ADVANCED COMMUNICATION SYSTEMS

Chapter 5
Part B: Digital Modulations
Analog Carrier, Digital Signals

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References:

- Behrous A. Forouzan, “Data Communications and networking”, Mc. Graw Hill, 2003, ISBN 007-123241-9.
- Bruce Carlson, Paul B. Crilly, Communication Systems, Mc. Graw Hill 5th Edi., 2010, ISBN 978-0-07-338040-7

1 Modulation of Digital Data

Digital-to-Analog Conversion

Amplitude Shift Keying (ASK)

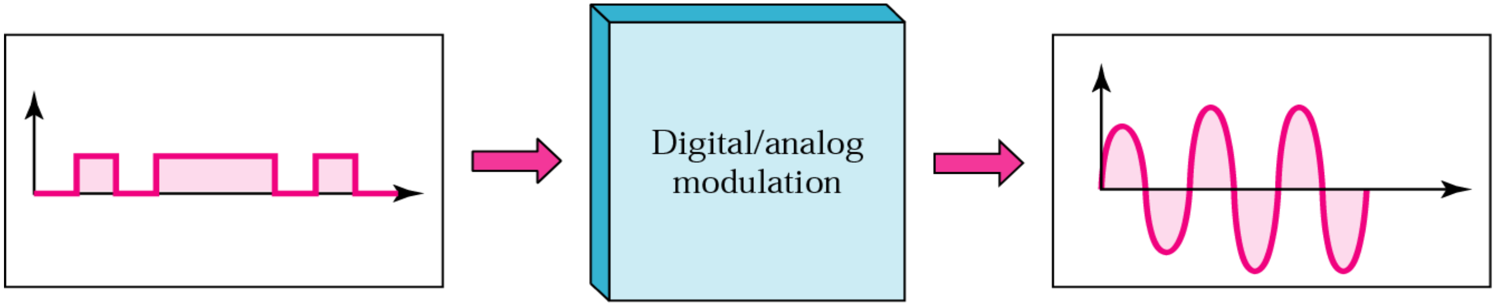
Frequency Shift Keying (FSK)

Phase Shift Keying (PSK)

Quadrature Amplitude Modulation

Bit/Baud Comparison

Figure 1 *Digital-to-analog modulation*



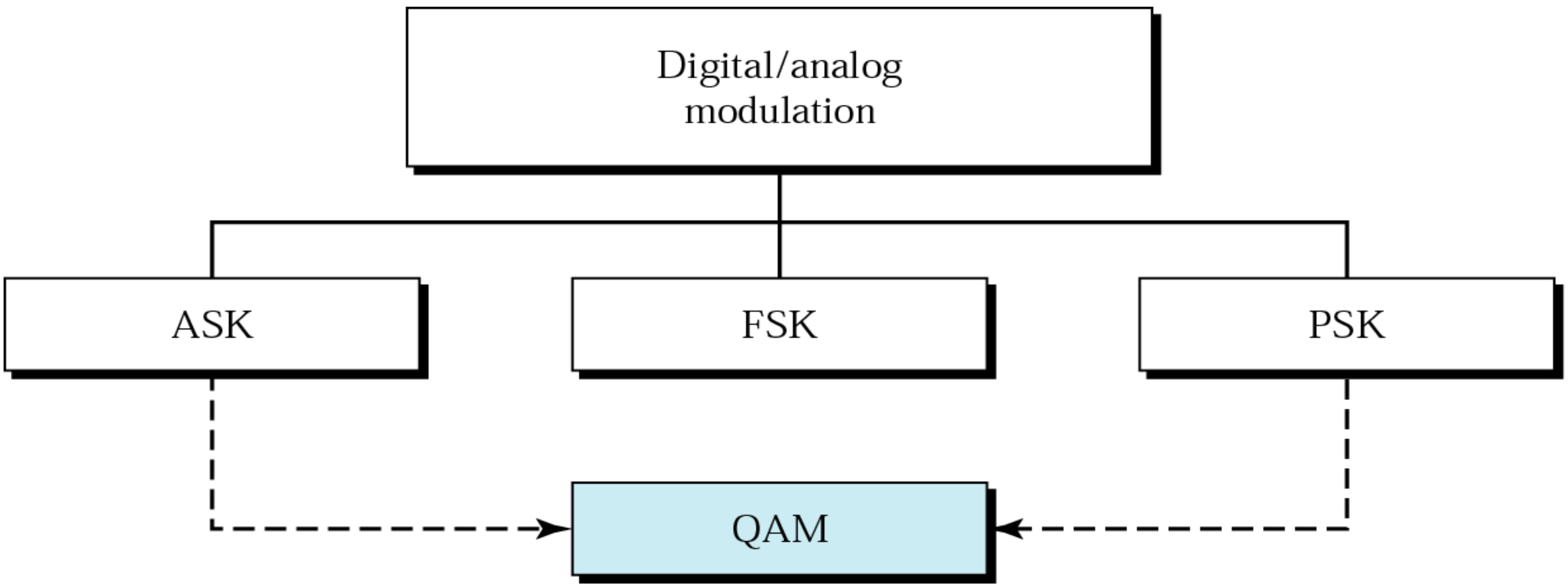
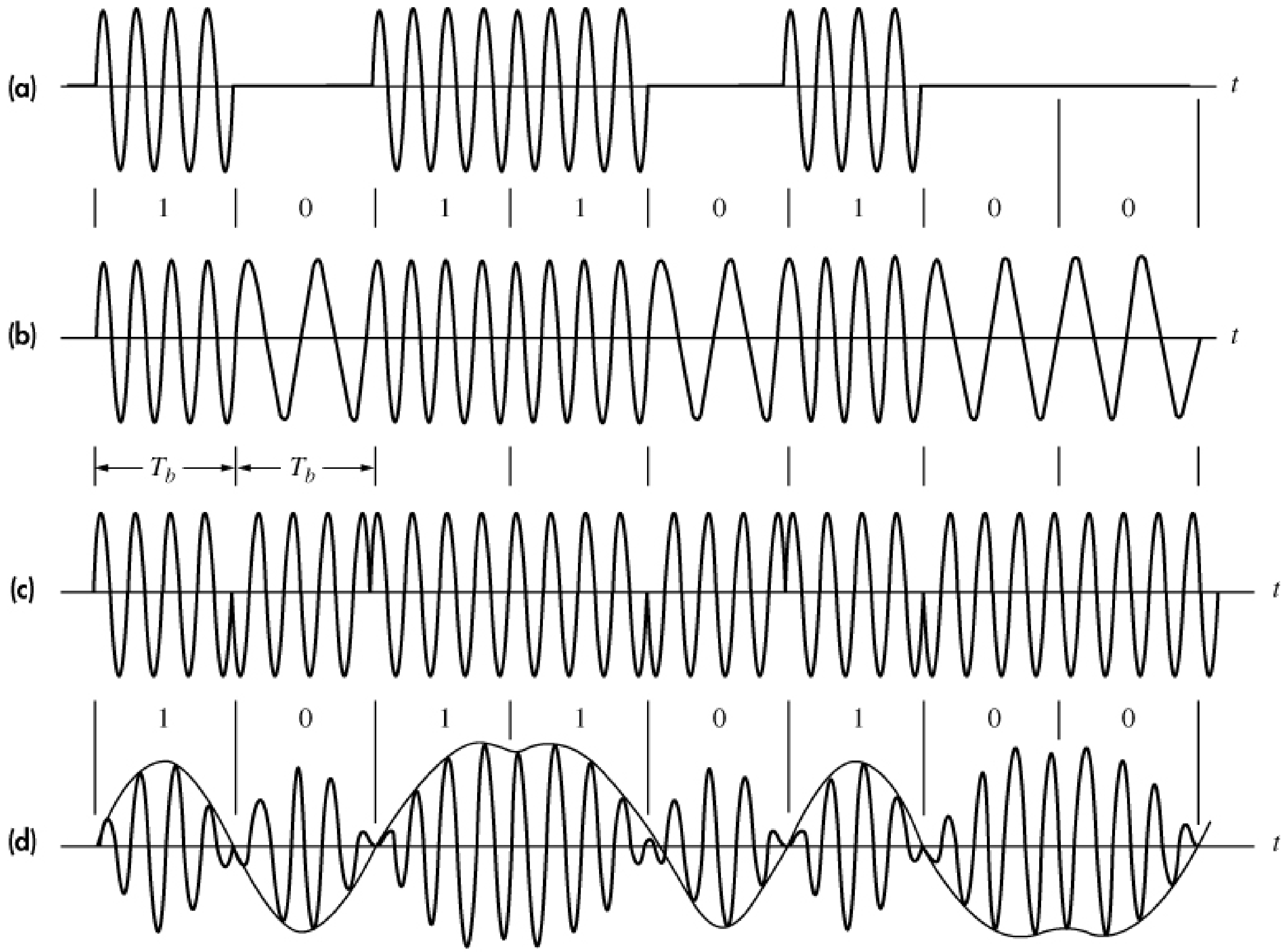


Figure 2 *Types of digital-to-analog modulation*

1. Digital CW modulation

Binary modulated waveforms (a) ASK (b) FSK (c) PSK (d) DSB with baseband pulse shaping



Spectral analysis of bandpass digital signals $x_c(t)$

$$x_c(t) = A_c[x_i(t)\cos(\omega_c t + \theta) - x_q(t)\sin(\omega_c t + \theta)]$$

Power spectrum of $x_c(t)$

$$G_c(f) = \frac{A_c^2}{4}[G_i(f - f_c) + G_i(f + f_c) + G_q(f - f_c) + G_q(f + f_c)]$$

The equivalent lowpass power spectrum

$$G_{\ell p}(f) \triangleq G_i(f) + G_q(f)$$

$$G_c(f) = \frac{A_c^2}{4}[G_{\ell p}(f - f_c) + G_{\ell p}(f + f_c)]$$

Supposed the i component is an M-ary digital signal with rate r=1/D

$$x_i(t) = \sum_k a_k p(t - kD)$$

Assumed the source digits are equiprobable and statistical independent

$$G_i(f) = \sigma_a^2 r|P(f)|^2 + (m_a r)^2 \sum_{n=-\infty}^{\infty} |P(nr)|^2 \delta(f - nr)$$

Where p(t) depends on the baseband filtering

$$p_D(t) \triangleq u(t) - u(t - D) = \begin{cases} 1 & 0 < t < D \\ 0 & \text{otherwise} \end{cases} \qquad |P_D(f)|^2 = D^2 \operatorname{sinc}^2 fD = \frac{1}{r^2}\operatorname{sinc}^2\frac{f}{r}$$

Bit rate is the number of bits per second. Baud rate is the number of signal units per second. Baud rate is less than or equal to the bit rate.

Example 1

An analog signal carries 4 bits in each signal unit. If 1000 signal units are sent per second, find the baud rate and the bit rate

Baud rate = 1000 bauds per second (baud/s)
Bit rate = 1000 x 4 = 4000 bps

Example 2

The bit rate of a signal is 3000. If each signal unit carries 6 bits, what is the baud rate?

Baud rate = 3000 / 6 = 500 baud/s

Amplitude Modulation method – ASK or On-Off keying

The i component (set q component = 0) for NRZ, M-ary ASK

$$x_i(t) = \sum_k a_k p_D(t - kD) \qquad a_k = 0, 1, \ldots, M - 1$$

The mean and variance of digital sequence

$$m_a = \overline{a_k} = \frac{M-1}{2} \qquad \sigma_a^2 = \overline{a_k^2} - m_a^2 = \frac{M^2-1}{12}$$

$$G_{\ell p}(f) = G_i(f) = \frac{M^2-1}{12\,r}\,\mathrm{sinc}^2\frac{f}{r} + \frac{(M-1)^2}{4}\,\delta(f)$$

Figure for ASK spectrum B_T=r, and M-ary ASK has B_T= r/logM)

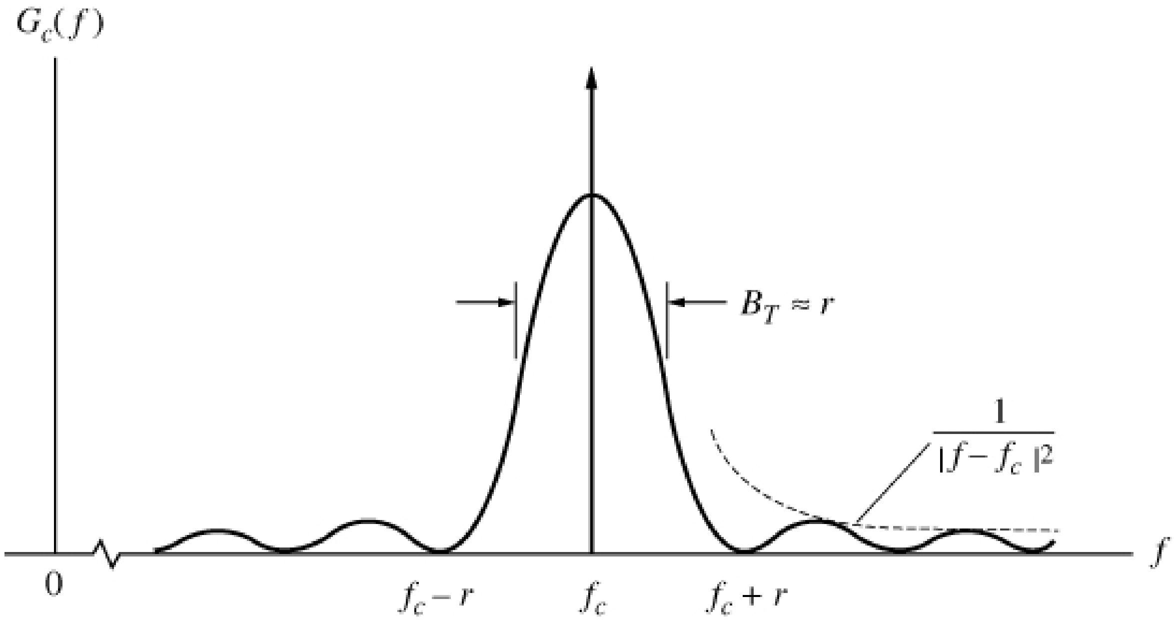
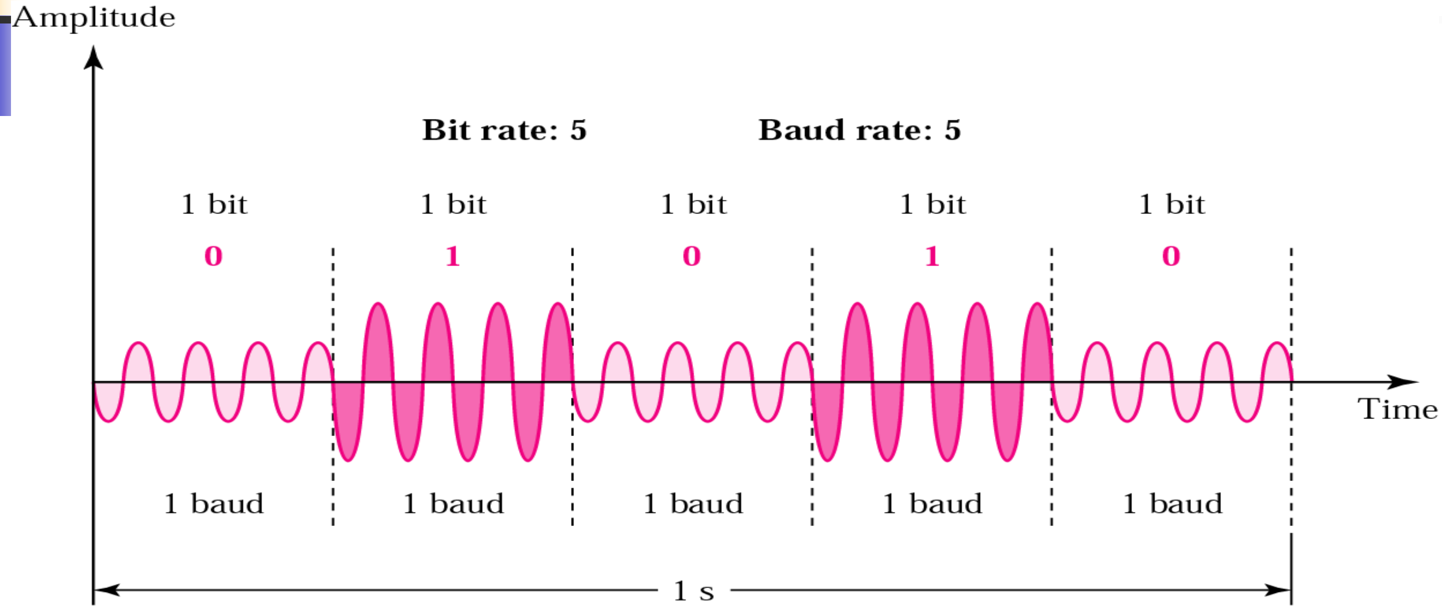


Figure 3 ***ASK***



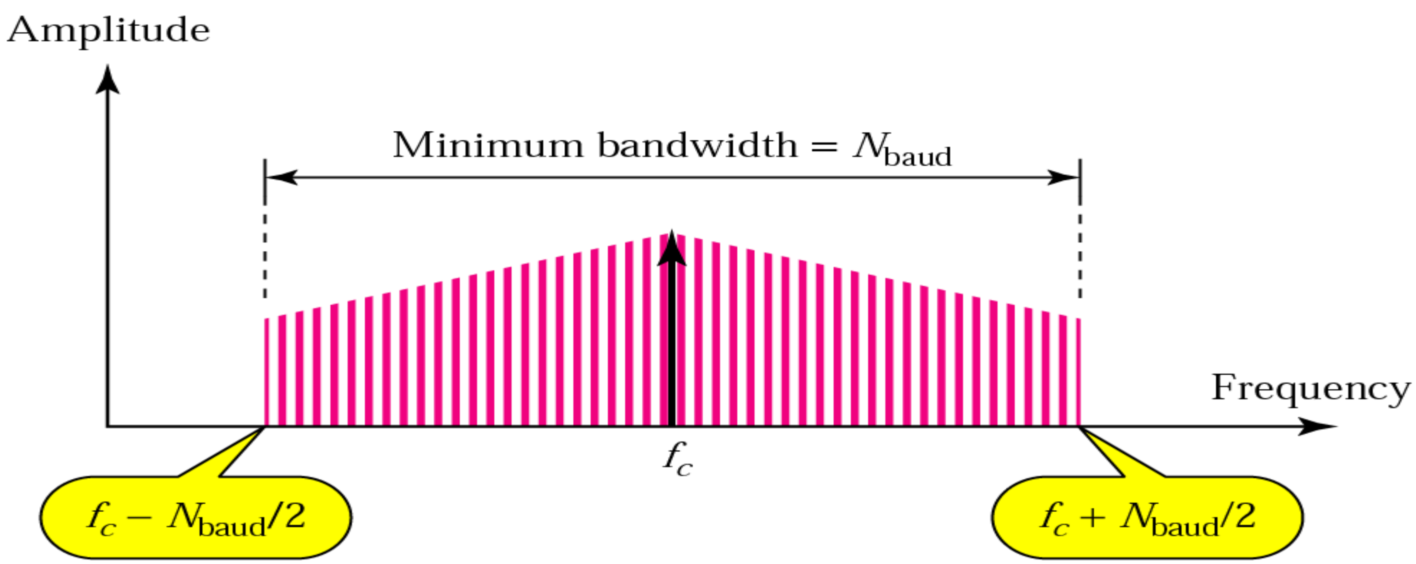


Figure 4 ***Relationship between baud rate and bandwidth in ASK***

Example 3

Find the minimum bandwidth for an ASK signal transmitting at 2000 bps. The transmission mode is half-duplex.

In ASK the baud rate and bit rate are the same. The baud rate is therefore 2000. An ASK signal requires a minimum bandwidth equal to its baud rate. Therefore, the minimum bandwidth is 2000 Hz.

Example 4

Given a bandwidth of 5000 Hz for an ASK signal, what are the baud rate and bit rate?

In ASK the baud rate is the same as the bandwidth, which means the baud rate is 5000. But because the baud rate and the bit rate are also the same for ASK, the bit rate is 5000 bps.

Example 5

Given a bandwidth of 10,000 Hz (1000 to 11,000 Hz), draw the full-duplex ASK diagram of the system. Find the carriers and the bandwidths in each direction. Assume there is no gap between the bands in the two directions.

For full-duplex ASK, the bandwidth for each direction is

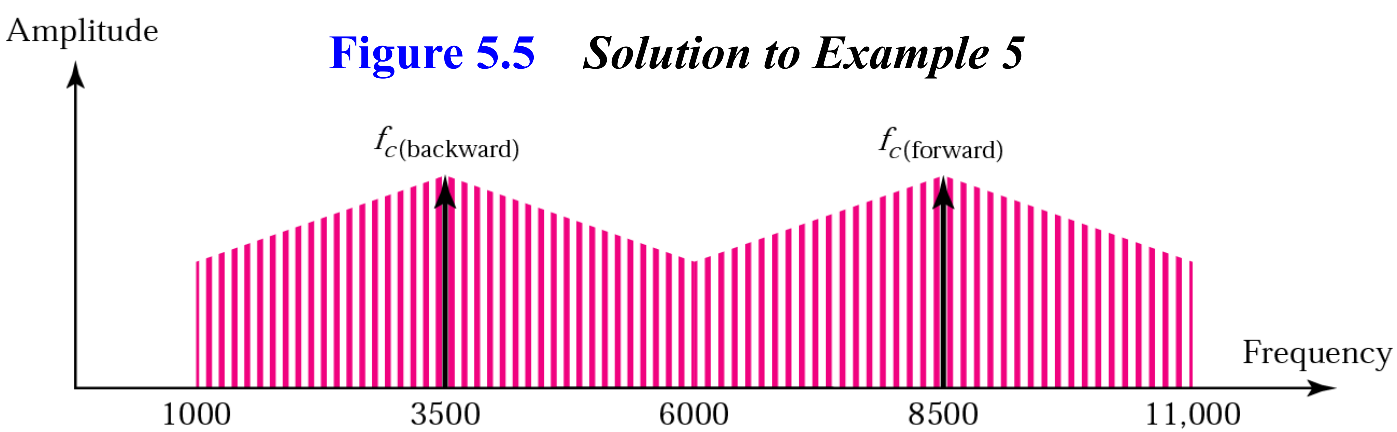
BW = 10000 / 2 = 5000 Hz

The carrier frequencies can be chosen at the middle of each band

fc (forward) = 1000 + 5000/2 = 3500 Hz

fc (backward) = 11000 – 5000/2 = 8500 Hz

Figure 5.5 ***Solution to Example 5***

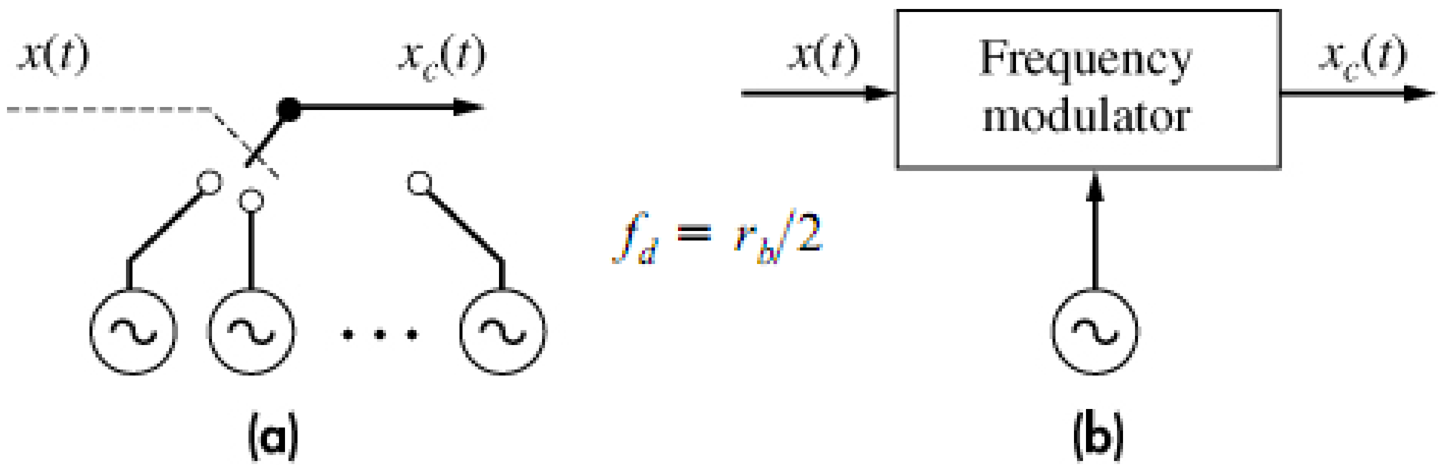


Frequency modulation method - FSK

Consider M-ary FSK

$$f_k = f_c + f_d a_k \qquad a_k = \pm 1, \pm 3, \ldots, \pm(M-1)$$

$$x_c(t) = A_c \sum_k \cos(\omega_c t + \theta + \omega_d a_k t) p_D(t - kD)$$



Digital frequency modulation (a) FSK (b) continuous-phase FSK

Binary FSK: $a_k = \pm 1$

$M = 2, D = T_b = 1/r_b,$ and $N = 1$. Then $p_D(t) = u(t) - u(t - T_b)$

$$\cos \omega_d a_k t = \cos \omega_d t \qquad \sin \omega_d a_k t = a_k \sin \omega_d t$$

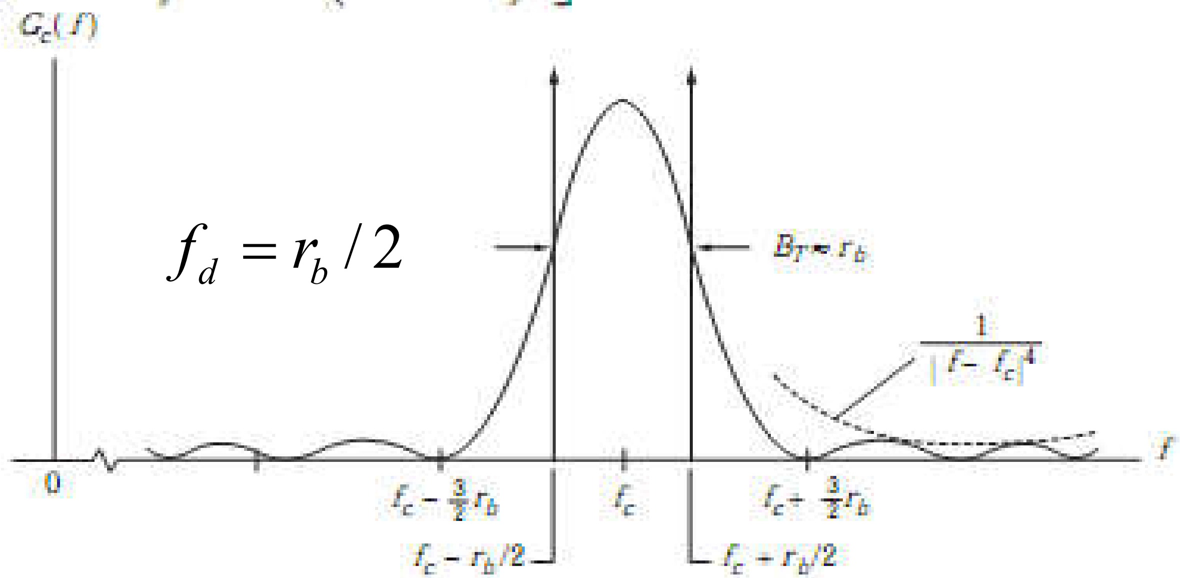
Then

$$x_q(t) = \sum_k a_k \sin(\pi r_b t)[u(t - kT_b) - u(t - kT_b - T_b)]$$

$$= \sum_k Q_k p(t - kT_b) \qquad Q_k = (-1)^k a_k$$

$x_i(t) = \cos \pi r_b t$ **where** $p(t) = \sin(\pi r_b t)[u(t) - u(t - T_b)]$

$$G_{\ell p}(f) = \frac{1}{4}\left[\delta\left(f - \frac{r_b}{2}\right) + \delta\left(f + \frac{r_b}{2}\right)\right] + r_b|P(f)|^2$$



Power spectrum of binary FSK with $f_d = r_b / 2$

Figure 6 *FSK*

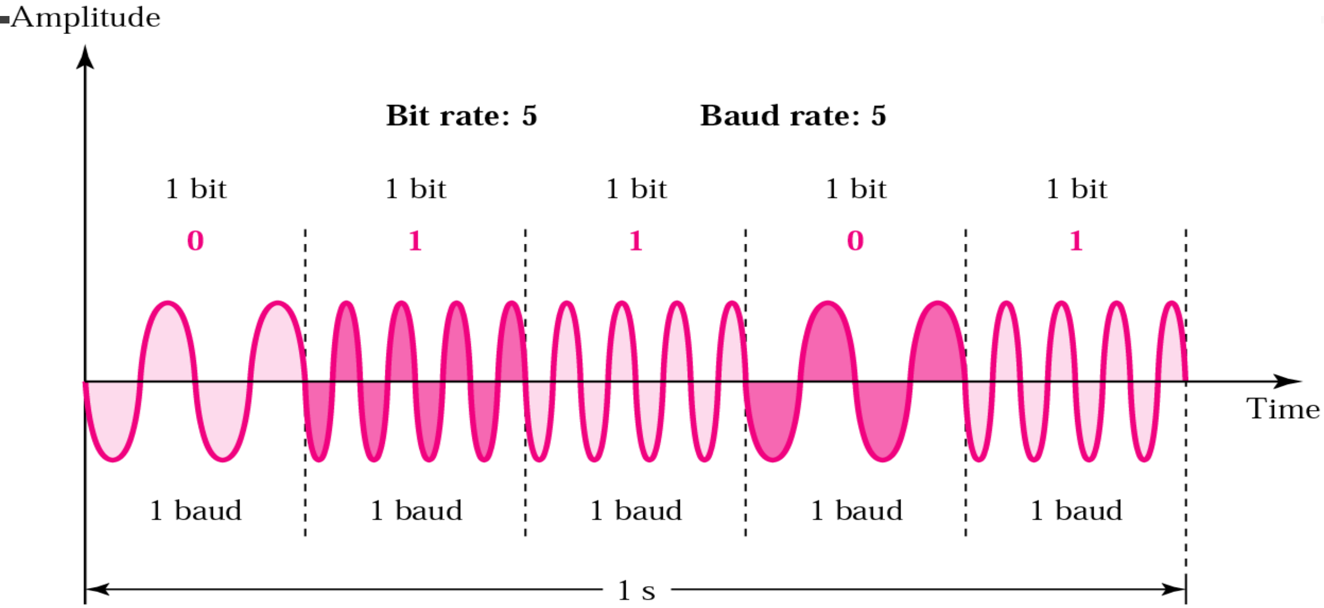
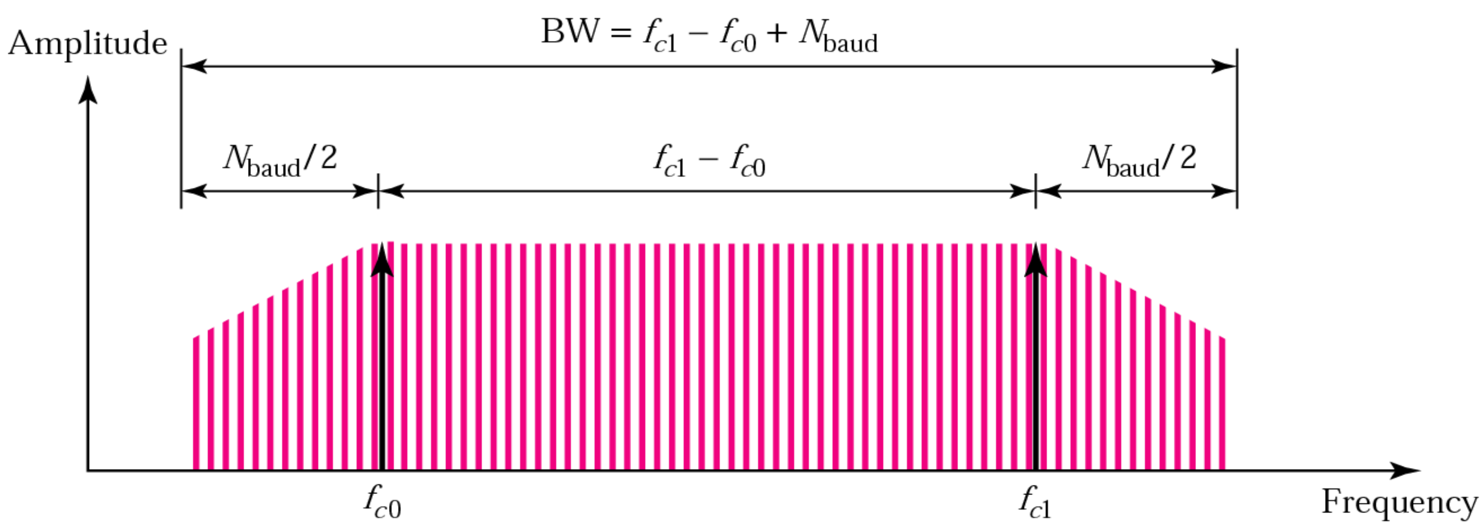


Figure 7 *Relationship between baud rate and bandwidth in FSK*



Example 6

Find the minimum bandwidth for an FSK signal transmitting at 2000 bps. Transmission is in half-duplex mode, and the carriers are separated by 3000 Hz.

For FSK

$$BW = \text{baud rate} + f_{c1} - f_{c0}$$

BW = bit rate + fc1 – fc0 = 2000 + 3000 = 5000 Hz

Example 7

Find the maximum bit rates for an FSK signal if the bandwidth of the medium is 12,000 Hz and the difference between the two carriers is 2000 Hz. Transmission is in full-duplex mode.

Because the transmission is full duplex, only 6000 Hz is allocated for each direction.

BW = baud rate + fc1 – fc0

Baud rate = BW – (fc1 – fc0) = 6000 – 2000 = 4000

But because the baud rate is the same as the bit rate, the bit rate is 4000 bps.

Phase Modulation methods - PSK

An M-ary PSK signals has phase shift ϕ_k in the time interval $kD < t < (k+1)D$

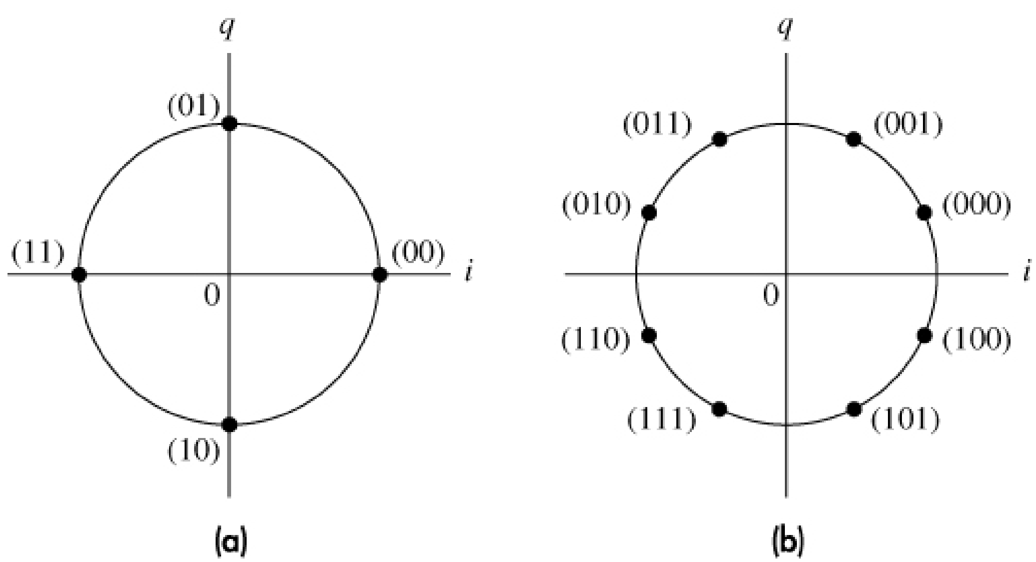
$$x_c(t) = A_c \sum_k \cos(\omega_c t + \theta + \phi_k) p_D(t - kD)$$

$$x_i(t) = \sum_k I_k p_D(t - kD) \qquad x_q(t) = \sum_k Q_k p_D(t - kD)$$

$$I_k = \cos\phi_k \qquad Q_k = \sin\phi_k$$

$$\phi_k = \pi(2a_k + N)/M \qquad a_k = 0, 1, \ldots, M-1$$

N=0 or 1

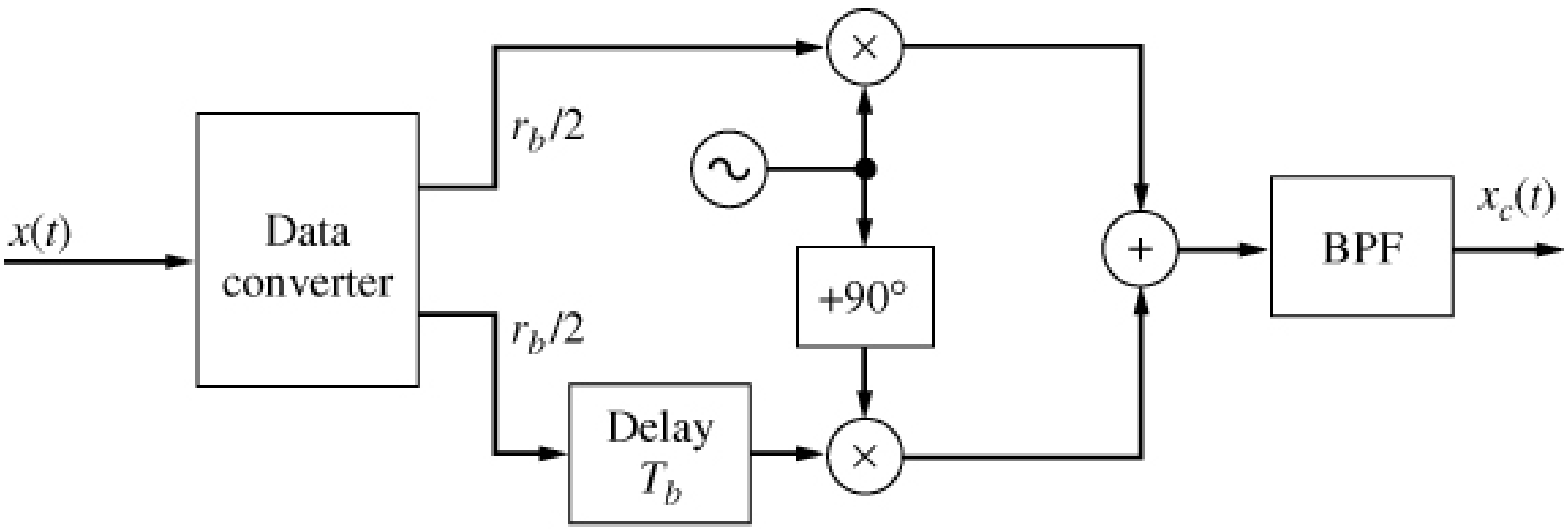


PSK signal constellations (a) *M*=4 (b) *M*=8

PSK spectral analysis

$$\overline{I_k} = \overline{Q_k} = 0 \qquad \overline{I_k^2} = \overline{Q_k^2} = 1/2 \qquad \overline{I_k Q_j} = 0$$

$$G_{\ell p}(f) = 2 \times \frac{r}{2} |P_D(f)|^2 = \frac{1}{r} \operatorname{sinc}^2 \frac{f}{r}$$



Offset-keyed QPSK transmitter

Figure 8 ***PSK***

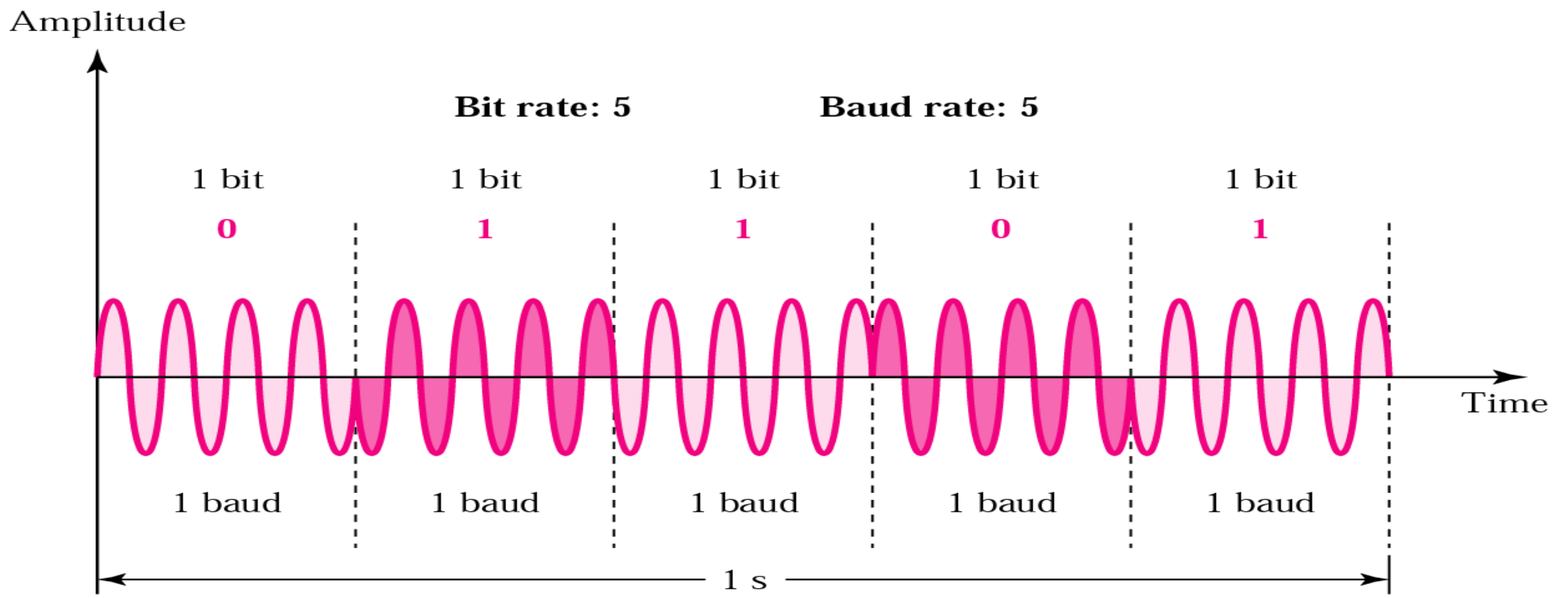
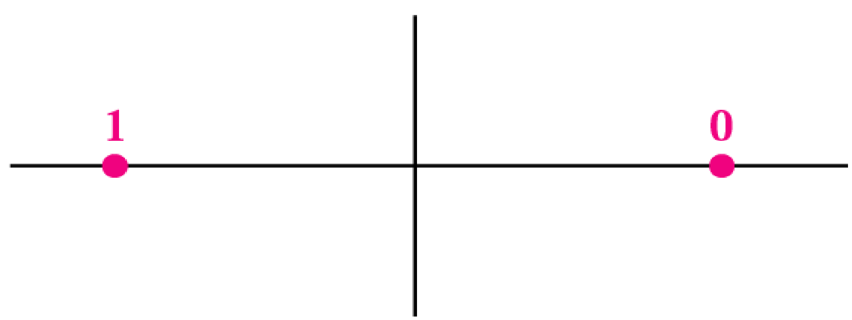


Figure 6.9 ***PSK constellation***

Bit	Phase
0	0
1	180

Bits



Constellation diagram

Figure 10 *The 4-PSK method*

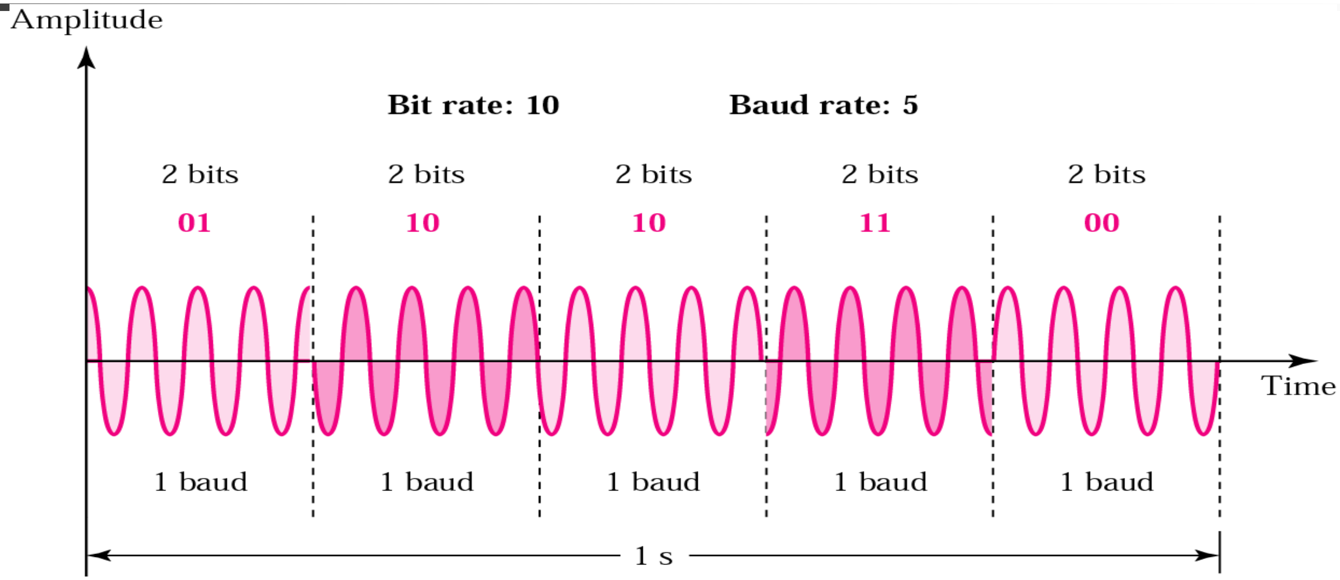
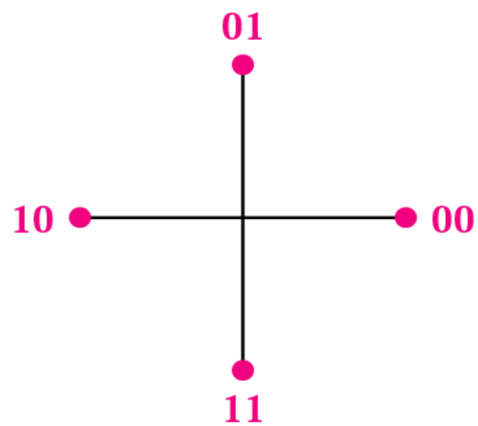


Figure 11 *The 4-PSK characteristics*

Dibit	Phase
00	0
01	90
10	180
11	270

Dibit
(2 bits)

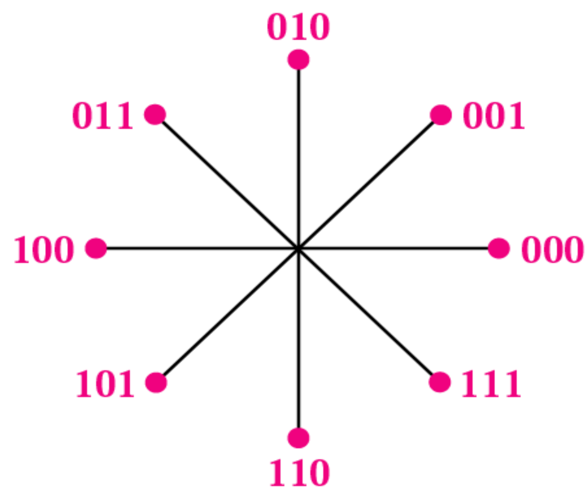


Constellation diagram

Figure 12 **The 8-PSK characteristics**

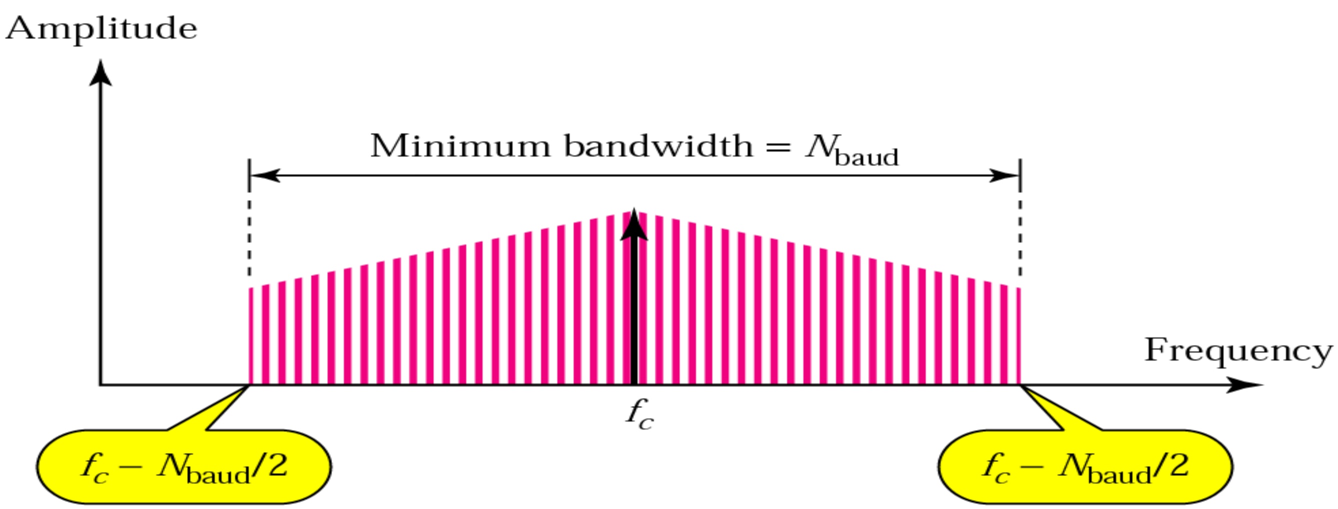
Tribit	Phase
000	0
001	45
010	90
011	135
100	180
101	225
110	270
111	315

Tribits
(3 bits)



Constellation diagram

Figure 13 ***Relationship between baud rate and bandwidth in PSK***



Example 8

Find the bandwidth for a 4-PSK signal transmitting at 2000 bps. Transmission is in half-duplex mode.

For PSK the baud rate is the same as the bandwidth, which means the bandwidth is 1000 equal to the baud rate.

Example 9

Given a bandwidth of 5000 Hz for an 8-PSK signal, what are the baud rate and bit rate?

For PSK the baud rate is the same as the bandwidth, which means the baud rate is 5000. But in 8-PSK the bit rate is 3 times the baud rate, so the bit rate is 15,000 bps.

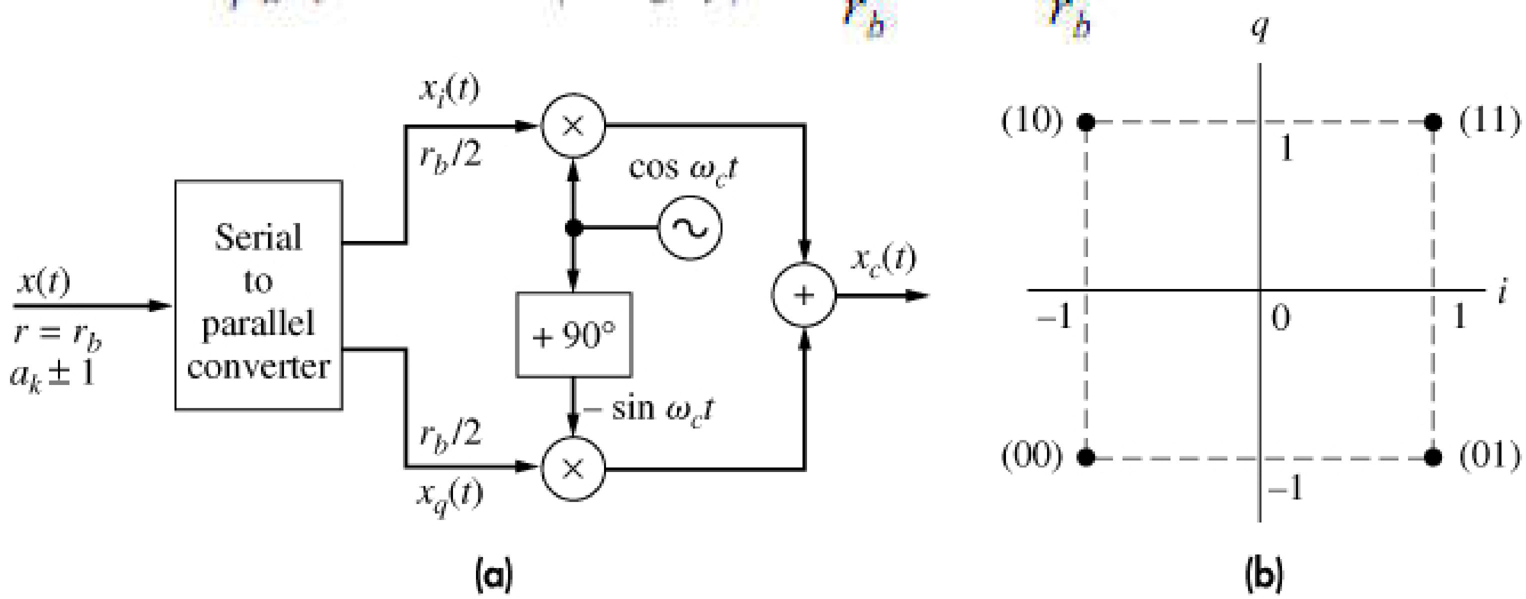
Quadrature carrier AM - QAM

$$x_i(t) = \sum_k a_{2k}\, p_D(t - kD) \qquad x_q(t) = \sum_k a_{2k+1}\, p_D(t - kD)$$

Where D=1/r=2T_b and a_k=+1 or -1, then r=r_b/2 and B_T=r_b/2

The i and q components are independent but having the same shape

$$G_{\ell p}(f) = 2 \times r\,|P_D(f)|^2 = \frac{4}{r_b}\,\mathrm{sinc}^2\,\frac{2f}{r_b}$$



Binary QAM (a) transmitter (b) signal constellation

Note:

Quadrature amplitude modulation is a combination of ASK and PSK so that a maximum contrast between each signal unit (bit, dibit, tribit, and so on) is achieved.

Figure 14 *The 4-QAM and 8-QAM constellations*

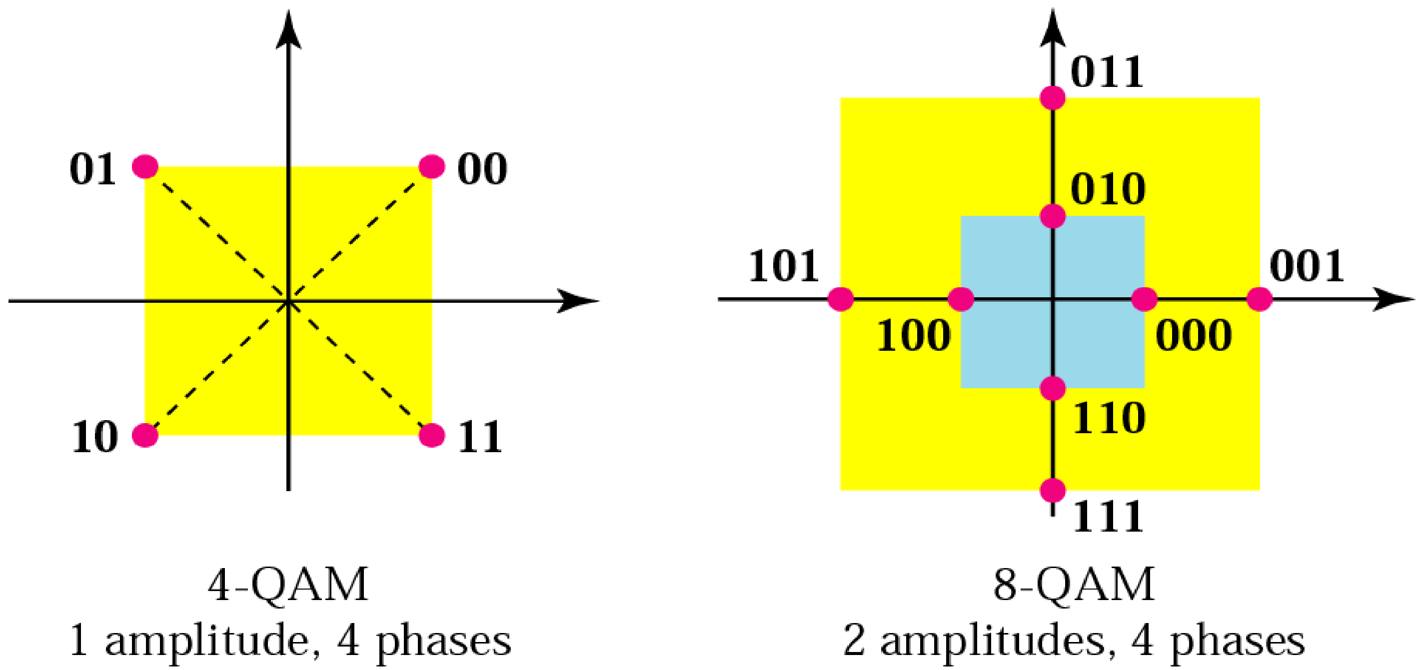


Figure 15 *Time domain for an 8-QAM signal*

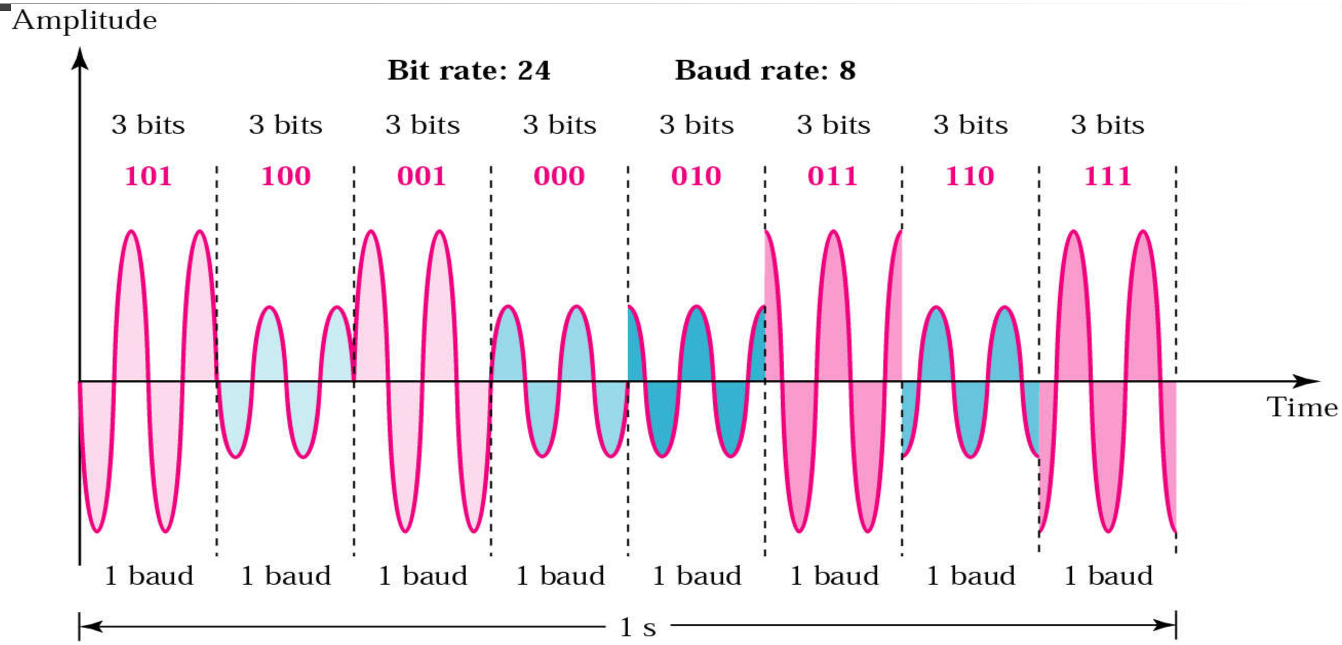


Figure 16 *16-QAM constellations*

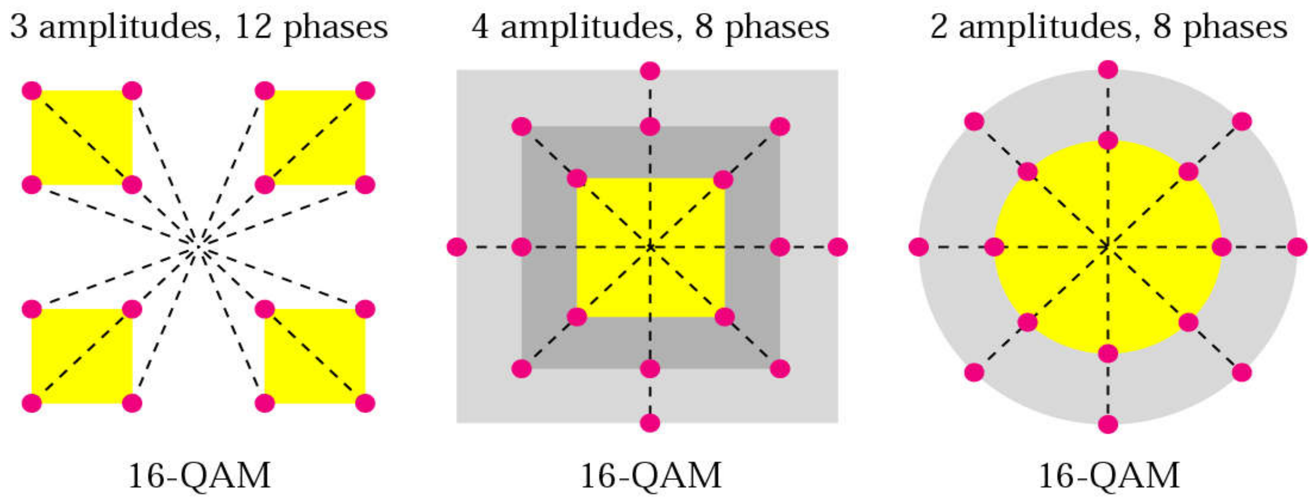


Figure 17 *Bit and baud*

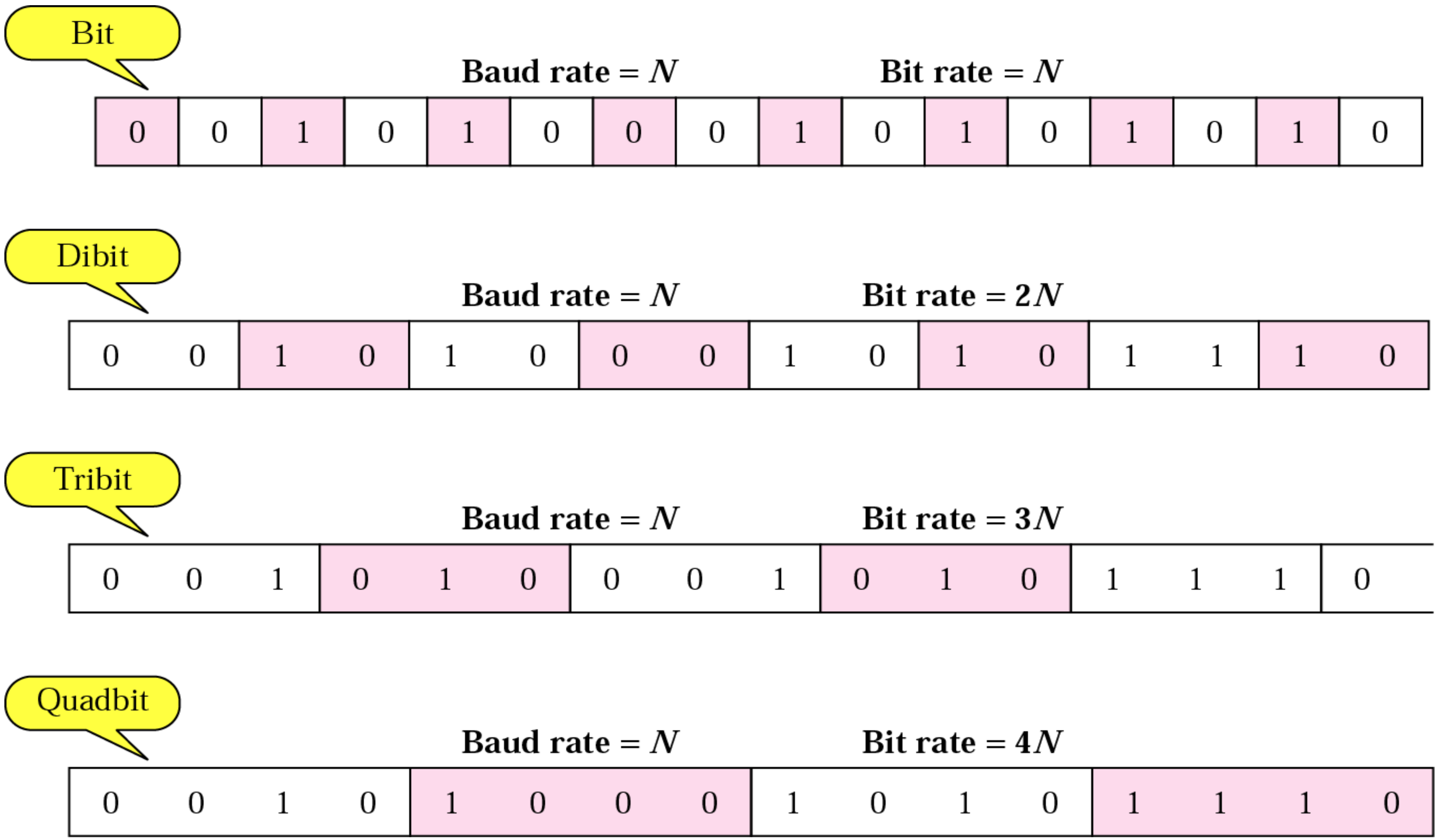


Table 1 Bit and baud rate comparison

Modulation	Units	Bits/Baud	Baud rate	Bit Rate
ASK, FSK, 2-PSK	Bit	1	N	N
4-PSK, 4-QAM	Dibit	2	N	2N
8-PSK, 8-QAM	Tribit	3	N	3N
16-QAM	Quadbit	4	N	4N
32-QAM	Pentabit	5	N	5N
64-QAM	Hexabit	6	N	6N
128-QAM	Septabit	7	N	7N
256-QAM	Octabit	8	N	8N

Example 10

A constellation diagram consists of eight equally spaced points on a circle. If the bit rate is 4800 bps, what is the baud rate?

The constellation indicates 8-PSK with the points 45 degrees apart. Since $2^3 = 8$, 3 bits are transmitted with each signal unit.
Therefore, the baud rate is

$$4800 / 3 = 1600 \text{ baud}$$

Example 11

Compute the bit rate for a 1000-baud 16-QAM signal.

A 16-QAM signal has 4 bits per signal unit since

$$\log_2 16 = 4.$$

Thus,

$$(1000)(4) = 4000 \text{ bps}$$

2 Telephone Modems

A telephone line has a bandwidth of almost 2400 Hz for data transmission.

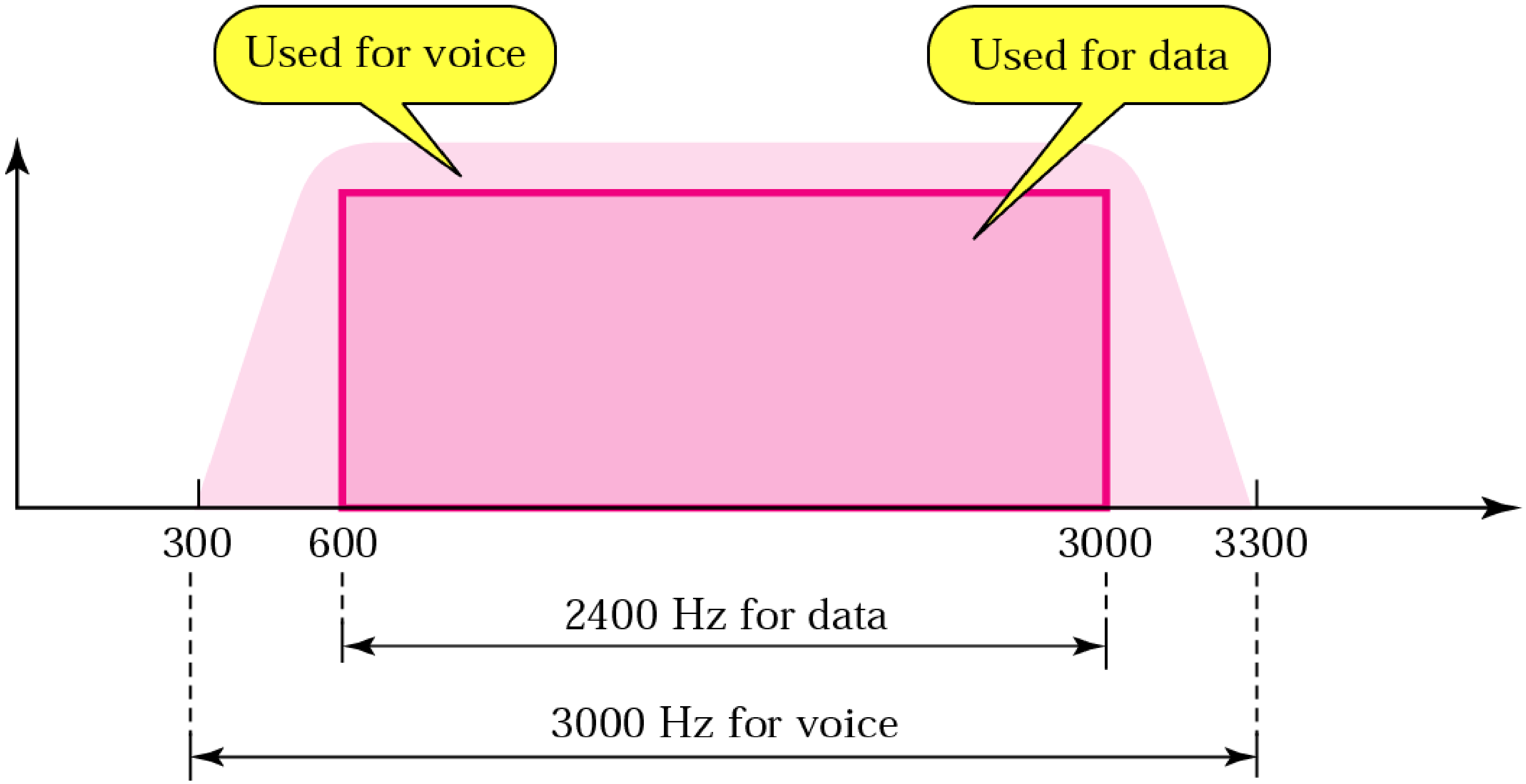


Figure 18 *Telephone line bandwidth*

Modem stands for modulator/demodulator.

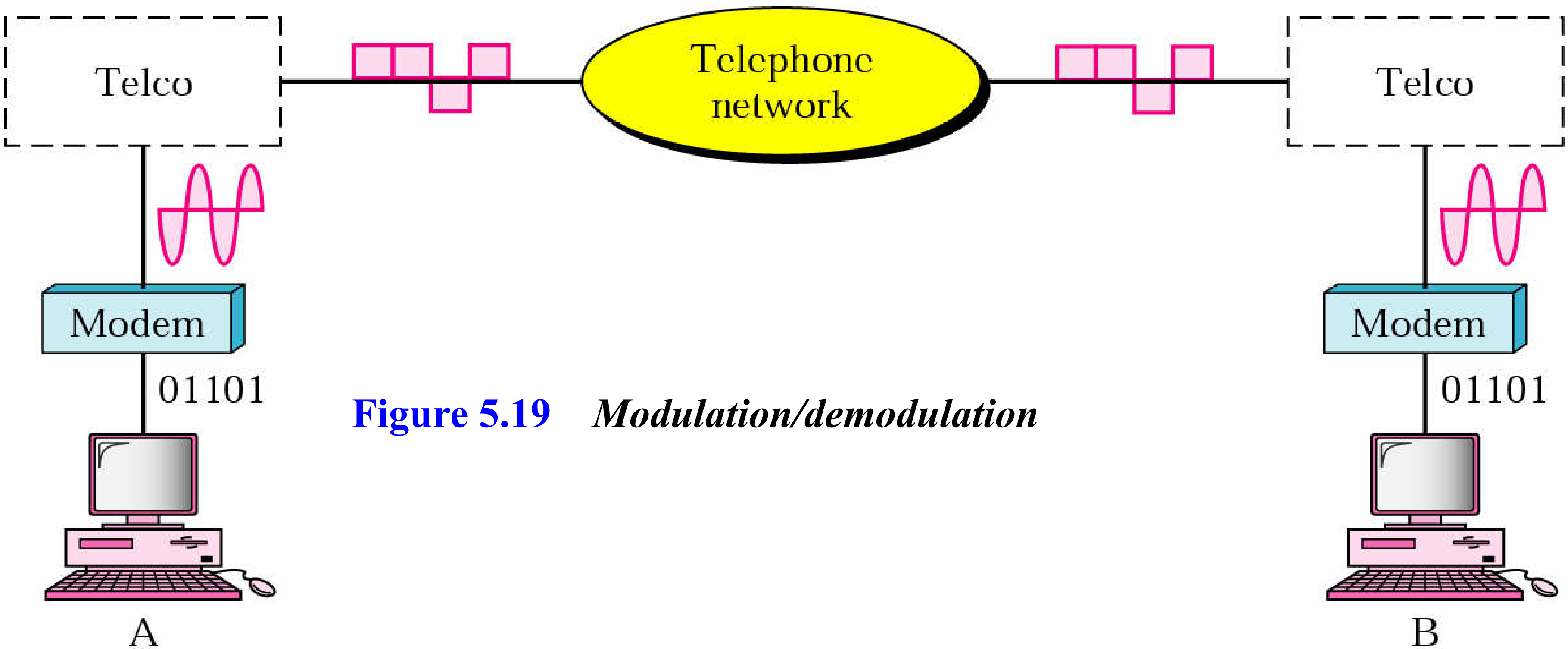


Figure 5.19 ***Modulation/demodulation***

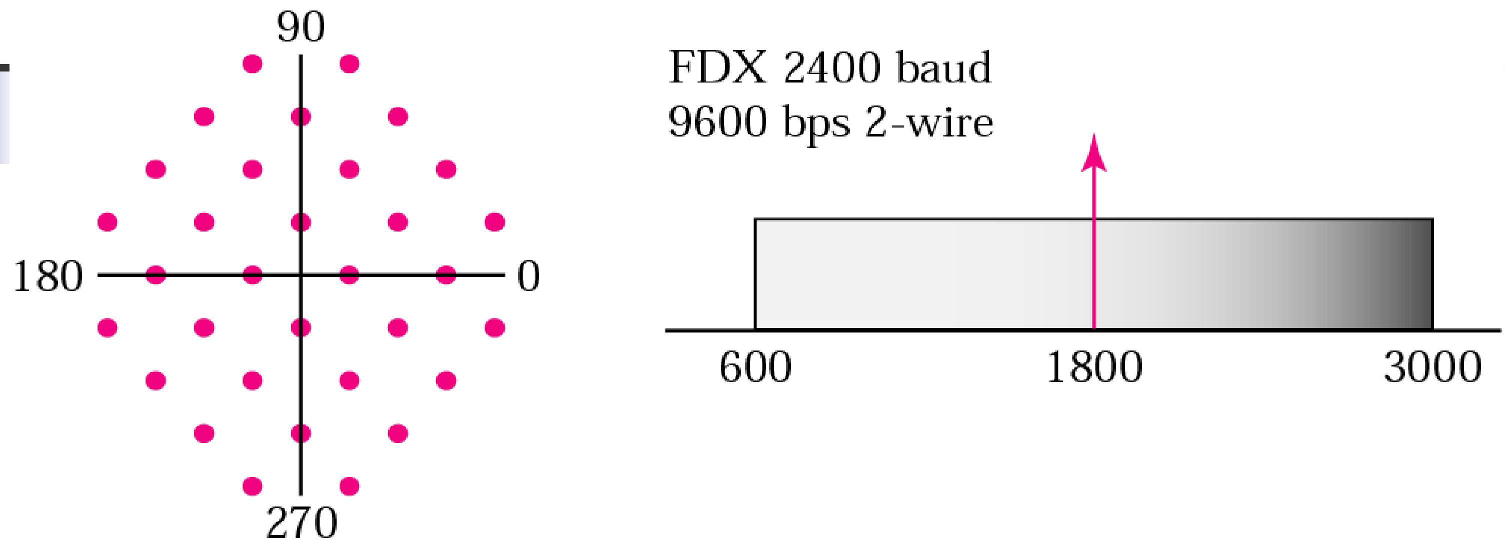


Figure 20 ***The V.32 constellation and bandwidth***

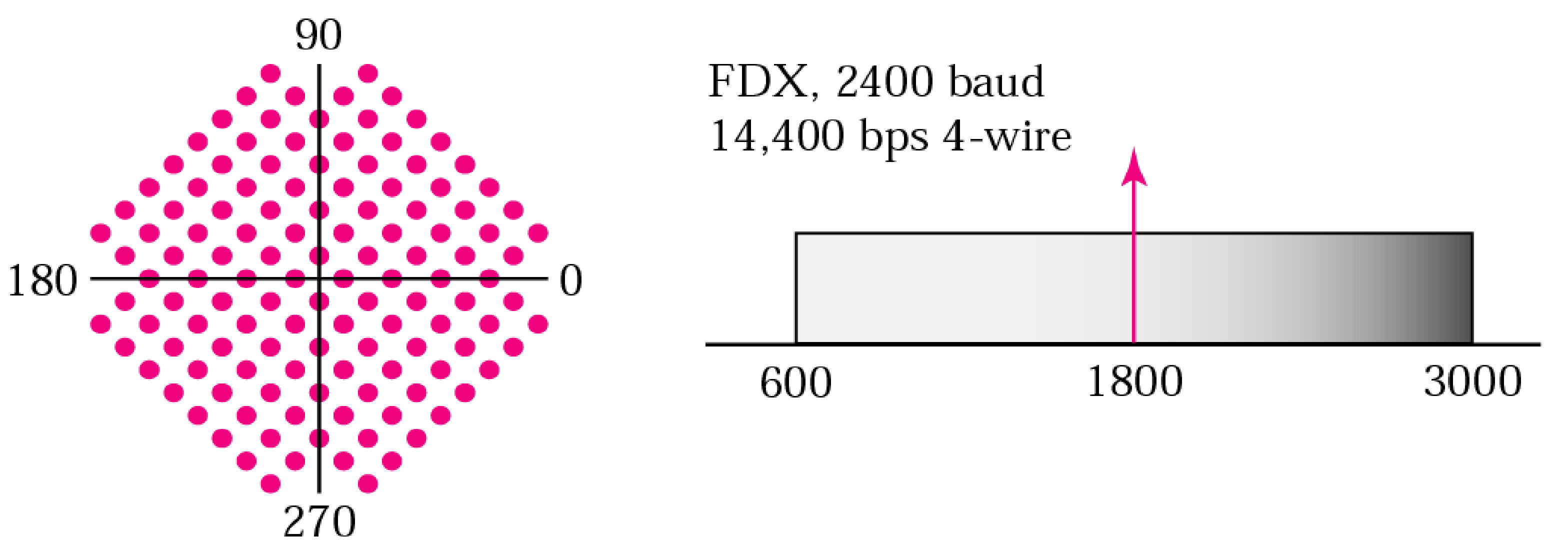


Figure 21 ***The V.32bis constellation and bandwidth***

Figure 22 *Traditional modems*

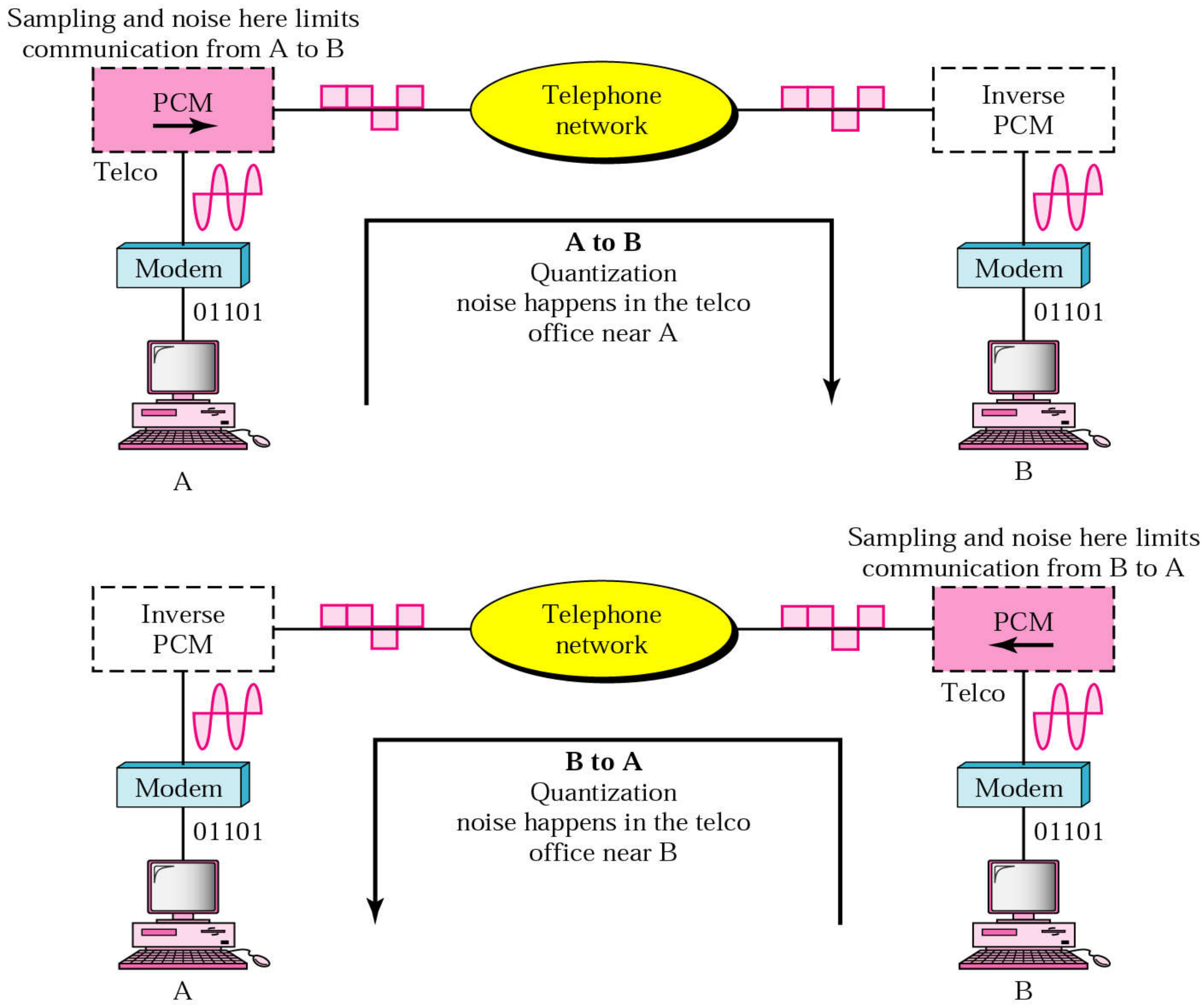


Figure 23 *56K modems*