Binary Modulated Bandpass Signals
(5-9 in text)

EELE445-13

Lecture 35

EELE445 Exam 2

- Exam Monday April 14th
- One 8x11page-both sides,
- 10 questions, 10 points per question, divided among 4-5 problems

Exam 2 EELE445

The exam will concentrate on lectures 17-32 and homework 5-7.

• Be sure to review and understand the Homework problems. The exam questions center on the material covered by the homework.

•Review the example problems worked in class

•Concepts highlighted in green or blue on the slides.

The following slides are indicative of the areas that will be covered on the exam,
BUT ARE NOT ALL INCLUSIVE!

TOPICS- exam 2

- **Review of Signals and Spectra**
- **Analysis and Transmission of Signals**
- **Sampling and pulse code modulation**
- **Principles of Digital Baseband Signals**
- **Bandpass Signaling Principles and Circuits**
- **Bandpass Modulated Systems-DSB_SC,AM,PM/FM**
- **Simple Digital Systems- OOK, FSK, PSK**
- **Introduction to the theory of probability**
- **Analog systems in the presence of noise**
- **Behavior of digital systems in the presence of noise**
- **Error correcting codes**
- **Example systems**

Exam 2 TOPICS

- **Line Codes 3-4**
  - Multi-level signaling 3-4
  - Line codes 3-5 fig 3-15
    - types
    - power spectra for Unipolar, polar, NRZ, RZ eq 3-36a, fig 3-16
    - Differential Coding fig 3-17
    - multi-level power spectra for Polar NRZ eq3-53
    - ISI and Raised Cosine-Rolloff filter
- **Bandpass Signals**
  - Complex Envelope g(t) –
    - relationship to s(t)
    - polar and rect forms
    - voltage and power spectrums
    - form for DSB-SC, SSB, AM, PM/FM
  - AM
    - envelope, modulation index, bandwidth
    - power-sideband, carrier, PEP, modulation efficiency
    - detection or demodulation
  - FM
    - sinewave spectrum- voltage and power using Bessel functions
    - Carson's Rule
- **Superhet Receiver- review the lab on the AM radio**
  - Image, IF, RF, Mixers, AGC, envelope detection,
- **Simple digital systems- OOK, FSK, PSK**

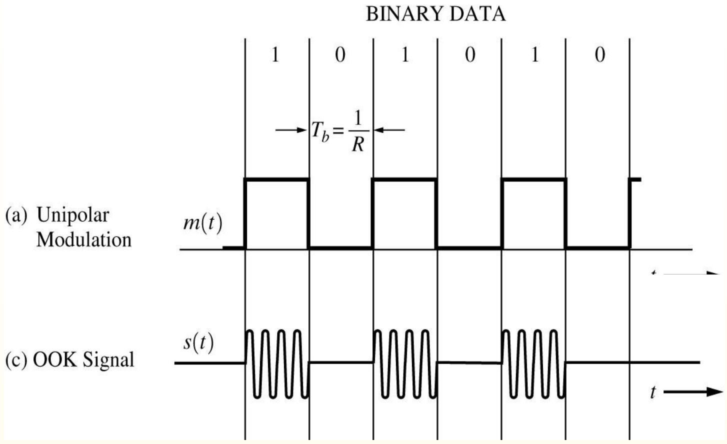
Simple Binary Bandpass Signals: 1-bit per symbol

- ASK- amplitude shift keying, OOK- on-off keying
- BPSK- Bi-phase Shift Keying
- FSK- Frequency Shift Keying
- MSK- Minimum Shift Keying
- GSMK- Gaussian pulse MSK

Binary Signals: OOK On-Off Keying

- Also called ASK - Amplitude Shift Keying
- DSB-SC with a unipolar binary line code
- Simple electronics to produce
- Morse code is OOK
- Simple envelope detection may be employed

Figure 5–19 Bandpass digitally modulated signals.



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Binary Signals: OOK, On-Off Keying

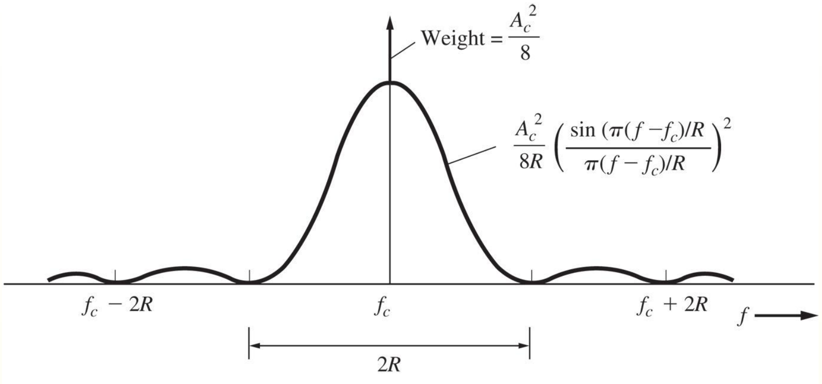
$$s(t) = A_c m(t)\cos(\omega_c t)$$ DSB-SC

$$g(t) = A_c m(t)$$ m(t) a NRZ unipolar code (3-39b)

From the text :

$$P_g(f) = \frac{A_c^2}{2}\left[\delta(f) + T_b\left(\frac{\sin \pi f T_b}{\pi f T_b}\right)^2\right]$$

Figure 5–20 PSD of bandpass digital signals (positive frequencies shown).



(a) OOK

see: eq 5-72, 3-39b and note $R=1/T_b$

Binary Signals: OOK with raised cosine-rolloff filtering for bandwidth and ISI control

null to null bandwidth : $B_T = 2R$

absolute bandwidth : $B_T = \infty$

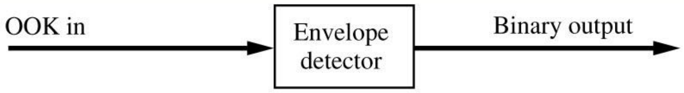
with raised cos filtering, from (eq 3 - 74) :

$$B = \frac{1}{2}(1+r)R \text{ (linecode BW)}$$

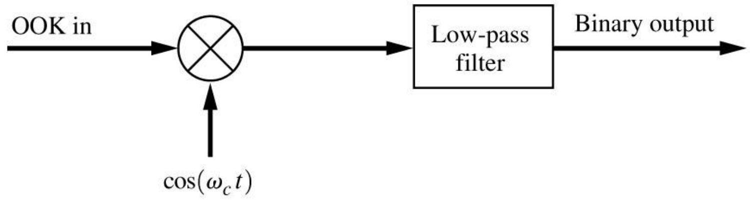
R is the bit Rate

r is the roll off factor for bandwidth control

then : $B_T = 2B = (1+r)R$



(a) Noncoherent Detection



(b) Coherent Detection with Low-Pass Filter Processing

Figure 5–21 Detection of OOK.

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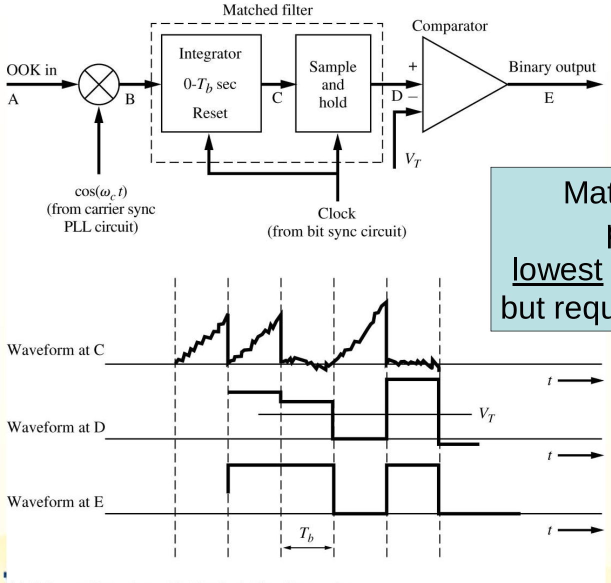
Figure 5–21 Matched Detection of OOK.



(c) Coherent Detection with Matched Filter Processing

Matched Detection provides the <u>lowest</u> BER (bit error rate) but requires more hardware

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Binary Signals: BPSK-Binary Phase Shift Keying

- The phase of the carrier is shifted +/-θ degrees
  - most common is +/-π/2
- The line code may take two forms
  - PM with unipolar line code for 0 or θ phase (not common)
  - PM with Polar line code for +/- θ phase (symmetrical phase shift from unmodulated carrier)
  - DSB-SC with a Polar line code, θ=+90, -90 degrees
- Simple electronics to produce
- Requires a form of synchronous demodulation unless DPSK is used

Binary Signals: BPSK- Binary Phase Shift Keying

$s(t) = A_c \cos\left\lfloor \omega_c t + D_p m(t) \right\rfloor$ m(t) Polar line code

expanding :

$$s(t) = A_c \cos(D_p m(t)) \cos(\omega_c t) - A_c \sin(D_p m(t)) \sin(\omega_c t)$$

$m(t) = + - 1$ and cos is even, sin odd :

$$s(t) = (A_c \cos D_p) \cos(\omega_c t) - (A_c \sin D_p) m(t) \sin(\omega_c t)$$

Pilot Carrier term data term

define *<u>digital modulation index</u>* : $h = \frac{2\Delta\theta}{\pi}$ *where* $\Delta\theta = D_p$

Binary Signals: BPSK- Binary Phase Shift Keying

$$s(t) = (A_c \cos D_p) \cos(\omega_c t) - (A_c \sin D_p) m(t) \sin(\omega_c t)$$

Pilot Carrier term data term

Notice : if $D_p = \frac{n\pi}{2}$ then all the power is in the data term :

pilot $= 0$ when $h = 1,2,3....$

define digital modulation index : $h = \frac{2\Delta\theta}{\pi}$ *where* $\Delta\theta = D_p$

Binary Signals: BPSK- Binary Phase Shift Keying

$$s(t) = A_c \cos\left[\omega_c t + D_p m(t)\right]$$

$$s(t) = (A_c \cos D_p)\cos(\omega_c t) - (A_c \sin D_p) m(t) \sin(\omega_c t)$$

$$...When\ \ h = 1, D_p = \frac{\pi}{2}:$$

$$s(t) = -A_c m(t) \sin \omega_c t$$

$g(t) = jA_c m(t)$ BPSK with m(t) $= \pm 1$ polar code

Using eq3 – 41,

$$P_g = A_c^2 T_b \left(\frac{\sin \pi f T_b}{\pi f T_b} \right)$$

Binary Signals: BPSK- Binary Phase Shift Keying

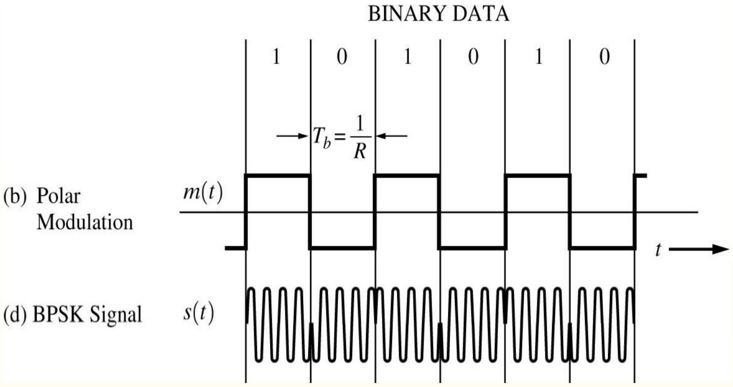
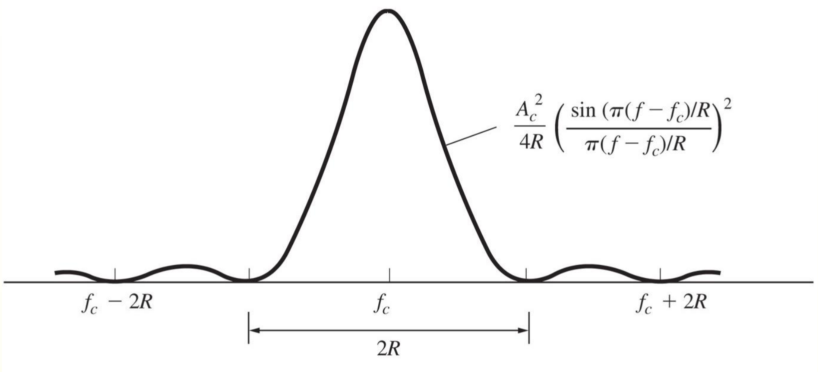


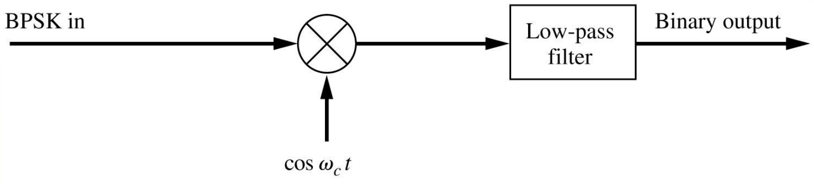
Figure 5–20 PSD of BPSK (positive frequencies shown).



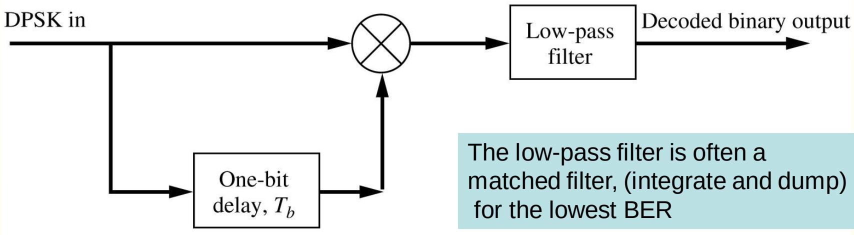
(b) BPSK (see Fig 5–15 for a more detailed spectral plot)

see: eq 5-79, 5-2b,3-41 and note R=1/T_b

Figure 5–22 Detection of BPSK and DPSK.



(a) Detection of BPSK (Coherent Detection)



The low-pass filter is often a matched filter, (integrate and dump) for the lowest BER

(b) Detection of DPSK (Partially Coherent Detection)

FSK- Frequency Shift Keying
MSK – Minimum Shift Keying
GMSK- Gaussian MSK

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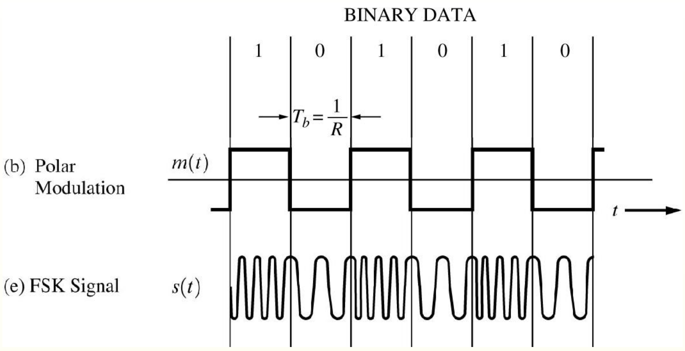
Lecture 34

Text Section 5-9,11

Binary Signals: BPSK- Binary Phase Shift Keying



Binary Signals: FSK - Frequency Shift Keying

- The Frequency of the carrier is shifted by Δf between sending binary 0 to binary 1
- FM signal line codes with 0-1 symmetry (polar etc) are used for the binary modulating signal
- FM demodulator: PLL, Ratio Detector, Foster Seeley Discriminator

$h \equiv \frac{2\Delta f}{R}$ the fm digital modulation constant or index

Δf is peak frequency deviation

R is the data rate in bits/sec

Figure 5–23 Generation of FSK.

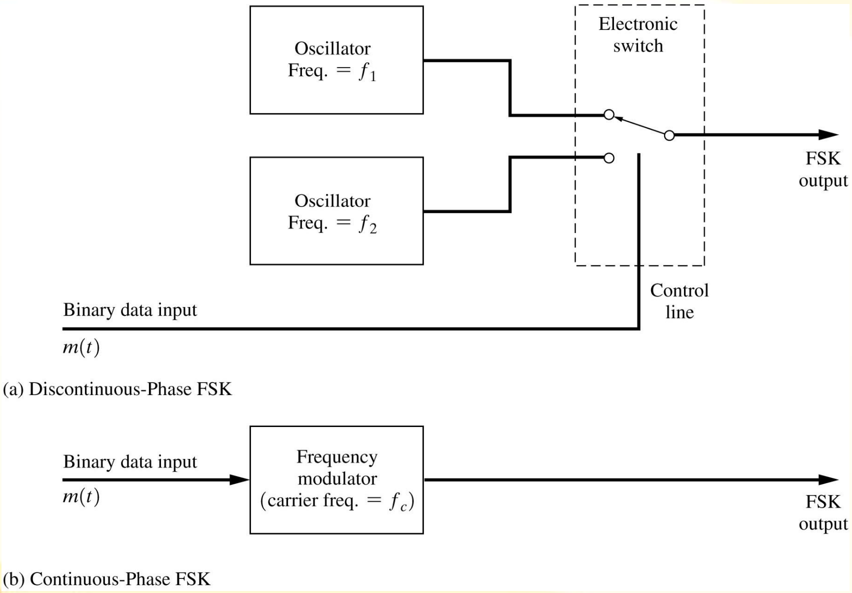


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Figure 5–24 Computer communication using FSK signaling.

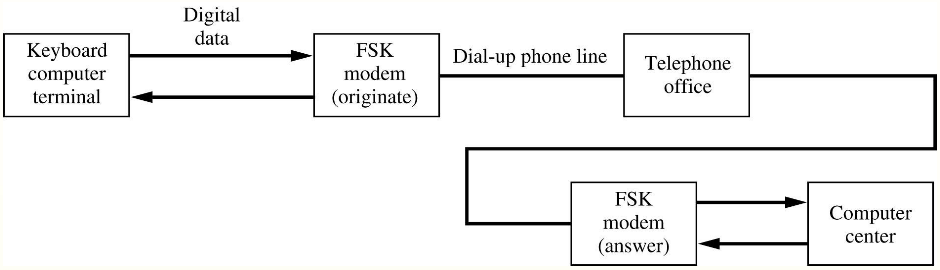

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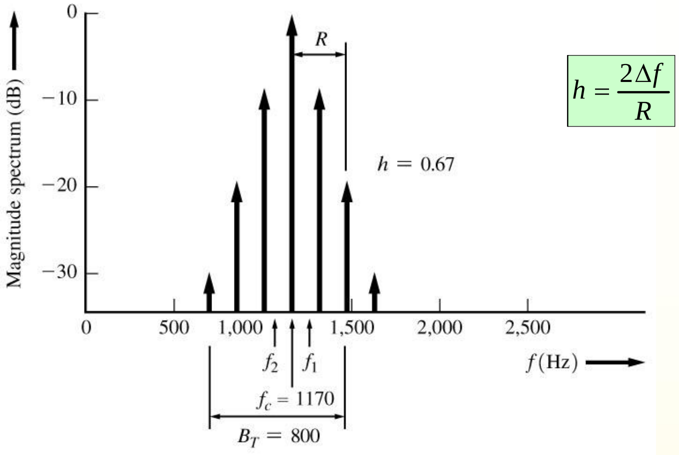
Figure 5–26 FSK spectra for alternating data modulation (positive frequencies shown with one-sided magnitude values).

$$h = \frac{2\Delta f}{R}$$



(a) FSK Spectrum with $f_2 = 1{,}070$ Hz, $f_1 = 1{,}270$ Hz, and $R = 300$ bits/sec (Bell 103 Parameters, Originate mode) for $h = 0.67$

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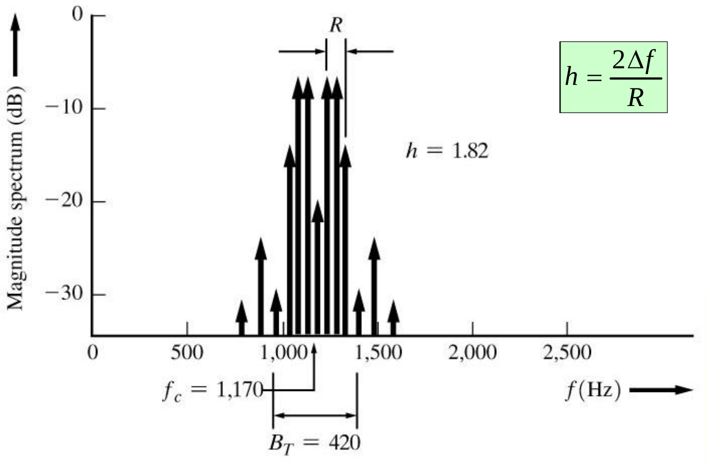
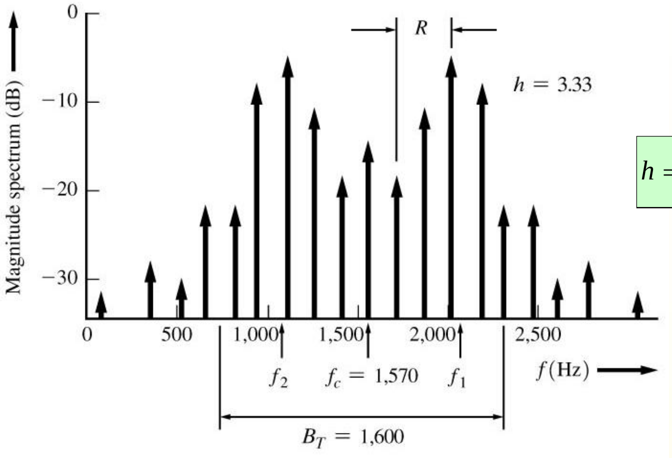
Figure 5–26 FSK spectra for alternating data modulation (positive frequencies shown with one-sided magnitude values).



(b) FSK Spectrum with $f_2 = 1{,}070$ Hz, $f_1 = 1{,}270$ Hz, and $R = 110$ bits/sec for $h = 1.82$

$$h = \frac{2\Delta f}{R}$$

Figure 5–26 FSK spectra for alternating data modulation (positive frequencies shown with one-sided magnitude values).



$$h = \frac{2\Delta f}{R}$$

(c) FSK Spectrum with $f_2 = 1{,}070$ Hz, $f_1 = 2{,}070$ Hz, and $R = 300$ bits/sec for $h = 3.33$

Figure 5–27 PSD for the complex envelope of FSK (positive frequencies shown).

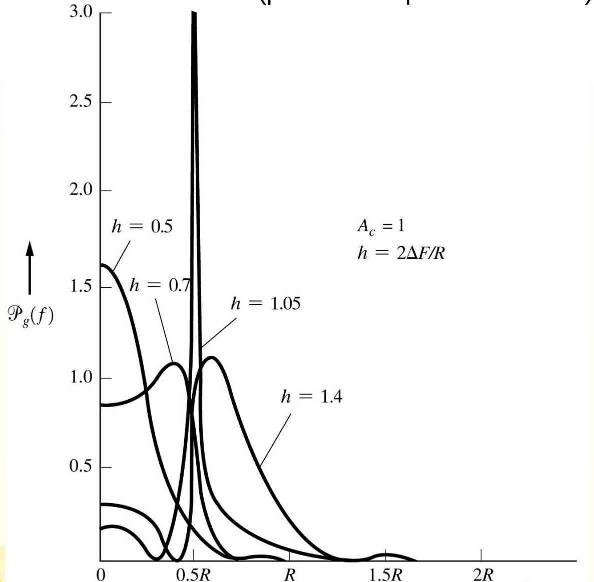
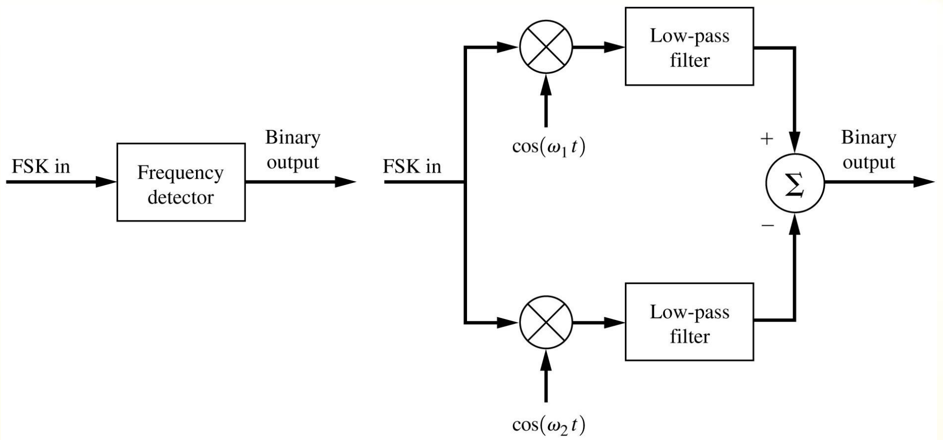


Figure 5–28 Detection of FSK.



(a) Noncoherent Detection

(b) Coherent (Synchronous) Detection

Binary Signals: MSK- Minimum Shift Keying

- MSK definition: *<u>Continuous-phase</u> FSK with a minimum modulation index (h=0.5) that will produce orthogonal signaling.* (see text for derivation)
- bandwidth conservation technique that has a constant envelope and low spectral side lobes
- Type 1 MSK pulse shape is alternating positive and negative half-cosinusoids. This reduces side-lobe amplitudes. Also called FFSK (fast frequency shift keying) when h=0.5
- When h>0.5, MSK is FSK with cosinusoidal pulses

$$h \equiv \frac{2\Delta f}{R}$$ the fm digital modulation constant or index

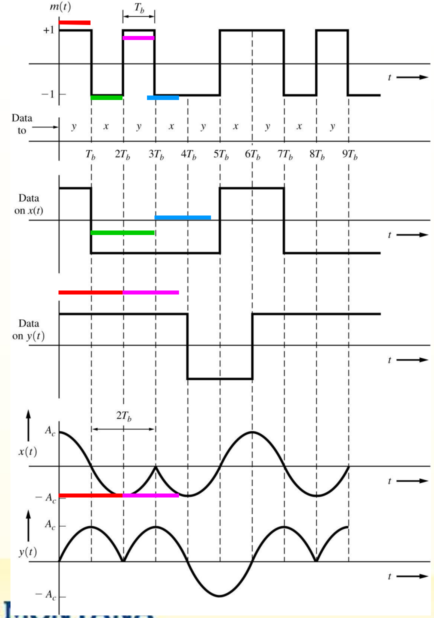
Δf is peak frequency deviation

R is the data rate in bits/sec

MSK, GMSK- Minimum-Shift Keying

- these are a type of M=4 modulation
- equivalent to OQPSK with sinusoidal pulse shaping
- Type 1 MSK- pulse is always pos ½ sinusoid
- Type 2 MSK- pulse alternates +/- amplitude ½ sinusoid.
- GMSK is MSK with Gaussian pulses

Figure 5–34 MSK quadrature component waveforms (Type II MSK).



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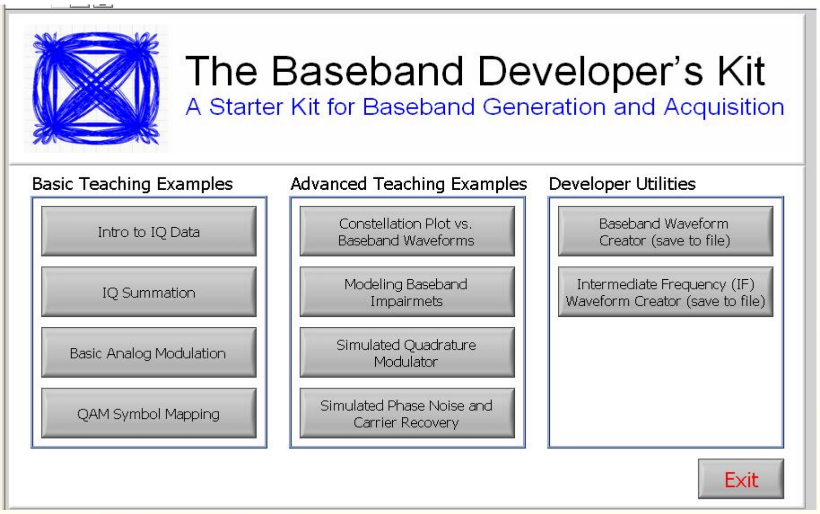
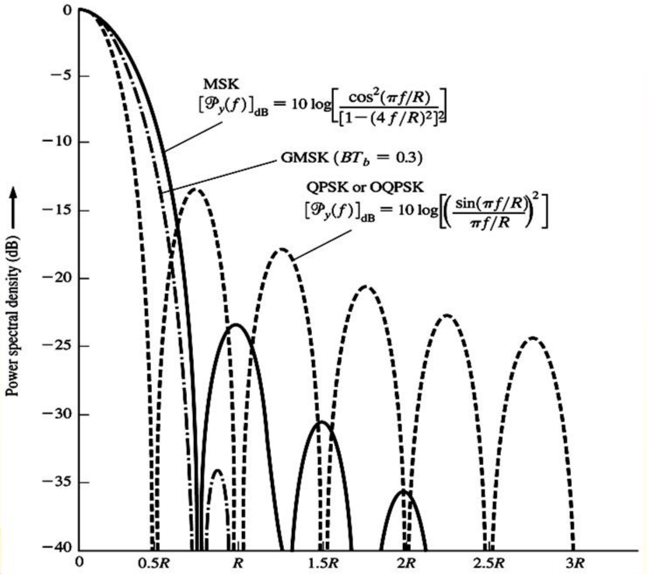
Signal examples using National Instruments:



This software (81Mb) is free at
https://decibel.ni.com/content/groups/rf-developers-network/blog/2008/11/17/baseband-developers-kit

Figure 5–35 PSD for complex envelope of MSK, GMSK, QPSK, and OQPSK, where *R* is the bit rate (positive frequencies shown).



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5-10 Multilevel Modulated Bandpass Signaling

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Lecture 35

Complex Envelope

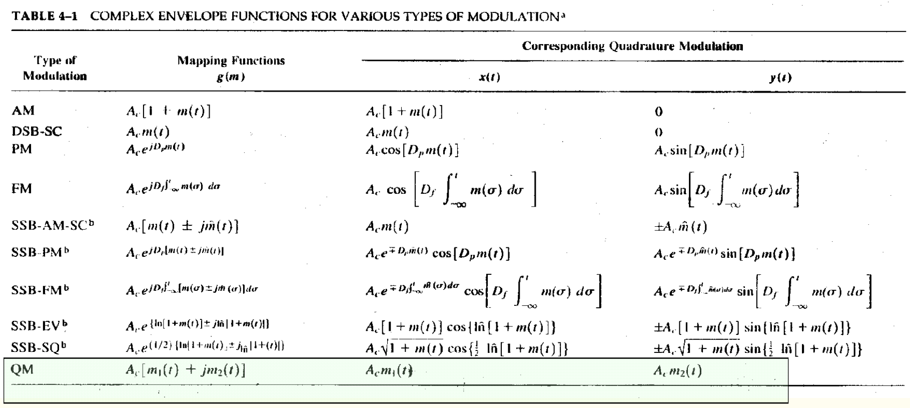


TABLE 4–1 COMPLEX ENVELOPE FUNCTIONS FOR VARIOUS TYPES OF MODULATION[a]

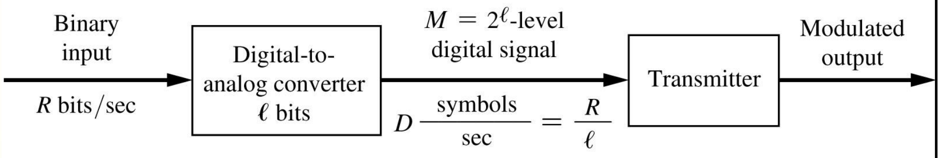
Type of Modulation	Mapping Functions $g(m)$	Corresponding Quadrature Modulation	
		$x(t)$	$y(t)$
AM	$A_c[1+m(t)]$	$A_c[1+m(t)]$	0
DSB-SC	$A_c m(t)$	$A_c m(t)$	0
PM	$A_c e^{jD_p m(t)}$	$A_c \cos[D_p m(t)]$	$A_c \sin[D_p m(t)]$
FM	$A_c e^{jD_f \int_{-\infty}^{t} m(\sigma)\, d\sigma}$	$A_c \cos\left[D_f \int_{-\infty}^{t} m(\sigma)\, d\sigma\right]$	$A_c \sin\left[D_f \int_{-\infty}^{t} m(\sigma)\, d\sigma\right]$
SSB-AM-SC[b]	$A_c[m(t) \pm j\hat{m}(t)]$	$A_c m(t)$	$\pm A_c \hat{m}(t)$
SSB-PM[b]	$A_c e^{jD_p[m(t) \pm j\hat{m}(t)]}$	$A_c e^{\mp D_p \hat{m}(t)} \cos[D_p m(t)]$	$A_c e^{\mp D_p \hat{m}(t)} \sin[D_p m(t)]$
SSB-FM[b]	$A_c e^{jD_f \int_{-\infty}^{t}[m(\sigma) \pm j\hat{m}(\sigma)]d\sigma}$	$A_c e^{\mp D_f \int_{-\infty}^{t} \hat{m}(\sigma)d\sigma} \cos\left[D_f \int_{-\infty}^{t} m(\sigma)\, d\sigma\right]$	$A_c e^{\mp D_f \int_{-\infty}^{t} \hat{m}(\sigma)d\sigma} \sin\left[D_f \int_{-\infty}^{t} m(\sigma)\, d\sigma\right]$
SSB-EV[b]	$A_c e^{\{\ln[1+m(t)] \pm j\hat{\ln}\|1+m(t)\|\}}$	$A_c[1+m(t)] \cos\{\hat{\ln}[1+m(t)]\}$	$\pm A_c[1+m(t)] \sin\{\hat{\ln}[1+m(t)]\}$
SSB-SQ[b]	$A_c e^{(1/2)\{\ln[1+m(t)] \pm j\hat{\ln}\|1+(t)\|\}}$	$A_c\sqrt{1+m(t)} \cos\{\frac{1}{2}\hat{\ln}[1+m(t)]\}$	$\pm A_c\sqrt{1+m(t)} \sin\{\frac{1}{2}\hat{\ln}[1+m(t)]\}$
QM	$A_c[m_1(t) + jm_2(t)]$	$A_c m_1(t)$	$A_c m_2(t)$

Figure 5–29 Multilevel digital transmission system.

$$D = R_s = \frac{R_b}{\ell}$$ Symbol Rate

R_b Bit rate

note that symbol error rate is not the same as bit error rate since a symbol error may result in more than one bit error.



M = number of required waveform possibilities per T_s
R = is the binary bit rate
T_b = is the binary symbol duration
D = the symbol Rate
T_s = the symbol duration

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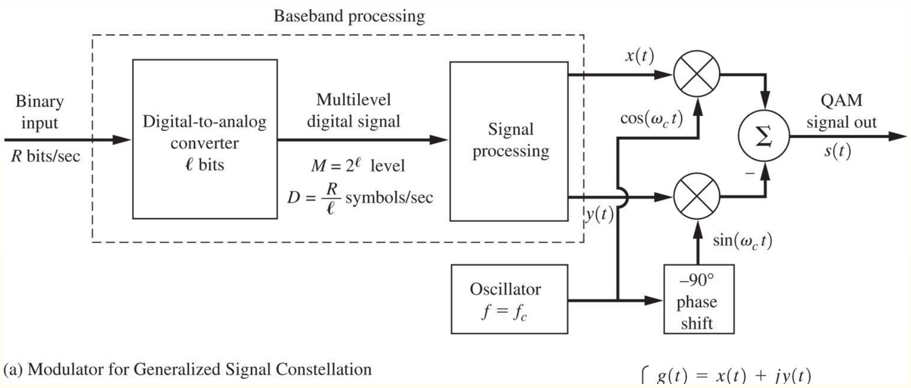
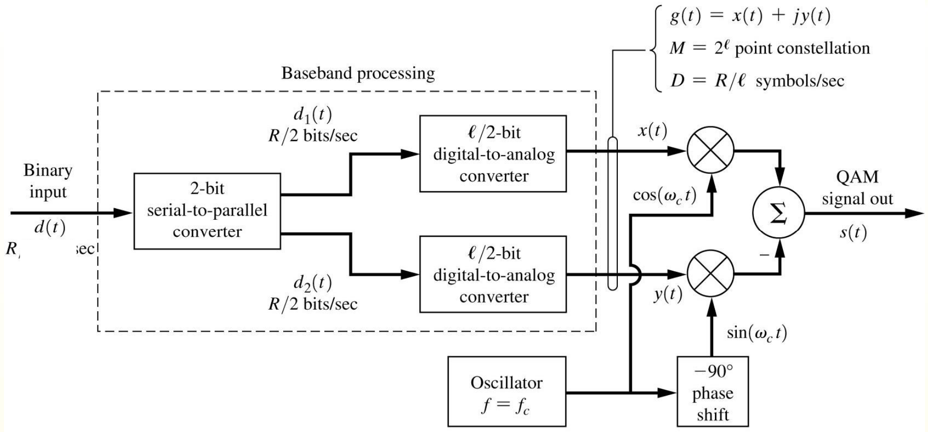
Figure 5–31 Generation of QAM signals.



(a) Modulator for Generalized Signal Constellation

Figure 5–31 Generation of QAM signals.



(b) Modulator for Rectangular Signal Constellation

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M=4- QPSK, OQPSK, and MPSK

- When M=4-level digital, M-ary phase shift keying is generated -MPSK.
- The complex envelope contains 4 points, one for each possible bit combination.
- This M-ary case is called Quadrature Phase Shift Keying- QPSK

M=4 QPSK, OQPSK, and MPSK

- OQPSK, Offset QPSK, the I and Q data streams are filtered and offset by ½ symbol. This reduces the magnitude of the envelope fluctuations.
- For MPSK with M>4, the possible states (symbols) are on a circle with a magnitude of A_c. All symbols have equal power, $<|g(t)|^2>$ is constant

M=4: QPSK, OQPSK, and MPSK

$$g(t) = A_c e^{j\theta(t)}$$

$$\Delta\theta = \frac{360}{M} \quad \text{for M} = 4,\ \Delta\theta = 90$$

possible sets are : $[0,90,180,270]$ $[45,135,225,315]$

Figure 5–30 QPSK and p/4 QPSK signal constellations (permitted values of the complex envelope).

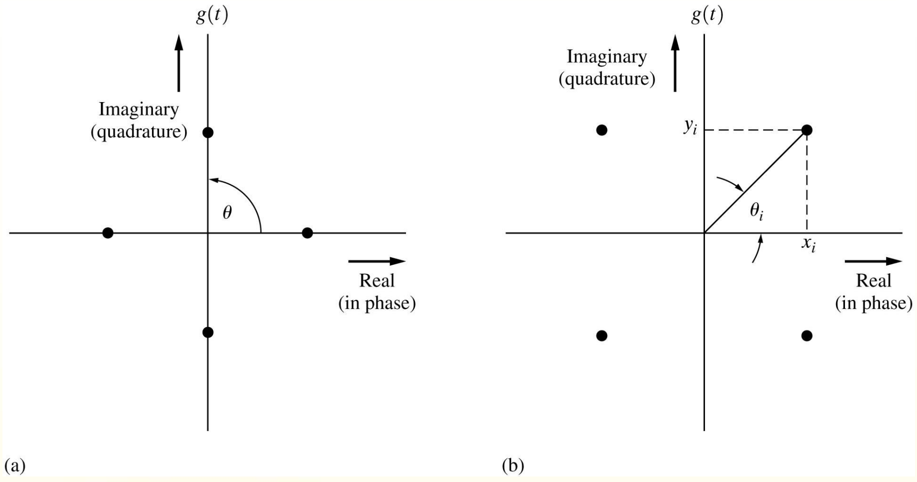
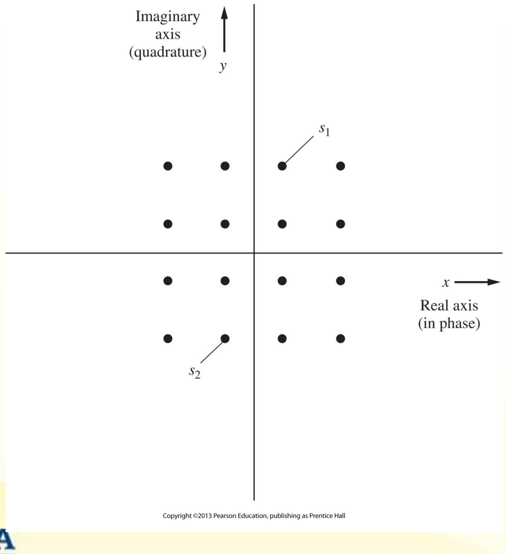


Figure 5–32 16-symbol QAM constellation (four levels per dimension).



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Multi-level: QAM and MPSK

$\underline{MPSK}: \; g(t) = Ae^{j\theta(t)} = A\cos(\theta(t)) + jA\sin(\theta(t))$

Possible values of $\theta(t)$: $\theta_m = \theta_0 + \frac{360}{M}m$

where m = 1..M is the m^{th} symbol correspond ing to the m^{th} bit pattern

$\underline{\text{QAM}}: \; g(t) = R(t)e^{j\theta(t)} = x(t) + jy(t)$

for retangular pulses the k^{th} symbol;

$$x_k(t) = A_k\Pi\left(\frac{t}{T_s}\right) \qquad A_k = -A + \frac{2A}{\frac{M}{2}-1}k \quad M = 2^l$$

A is the peak voltage of a zero or one for a polar line code

$l = 2$ for QPSK, $l = 4$ for 16QAM

TABLE 5–6 V.32 MODEM STANDARD

TABLE 5–6 V.32 MODEM STANDARD

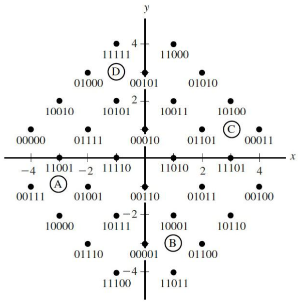
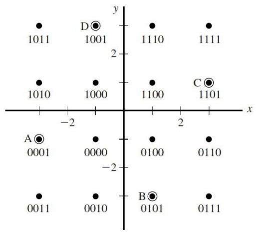
	Item	Signal Constellation
Data	Serial binary, Asynchronous or synchronous Full duplex over two-wire line[a]	*Option 2*: 32 QAM or QPSK 
Carrier frequency	Transmit[a]: 1,800 Hz Receive[a]: 1,800 Hz	
Option 1	9,600 b/s for high SNR	
DATA rate	4,800 b/s for low SNR	
Modulation	32 QAM, 2400 baud, for high SNR using trellis-coded modulation (see Fig. 1–9, where $n = 3$ and $m - k = 2$) with 4 data bits plus 1 coding bit per symbol QPSK, 2,400 baud (states A, B, C, D) for low SNR	

TABLE 5–6 (continued) V.32 MODEM STANDARD

TABLE 5–6 V.32 MODEM STANDARD

	Item	Signal Constellation
		Option 2: 16 QAM or QPSK 
Option 2		
. DATA rate	9,600 b/s for high SNR	
	4,800 b/s for low SNR	
Modulation	16 QAM, 2,400 baud, for high SNR	
	QPSK, 2,400 baud (states A, B, C, D) for low SNR	

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[a] A two-wire to four-wire hybrid is used in this modem to obtain the transmit and receive lines.

TABLE 5–7 V.32BIS AND V.33 MODEM STANDARDS

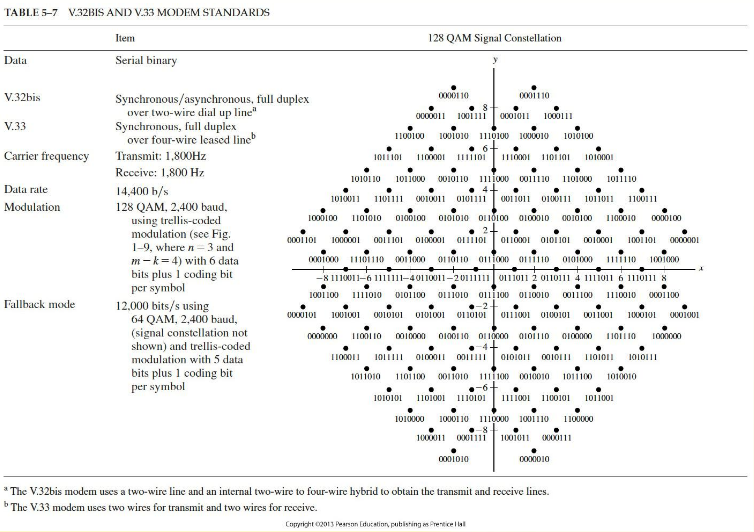

TABLE 5–7 V.32BIS AND V.33 MODEM STANDARDS

	Item	128 QAM Signal Constellation
Data	Serial binary	
V.32bis	Synchronous/asynchronous, full duplex over two-wire dial up line[a]	
V.33	Synchronous, full duplex over four-wire leased line[b]	
Carrier frequency	Transmit: 1,800Hz Receive: 1,800 Hz	
Data rate	14,400 b/s	
Modulation	128 QAM, 2,400 baud, using trellis-coded modulation (see Fig. 1–9, where $n = 3$ and $m - k = 4$) with 6 data bits plus 1 coding bit per symbol	
Fallback mode	12,000 bits/s using 64 QAM, 2,400 baud, (signal constellation not shown) and trellis-coded modulation with 5 data bits plus 1 coding bit per symbol	

[a] The V.32bis modem uses a two-wire line and an internal two-wire to four-wire hybrid to obtain the transmit and receive lines.

[b] The V.33 modem uses two wires for transmit and two wires for receive.

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data pulses, where

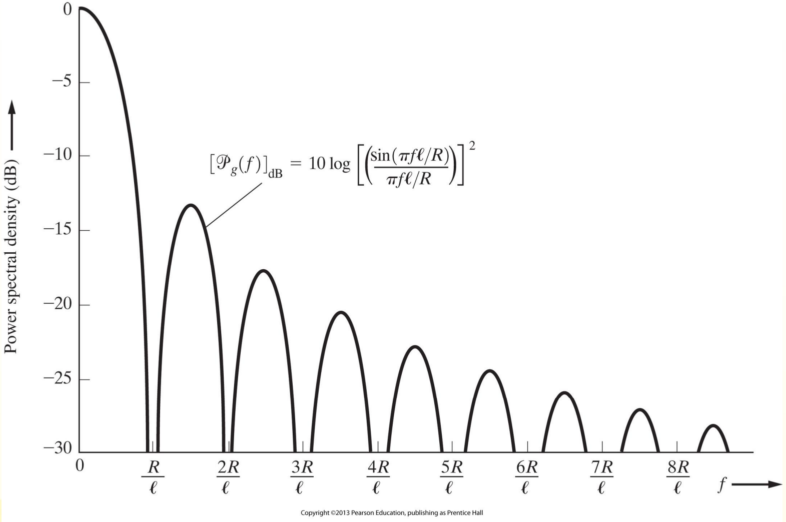
R is the bit rate, and

is the baud rate (positive

$R / \ell = D$

$\ell = 2$

$M = 2^{\ell}$



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EFFICIENCY FOR QAM SIGNALING WITH RAISED COSINE-ROLLOFF PULSE SHAPING (USE *M* = 4 for

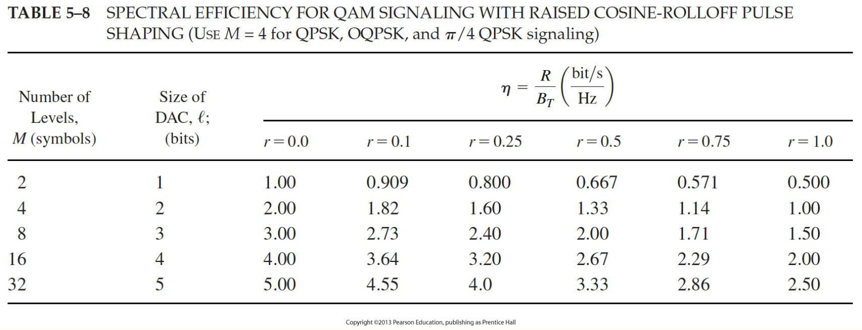
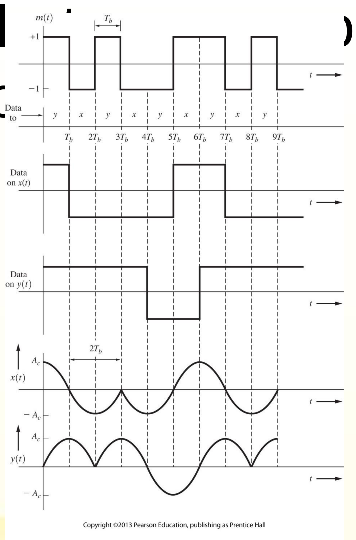


TABLE 5–8 SPECTRAL EFFICIENCY FOR QAM SIGNALING WITH RAISED COSINE-ROLLOFF PULSE SHAPING (USE $M = 4$ for QPSK, OQPSK, and $\pi/4$ QPSK signaling)

Number of Levels, M (symbols)	Size of DAC, ℓ; (bits)	$\eta = \frac{R}{B_T}\left(\frac{\text{bit/s}}{\text{Hz}}\right)$					
		$r = 0.0$	$r = 0.1$	$r = 0.25$	$r = 0.5$	$r = 0.75$	$r = 1.0$
2	1	1.00	0.909	0.800	0.667	0.571	0.500
4	2	2.00	1.82	1.60	1.33	1.14	1.00
8	3	3.00	2.73	2.40	2.00	1.71	1.50
16	4	4.00	3.64	3.20	2.67	2.29	2.00
32	5	5.00	4.55	4.0	3.33	2.86	2.50

Figure 5–34 MSK quad onent wavefo MSK).



complex envelope of MSK,
GMS PSK,
wh te
(positi own).

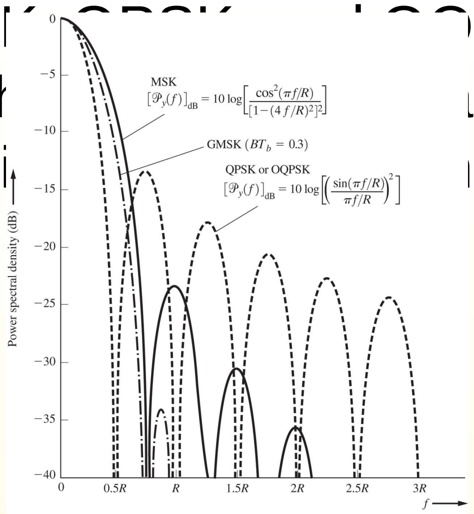


Figure 5–36 Generation of

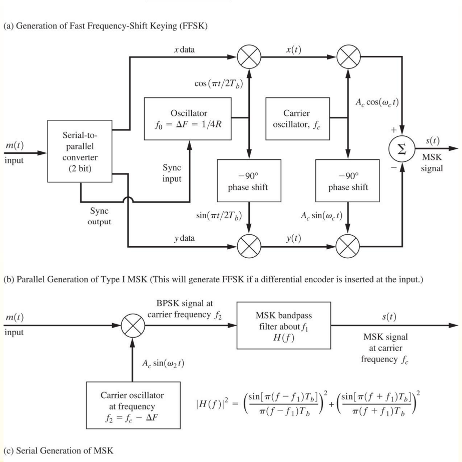
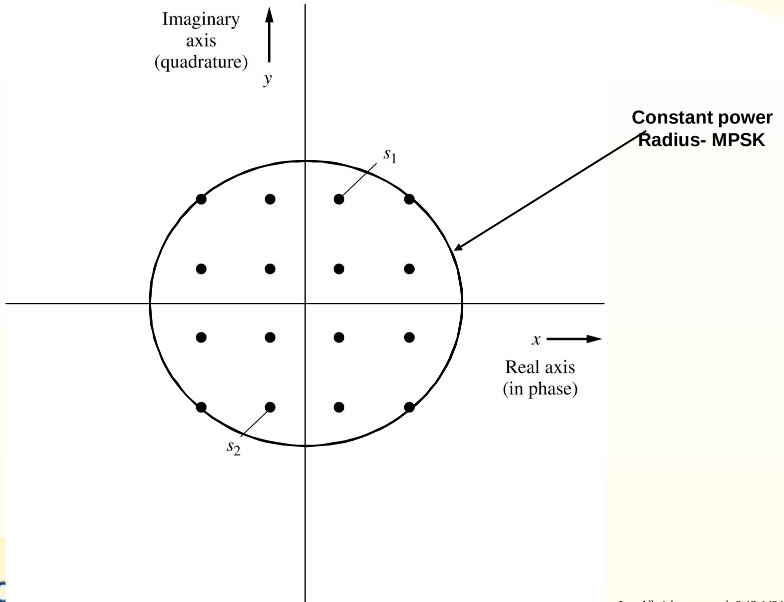


TABLE 5–9 SPECTRAL EFFICIENCY OF DIGITAL SIGNALS

TABLE 5–9 SPECTRAL EFFICIENCY OF DIGITAL SIGNALS

	Spectral Efficiency, $= \frac{R}{B_T}\left(\frac{\text{bit/s}}{\text{Hz}}\right)$	
Type of Signal	Null-to-Null Bandwidth	30-dB Bandwidth
OOK and BPSK	0.500	0.052
QPSK, OQPSK, and $\pi 4$/QPSK	1.00	0.104
MSK	0.667	0.438
16 QAM	2.00	0.208
64 QAM	3.00	0.313

Figure 5–32 16-symbol QAM constellation four levels per dimension).



Constant power Radius- MPSK