# A Comparison of Modulation Techniques for Digital Radio

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***Abstract*—This paper describes and summarizes the characteristics of the modulation techniques most applicable to digital radio. The modulation techniques discussed are on-off-keying (OOK) with coherent and noncoherent detection, quadrature amplitude modulation (QAM), quadrature partial response (QPR), frequency-shift-keying (FSK) with noncoherent detection, continuous phase FSK (CP-FSK) with coherent and noncoherent detection, minimum-shift-keying (MSK), binary and quaternary phase-shift-keying (BPSK, QPSK) with coherent and differentially coherent detection, offset-keyed QPSK (OK-QPSK), $M$-ary PSK with coherent detection ($M = 8, 16$), and 16-ary amplitude and phase-shift-keying (APK). Functional descriptions of these schemes are provided and their performance is compared in a series of tables summarizing the results of the literature of the past 20 years. The modulation schemes are compared with respect to ideal (white Gaussian noise) performance, spectral properties, signaling speed, complexity, and the effects on performance of interference, fading and delay distortion.**

## I. INTRODUCTION

THE crowded conditions prevailing in many regions of the radio spectrum combined with the increased emphasis on digital transmission have created a need for improved spectrum utilization techniques. The intelligent application of efficient digital modulation techniques provides one means of achieving improved spectral efficiency at a reasonable cost. This survey identifies and describes some of the more important modulation schemes applicable to digital radio, including some that have been developed in recent years and are not discussed in the classic textbooks. This paper should be of interest to anyone involved in communications planning and communications system engineering.

Much previously published material has been devoted to comparing the performance of digital modulation methods. In many cases, comparisons were limited to one performance criterion (e.g., performance in a restricted band [26], spectral occupancy [76], effects of phase distortion [116], or crosstalk [118, 115]). In other cases [77, 98, 165, 192], relatively few modulation schemes were considered. This paper presents an up-to-date comparison of the modulation methods of particular applicability to digital radio channels, and provides an indexed bibliography for readers interested in greater depth.

Section II provides functional descriptions of the modulation schemes considered to be representative of the techniques appropriate for digital radio applications. Section III summarizes the performance characteristics of the representative modulation schemes by means of a series of tables together with source references where complete details can be found. The modulation schemes are compared with respect to ideal performance, spectral properties, signaling speed, complexity and the effects on performance of interference, fading and delay distortion.

## II. DESCRIPTIONS OF THE REPRESENTATIVE MODULATION SCHEMES

There are three basic modulation techniques: amplitude modulation (AM), frequency modulation (FM), and phase modulation (PM). Each of these basic techniques has a large number of variants, the most relevant of which will be discussed briefly in this section. In recent years hybrid schemes (e.g., amplitude-and-phase-shift-keying—APK) have received increased attention because of their inherent economical use of bandwidth. Therefore, 16-ary APK is included as being representative of this large class of modulation techniques [177].

The primary components of a system for transmitting digital data over a radio channel are illustrated in Figure 1. All of the digital modulation schemes discussed in this paper can be conceptualized in terms of radio frequency sinusoids (carriers) modulated by low frequency (baseband modulation) signals that convey the digital information. These baseband modulation signals may be filtered, weighted, or otherwise shaped prior to modulating the carrier in order to achieve desirable results. At the receiver, the baseband information is recovered by a detection process. Coherent detection requires a sinusoidal reference signal perfectly matched in both frequency and phase to the received carrier. This phase reference may be obtained either from a transmitted pilot tone or from the modulated signal itself. Noncoherent detection, being based on waveform characteristics independent of phase (e.g., energy or frequency) does not require a phase reference.

Usually, detection is followed by a decision process that converts the recovered baseband modulation signal into a sequence of digital bits. This process requires bit synchronization, which is generally extracted from the received waveform. With most modulation schemes, decisions can be made on a bit-by-bit basis with no loss in performance, but with some schemes an advantage can be gained by examining the signal over several bit intervals prior to making each bit decision. The portion of the received waveform examined by the decision device in making a single bit decision is called the observation interval.

### *Amplitude Modulation (AM) Techniques*

The simplest digital AM technique is double sideband (DSB) AM [79, pp. 173 ff] modulated by a binary signal. The double

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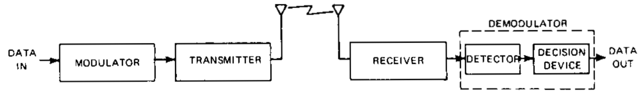

Figure 1: Primary Components of a Digital Radio System

sideband waveform is represented as:

$$f_{\mathrm{DSB}}(t) = \frac{A}{2}\,[1 + m(t)]\cos \omega_c t \qquad (1)$$

where $m(t)$ is the modulating signal and $\omega_c$ is the carrier frequency (in radians per second). For the case of 100 percent modulation by a non-return-to-zero (NRZ) binary data waveform ($m(t) = \pm 1$), we have on-off-keying (OOK) modulation. Such an OOK waveform can be detected either coherently or noncoherently, but the difference in performance is slight compared to the required increase in complexity so that coherent detection of OOK is not employed over radio channels. The properties of the DSB waveform can be modified by replacing the NRZ $m(t)$ by some other type of binary baseband signal[1] (e.g., the "partial response" signal [18, 20, 34]).

Since the carrier conveys no information, efficiency can be improved by the use of double sideband suppressed carrier (DSB-SC) AM. The general form of the DSB-SC signal is:

$$f_{\mathrm{SC}}(t) = A\, m(t) \cos \omega_c t. \qquad (2)$$

For the case where $m(t)$ takes on the values 0 and 1, we have the OOK situation described in the previous paragraph. When $m(t)$ takes on the values $-1$ and 1, we have the case of binary phase-shift-keying (PSK), which will be discussed under PM techniques.

Both DSB techniques involve the transmission of a redundant sideband. For applications in which spectral efficiency is important, the occupied bandwidth can be reduced by a factor of two by the use of single sideband (SSB) modulation. The SSB signal can be written as:

$$f_{\mathrm{SSB}}(t) = A[m(t) \cos \omega_c t + m(t) \sin \omega_c t] \qquad (3)$$

where $\hat{m}(t)$ is the Hilbert transform [79, p. 31] of $m(t)$. In practice, SSB signals are usually generated by the use of a bandpass filter to suppress the upper or lower sideband. The sharp cutoff characteristic required for the bandpass filter presents implementation problems. Thus, a bandpass filter with smooth roll-off is often used. This procedure results in a vestigial sideband (VSB) signal [79, p. 192].

Quadrature Amplitude Modulation (QAM) is yet another AM alternative. This technique involves summing two DSB-SC signals 90° apart in phase as follows:

$$f_{\mathrm{QAM}}(t) = A[m_I(t) \cos \omega_c t + m_Q(t) \sin \omega_c t]. \qquad (4)$$

When $m_Q(t)$ is the Hilbert transform of $m_I(t)$, QAM reduces to SSB. When $m_I(t)$ and $m_Q(t)$ are independent binary data signals, QAM is as efficient in required power and bandwidth as ideal SSB without the stringent filtering requirements. If $m_I(t)$ and $m_Q(t)$ are three-level duobinary signals ($+1$, $-1$ or 0) coded in such a way as to minimize intersymbol interference caused by filtering, the result is quadrature partial response (QPR), which has been proposed for use in the Canadian 8 GHz frequency band [178]. All of these techniques require coherent detection. Any phase tracking errors that occur result in interference between the $I$ and $Q$ channels, thereby degrading performance.

When $m_I(t)$ and $m_Q(t)$ take on the values $\pm 1$, QAM is identical to quaternary phase-shift-keying (QPSK) discussed in the section on phase modulation techniques. These two techniques will differ, however, when $m_I(t)$ and $m_Q(t)$ are not rectangular pulses.[2]

### *Frequency Modulation (FM) Techniques*

The simplest FM technique is frequency-shift-keying (FSK) involving binary signaling by the use of two frequencies separated by $\Delta f$ Hz, where $\Delta f$, the frequency deviation, is small compared to the carrier frequency, $f_c$. With FSK schemes, it is common practice to specify the frequency spacing in terms of the modulation index, $d$, defined as:

$$d = \Delta f T \qquad (5)$$

where $T$ is the symbol duration (equal to the inverse of the data rate for binary schemes).

As with other modulation schemes, FSK can be detected either coherently or noncoherently. Noncoherent detection can be effected by two bandpass filters followed by envelope detectors and a decision device [79, p. 297]. With this approach, the frequency spacing must be at least $1/T\,(d \geqslant 1)$ to prevent significant overlap of the passbands of the two filters. Alternately, a discriminator can be used to convert the frequency variations to amplitude variations, so that AM envelope detection can be employed [82]. This approach eliminates the above constraint on $d$.

Recently, considerable interest has arisen in modified versions of FSK, including some coherent schemes. These schemes are based on the idea of continuous phase FSK (CP-FSK), in which the abrupt phase changes at the bit transition instants characteristic of other FSK implementations are avoided. This implementation of FSK results in rapid spectral roll-off and improved efficiency. The improvement is attained by the use of observation intervals greater than one bit [1, 40]. This feature enables narrower filter bandwidths than would otherwise be feasible. With coherent detection, values of $d$ in the neighborhood of 0.7 have been shown to provide optimal performance for any observation interval [123].

Another FM technique that has received considerable interest in recent years is minimum-shift-keying (MSK), also called fast frequency-shift-keying. MSK is a special case of

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[1] Radios designed for analog AM transmission are sometimes used to transmit digital signals. These radios distort the digital signal through inefficient high frequency or low frequency signal response. Occasionally, other distortions are deliberately introduced to improve spectral performance at the expense of communications efficiency.

[2] Nonrectangular pulses can be employed to eliminate abrupt transitions in the modulated waveform, thereby improving spectral characteristics and easing transmitter implementation.

CP-FSK for which $d = 0.5$ and coherent detection is used. This technique achieves performance identical to coherent PSK and exhibits the superior spectral properties of CP-FSK. MSK has the additional advantage of the possibility of a relatively simple self-synchronizing implementation [59], an advantage that coherent CP-FSK with $d = 0.7$ does not share.

### *Phase Modulation (PM) Techniques*

Almost by definition, digital PM schemes require coherent detection. There are three basic variations of binary phase-shift-keying (BPSK). The most straightforward approach is coherent BPSK, in which the carrier phase is shifted by 0 or 180 degrees. Detection requires a precise phase reference, which is normally obtained by performing a nonlinear operation on the received waveform. Since some phase reference extraction techniques exhibit 180° phase ambiguities, a modified form of PSK called Differentially Encoded PSK (DE-PSK) is often used. With DE-PSK, information is conveyed via transitions in carrier phase (e.g., no transition may correspond to a space and a 180° transition may correspond to a mark). Since a bit decision error on the current bit will induce another error on the subsequent bit, the performance of DE-PSK is slightly inferior to that of coherent PSK.

The third version of binary PSK is Differential PSK (DPSK), in which, as with DE-PSK, the information is differentially encoded. The difference between DPSK and DE-PSK lies in the detector. With DPSK, no attempt is made to extract a coherent phase reference. Rather, the signal from the previous bit interval is used as a phase reference for the current bit interval. Since the phase reference signal is not smoothed over many bit intervals, the performance of DPSK is somewhat worse than that of DE-PSK.

Quaternary PSK (QPSK) schemes will also be considered. Coherent QPSK involves encoding two bits at a time into one of four possible carrier phases spaced 90° apart. As in the binary case, the data can be differentially encoded and differentially detected with a concomitant loss in performance (this scheme will be denoted DQPSK). In recent years, a modified version of QPSK, called offset-keyed QPSK (OK-QPSK) or staggered QPSK (SQPSK), has come into use. This scheme offers advantages over conventional QPSK with regard to spectral efficiency, sideband regeneration and synchronization [45, 50, 94, 144].

OK-QPSK can be visualized by considering the QPSK signal to consist of in-phase and quadrature components (as with QAM). With normal QPSK, during each 2 bit time interval of $T$ seconds, the $I$ carrier is binary PSK modulated by one bit and the $Q$ carrier is modulated by the other bit. The resulting signal can take on any one of four possible phases, and abrupt phase transitions of 0°, 90°, or 180° can occur. With OK-QPSK, the $Q$ channel is shifted by $T/2$ seconds with respect to the $I$ channel. The transition rules are designed so that when the $I$ and $Q$ channels are added together, the resulting signal can shift abruptly by 90° at most (but shifts can occur every $T/2$ seconds, compared to every $T$ seconds for standard QPSK).

### *Hybrid AM/PM Techniques*

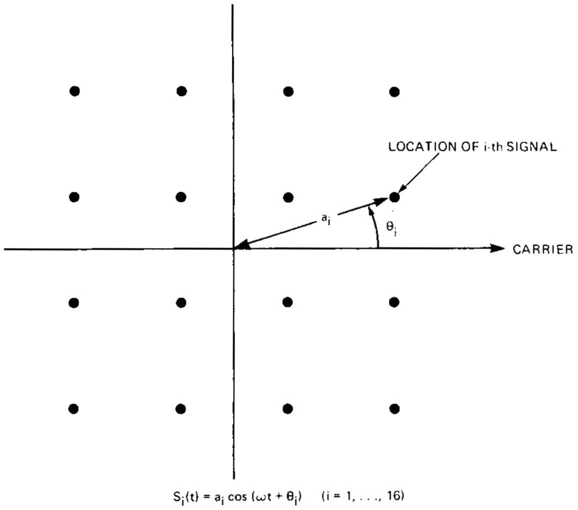

Figure 2: Location of 16-ary APK Waveforms in Phase-Amplitude Space

amplitude and phase-shift-keying (APK) [177]. The resulting information signals are best visualized by a representation in a phase-amplitude signal space. Figure 2 shows the signal space location of each of the 16 possible transmitted signals for 16-ary APK. Because this scheme conveys four bits of information during each signaling interval, it has been proposed for use over digital radio channels [176].

## III. COMPARISON OF REPRESENTATIVE MODULATION SCHEMES

In this section, the modulation schemes described in Section II are compared with respect to their performance under a variety of conditions characteristic of digital radio channels. A performance measure utilized throughout this section is the baseband equivalent $E_B/N_0$ (defined as the ratio of average signal energy per bit to noise power spectral density, as measured at the input to the receiver) required to achieve a bit error rate of $10^{-4}$. This error rate is adequate for most general purpose digital radio applications.

### *Ideal Performance*

In order to establish a baseline for comparison, Table 1 presents the ideal performance of the representative modulation techniques in the presence of additive white Gaussian noise. References are included with each entry to facilitate obtaining values of required $E_B/N_0$ for other error rates.[3] Of particular interest is the fact that CP-FSK with coherent detection over a 3-bit observation interval can outperform BPSK and other equivalent techniques (which are optimal only when the observation interval is confined to one bit). The identical ideal performance of QAM, MSK, and QPSK attests to their underlying similarities, often discussed in the literature [17, 60]. Indeed, offset-keyed QAM [45], MSK, and OK-QPSK differ only in the weighting functions applied to the $I$ and $Q$ channels.

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[3] Care must be exercised to convert various SNR measures to $E_B/N_0$ and to convert symbol error rates to bit error rates. Also, since average

TABLE 1
IDEAL PERFORMANCE OF REPRESENTATIVE MODULATION SCHEMES

| TYPE | MODULATION SCHEME | $E_B/N_O$ (dB)* | REFERENCE |
|---|---|---|---|
| AM | OOK – COHERENT DETECTION | 11.4 | 26,77 |
| | OOK – ENVELOPE DETECTION | 11.9 | 77 |
| | QAM | 8.4 | 77 |
| | QPR | 10.7 | 119 |
| FM | FSK – NONCOHERENT DETECTION (d = 1) | 12.5 | 24,27 |
| | CP-FSK – COHERENT DETECTION (d = .7) | 7.4** | 1,40 |
| | CP-FSK – NONCOHERENT DETECTION (d = .7) | 9.2** | 1,40 |
| | MSK (d = .5) | 8.4 | 17 |
| | MSK – DIFFERENTIAL ENCODING (d = .5) | 9.4 | 71 |
| PM | BPSK – COHERENT DETECTION | 8.4 | 1,78 |
| | DE-BPSK | 8.9 | 22,100 |
| | DPSK | 9.3 | 22,100 |
| | QPSK | 8.4 | 12 |
| | DQPSK | 10.7 | 100 |
| | OK-QPSK | 8.4 | 50 |
| | 8-ary PSK – COHERENT DETECTION | 11.8 | 57 |
| | 16-ary PSK – COHERENT DETECTION | 16.2 | 3 |
| AM/PM | 16-ary APK | 12.4 | 189 |

* FOR BIT ERROR RATE OF $10^{-4}$
** ASSUMES THREE-BIT OBSERVATION INTERVAL
d = FM MODULATION INDEX

TABLE 2
RELATIVE SIGNALING SPEEDS OF REPRESENTATIVE MODULATION SCHEMES

| TYPE | MODULATION SCHEME | SPEED (b/s PER Hz) | $E_B/N_O$ (dB)* | REFERENCE |
|---|---|---|---|---|
| AM | OOK – COHERENT DETECTION | 0.8 | 12.5 | 26 |
| | OOK – ENVELOPE DETECTION | | | |
| | QAM | 1.7 | 9.5 | 145 |
| | QPR | 2.25 | 11.7 | 178 |
| FM | FSK – NONCOHERENT DETECTION (d = 1) | 0.8 | 11.8** | 64 |
| | CP-FSK – COHERENT DETECTION (d = .7) | | | |
| | CP-FSK – NONCOHERENT DETECTION (d = .7) | 1.0 | 10.7 | 26 |
| | MSK (d = .5) | 1.9 | 9.4 | 44 |
| | MSK – DIFFERENTIAL ENCODING (d = .5) | 1.9 | 10.4 | 44 |
| PM | BPSK – COHERENT DETECTION | 0.8 | 9.4 | 26 |
| | DE-BPSK | 0.8 | 9.9 | 26† |
| | DPSK | 0.8 | 10.6 | 87 |
| | QPSK | 1.9 | 9.9 | 57 |
| | DQPSK | 1.8 | 11.8 | 165 |
| | OK-QPSK | | | |
| | 8-ary PSK – COHERENT DETECTION | 2.6 | 12.8 | 57 |
| | 16-ary PSK – COHERENT DETECTION | 2.9 | 17.2 | 176 |
| AM/PM | 16-ary APK | 3.1 | 13.4 | 176 |

* FOR BIT ERROR RATE OF $10^{-4}$
† CALCULATED FROM RESULTS FOR BPSK
** DISCRIMINATOR DETECTION
d = FM MODULATION INDEX

### *Spectral Characteristics*

The spectral characteristics of the modulation schemes can be compared in many ways. Of particular interest is the extent to which a signal will interfere with signals in adjacent channels. One measure of this quality is the attenuation of a signal's power spectrum a specified distance from the center frequency. If, for example, we examine the attenuation at an arbitrary distance of $8/T$ Hz from the center frequency ($T$ is the symbol duration), we find that with AM schemes the sidelobes are down by about 25 dB, with PM schemes the sidelobes are down by about 33 dB, and with continuous phase FM the sidelobes are down by 60 dB or more.[4] In general, for frequencies far from the center frequency (large $(f - f_c)T$), the spectrum of AM and PM signals falls off as $f^{-2}$ while that of CP-FM signals falls off as $f^{-4}$.

While these numbers appear to indicate a significant advantage for FM schemes, they should be put in the proper perspective. First, the figures quoted for PM systems assume that abrupt phase transitions occur. If phase transitions can be made to occur more smoothly, improved spectral characteristics can be achieved. Second, modifications can be made to AM schemes. For example, Shehadeh and Chiu [105] show that a type of continuous phase AM exhibits a spectrum that falls off as $f^{-4}$. Finally, sidelobes can always be reduced by suitable post modulation filtering, although a penalty in performance is incurred. Thus, the spectral merits of the various schemes can only be judged on the basis of a detailed study of the tradeoffs between cost and performance.

Another spectral property of interest is the bandwidth required to transmit at a specified information rate. The so-called "speed" of a modulation technique (equal to $R/W$, where $R$ is the data rate and $W$ is the IF bandwidth) is an important figure of merit. In Table 2, we list the speeds for each technique, together with the $E_B/N_0$ required for a $10^{-4}$ BER when the signal is filtered at the indicated bandwidth (i.e., the degrading effects of finite bandwidth are included). The results presented in Table 2 were derived from many different sources, so that slightly different filters[5] were used in obtaining the results, but these figures are indicative of the results to be expected. It should also be noted that, in most cases, no rigorous attempt was made to achieve the optimum combination of speed and efficiency.

### *Effects of Interference*

Another factor in evaluating potential modulation schemes for digital radio is the effects of co-channel and adjacent channel interference. We have already discussed one aspect of adjacent channel interference—the out-of-band attenuation of the various schemes. It was pointed out that MSK and the other CP-FSK schemes enjoy a large advantage over the AM and PM schemes, when no post-modulation filtering is employed. Another aspect of adjacent channel interference is the amount of performance degradation caused by a specified level of interference. Table 3 illustrates the effect of an in-band CW interferer (10 dB or 15 dB down in power from the desired signal) on the $E_B/N_0$ required for a $10^{-4}$ BER. This situation can be a model either for interfering sidelobes from adjacent channels or for the main lobe from a co-channel interferer. Of the schemes for which data are available, noncoherent FSK and BPSK show the least degradation from ideal performance, while the 8-ary and 16-ary schemes exhibit the most degradation (compare to Table 1). Unfortunately, no analytical or

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[4] A modified version of MSK known as sinusoidal FSK (SFSK)

[5] In most cases, a simple three-pole filter or a Gaussian filter was

TABLE 3
PERFORMANCE OF REPRESENTATIVE MODULATION SCHEMES IN THE PRESENCE OF CW INTERFERENCE

| TYPE | MODULATION SCHEME | $E_B/N_O$ REQUIRED* | | REFERENCE |
|---|---|---|---|---|
| | | S/I = 10 dB | S/I = 15 dB | |
| AM | OOK – COHERENT DETECTION | | | |
| | OOK – ENVELOPE DETECTION | ~ 20 | 14.5 | 70 |
| | QAM | | | |
| | QPR | | | |
| FM | FSK – NONCOHERENT DETECTION (d = 1) | 14.7 | 13.3 | 41 |
| | CP-FSK – COHERENT DETECTION (d = .7) | | | |
| | CP-FSK – NONCOHERENT DETECTION (d = .7) | | | |
| | MSK (d = .5) | | | |
| | MSK – DIFFERENTIAL ENCODING (d = .5) | | | |
| PM | BPSK – COHERENT DETECTION | 10.5 | 9.2 | 147, 191 |
| | DE-BPSK | 11.0 | 9.7 | 147 |
| | DPSK | 12.0 | 10.3 | 147 |
| | QPSK | 12.2 | 9.8 | 147, 191 |
| | DQPSK | > 20 | 14.0 | 147 |
| | OK-QPSK | | | |
| | 8-ary PSK – COHERENT DETECTION | ~ 20 | 15.8 | 191 |
| | 16-ary PSK – COHERENT DETECTION | | > 24 | 191 |
| AM/PM | 16-ary APK | | | |

* FOR BIT ERROR RATE OF $10^{-4}$

d = FM MODULATION INDEX

simulation results are available for any of the CP-FSK schemes or for OK-QPSK.

### *Effects of Fading*

Fading is another problem often encountered on digital radio links. If the fading is caused by two resolvable multipath components, then the results of Table 3 can be utilized (the CW interferer can represent the signal from the secondary path). If the fading is caused by a large number of equal amplitude components, the Rayleigh fading model [79, p. 348] is more appropriate.[6] Table 4 presents the performance results for a Rayleigh fading channel. Because of the severe effects of Rayleigh fading, a required bit error rate of $10^{-2}$ is assumed in this table (although this error rate is rather high for digital radio applications, error control coding could be used to achieve the desired rate). Because the values of Table 4 represent simply a weighted average of the ideal performance curves, the relative performance of the schemes does not differ markedly from that indicated by Table 1. It should be emphasized that for the AM and AM/PM schemes, the fading is assumed to be slow enough that the decision threshold can be continuously adjusted to the optimal value.

TABLE 4
PERFORMANCE OF REPRESENTATIVE MODULATION SCHEMES ON A RAYLEIGH FADING CHANNEL

| TYPE | MODULATION SCHEME | AVERAGE $E_B/N_O$ (dB)* | REFERENCE |
|---|---|---|---|
| AM | OOK – COHERENT DETECTION | $17^{\dagger}$ | 79 |
| | OOK – ENVELOPE DETECTION | $19^{\dagger}$ | 79 |
| | QAM | 14 | |
| | QPR | | |
| FM | FSK – NONCOHERENT DETECTION (d = 1) | 20 | 68 |
| | CP-FSK – COHERENT DETECTION (d = .7) | $13^{**}$ | 174 |
| | CP-FSK – NONCOHERENT DETECTION (d = .7) | $18^{**}$ | 174 |
| | MSK (d = .5) | 14 | |
| | MSK – DIFFERENTIAL ENCODING (d = .5) | 17 | |
| PM | BPSK – COHERENT DETECTION | 14 | 79, 161 |
| | DE-BPSK | 17 | 161 |
| | DPSK | 17 | 68, 79 |
| | QPSK | 13.5 | 161 |
| | DQPSK | 20 | 37 |
| | OK-QPSK | 13.5 | |
| | 8-ary PSK – COHERENT DETECTION | 16.5 | 161 |
| | 16-ary PSK – COHERENT DETECTION | 21 | 161 |
| AM/PM | 16-ary APK | 18 | 174 |

* FOR BIT ERROR RATE OF $10^{-2}$
† ASSUMES OPTIMUM VARIABLE THRESHOLD
** ASSUMES THREE-BIT OBSERVATION INTERVAL

d = FM MODULATION INDEX

TABLE 5
PERFORMANCE OF REPRESENTATIVE MODULATION SCHEMES IN THE PRESENCE OF DELAY DISTORTION ($d/T = 1$)

| TYPE | MODULATION SCHEME | $E_B/N_O$ (dB)* | | REFERENCE |
|---|---|---|---|---|
| | | QUADRATIC | LINEAR | |
| AM | OOK– COHERENT DETECTION | 12.8 | 12.4 | 116 |
| | OOK – ENVELOPE DETECTION | 13.3 | 16.9 | 116 |
| | QAM | 9.8 | 15.8 | 116 |
| | QPR | | >25 | 178 |
| FM | FSK – NONCOHERENT DETECTION (d = 1) | 13.5 | 16.0 | 116 |
| | CP-FSK – COHERENT DETECTION (d = .7) | $8.8^{**}$ | $8.6^{**}$ | 116 |
| | CP-FSK – NONCOHERENT DETECTION (d = .7) | $10.2^{**}$ | $12.7^{**}$ | 116 |
| | MSK (d = .5) | 9.8 | 15.8 | 116 |
| | MSK – DIFFERENTIAL ENCODING (d = .5) | 10.8 | 16.8 | 116 |
| PM | BPSK – COHERENT DETECTION | 9.8 | 9.6 | 116 |
| | DE-BPSK | 10.3 | 10.1 | 116 |
| | DPSK | 11.8 | | 116 |
| | QPSK | 9.8 | 15.8 | 116 |
| | DQPSK | 16.3 | | 116 |
| | OK-QPSK | 9.8 | 15.8 | 116 |
| | 8-ary PSK – COHERENT DETECTION | <25 | ~25 | 175 |
| | 16-ary PSK – COHERENT DETECTION | | | |
| AM/PM | 16-ary APK | | | |

* FOR BIT ERROR RATE OF $10^{-4}$
** ASSUMES THREE-BIT OBSERVATION INTERVAL

d = FM MODULATION INDEX

### *Effects of Delay Distortion*

Yet another factor that should be considered in selecting a modulation scheme for digital radio applications is the effect of delay distortion.[7] Most of the delay distortion observed on line-of-sight radio links is introduced by the radios and not the channel. Table 5 presents some results derived primarily from Sunde's comprehensive treatment of the effects of delay distortion on pulse transmission [116]. The performance of the representative systems is shown for quadratic and linear delay distortion for the case in which the maximum differential delay (relative to the mid-band delay) is equal to the symbol

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[6] Neither of these models takes into account the fade rate of the signal. A discussion of the effects of fade rate on the probability of error is beyond the scope of this paper, but these effects are discussed in some of the references [14, 28, 35; 37, 47, 65, 79, 161].

[7] If the distortion observed on the received signal can be modeled by passage of the transmitted signal through a linear filter, the delay

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