EC744 Wireless Communication
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Wireless Communication Fading Modulation

Syllabus

- Tentatively

Week 1	Overview wireless communications, Probabilities
Week 2	Digital Communication fundamentals
Week 3	Channel characteristics (AWGN, fading)
Week 4	Modulation techniques Demodulation techniques (coherent and non-coherent)
Week 5	Source coding techniques
Week 6	Channel coding techniques
Week 7	Mid Term exam (take home), Diversity techniques
Week 8	Equalization techniques
Week 9	Spread spectrum, MIMO and OFDM
Week 10	Wireless networking: 802.11, 802.16, UWB
Week 11	Hot topics
Week 12	Presentations
Week 13	Presentations
Week 14	Presentations
Week 15	Final Exam

What is modulation

- **Modulation** is the process of encoding information from a message source in a manner suitable for transmission
- It involves translating a baseband message signal to a bandpass signal at frequencies that are very high compared to the baseband frequency.
- Baseband signal is called *modulating* signal
- Bandpass signal is called *modulated* signal

Baseband and Carrier Communication

- Baseband:
  - Describes signals and systems whose range of frequencies is measured from 0 to a maximum bandwidth or highest signal frequency
  - Voice: Telephone 0-3.5KHz; CD 0-22.05KHz
  - Video: Analog TV 4.5MHz, TV channel is 0-6MHz. Digital, depending on the size, movement, frames per second, …
  - Example: wire, coaxial cable, optical fiber, PCM phone
- Carrier Communication:
  - **Carrier**: a waveform (usually sinusoidal) that is modulated to represent the information to be transmitted. This carrier wave is usually of much higher frequency than the modulating (baseband) signal.
  - Modulation: is the process of varying a *carrier signal* in order to use that signal to convey information.
  - .

Modulation Techniques

- Modulation can be done by varying the
  - Amplitude
  - Phase, or
  - Frequency

  of a high frequency carrier in accordance with the amplitude of the message signal.
- **Demodulation** is the inverse operation: *extracting the baseband message from the carrier* so that it may be processed at the receiver.

Goal of Modulation Techniques

- Modulation is difficult task given the hostile mobile radio channels
  - *Small-scale fading and multipath conditions*.
- The goal of a modulation scheme is:
  - Transport the message signal through the radio channel with best possible quality
  - Occupy least amount of radio (RF) spectrum.

Frequency versus Amplitude Modulation

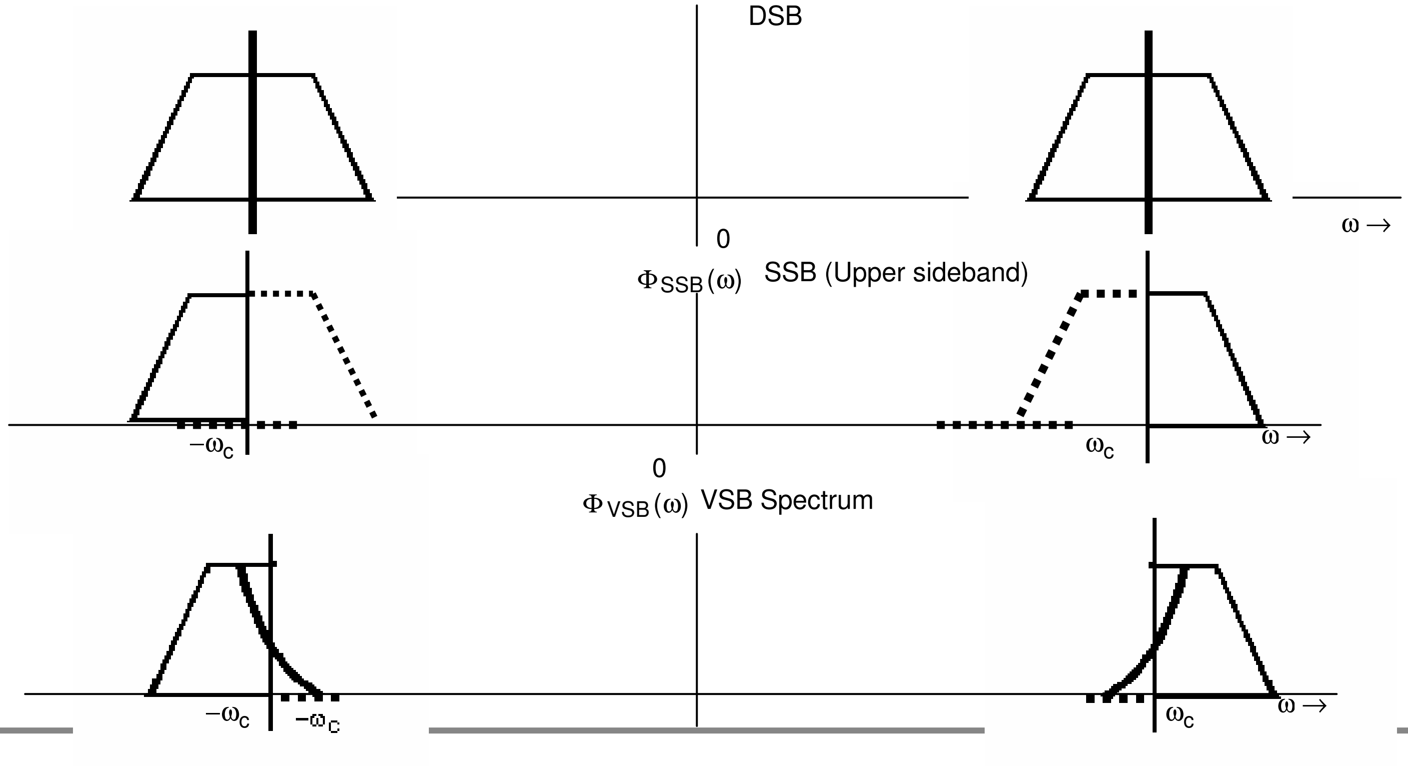
- Amplitude Modulation (AM)
  - Changes the amplitude of the carrier signal according to the amplitude of the message signal
  - All info is carried in the amplitude of the carrier
  - There is a linear relationship between the received signal quality and received signal power.
  - AM systems usually occupy less bandwidth then FM systems.
  - AM carrier signal has time-varying envelope.

AM Broadcasting

- History
- Frequency
  - Long wave: 153-270kHz
  - Medium wave: 520-1,710kHz, AM radio
  - Short wave: 2,300-26,100kHz, long distance, SSB, VOA
- Limitation
  - Susceptibility to atmospheric interference
  - Lower-fidelity sound, news and talk radio

Vestigial Sideband (VSB)

- VSB is a compromise between DSB and SSB. To produce SSB signal from DSB signal ideal filters should be used to split the spectrum in the middle so that the bandwidth of bandpass signal is reduced by one half. In VSB system one sideband and a vestige of other sideband are transmitted together. The resulting signal has a bandwidth > the bandwidth of the modulating (baseband) signal but < the DSB signal bandwidth.

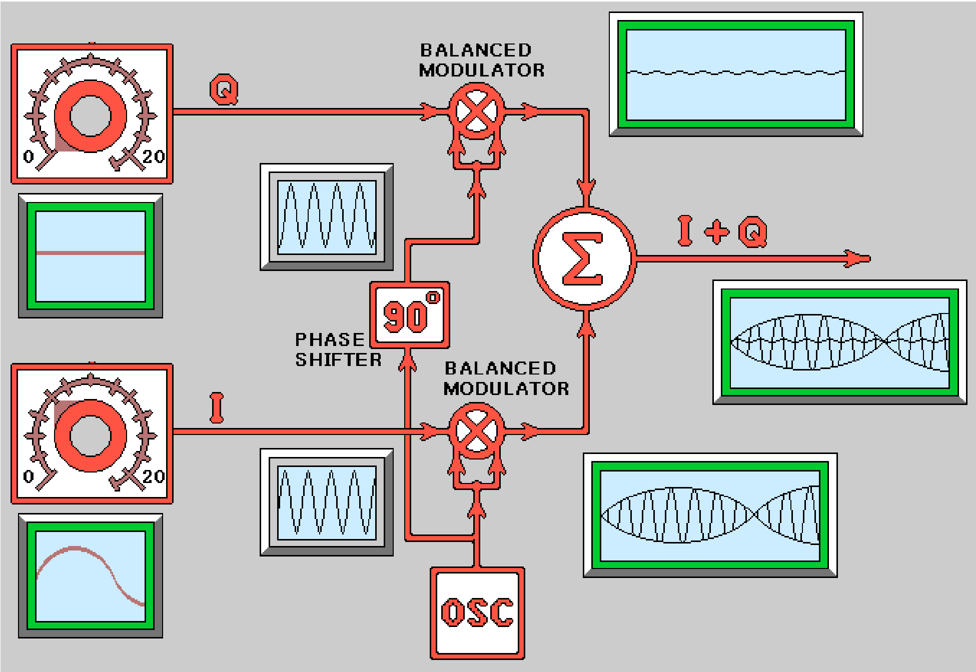


QAM

- AM signal BANDWIDTH : AM signal bandwidth is twice the bandwidth of the modulating signal. A 5kHz signal requires 10kHz bandwidth for AM transmission. If the carrier frequency is 1000 kHz, the AM signal spectrum is in the frequency range of 995kHz to 1005 kHz.
- QUADRARTURE AMPLITUDE MODULATION is a scheme that allows two signals to be transmitted over the same frequency range.
- Equations
- Coherent in frequency

and phase. Expensive

- TV for analog
- Most modems



Angle Modulation

- Angle of the carrier is varied according to the amplitude of the modulating baseband signal.
- Two classes of angle modulation techniques:
  - Frequency Modulation
    - Instantaneous frequency of the carrier signal is varied linearly with message signal m(t)
  - Phase Modulation
    - The phase $\theta(t)$ of the carrier signal is varied linearly with the message signal m(t).

Angle Modulation

FREQUENCY MODULATION

$$s_{FM}(t) = A_c \cos(2\pi f_c t + \theta(t)] = A_c \cos\left[2\pi f_c t + 2\pi k_f \int_{-\infty}^{t} m(x)dx\right]$$

k_f is the frequency deviation constant (kHz/V)

If modulation signal is a sinusoid of amplitude A_m, frequency f_m:

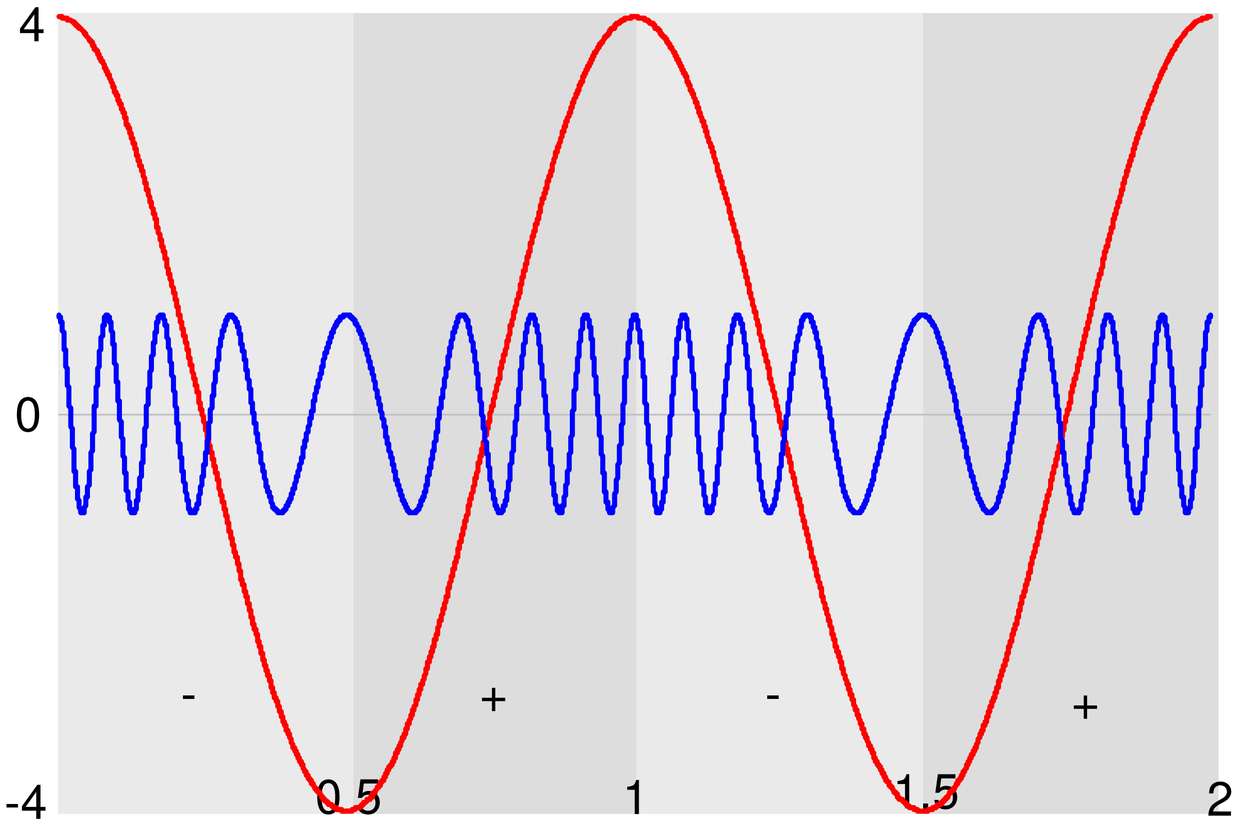
$$s_{FM}(t) = A_c \cos(2\pi f_c t + \frac{k_f A_m}{f_m} \sin(2\pi f_m t)]$$

PHASE MODULATION

$$s_{PM}(t) = A_c \cos\left[2\pi f_c t + k_\theta m(t)\right]$$

k_θ is the phase deviation constant

FM Example



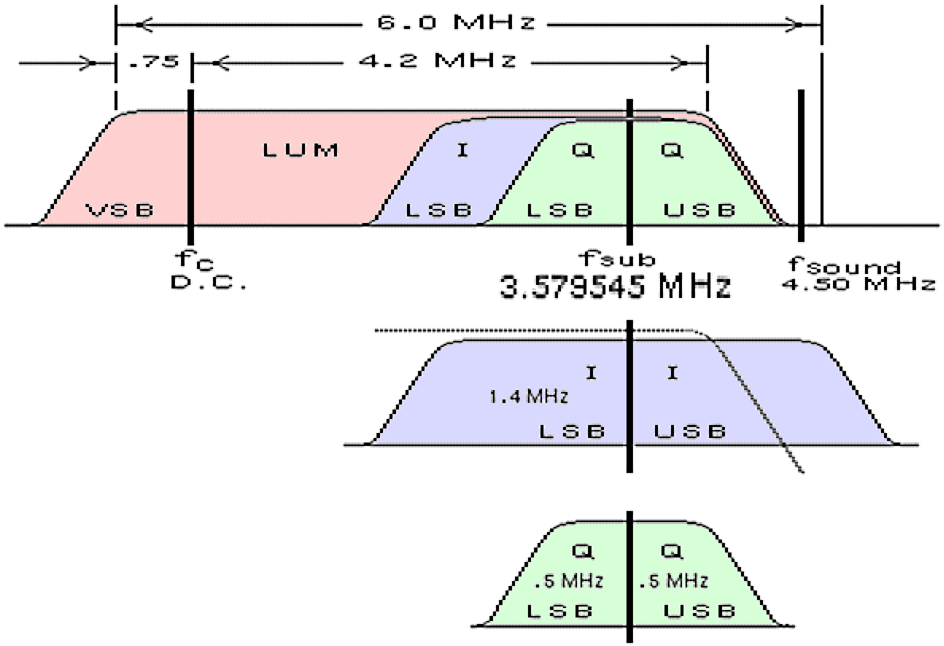
Message signal $m(t) = 4\cos(2\pi t)$

FM Signal $s(t) = \cos[2\pi 8t + 4\sin(2\pi t)]$

Carrier Signal $\cos(2\pi 8t)$

TV broadcasting

- f_m=15KHz, Δf=25KHz, β=5/3, B=2(f_m+Δf)=80kHz
- Center f_c+4.5MHz



Comparison of modulation systems

Type	$b = B_T/W$	$(S/N)_D/\gamma$	γ_{th}	DC	Complexity	Comments	Typical applications
Baseband	1	1	…	No†	Minor	No modulation	Short-haul links
AM	2	$\frac{\mu^2 S_x}{1+\mu^2 S_x}$	20	No	Minor	Envelope detection $\mu \leq 1$	Broadcast ratio
DSB	2	1	…	Yes	Major	Synchronous detection	Analog data, multiplexing
SSB	1	1	…	No	Moderate	Synchronous detection	Point-to-point voice, multiplexing
VSB	1+	1	…	Yes	Major	Synchronous detection	Digital data
VSB + C	1+	$\frac{\mu^2 S_x}{1+\mu^2 S_x}$	20	Yes‡	Moderate	Envelope detection $\mu < 1$	Television video
PM§	$2M(\phi_\Delta)$	$\phi_\Delta^2 S_x$	$10b$	Yes	Moderate	Phase detection $\phi_\Delta \leq \pi$	Digital data
FM§¶	$2M(D)$	$3D^2 S_x$	$10b$	Yes	Moderate	Frequency detection	Broadcast radio, microwave relay, satellite systems

† Unless direct-coupled.
‡ With electronic DC restoration.
§ $b \geq 2$.
¶ Deemphasis not included.

Satellite Radio

- WorldSpace outside US, XM Radio and Sirius in North America

	XM Satellite Radio	Sirius
Company info	XMSR, $2billion, DC	SIRI, $5 billion, NYC
Current Subscribers	7,000,000+	4,000,000+
Monthly rate	12.95/month	12.95/month
Total channel	170+, 90+streams of music	165+, 80+streams of music
Satellite	2 Boeing geostationary satellites	3 Loral satellites at high-elevation geosynchronous orbit

Provider	BMW MINI Rolls-Royce	Chrysler Dodge Mercedes-Benz Jeep	Ford Lincoln Mercury Volvo Land Rover Jaguar Mazda	GM Cadillac Chevrolet Buick Pontiac GMC Opel Vauxhall Saab	Honda Acura	Hyundai Kia	Nissan Infiniti	Porsche	Toyota Lexus Scion	VW Audi	Suzuki
Sirius	Y	Y	Y				Y	Y	Y	Y	
XM				Y	Y	Y	Y	Y	Y		Y

Geometric Representation of Modulation Signal

- Digital Modulation involves
  - Choosing a particular signal waveform for transmission for a particular symbol or signal
  - For M possible signals, the set of all signal waveforms are:

$$S = \{s_1(t), s_2(t), \ldots, s_M(t)\}$$

- For binary modulation, each bit is mapped to a signal from a set of signal set S that has two signals
- We can view the elements of S as points in vector space

Geometric Representation of Modulation Signal

- Vector space
  - We can represented the elements of S as linear combination of <u>basis signals.</u>
  - The number of basis signals are the dimension of the vector space.
  - Basis signals are orthogonal to each-other.
  - Each basis is normalized to have unit energy:

$$s_i(t) = \sum_{j=1}^{N} s_{ij}\phi_j(t)$$

$$\int_{-\infty}^{\infty} \phi_i(t)\phi_j(t)dt = 0$$

$$E = \int_{-\infty}^{\infty} \phi_i^2(t)dt = 1$$

$\phi_i(t)$ is the i^{th} basis signal.

Example

$$s_1(t) = \sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t) \quad 0 \le t \le T_b$$

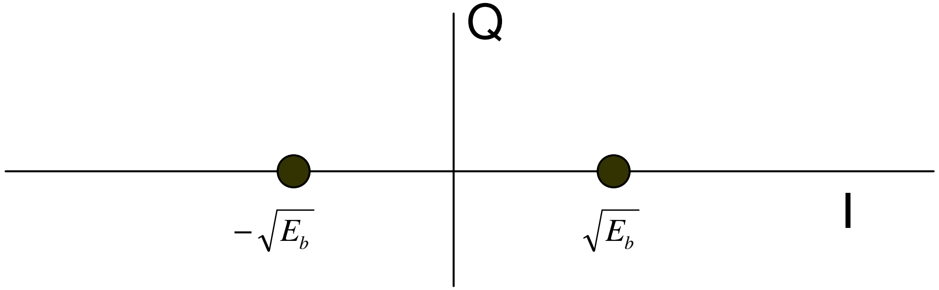
$$s_2(t) = -\sqrt{\frac{2E_b}{T_b}}\cos(2\pi f_c t) \quad 0 \le t \le T_b$$

Two signal waveforms to be used for transmission

$$\phi_1(t) = \sqrt{\frac{2}{T_b}}\cos(2\pi f_c t)$$

The basis signal

$$S = \left\{\sqrt{E_b}\,\phi_1(t), -\sqrt{E_b}\,\phi_1(t)\right\}$$

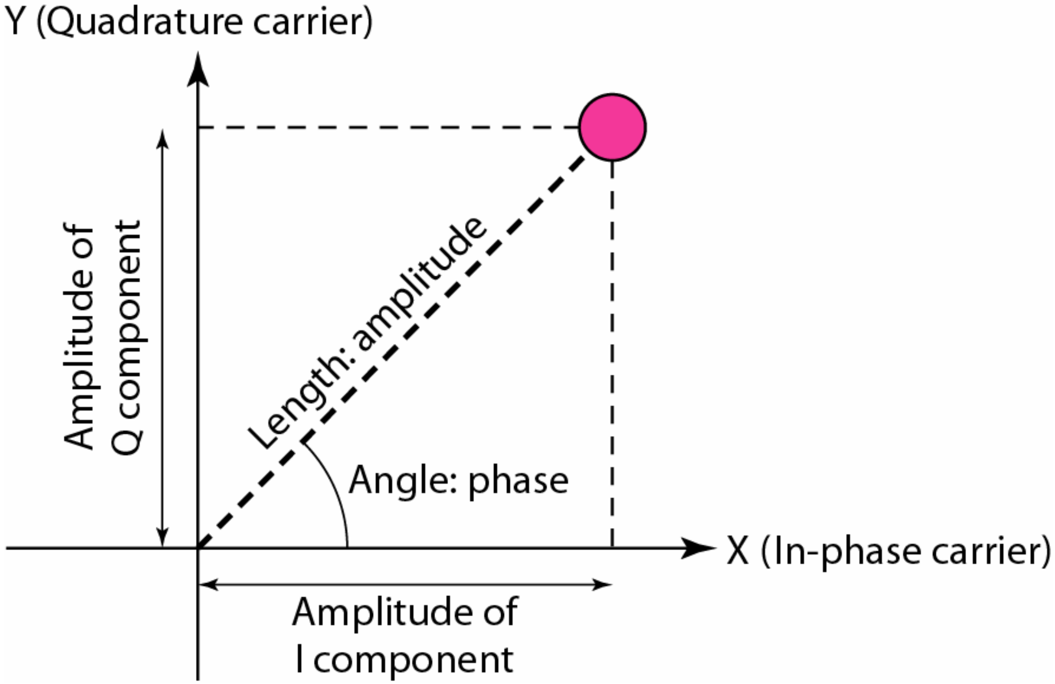


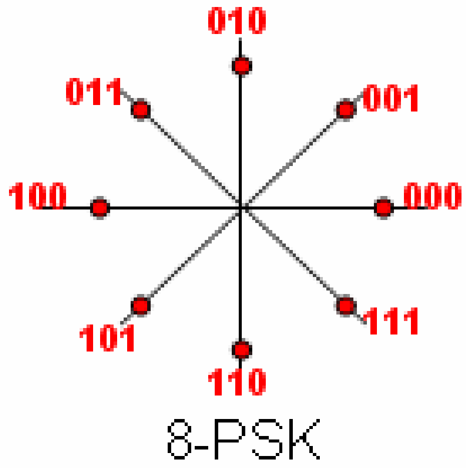
Constellation Diagram
Dimension = 1

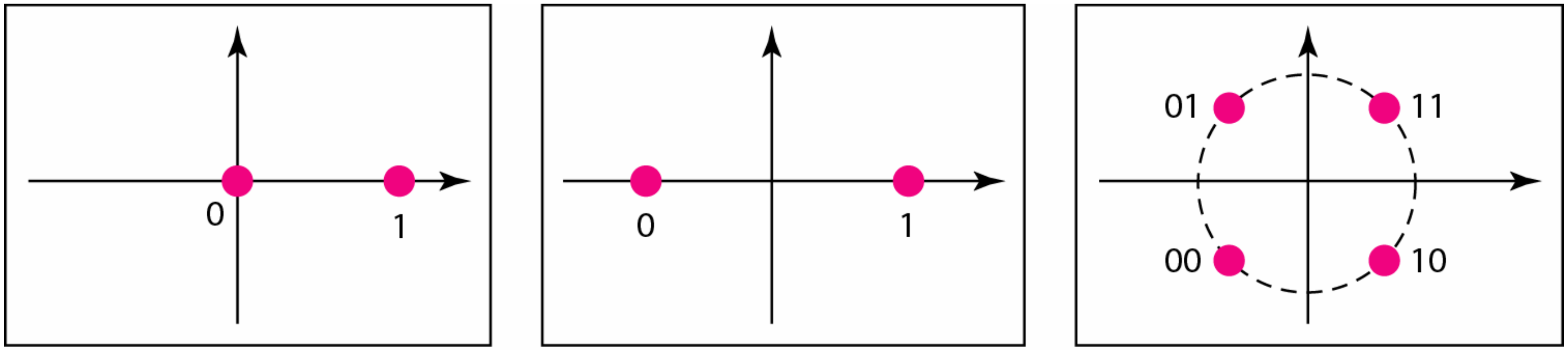
Constellation Diagram

- Properties of Modulation Scheme can be inferred from Constellation Diagram
  - Bandwidth occupied by the modulation increases as the dimension of the modulated signal increases
  - Bandwidth occupied by the modulation decreases as the signal points per dimension increases (getting more dense)
  - Probability of bit error is proportional to the distance between the closest points in the constellation.
    - *Bit error decreases as the distance increases (sparse).*

Concept of a constellation diagram







a. ASK (OOK) b. BPSK c. QPSK

Linear Modulation Techniques

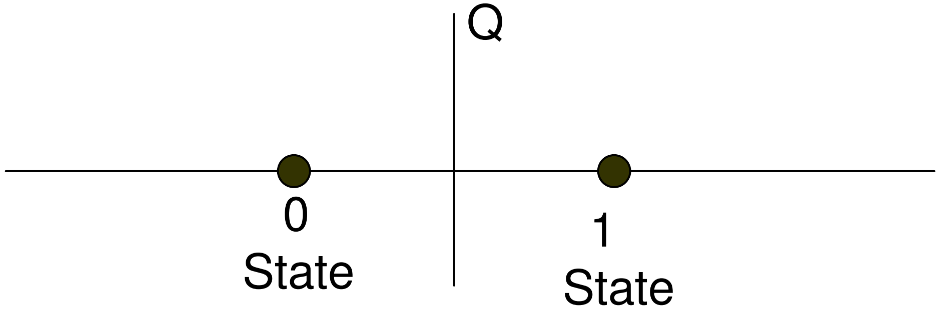
- Classify digital modulation techniques as:
  - Linear
    - *The amplitude of the transmitted signal varies linearly with the modulating digital signal, m(t).*
    - *They usually do not have constant envelope.*
    - *More spectral efficient.*
    - *Poor power efficiency*
    - *Example: BPSK, QPSK.*
  - Non-linear

Binary Phase Shift Keying

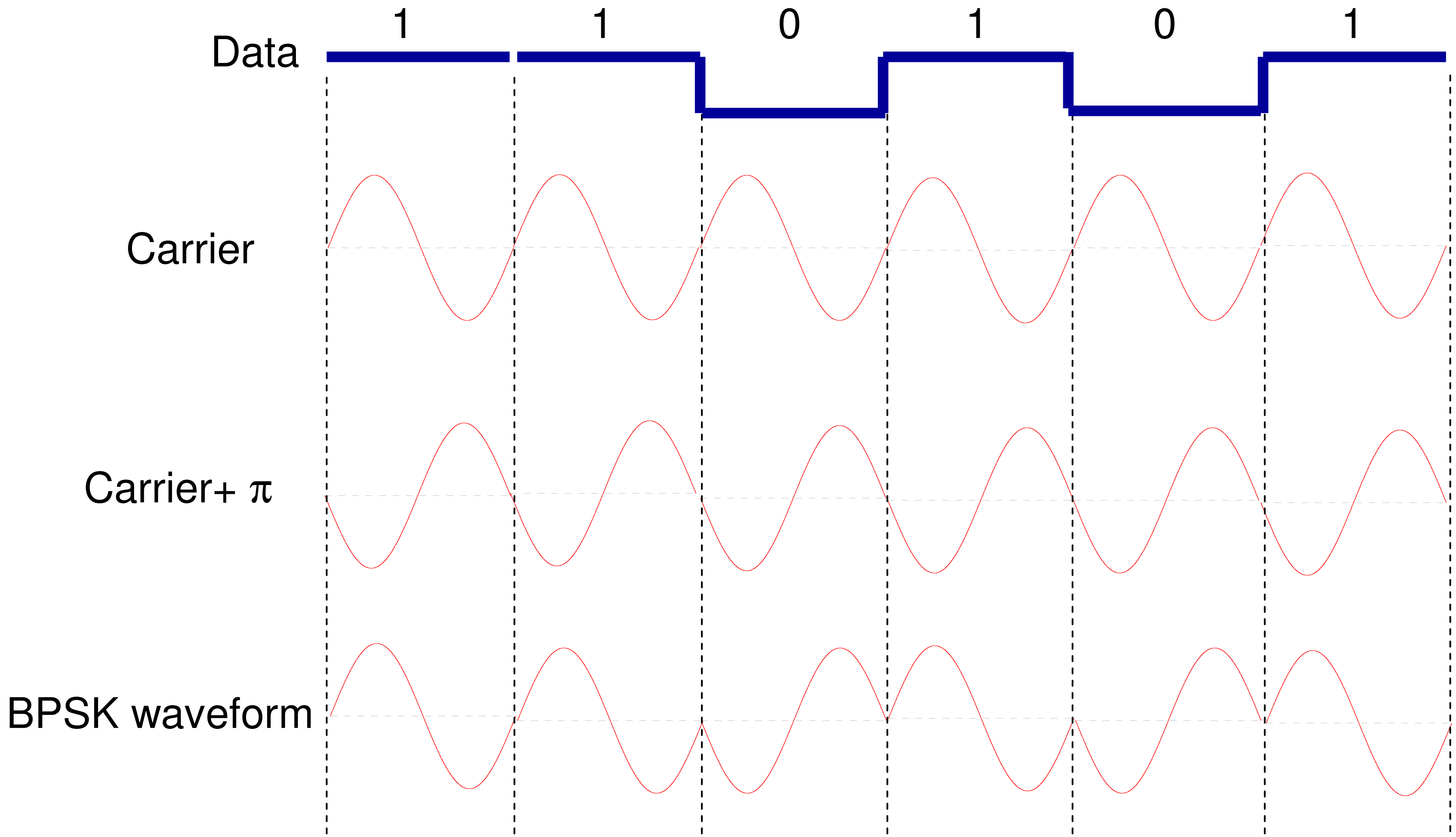
- Use alternative sine wave phase to encode bits
  - Phases are separated by 180 degrees.
  - Simple to implement, inefficient use of bandwidth.
  - Very robust, used extensively in satellite communication.

$$s_1(t) = A_c \cos(2\pi f_c + \theta_c) \quad \text{binary 1}$$

$$s_2(t) = A_c \cos(2\pi f_c + \theta_c + \pi) \quad \text{binary 0}$$



BPSK Example



BPSK Virtue of pulse shaping

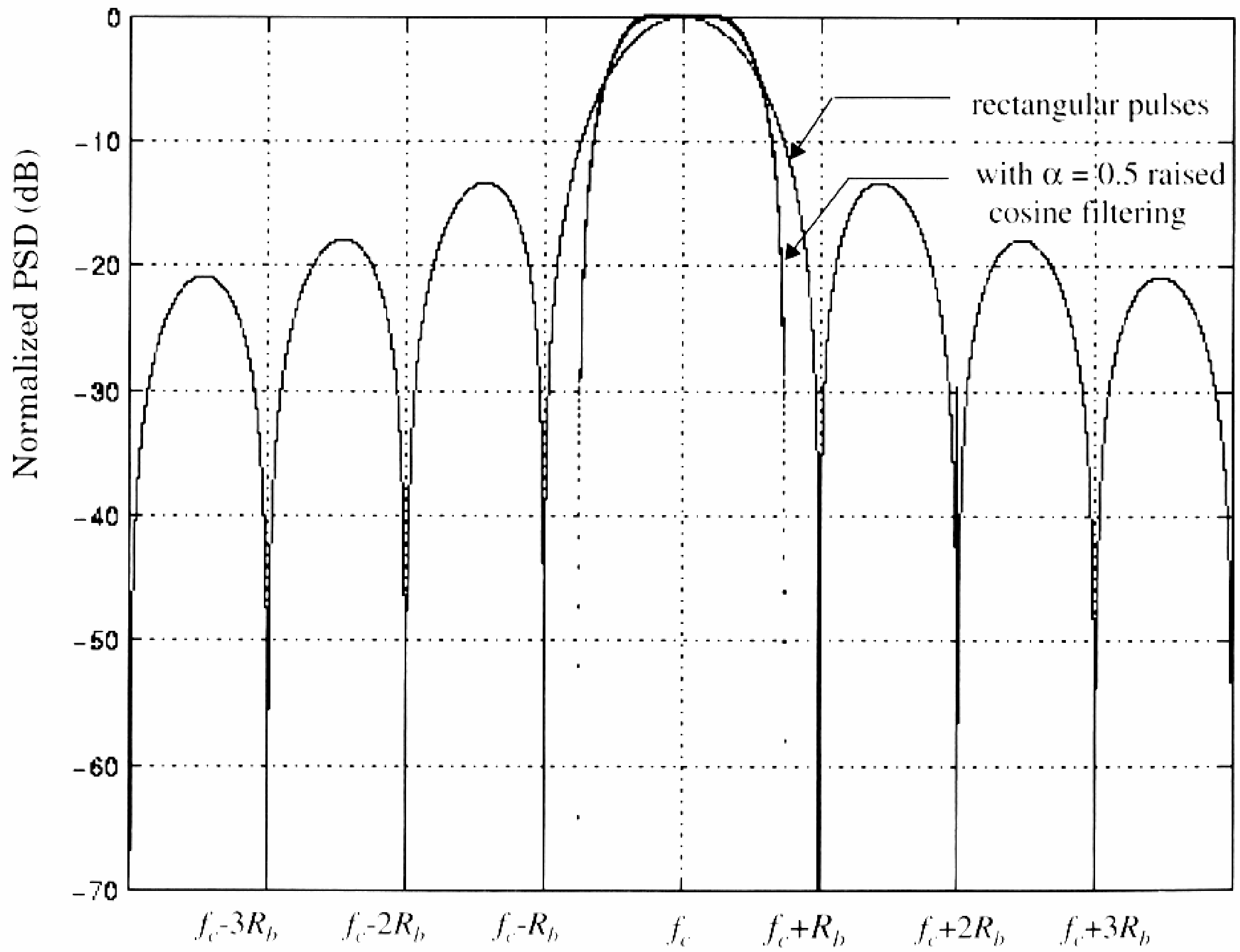


Figure 6.22 Power spectral density (PSD) of a BPSK signal.

BPSK Coherent demodulator

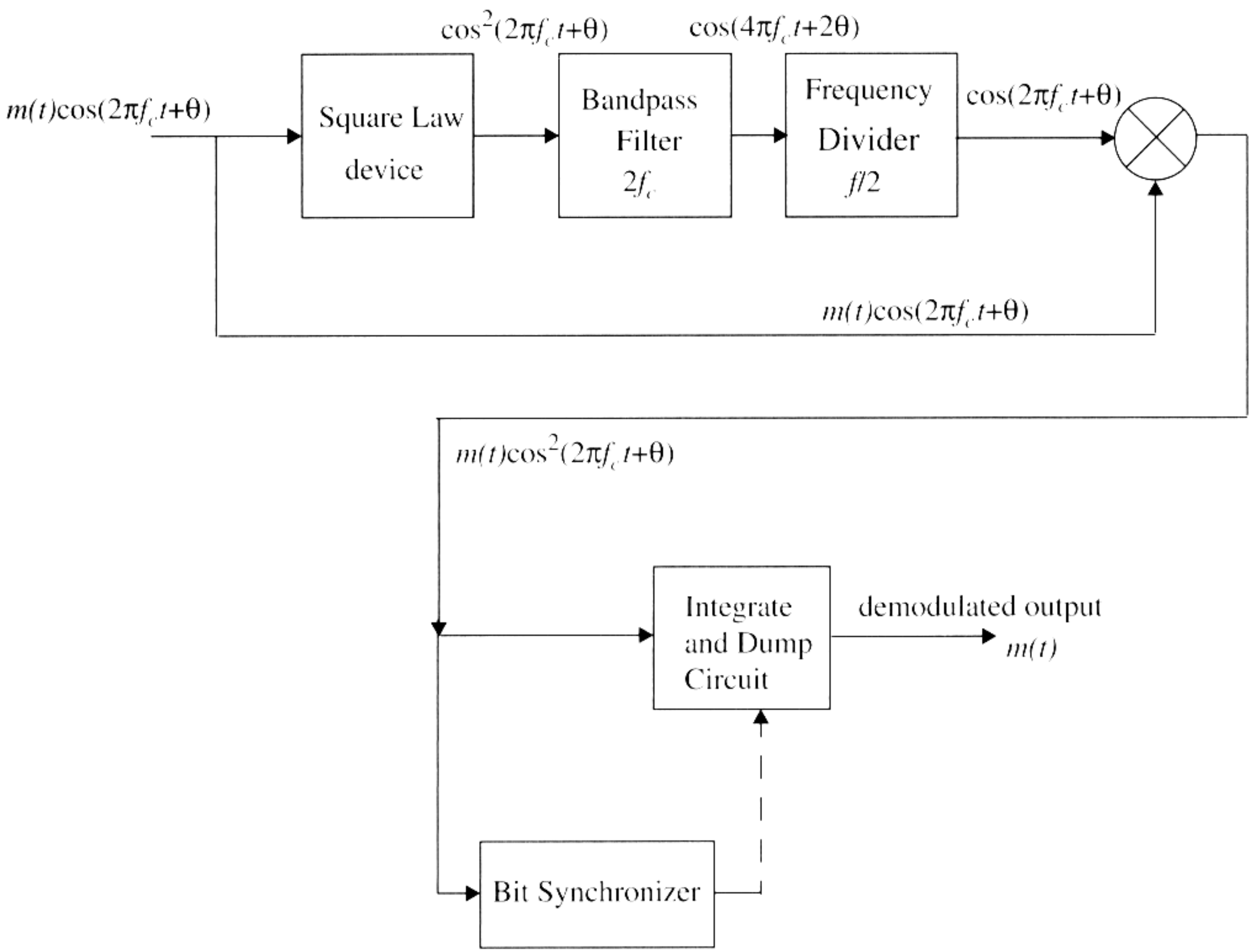


Figure 6.23 BPSK receiver with carrier recovery circuits.

Differential PSK encoding

- Differential BPSK
  - 0 = same phase as last signal element
  - 1 = 180º shift from last signal element

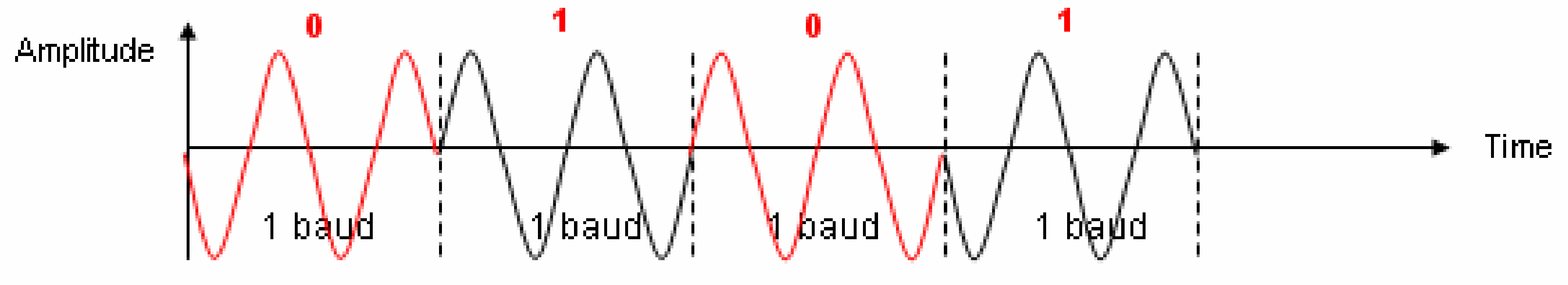


Table 6.1 Illustration of the Differential Encoding Process

$\{m_k\}$		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

DPSK modulation and demodulation

- 3dB loss

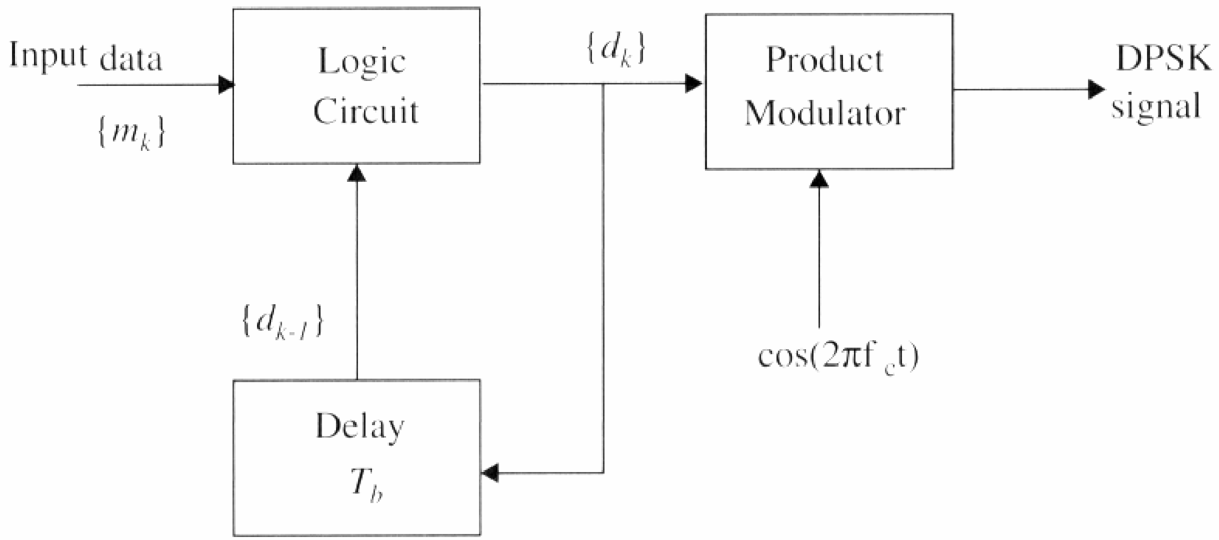


Figure 6.24 Block diagram of a DPSK transmitter.

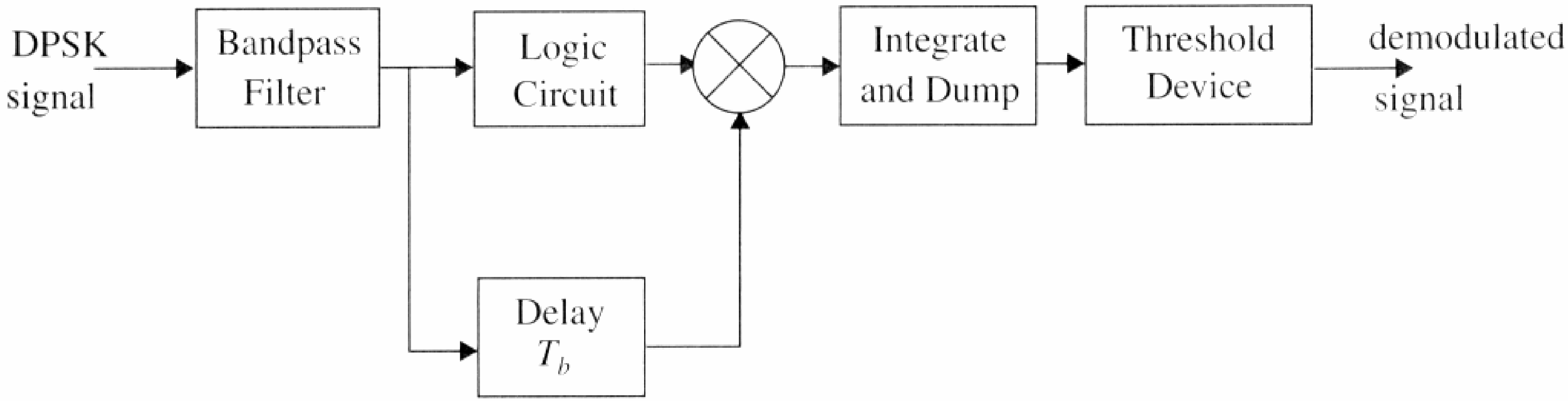
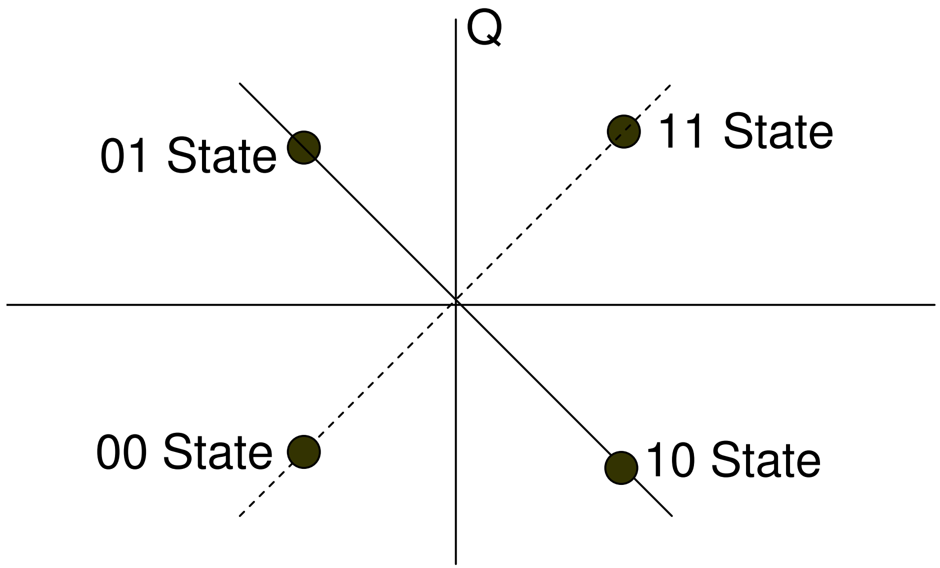


Figure 6.25 Block diagram of DPSK receiver.

Quadrature Phase Shift Keying

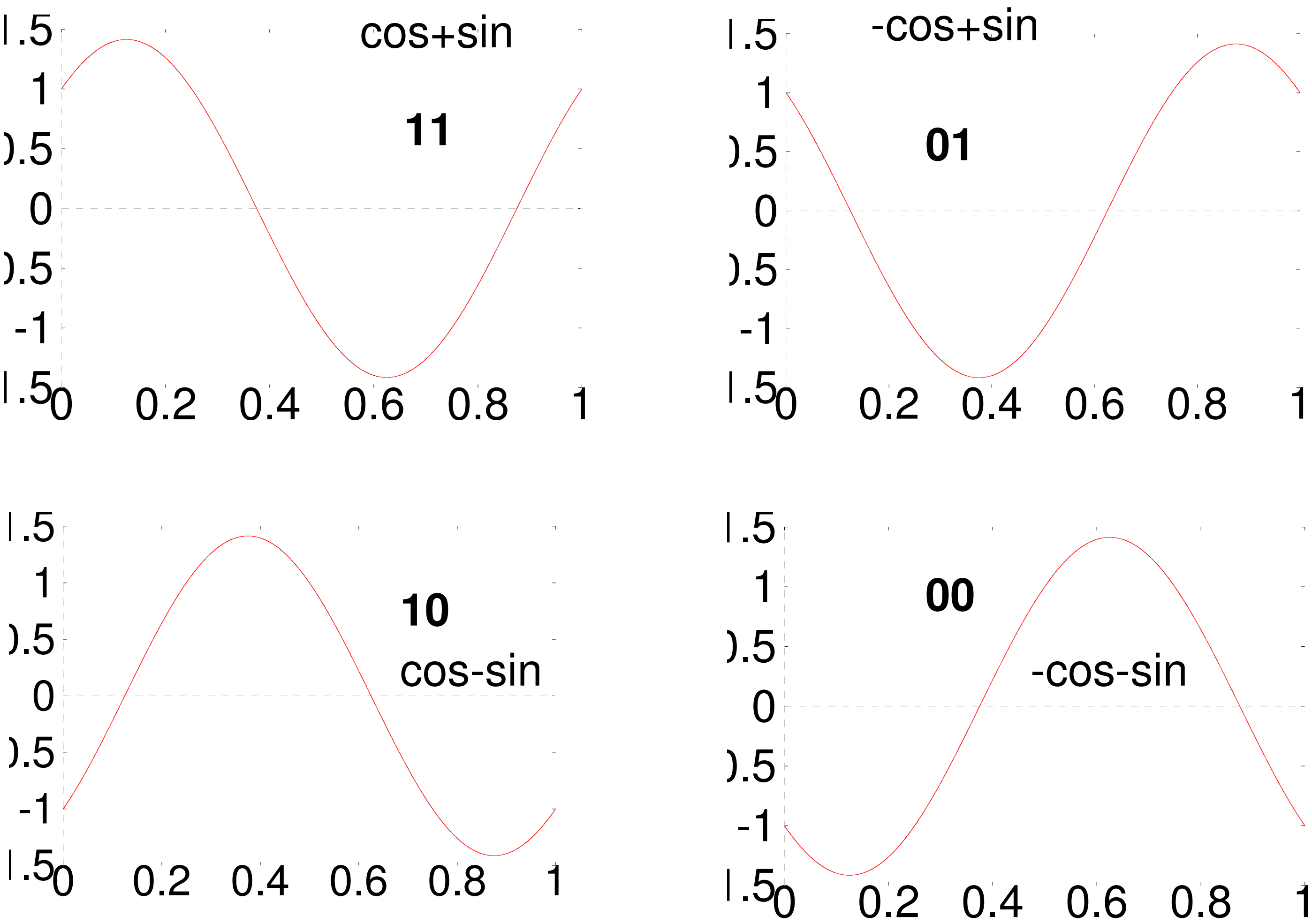
- Multilevel Modulation Technique: 2 bits per symbol
- More spectrally efficient, more complex receiver.
- Two times more bandwidth efficient than BPSK



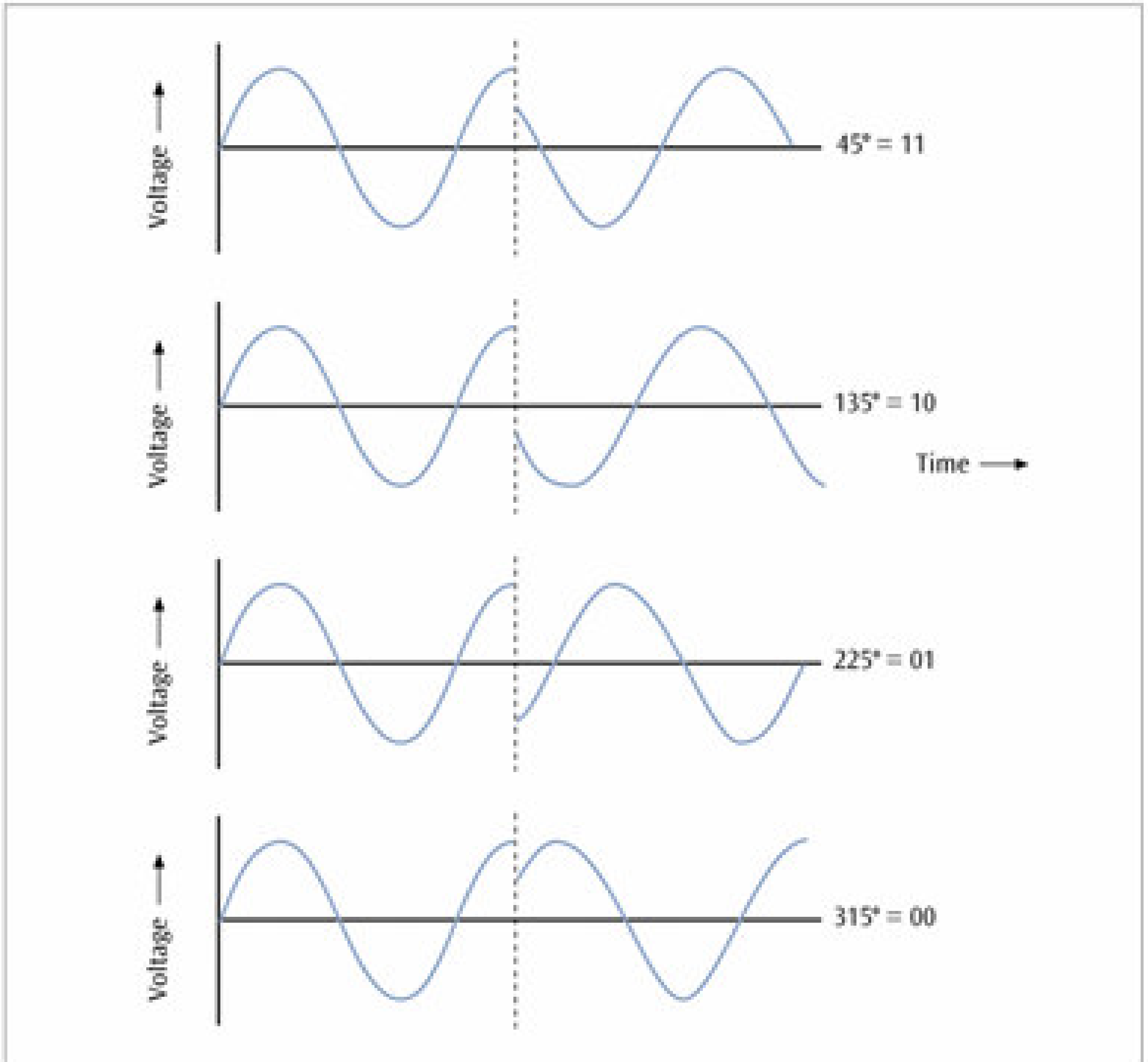
Phase of Carrier: π/4, 2π/4, 5π/4, 7π/4

$$s(t) = \begin{cases} A\cos\left(2\pi f_c t + \frac{\pi}{4}\right) & 11 \\ A\cos\left(2\pi f_c t + \frac{3\pi}{4}\right) & 01 \\ A\cos\left(2\pi f_c t - \frac{3\pi}{4}\right) & 00 \\ A\cos\left(2\pi f_c t - \frac{\pi}{4}\right) & 10 \end{cases}$$

4 different waveforms



QPSK Example



QPSK Virtue of pulse shaping

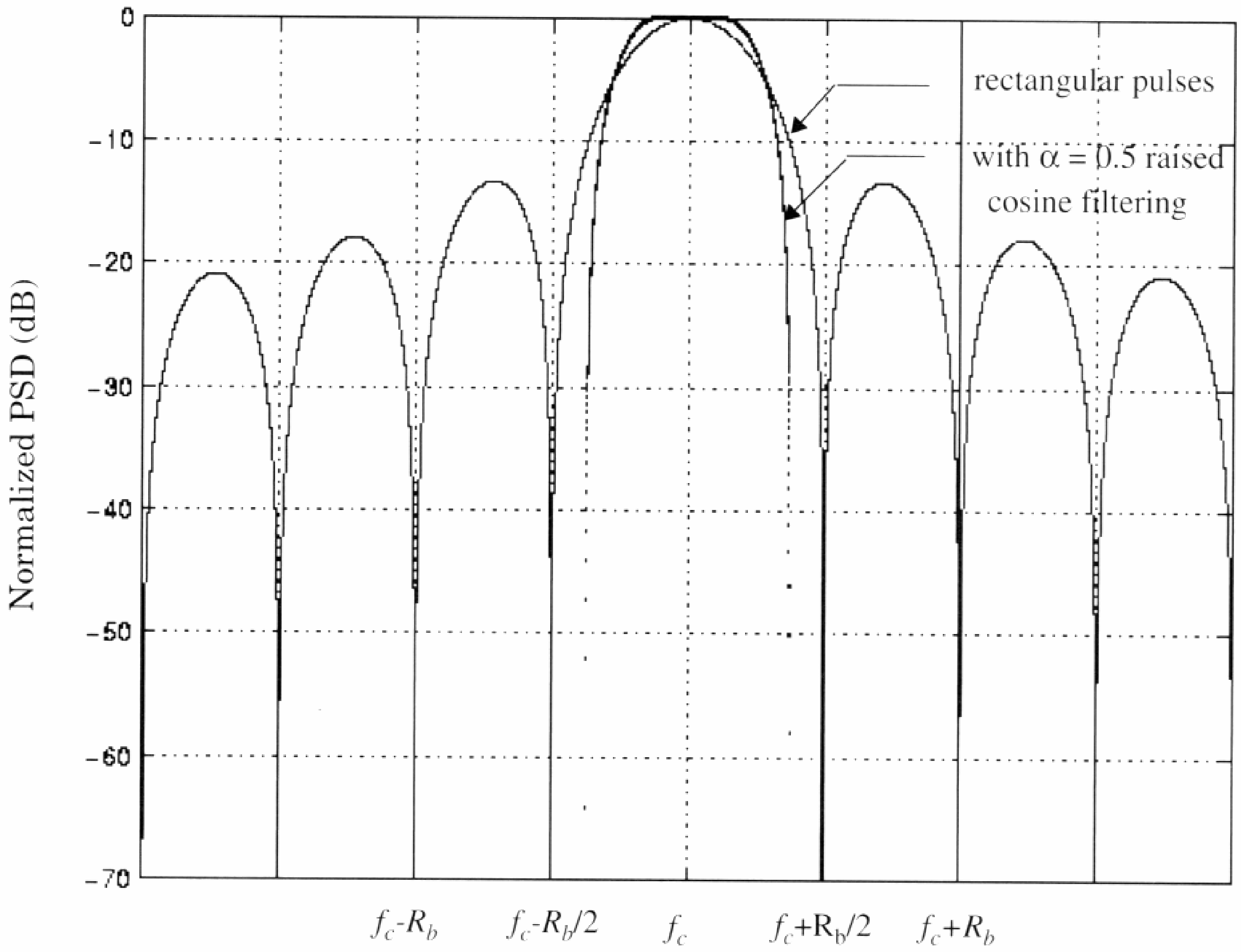


Figure 6.27 Power spectral density of a QPSK signal.

QPSK modulation

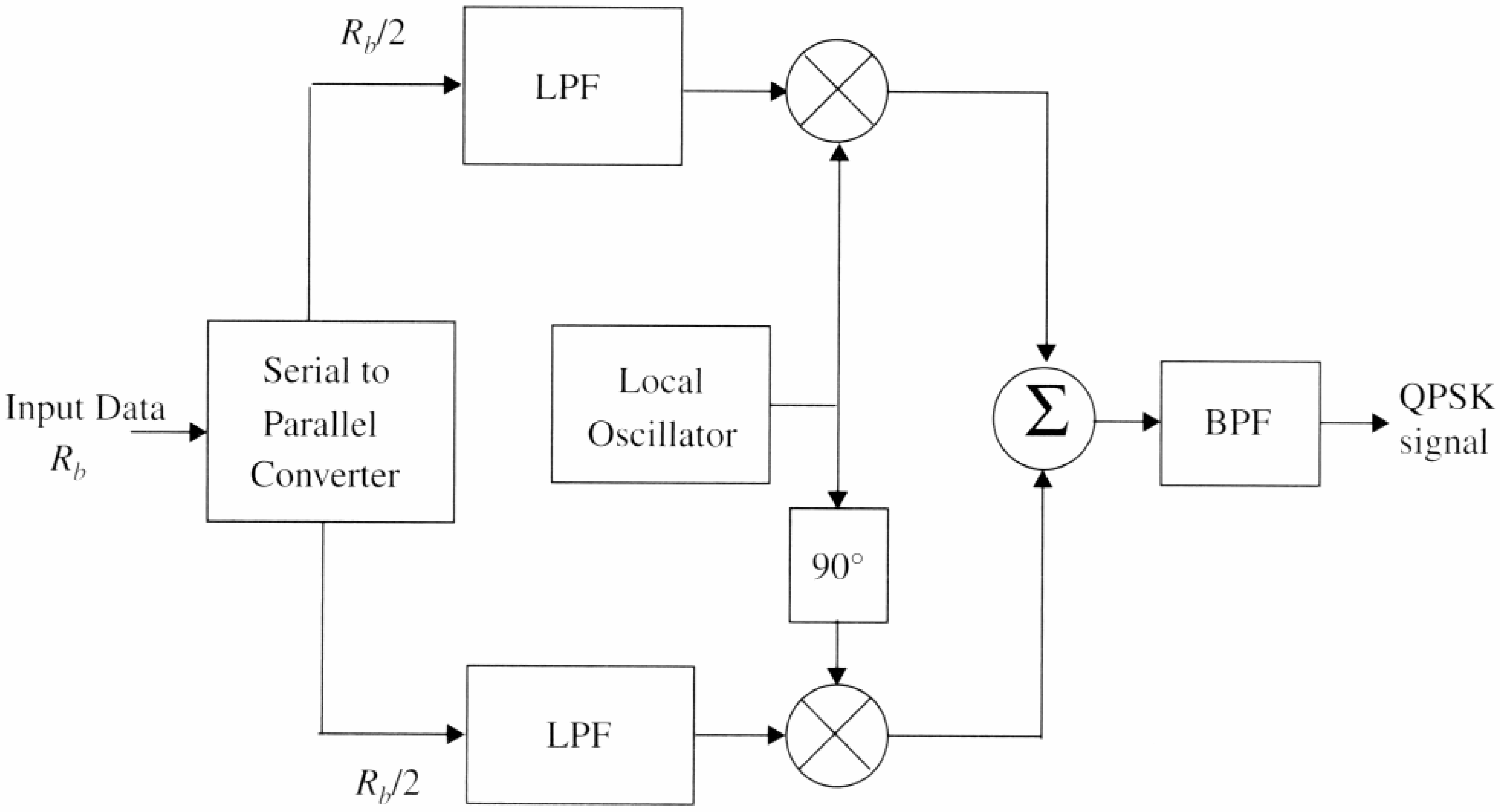


Figure 6.28 Block diagram of a QPSK transmitter.

QPSK receiver

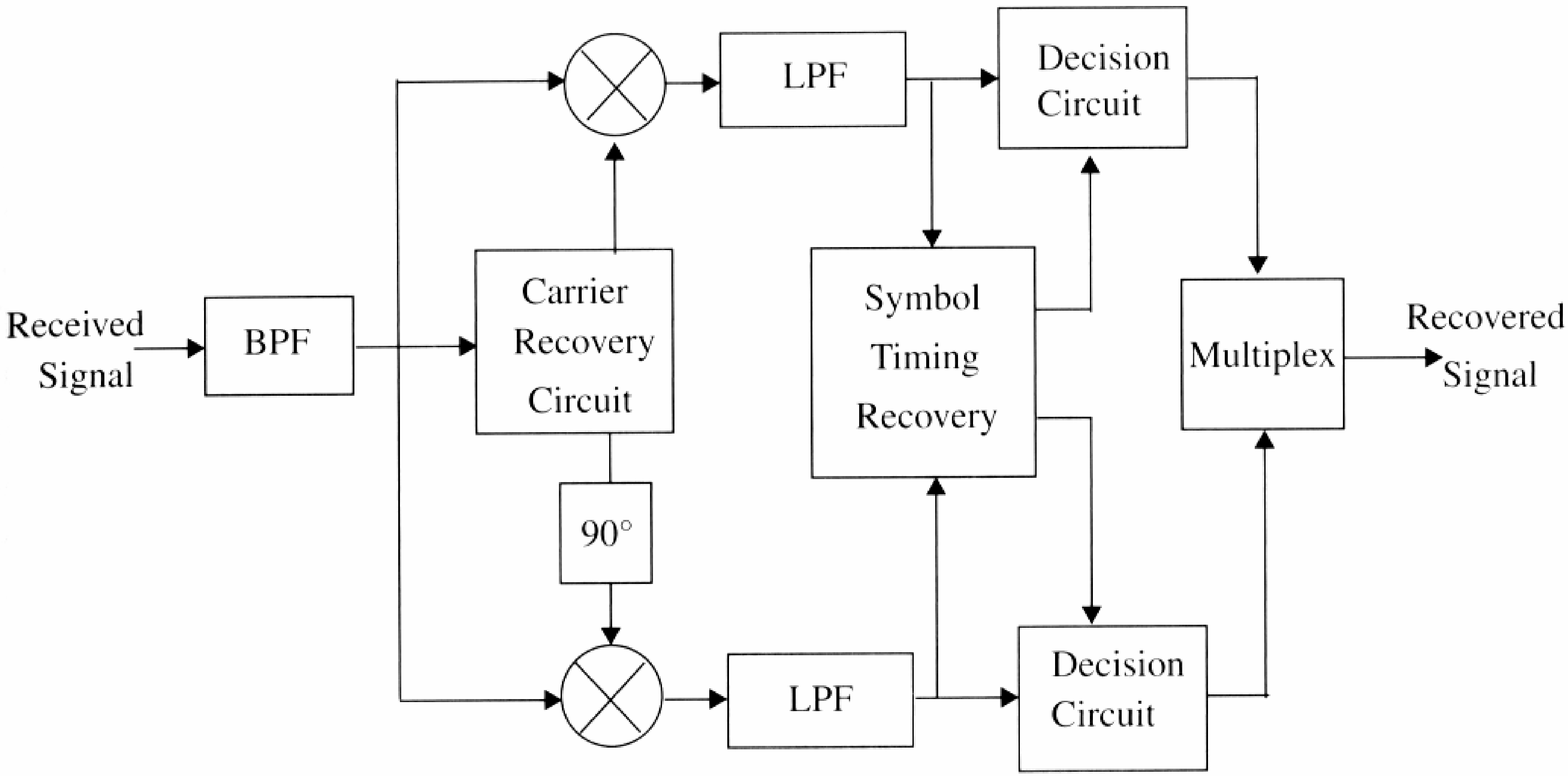
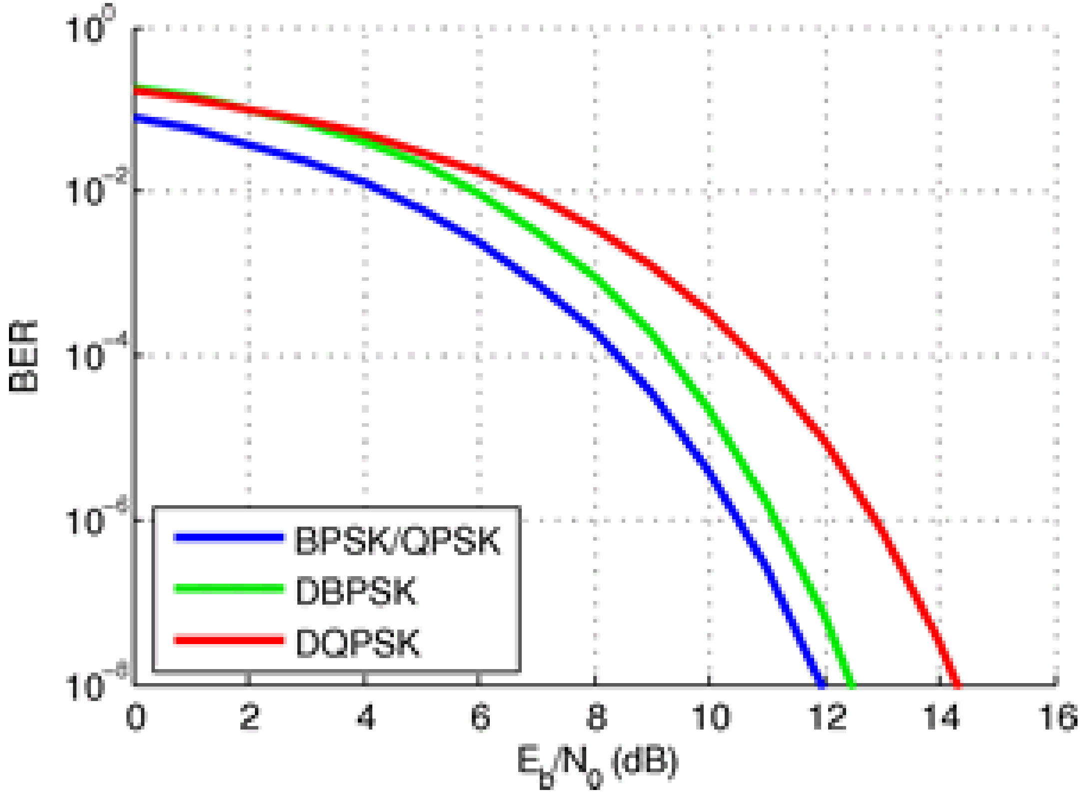


Figure 6.29 Block diagram of a QPSK receiver.

Differential Coherent

- DBPSK $P_b = \frac{1}{2} e^{-E_b/N_0}$
- 3dB loss
- QPSK BER, the same as BPSK



Offset QPSK waveforms

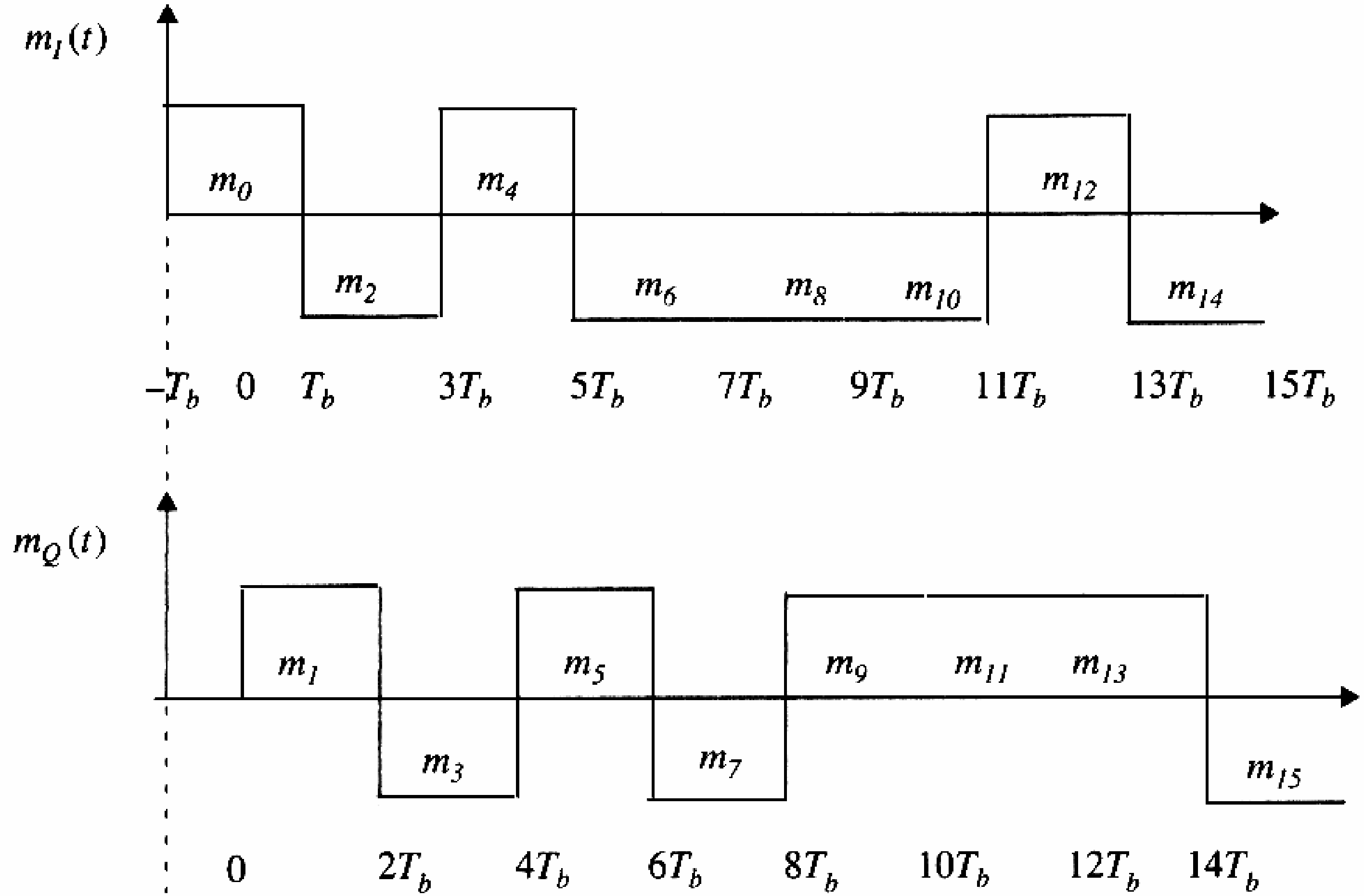
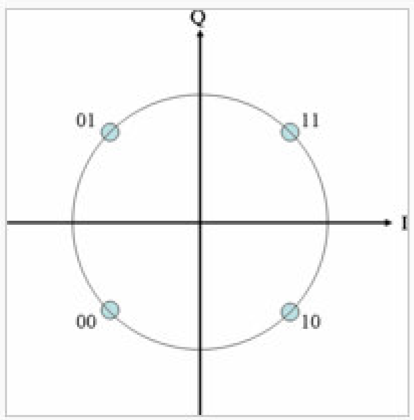


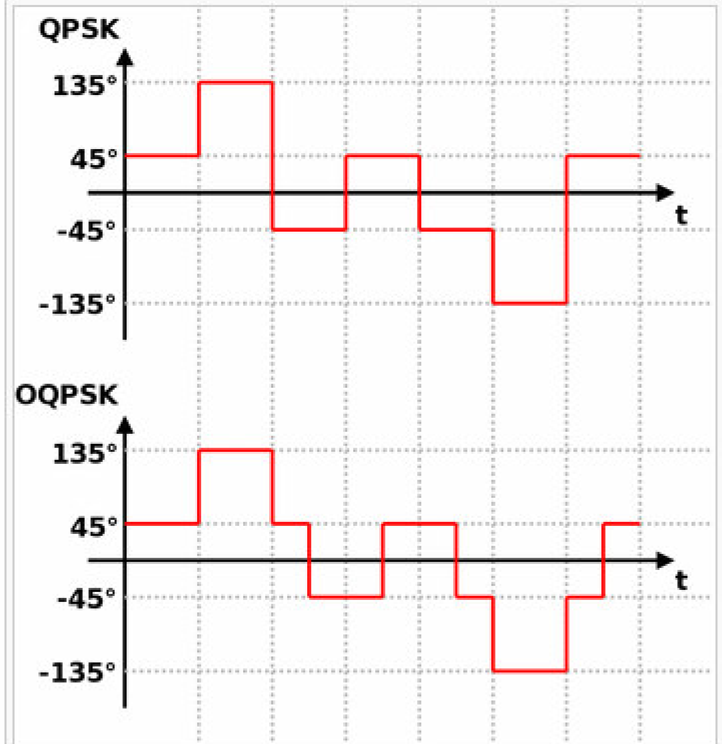
Figure 6.30 The time offset waveforms that are applied to the in-phase and quadrature arms of an OQPSK modulator. Notice that a half-symbol offset is used.

Offset OQPSK

- QPSK can have 180 degree jump, amplitude fluctuation
- By offsetting the timing of the odd and even bits by one bit-period, or half a symbol-period, the in-phase and quadrature components will never change at the same time.
- 90 degree jump



Constellation diagram for QPSK. Each adjacent symbol only differs by one bit.



Difference of the phase between QPSK and OQPSK

Pi/4 QPSK signaling

- 135 degree
- Non-coherent detection

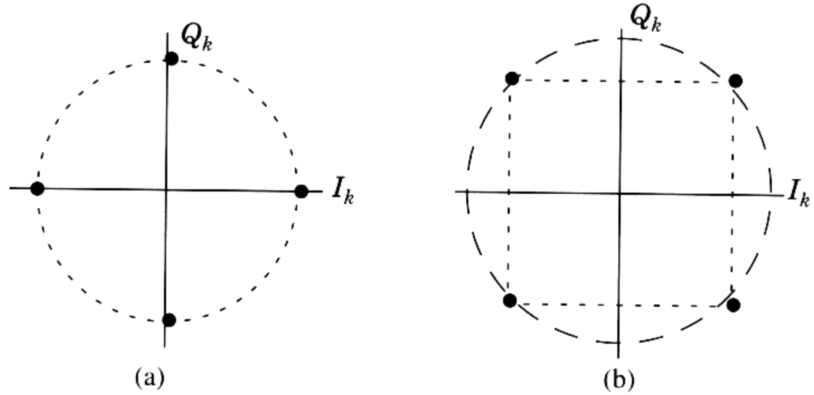


Table 6.2 Carrier Phase Shifts Corresponding to Various Input Bit Pairs [Feh91], [Rap91b]

Information bits m_{Ik}, m_{Qk}	Phase shift ϕ_k
1 1	$\pi/4$
0 1	$3\pi/4$
0 0	$-3\pi/4$
1 0	$-\pi/4$

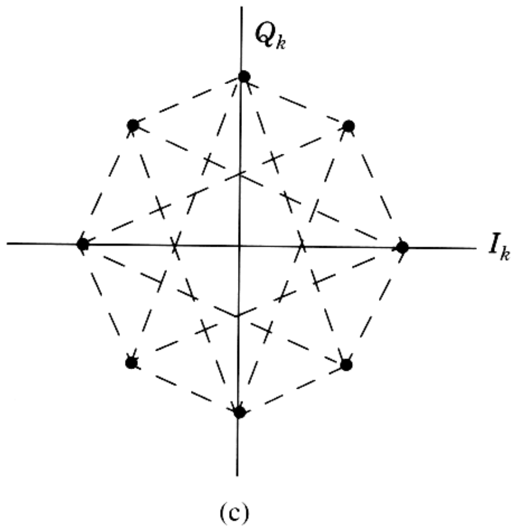


Figure 6.31 Constellation diagram of a $\pi/4$ QPSK signal: (a) possible states for θ_k when $\theta_{k-1} = n\pi/4$; (b) possible states when $\theta_{k-1} = n\pi/2$; (c) all possible states.

Pi/4 QPSK transmitter

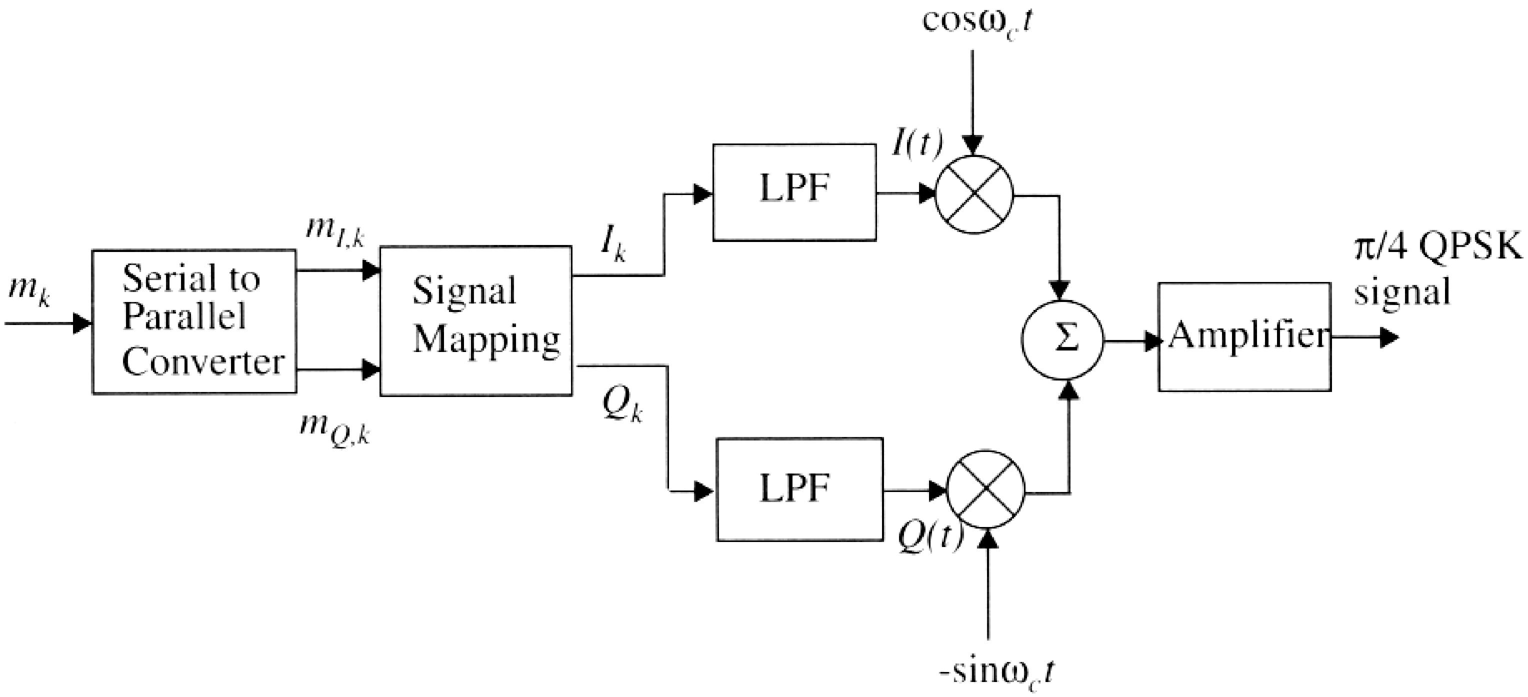


Figure 6.32 Generic π/4 QPSK transmitter.

I. Differential detection of pi/4 QPSK

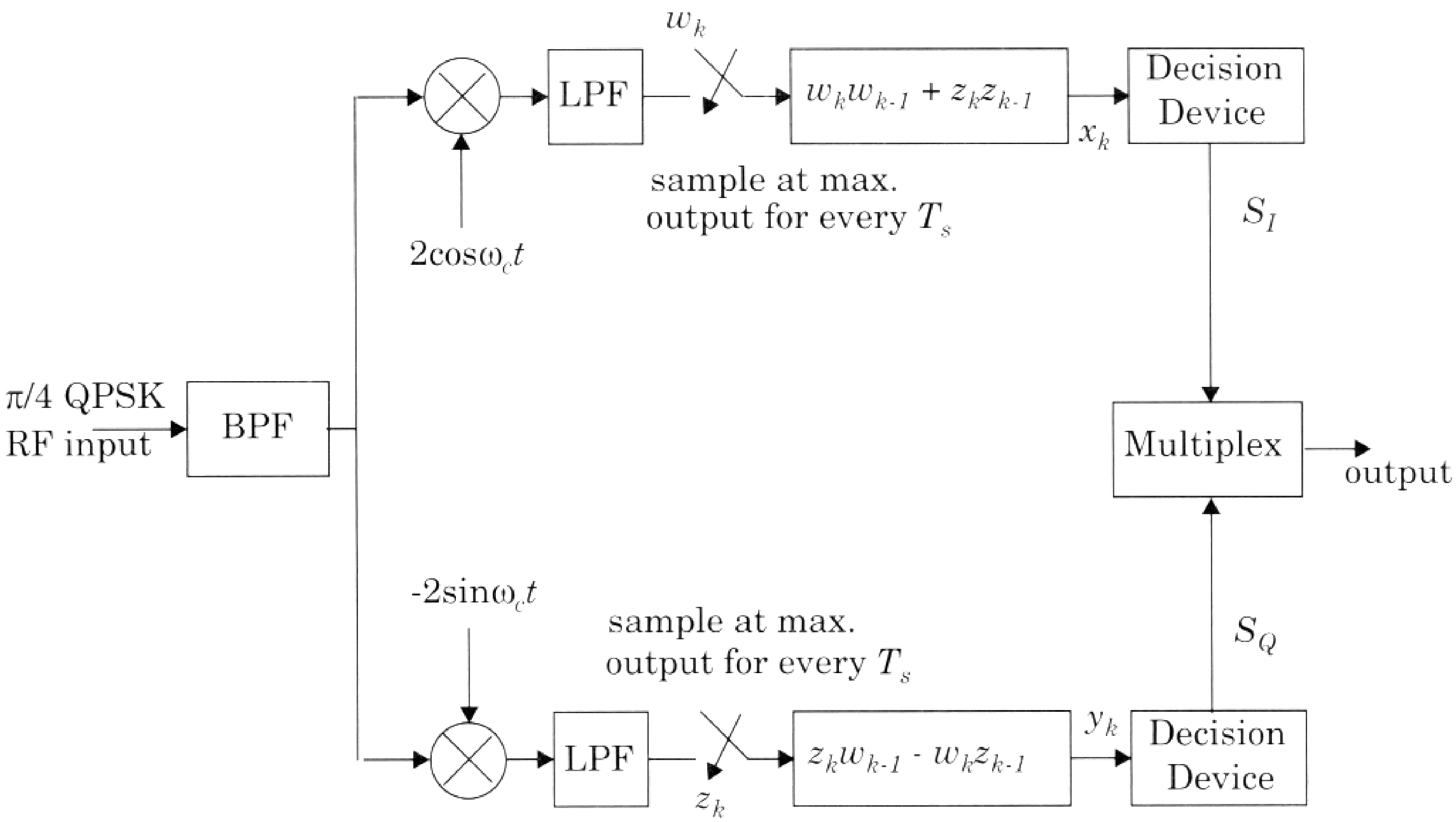


Figure 6.33 Block diagram of a baseband differential detector [from [Feh91] © IEEE].

III. FM Discriminator detector

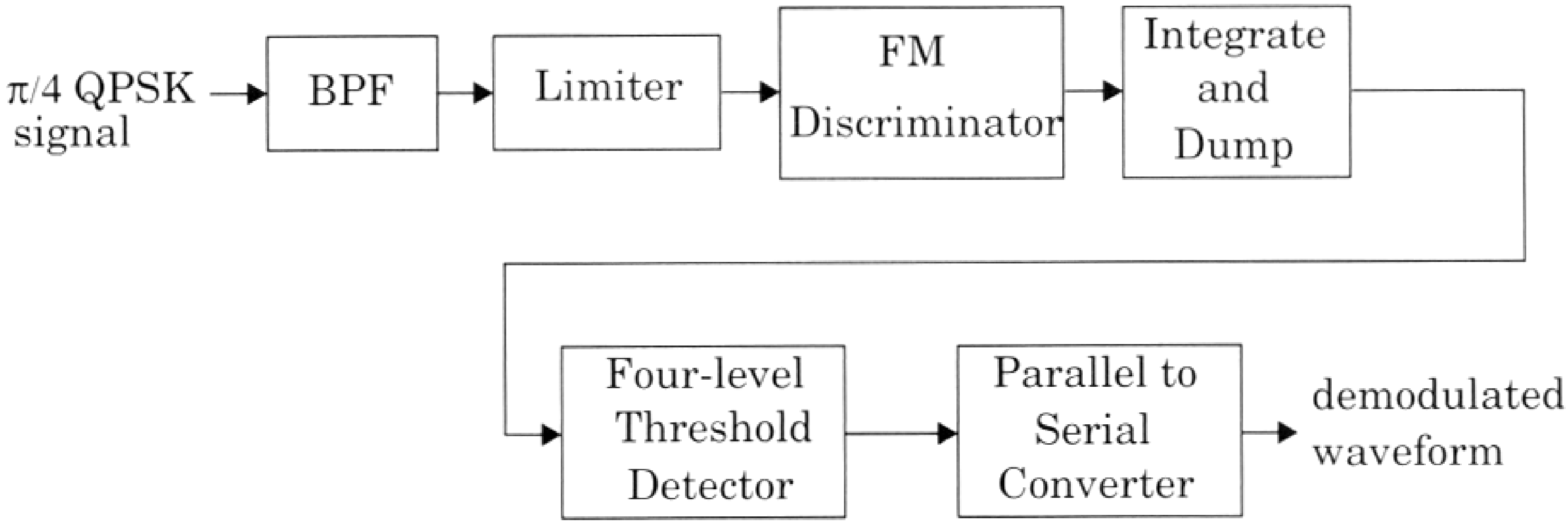


Figure 6.35 FM discriminator detector for $\pi/4$ DQPSK demodulation.

Constant Envelope Modulation

- Amplitude of the carrier is constant, regardless of the variation in the modulating signal
  - Better immunity to fluctuations due to fading.
  - Better random noise immunity
  - Power efficient
- They occupy larger bandwidth

Frequency Shift Keying (FSK)

- The frequency of the carrier is changed according to the message state (high (1) or low (0)).

$$s_1(t) = A\cos(2\pi f_c + 2\pi\Delta f)t \quad 0 \le \mathrm{t} \le \mathrm{T_b} \ (\mathrm{bit} = 1)$$

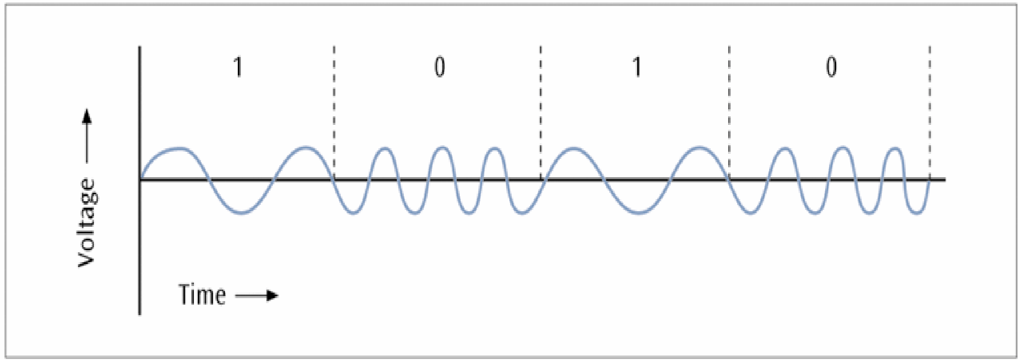
$$s_2(t) = A\cos(2\pi f_c - 2\pi\Delta f)t \quad 0 \le \mathrm{t} \le \mathrm{T_b} \ (\mathrm{bit} = 0)$$

Continues FSK $s(t) = A\cos(2\pi f_c + \theta(t))$ Integral of m(x) is continues.

$$s(t) = A\cos(2\pi f_c t + 2\pi k_f \int_{-\infty}^{t} m(x)dx)$$

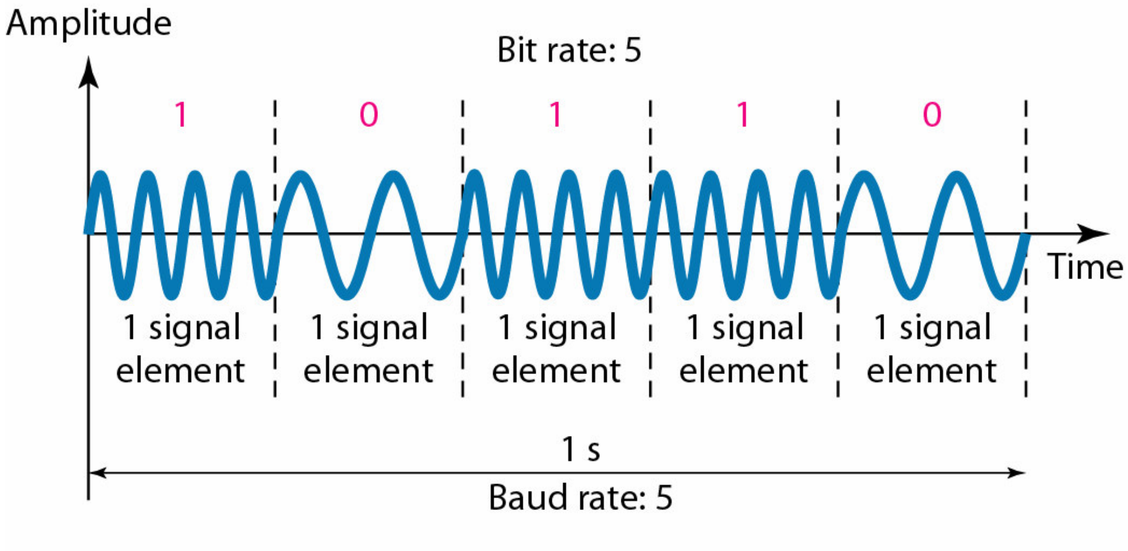
- One frequency encodes a 0 while another frequency encodes a 1 (a form of frequency modulation)

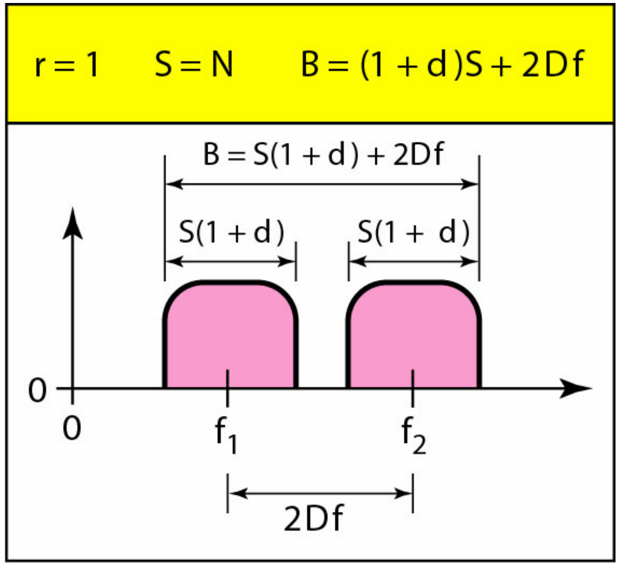
Figure 2-17
Simple example of frequency shift keying



FSK Bandwidth

- Limiting factor: Physical capabilities of the carrier
- Not susceptible to noise as much as ASK





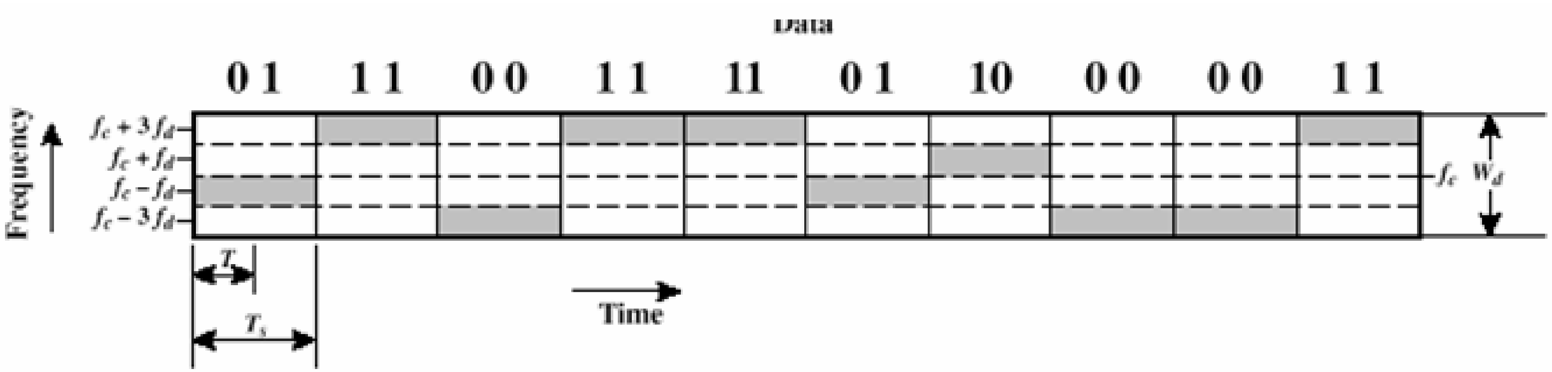
- Applications
  - On voice-grade lines, used up to 1200bps
  - Used for high-frequency (3 to 30 MHz) radio transmission
  - used at higher frequencies on LANs that use coaxial cable

Multiple Frequency-Shift Keying (MFSK)

- More than two frequencies are used
- More bandwidth efficient but more susceptible to error

$$s_i(t) = A\cos 2\pi f_i t \qquad 1 \le i \le M$$

- $f_i = f_c + (2i - 1 - M) f_d$
- f_c = *the carrier frequency*
- f_d = *the difference frequency*
- M = *number of different signal elements* = 2^L
- L = *number of bits per signal element*



FSK Coherent Detection

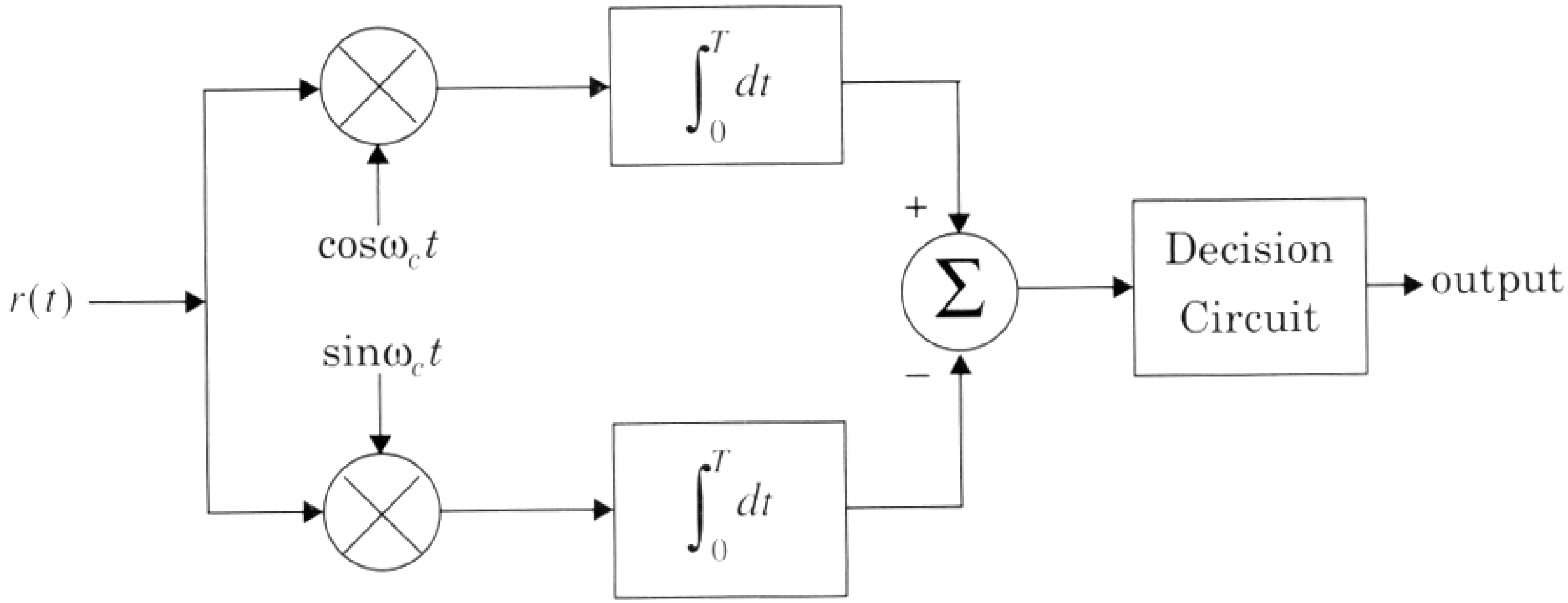


Figure 6.36 Coherent detection of FSK signals.

Noncoherent FSK

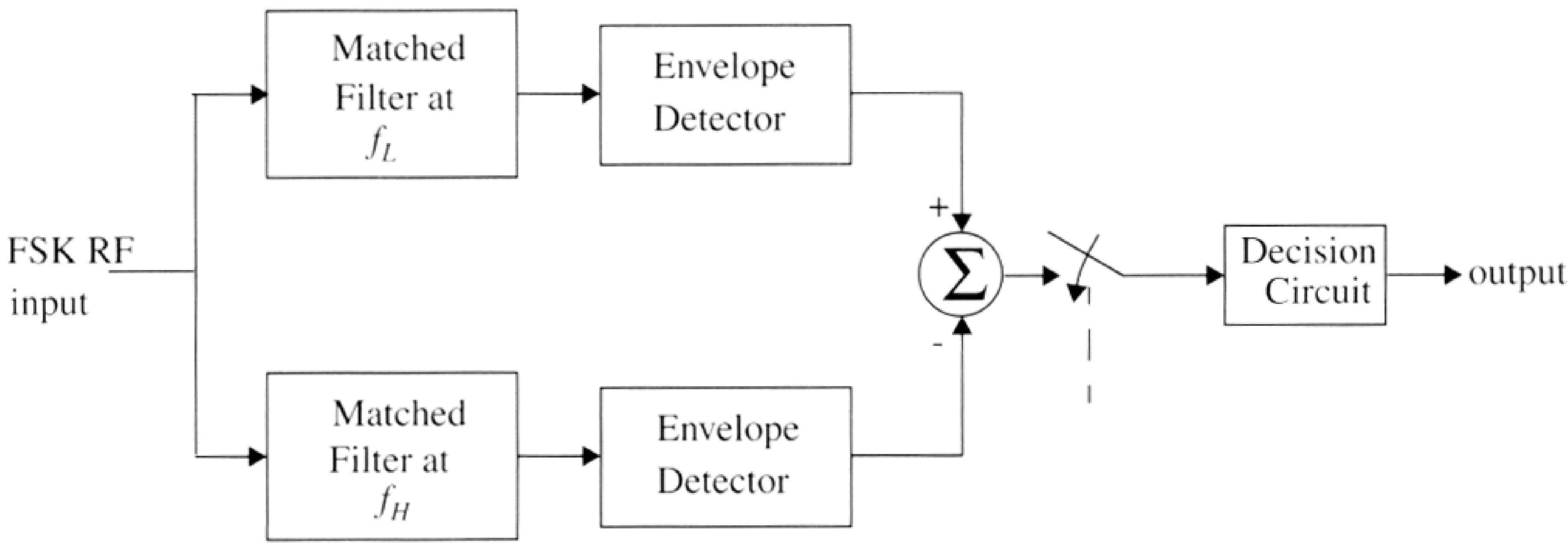


Figure 6.37 Block diagram of noncoherent FSK receiver.

MSK modulation

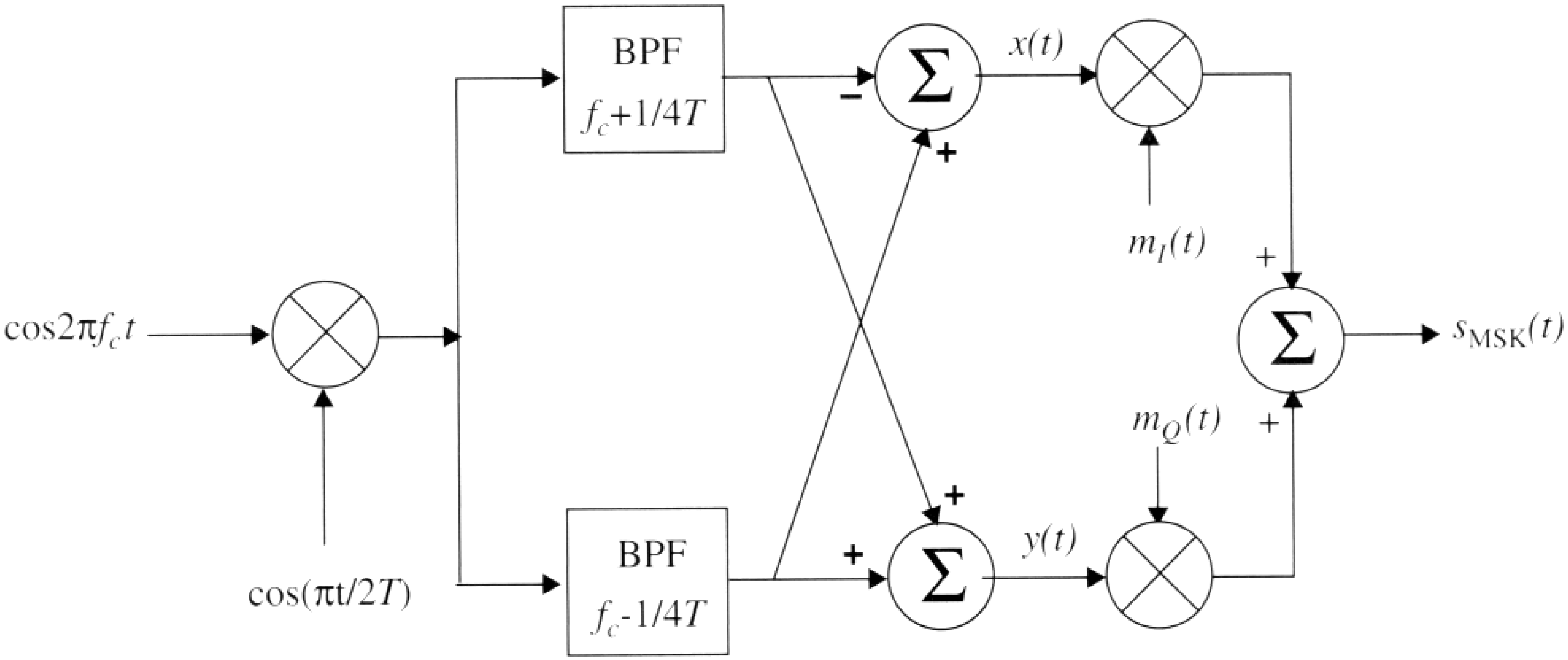


Figure 6.39 Block diagram of an MSK transmitter. Note that $m_I(t)$ and $m_Q(t)$ are offset by T_b.

MSK reception

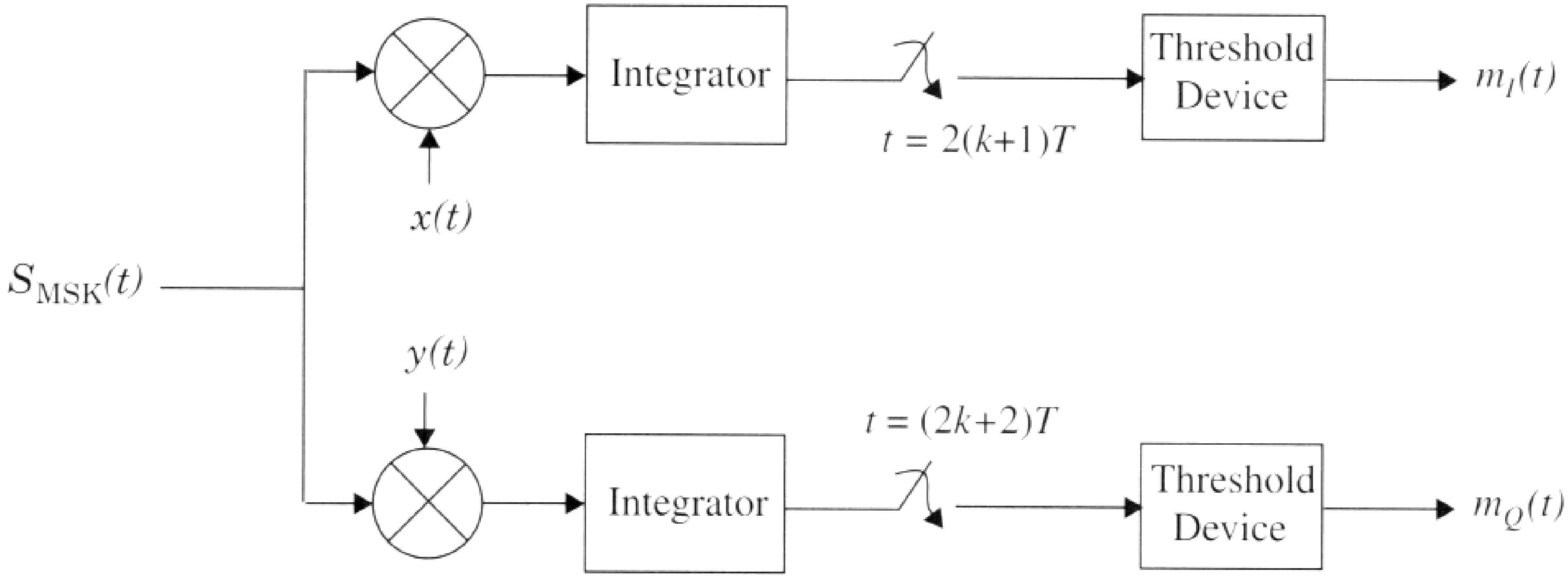


Figure 6.40 Block diagram of an MSK receiver.

Minimum Shift Keying spectra

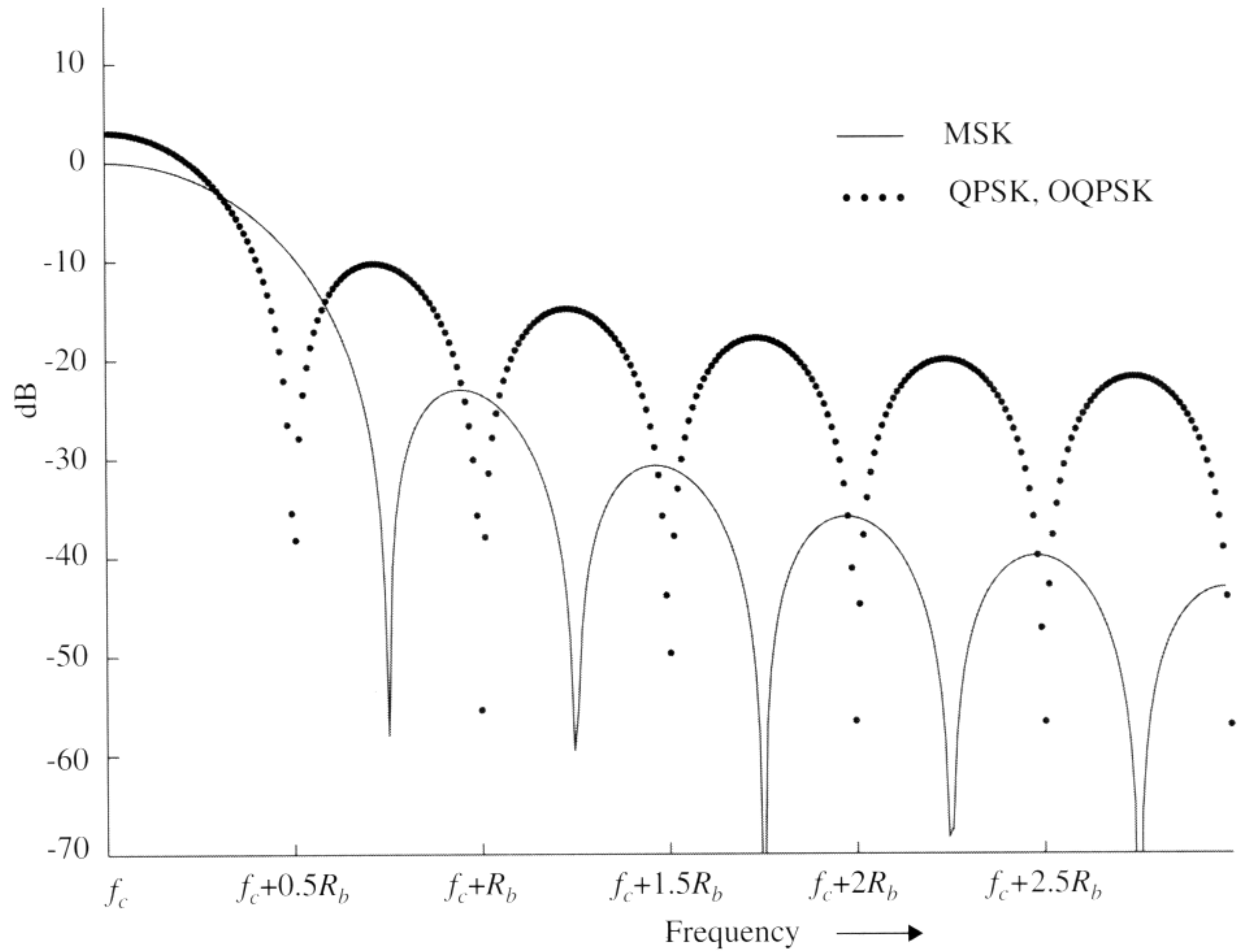


Figure 6.38 Power spectral density of MSK signals as compared to QPSK and OQPSK signals.

GMSK spectral shaping

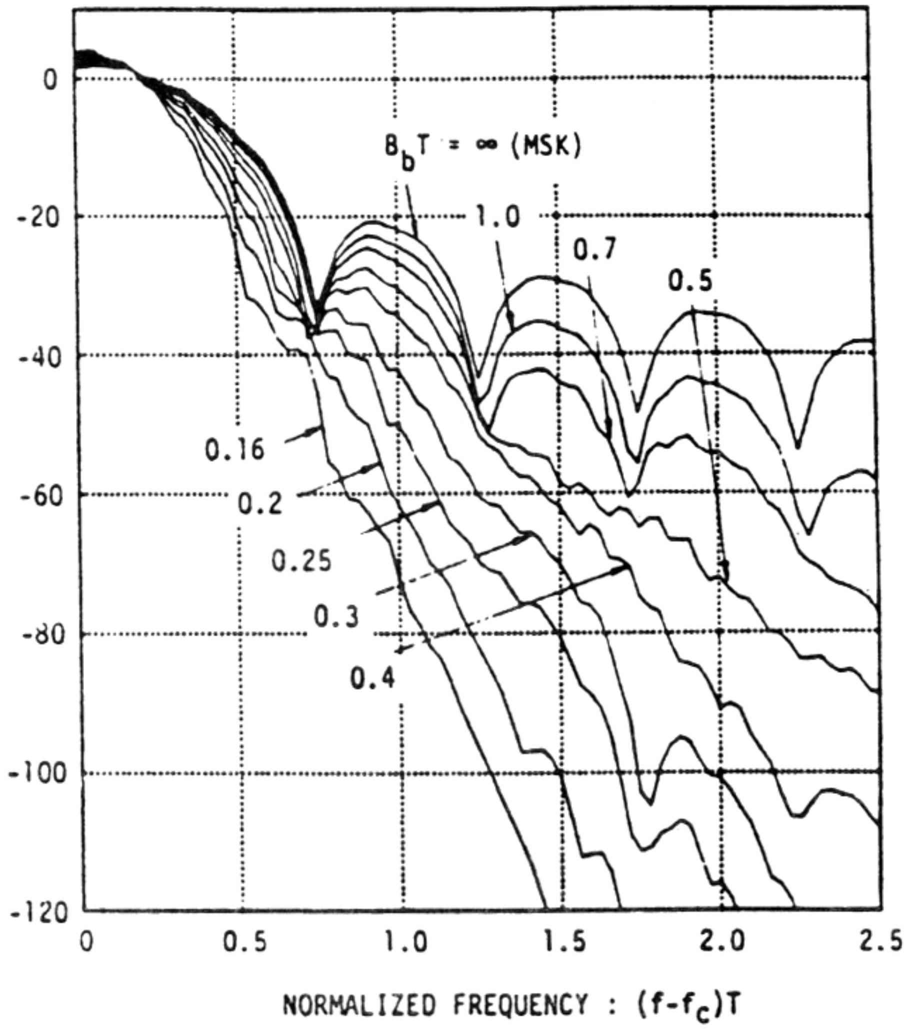


Figure 6.41 Power spectral density of a GMSK signal [from [Mur81] © IEEE].

Simple GMSK modulation and demodulation

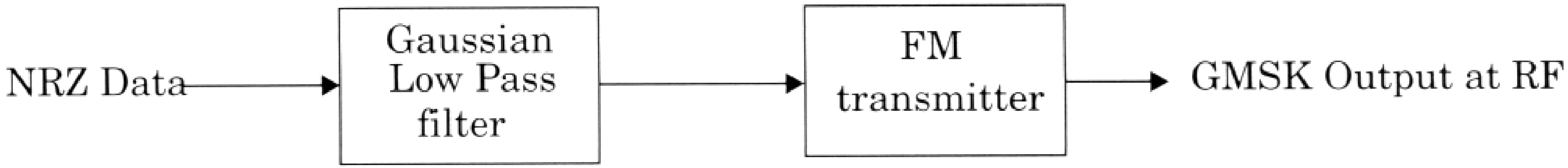


Figure 6.42 Block diagram of a GMSK transmitter using direct FM generation.

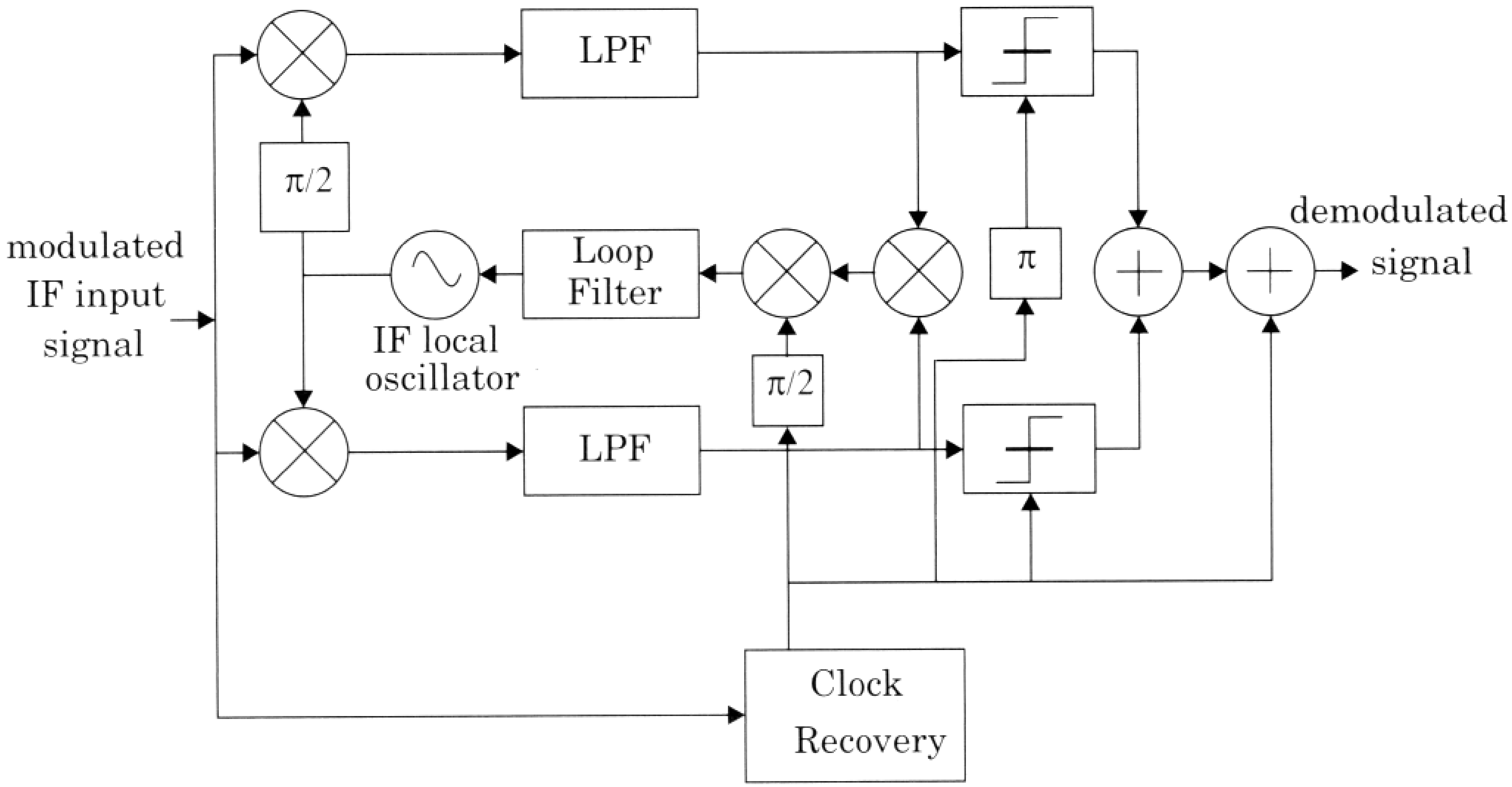


Figure 6.43 Block diagram of a GMSK receiver.

Pulse Shaped M-PSK

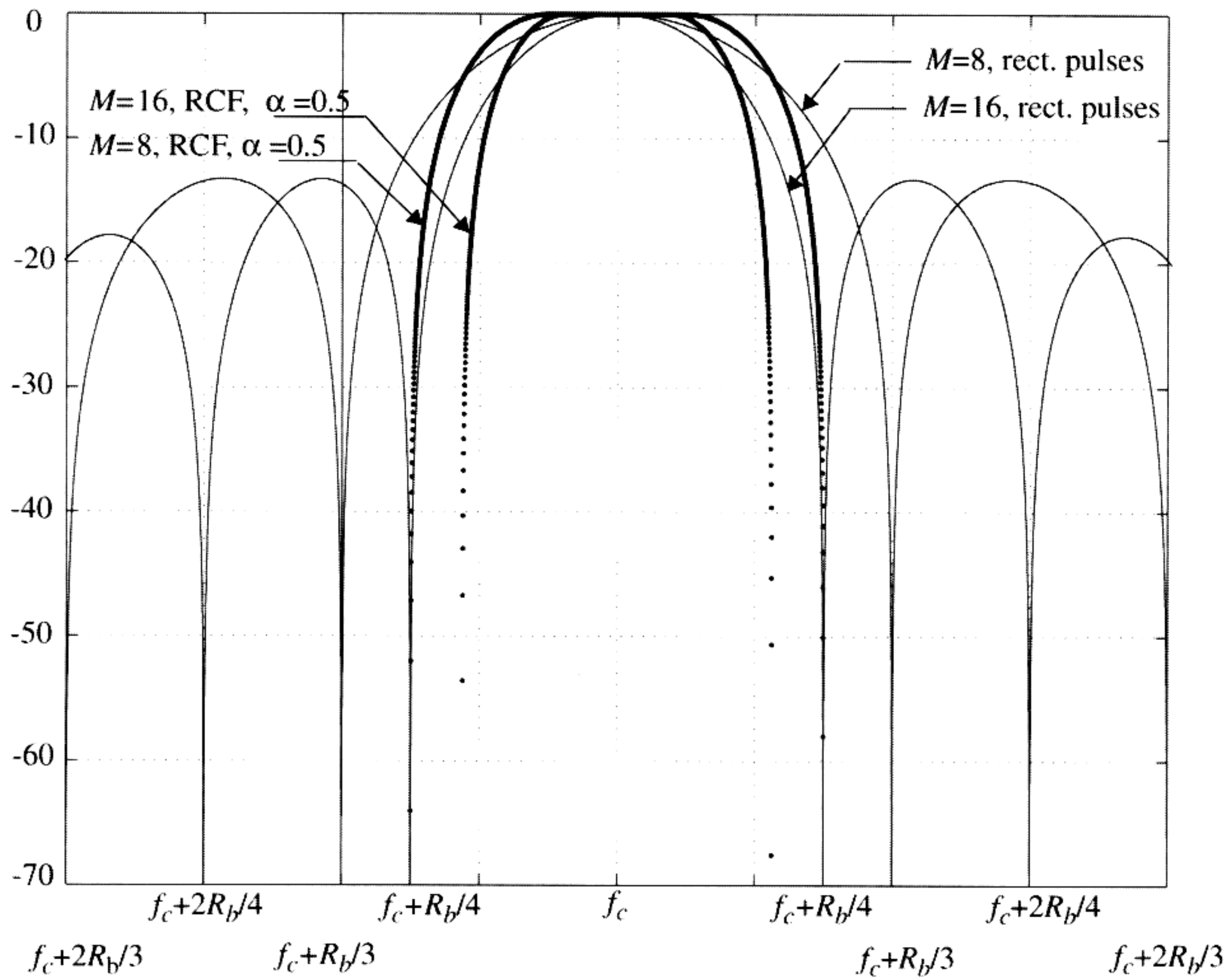
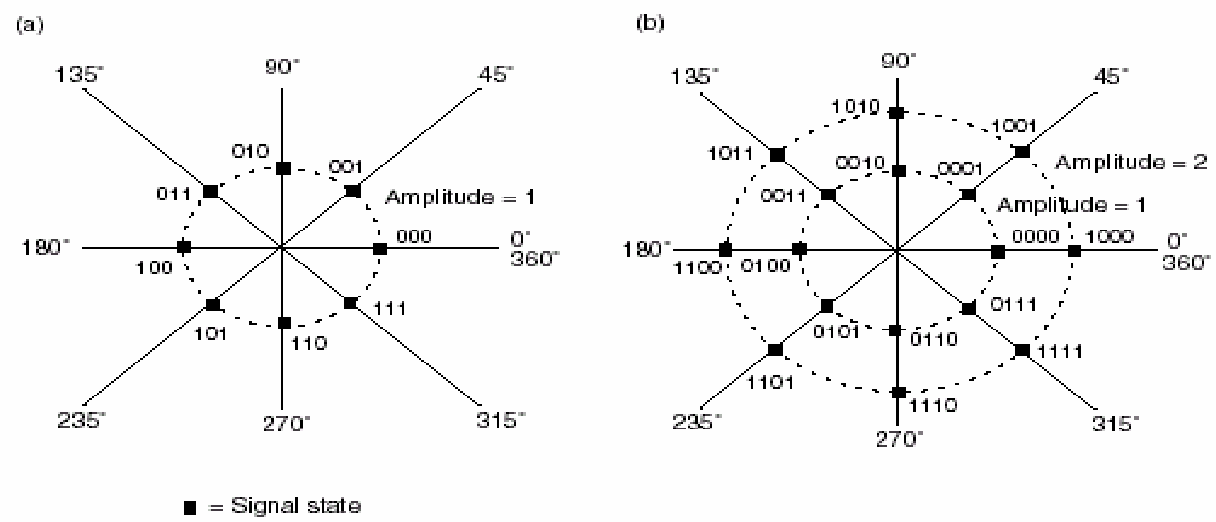


Figure 6.46 M-ary PSK power spectral density, for M = 8, 16 (PSD for both rectangular and raised cosine filtered pulses are shown for fixed R_b).

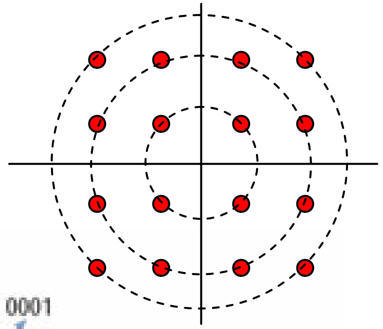
QAM – Quadrature Amplitude Modulation

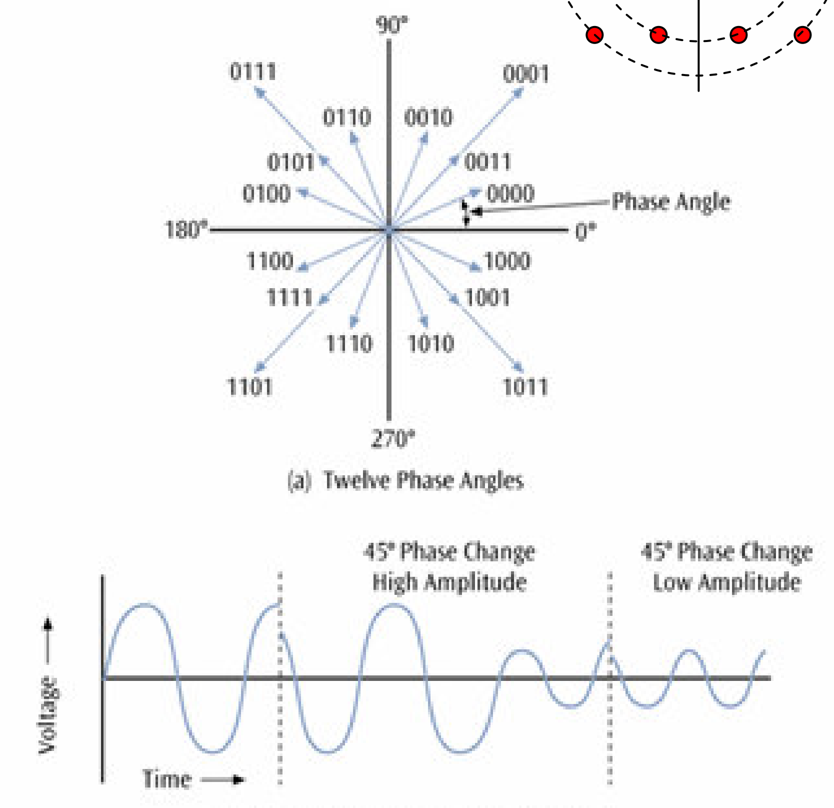
- **Modulation technique used in the cable/video networking world**
- **Instead of a single signal change representing only 1 bps – multiple bits can be represented buy a single signal change**
- **Combination of phase shifting and amplitude shifting (8 phases, 2 amplitudes)**



QAM

- QAM
  - As an example of QAM, 12 different phases are combined with two different amplitudes
  - Since only 4 phase angles have 2 different amplitudes, there are a total of 16 combinations
  - With 16 signal combinations, each baud equals 4 bits of information (2 ^ 4 = 16)
  - Combine ASK and PSK such that each signal corresponds to multiple bits
  - More phases than amplitudes
  - Minimum bandwidth requirement same as ASK or PSK





(a) Twelve Phase Angles

(b) A Phase Change with Two Amplitudes

16-QAM Signal Constellation

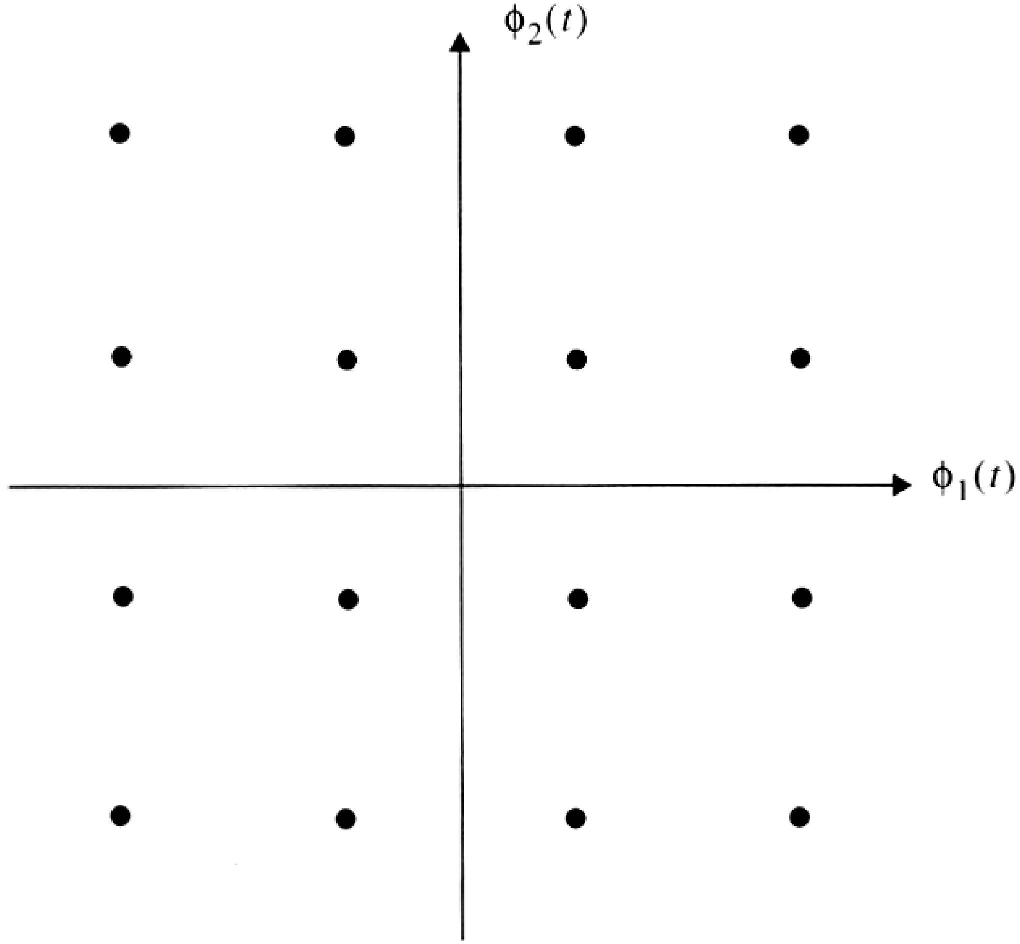


Figure 6.47 Constellation diagram of an M-ary QAM ($M = 16$) signal set.

QAM vs. MFSK

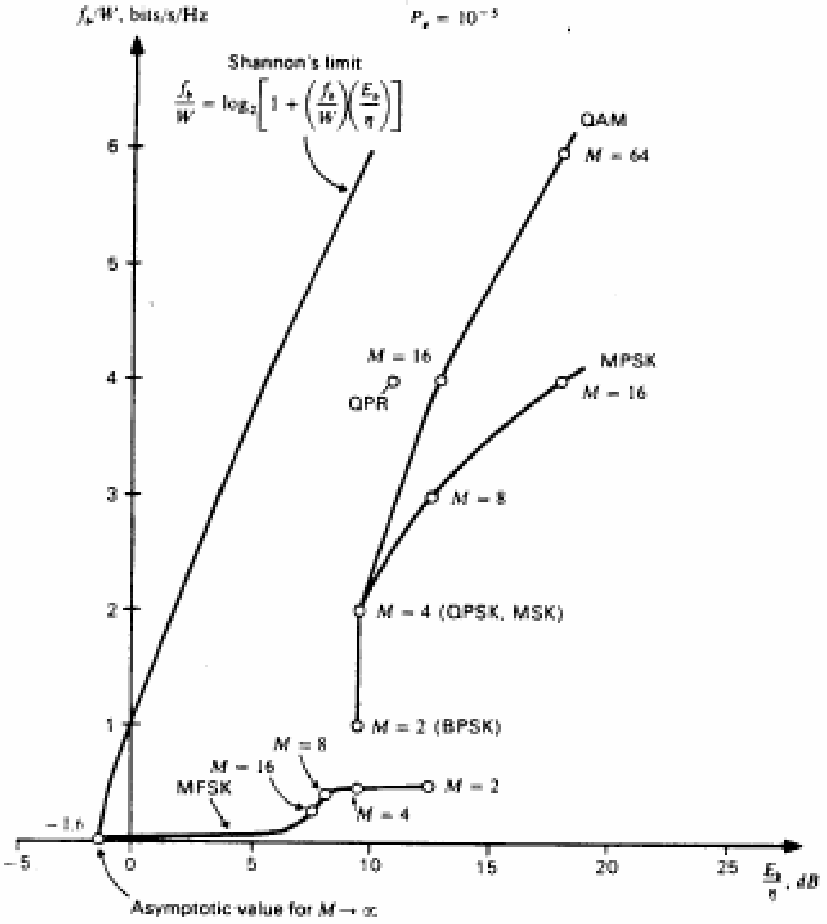
Table 6.5 Bandwidth and Power Efficiency of QAM [Zie92]

M	4	16	64	256	1024	4096
η_B	1	2	3	4	5	6
E_b/N_o for BER = 10^{-6}	10.5	15	18.5	24	28	33.5

Table 6.6 Bandwidth and Power Efficiency of Coherent M-ary FSK [Zie92]

M	2	4	8	16	32	64
η_B	0.4	0.57	0.55	0.42	0.29	0.18
E_b/N_o for BER = 10^{-6}	13.5	10.8	9.3	8.2	7.5	6.9

Comparison of Digital Modulation



bits/s/Hz vs. $E_b/$ for Probability of Error = 10^{-5}
taken from "Principle of Communication Systems"
Taub & Schilling, page 482

- This graph shows that *bandwidth efficiency* is traded off against *power efficiency*.
- MFSK is power efficient, but not bandwidth efficient.
- MPSK and QAM are bandwidth efficient but not power efficient.
- Mobile radio systems are *bandwidth limited*, therefore PSK is more suited.

Modulation Summary

- Phase Shift Keying is often used, as it provides a highly bandwidth efficient modulation scheme.
- QPSK, modulation is very robust, but requires some form of linear amplification. OQPSK and **p**/4-QPSK can be implemented, and reduce the envelope variations of the signal.
- High level M-ary schemes (such as 64-QAM) are very bandwidth efficient, but more susceptible to noise and require linear amplification.
- Constant envelope schemes (such as GMSK) can be employed since an efficient, non-linear amplifier can be used.
- Coherent reception provides better performance than differential, but requires a more complex receiver.