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AN EVALUATION OF MODULATION SYSTEMS

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An Evaluation of Modulation Systems

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13. ABSTRACT

This report summarizes the results of a theoretical and experimental study of the relative strengths and weaknesses of ASK, PSK, and QPSK systems. The report is a combination review report and research monograph. Ideal theoretical results are discussed, and methods of practical realization are described. New research results include the determination of the standard deviation of the arrival time as a function of modulation, simple formulas for the degradation in both digital and analog systems due to adjacent-channel interference, and simple upper bounds for intersymbol interferences. The use of the formulas are all examined experimentally.

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Quadriphase shift keying						
ASK						
PSK						
QPSK						

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AN EVALUATION OF MODULATION SYSTEMS

INTRODUCTION

In this report the following types of modulation are analyzed and compared: amplitude shift keying (ASK), phase shift keying (PSK), and Quadriphase shift keying (QPSK). An ASK system was chosen because it is one of the simplest to implement. A PSK system was selected because it yields the lowest bit error rate for a given signal-to-noise ratio. A QPSK system was chosen because of its narrow-bandwidth requirement and the resulting resistance to adjacent-channel interference. Frequency shift keying (FSK) was not considered because it has a significantly higher bit error rate than PSK and lacks the simplicity of ASK.

Only digital modulation types were actually studied. However, the results of the study easily could be applied to certain analog systems.

In comparing the modulation techniques, the following criteria were considered the most relevant: bit error rate, standard deviation of arrival time, adjacent-channel interference, and intersymbol interference. The standard deviation of arrival time is an important parameter in analog systems employing pulse-duration modulation (PDM) or pulse-position modulation (PPM), e.g., the analog AN/PPM, AM/PDM, PM/PPM, or PM/PDM systems.

The digital symbols were represented by nonreturn-to-zero (NRZ) signals, which are full-symbol-length pulses. The NRZ format was employed because of its simplicity and relatively narrow bandwidth requirements. The modulation methods will now be defined precisely.

ASK is amplitude modulation with a two-level modulating signal; i.e., either $s_1(t) = A \cos wt$ or $s_2(t) = 0$ is transmitted. In noncoherent ASK, no detection of the carrier is attempted, but envelope demodulation is employed.

In PSK the two possible transmitted waveforms are $s_1(t) = A \cos wt$ and $s_2(t) = A \cos (wt + \beta)$. In this report we consider the base where $\beta = \pi$, which is the optimum choice in terms of bit error rate. Coherent demodulation usually involves a phase-locked loop. Differential PSK is a noncoherent mode of reception. In this method, instead of detecting the carrier, two successive bits are compared to determine the relative phases.

In QPSK, one of four possible waveforms is transmitted during each bit interval. The waveforms are

$$s_1(t) = \sqrt{2} A \cos \left(\omega t + \frac{\pi}{4}\right) = A \cos wt - A \sin wt;$$

$$s_2(t) = \sqrt{2} A \cos \left(wt + \frac{3\pi}{4}\right) = -A \cos wt - A \sin wt;$$

$$s_3(t) = \sqrt{2}\,A\cos\left(wt - \frac{\pi}{4}\right) = A\cos wt - A\sin wt;$$

$$s_4(t) = \sqrt{2}\,A\cos\left(wt - \frac{3\pi}{4}\right) = -A\cos wt + A\cos wt.$$

In the receiver, two synchronous correlators are required. During each bit interval of transmission, two bits of information can be transmitted. Thus the bandwidth requirement of QPSK is half of the PSK requirement.

A theoretical analysis of various factors will now be undertaken. The goal is to obtain simple formulas from which relevant data can be computed readily. To evaluate their use, predictions of these formulas will be compared to the empirical results.

THEORETICAL DISCUSSION

Bit Error Rate

The probability of bit error for an ideal coherent ASK system is (1,2)

$$P_b = erfc\sqrt{\frac{E_b}{2N_0}}, \tag{1}$$

where E_b is the energy per bit in the ONE state, N_0 is the noise power spectral density, and

$$erfc\,(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} \exp\left(-\frac{x^2}{2}\right)dx. \tag{2}$$

An ideal noncoherent ASK system has a bit error given by (2)

$$P_b = \frac{1}{2}\exp\left(-\frac{E_b}{4N_0}\right). \tag{3}$$

A parameter which is sometimes more significant than E_b is $\overline{E}_b$, the mean energy per bit. Assuming a 50% duty cycle for ASK signals, we have

$$\overline{E}_b = \frac{1}{2}E_b. \tag{4}$$

Using Eq. (4) in Eqs. (1) and (3), we obtain the ASK bit error curves shown in Fig. 1. The noncoherent system is seen to be approximately 1 dB worse than the coherent system for P_b less than 10^{-4}.

The bit error rate for an ideal coherent PSK system is (1,2)

$$P_b = erfc\sqrt{\frac{2E_b}{N_0}}. \tag{5}$$

For differential PSK, the bit error rate becomes (2)

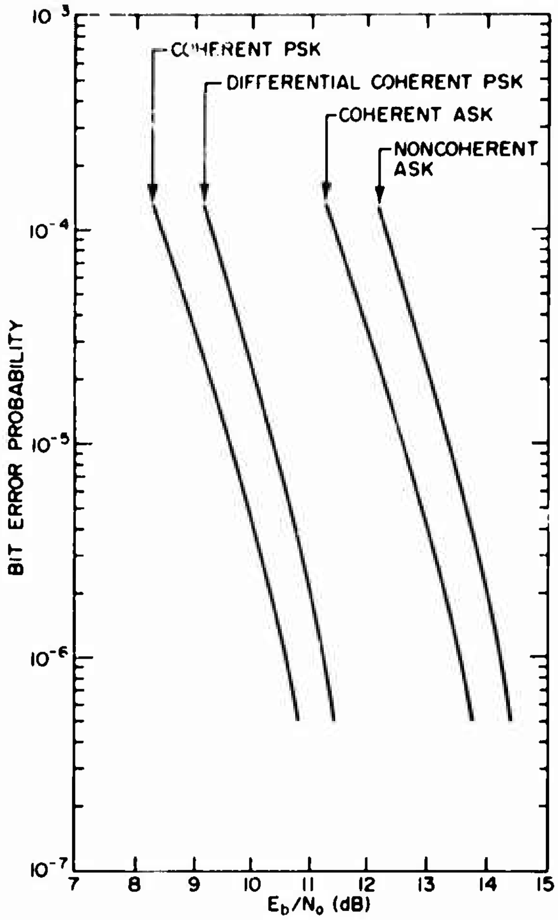


Fig. 1—Error probability curves for ASK and PSK systems

$$P_b = \frac{1}{2}\exp\left(-\frac{E_b}{N_0}\right). \tag{6}$$

We note that for PSK systems, $\overline{E}_b = E_b$. Thus Eqs. (5) and (6) yield the PSK bit error curves shown in Fig. 1. Once again, the noncoherent system is 1 dB less efficient than the corresponding coherent system.

It is seen that the coherent PSK system has a 3-dB advantage over the coherent ASK system and a 4-dB advantage over the noncoherent ASK system. Our result is contingent on the assumption of a 50% duty cycle for the ONE state in the ASK systems. If the duty cycle is sufficiently low, the ASK systems will surpass the performance of the coherent PSK system.

Our comparison has been in terms of $\overline{E}_b$. If the criterion is E_b, the coherent PSK system has a 6-dB advantage over the coherent ASK system and a 7-dB advantage over the noncoherent ASK system.

The ideal coherent QPSK system has a symbol error rate given by (1,2)

$$P_s = 2\, erfc \sqrt{\frac{E_s}{N_0}} - erfc^2 \sqrt{\frac{E_s}{N_0}}\,, \tag{7}$$

where E_s is the mean energy per symbol. If the noise in each correlator oı the QPSK receiver is independent and if the bit error rate is much less than unity, it follows that

$$P_b \approx \frac{1}{2} P_s. \tag{8}$$

Since there are two bits per symbol,

$$E_b = \frac{1}{2} E_s. \tag{9}$$

Neglecting the second term in Eq. (7) and substituting Eqs. (8) and (9), we obtain

$$P_b \approx erfc \sqrt{\frac{2E_b}{N_0}}\,, \tag{10}$$

which is the same expression as Eq. (5). Thus the performance of an ideal coherent QPSK system is almost identical to that of a coherent PSK system.

Usually measurements specify P_b as a function of the signal-to-noise ratio. If it is desired to compare the experimental results with the theoretical expressions, we must relate the signal-to-noise ratio to E_b.

Let us suppose that the signal-to-noise ratio is measured at the output of an intermediate-frequency (IF) filter having a transfer function $H(f)$. If white Gaussian noise enters this IF filter, we may define a noise bandwidth by

$$B = \int_{-\infty}^{\infty} |H(f)|^2\, df. \tag{11}$$

If the bandwidth is sufficiently wide to pass the signal energy, we then have

$$\frac{E_b}{N_0} = \frac{S}{N_0 B}(BT) = \frac{S}{N}(BT) \tag{12}$$

where S is the mean signal power in the ONE state, N is the mean noise power, and T is the bit period of the ONE state. This equation is the desired relation between E_b and S/N. If we transmit completely random NRZ patterns and if the IF filter is rectangular, we require that

$$BT \geqslant 2 \tag{13}$$

if 90% or more of the signal power is to pass the IF filter. In this case, Eq. (13) is the condition for the validity of Eq. (12).

Standard Deviation of the Arrival Time

The time at which a demodulated video signal crosses a threshold level fluctuates due to the presence of noise. In the case of coherent ASK or coherent PSK systems, the noise is stationary Gaussian. If an adaptive thresholder is used, it can be shown that the variance of the arrival time is approximately (3)

$$\sigma^2 = \frac{N}{M^2}, \tag{14}$$

where N is the mean-square value of the noise and M is the absolute value of the slope at the midpoint of the leading edge of the video pulse.

Both the signal and noise are band limited by the IF filter. If the bandwidth of the IF filter passband is sufficiently narrow, the effect of the IF filter on the video signal and noise is the same as the effect of passing the signal through a baseband filter of the same shape. To use Eq. (14), we must relate M to the parameters of this equivalent baseband filter.

Since it is desired to determine the position of the edge of a pulse, we may approximate the pulse by a step function if the pulse width is several times as great as the rise time. Assuming that the phase response of the IF filter is linear, it is easy to show that (3)

$$M = D \int_{-\infty}^{\infty} |H(f)|\, df, \tag{15}$$

where $H(f)$ is the magnitude of the transfer function of the equivalent baseband filter and D is the absolute value of the difference in voltage levels at the thresholder between the ONE state and the ZERO state. For an ASK system with a voltage level of A volts in the ONE state and 0 volts in the ZERO state, it is clear that

$$D_{\text{ASK}} = A = \sqrt{2S}, \tag{16}$$

where S is the mean power at the receiver. For a PSK system with the same mean power in the ONE state, the voltage levels are A volts in the ONE state and $-A$ volts in the ZERO state. Thus

$$D_{\text{PSK}} = 2A = 2\sqrt{2S}. \tag{17}$$

To obtain a simple expression for the standard deviation of the arrival time, it is now assumed that

$$|H(f)| = \exp\left(-\frac{f^2}{2f_0^2}\right). \tag{18}$$

From Eqs. (11) and (18), it is seen that the parameter f_0 is related to the noise bandwidth by

$$f_0 = \sqrt{\pi}\, B. \tag{19}$$

Combining Eqs. (15), (18), and (19), we have

$$M = \sqrt{2}DB. \tag{20}$$

For an ASK system, it follows from Eqs. (14), (16), and (20) that the standard deviation of the arrival time is

$$\sigma_{\text{ASK}} = \frac{0.5}{B\sqrt{\frac{S}{N}}}. \tag{21}$$

For a PSK system, it follows from Eqs. (14), (17), and (20) that

$$\sigma_{\text{PSK}} = \frac{0.25}{B\sqrt{\frac{S}{N}}}. \tag{22}$$

The comparison the Eqs. (21) and (22) indicates that the PSK system has a 6-dB better performance than the ASK system of equal mean power in the ONE state. It is noteworthy that the degree of improvement is exactly the same (6 dB) as that obtained for the bit error rate.

When noncoherent ASK is employed, the envelope-detector output has a Rice distribution; therefore, the above formulas do not apply. However, it can be shown (4) that noncoherent ASK performance will be degraded less than 0.5 dB with respect to coherent ASK when the video signal-to-noise ratio exceeds 12 dB. When this ratio exceeds 18 dB the degradation is less than 0.1 dB.

It can be shown, by methods similar to those previously described, that an ideal QPSK system has a standard deviation of arrival time which is equal to that of a PSK system with the same mean power and the same bandwidth.

Adjacent-Channel Interference

Before discussing adjacent-channel interference, it is necessary to examine the spectra of the transmitted waveforms. For an ASK system, a completely random signal process can be written as

$$s(t) = \sum_{n=-N}^{N} Ah(t - nT)a_n \cos(2\pi f_c t + \theta), \tag{23}$$

where $h(t)$ is an even function with respect to the origin and controls bit transitions, T is the bit period of the modulation, f_c is the carrier frequency, and a_n is equal to 1 with a probability of 1/2 and equal to 0 with a probability of 1/2. If can be shown that in the limit of large N the one-sided power spectral density is (5)

$$W(f) = \frac{1}{2T}|G(f)|^2 + \frac{1}{4T^2}G^2(0)\delta(f) + \frac{1}{2T^2}\sum_{m=1}^{\infty}\left|G\left(\frac{m}{T}\right)\right|^2\delta\left(f - \frac{m}{T}\right), \tag{24}$$

where

$$G(f) = \frac{A}{2}e^{j\theta}H(f - f_c) + \frac{A}{2}e^{-j\theta}H(f + f_c) \tag{25}$$

and

$$H(f) = \int_{-\infty}^{\infty} h(t)e^{-j2\pi ft}\,dt. \tag{26}$$

If the carrier frequency is sufficiently high with respect to the bandwidth of $H(f)$, we can neglect the second term of Eq. (24) and the second term of Eq. (25). Under this assumption we are left with

$$W(f) = \frac{A^2}{8T}|H(f - f_c)|^2 + \frac{A^2}{8T^2}\sum_{m=1}^{\infty}\left|H\left(\frac{m}{T} - f_c\right)\right|^2\delta\left(f - \frac{m}{T}\right). \tag{27}$$

If $h(t)$ is assumed to be an ideal rectangular pulse of duration T, it follows from Eq. (26) that

$$H(f) = \frac{\sin \pi fT}{\pi f}. \tag{28}$$

To reduce the interference with other channels, it is desirable to eliminate as many terms in Eq. (27) as possible. Examination of Eqs. (27) and (28) shows that if $f_c T$ is equal to an integer, all the terms of the summation in Eq. (27) vanish except one. We then have

$$W(f) = \frac{A^2T}{8}\left[\frac{\sin^2 \pi(f - f_c)T}{\pi^2(f - f_c)^2T^2}\right] + \frac{A^2}{8}\delta(f - f_c). \tag{29}$$

The second term in Eq. (29) does not contribute to the interference with adjacent channels and can be ignored in this application. Another way of reducing the interference produced by a channel is to use an $h(t)$ with rise and fall times less abrupt than those of the ideal rectangular pulse. This approach will be examined experimentally.

The total mean power contributed by the first term in Eq. (29) is equal to $A^2/8$. The bracketed part is plotted for $(f - f_c)T > 1$ in Fig. 2 which depicts the power distribution on one side of the carrier frequency. Approximately 90% of the power is contained in the frequency span $-T^{-1} < f - f_c < T^{-1}$. As shown in Fig. 2, 2.36% of the power then occupies the frequency span $T^{-1} < f - f_c < 2T^{-1}$, and so forth. This figure can be used to determine the interference with an adjacent channel which has a nearby carrier frequency.

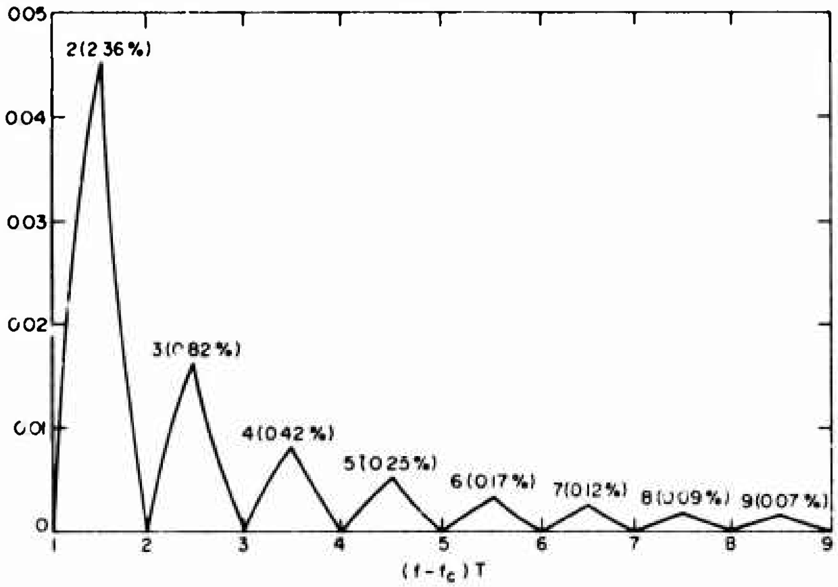


Fig. 2—Normalized power spectral density

For a PSK system, a completely random signal process can be described by Eq. (23) with a_n equal to 1 with a probability of 1/2 and equal to -1 with a probability of 1/2. It can be shown that in the limit of large N the one-sided power spectral density is

$$W(f) = \frac{2|G(f)|^2}{T}, \tag{30}$$

where $G(f)$ is given by Eq. (25). Under the assumption that the second term in Eq. (25) is negligible in the frequency range of interest, Eq. (30) becomes

$$W(f) = \frac{A^2}{2T}|H(f - f_c)|^2. \tag{31}$$

Looking at Eq. (27), it is seen that except for a scale factor the PSK spectrum has the same shape as the continuous part of the ASK spectrum. When Eq. (28) applies,

$$W(f) = \frac{A^2}{2}T\left[\frac{\sin^2 \pi(f - f_c)T}{\pi^2(f - f_c)^2T^2}\right], \tag{32}$$

which yields the same distribution as ASK, except that the ordinates must be multiplied by a factor of 4.

For a QPSK system with equally likely symbols, it can be shown that the one-sided power spectral density is (5)

$$W(f) = \frac{A^2}{2T_s}\left[|H(f - f_c)|^2 + |H(f + f_c)|^2\right], \tag{33}$$

where T_s is now the symbol period. Under the usual assumption that the second term in Eq. (33) is negligible and assuming that the symbol period is twice the bit period, the latter equation becomes

$$W(f) = \frac{A^2}{4T} |H(f - f_c)|^2. \tag{34}$$

If $h(t)$ is an ideal rectangular pulse of duration $T_s = 2T$, from Eqs. (26) and (34) we obtain

$$W(f) = A^2 T \left[\frac{\sin^2 2\pi(f - f_c)T}{4\pi^2 (f - f_c)^2 T^2}\right], \tag{35}$$

which has the shape indicated in Fig. 2 except that now the abcissa values must be multiplied by 2. Clearly, QPSK achieves a substantial reduction in adjacent-channel interference with respect to PSK.

The degradation due to adjacent-channel interference will now be investigated. To obtain simple formulas, it is assumed that the intefering channels operate asynochronously and that the interference has the characteristics of white Gaussian noise. The synchronous case will be studied experimentally.

According to Eq. (12), the degradation in bit error rate, at a fixed value of BT, can be determined by calculating the decrease in the signal-to-noise ratio due to the presence of an interfering channel.

We now make the following definitions:

S = the signal power at the receiver;

N = the noise power at the receiver;

N' = the equivalent noise power at the receiver due to the interference of an asynchronous adjacent channel.

The signal-to-noise ratio is reduced by the presence of N', which is independent of N. The signal-to-noise ratio, the decibels, can be expressed as:

$$10 \log \frac{S}{N + N'} = 10 \log \frac{S}{N} - 10 \log \left(1 + \frac{N'}{N}\right). \tag{36}$$

Thus the change in signal-to-noise ratio due to adjacent channel is

$$C = 10 \log \left(1 + \frac{N'}{N}\right), \tag{37}$$

where the units of C are in decibels and

$$N' = \int_{-\infty}^{\infty} |R(f)|^2 W(f)\, df. \tag{38}$$

In this equation, $R(f)$ is the transfer function of the IF filter of the receiver of interest, and $W(f)$ is the power spectral density of the interfering channel.

It can be shown, by similar methods, that the standard deviation of a detected pulse is given by

$$\sigma = \sigma_0 \sqrt{1 + \frac{N'}{N}}, \tag{39}$$

where σ_0 is the standard deviation that would exist in the absence of adjacent-channel interference.

Intersymbol Interference

Intersymbol interference is due to signal overlap from one bit interval to the next. In this section we will obtain an upper bound for the degradation due to this effect. We assume that a received bit is appreciably affected only by the preceding bit and the succeeding bit. In the worst case, these two interfering bits are in opposite states to the received bit. For example, a bit in the ZERO state flanked by bits in the ONE state is shown in Fig. 3. Due to the finite bandwidth of the IF filter, each flanking bit contributes $\Delta/2$ volts of interference at the midpoint of the interval of the ZERO bit. The midpoint is the sampling time of the ZERO bit. At this time the detector makes a decision regarding the state of the bit. Suppose the threshold level is L volts above the level of a ZERO bit. Clearly, if the bit error probability is to remain the same as it would be in the absence of intersymbol interference, the threshold level should be raised to $L + \Delta$ volts above the level of a ZERO bit. For ASK systems, $L = A/2$, where A is the amplitude of a bit in the ONE state. For PSK and QPSK systems, $L = A$. Thus for the modulation systems under consideration, the received power is proportional to the square of the threshold level. Let P_1 be the power in a system without intersymbol interference. Let P_2 be the power required to maintain the same bit error rate in the presence of intersymbol interference. It follows from this previous discussion that

$$\frac{P_2}{P_1} = \frac{(L + \Delta)^2}{L^2}. \tag{40}$$

The degradation, measured in decibels, is

$$C = 10 \log_{10} \left[\frac{(L + \Delta)^2}{L^2}\right] \tag{41}$$

To calculate the value of Δ, one must know the filter shape and bandwidth.. If the filter is Gaussian with bandwidth B, it can easily be shown, using Eqs. (18) and (19), that

$$\Delta = 2A\, erfc\left(\sqrt{\pi} BT\right), \tag{42}$$

where T is the bit period and $erfc\ (x)$ was defined in Eq. (2). Substituting Eq. (44) into Eq. (43), there results

$$C = 20 \log_{10} \left[1 + \frac{2A}{L} erfc\left(\sqrt{\pi} BT\right)\right]. \tag{43}$$

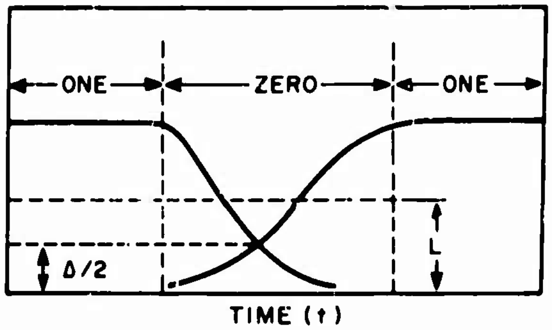


Fig. 3—Intersymbol interference

When Eq (13) is satisfied, the second term in the brackets of Eq. (43) is very small for the modulation systems under consideration. Thus, retaining only the first term in a Taylor-series expansion, Eq. (43) simplifies to

$$C = (40 \log_{10} e) \frac{A}{L} \, erfc \, \sqrt{\pi} BT. \tag{44}$$

For ASK systems, it follows that

$$C = (80 \log_{10} e) \, erfc \, (\sqrt{\pi} BT). \tag{45}$$

For PSK and QPSK systems, it follows that

$$C = (40 \log_{10} e) \, erfc \, (\sqrt{\pi} BT). \tag{46}$$

For the practical case of $BT > 2$, it is seen that $C < 0.035$ dB for all three modulation systems. Thus intersymbol interference is a minor effect which will be ignored in the remainder of this report.

EXPERIMENTAL DATA

Amplitude Shift Keying (ASK)

The data presented for this study were measured on a breadboard nonsynchronous ASK receiver and on a breadboard adaptive thresholder. This thresholder, called the peak-amplitude estimator, has been described in the literature (3).

This section will be presented in three parts: (a) measurements of standard deviation vs signal level (b) the effect on standard deviation due to the presence of an adjacent channel, and (c) bit error rate of an ASK system vs signal level. Each section will provide a brief description and the results of the test.

Figure 4 is a test block diagram illustrating the setup used to measure standard deviation σ vs signal level for a noncoherent ASK system. The receiver for this test has a noise bandwidth of 707 kHz and a tangential sensitivity of -103.2 dBm (with a 2.8-dB system noise figure). The video pulses out of the receiver are detected by a 50%-amplitude thresholder.

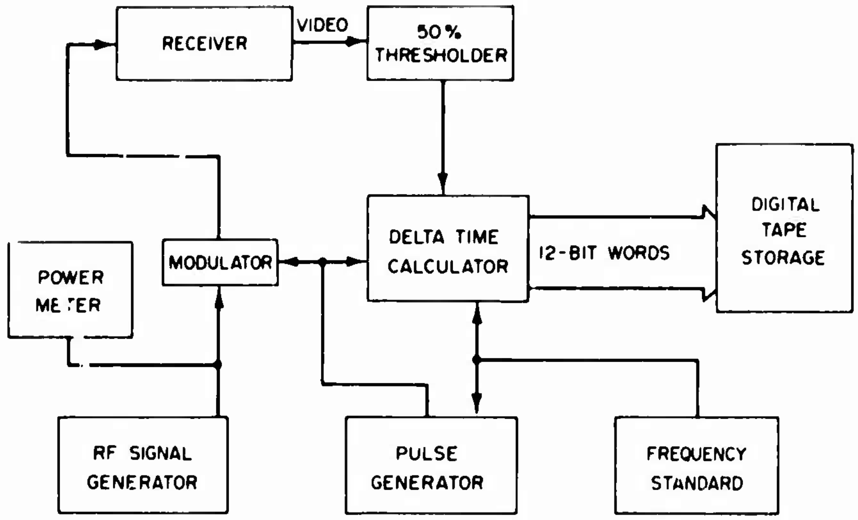


Fig. 4—Test setup to measure standard deviation in the ASK system

The time interval between the modulation pulse or reference pulse and the detected pulse is measured by the Delta time calculator. This unit quantizes the time interval to 0.05μs and outputs two 6-bit words for each event. The data is then stored on magnetic tape and processed on the CDC 3800 computer.

Figure 5 illustrates the effects of transmitter rise time on system standard deviation. Shown here is a family of curves plotted at three signal strengths. From this graph it can be observed that there is little degradation of standard deviation at 750-ns transmitter rise-time. With the assumption that a 750-ns risetime is desired, data of standard deviation vs signal level were taken and the results plotted in Fig. 6.

The predictions of Eq. (21), when B = 707 kHz, are shown in Table 1. Most of the difference between these values and the measured ones results because Eq. (1) refers to a coherent ASK system, whereas the measurements were made with a noncoherent ASK system. However, at 28.5 dB the error is primarily due to quantization effects.

This paragraph will describe the effects on standard deviation of an ASK system due to the presence of an adjacent channel separated by 2 MHz. Figure 7 is a block diagram of the system used to conduct this test. The receiver is the ASK receiver with the 707-kHz noise bandwidth used in the previous test. This test will be conducted in two parts: (1) with the modulation of the two carriers synchronous, i.e., both modulated at the same time and (2) with the modulation of the two carriers nonsynchronous.

Test 1 was conducted with two signals: f_0 the desired signal, and f_2 the adjacent-channel signal, with both signals at the same strength and modulated simultaneously. The family of curves of Fig. 8 shows the transmitter rise time and its effects on system standard deviation. The vertical axis is the percent of degradation with respect to a received channel without an adjacent channel. The three curves are measured at representative signal levels.

Test 2 was conducted with the modulations of the two signals (f_0 and f_2) nonsynchronized, and the results are plotted as Fig. 9. This test is the more representative situation that can be expected in actual operation.

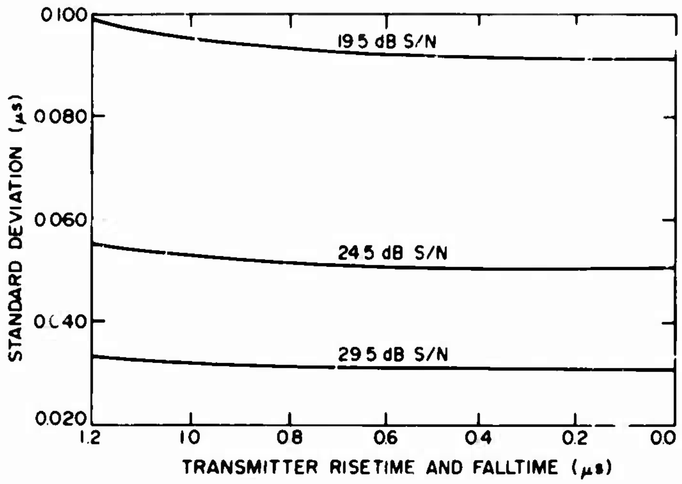


Fig. 5—Effects of the transmitter rise time of the ASK system for three signal-to-noise ratios

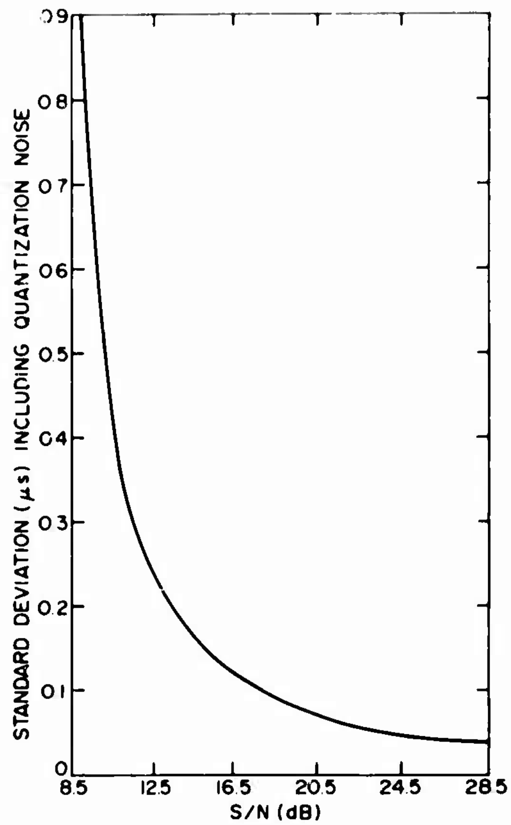


Fig. 6—ASK standard deviation. Transmitter rise time and fall time are 750 ns; receiver bandwidth is 707 kHz.

Table 1
ASK Standard Deviation

S/N (dB)	σ (μs)
12.5	0.168
16.5	0.106
20.5	0.067
24.5	0.042
28.5	0.027

Assuming a Gaussian IF filter with a 707-kHz noise bandwidth, Eqs. (29), (38), and (39) can be used to compute the theoretical degradation in the 0-rise-time case. The results are indicated in Table 2 and should be compared with Fig. 9. The symbol *S/N* is the ratio of mean signal power in the ONE state of the interfering channel to the mean noise power in the receiver. If all channels transmit the same mean signal power, *S/N* is the usual signal-to-noise ratio at the receiver IF filter output.

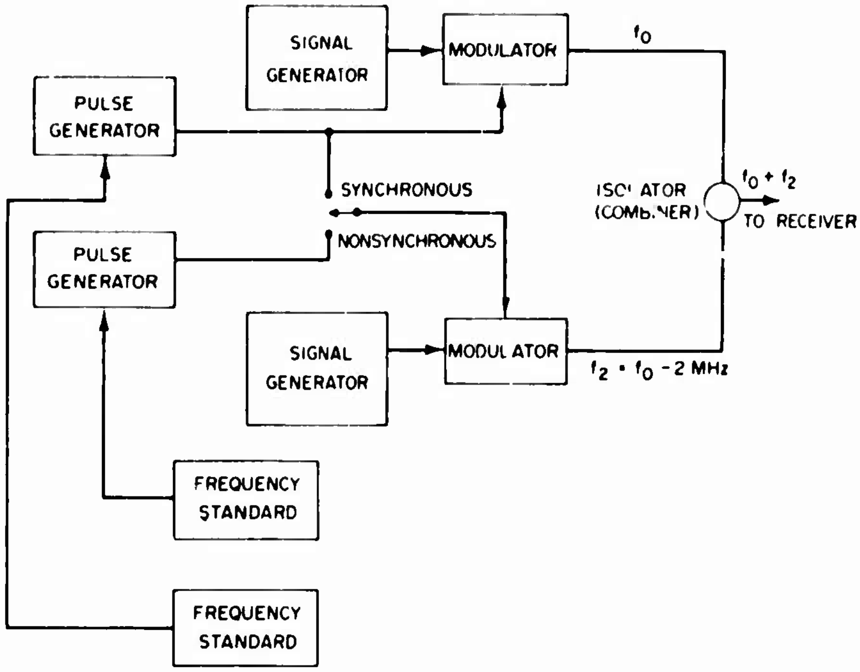


Fig. 7—Test setup for the effects of an adjacent channel on the ASK system

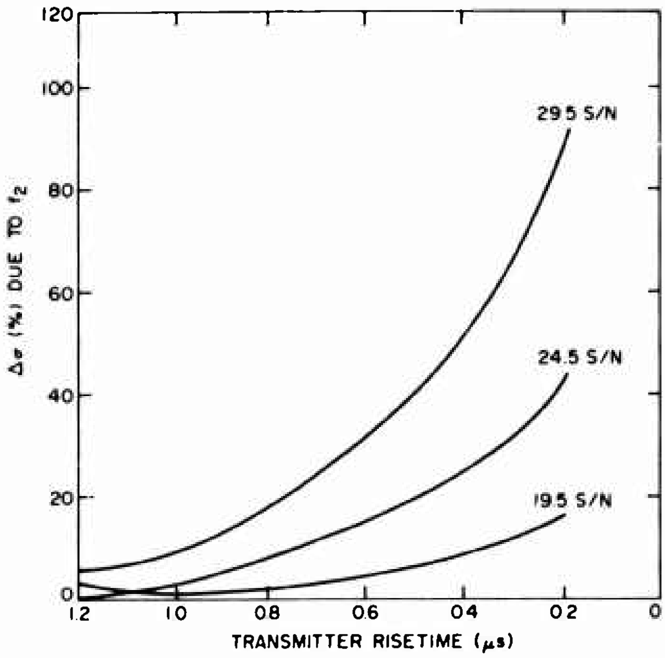


Fig. 8—Test results for synchronous carriers

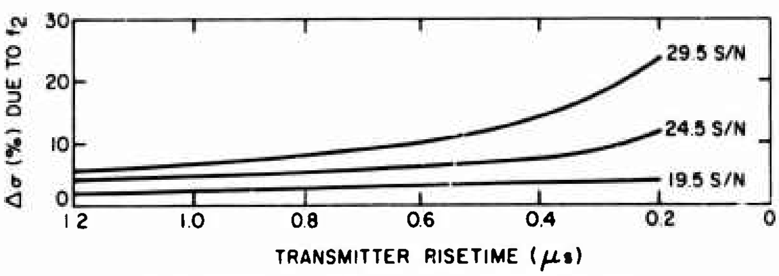


Fig. 9—Test results for nonsynchronous carriers

Table 2
ASK Adjacent-Channel Interference

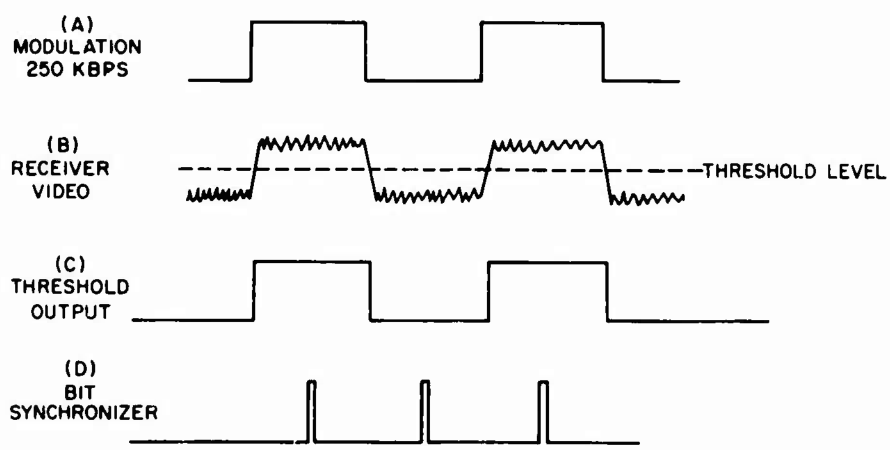
S/N (dB)	$\Delta\sigma$ (%)
19.5	15.9
24.5	44.5
29.5	110.7

The breadboard ASK receiver was used to test for bit errors of a digital data stream. A simple bit synchronizer was constructed for this test, and a brief description of this unit is shown in Fig. 10. The ASK receiver for this test has a bandwidth of 707 kHz, with a fixed thresholder set at the 50%-amplitude points of the data. The results of this test are provided in Fig. 11, which is a plot of signal-to-noise ratio vs bit error. This test was run at 250 kbps.

A comparison of Fig. 11 with the performance of an ideal noncoherent ASK receiver can be obtained by using Eqs. (5) and (12). It is found that the experimental system is approximately 2 dB less than ideal in the vicinity of $P_b = 10^{-6}$.

Phase Shift Keying (PSK)

The data presented were measured on a breadboard synchronous PSK biphase receiver. The data will be presented in three parts: (a) bit error rate vs signal-to-noise ratio, (b) the effects of cross-channel interference, and (c) standard deviation vs signal level. Each part will provide a brief description and the results of each test.



$$\text{BIT ERROR} = (A \cdot \bar{C}) + (\bar{A} \cdot C)$$

$$\text{BIT ERROR RATE} = \frac{\text{NUMBER OF BIT ERRORS}}{\text{NUMBER OF SAMPLES}}$$

Fig. 10—Bit-error-rate detector waveforms

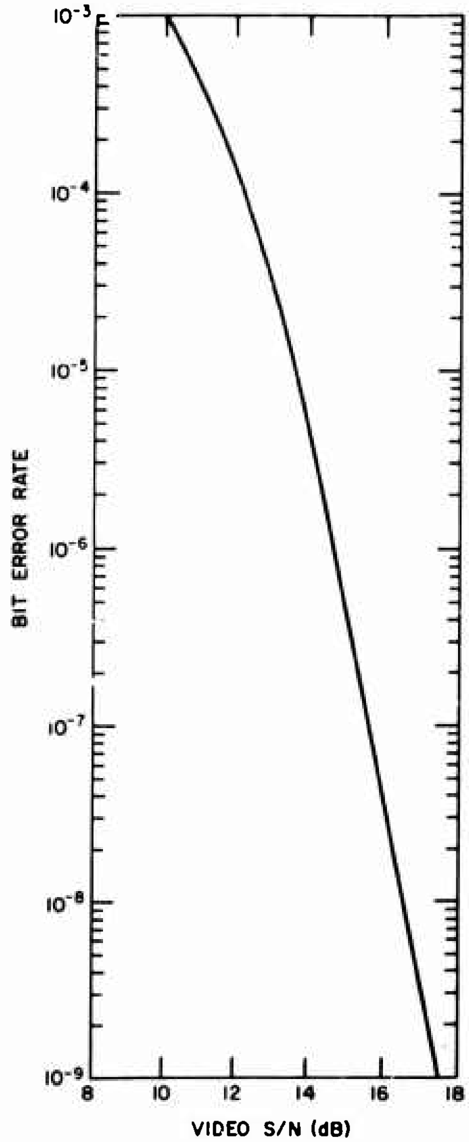


Fig. 11—ASK bit error probability

Most of the tests were performed with the following assumptions:

- Data rate = 333.33 kbps
- Modulation type = Biphase, 180° separation
- Receiver IF noise bandwidth = 766 kHz
- Modulation type = NRZ psuedorandom code
- Modulation bandwidth = 750-ns rise time for a 180° shift

Figure 12 illustrates the test setup for the PSK measurements. Shown here are three frequency sources f_1, f_2, and f_3 which are phase modulated by balanced mixers. The receiver for all these tests will be tuned to f_2, so that f_1 and f_3 are adjacent channels which are ± 2 MHz from f_2. Signals f_1 and f_3 will be injected for cross-channel-interference measurements.

All data will be pseudorandom in nature and are passed through a low-pass filter to control the rise time of the modulators.

Figure 13 is a block diagram of the receiver; Figure 14 is a block diagram of the bit synchronizer used in this test. The manner in which the phase-locked loop of Fig. 13 coherently demodulates the PSK signal is described in the literature (6).

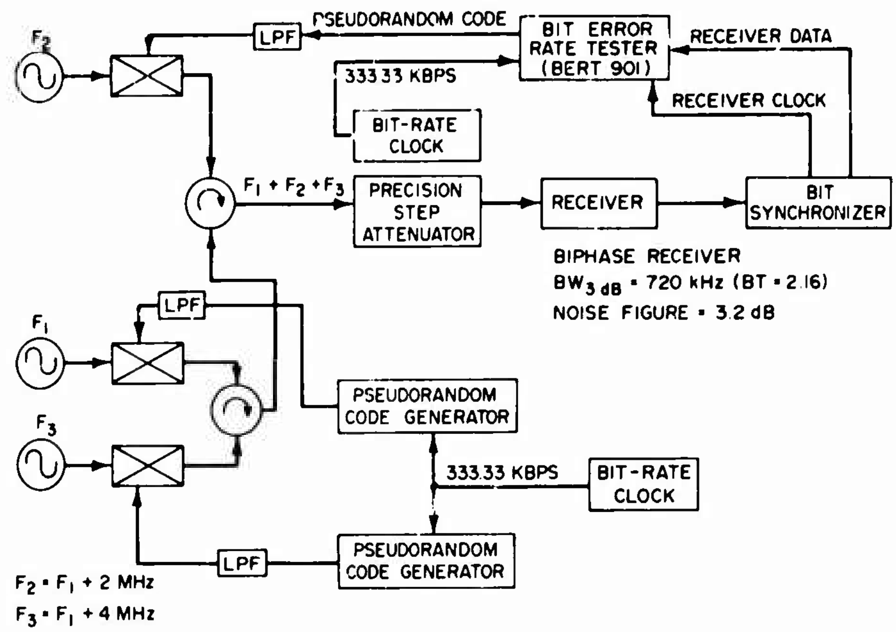


Fig. 12—Biphase bit-error setup

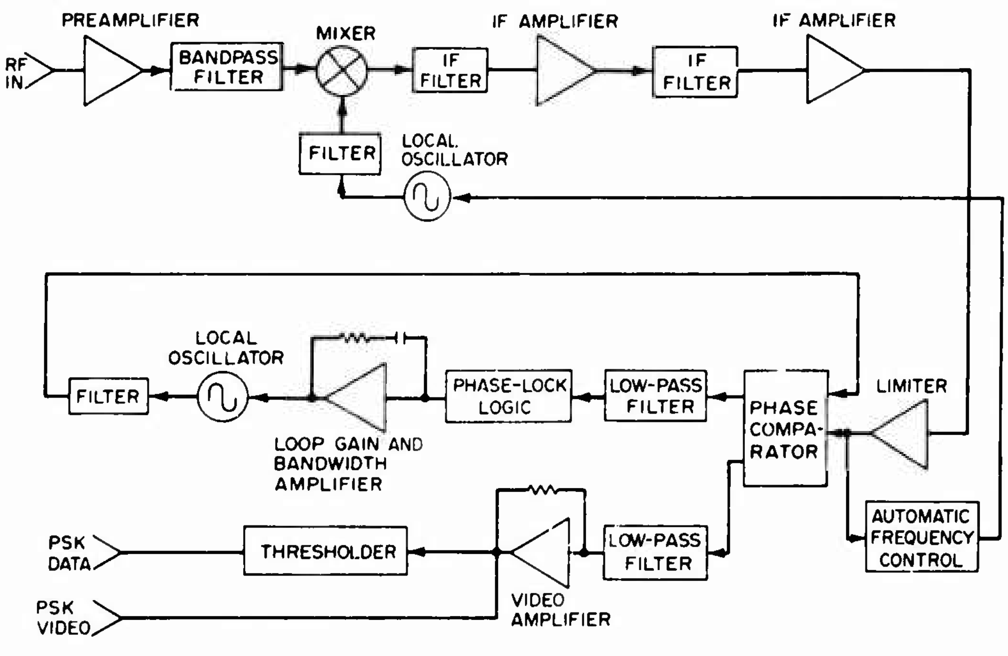


Fig. 13—Biphase PSK receiver

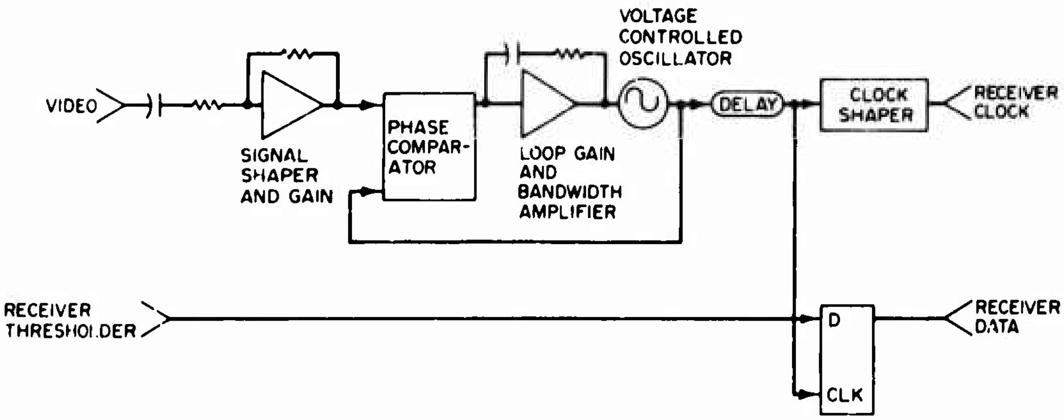


Fig. 14—Bit synchronizer

The spectrum reduction due to the addition of the low-pass filter is shown in Figs. 15a and 15b, and the addition of adjacent channels, f_1 and f_3, is shown in Fig. 15c. The receiver IF response is shown in Fig. 16. These illustrations are intended to document the type of test conducted.

The following test was conducted by modulating f_2 with a pseudorandom code, detecting it in the receiver/bit synchronizer, and comparing the transmit/receive data patterns with a bit-error-rate tester. The signal-level calibration was accomplished by measuring the IF noise power with a true-RMS meter and then adjusting the signal level until the noise power and signal power were identical (0 dB S/N). With the accuracy of equipment used, the setting accuracy of 0-dB S/N is approximately ±0.1 dB, and this accuracy can be maintained through 20 dB S/N to a confidence of ±0.12-dB S/N.

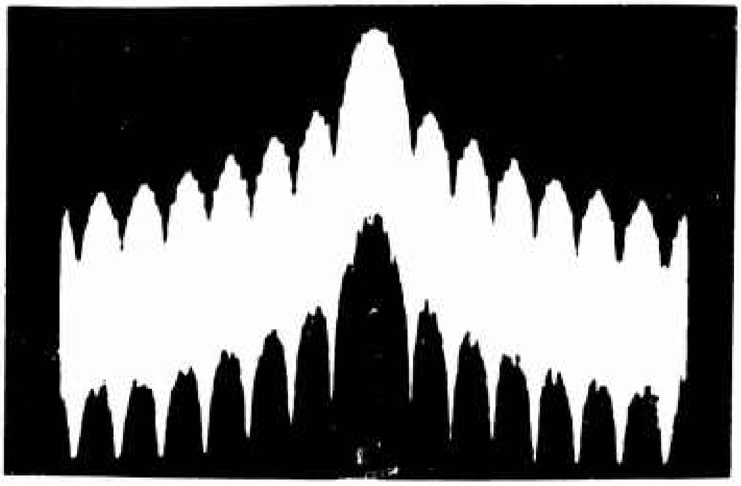
Figure 17 shows the measured data of bit error rate vs signal-to-noise ratio. It is obvious from this graph that an 8.5-dB S/N is required to maintain a bit error rate of 1 in 10^6.

A comparison of Fig. 17 with the performance of an ideal coherent PSK receiver can be obtained by Using Eqs. (5) and (12). It is found that the experimental system is approximately 1.3 dB less than ideal in the vicinity of $P_b = 10^{-6}$.

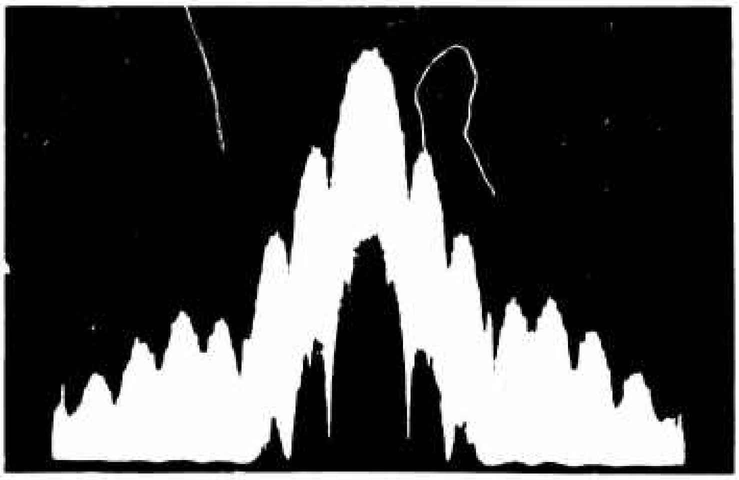
A test of adjacent-channel interference is conducted by injecting adjacent channels f_1 and f_3 with the receiver tuned to f_2. The channel separation is 2 MHz, and the data are pseudorandom at 333.33 kbps. The bit-rate clocks for each channel are nonsynchronous to produce an operational condition.

Figure 18 illustrates the degradation of the receiver performance in the presence of (a) one adjacent channel f_1 and (b) two adjacent channels f_1 and f_2. It is noted that the worst case degradation of 0.25 dB is measured at 9-dB S/N.

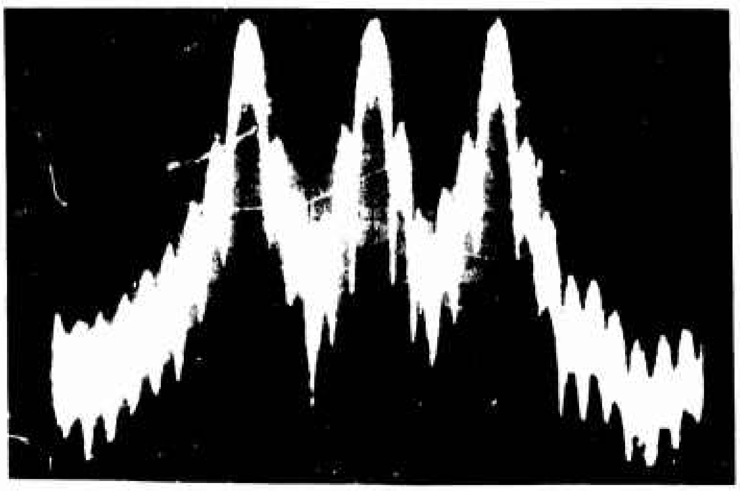
Assuming a Gaussian IF filter with a 766-kHz noise bandwidth, Eqs. (32), (37), and (38) can be employed to calculate the loss in signal-to-noise ratio in the 0-rise-time case. Table 3 shows the results for one or two interfering channels. It is assumed that all channels transmit the same mean signal power. Hence, S/N is the signal-to-noise ratio at the output of the receiver IF filter.



(a) PSK biphase modulation; 30-ns rise time; 0.5 mHz per horizontal division



(b) PSK biphase modulation; 750-ns rise time; 0.5 mHz per horizontal division.



(c) PSK biphase modulations; $f_1 + f_2 + f_3$; 750-ns rise time; 1 MHz per horizontal division

Fig. 15—PSK modulation spectrum; NRZ pseudorandom code at 333.33 kbps; 10 dB per vertical division

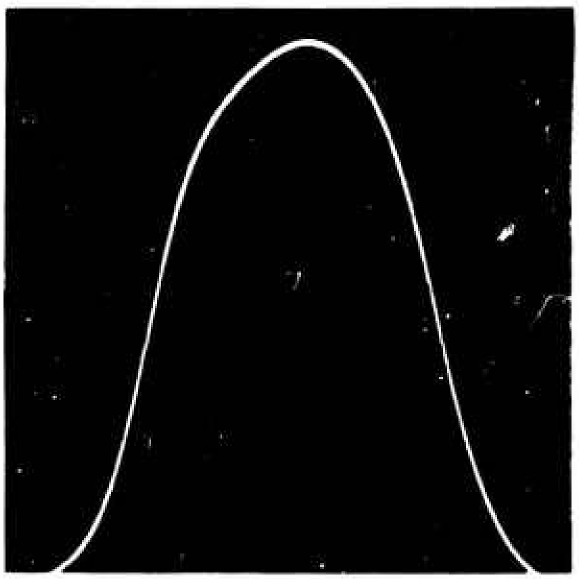


Fig. 16—If bandwidth of PSK biphase receiver; 200 kHz per horizontal division; 1 V^2 per vertical division

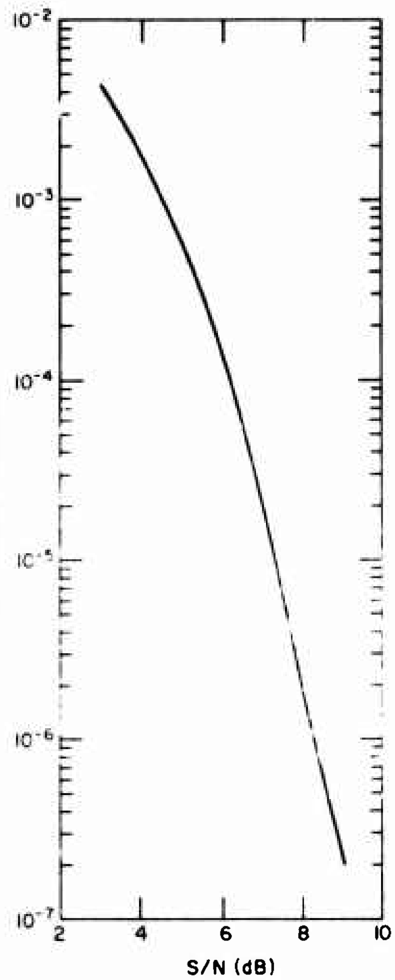


Fig. 17—Biphase PSK bit error probability

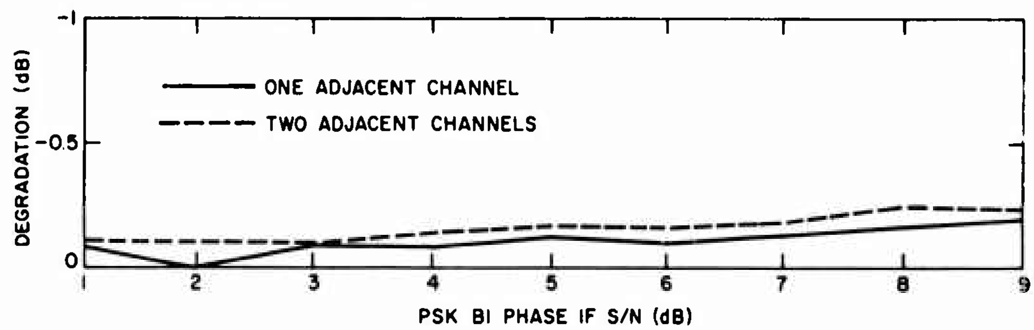


Fig. 18—Degradation of signal-to-noise ratio due to cross-channel interference

Table 3
PSK Adjacent-Channel Interference

S/N (dB)	Degradation with one interfering channel (dB)	Degradation with two interfering channels (dB)
3	0.023	0.045
6	0.045	0.089
9	0.089	0.177

The standard deviation vs signal-to-noise ratio of a biphase PSK receiver is illustrated in Fig. 19. This test was conducted by thresholding the video output at the 50%-amplitude points and computing the standard deviation of 5000 events. Time intervals are quantized to 0.05 μs. The predictions of Eq. (22), when B = 766 kHz, are given in Table 4. Even when quantization effects are taken into account, it is found that there is considerable difference between the measured values and the computed ones for the lower values of S/N. Better agreement is obtained when more accurate formulas found in the literature (3) are used in place of Eq. (22).

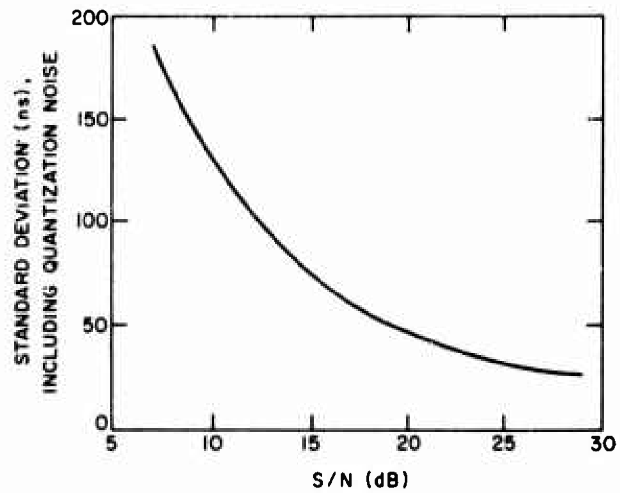


Fig. 19—Biphase PSK standard deviation

Table 4
PSK Standard Deviation

S/N (dB)	σ (ns)
12.5	77.5
16.5	48.9
20.5	30.9
24.5	19.4
28.5	12.5

Quadriphase Shift Keying (QPSK)

The data presented for the study were measured on a breadboard quadriphase PSK receiver. The data are presented in three parts: (a) bit error probability vs signal-to-noise ratio, (b) the effects of cross-channel interference, and (c) standard deviation vs signal level. Each part will show the test results along with a brief description of each test.

All of the following tests were conducted with the following conditions:

- Modulation type = quadriphase
- Data type = NRZ pseudorandom code
- Data rate = 166.66×10^3 symbols/s
- Modulation bandwidth = 1500-ns rise time
- Receiver IF noise bandwidth = 395 kHz

Figure 20 illustrates the test setup for QPSK measurements and shows two frequency sources f_1 and f_2 which are quadriphase modulated. The receiver is tuned to the test-channel f_2; the adjacent-channel f_1 is separated from f_2 by 2 MHz. All data are pseudorandom in nature and passed through a low-pass filter to control the transmission bandwidth.

Figure 21 illustrates the QPSK receiver and demodulator with the parallel data outputs. The test was accomplished by converting a serial 333.33-kbps data stream into a parallel 166.66-kbps data stream at the modulator and by recombining the parallel receiver outputs back into a serial data stream. The input/output errors are compared in a bit-error tester. Figure 22 and 23 illustrate the transmission spectrum and the receiver IF response for these tests respectively.

The bit-error test was conducted by modulating f_2 with a pseudorandom code, detecting it in the receiver/bit synchronizer, and comparing the transmit/receive data patterns

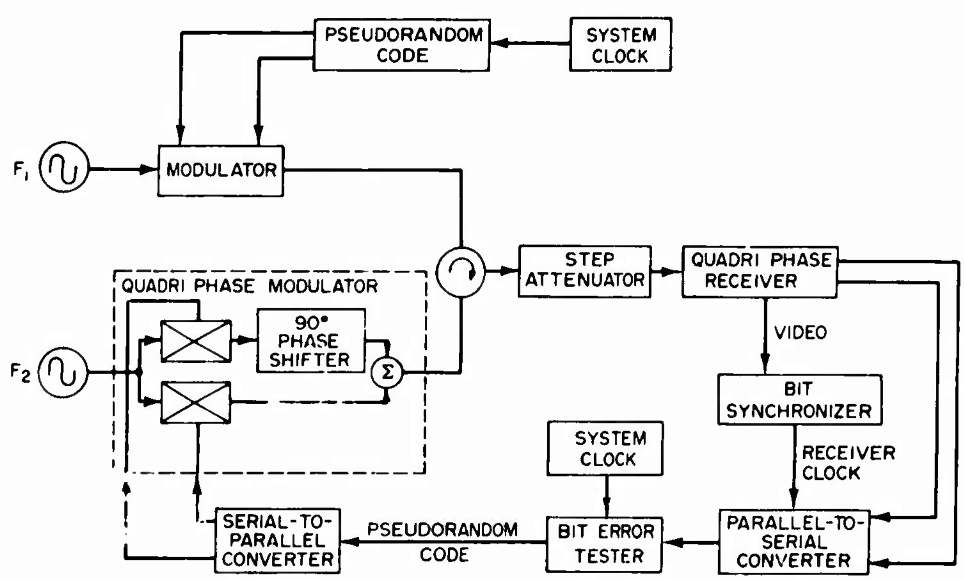


Fig. 20—Quadriphase test setup

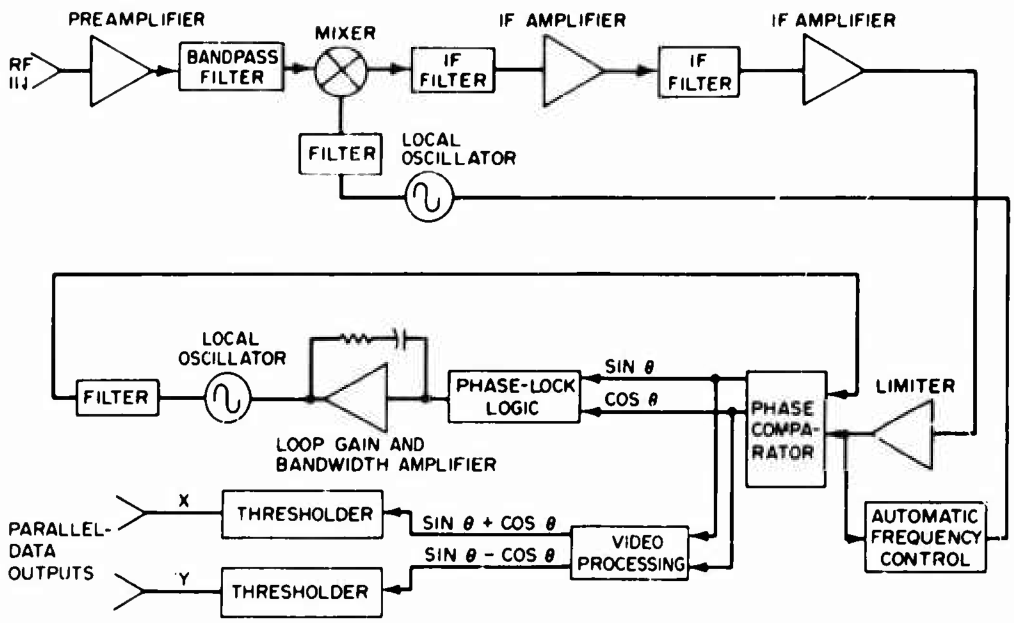


Fig. 21—Quadriphase PSK receiver

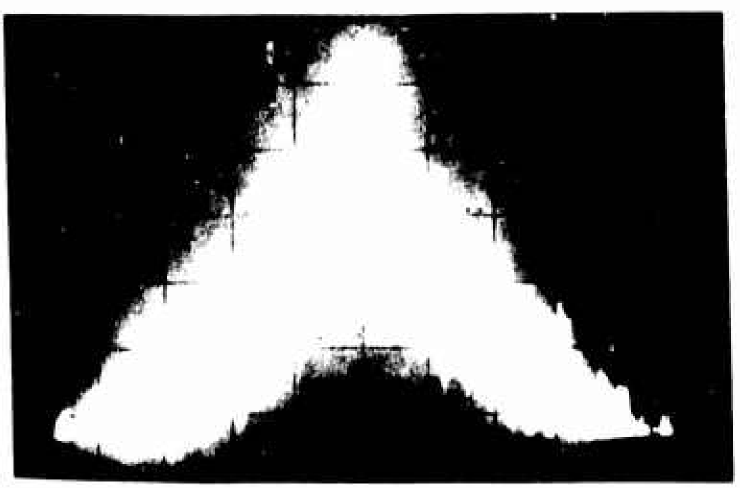


Fig. 22—Quadriphase phase spectrum. Quadriphase modulation; 1500-ns rise time; NRZ pseudorandom code at 333.33 kbps; 0.5 MHz per horizontal division; 16 dB per vertical division

with a bit-error-rate tester. The signal-to-noise ratio is measured by the same method as that for biphase PSK measurements. Figure 24 shows the results of these tests by plotting bit error probability vs signal-to-noise ratio in the IF filter of the receiver. From this test it can be seen that for an error probability of 1 in 10^6, a 11.4-dB S/N is necessary.

Equations (10) and (12) can be used to plot the theoretical and experimental results on the same set of axes. It is found that the experimental system is approximately 1.55 dB worse than the ideal in the vicinity of $P_b = 10^{-6}$.

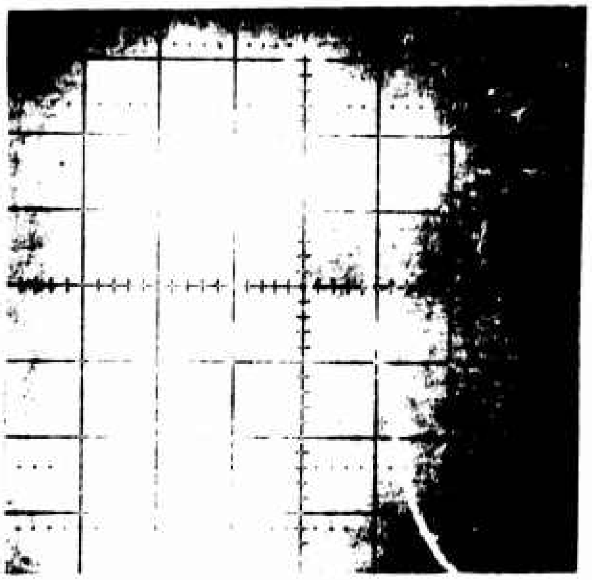


Fig. 23—IF response of quadriphase PSK receiver; 200 kHz per horizontal division; 1 V^2 per vertical division

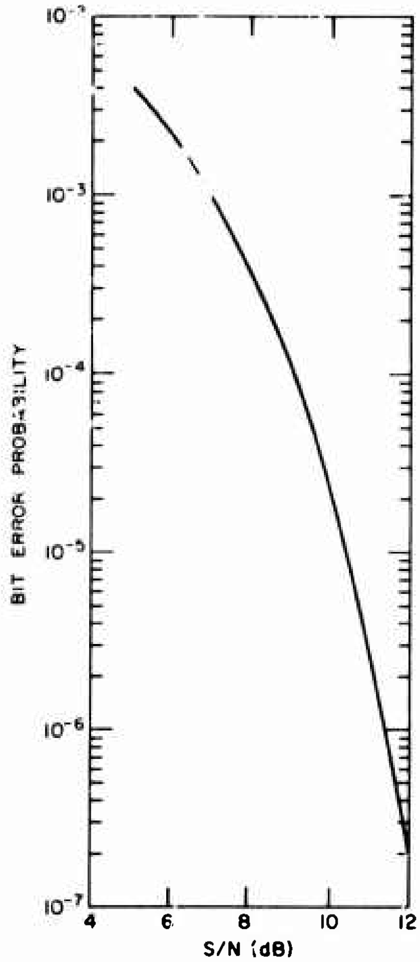


Fig. 24—Quadriphase bit error probability

The tests conducted by injecting an adjacent channel $f_1 = f_2 - 2$ MHz at the same power level showed that no detectable interference can be expected; therefore, no data are presented. The reasonableness of this observation can be established by substituting Eqs. (35) and (38) into Eq. (37) or Eq. (39).

SUMMARY

The most important relation for purposes of comparison of digital systems is the probability of bit error as a function of mean power per bit. This function can be plotted from the theoretical or experimental plots of this report by using Eqs. (4) and (12). Equation (4) applies in the case of ASK with a 50% duty cycle.

The theoretical bit-error rates are shown in Fig. 1. The relatively inferior performance of ASK systems is partially compensated by their simplicity and reliability. Since PSK and QPSK systems give nearly identical bit error rates, other criteria must be considered in comparing these systems. The two most important are adjacent-channel interference and ease of implementation.

It was shown that QPSK systems are considerably more resistant to adjacent-channel interference than are PSK systems. However, it should be noted that the PSK degradation can be reduced by extending the rise times of the modulating pulses.

The difficulties encountered in implementing a QPSK system are much greater than those for a PSK system. Also, the extra hardware required by a QPSK system lowers its reliability relative to that of a PSK system.

An upper bound on intersymbol interference was derived. For the modulation systems studied, intersymbol interference could be neglected as long as $BT > 2$, where B is the receiver noise bandwidth.

In comparing analog modulation systems, the standard deviation of the arrival time of received pulses is the most important parameter. The results obtained for the standard deviation in ASK and PSK systems can be applied readily to AM/PDM, PM/PDM, AM/PPM, and PM/PPM systems. Both theory and experiment confirm the significantly lower standard deviation in the PM systems. However, the AM systems are simpler and more reliable and conserve energy when the duty time of transmitted pulses is small.

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