

DPSK

5.7.2 Differential Phase Shift Keying (DPSK)

Differential PSK is a noncoherent form of phase shift keying which avoids the need for a coherent reference signal at the receiver. Noncoherent receivers are easy and cheap to build, and hence are widely used in wireless communications. In DPSK systems, the input binary sequence is first differentially encoded and then modulated using a BPSK modulator. The differentially encoded sequence $\{d_k\}$ is generated from the input binary sequence $\{m_k\}$ by complementing the modulo-2 sum of m_k and d_{k-1} . The effect is to leave the symbol d_k unchanged from the previous symbol if the incoming binary symbol m_k is 1, and to toggle d_k if m_k is 0. Table 5.1 illustrates the generation of a DPSK signal for a sample sequence m_k which follows the relationship $d_k = \overline{m_k \oplus d_{k-1}}$.

$$d_k = m_k \oplus d_{k-1}$$

Table 5.1 Illustration of the Differential Encoding Process

$\{m_k\}$		1	0	0	1	0	1	1	0
$\{d_{k-1}\}$		1	1	0	1	1	0	0	0
$\{d_k\}$	1	1	0	1	1	0	0	0	1

While DPSK signaling has the advantage of reduced receiver complexity, its energy efficiency is inferior to that of coherent PSK by about 3 dB. The average probability of error for DPSK in additive white Gaussian noise is given by

$$P_{e, \text{DPSK}} = \frac{1}{2} \exp\left(-\frac{E_b}{N_0}\right) \quad (5.75)$$

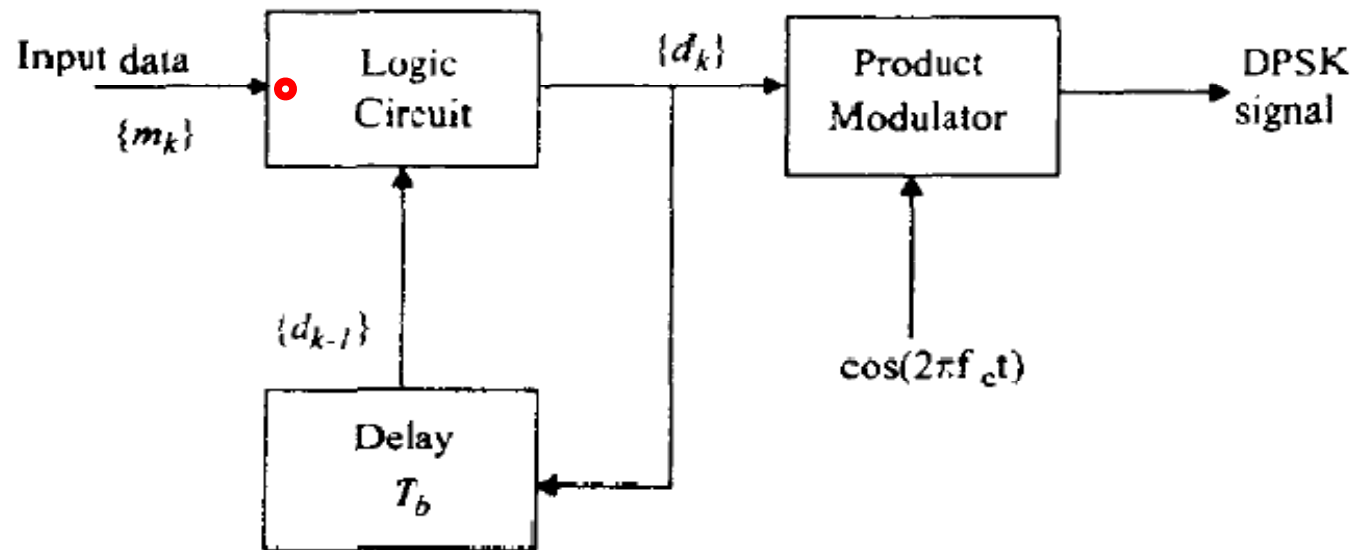


Figure 5.24
Block diagram of a DPSK transmitter.

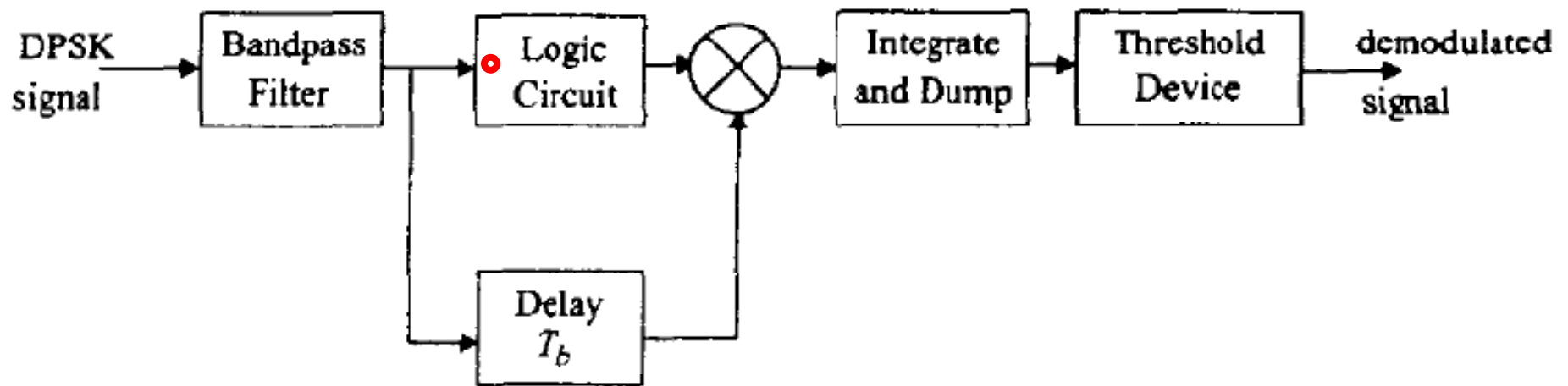


Figure 5.25
Block diagram of DPSK receiver.

Non-coherent detection

- Non-coherent detection:
 - *No need for a reference in phase* with the received carrier
 - *Less complexity* compared to coherent detection at the price of *higher error rate*.

■ Differential coherent detection

- Differential encoding of the message
 - The symbol phase changes if the current bit is different from the previous bit.

$$s_i(t) = \sqrt{\frac{2E}{T}} \cos(\omega_0 t + \theta_i(t)), \quad 0 \leq t \leq T, \quad i = 1, \dots, M$$

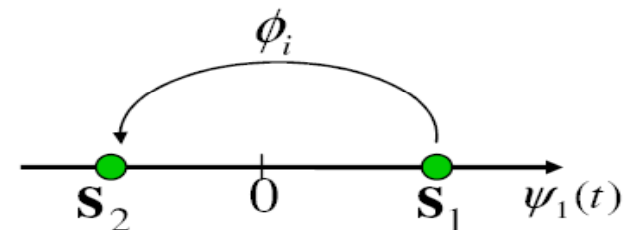
$$\theta_k(nT) = \theta_k((n-1)T) + \phi_i(nT)$$

Symbol index: k

Data bits: m_k

Symbol phase: θ_k

0	1	2	3	4	5	6	7
1	1	0	1	0	1	1	
π	π	π	0	π	0	π	π



FSK

5.8.1 Binary Frequency Shift Keying

In binary frequency shift keying (BFSK), the frequency of a constant amplitude carrier signal is switched between two values according to the two possible message states (called *high* and *low* tones), corresponding to a binary 1 or 0. Depending on how the frequency variations are imparted into the transmitted waveform, the FSK signal will have either a discontinuous phase or continuous phase between bits. In general, an FSK signal may be represented as

$$s_{\text{FSK}}(t) = v_H(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c + 2\pi\Delta f)t \quad 0 \leq t \leq T_b \quad (\text{binary 1}) \quad (5.95.a)$$

$$s_{\text{FSK}}(t) = v_L(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c - 2\pi\Delta f)t \quad 0 \leq t \leq T_b \quad (\text{binary 0}) \quad (5.95.b)$$

where $2\pi\Delta f$ is a constant offset from the nominal carrier frequency.

One obvious way to generate an FSK signal is to switch between two independent oscillators according to whether the data bit is a 0 or a 1. Normally, this form of FSK generation results in a waveform that is discontinuous at the switching times, and for this reason this type of FSK is called *discontinuous* FSK. A discontinuous FSK signal is represented as

$$s_{\text{FSK}}(t) = v_H(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_H t + \theta_1) \quad 0 \leq t \leq T_b \quad (\text{binary 1}) \quad (5.96.a)$$

$$s_{\text{FSK}}(t) = v_L(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_L t + \theta_2) \quad 0 \leq t \leq T_b \quad (\text{binary 0}) \quad (5.96.b)$$

Since the phase discontinuities pose several problems, such as spectral spreading and spurious transmissions, this type of FSK is generally not used in highly regulated wireless systems.

■ BINARY FSK

In a *binary FSK system*, symbols 1 and 0 are distinguished from each other by transmitting one of two sinusoidal waves that differ in frequency by a fixed amount. A typical pair of sinusoidal waves is described by

$$s_i(t) = \begin{cases} \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_i t), & 0 \leq t \leq T_b \\ 0, & \text{elsewhere} \end{cases} \quad (6.86)$$

where $i = 1, 2$, and E_b is the transmitted signal energy per bit; the transmitted frequency is

$$f_i = \frac{n_c + i}{T_b} \quad \text{for some fixed integer } n_c \text{ and } i = 1, 2 \quad (6.87)$$

Thus symbol 1 is represented by $s_1(t)$, and symbol 0 by $s_2(t)$. The FSK signal described here is known as *Sunde's FSK*. It is a *continuous-phase signal* in the sense that phase continuity is always maintained, including the inter-bit switching times. This form of digital modulation is an example of *continuous-phase frequency-shift keying* (CPFSK), on which we have more to say later on in the section.

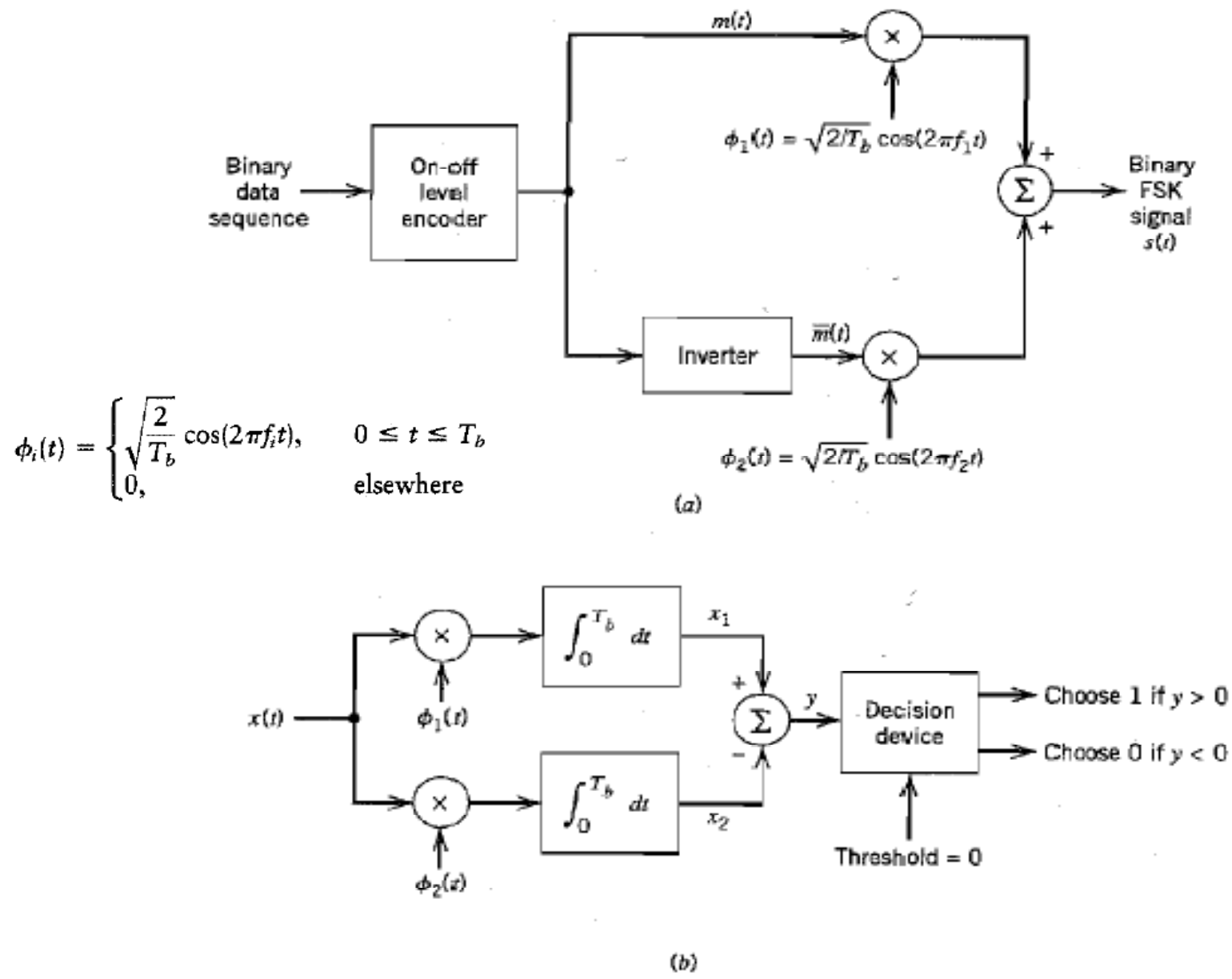
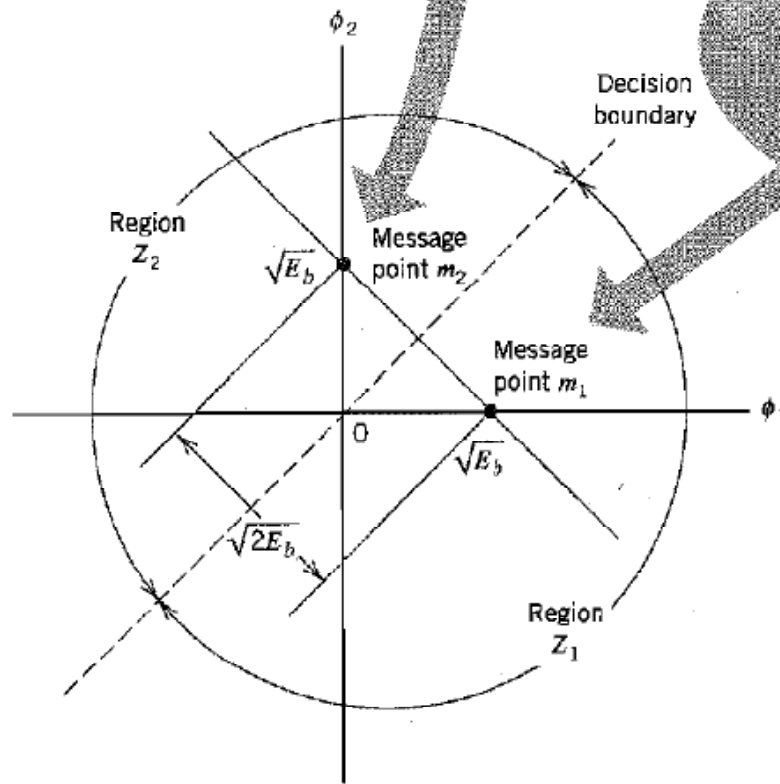
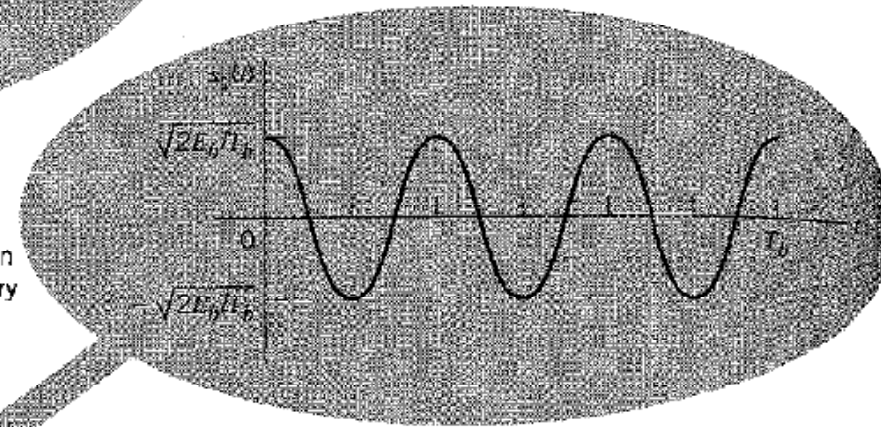
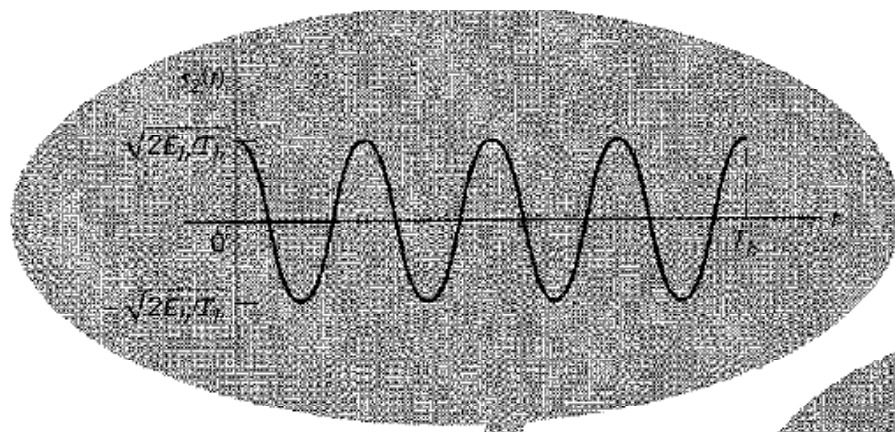


FIGURE 6.26 Block diagrams for (a) binary FSK transmitter and (b) coherent binary FSK receiver.



$$\phi_i(t) = \begin{cases} \sqrt{\frac{2}{T_b}} \cos(2\pi f_i t), & 0 \leq t \leq T_b \\ 0, & \text{elsewhere} \end{cases}$$

The more common method for generating an FSK signal is to frequency modulate a single carrier oscillator using the message waveform. This type of modulation is similar to analog FM generation, except that the modulating signal $m(t)$ is a binary waveform. Therefore, FSK may be represented as

$$\begin{aligned} s_{\text{FSK}}(t) &= \sqrt{\frac{2E_b}{T_b}} \cos [2\pi f_c t + \theta(t)] \\ &= \sqrt{\frac{2E_b}{T_b}} \cos \left[2\pi f_c t + 2\pi k_f \int_{-\infty}^t m(\eta) d\eta \right] \end{aligned} \quad (5.97)$$

It should be noted that even though the modulating waveform $m(t)$ is discontinuous at bit transitions, the phase function $\theta(t)$ is proportional to the integral of $m(t)$ and is continuous.

Coherent Detection of Binary FSK

A block diagram of a coherent detection scheme for demodulation of binary FSK signals is shown in Figure 5.36. The receiver shown is the optimum detector for coherent binary FSK in the presence of additive white Gaussian noise. It consists of two correlators which are supplied with locally generated coherent reference signals. The difference of the correlator outputs is then compared with a threshold comparator. If the difference signal has a value greater than the threshold, the receiver decides in favor of a 1, otherwise it decides in favor of a 0.

It can be shown that the probability of error for a coherent FSK receiver is given by

$$P_{e, \text{FSK}} = Q\left(\sqrt{\frac{E_b}{N_0}}\right) \quad (5.101)$$

MSK

5.8.2 Minimum Shift Keying (MSK)

Minimum shift keying (MSK) is a special type of *continuous phase-frequency shift keying* (CPFSK) wherein the peak frequency deviation is equal to $1/4$ the bit rate. In other words, MSK is continuous phase FSK with a modulation index of 0.5. The modulation index of an FSK signal is similar to the FM modulation index, and is defined as $k_{\text{FSK}} = (2\Delta F)/R_b$, where ΔF is the peak RF frequency deviation and R_b is the bit rate. A modulation index of 0.5 corresponds to the minimum frequency spacing that allows two FSK signals to be coherently orthogonal, and the name minimum shift keying implies the minimum frequency separation (i.e. bandwidth) that allows orthogonal detection. Two FSK signals $v_H(t)$ and $v_L(t)$ are said to be orthogonal if

$$\int_0^T v_H(t)v_L(t)dt = 0 \quad (5.103)$$

MSK is sometimes referred to as *fast FSK* as the frequency spacing used is only half as much as that used in conventional noncoherent FSK [Xio94].

MSK is a spectrally efficient modulation scheme and is particularly attractive for use in mobile radio communication systems. It possesses properties such as constant envelope, spectral efficiency, good BER performance, and self-synchronizing capability.

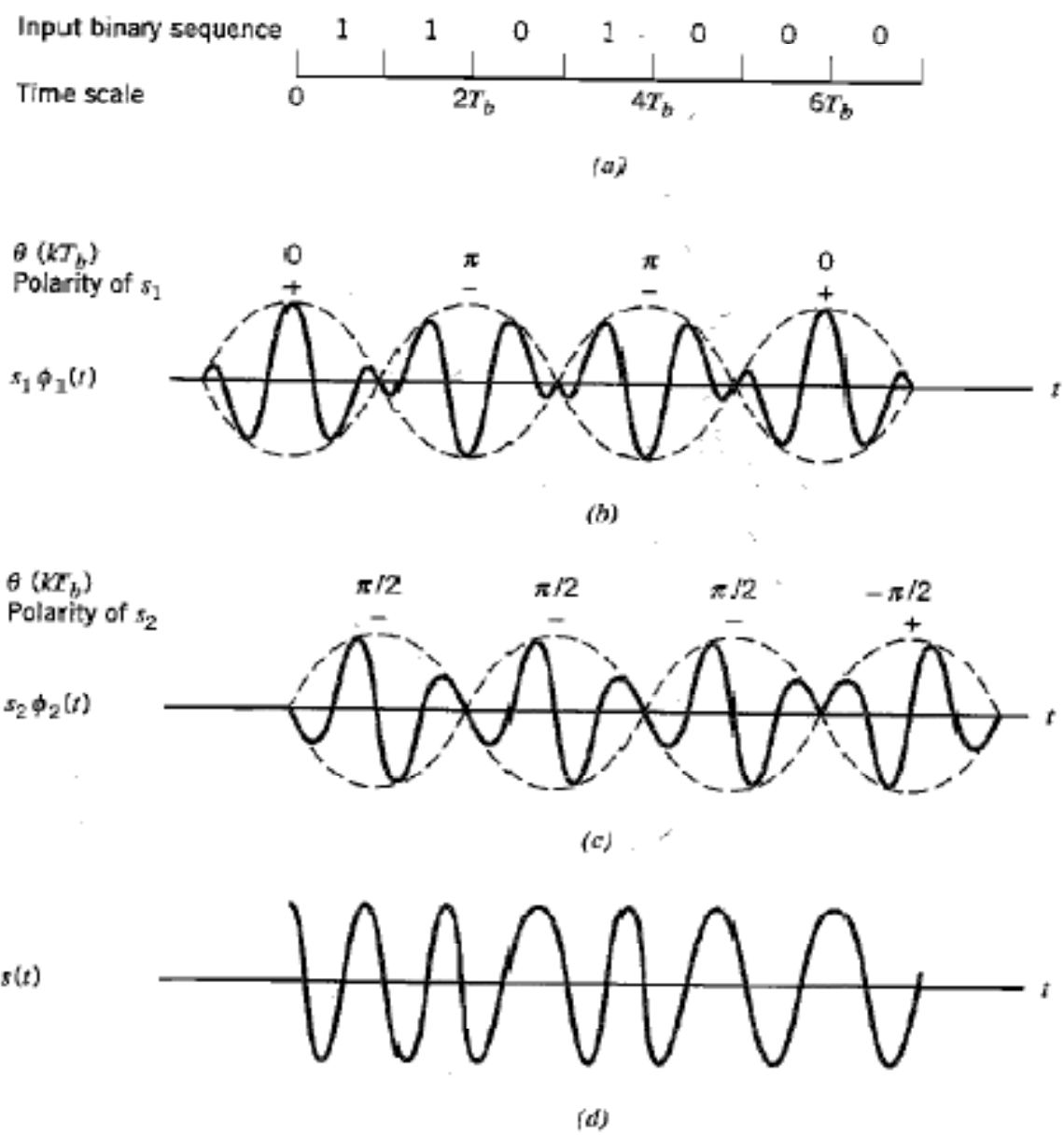
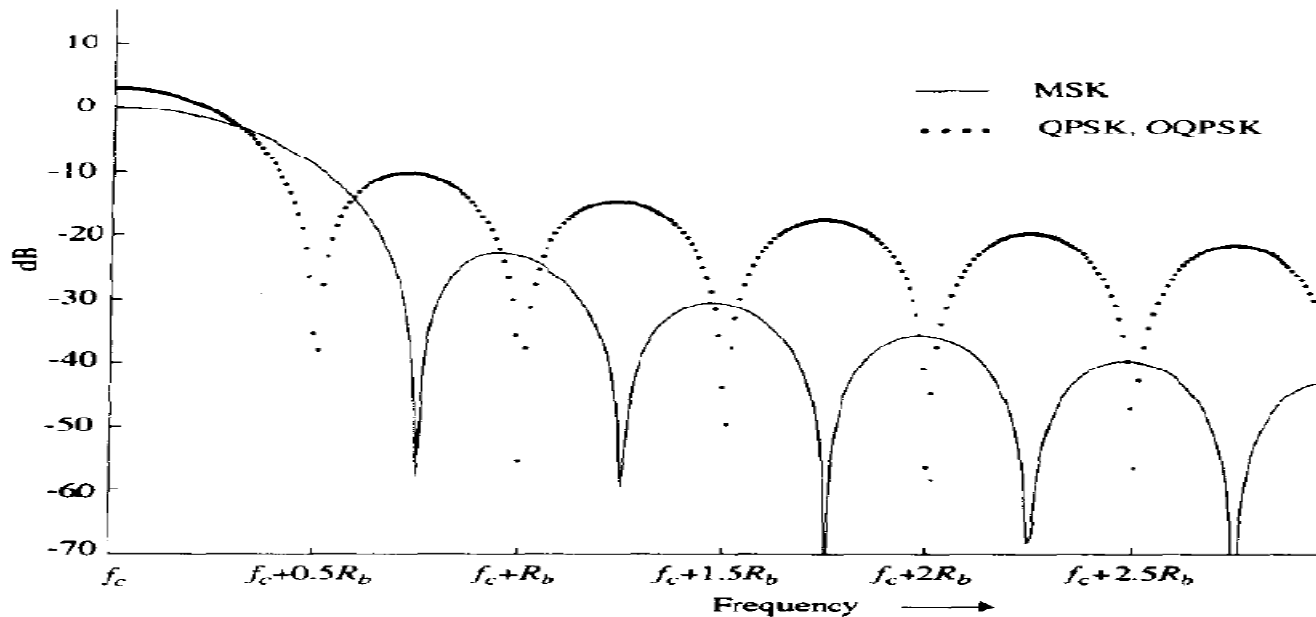


FIGURE 6.30 (a) Input binary sequence, (b) Waveform of scaled time function $s_1 \phi_1(t)$, (c) Waveform of scaled time function $s_2 \phi_2(t)$, (d) Waveform of the MSK signal $s(t)$ obtained by adding $s_1 \phi_1(t)$ and $s_2 \phi_2(t)$ on a bit-by-bit basis.



Thus the normalized power spectral density for MSK is given by [Pas79]

$$P_{\text{MSK}} = \frac{16}{\pi^2} \left(\frac{\cos 2\pi(f + f_c)T}{1.16f^2T^2} \right)^2 + \frac{16}{\pi^2} \left(\frac{\cos 2\pi(f - f_c)T}{1.16f^2T^2} \right)^2 \quad (5.107)$$

Figure 5.38 shows the power spectral density of an MSK signal. The spectral density of QPSK and OQPSK are also drawn for comparison. From Figure 5.38 it is seen that the MSK spectrum has lower sidelobes than QPSK and OQPSK. Ninety-nine percent of the MSK power is contained within a bandwidth $B = 1.2/T$, while for QPSK and OQPSK, the 99 percent bandwidth B is equal to $8/T$. The faster rolloff of the MSK spectrum is due to the fact that smoother pulse functions are used. Figure 5.38 also shows that the main lobe of MSK is wider than that of QPSK and OQPSK, and hence when compared in terms of first null bandwidth, MSK is less spectrally efficient than the phase-shift keying techniques [Pas79].

► EXAMPLE 6.6 **GMSK for GSM Wireless Communications**

An important application of GMSK is in a standardized wireless communication system widely known as GSM, which is a time-division multiple-access system that is discussed in Chapter 8. For this application, the time-bandwidth product WT_b of GMSK is standardized at 0.3, which provides the best compromise between increased bandwidth occupancy and resistance to co-channel interference. Ninety-nine percent of the radio frequency (RF) power of GMSK signals so specified is confined to a bandwidth of 250 kHz, which means that, for all practical purposes, the sidelobes are virtually zero outside this frequency band.

The available spectrum is divided into 200 kHz-wide subchannels. Each subchannel is assigned to a GSM system transmitting data at 271 kb/s. Figure 6.35 depicts the power spectrum of a subchannel in relation to its two adjacent subchannels; this plot is the passband version of the baseband power spectrum of Figure 6.33 corresponding to $WT_b = 0.3$. From Figure 6.35 we may make the following important observation: The RF power spectrum of the subchannel shown shaded is down by an amount larger than 40 dB at the carrier frequencies of both adjacent subchannels, which means that the effect of co-channel interference is practically negligible. ◀

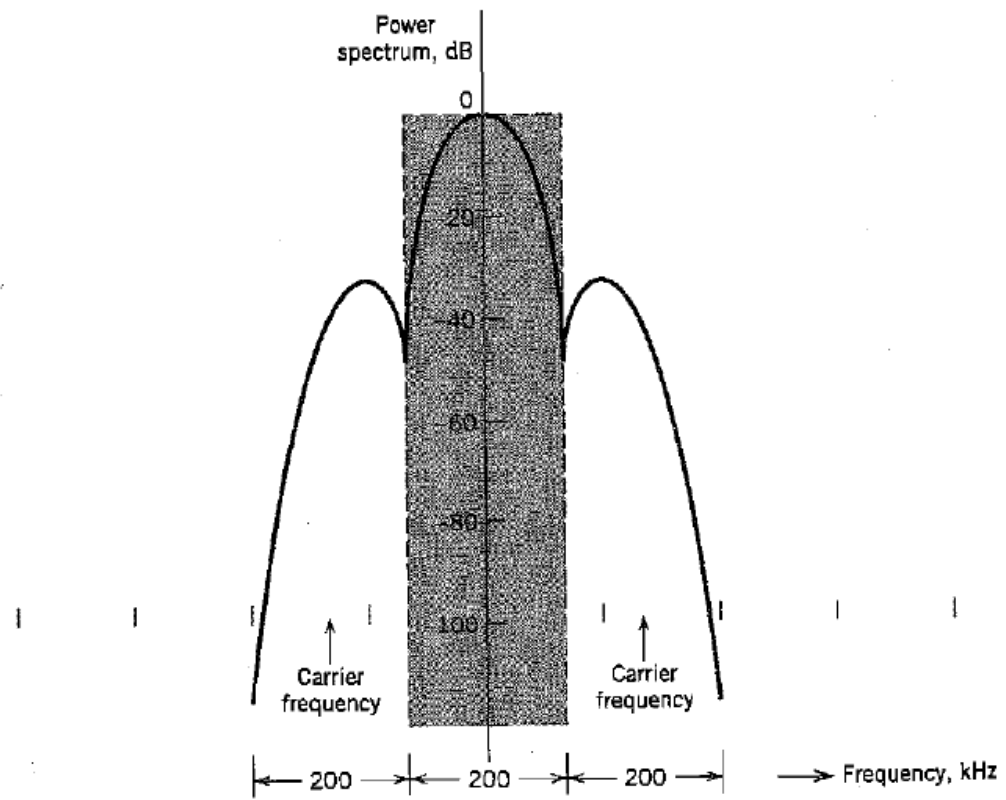


FIGURE 6.35 Power spectrum of GMSK signal for GSM wireless communications.

GMSK Bit Error Rate

The bit error rate for GMSK was first found in [Mur81] for AWGN channels, and was shown to offer performance within 1 dB of optimum MSK when $BT=0.25$. The bit error probability is a function of BT , since the pulse shaping impacts ISI. The bit error probability for GMSK is given by

$$P_e = Q \left\{ \sqrt{\frac{2\gamma E_b}{N_0}} \right\} \quad (5.111.a)$$

where γ is a constant related to BT by

$$\gamma \equiv \begin{cases} 0.68 & \text{for GMSK with } BT = 0.25 \\ 0.85 & \text{for simple MSK } (BT = \infty) \end{cases} \quad (5.111.b)$$

GMSK Transmitter and Receiver

The simplest way to generate a GMSK signal is to pass a NRZ message bit stream through a Gaussian baseband filter having an impulse response given in equation (5.108), followed by an FM modulator. This modulation technique is shown in Figure 5.42 and is currently used in a variety of analog and digital implementations for the U.S. Cellular Digital Packet Data (CDPD) system as well as for the Global System for Mobile (GSM) system. Figure 5.42 may also be implemented digitally using a standard I/Q modulator.

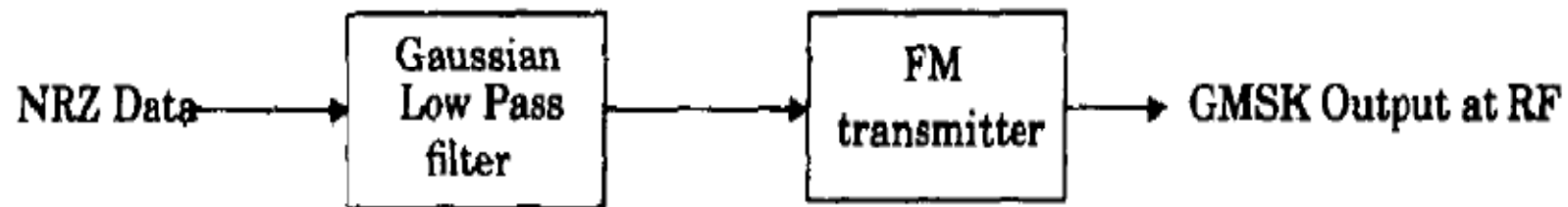


Figure 5.42

Block diagram of a GMSK transmitter using direct FM generation.