

Communication Systems

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Chapter 6

Passband Data Transmission

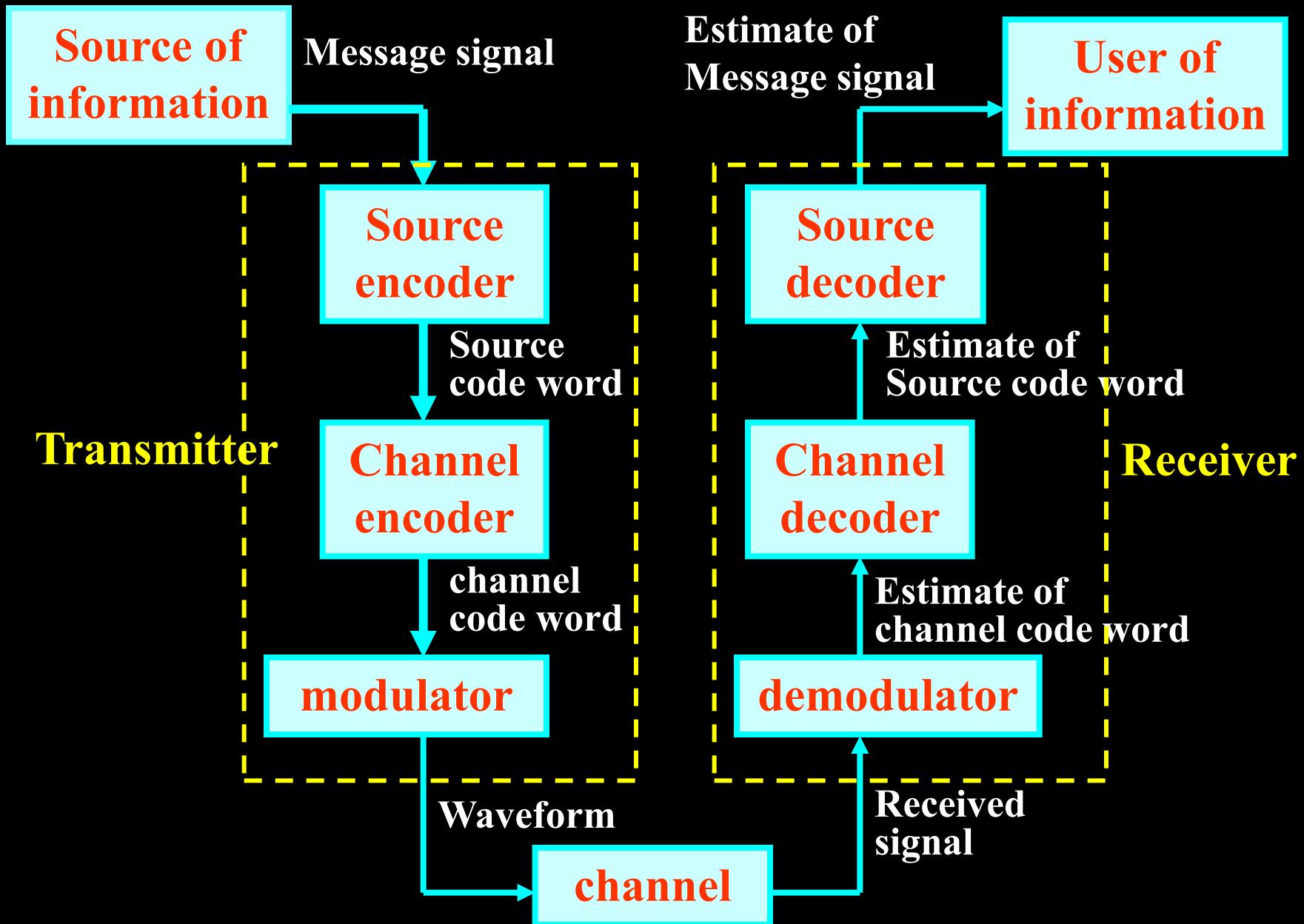


Figure 9 Block diagram of digital communication system.

contents

- Different methods of digital modulation
ASK PSK FSK
- Coherent detection
- Noncoherent detection
- Modems
- Sophisticated modulation techniques
- Synchronization techniques

6.1 Introduction

- In **baseband pulse transmission**, a data stream, which is represented in the form of a discrete PAM signal, is transmitted directly over a **low-pass channel**.
- In **digital passband transmission**, the incoming data stream is modulated onto a carrier and transmitted over a **band-pass channel**.

Three basic digital modulations

- { ASK: amplitude-shift keying 幅度键控
- FSK: frequency-shift keying 频移键控
- PSK: phase-shift keying 相移键控

They may be viewed as special cases of AM, FM and PM, respectively.

hierarchy of digital modulation techniques

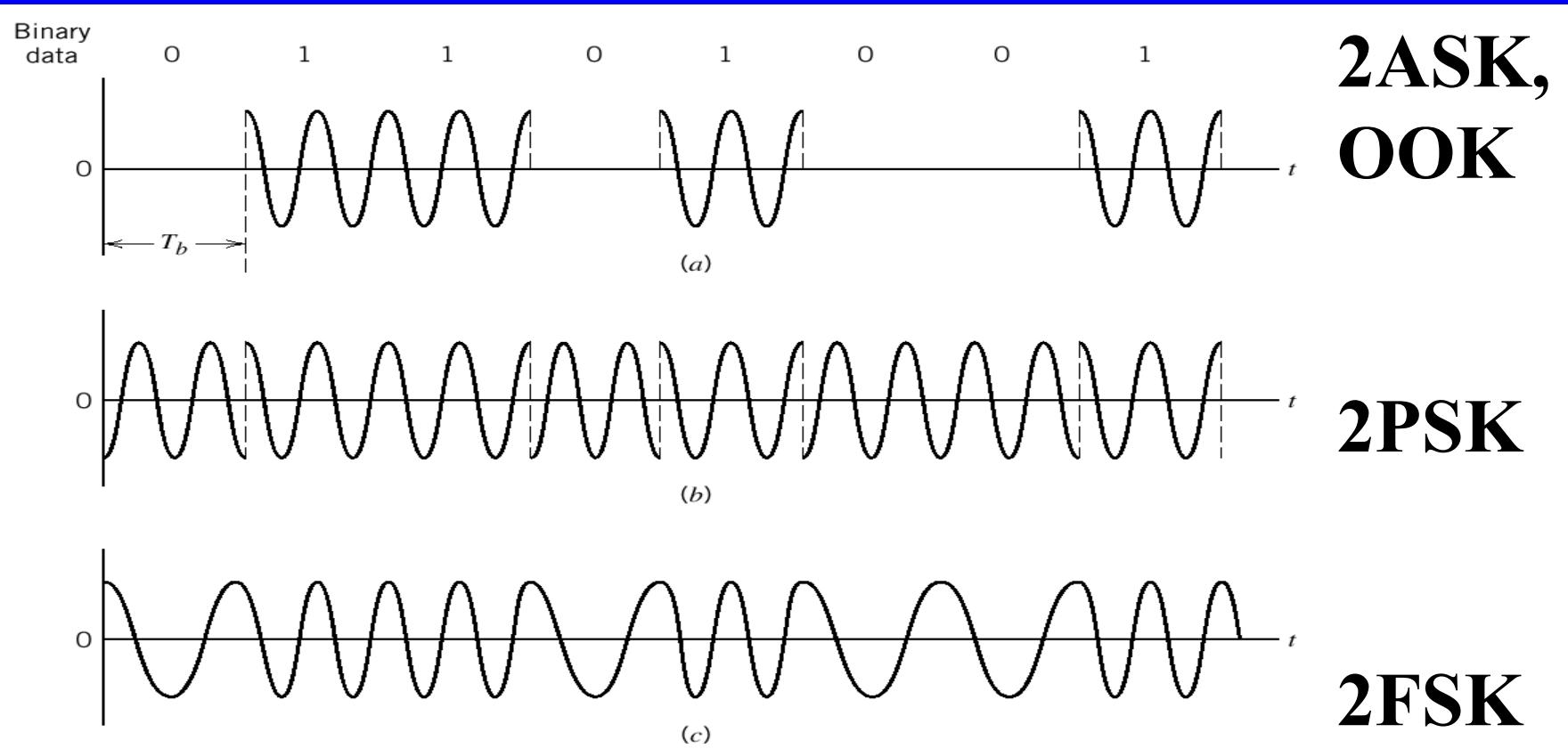
基本调制方式
Basic modulations

2ASK、OOK、MASK
2FSK、MFSK、MSK、GMSK
2PSK、MPSK、QPSK、 $\pi/4$ QPSK、
Offset-QPSK, 2DPSK、MDPSK

联合调制方式
Hybrid modulations

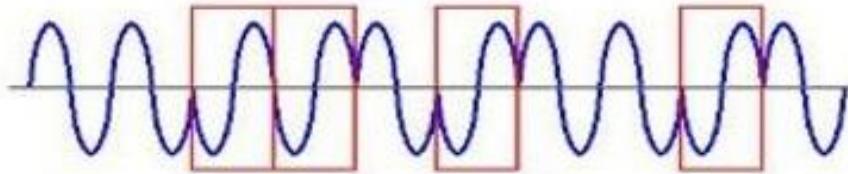
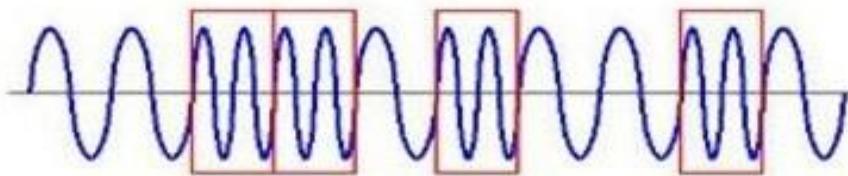
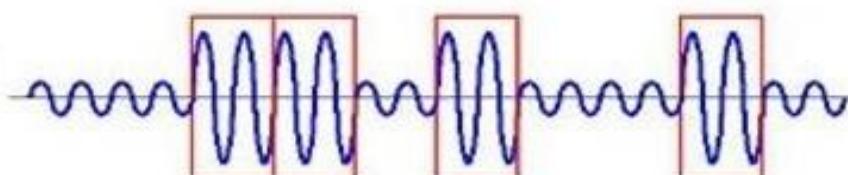
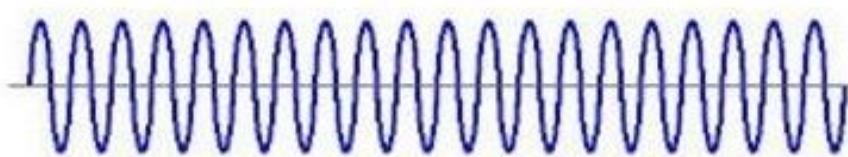
幅度与相位: APK, QAM
幅度与频率
相位与频率

Binary digital modulations 二进制数字调制



OOK: on-off keying 通断键控

0 0 1 1 0 1 0 0 1 0



原始信号
数字信号



高频载波
电磁波



ASK 移幅键控
Amplitude-shift keying

FSK 移频键控
Frequency-shift keying

PSK 移相键控
Phase-shift keying

Observations from Fig. 6.1

1. There are **Step** changes in the amplitude, frequency or phase.
2. It is hard to distinguish FM and PM, but it is easy to distinguish PSK and FSK.
3. Unlike ASK signals, both PSK and FSK signals have a **constant envelope** 包络恒定.

The latter property makes PSK and FSK impervious (不受影响) to amplitude nonlinearities. Thus, PSK and FSK are preferred to ASK over nonlinear channels.

多进制数字调制

{ M-ary ASK
M-ary FSK
M-ary PSK

M-ary modulations can reduce transmission bandwidth.

M进制系统中，波特率与比特率的关系：

$$\frac{1}{T_b} = \frac{1}{T} \log_2^M$$

T_b 比特持续时间, T 符号（码元）持续时间

Hybrid modulation 混合调制

APK: M-ary amplitude-phase keying
幅相键控

QAM: M-ary quadrature-amplitude modulation
正交幅度调制

Coherent and noncoherent techniques

Digital modulation techniques may be classified into coherent and noncoherent techniques, depending on whether the receiver is equipped with a phase-recovery circuit 相位恢复电路 or not.

- Coherent detector consists of a product followed by a low pass filter.
- 相干检测器从原理上看相当于一个乘法器后接一个低通滤波器。



二进制数字调制的解调方法

2ASK (OOK)：包络检波，相干解调

2PSK：相干解调

2DPSK：差分相干解调（非相干解调）

2FSK：相干解调，包络检波

AM、ASK 信号可以采用相干解调吗？

Probability of Error 差错概率

通带数据传输系统的一个主要目标就是接收机的优化设计，从而在存在加性高斯白噪声的情况下使平均差错概率最小。

Power Spectra 功率谱

为了全面地理解各种不同数字调制方式的优点，还需要对调制信号的功率谱进行研究，这对于信道带宽和复用系统的信道间干扰问题，都具有及其重要的意义。

Modulated signal can be described in terms of in-phase and quadrature components:

$$\begin{aligned}s(t) &= s_I(t) \cos(2\pi f_c T) - s_Q(t) \sin(2\pi f_c t) \\ &= \text{Re}[\tilde{s}(t) \exp(j2\pi f_c t)]\end{aligned}$$

where $\tilde{s}(t) = s_I(t) + j s_Q(t)$

$$\exp(j2\pi f_c T) = \cos(2\pi f_c t) + j \sin(2\pi f_c t)$$

Suppose : $\tilde{s}(t) \xleftrightarrow{\text{power spectra}} S_B(f)$

Then $s(t) \xleftrightarrow{\text{power spectra}} S_s(f) = \frac{1}{4} [S_B(f - f_c) + S_B(f + f_c)]$

Bandwidth Efficiency 带宽效率

Primary communication resources:

Channel Bandwidth and Transmitted Power

频谱有效调制的主要目标就是最大化带宽效率；另一个目标则是在AWGN信道，以最小的平均信噪比代价实现上述带宽效率。

Bandwidth
Efficiency

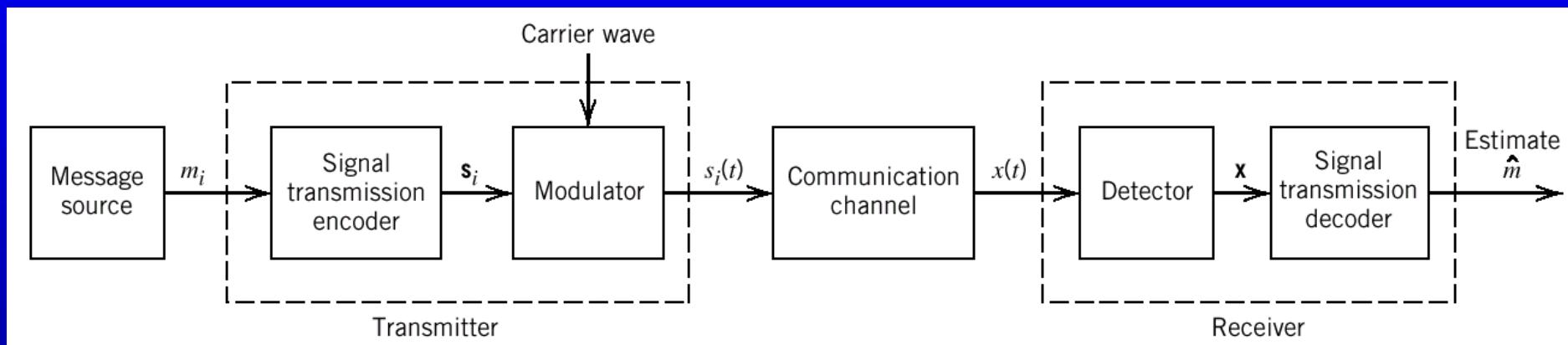
$$\rho = \frac{R_b}{B} \quad (\text{bits / s / Hz})$$

提高带宽效率的因素：

- 多级编码（多进制）： multilevel encoding
- 频谱整形： spectral shaping 通过使用脉冲整形滤波器平滑掉传输波形的突变尖峰，可以减少所需信道带宽。

6.2 Passband Transmission Model

Figure 6.2
Functional model of passband data transmission system.



Assumptions:

The channel is linear

The channel noise $w(t)$ is AWGN

M-ary systems have M symbols, denoted as m_1, m_2, \dots, m_M . When they are equally likely, we have

$$p_i = P(m_i) = \frac{1}{M} \quad \text{for all } i$$

The energy of the energy signal $s_i(t)$ is

$$E_i = \int_0^T s_i^2(t) dt, \quad i = 1, \dots, M$$

补充：幅度键控（ASK）

Amplitude Shift Keying

二进制幅度键控 (2ASK)

二进制数字序列

$$m(t) = \sum_n a_n g(t - n T_b)$$

单极性 $a_n = \begin{cases} 1 & \text{代表“1”码, 出现概率为 } p \\ 0 & \text{代表“0”码, 出现概率为 } 1-p \end{cases}$

双极性 $a_n = \begin{cases} +1 & \text{代表“1”码, 出现概率为 } p \\ -1 & \text{代表“0”码, 出现概率为 } 1-p \end{cases}$

在二进制数字调幅中, 载波的幅度只有两种变化状态。

(1) 时域和频域表示:

在幅度键控中载波幅度是随着调制信号而变化的。最简单的形式是在单极性二进制数字信息序列的控制下，为1时发送载波，为零时不发送载波，通常把这种二进制幅度键控方式称为通断键控(OOK)。它的第 n 个码元已调信号的时域表达式为：

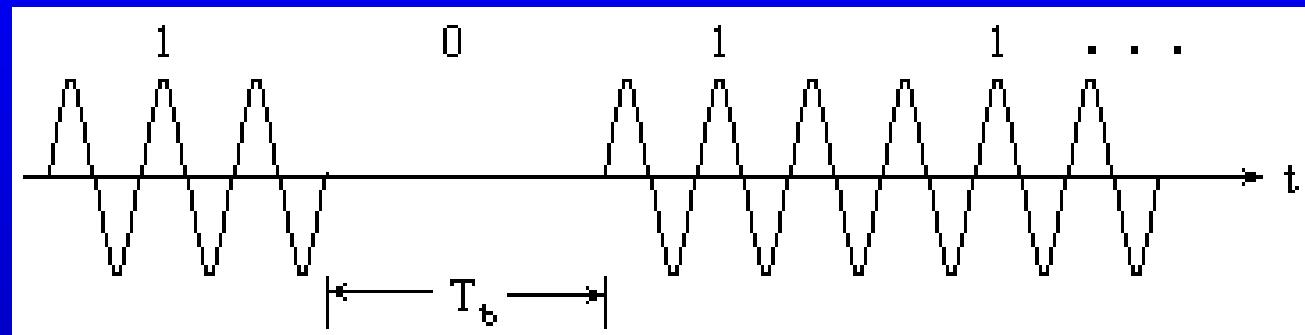
$$s_{OOK}(t) = a_n \cdot A \cos \omega_c t$$

一般形式： $s_{ASK}(t) = [\sum_n a_n g(t - nT_b)] \cos \omega_c t$

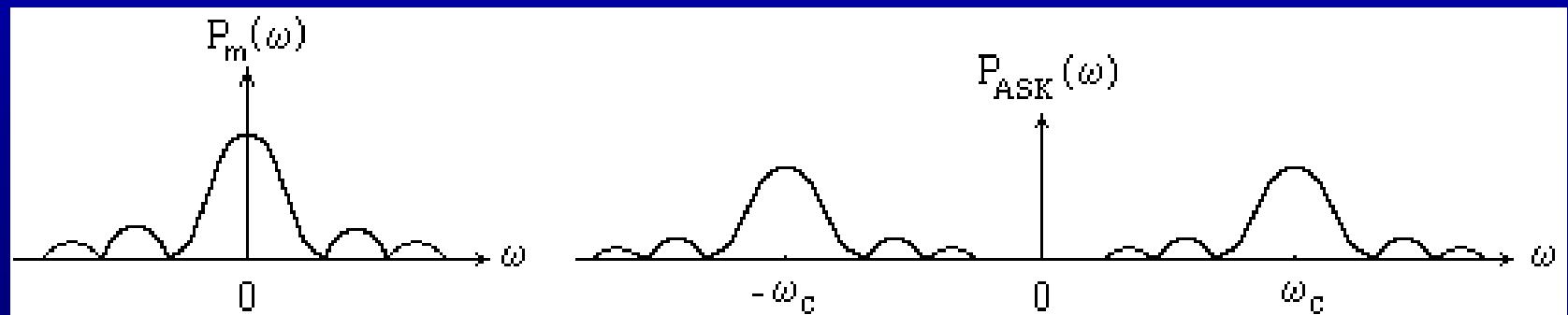
功率谱： $P_{ASK}(\omega) = \frac{1}{4}[P_m(\omega + \omega_c) + P_m(\omega - \omega_c)]$

(2) 波形和功率谱示意图:

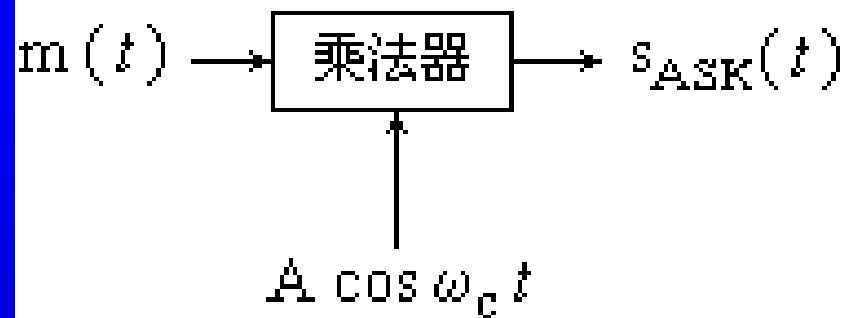
波形: $s_{2ASK}(t) = \left[\sum_n a_n g(t - n T_b) \right] \cos \omega_c t$



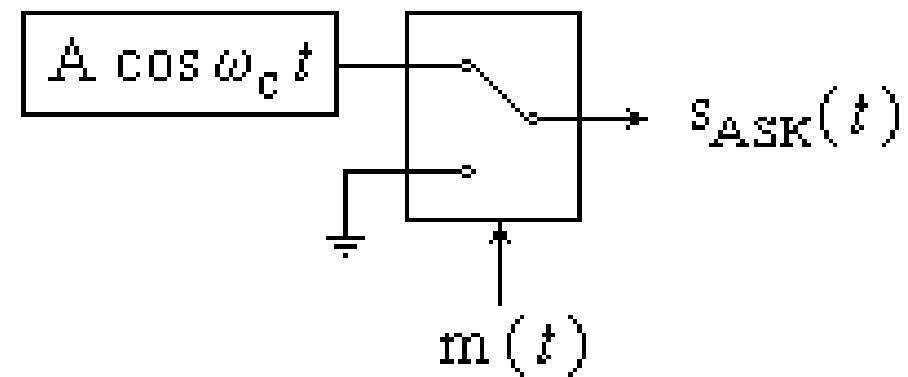
功率谱: $P_{ASK}(\omega) = \frac{1}{4} [P_m(\omega + \omega_c) + P_m(\omega - \omega_c)]$



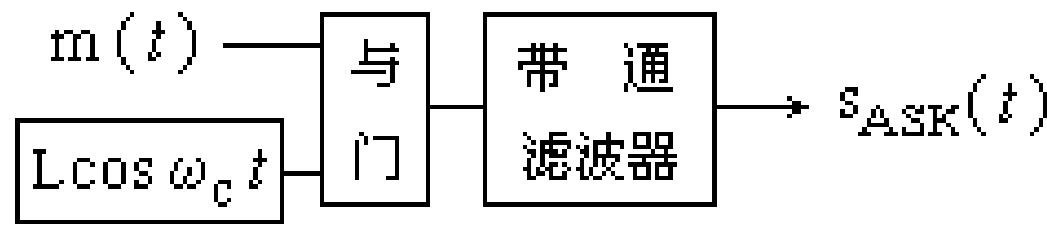
(3) 调制方法:



(a)



(b)



(c)

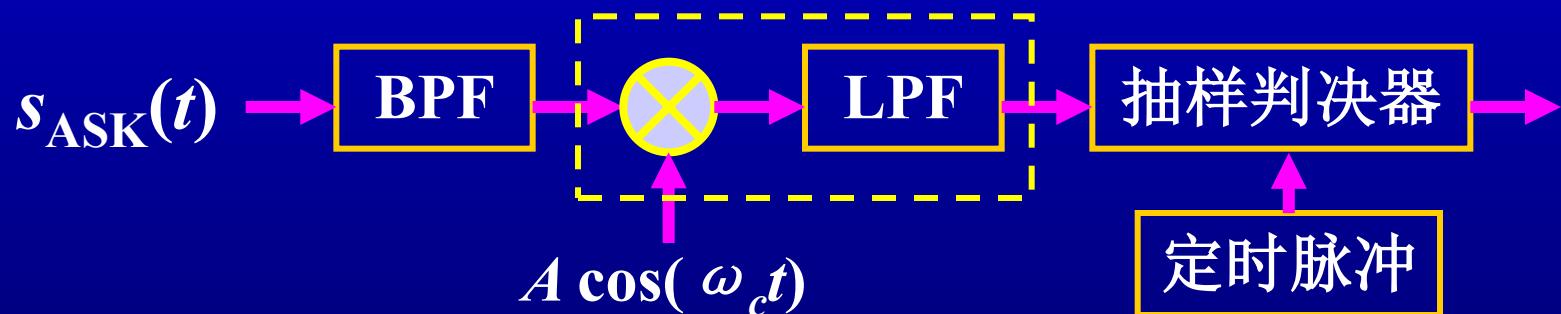
图6.2.3 二进制幅度键控信号的产生方法

(4) 解调方法：

① 包络检测。



② 相干解调。



2 多进制幅度键控 (MASK)

M 进制数字基带信号可一般地表示为:

$$m(t) = \sum_n a_n g(t - n T_b)$$

$$a_n = \begin{cases} 0 & \text{出现概率为 } P_0 \\ 1 & \text{出现概率为 } P_1 \\ 2 & \text{出现概率为 } P_2 \\ \vdots & \vdots \\ M-1 & \text{出现概率为 } P_{M-1} \end{cases}$$

$$\sum_{i=0}^{M-1} P_i = 1$$

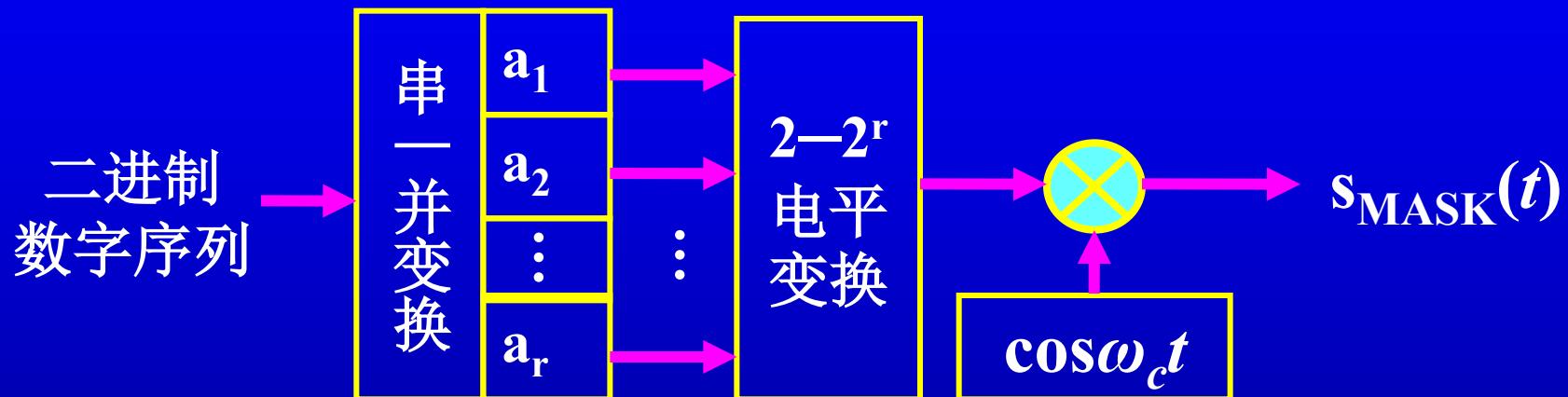
多进制幅度键控（MASK）

在 M 进制幅度键控信号中，载波幅度有 M 种取值，每个码元间隔内发送一种幅度的载波信号。 M 进制幅度键控信号的时域表达式为：

$$s_{MASK}(t) = \left[\sum_k a_k g(t - kT_b) \right] \cos \omega_c t$$

MASK的调制方法

MASK调制的原理框图：



MASK的调制方法与2ASK相同，不同的只是基带信号由二电平变为多电平。为此，可以将二进制信息序列每 r 位分为一组， $r=\log_2 M$ ，然后变换为 M ($=2^r$) 电平基带信号，再送入调制器。由于采用多电平，因而要求调制器为线性调制器，即已调信号幅度应与输入基带信号幅度成正比。

MASK调制中最简单的基带信号波形是矩形，为了限制信号频谱也可以采用其他波形，例如升余弦滚降信号，或部分响应信号等。

MASK信号可以采用包络检波或相干解调的方法恢复基带信号，其原理与2ASK完全相同。采用相干解调时，MASK信号的误符号率与 M 电平基带信号的误符号率相同，随着 M 的增大，误符号率增大。

MASK信号的功率谱与2ASK时的完全相同，它相当于 M 电平基带信号对载波进行双边带调幅，因此带宽是 M 电平基带信号的两倍。由于 M 电平信号每个码元间隔内可以传送 $\log_2 M$ 比特信息，码元速率降为信息速率的 $1/\log_2 M$ 倍，因此MASK信号的带宽在相同信息速率时是2ASK的 $1/\log_2 M$ 倍。

补充内容结束！

6.3 Coherent Phase Shift Keying

{ Coherent PSK
Noncoherent PSK: DPSK (Section 6.9)

In this section we focus on coherent PSK by considering binary PSK, QPSK and its variants, and finish up with M-ary PSK.

6.3.1 Binary PSK (BPSK, 2PSK)

在PSK调制中，是利用已调载波的相位来携带数字信息。BPSK（2PSK）则用两种载波相位来表示数字信息“1”和“0”。

载波: $A \cos(2\pi f_c t + \theta)$

可以规定: $\theta(a_n) = \begin{cases} 0 & a_n = 1 \\ \pi & a_n = 0 \end{cases}$

textbook

也可做相反的规定:

$$\theta(a_n) = \begin{cases} \pi & a_n = 1 \\ 0 & a_n = 0 \end{cases}$$

$$s_1(t) = \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_c t) \quad \text{“1”}$$

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

$0 \leq t \leq T_b$ E_b : transmitted signal energy per bit

$s_2(t)$ is the Antipodal signal 反相信号 of $s_1(t)$.

Usually, $f_c = n_c f_b$

一个码元周期包含整数个载波周期。

Define a basis function:

$$\phi_1(t) = \sqrt{\frac{2}{T_b}} \cos(2\pi f_c t), \quad 0 \leq t < T_b$$

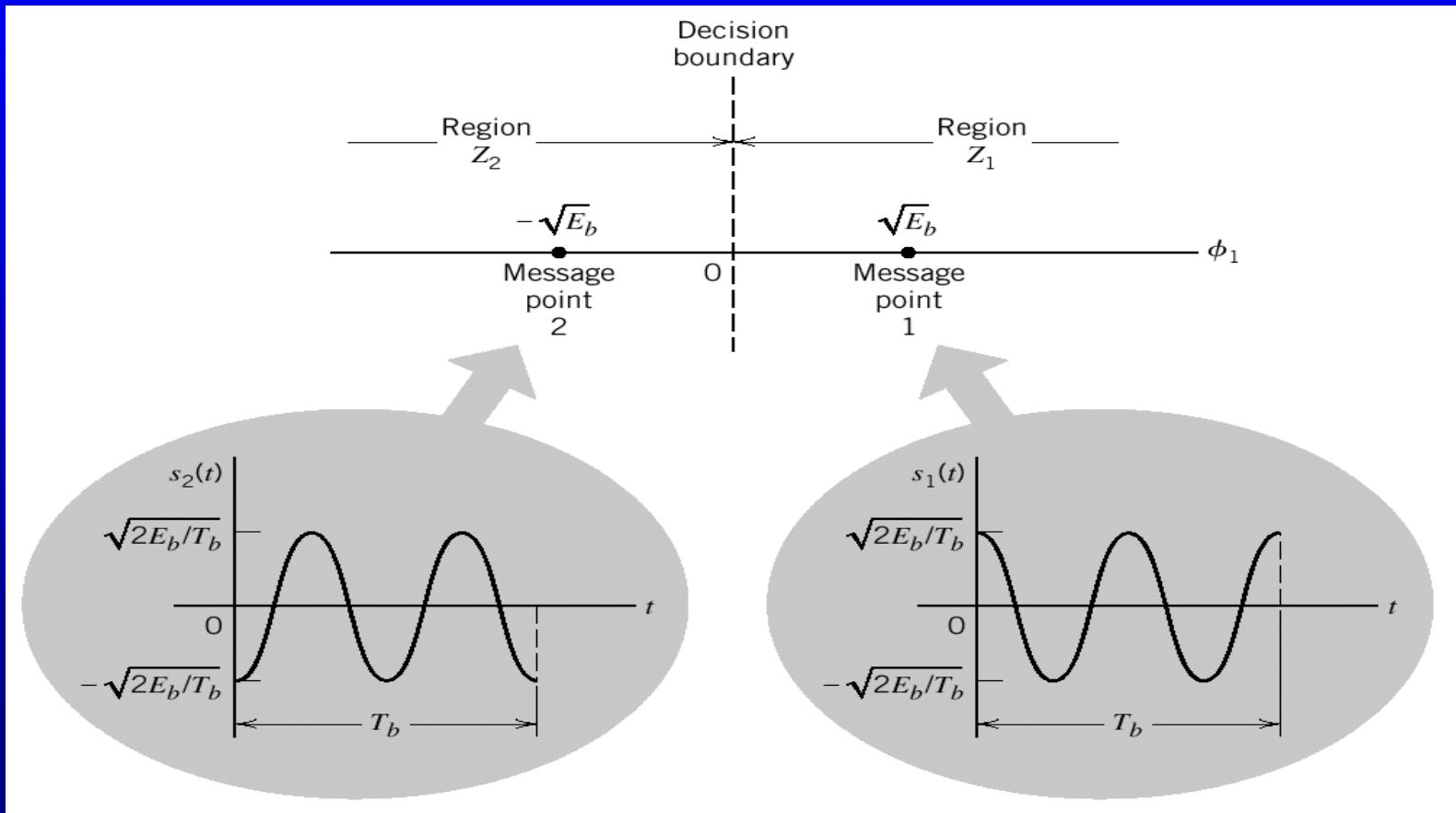
Then we rewrite $s_1(t)$ and $s_2(t)$

$$s_1(t) = \sqrt{E_b} \phi_1(t), \quad 0 \leq t < T_b$$

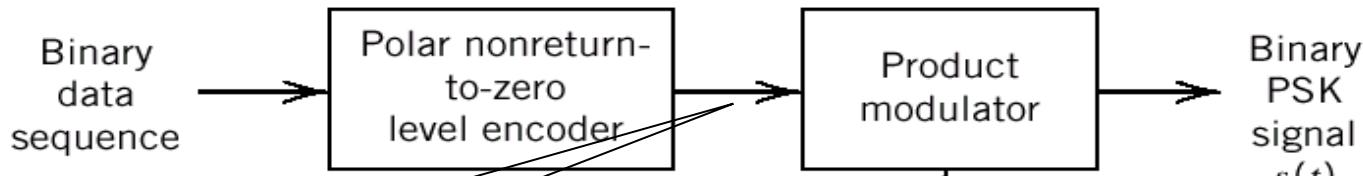
$$s_2(t) = -\sqrt{E_b} \phi_1(t), \quad 0 \leq t < T_b$$

Constellation 星座图

Signal-space diagram for coherent binary PSK system. The waveforms depicting the transmitted signals $s_1(t)$ and $s_2(t)$, displayed in the inserts, assume $n_c = 2$.



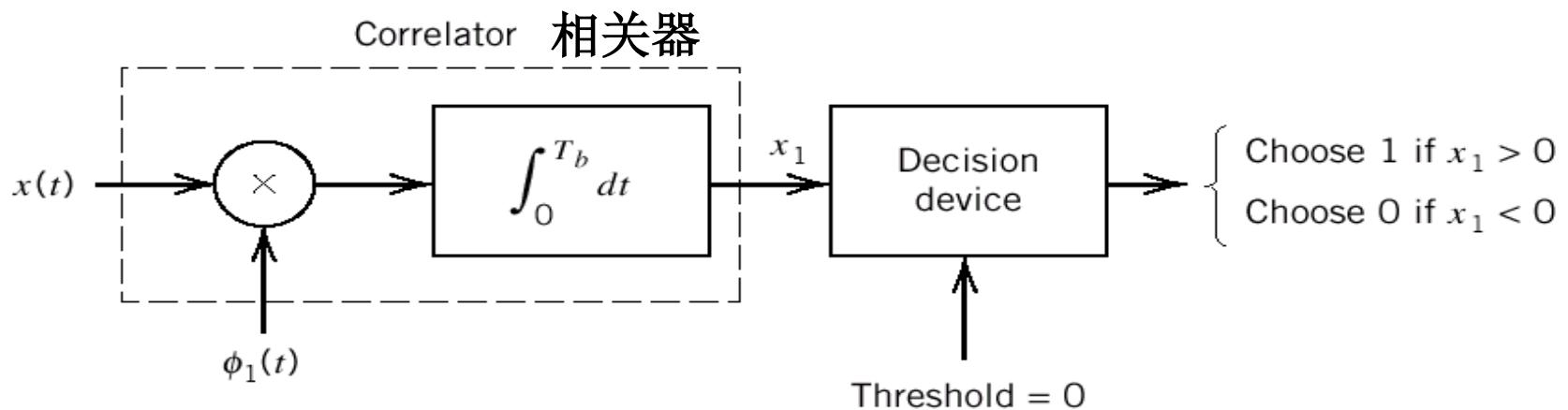
Generation and Detection of Coherent BPSK signals



数字基带信号

$$m(t) = \sum_n a_n g(t - nT_b)$$

(a) binary PSK transmitter



(b) coherent binary PSK receiver

数字基带信号: $m(t) = \sum a_n g(t - nT_b)$

$$a_n \text{为双极性信号, 即: } a_n = \begin{cases} +1 \\ -1 \end{cases}$$

2PSK信号的一般描述式:

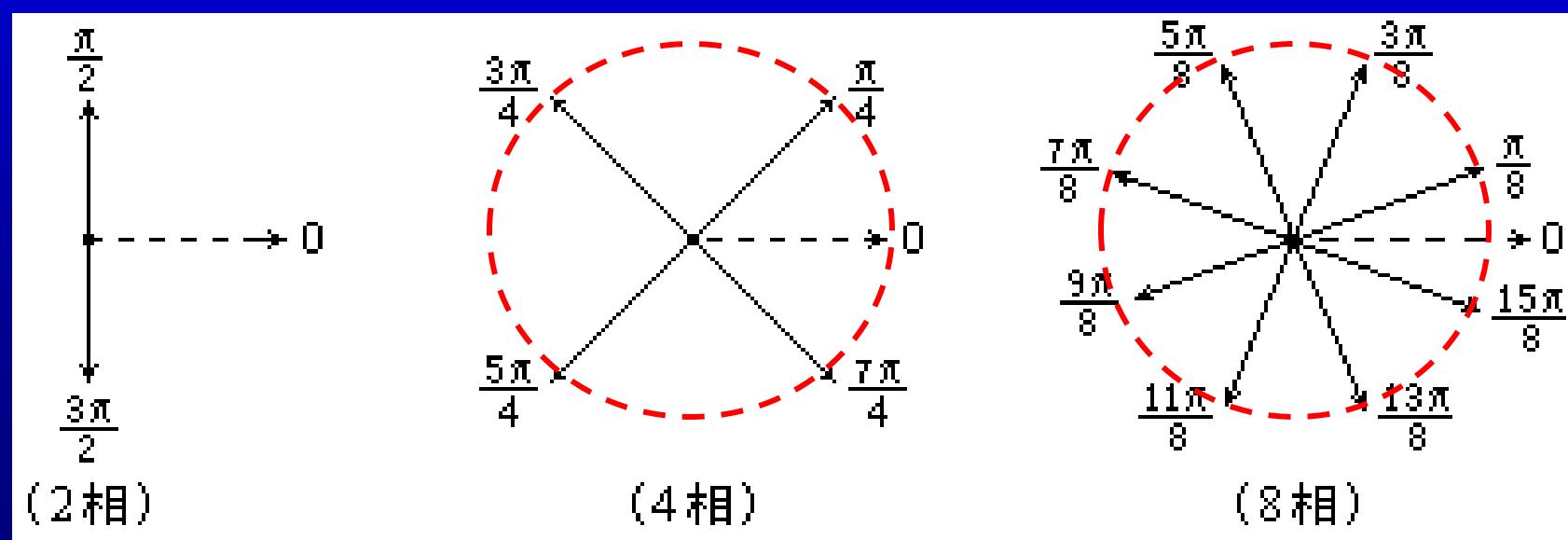
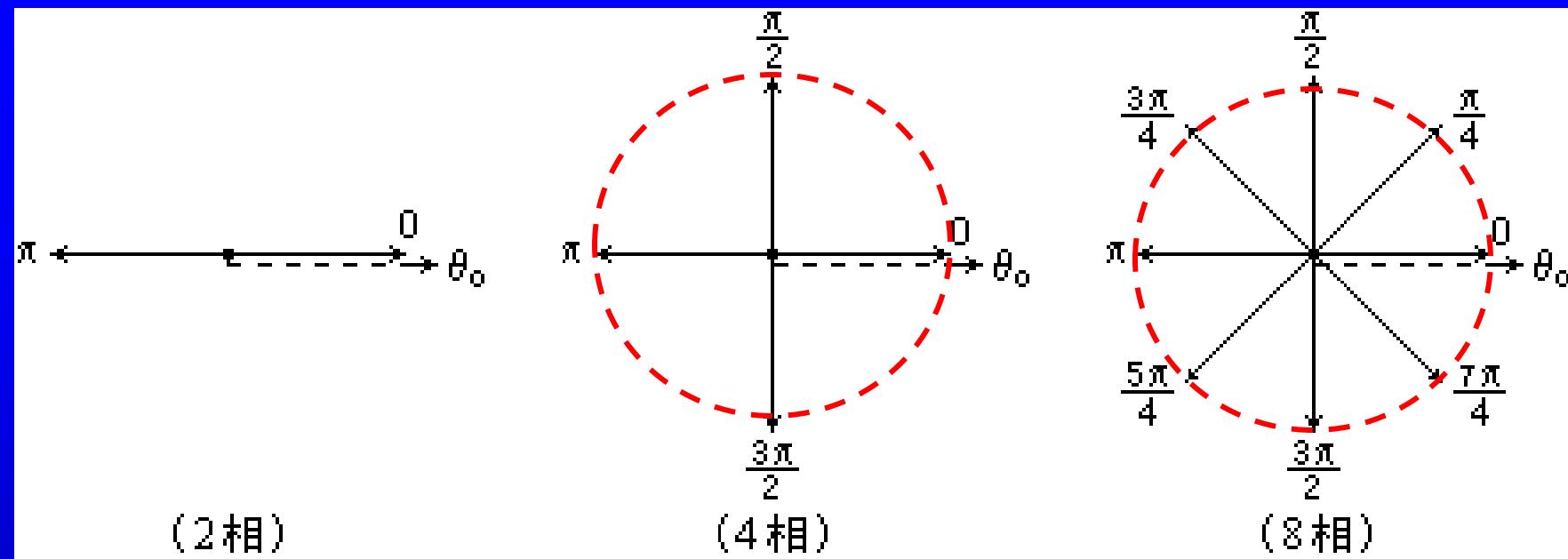
$$s_{2PSK}(t) = \left[\sum_n a_n g(t - nT_b) \right] \cos(\omega_c t)$$

$$= m(t) \cos(\omega_c t)$$

Similar to DSB



6.3.2 Quadriphase-Shift Keying QPSK, 4PSK, 四相相移键控



QPSK的相位逻辑

四进制码元 a_n	载波初相位	格雷码	自然码
0	$\pi/4$	1 0	0 0
1	$3\pi/4$	0 0	0 1
2	$5\pi/4$	0 1	1 0
3	$7\pi/4$	1 1	1 1

Transmitted signal is defined as

$$s_i(t) = \begin{cases} \sqrt{\frac{2E}{T}} \cos\left[2\pi f_c t + (2i-1)\frac{\pi}{4}\right], & 0 \leq t < T \\ 0, & \text{elsewhere} \end{cases} \quad 6.23$$

i=1, 2, 3, 4, E: transmitted signal energy per symbol

Signal-space Diagram of QPSK

在一个码元内对公式6.23进行三角函数展开，有

$$s_i(t) = \sqrt{\frac{2E}{T}} \cos\left[(2i-1)\frac{\pi}{4}\right] \cos(2\pi f_c t) - \sqrt{\frac{2E}{T}} \sin\left[(2i-1)\frac{\pi}{4}\right] \sin(2\pi f_c t)$$

Define a pair of quadrature carriers:

$$\phi_1(t) = \sqrt{\frac{2}{T}} \cos(2\pi f_c t), \quad 0 \leq t \leq T$$

$$\phi_2(t) = \sqrt{\frac{2}{T}} \sin(2\pi f_c t), \quad 0 \leq t \leq T$$

Define signal vectors

$$s_i = \begin{bmatrix} \sqrt{E} \cos((2i-1)\frac{\pi}{4}) \\ -\sqrt{E} \sin((2i-1)\frac{\pi}{4}) \end{bmatrix} = \begin{bmatrix} s_{i1} \\ s_{i2} \end{bmatrix}$$

Example 6.1 generation of a QPSK signal

Input binary sequence

0 1
Dibit 01

1 0
Dibit 10

1 0
Dibit 10

0 0
Dibit 00

(a)

Odd-numbered sequence 0
Polarity of coefficient s_{i1}

1
+
-

1
+
-

0
-
-

$s_{i1}\phi_1(t)$



(b)

Even-numbered sequence
Polarity of coefficient s_{i2}

1
+
-

0
-
-

0
-
-

0
-
-

$s_{i2}\phi_2(t)$



(c)

$$s(t) = s_{i1}\phi_1(t) + s_{i2}\phi_2(t)$$

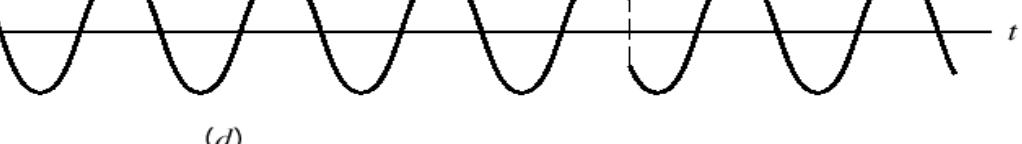
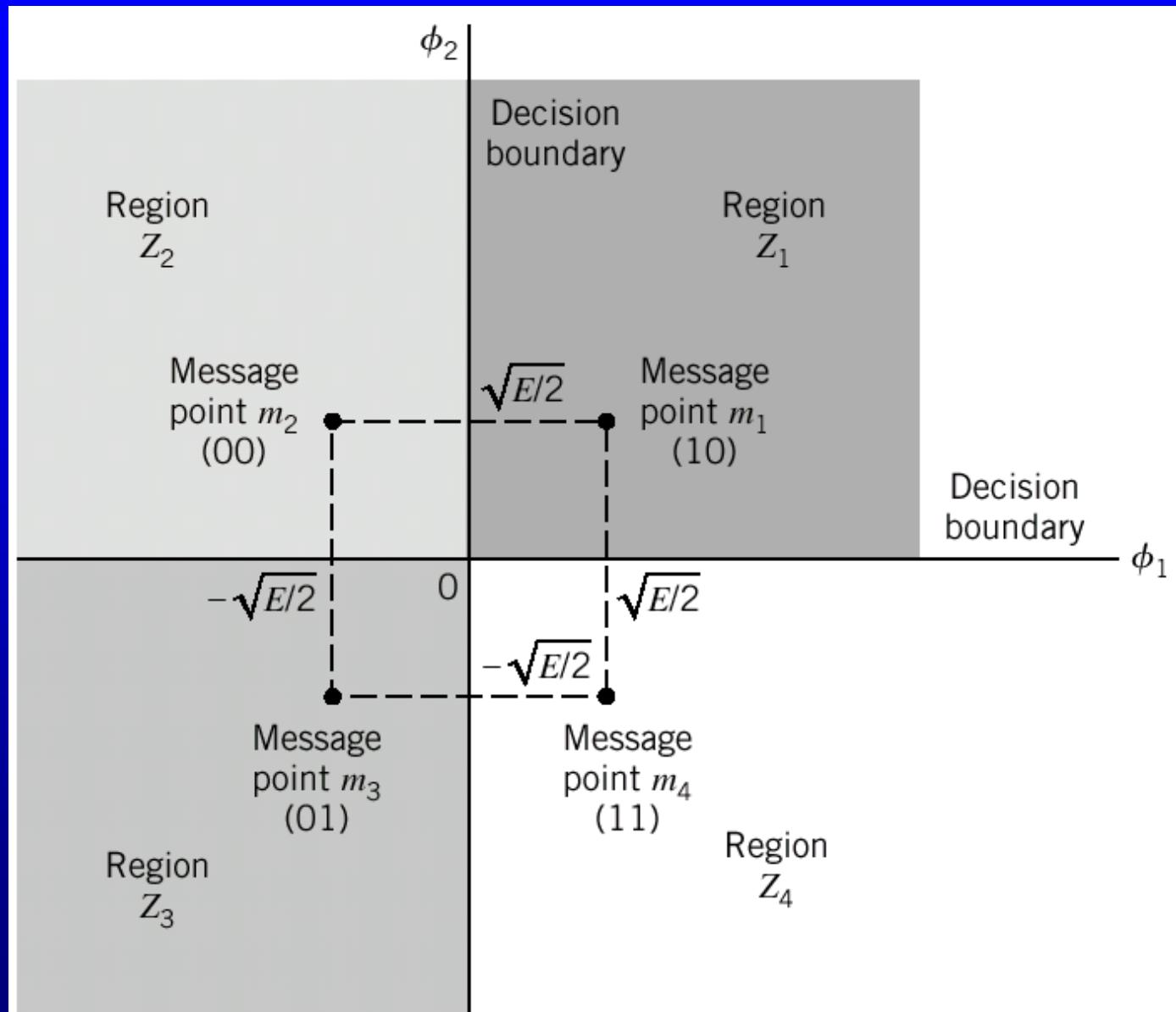
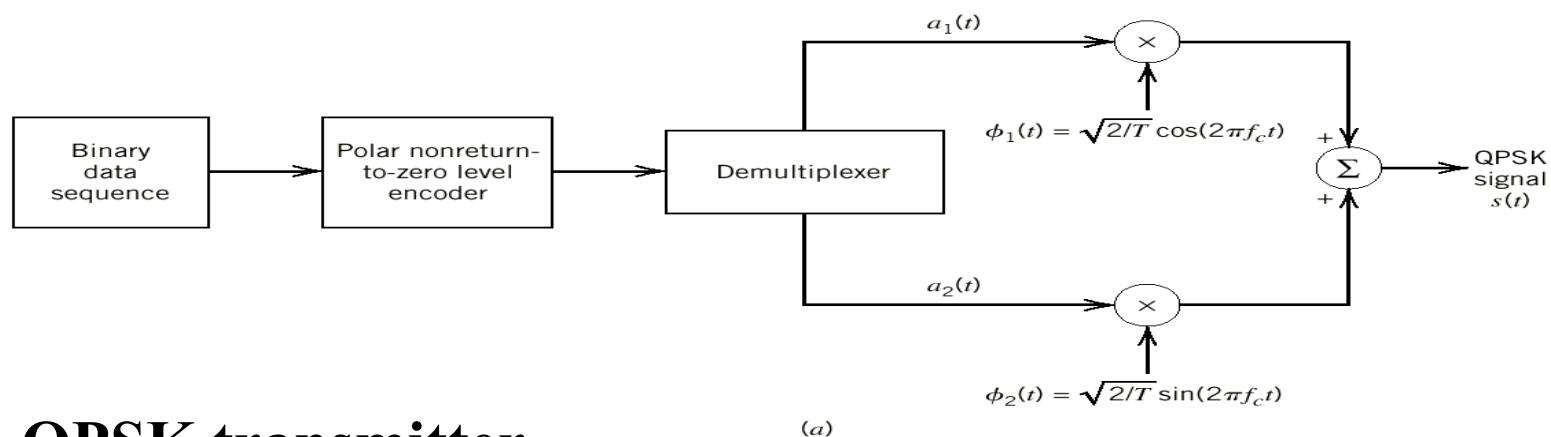


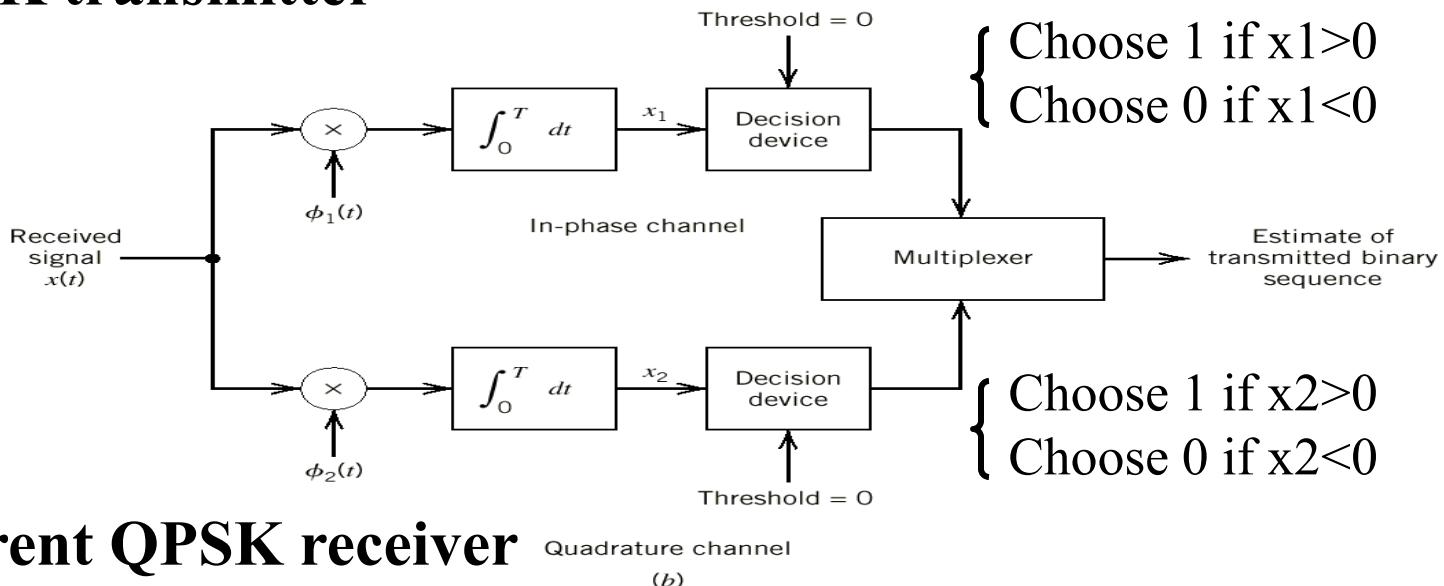
Figure 6.6 Signal-space diagram of coherent QPSK



Generation and Detection of Coherent QPSK signal



QPSK transmitter



coherent QPSK receiver

PSK的差错概率

BPSK的平均符号差错概率, 误比特率

$$P_{e,BPSK} = BER = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \quad 6.20$$

QPSK的平均符号差错概率,

$$P_{e,QPSK} \approx erfc\left(\sqrt{\frac{E}{2N_0}}\right) \quad 6.34$$

因为

$$E = 2E_b$$

当采用格雷编码

$$BER_{QPSK} = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right) \quad 6.38$$

结 论

- 当比特率和 E_b/N_0 的值都相同时, 相干QPSK系统具有与相干BPSK系统相同的平均误比特率, 但其占用的信道带宽仅为后者的一半;
- 换言之, 对于相同的 E_b/N_0 和平均误比特率, 占用相同的信道带宽的相干QPSK系统的发送信息比特速率是相干BPSK的两倍. 对于指定的性能要求, QPSK的信道带宽性能优于BPSK.

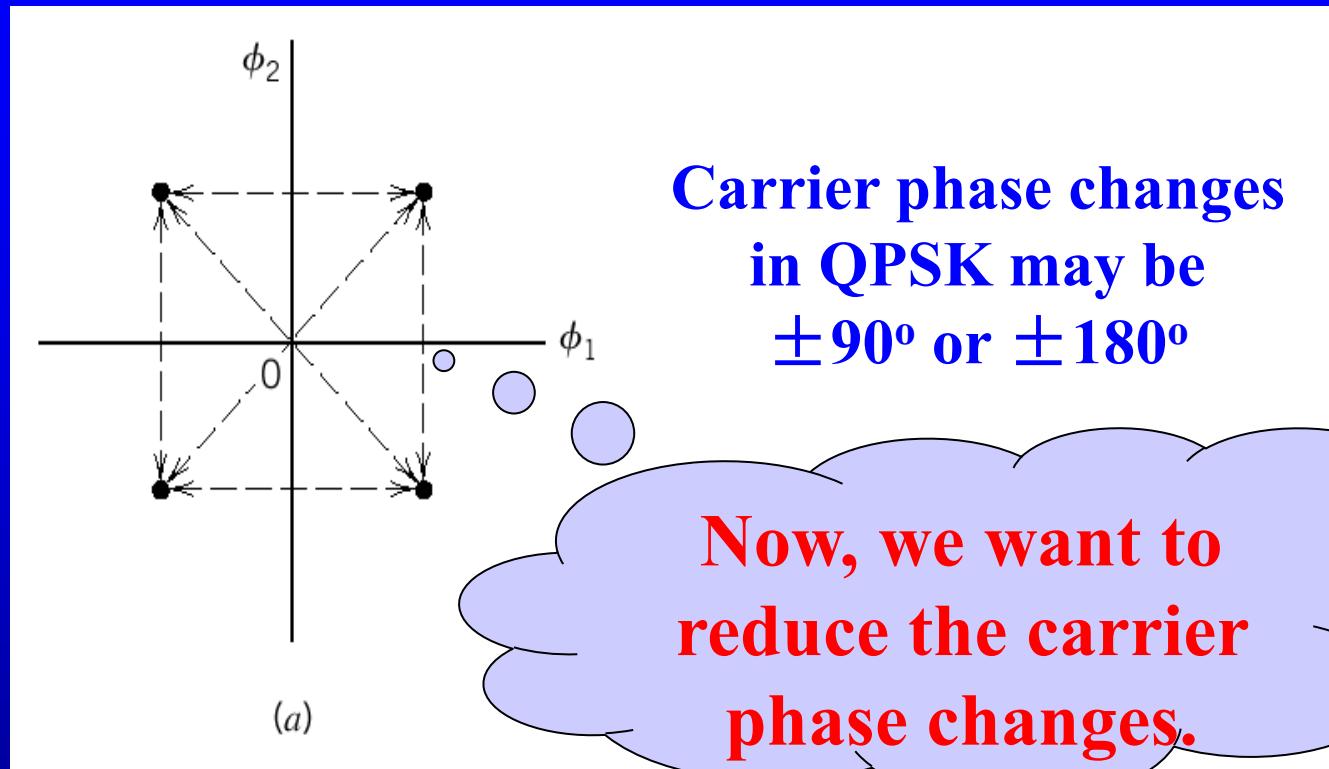
因此, QPSK比BPSK应用更为广泛.



Problem

- PSK信号是用载波的相位来携带信息，从原理上看，包络是恒定的。但实际上，由于相邻符号可能不同，导致在码元变换时刻相位会发生跳变。经过实际的滤波器后，这种相位的跳变将带来载波幅度的变化，从而在检测时带来额外的符号差错。
- 因此，我们希望减小相位跳变，尽量保持幅度恒定，从而提高系统性能。

Figure 6.10 Possible paths for switching between the message points in QPSK

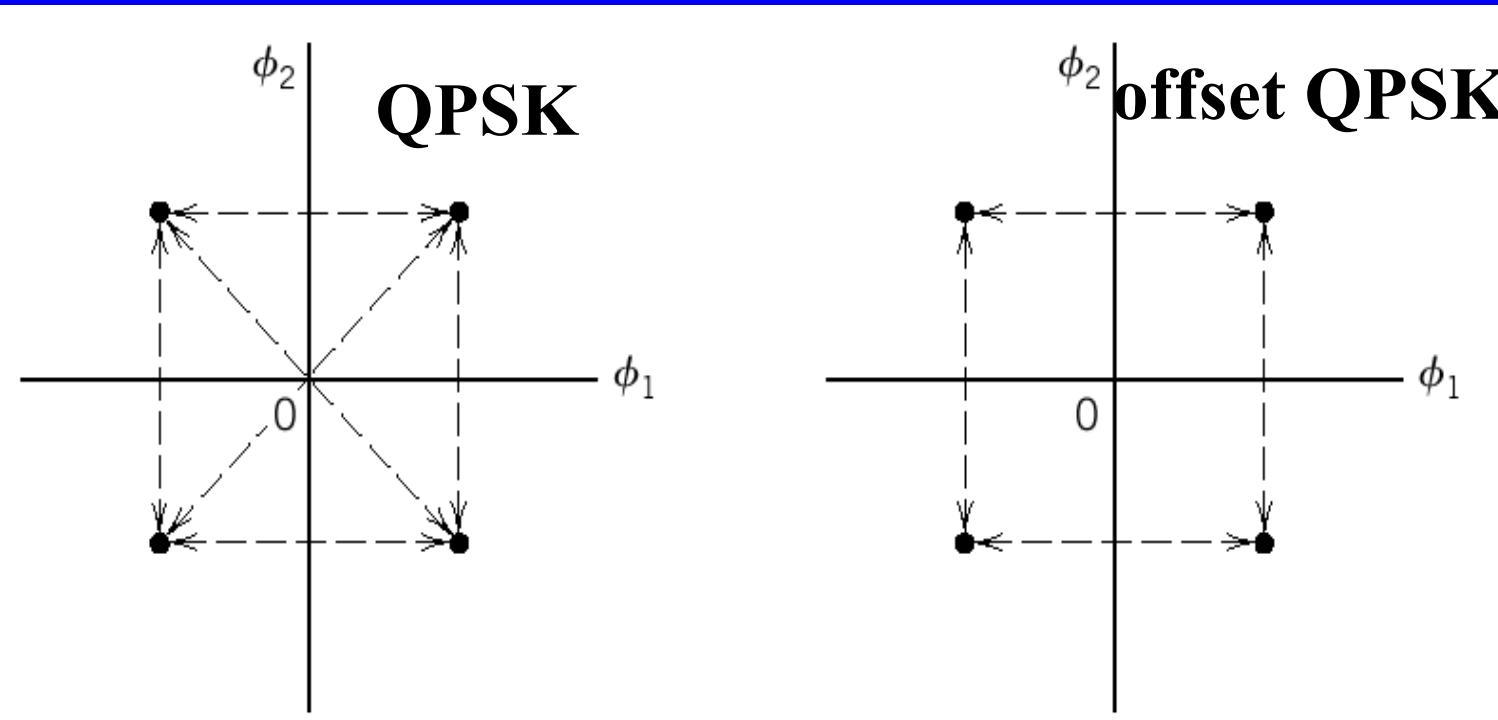


Resolution:

6.3.3 Offset QPSK (OQPSK, 偏移QPSK)

6.3.4 $\pi/4$ -shifted QPSK ($\pi/4$ 移相QPSK)

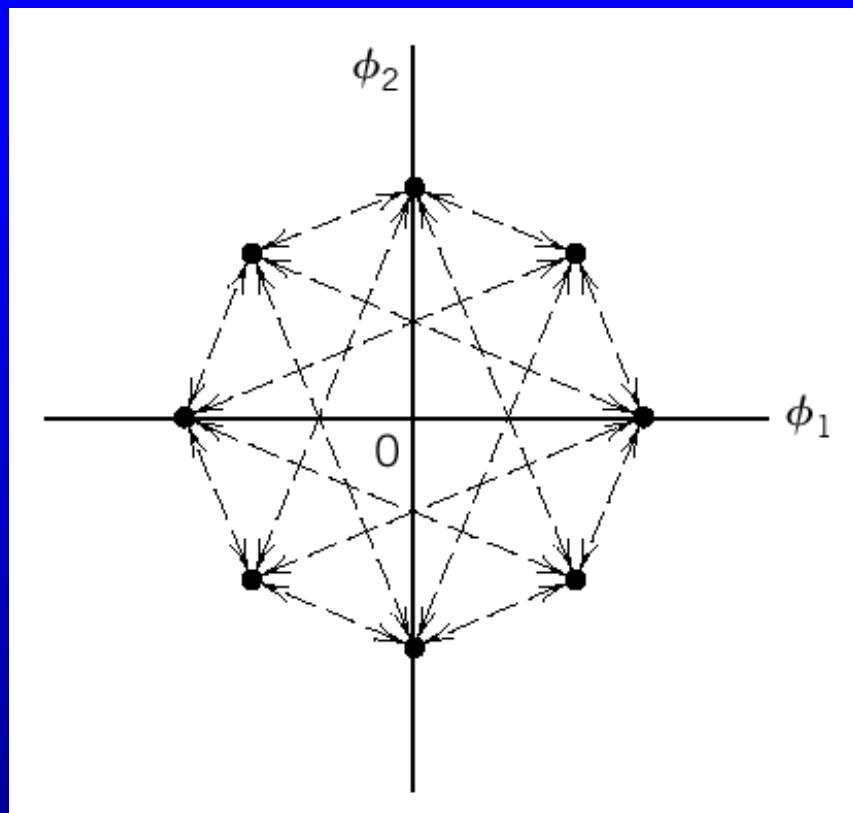
Figure 6.10 Possible paths for switching between the message points in (a) QPSK and (b) offset QPSK.



Carrier phase changes
in QPSK may be
 $\pm 90^\circ$ or $\pm 180^\circ$

Carrier phase changes
in offset QPSK are
confined to $\pm 90^\circ$

Figure 6.12 Eight possible phase states for the $\pi/4$ -shifted QPSK modulator.



The phase transitions from one symbol to the next are restricted to $\pm \pi/4$ and $\pm 3\pi/4$, which is to be smaller than $\pm \pi/2$ and $\pm \pi$ in QPSK. Consequently, envelope variations are reduced.

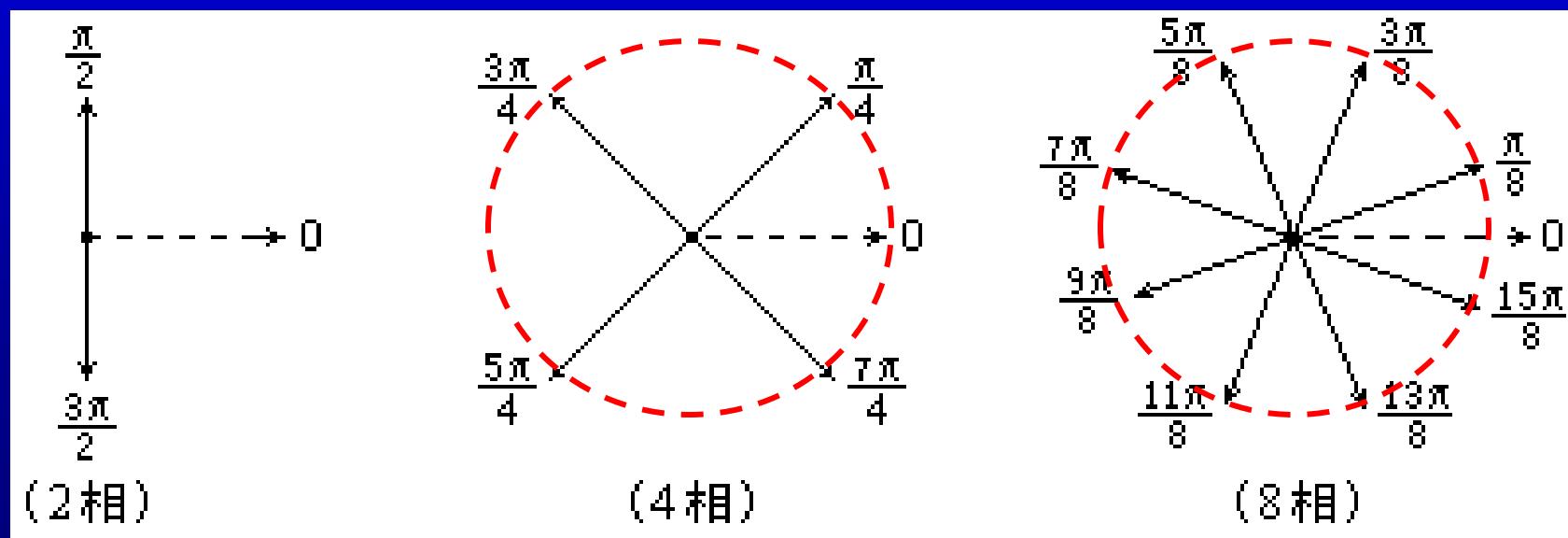
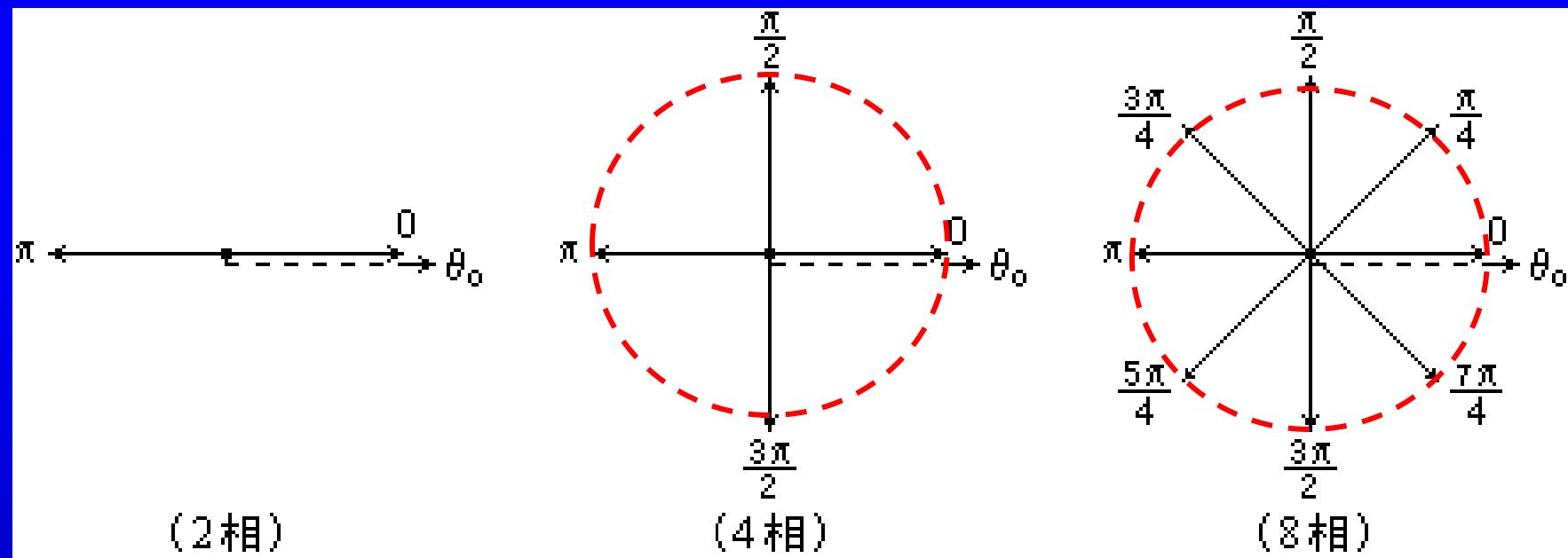
6.3.5 M-ary PSK

In MPSK, the phase of the carrier takes one of M possible values, namely,

$$\theta_i = (i-1) \frac{2\pi}{M}, \quad i=1,2,\dots,M$$

Accordingly, during each signaling interval of duration T, one of the M possible signals can be defined as:

$$s_i(t) = \sqrt{\frac{2E}{T}} \cos\left(2\pi f_c t + \frac{2\pi}{M}(i-1)\right), \quad i=1,2,\dots,M \quad (6.46)$$



6.9 Differential Phase-Shift Keying

差分相移键控， 相对相移键控

DPSK的概念：

所谓差分相移键控（DPSK）是以相邻前一码元的已调载波相位作为基准的数字调相，是利用相邻码元载波相位的相对变化（relative phase difference）来传递数字信息。最简单的 DPSK 是 2DPSK。在解调时，可以不需要产生同频同相的本地载波，故 DPSK 属于非相干 PSK。

2DPSK利用相位差表示二进制码元的不同状态信息，可以有两种规则

1) “1”差分

$$\Delta\theta = \Delta\theta(a_n) = \theta(a_n) - \theta(a_{n-1}) = \begin{cases} 0 & \text{传送 “0”} \\ \pi & \text{传送 “1”} \end{cases}$$

$$\Delta\theta(a_n) = \theta(a_n) - \theta(a_{n-1}) = \pi \cdot a_n$$

$\{a_n\}$ 是输入的二进制序列

$$a_n = \begin{cases} 1 \\ 0 \end{cases}$$

DPSK信号表示式：

$$s_{2DPSK}(t) = \sum_n g(t - nT_b) \cos[\omega_c t + \theta(a_n)]$$

$$\theta(a_n) = \theta(a_{n-1}) + \Delta\theta = \theta(a_{n-1}) + a_n \cdot \pi$$

2) “0”差分

$$\Delta\theta = \Delta\theta(a_n) = \theta(a_n) - \theta(a_{n-1}) = \begin{cases} 0 & \text{传送 “1”} \\ \pi & \text{传送 “0”} \end{cases}$$

$$\Delta\theta(a_n) = \theta(a_n) - \theta(a_{n-1}) = \pi \bar{a}_n$$

$$a_n = \begin{cases} 1 & \\ 0 & \end{cases}$$

DPSK信号表示式:

$$s_{2DPSK}(t) = \sum_n g(t - nT_b) \cos[\omega_c t + \theta(a_n)]$$

$$\theta(a_n) = \theta(a_{n-1}) + \Delta\theta = \theta(a_{n-1}) + \bar{a}_n \cdot \pi$$

In our textbook: 教材上采用的是规则几?

$$s_1(t) = \begin{cases} \sqrt{\frac{E_b}{2T_b}} \cos(2\pi f_c t), & 0 \leq t \leq T_b \\ \sqrt{\frac{E_b}{2T_b}} \cos(2\pi f_c t + \pi), & T_b \leq t \leq 2T_b \end{cases} "1"$$

$$s_2(t) = \begin{cases} \sqrt{\frac{E_b}{2T_b}} \cos(2\pi f_c t), & 0 \leq t \leq T_b \\ \sqrt{\frac{E_b}{2T_b}} \cos(2\pi f_c t + \pi), & T_b \leq t \leq 2T_b \end{cases} "0"$$

对应“0”差分的规则 (2)。

- **BPSK**

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

“1”

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

“0”

- **2DPSK**

$$s_1(t) = \begin{cases} \sqrt{\frac{E_b}{2T_b}} \cos(2\pi f_c t), & 0 \leq t \leq T_b \\ \sqrt{\frac{E_b}{2T_b}} \cos(2\pi f_c t), & T_b \leq t \leq 2T_b \end{cases}$$

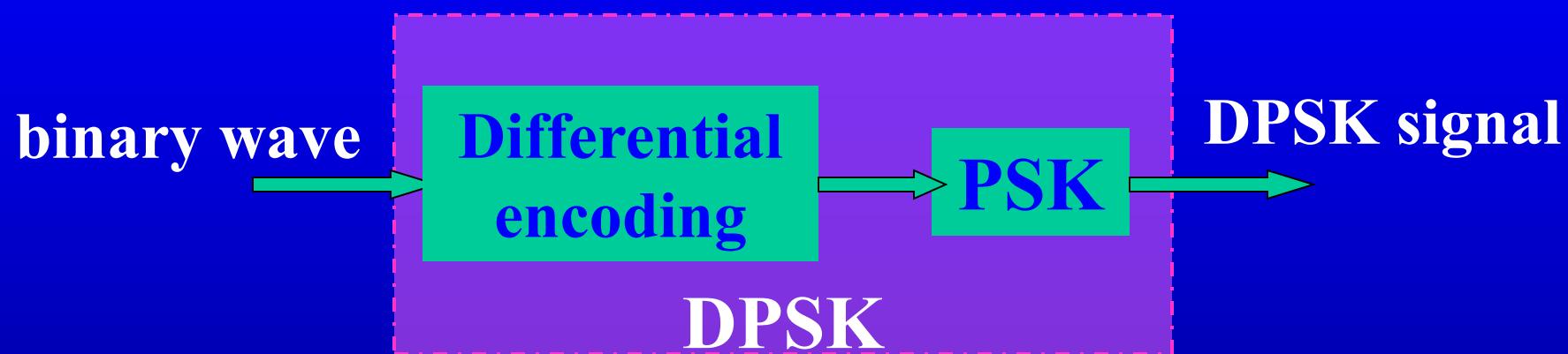
"1"

“0” 差分

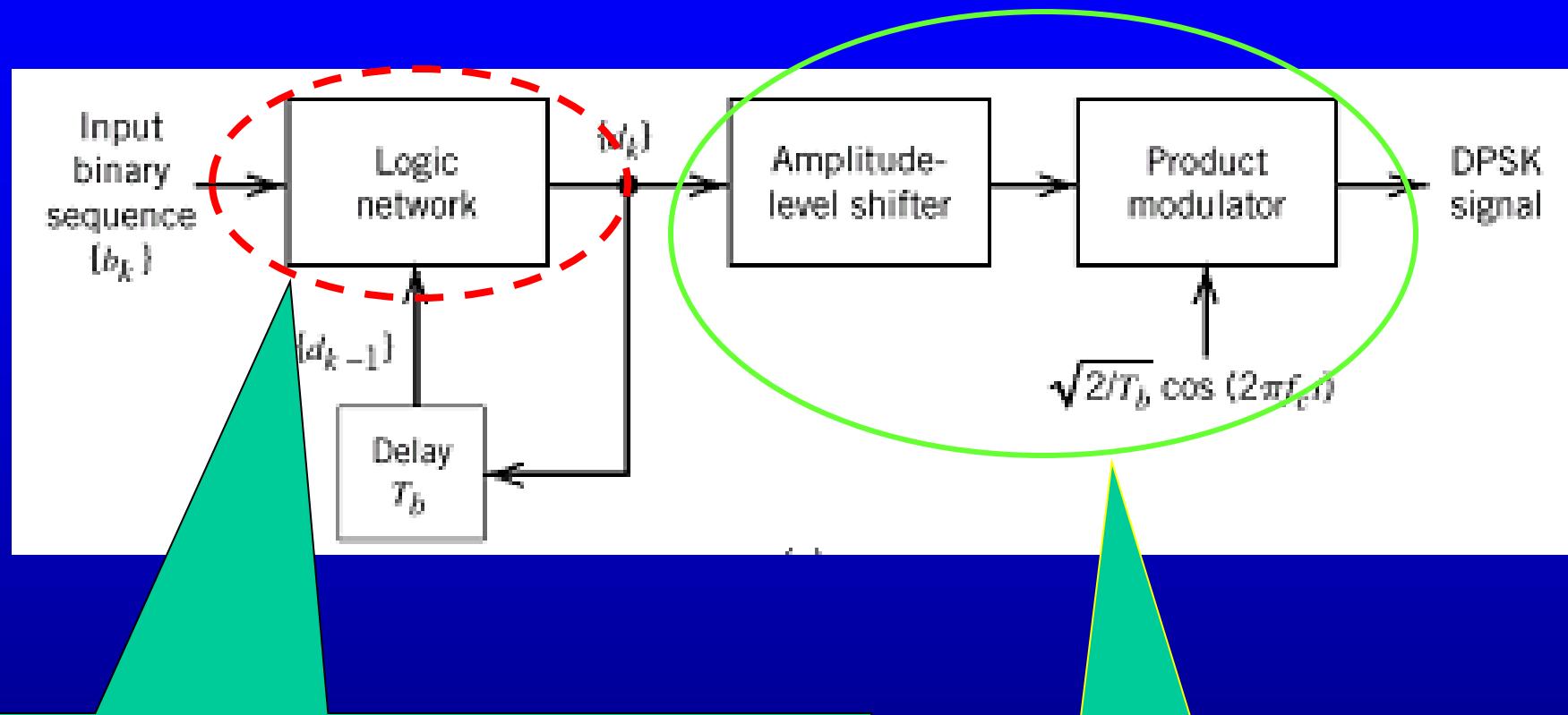
$$s_2(t) = \begin{cases} \sqrt{\frac{E_b}{2T_b}} \cos(2\pi f_c t), & 0 \leq t \leq T_b \\ \sqrt{\frac{E_b}{2T_b}} \cos(2\pi f_c t + \pi), & T_b \leq t \leq 2T_b \end{cases}$$

"0"

Implementation of DPSK 实现方法:



Generation of DPSK



“1” 差分： 异或逻辑 \oplus

“0” 差分： 同逻辑 \odot

PSK

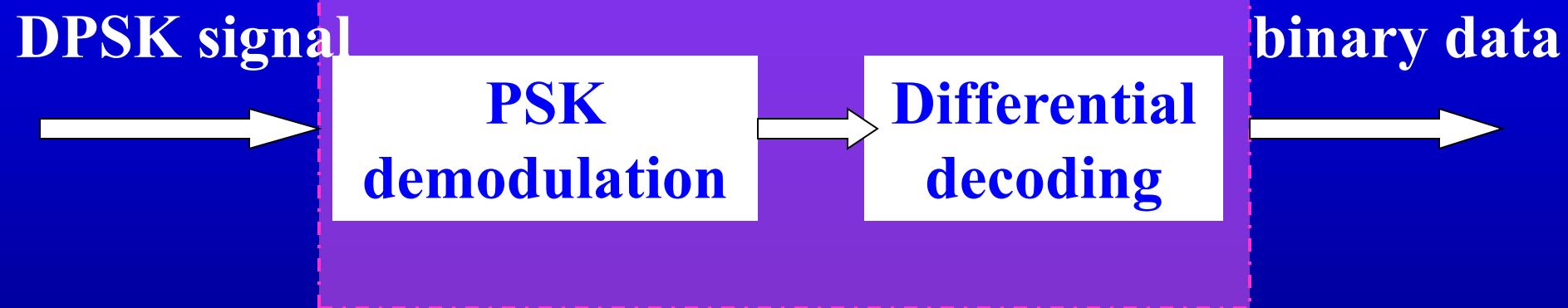
Table 6.7 Illustrating the generation of DPSK signal

Binary sequence $\{b_k\}$		1	0	0	1	0	0	1	1
Differential encoded sequence $\{d_k\}$	1	1	0	1	1	0	1	1	1
Transmitted phase	0	0	π	0	0	π	0	0	0

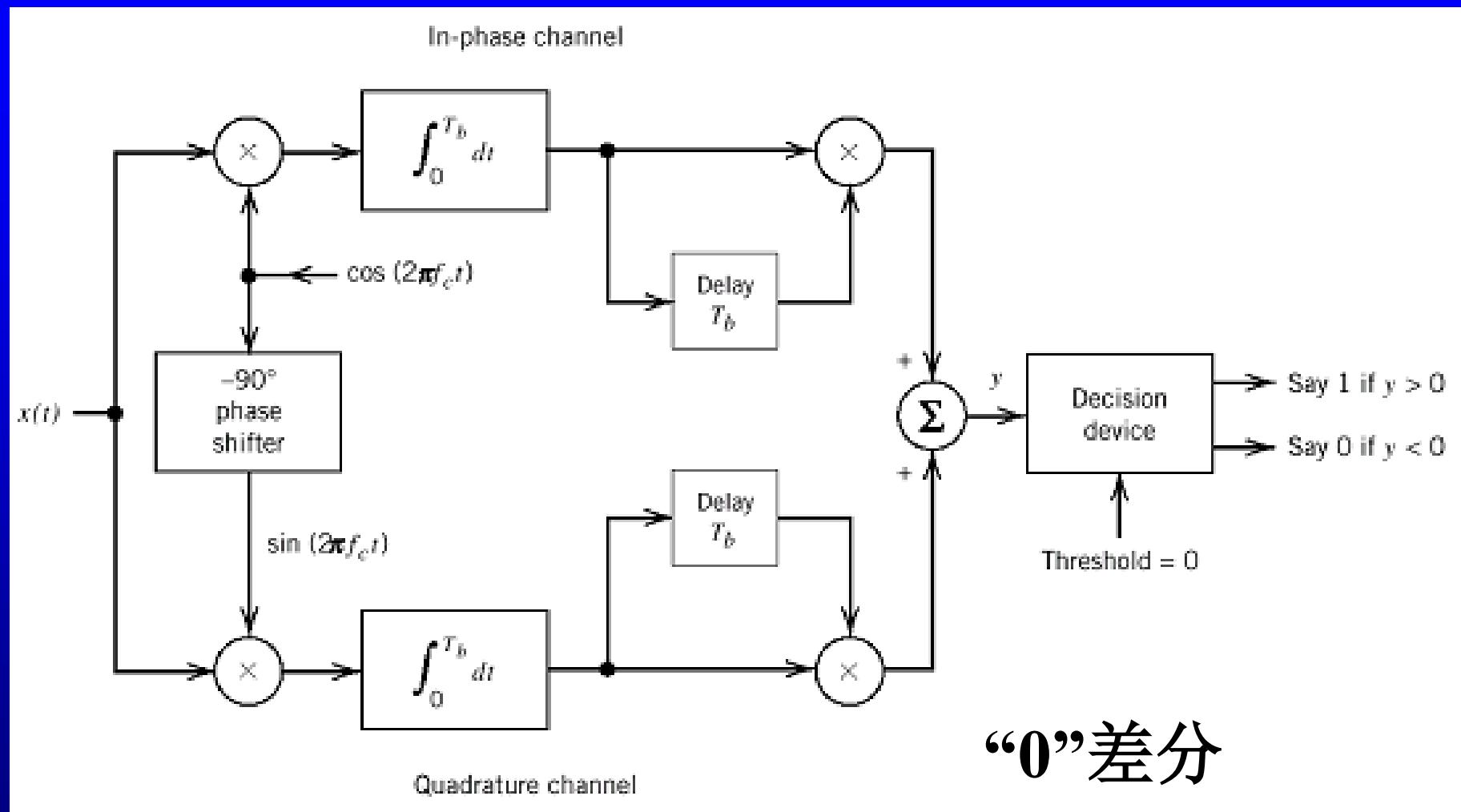
如果采用“1”差分，参考码元为“1”，上表又如何？画出DPSK信号的波形示意图。

Detection of DPSK

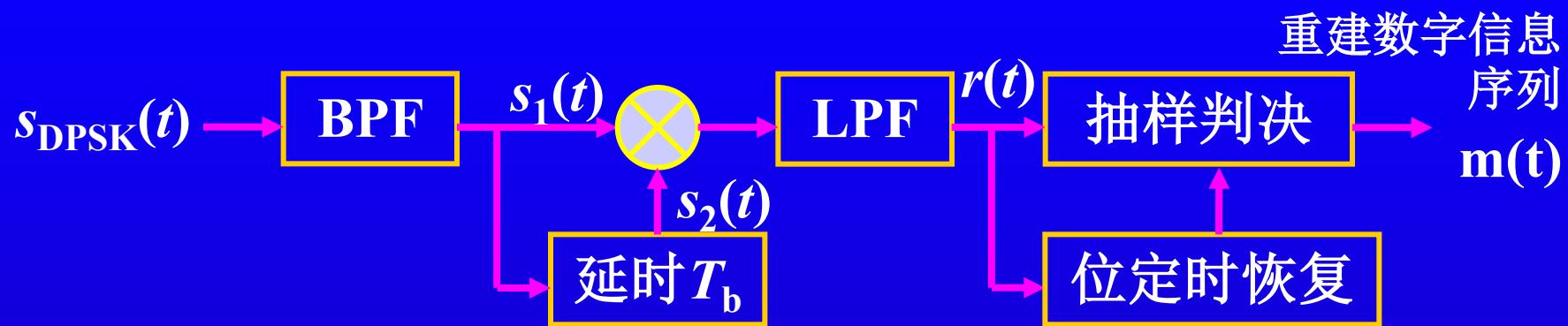
方法一：



方法二：



方法三：2DPSK信号的差分相干解调



2DPSK信号的差分相干解调不需要恢复本地载波，只需将DPSK信号延时一个码元间隔，然后与DPSK信号本身相乘。

$$s_1(t) = A \cos(\omega_c t + \theta_1)$$

$$s_2(t) = A \cos(\omega_c t + \theta_2)$$

$$s_1(t) \cdot s_2(t) = \frac{A^2}{2} [\cos(\theta_2 - \theta_1) + \cos(2\omega_c t + \theta_1 + \theta_2)]$$

$$r(t) = \frac{A^2}{2} \cos(\theta_2 - \theta_1) = \frac{A^2}{2} \cos \Delta\theta$$

“1”差分:

$$\Delta\theta = \theta_2 - \theta_1 = \begin{cases} \pi & \text{发送 “1”} \\ 0 & \text{发送 “0”} \end{cases}$$

则，判决规则

$r(kT_b)$	$\begin{cases} < 0 & \text{判发送 “1”} \\ > 0 & \text{判发送 “0”} \end{cases}$
-----------	--

“0”差分:

$$\Delta\theta = \theta_2 - \theta_1 = \begin{cases} \pi & \text{发送 “0”} \\ 0 & \text{发送 “1”} \end{cases}$$

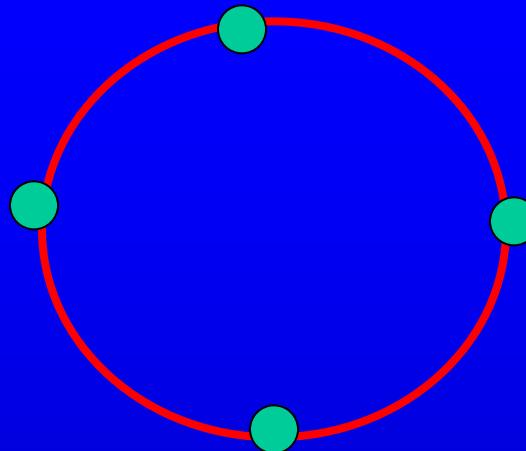
则，判决规则

$r(kT_b)$	$\begin{cases} < 0 & \text{判发送 “0”} \\ > 0 & \text{判发送 “1”} \end{cases}$
-----------	--

6.4 Hybrid Amplitude/Phase Modulation Schemes

1. PAK: Phase Amplitude keying 幅相键控
2. QAM—M-ary quadrature amplitude modulation. 多进制（电平）正交幅度调制

idea



QPSK



4ASK

6.4.1 QAM—M-ary quadrature amplitude modulation

In QAM, there are two basis functions

$$\phi_1(t) = \sqrt{\frac{2}{T}} \cos(2\pi f_c t), \quad 0 \leq t \leq T$$

$$\phi_2(t) = \sqrt{\frac{2}{T}} \sin(2\pi f_c t), \quad 0 \leq t \leq T$$

The transmitted M-ary QAM signal for symbol k is defined by

$$s_k(t) = \sqrt{\frac{2E_0}{T}} a_k \cos(2\pi f_c t) - \sqrt{\frac{2E_0}{T}} b_k \sin(2\pi f_c t), \quad k=0, \pm 1, \pm 2, \dots$$

Depending on M , $M=2^n$, there are two kinds of constellations:

- Square constellation when n is even;
方形星座图
- Cross constellation when n is odd.
十字形星座图

QAM Square Constellation

When an **even number** of bits per symbol, we may write $L=\sqrt{M}$ L is a positive integer.

M 进制QAM的正方形星座图可看成是一维 L 元PAM信号与其自身的笛卡儿积.

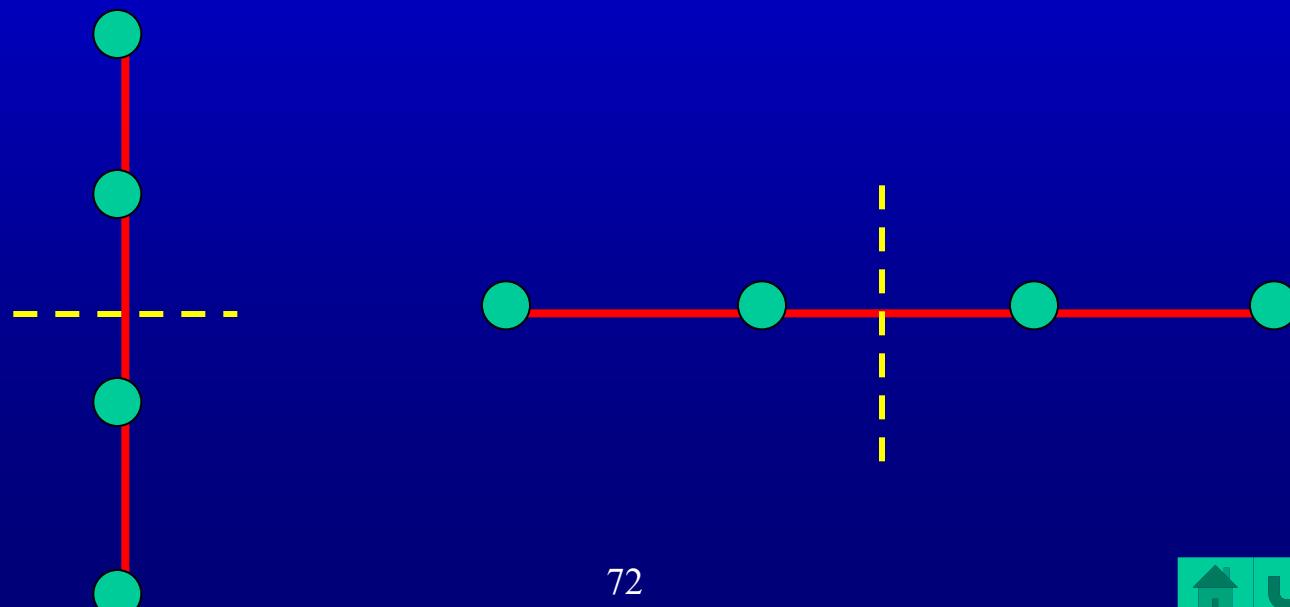


Figure 6.17 16QAM

(a) Signal-space diagram of M -ary QAM for $M = 16$; the message points in each quadrant are identified with Gray-encoded quadbits. (b) Signal-space diagram of the corresponding 4-PAM signal.

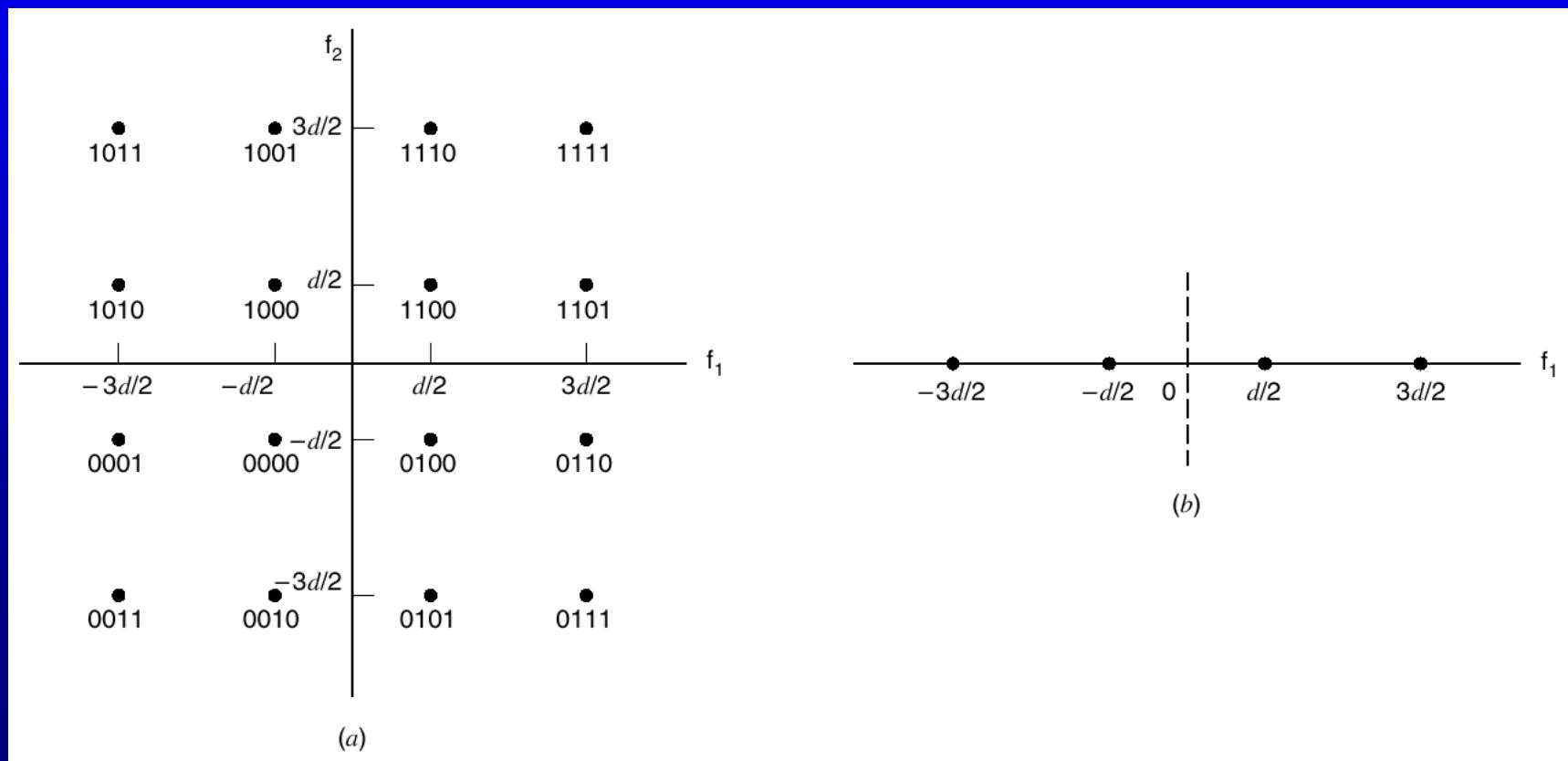
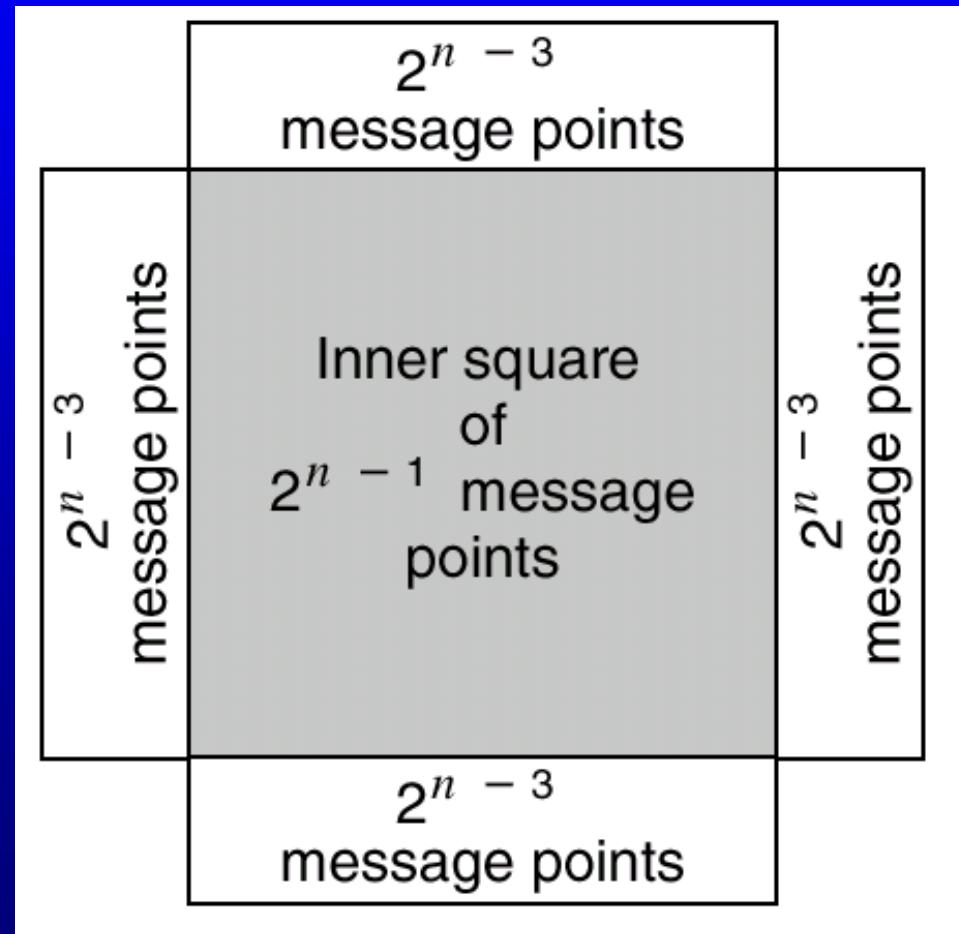


Figure 6.18

Illustrating how a square QAM constellation can be expanded to form a QAM cross-constellation.



5G速度那么快，它是怎么调制的呢？

在3GPP协议（TS 38.201）中，定义了5G支持的调制方式如下：

下行支持的调制

QPSK

16QAM

64QAM

256QAM

上行支持的调制

对于OFDM + CP

QPSK

16QAM

64QAM

256QAM

对于DFT-s-OFDM + CP

QPSK

16QAM

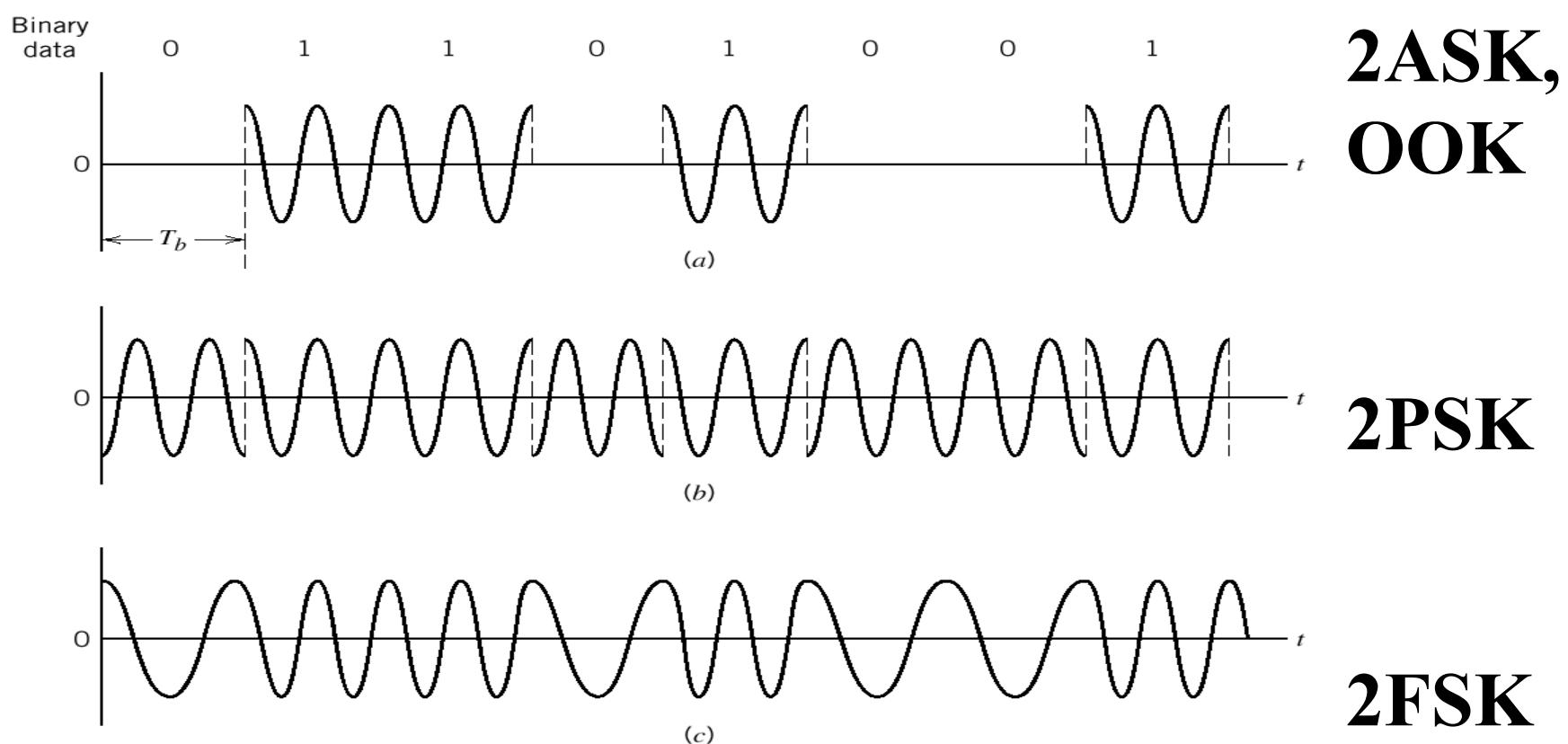
64QAM

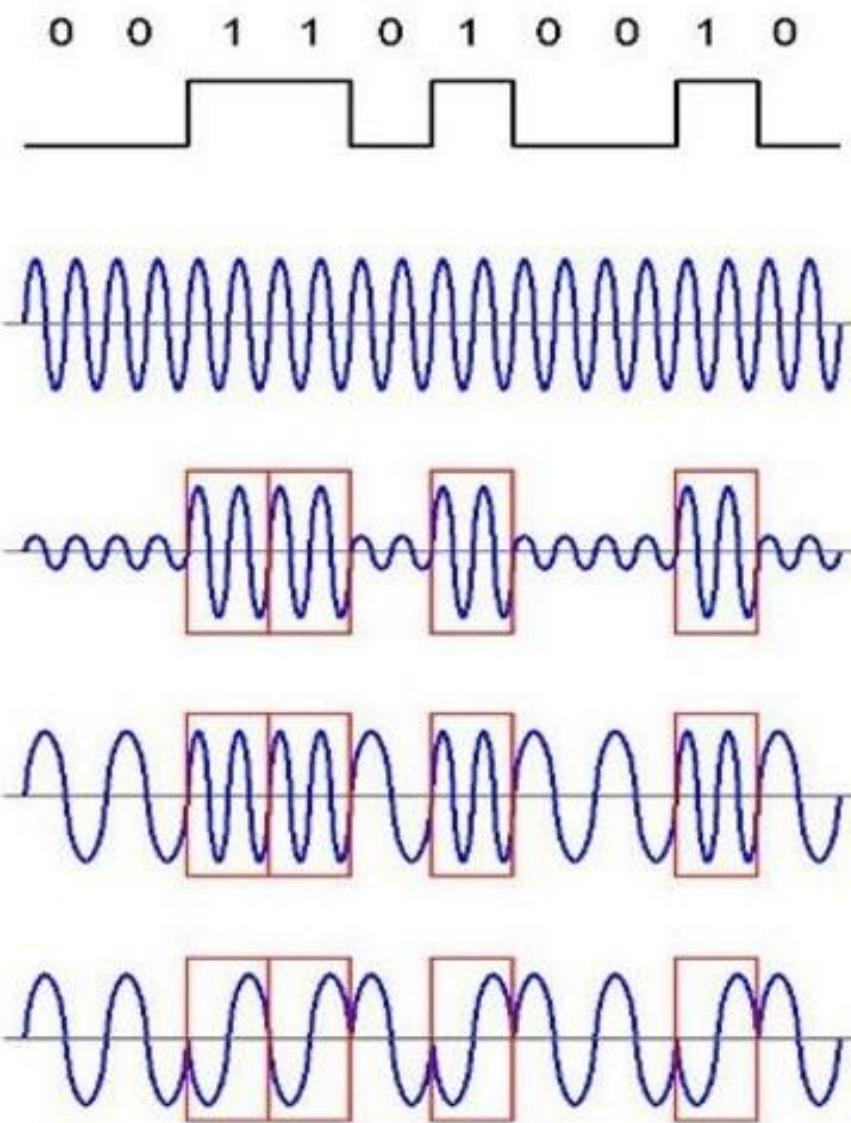
256QAM

$\pi/2$ -BPSK

6.5 Coherent Frequency-Shift Keying 相干频移键控

利用载波频率的不同来表示数字信息。





原始信号
数字信号



高频载波
电磁波



ASK 移幅键控
Amplitude-shift keying

FSK 移频键控
Frequency-shift keying

PSK 移相键控
Phase-shift keying

6.5.1 Binary FSK 二进制频移键控

In 2FSK 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.
用两个具有固定频差的正弦信号分别表示1和0.

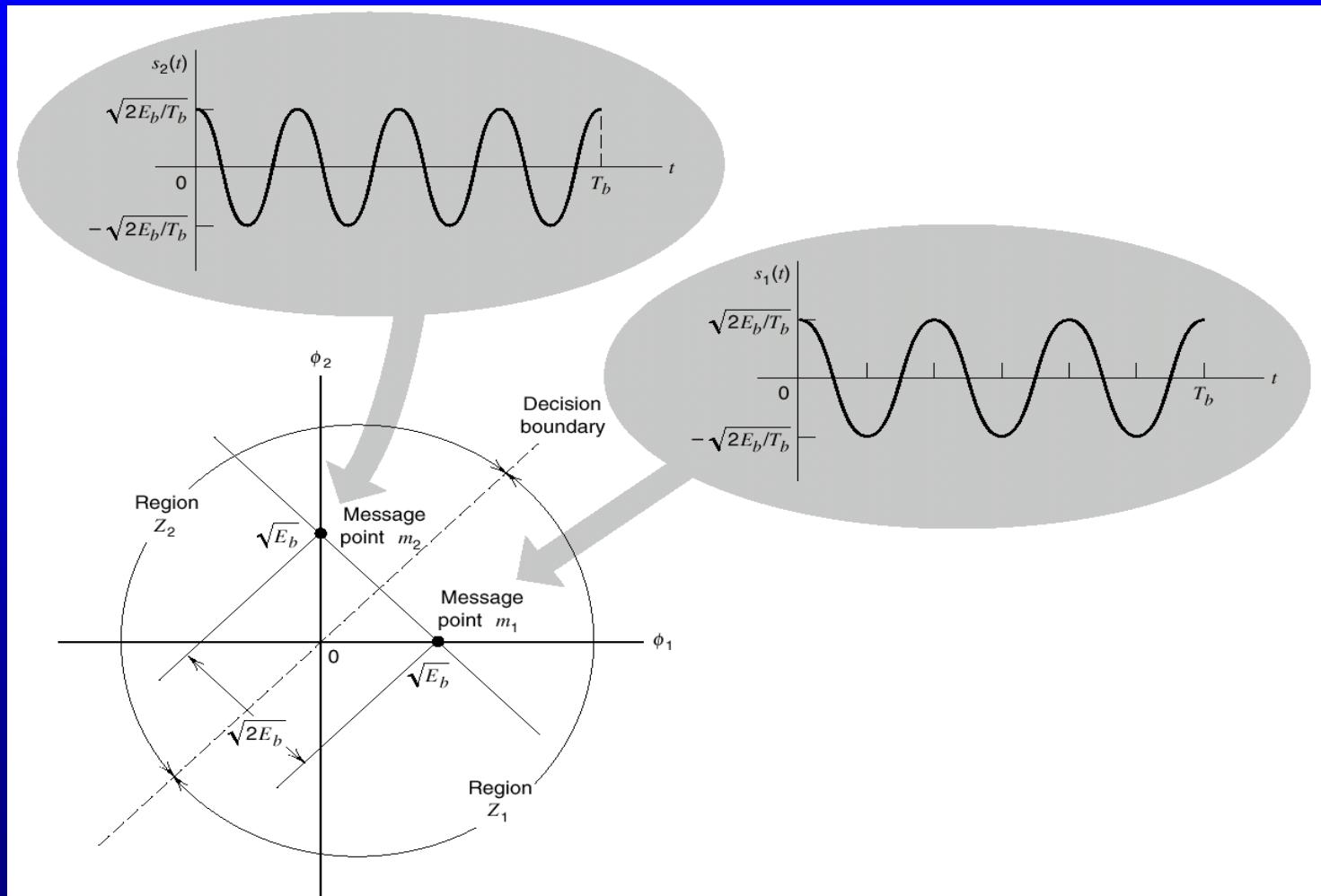
$$s_i(t) = \begin{cases} \sqrt{\frac{2E_b}{T_b}} \cos(2\pi f_i t), & 0 \leq t < T_b \\ 0, & \text{elsewhere} \end{cases} \quad \begin{matrix} i=1,2 & \text{symbol 1} \\ & \text{symbol 0} \end{matrix}$$

E_b 为每比特的发射信号能量.

$$f_i = \frac{n_c + i}{T_b} \quad n_c \text{ interer, } i=1,2$$

两个频率与码元速率都是整数倍关系, 保证了两个正弦信号正交.

Binary FSK (2FSK)



In theory, f_i can be arbitrary only if f_1 and f_2 are different, therefore,

Based on phase {

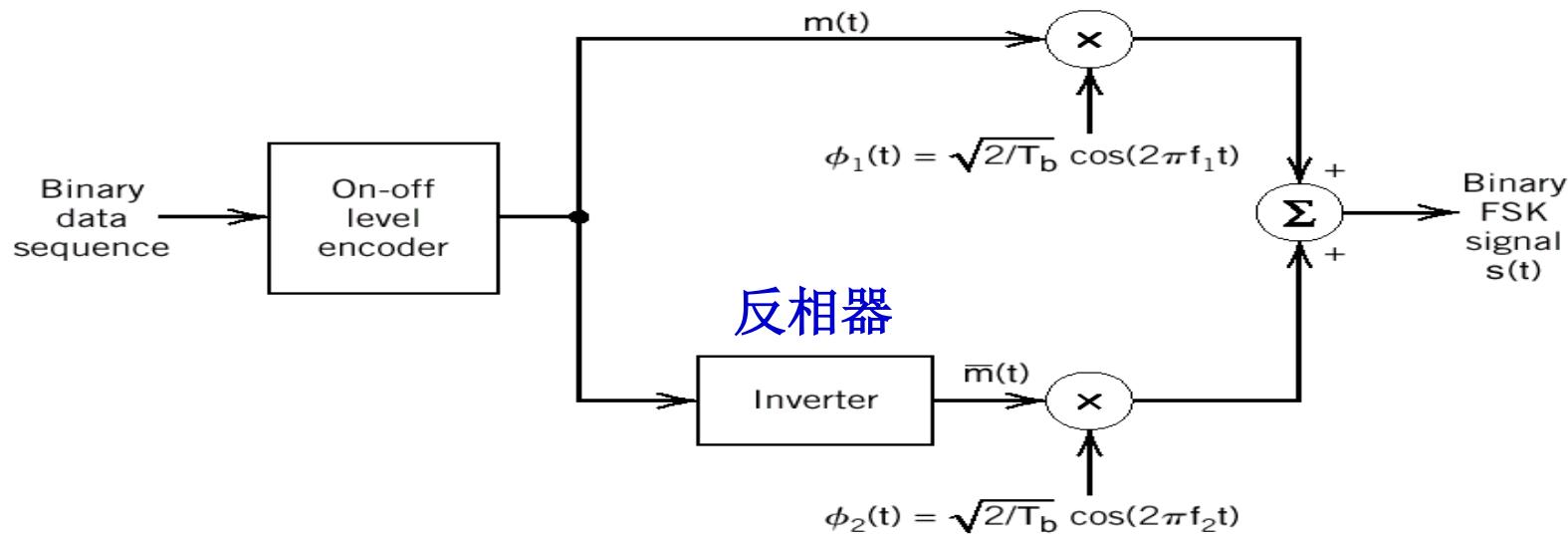
- Continuous-phase FSK (CPFSK)
相位连续的FSK
- Non-continuous-Phase FSK
相位不连续的FSK

In CPFSK, f_i should satisfy

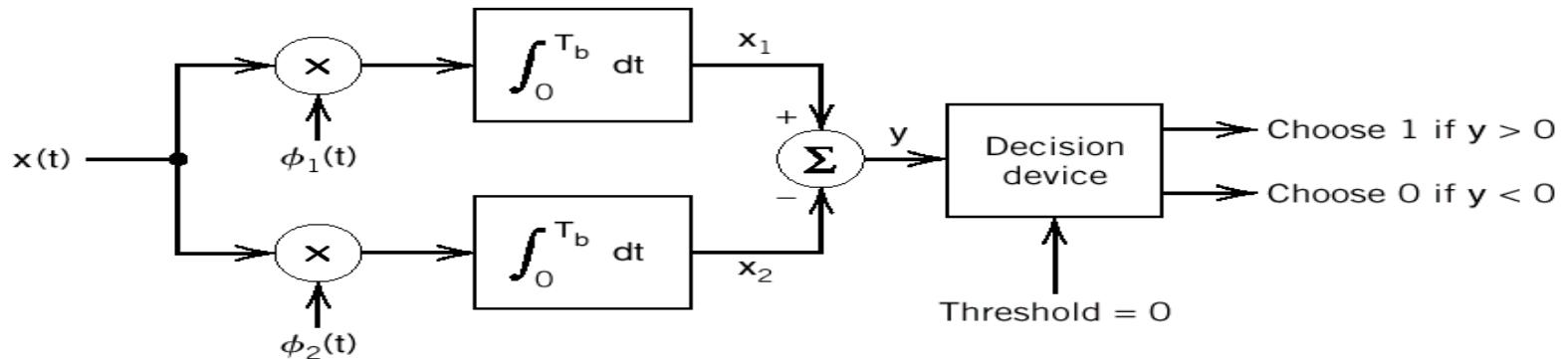
$$f_i = \frac{n_c + i}{T_b} \quad \text{for some fixed integer } n_c \text{ and } i = 1, 2$$

即，一个码元周期内包括整数个载波周期。两个频率与码元速率都是整数倍关系，保证了两个正弦信号正交。

Generation and detection of 2FSK

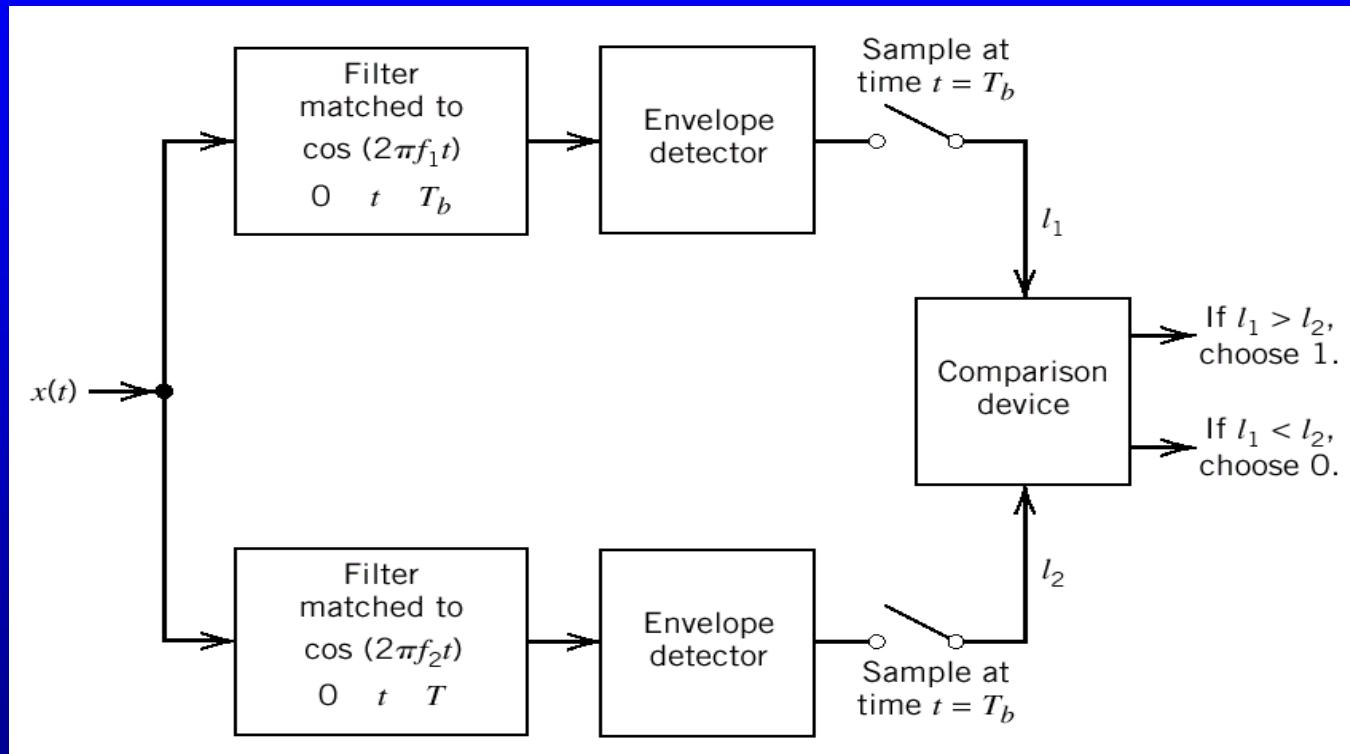


(a) binary FSK transmitter



(b) coherent binary FSK receiver.

Figure 6.42
Noncoherent receiver for the detection of binary FSK signals.



FSK信号既可以采用相干解调，也可以采用非相干解调（包络检波）。

Minimum Shift Keying 最小频移键控

相位连续且具有最小调频指数0.5的频移键控FSK信号满足两个信号正交的条件，频偏最小，包络恒定，故称之为最小频移键控（MSK）。也因为它比一般的2FSK在相同的频带内可传输更高的比特率，故又名快速频移键控（FFSK）。

Gaussian-Filtered MSK

高斯预滤波的最小频移键控

MSK信号虽然具有频谱特性和误码性能好的优点，但就移动通信的应用而言，它占用带宽仍较宽。此外，其频谱的带外衰减仍不够快，以致在25kHz信道间隔内传输16kb/s的数字信号时，不可避免地会产生邻频道干扰。因此，必须设法对MSK的调制方式进行改进，使其在保持MSK信号基本特性的基础上，尽可能加速信号带外频谱的衰减。

用高斯型滤波器（这个滤波器通常称为“预调滤波器”）先对原始数据进行滤波，再进行MSK调制。这就是所谓“用高斯滤波的最小频移键控”，简记为GMSK。用这种方法可以做到在25kHz信道间隔内传输16kb/s的数字信号时，邻频道辐射功率低于-60~-70dB，并保持较好的误码性能。

GMSK是第二代移动通信GSM系统的关键技术.

6.10 Comparison of digital modulation schemes 数字调制性能比较

数字调制系统的带宽

ASK, PSK, DPSK信号的带宽是基带信号带宽的2倍.

$$B_{2ASK} = B_{2PSK} = B_{2DPSK} = 2W$$

FSK信号的带宽是基带信号带宽2倍再加频率偏移.

$$B_{2FSK} = |f_1 - f_2| + 2W$$

Bandwidth Efficiency 带宽效率, 频带利用率

Primary communication resources:

Channel Bandwidth and Transmitted Power

频谱有效调制的主要目标就是最大化带宽效率；另一个目标则是在AWGN信道，以最小的平均信噪比代价实现上述带宽效率。

Bandwidth
Efficiency

$$\rho = \frac{R_b}{B} \quad (\text{bits / s / Hz})$$

- 根据奈奎斯特准则,二进制系统中,对于基带信号,信道频带利用率可达到 $2b/s/Hz$, 也就是说每赫兹带宽每秒可以传输 2b 的信息.
- 按照这一准则, 由于2ASK, 2PSK, 2DPSK信号的带宽是基带信号的2倍, 故其频带利用率最高是 $1b/s/Hz$.
- 4 进制系统中, 一个码元携带2 bit 的信息, 所以基带传输时候, 频带利用率可达到 $4b/s/Hz$.
- 4ASK, 4PSK, 4DPSK信号的带宽与2ASK, 2PSK, 2DPSK 的带宽相同, 因此它们的频带利用率是 $2b/s/Hz$.

Table 6.8 Summary of formulas for the BER of different digital modulation schemes

Signal scheme	BER
Coherent binary PSK Coherent QPSK Coherent MSK	$\frac{1}{2}\text{erfc}(\sqrt{E_b/N_0})$
Coherent binary FSK	$\frac{1}{2}\text{erfc}(\sqrt{E_b / 2N_0})$
DPSK	$\frac{1}{2}\exp(-E_b/N_0)$
Noncoherent binary FSK	$\frac{1}{2}\exp(-E_b/2N_0)$

数字调制的BER（抗噪声性能， noise performance）

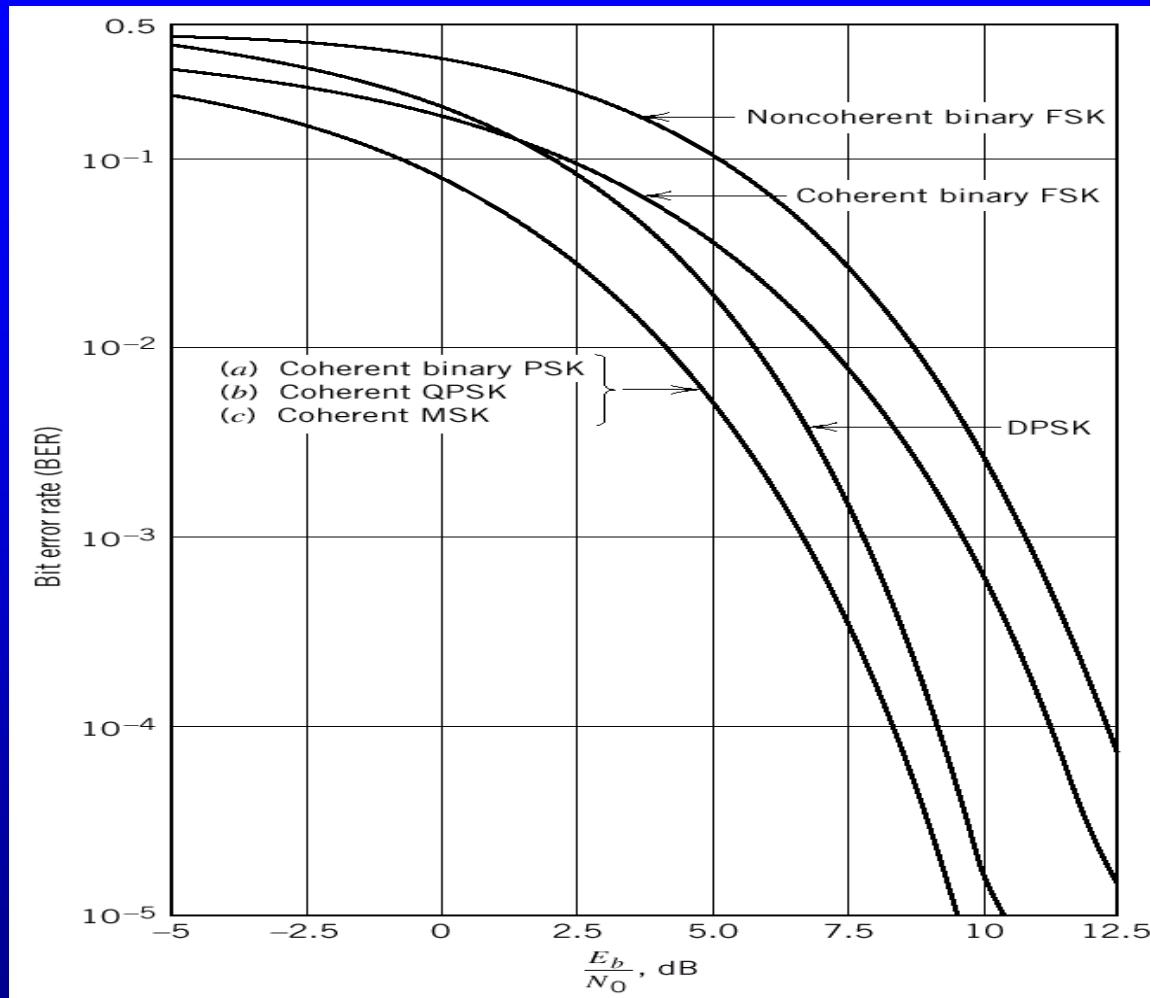


Figure 6.45 Comparison of the noise performance of different PSK and FSK schemes

Based on table 6.8 and figure 6.45, we can make the following statements:

1. The BER for all the systems decrease monotonically with increasing values of E_b/N_0 ; the defining curves have a similar shape in the form of waterfall.
2. For any value of E_b/N_0 , coherent binary PSK, QPSK, and MSK produce a smaller BER than any other modulation schemes.
3. Coherent binary PSK and DPSK require an E_b/N_0 that 3 dB less than the corresponding values for conventional coherent binary FSK and noncoherent binary FSK respectively, to realize the same BER.

二进制数字调制系统的性能比较

- ◆ 在码元速率相同的情况下，ASK、PSK和DPSK系统占据的频带比FSK的窄。所以从信道带宽利用率来看，ASK、PSK 和 DPSK 系统一样好，FSK 系统较差。
- ◆ 在同一类型的相干和非相干系统中，所有的相干方式都比同一类型的非相干方式的抗噪声性能好（误码率低）。但前者需要提取本地相干载波，增加了系统的复杂性。

- ◆ 在不同类型的调制方式中，当 P_e 相同时，从平均功率信噪比的角度来说，PSK要求的平均功率信噪比比FSK和ASK小3dB，FSK和ASK要求的平均功率信噪比相同；但从瞬时功率信噪比的角度来说，FSK要求的瞬时功率信噪比比ASK小3dB，PSK又比FSK方式小3dB。所以，PSK的抗噪声性能最好。
- ◆ 就频带利用率和抗噪声性能两方面来看，理论上都是PSK系统最佳，DPSK系统次之。考虑到解调PSK信号可能出现相位模糊而使被传输的码元“0”、“1”倒置，而DPSK系统又克服了这一问题，因此在实际应用中，DPSK系统就成为“最佳”系统，得到了广泛的应用。

Summary

- Digital modulation ASK PSK FSK
- 2PSK: Generation and coherent detection
- 2DPSK: Generation and detection
- 2FSK: Generation and detection
- Performance comparison

Homework

6.5 6.33

1. 假设输入的二进制序列 $\{a_n\}$ 是1100101010, 画出对应的2ASK, 2FSK, 2PSK, 2DPSK, QPSK, 信号的波形示意图（设一个码元周期含有两个载波周期）。
2. 复习2PSK, 2DPSK, QPSK, 2FSK的调制解调原理框图, 以及框图中各点波形示意图）。