MSB decision point of the A/D.

The CEP curves are shown in figure 5 for X = N. For the conditions of mode I, there is a 2-dB degradation each time one more bit is transmitted per channel. This improvement relates directly to the decreasing size of the LSB voltage as N increases. Comparison of the respective LSB error curves in figure 7 with the CEP curves in figure 5 indicate that CEP is very nearly the same as the LSB BEP. This is to be expected. The only time a channel error occurs in the absence of an LSB error is when the decommutator noise jumps two (or a multiple of two) LSB decision levels. Therefore, the CEP and LSB BEP curves should be identical at their lower ends and only slightly different at their upper ends. This result, as shown later, is important in estimating WEP_{XN} when $1<X<N$.

The MSB error curves are shown in figure 6. They were used to calculate the WEP_{1N} curves of figure 3. As N decreases, the closest modulation level pseudorandom voltage level) on either side of the MSB decision point gets further away. Consequently, the 1.5 dB improvement for each decrease of N by 1 is because a lower SNR is required for decommutation noise to cross the MSB decision point.

Figure 8 presents the BEP's of the second MSB of N = 3 and the second and third MSB's of N = 4. Because the A/D decision levels of these bits are further apart than LSB decision levels but not as far apart as the MSB decision level, these curves are approximately equally spaced between their respective LSB and MSB BEP curves.

The effect of increasing the sample rate and decreasing the IF filter and demodulator bandwidth on WEP is shown in figure 4 for N = X = 3. The increased sample rate resulted in a 2 dB degradation in WEP. A degradation is to be expected because of the wider baseband bandwidth. The decreased i-f bandwidth resulted in a slight degradation of WEP for a given i-f SNR because of phase nonlinearities and signal power loss in the narrower IF bandwidth. However, the reduced bandwidth actually resulted in a 2 dB RF power improvement.

If needed, WEP curves not shown, such as WEP_{23}, can be generated from the other experimental curves. Channel error probability and LSB bit error probability are, for all practical purposes, the same. This suggests that CEP_{23} is the same as the BEP of the second most significant bit for N = 3 of figure 8. In general then, WEP_{XN} for $1<X<N$ can be calculated from:

$$WEP_{XN} = 1-(1-CEP_{XN})^{M/X}$$

Where N is bits per channel; X is the number of bit locations used for word bits out of the N per channel; M is the bits per word; and CEP_{XN} is the probability of one or more of the X most significant bits in a channel being in error. In these cases, CEP_{XN} is approximated by the BEP of the Xth bit. M/X must be an integer. Because of the nature of the weighting in the D/A and A/D conversions, WEP_{23}, should fall about halfway between WEP_{13}, and WEP_{33},. WEP_{24} and WEP_{34} should fall from WEP_{14} about 1/3 and 2/3 respectively, the distance between WEP_{14} and WEP_{44}. If M/X is not an integer, then the above formula can be modified to:

$$WEP_{XN} = 1 - (1-CEP_{ZN})\ (1-CEP_{XN})^{T_I(M/X)}$$

Where Z is the remaining bits of M/X and T_I (M/X) is the truncation of M/X to its integral number part.

PAM With Digital Data. The quantity of digital data that can be transmitted per PAM channel is limited by the system's noise floor and static biases. The SNR at the decommutator output for the noise floor level was observed in the laboratory to be approximately 46 dB with respect to full scale sine wave modulation. Assuming an approximately gaussian distribution of decommutator noise at this signal-to-noise level, the standard deviation (σ) of the noise will be 36 millivolt (mV) for 10 volts (V) full scale.

$$20 \log \frac{S_{rms}}{N_{rms}} = 46 \text{ dB}$$

$$N_{rms} = 10^{-46/20} (S_{rms}) = 36\text{mV}$$

Where $S_{rms} = 7.07\text{V}$

$$\sigma = N_{rms} = 36\text{mV}$$

$$2\sigma = 72\text{mV}$$

$$5\sigma = 180\text{mV}$$

If nonlinearities and crosstalk at the decommutator output for some modulation levels are around ±1 percent, then, for 10 V full scale, a 100 mV offset of the noise floor PDF distribution from the correct amplitude of the sample occurs. For N = 5, the LSB decision levels are 156 mV from the correct amplitude of the converted digital data at the decommutator output.

$$\frac{1}{2} \text{ LSB} = \frac{1}{2} \times \frac{1}{2^5} \times 10\text{V} = 156 \text{ mV}$$

Consequently, one LSB decision level falls within the 2 σ point of the shifted noise distribution and significant errors can result.

$$\text{Shift} + 2\sigma = 100\text{mV} + 72\text{mV} = 172 \text{ mV}$$

For N = 4, the LSB decision levels are 312 mV from the correct amplitude of a sample and lie outside of the 5σ point of the shifted noise distribution.

$$\frac{1}{2} \text{ LSB} = \frac{1}{2} \times \frac{1}{2^4} \times 10\text{V} = 312 \text{ mV}$$

Therefore, relatively few errors will occur for 4 bits per channel at high SNR levels. This establishes N = 4 as the maximum quantity of digital bits per channel. However, it is not uncommon for higher static biases and a larger noise floor to exist in the field such that it is possible for N = 4 to be of marginal use. Other constraints may limit N even further.

As an example of the determination of N, consider the following system. Assume that a 25 kHz, 64-channel, PAM system with 1 MHz i-f is required to telemeter a 12-bit word every

PAM frame. Additional digital data include 20 discrete information bits, each of which must be telemetered every 2 PAM frames. Furthermore, only 12 PAM channels can be allocated for the digital data and the maximum word error probability must be no more than 10^{-4} and the maximum discrete error probability must be no more than 10^{-2} at 11 dB i-f SNR. Can all the data be transmitted? What should N be? How should the word bits and discrete bits be arranged so that channel allocation and error constraints are met?

Figure 3 indicates that the only way to meet the word error constraint at 11 dB i-f SNR is with N = 2. N = 1 will not meet the channel constraint. For the discrete data, figure 7 shows N = 3 or 2 will meet the discrete error constraint.

There are three possible methods to handle the digital data using these results. Two of the methods involve N = 2 and the other involves a combination of N = 2 and 3. The first method for N = 2 is to break the word up into 6 two-bit segments leaving 6 channels for the discrete bits. Since the 20 discrete bits are required only once every two frames, then the subcommutation of 5 channels at 2 bits/channel results in 20 bits every 2 frames and one channel is saved for other applications. WEP_{22} for this method is, from figure 3, ~ 10^{-4} at 11 dB i-f SNR. The discrete error probability depends on the location of the bit in the channel; for the MSB location, the BEP is, from figure 6, 10^{-6}; for the LSB location, the BEP is, from figure 7, 1.5×10^{-5}. The difference in BEP of the MSB and LSB for N = 2 suggests that the six most significant bits of the word should occupy the MSB positions of the 6-word channels. This assumes that the MSB's of the word are of more value than the LSB's. Such is not the case if the word represents a code in which all bits are of equal importance.

If the bits of the word are all of equal importance, then the second method for N = 2 may be preferred over the other methods. This method places all 12 bits of the word in the MSB locations of the 12 channels and results in equal error probability for all word bits. The discrete bits fill the 12 LSB channel positions, 8 of whose positions must be subcommutated. WEP_{12}, for this method is, from figure 3, 5×10^{-5} at 11.0 dB IF SNR. The discrete error probability is, from figure 7, 1.5×10^{-5}. This method uses all 12 channels, decreases the word error probability, and increases the discrete error probability.

If it is desired to allocate as few channels as possible to the digital data, then method one above is a possibility. However, a third method using 2 and 3 bits per channel results in a savings of an additional channel. The word is transmitted, as in method one, on 6 two-bit channels. The discretes are transmitted on 4 three-bit channels. The 8 bit locations comprising the most significant bits and the second most significant bits of the four discrete channels are subcommutated. The number of channels used is 10. WEP_{22} is once again ~ 10^{-4} at 11.0 dB i-f SNR. The discrete error probabilities depend on the bit location in the channel. For the MSB location, the BEP is, from figure 6, ~ 10^{-4}; for the second

MSB location, the BEP is, from figure 8, 4×10^{-4} ; for the LSB location, the BEP is, from figure 7, 10^{-3}.

Conclusions. The above example illustrates some of the key considerations involved in transmitting digital data in a PAM communication system. The quality requirements for digital data should be determined before selection of N. In some cases N will be completely specified by the quantity of data and quality constraints. In cases where it is not, as in the above example, N may be chosen with one of two objectives in mind: maximization of data quality of WEP or BEP, or minimization of digital data channels. Maximization of data quality generally results in utilization of all available digital channels, whereas minimization of digital channels reduces the data quality.

The weighting of the bits in the D/A conversion results in some important considerations. The difference in BEP of the bit locations of a channel is due to this weighting. The more significant the bit of the channel, the lower the error probability for a given SNR. Consequently, the most important bits of the digital data should be located in the MSB positions of the data channels. For a word representing a value, these positions are filled with the MSB's of the word. If the word is a code where all bits are of equal importance, then the bits must be placed in the same bit location of each channel or they will have different weights and BEP's. Since WEP constraints will usually be the most difficult to meet, the most significant bits of a channel should be reserved for word bits. The remaining bit locations are filled with discretes. The most important discretes are placed in the most significant position of the remaining channel bits.

Practical accuracy limitations of PAM systems restrict the number of digital bits that can be accurately transmitted in a single PAM channel to 4 bits for modes I and II and to 3 bits for mode III. The implementation of digital data in PAM telemetry systems requires:

a. The determination of required digital and analog data quantities.

b. The determination of the digital data quality constraints with minimum expected RF signal power at the receiver.

c. The determination of the number of channels to be allocated to the digital data based on the primary (analog and/or digital) data requirements.

d. The selection of N to meet channel allocation and digital quantity and quality requirements.

e. The determination of the channel bit packing of words and discretes to meet channel allocation and data quality requirements.

f. The design of commutation, conversion, and decommutation equipment for the packing, encoding, recovery, and reconstruction of digital words and discrete bits.

Reference.

1) King, D. A., "Digital Data Transmission in a Pulse Amplitude Modulation (PAM) Communication System," Pacific Missile Test Center, Point Mugu, California, TP-75-46, 14 August 1975.

Table 1 System Parameters for Three Modes of Operation

SYSTEM PARAMETERS FOR THREE MODES OF OPERATION

Mode I.
Sample Rate: 25 kHz, non-return to zero (NRZ), 64 channels
Premodulation Filter: 50 kHz
Transmitter Deviation: ± 125 kHz
i-f Filter: 1 MHz
Demodulator Bandwidth: 1 MHz
Video Filter: 50 kHz

Mode II.
Sample Rate: 25 kHz, NRZ, 64 channels
Premodulation Filter: 50 kHz
Transmitter Deviation: ±125 kHz
i-f Filter: 500 kHz
Demodulator Bandwidth: 500 kHz
Video Filter: 50 kHz

Mode III.
Sample Rate: 100 kHz, NRZ, 64 channels
Premodulation Filter: 200 kHz
Transmitter Deviation: ±250 kHz
i-f Filter: 1 MHz
Demodulator Bandwidth: 1 MHz
Video Filter: 200 kHz

Table 2 Frame Channel Assignments

FRAME CHANNEL ASSIGNMENTS

1. GND
2. SINE WAVE
3. DIGITAL DATA
4. GND
5. GND
6. SINE WAVE
7. DIGITAL DATA
8. +2.5V
9. -2.5V
10. SINE WAVE
11. DIGITAL DATA
12. GND
13. GND
14. SINE WAVE
15. DIGITAL DATA
16. +2.5V
17. -2.5V
18. SINE WAVE
19. DIGITAL DATA
20. GND
21. GND
22. SINE WAVE
23. DIGITAL DATA
24. +2.5V
25. -2.5V
26. SINE WAVE
27. DIGITAL DATA
28. GND
29. GND
30. SINE WAVE
31. DIGITAL DATA
32. +2.5V
33. -2.5V
34. SINE WAVE
35. DIGITAL DATA
36. GND
37. GND
38. SINE WAVE
39. DIGITAL DATA
40. +2.5V
41. -2.5V
42. SINE WAVE
43. DIGITAL DATA
44. GND
45. GND
46. SINE WAVE
47. DIGITAL DATA
48. +2.5V
49. -2.5V
50. SINE WAVE
51. DIGITAL DATA
52. GND
53. GND
54. SINE WAVE
55. DIGITAL DATA
56. +2.5V
57. -2.5V
58. SINE WAVE
59. DIGITAL DATA
60. -2.5V
61. +2.5V
62. +2.5V
63. +2.5V
64. GND

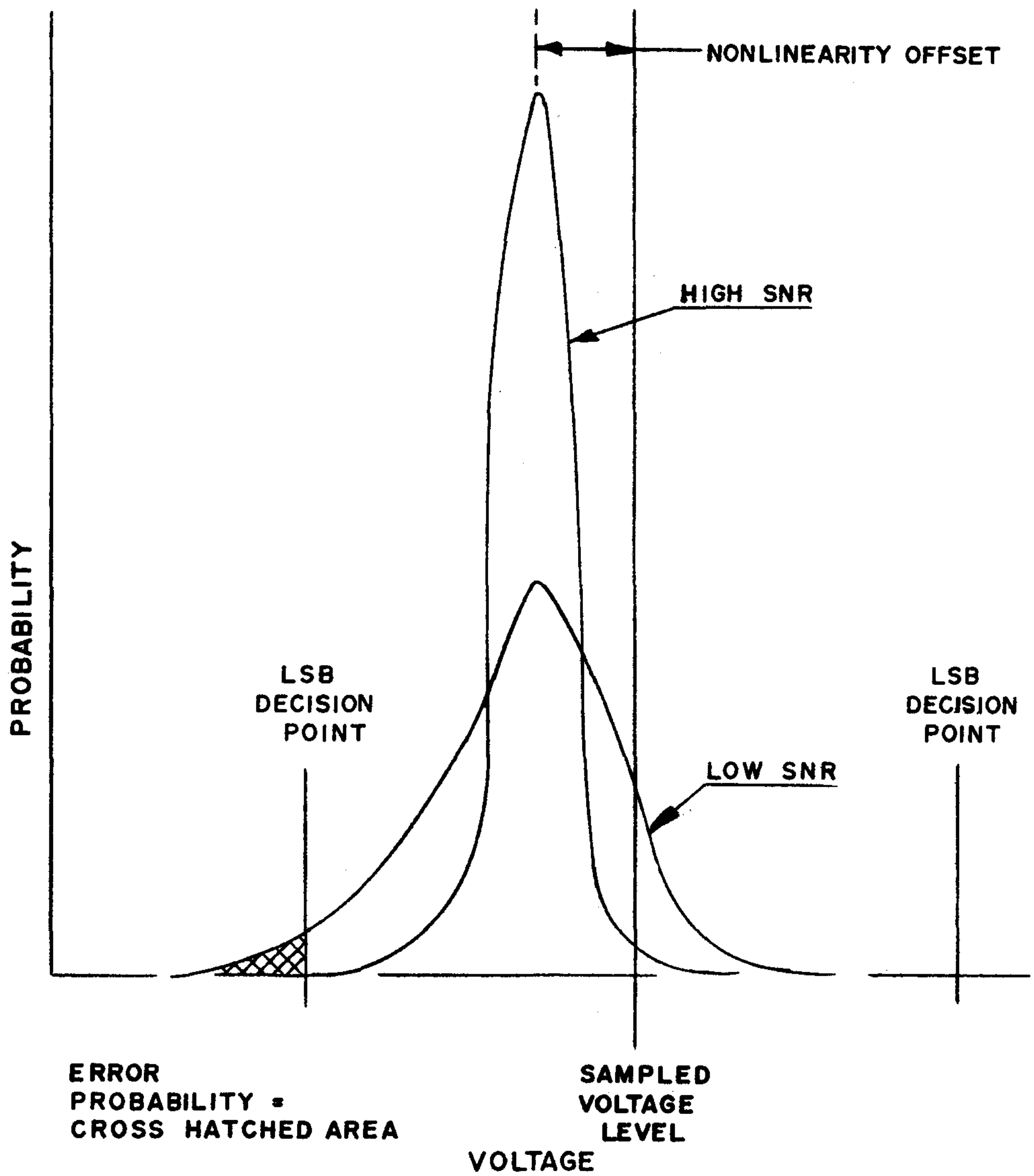

Figure 1 PDF Distribution for Voltage Level of a Decommutated Channel

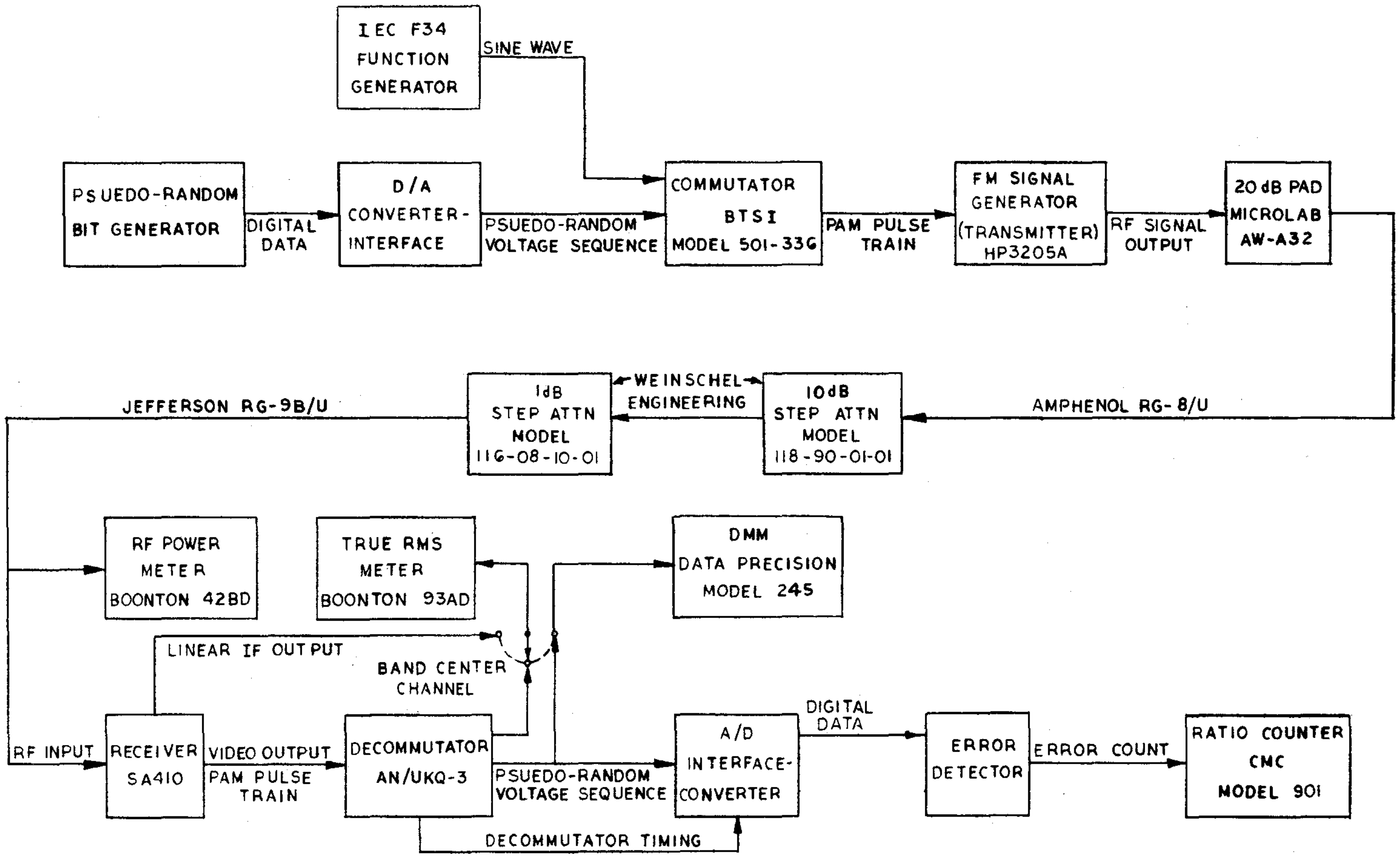

Figure 2 Block Diagram for Test Configuration

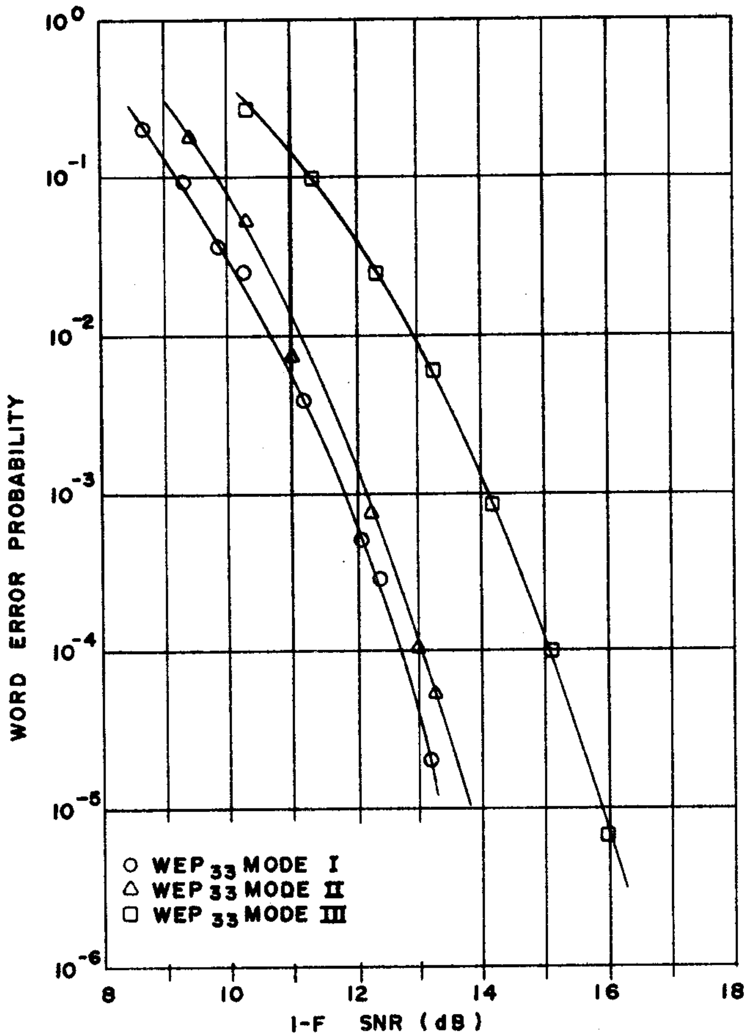

Figure 4 Variation of WEP with System Mode

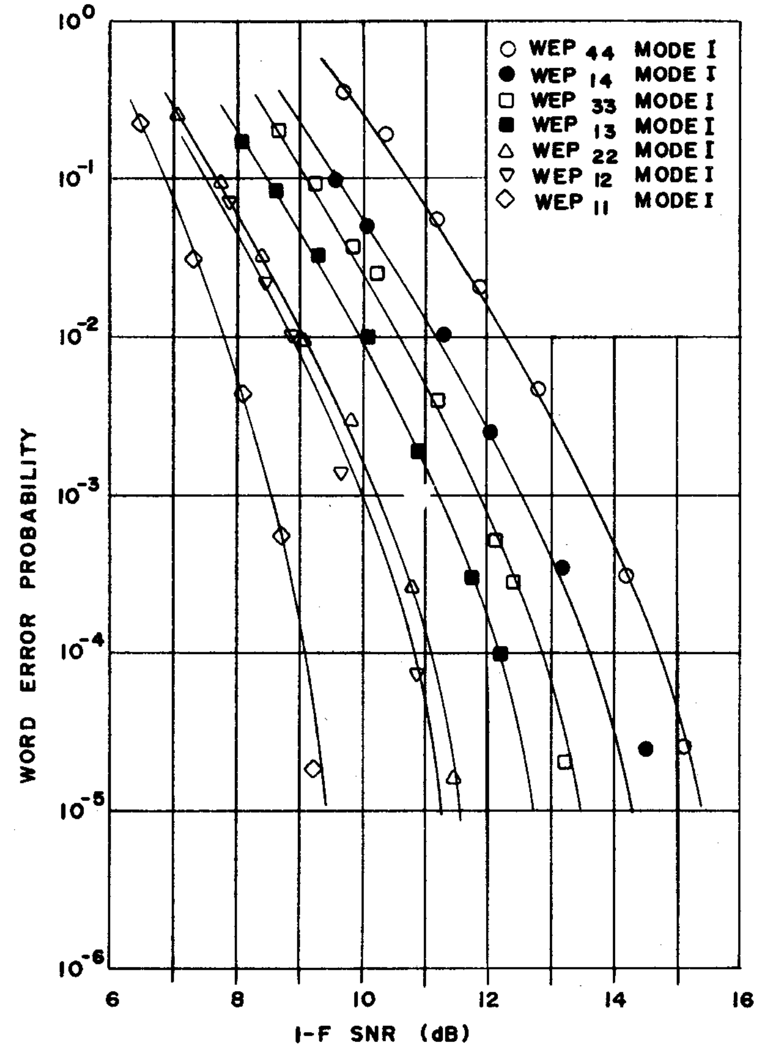

Figure 3 Variation of Word Error Probability with I-F SNR for N Bits/Channel

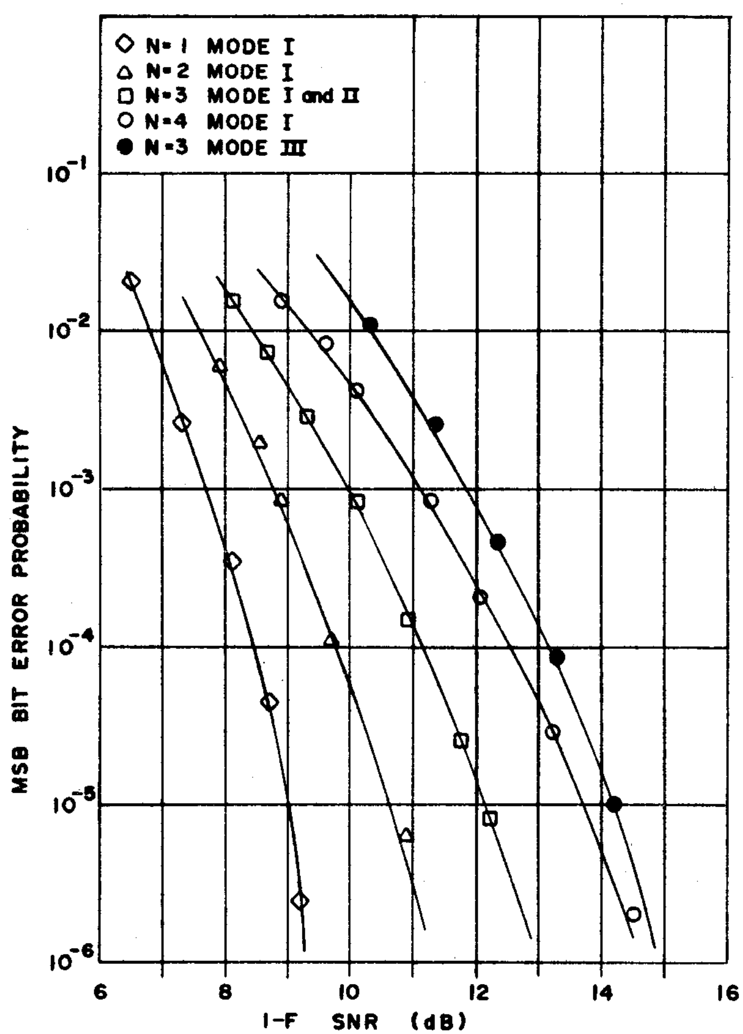

Figure 6 Variation of MSB BEP with I-F SNR

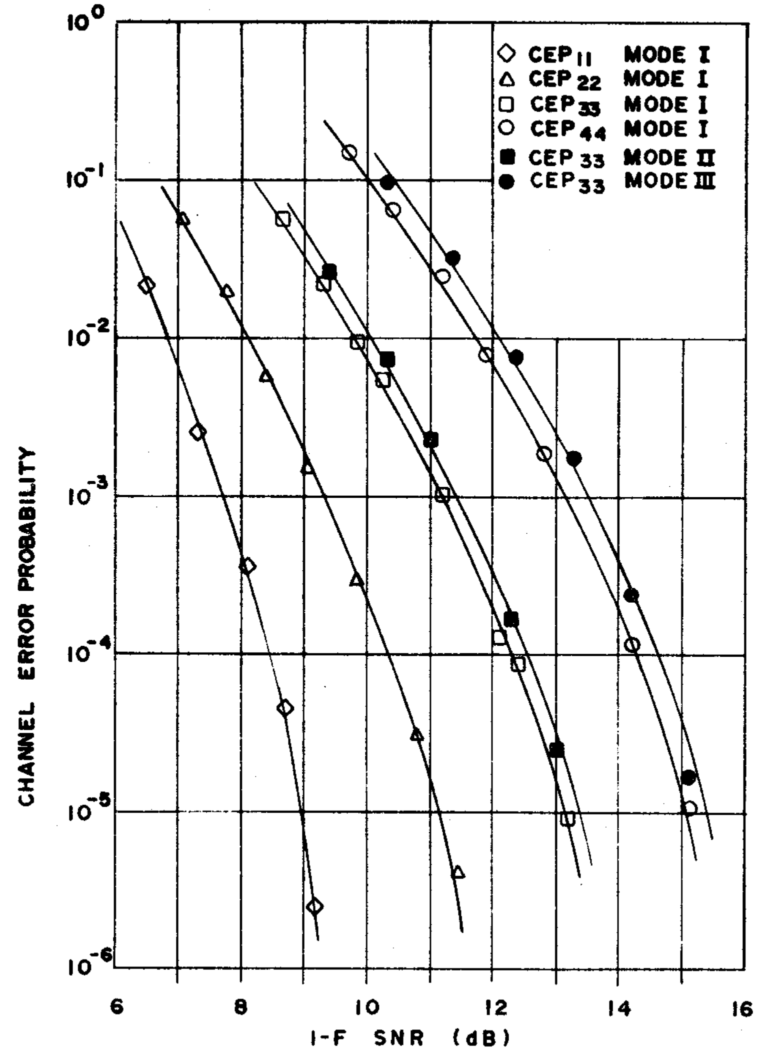

Figure 5 Variation of CEP with I-F SNR

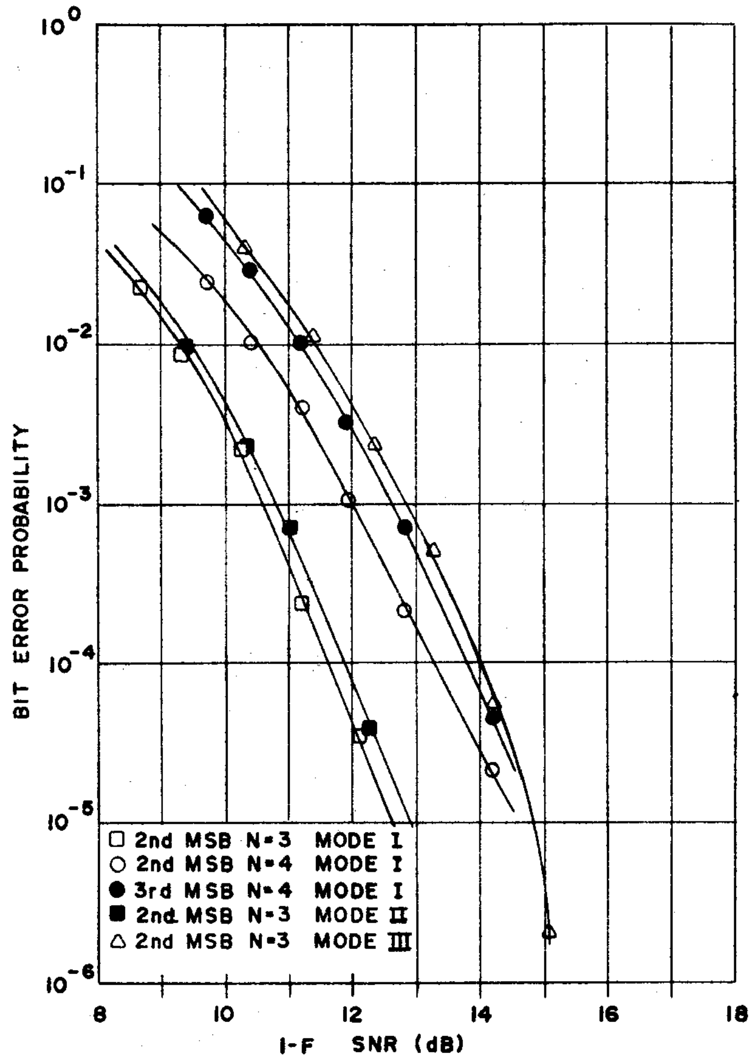

Figure 8 Variation of BEP of Middle Bits for N=3 and 4

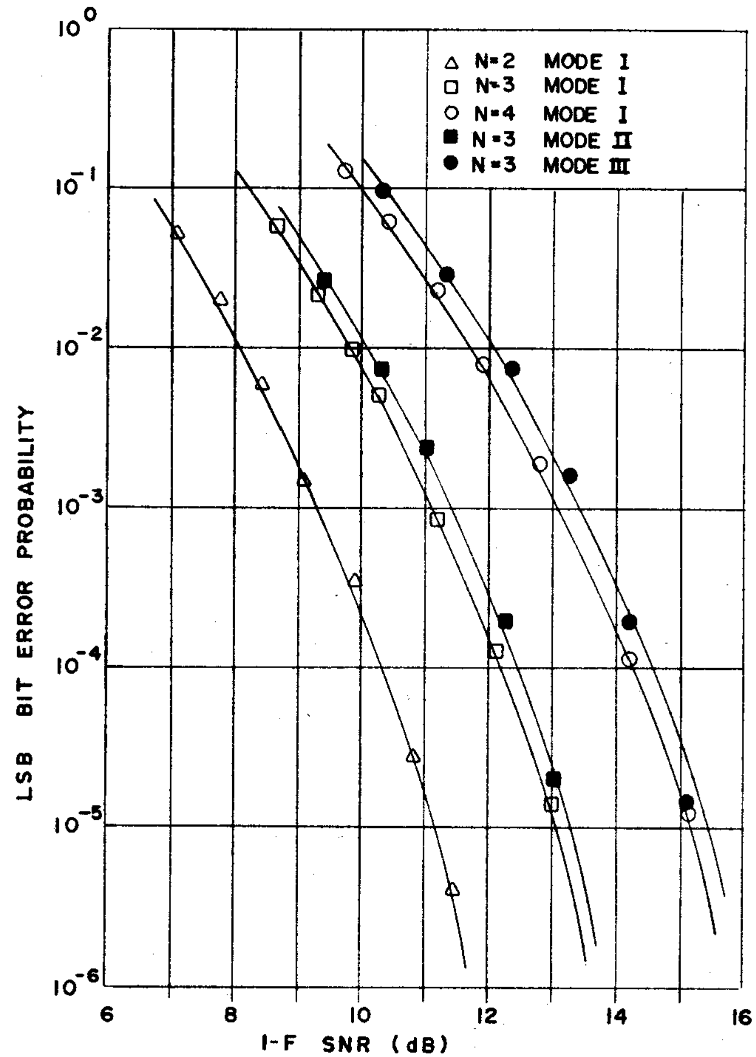

Figure 7 Variation of LSB BEP with I-F SNR