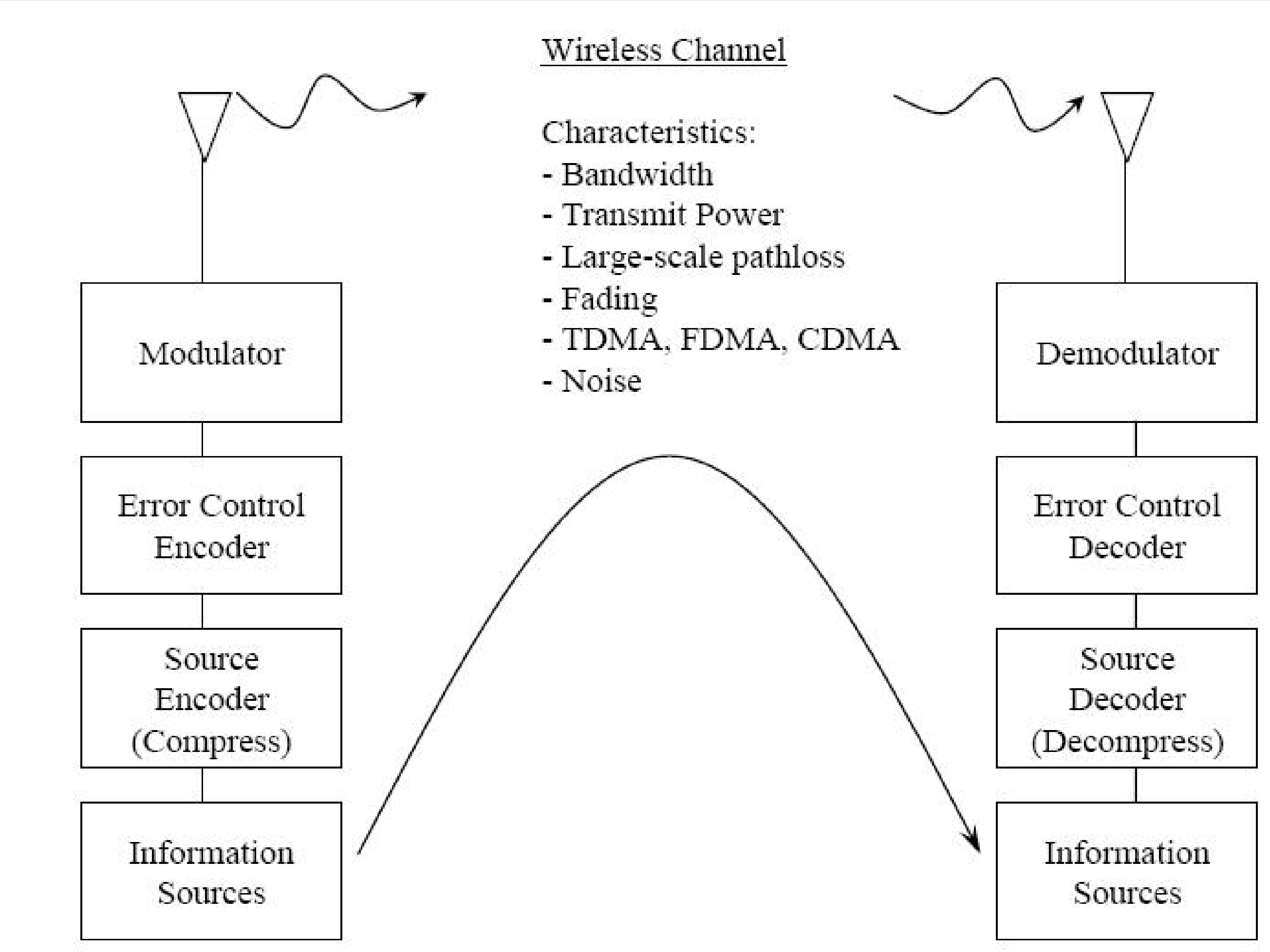
Digital Modulation II

Modulation Techniques for Mobile Radio

- Recall our picture of the overall wireless transmission and receiving system:



- Recap..
  - Analog AM and FM
  - Benefits of Digital Modulation
  - Power and Bandwidth Efficiencies
  - Linear Modulation – BPSK, DPSK, QPSK
  - Bit error rate computations.

Constant Envelope Modulation Methods

- Constant Envelope as compared to AM
  - Linear: Amplitude of the signal varies according to the message signal.
  - Constant Envelope: The amplitude of the carrier is constant, regardless of the variation in the message signal. It is the phase that changes.

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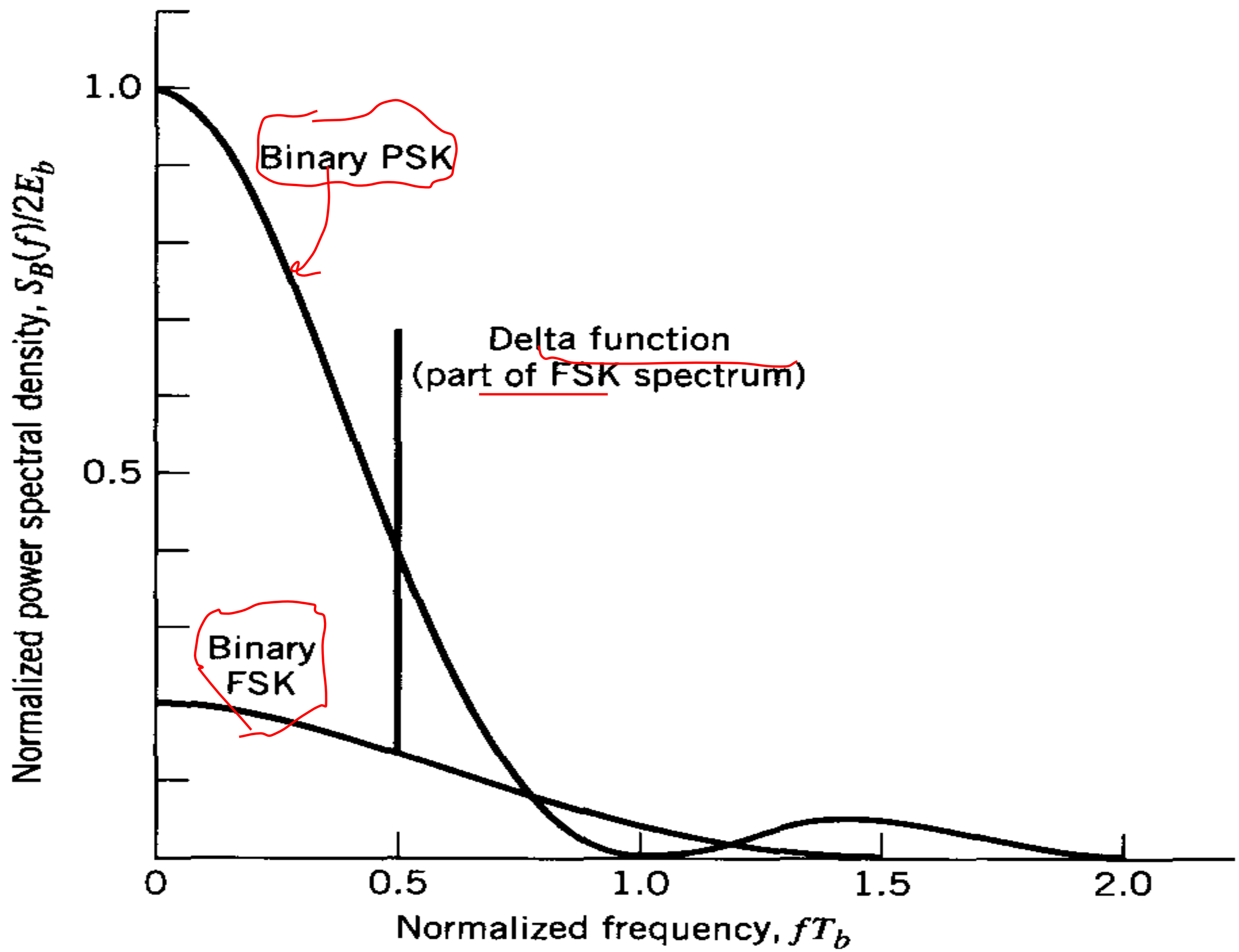
- Benefits of Constant Envelope
  - Power efficient
  - low out-of-band radiation of the order of -60dB to -70 dB
  - Simpler receiver design can be used.
  - High immunity against random FM noise and Rayleigh fading.
- Disadvantage of Constant Envelope
  - Occupies larger bandwidth than linear modulation.



Normalized power spectral density, $S_B(f)/2E_b$
1.0
0.5
Binary PSK
Delta function
(part of FSK spectrum)
Binary
FSK
0
0.5
1.0
1.5
2.0
Normalized frequency, fT_b

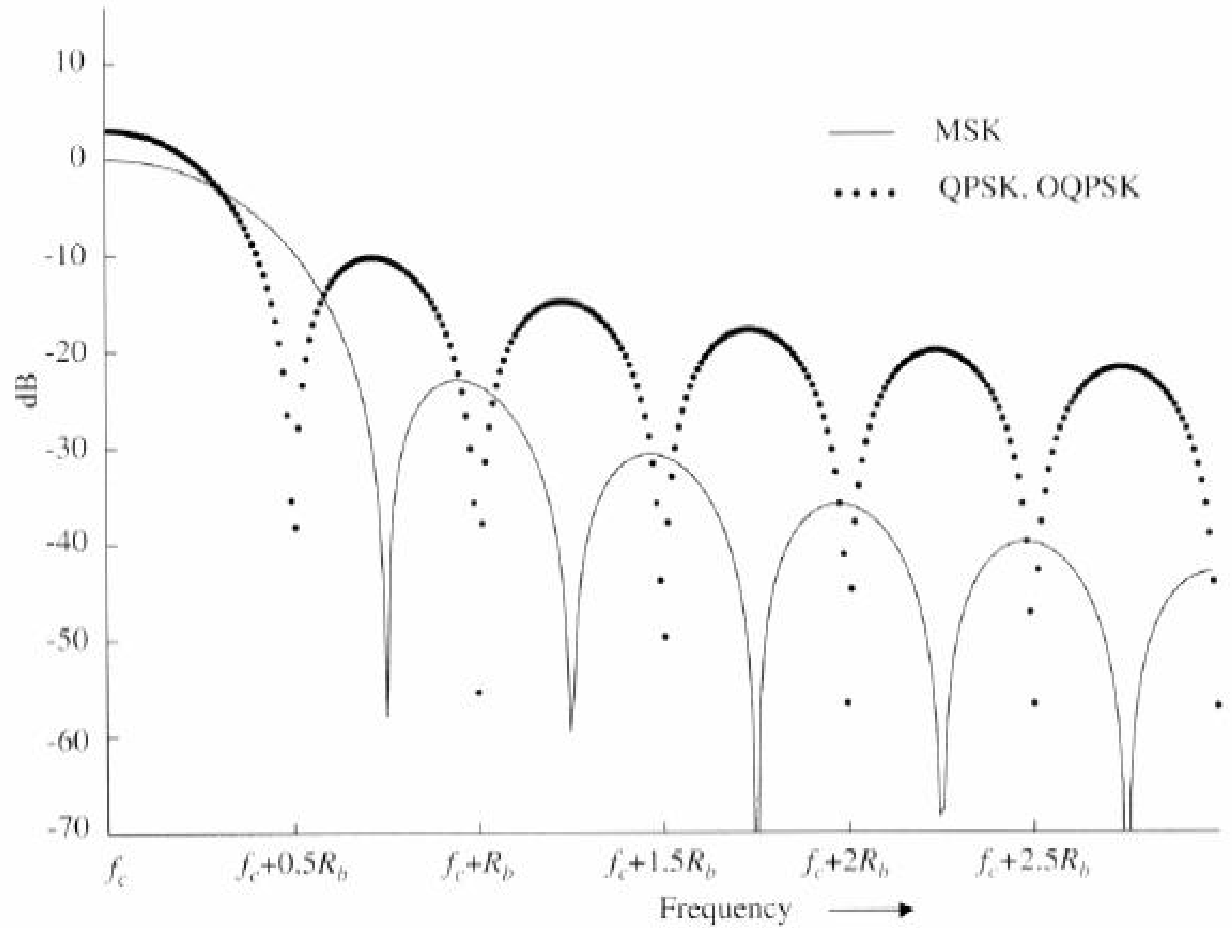


Figure 6.38 Power spectral density of MSK signals as compared to QPSK and OQPSK signals.

- In the figure above, MSK is a type of constant envelope modulation.
  - MSK has lower sidelobes than QPSK → –23 dB vs. –10 dB
  - MSK has larger null-to-null BW than QPSK → 1.5 R_b vs. 1.0 R_b
  - But 99% RF BW is **much** better than QPSK (1.2 R_b vs. 8.0 R_b)
    - very low ACI

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- Need
  - When responding to natural or man-made emergencies, cellular systems are *heavily* congested.
  - And users cannot be expected to regulate their behavior to allow emergency workers to use the spectrum.

- GSM has a mechanism for identifying priority calls and queueing those calls if they are not first accepted.
  - Called the Wireless Priority Service (WPS).
  - This gives a lower blocking probability for those calls.
- But this still does not alleviate congestion.
  - GSM uses a constant envelope modulation scheme (discussed below) that is not bandwidth efficient.

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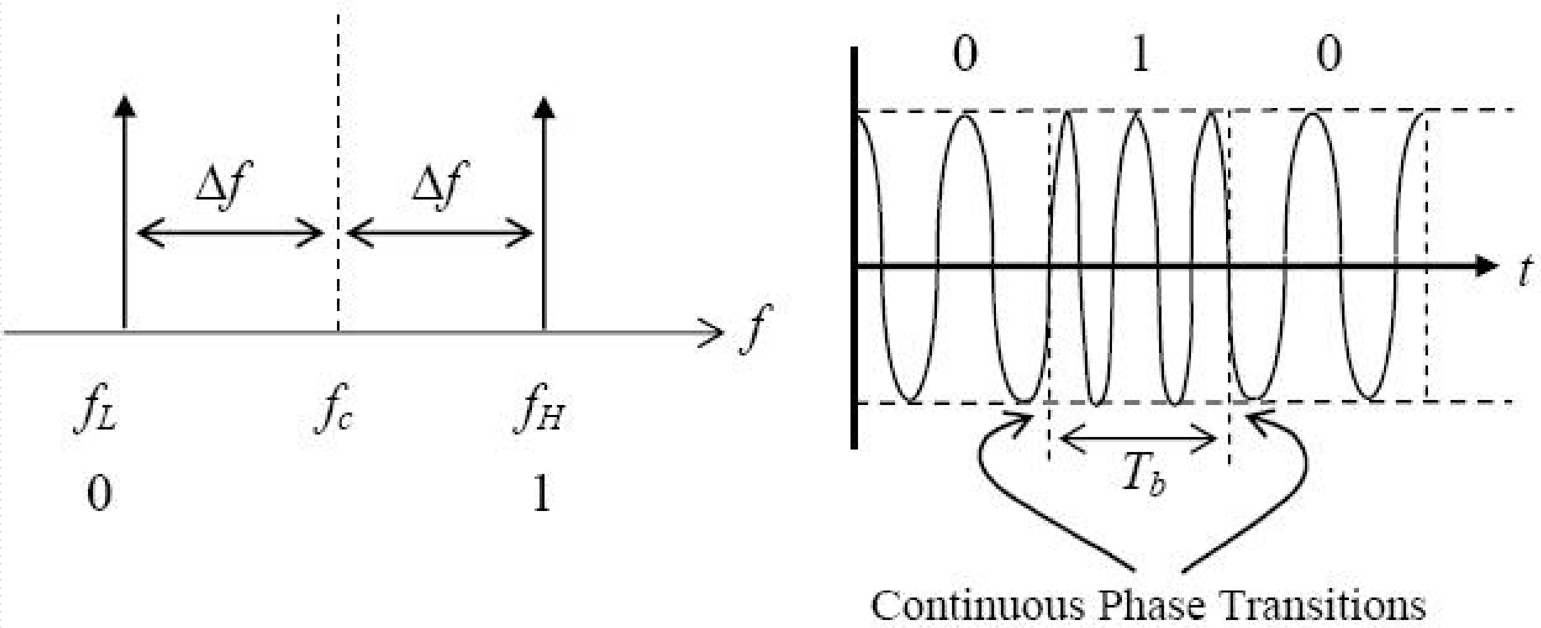
- proposal:
  - Allow users to switch to a linear modulation scheme – to be more bandwidth efficient, needing less bandwidth to be used per channel, creating more channels.
  - But linear modulation also has more out-of-band ACI problems, so we must compensate for that.

- Software-defined radios can be used to change modulation schemes on demand in software when a disaster occurs.
- A part of the spectrum is set aside for the new modulation scheme.
- And existing phones could still use standard GSM using another part of the spectrum.

- Motivation: Finding a good linear modulation scheme, reducing ACI, and implementing the software defined radio.

BFSK

- BFSK → Binary Frequency Shift Keying
  - Frequency of constant amplitude carrier shifted between two possible frequencies → f_H = "1" and f_L = "0"



  - Δf = frequency offset from f_c

- BFSK signal

$$s(t)=\sqrt{\frac{2E_b}{T_b}}\cos\left(2\pi f_c t \pm 2\pi\left(\frac{1}{2T_b}\right)t\right)$$

- Can use a simple method to switch between two oscillators
  - but this might cause discontinuities
  - if the switching between signals is done when either one is not at a zero value
  - What problems do discontinuities cause?

- But the phase between bits **can** be made to be continuous
  - no discontinuity → constant envelope retained
  - if we design the circuits based on the definition of FM from before:

$$S_{FM}(t) = A_c \cos\left(2\pi f_c t + 2\pi k_f \int_{-\infty}^{t} m(\eta) d\eta\right)$$

- Then even if the message signal *m* (η) is discontinuous, the integral of it will not be and the signal will then be continuous.
- But this is more complicated than simply switching between two oscillators.

- BFSK BW
  - If B = baseband BW of the message signal
  - RF BW = 2 Δf + 2 B
- Assume that first null BW is used, the BW of rectangular pulses is $B=R$
  - RF BW = 2 Δf + 2 R
- BER for Coherent detection of BFSK

$$P_{e,FSK} = Q\left(\sqrt{\frac{E_b}{N_o}}\right)$$

MSK

Minimum Shift Keying

- MSK → Minimum Shift Keying
- MSK is a variant of OQPSK
- The rectangular symbol pulse is replaced by a half cycle sinusoidal symbol pulse.
- MSK provides a constant envelope signal which has it's phase continous at all times including the interbit switching times.

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Minimum Shift Keying

- **In MSK, also the phase shifts can be detected with an I or Q modulator.**

- **At even numbered symbols, the polarity of I channel conveys the transmitted data and at odd numbered symbols the polarity of Q channel conveys the data.**

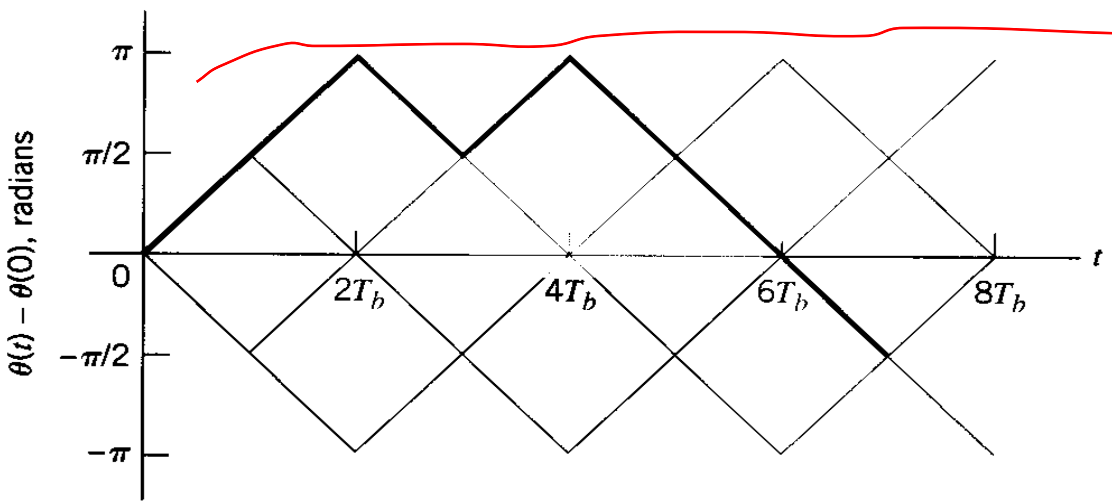
- A phase shift of + 90 degrees represents a data bit equal to 1 and a phase shift of –90 degrees represents a data bit equal to zero.

MSK..

- Specific type of continuous phase (CP) FSK
- Special condition: Peak frequency deviation is ¼ of the bit rate, so $\Delta f = 0.25\, R_b$
  - This is a smaller frequency separation (half that of conventional FSK) and has easier detection.
- It possesses properties such as:
  - **constant envelope**
  - **spectral efficiency**
  - **good BER performance**
  - **self-synchronizing capability**.

$$s(t) = \sqrt{\frac{2E_b}{T_b}} \cos[\theta(t)] \cos(2\pi f_c t) - \sqrt{\frac{2E_b}{T_b}} \sin[\theta(t)] \sin(2\pi f_c t)$$

$$\theta(t) = \theta(0) \pm \frac{\pi}{2T_b} t, \qquad 0 \le t \le T_b$$



Phase trellis; boldfaced path represents the sequence 1101000.

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$$s(t) = s_1\phi_1(t) + s_2\phi_2(t), \qquad 0 \le t \le T_b$$

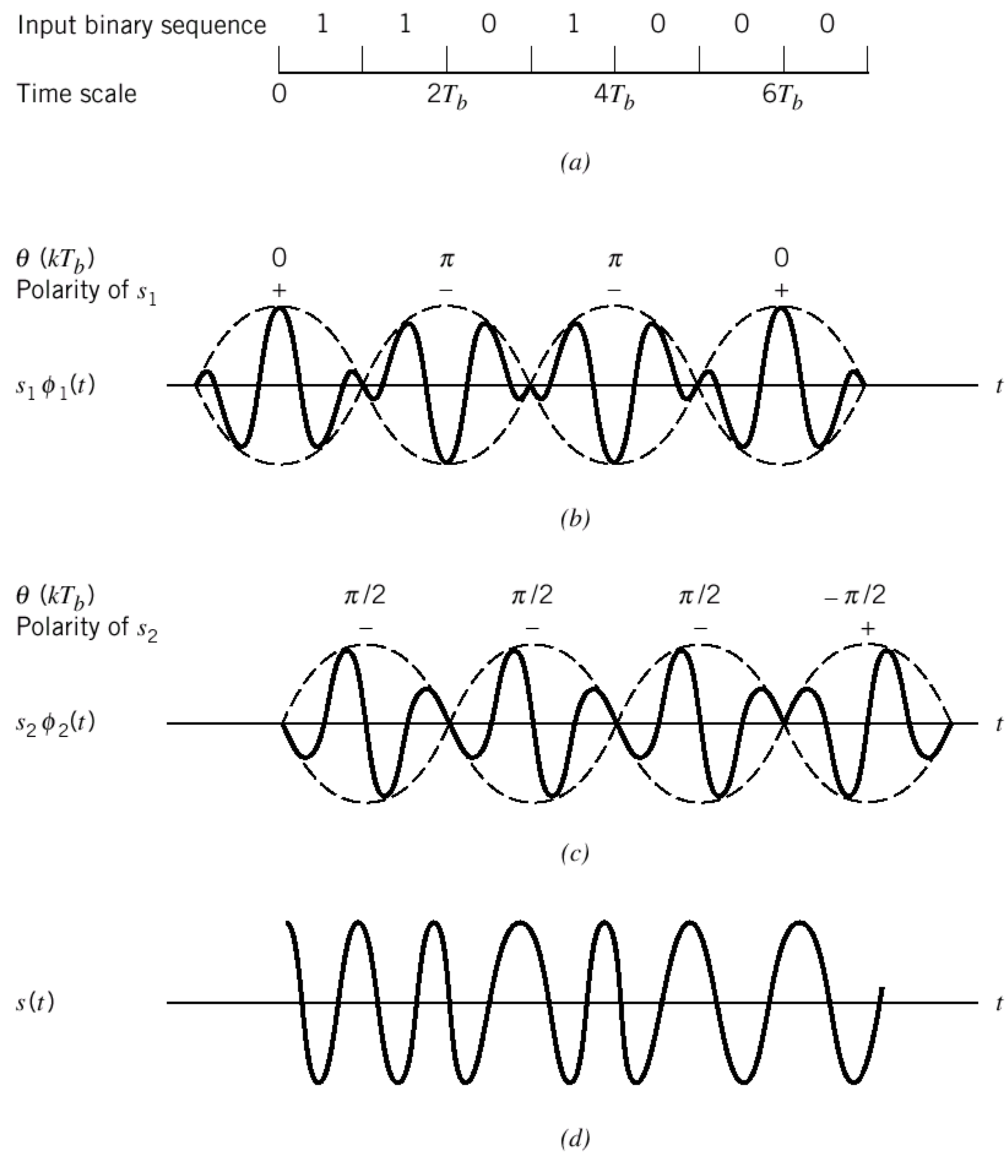
$$\phi_1(t) = \sqrt{\frac{2}{T_b}}\cos\left(\frac{\pi}{2T_b}t\right)\cos(2\pi f_c t), \qquad 0 \le t \le T_b$$

$$\phi_2(t) = \sqrt{\frac{2}{T_b}}\sin\left(\frac{\pi}{2T_b}t\right)\sin(2\pi f_c t), \qquad 0 \le t \le T_b$$

$$\begin{aligned} s_1 &= \int_{-T_b}^{T_b} s(t)\phi_1(t)\,dt \\ &= \sqrt{E_b}\cos[\theta(0)], \qquad -T_b \le t \le T_b \end{aligned}$$

$$\begin{aligned} s_2 &= \int_{0}^{2T_b} s(t)\phi_2(t)\,dt \\ &= -\sqrt{E_b}\sin[\theta(T_b)], \qquad 0 \le t \le 2T_b \end{aligned}$$

- An MSK signal can be thought of as a special form of OQPSK where the baseband rectangular pulses are replaced with half-sinusoidal pulses during a period of 2T



- can be deduced that
  - MSK has a constant amplitude.
  - Phase continuity at the bit transition periods is ensured by choosing the carrier frequency to be an integral multiple of one fourth the bit rate, 1/4T.
  - the MSK signal is an FSK signal with binary signaling frequencies of f_c + 1/4T and f_c - 1/4T.

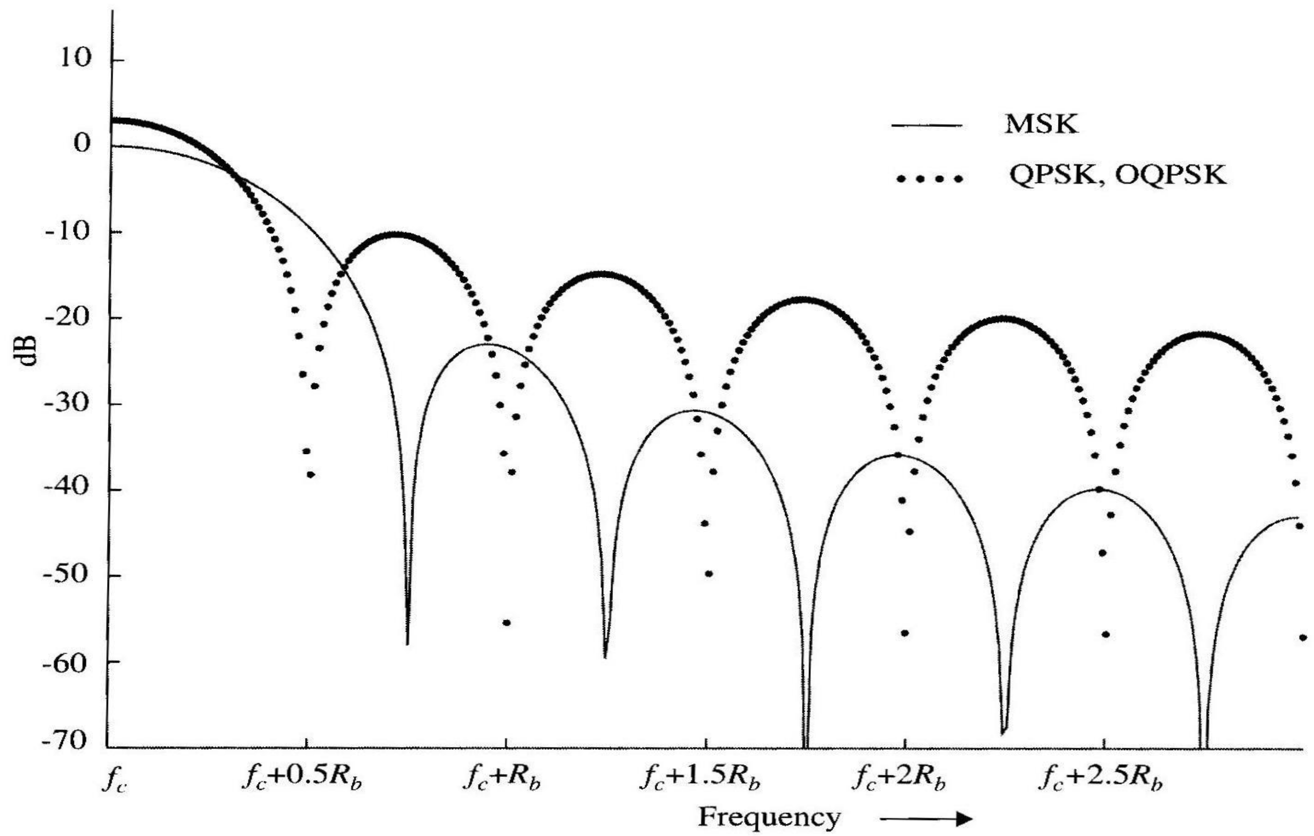


Figure 6.38 Power spectral density of MSK signals as compared to QPSK and OQPSK signals.

- MSK RF signal BW
  - MSK has lower sidelobes than QPSK → –23 dB vs. –10 dB
  - MSK has larger null-to-null BW than QPSK → 1.5 R_b vs. 1.0 R_b
  - But 99% RF BW is **much** better than QPSK (1.2 R_b vs. 8.0 R_b !!) – very low ACI
- Very popular modulation scheme for mobile radio

GMSK(Gaussian Minimum Shift Keying)

- MSK with a gaussian filter is termed as GMSK
- With GMSK, the phase change which represents the change from a digital 1 or 0 does not occur instantaneously but occurs over a period of time.
- In GMSK, the digital signal is first passed through a gaussian filter
- the filter generates a signal with low side lobes and narrower main lobe than the rectangular pulse.The resulting distorted signal is used to shift the carrier phase.
- The phase change is not instantaneous but spread out.

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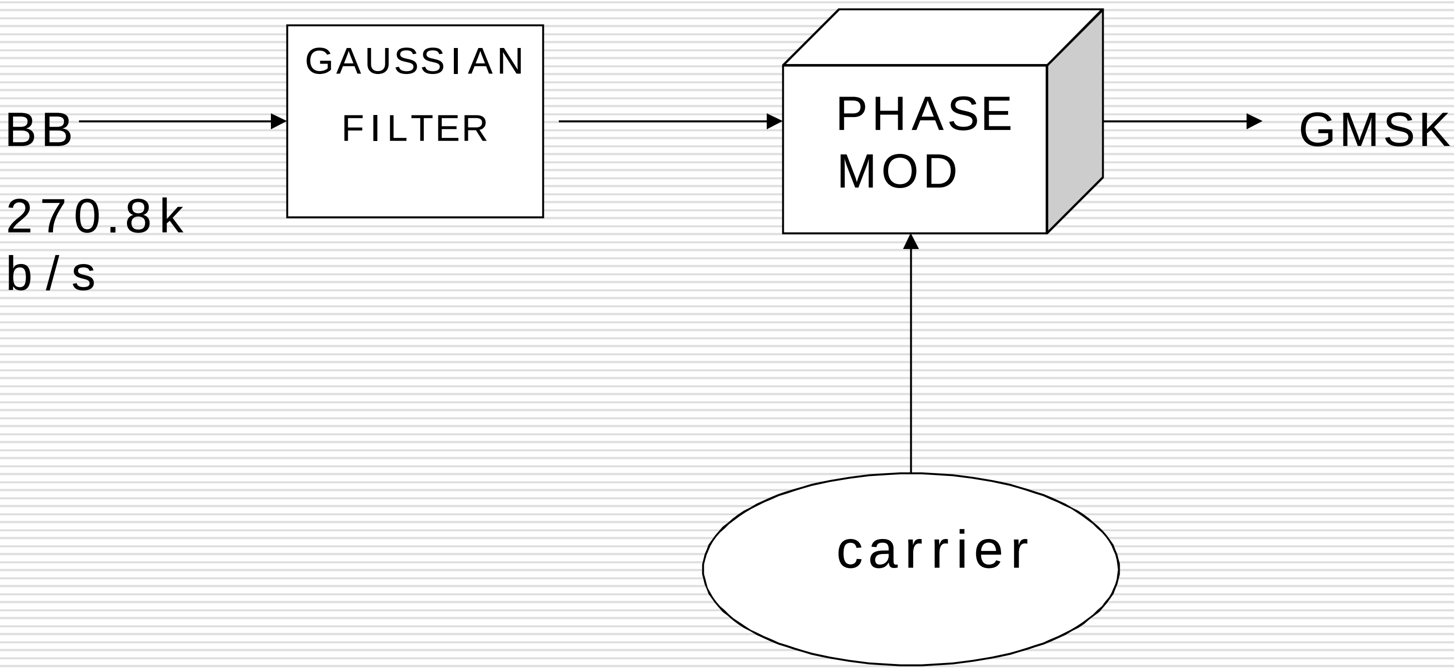
GMSK Modulator



GMSK

- GMSK → Gaussian MSK
  - The spectral efficiency of MSK is further enhanced by filtering the baseband signal of square pulses with a Gaussian filter.

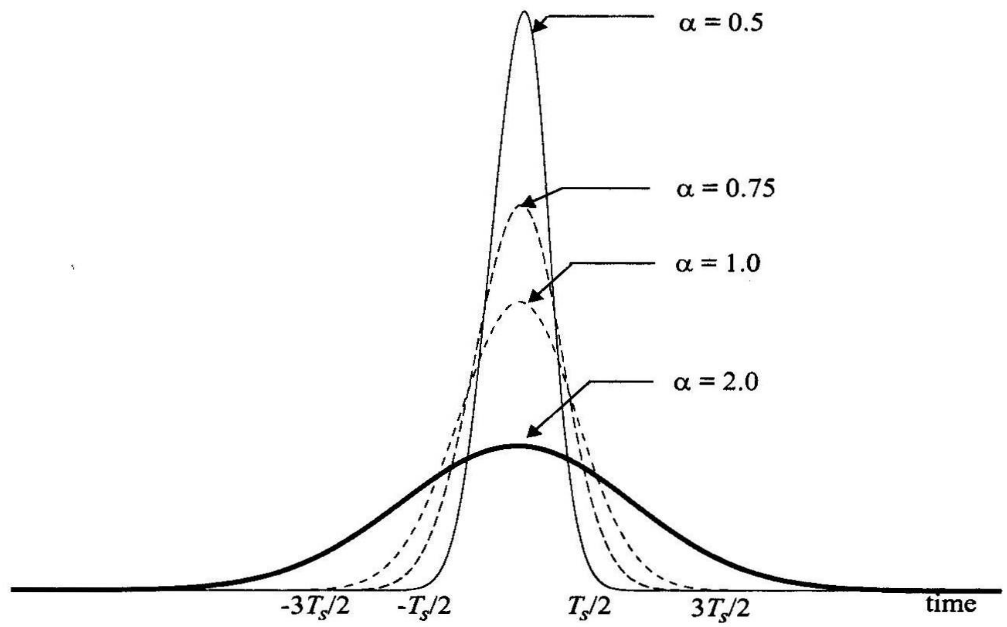


Figure 6.20 Impulse response of a Gaussian pulse-shaping filter.

- Further reduces sidelobes.
- Designed based on the product of the filter bandwidth (B_b) and the symbol period (T)
- $B_b T = \infty$ corresponds to MSK
- GSM uses $B_b T = 0.3$, which defines the bandwidth of the Gaussian filter
- The smaller the value of $B_b T$, however, the higher the error rates.
- Sacrifices the irreducible error rate in exchange for extremely good spectral efficiency and constant envelop properties

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- GMSK premodulation filter has an impulse response given by

$$h_G(t) = \frac{\sqrt{\pi}}{\alpha} \exp\left(-\frac{\pi^2}{\alpha^2} t^2 \right)$$

$$H_G(f) = \exp(-\alpha^2 f^2) \qquad \alpha = \frac{\sqrt{\ln 2}}{\sqrt{2}B} = \frac{0.5887}{B}$$

Table 6.3 Occupied RF Bandwidth (for GMSK and MSK as a fraction of R_b) Containing a Given Percentage of Power [Mur81]. Notice that GMSK is Spectrally Tighter than MSK

BT	90%	99%	99.9%	99.99%
0.2 GMSK	0.52	0.79	0.99	1.22
0.25 GMSK	0.57	0.86	1.09	1.37
0.5 GMSK	0.69	1.04	1.33	2.08
MSK	0.78	1.20	2.76	6.00

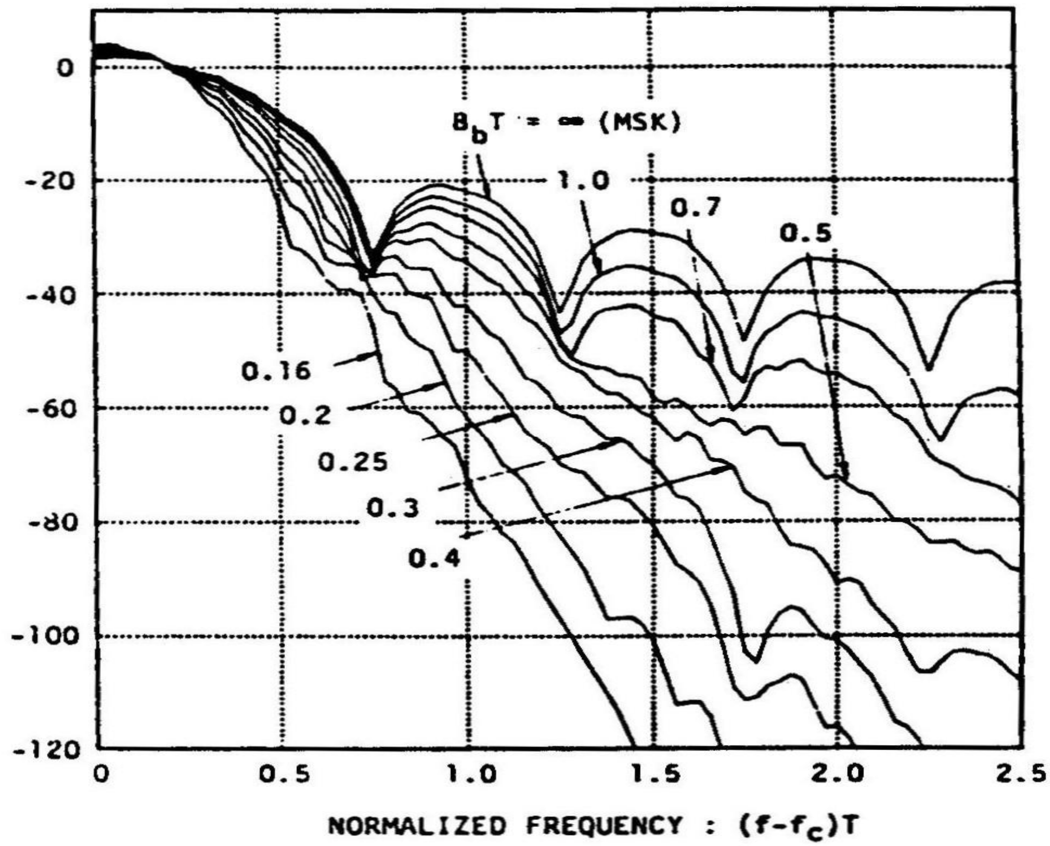

Figure 6.41 Power spectral density of a GMSK signal [from [Mur81] © IEEE].

Summary: OQPSK (IS-95) and GMSK (GSM) are the two main modulation methods for 2G systems.

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Example 6.11

Find the 3-dB bandwidth for a Gaussian low pass filter used to produce 0.25 GMSK with a channel data rate of $R_b = 270$ kbps. What is the 90% power bandwidth in the RF channel? Specify the Gaussian filter parameter α.

Solution

From the problem statement

$$T = \frac{1}{R_b} = \frac{1}{270 \times 10^3} = 3.7\ \mu s$$

Solving for B, where $BT = 0.25$,

$$B = \frac{0.25}{T} = \frac{0.25}{3.7 \times 10^{-6}} = 67.567\ \text{kHz}$$

Thus the 3-dB bandwidth is 67.567 kHz. To determine the 90% power bandwidth, use Table 6.3 to find that $0.57R_b$ is the desired value. Thus, the occupied RF spectrum for a 90% power bandwidth is given by

$$\text{RF } BW = 0.57R_b = 0.57 \times 270 \times 10^3 = 153.9\ \text{kHz}$$

Combined Linear and Constant Envelope Modulation Techniques

- We can allow both the phase and the amplitude to change at the same time – this would be a combination of linear and constant envelop methods.
- We can extend the idea of QPSK to create symbols with M possible states (instead of just 2 or 4).
- $M = 2^n$ so each symbol encompasses n bits of data.

M-ary PSK

- M-ary PSK - constant envelope with more phase possibilities

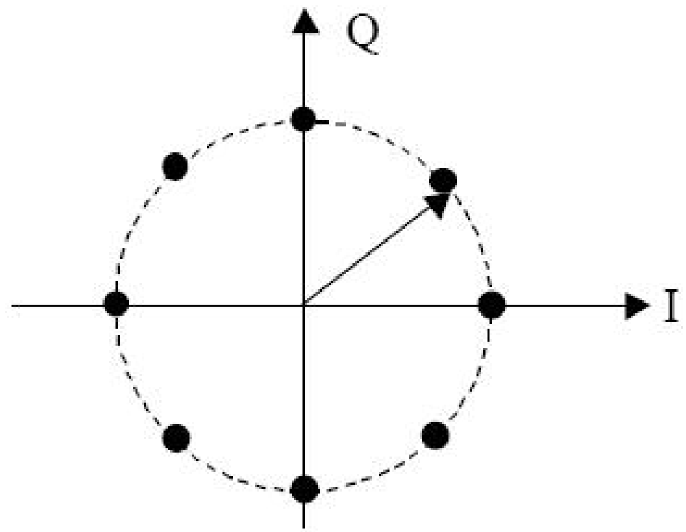
$$s_i(t) = \sqrt{\frac{2E_s}{T_s}} \cos\left(2\pi f_c t + \frac{2\pi}{M}(i-1)\right), \; 0 \le t \le T_s \quad i = 1, 2, \ldots, M$$

$$s_i(t) = \sqrt{\frac{2E_s}{T_s}} \cos\left[(i-1)\frac{2\pi}{M}\right] \cos(2\pi f_c t) - \sqrt{\frac{2E_s}{T_s}} \sin\left[(i-1)\frac{2\pi}{M}\right] \sin(2\pi f_c t) \quad i = 1, 2, \ldots, M$$

$$\phi_1(t) = \sqrt{\frac{2}{T_s}}\cos(2\pi f_c t), \text{ and } \phi_2(t) = \sqrt{\frac{2}{T_s}}\sin(2\pi f_c t)$$

$$s_{\mathrm{M-PSK}}(t) = \left\{\sqrt{E_s}\cos\left[(i-1)\frac{2\pi}{M}\right], -\sqrt{E_s}\sin\left[(i-1)\frac{2\pi}{M}\right]\right\}$$

$$i = 1,2,\ldots,M$$



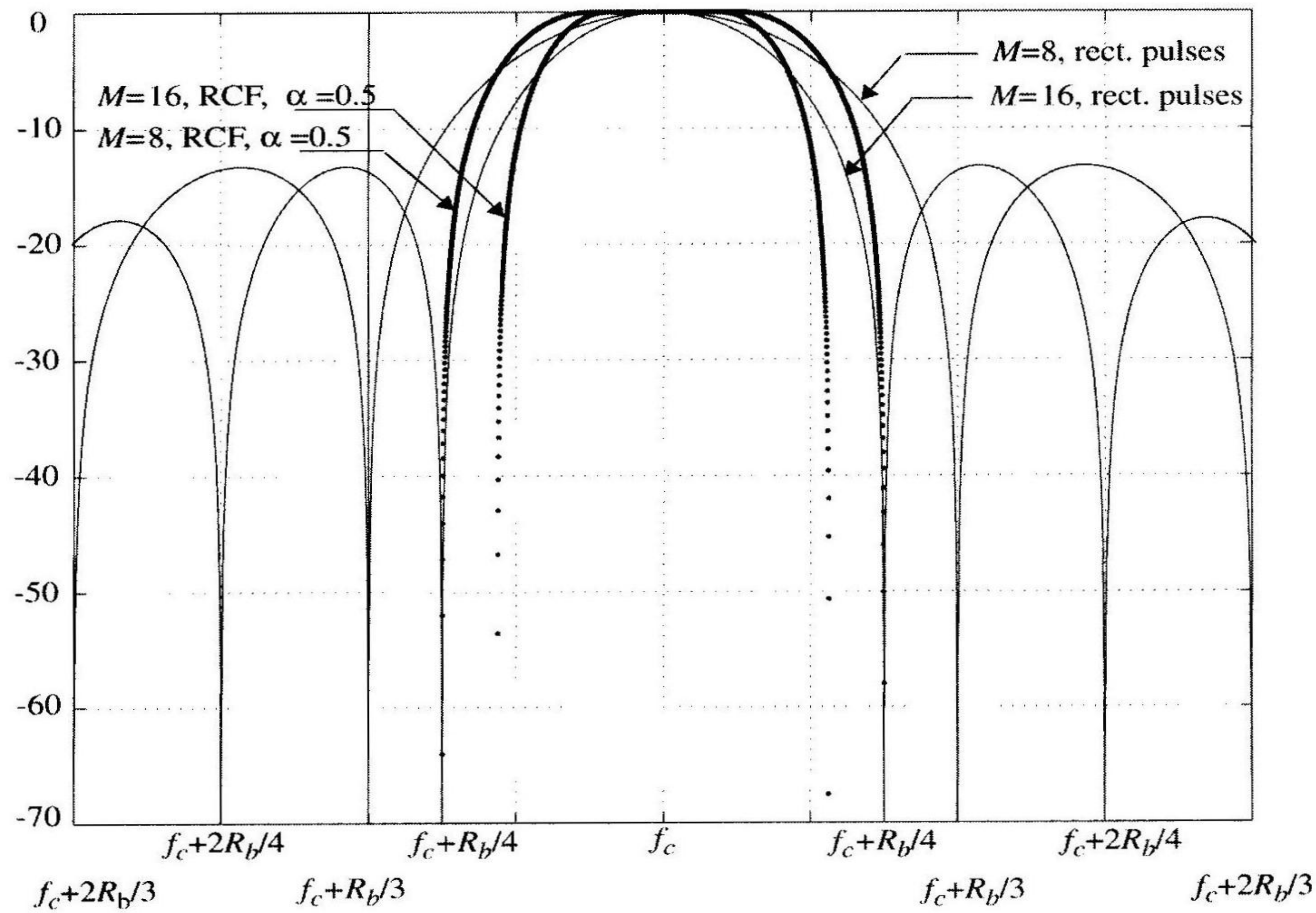


Figure 6.46 M-ary PSK power spectral density, for M = 8, 16 (PSD for both rectangular and raised cosine filtered pulses are shown for fixed R_b).

- the first null bandwidth of M-ary PSK signals decrease as M increases while R_b is held constant.

- for fixed R_b , B ↓ and η_b ↑ as M ↑.
- At the same time, M ↑ implies that the constellation is more densely packed, and hence the power efficiency η_p (noise tolerance) ↓.

Table 6.4 Bandwidth and Power Efficiency of M-ary PSK Signals

M	2	4	8	16	32	64
$\eta_B = R_b/B$ *	0.5	1	1.5	2	2.5	3
E_b/N_o for BER=10^{-6}	10.5	10.5	14	18.5	23.4	28.5

* B: First null bandwidth of M-ary PSK signals

QAM

- Quadrature Amplitude Modulation (QAM) – Change both amplitude and phase.
- The general form of an M-ary QAM signal

$$s_i(t) = \sqrt{\frac{2E_{\min}}{T_s}} a_i \cos(2\pi f_c t) + \sqrt{\frac{2E_{\min}}{T_s}} b_i \sin(2\pi f_c t)$$

$$0 \le t \le T \qquad i = 1, 2, \dots, M$$

$$\{a_i, b_i\} = \begin{bmatrix} (-L+1, L-1) & (-L+3, L-1) & (L-1, L-1) \\ (-L+1, L-3) & (-L+3, L-3) & (L-1, L-3) \\ \vdots & \vdots & \vdots \\ (-L+1, -L+1) & (-L+3, -L+1) & (L-1, -L+1) \end{bmatrix}$$

where $L = \sqrt{M}$

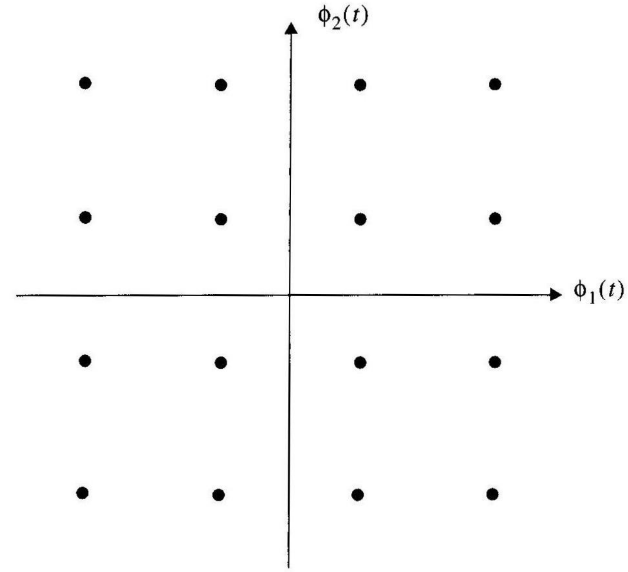


Figure 6.47 Constellation diagram of an M-ary QAM ($M = 16$) signal set.

$$L = \sqrt{M}$$

$$\{a_i, b_i\} = \begin{bmatrix} (-3,3) & (-1,3) & (1,3) & (3,3) \\ (-3,1) & (-1,1) & (1,1) & (3,1) \\ (-3,-1) & (-1,-1) & (1,-1) & (3,-1) \\ (-3,-3) & (-1,-3) & (1,-3) & (3,-3) \end{bmatrix}$$

- Basic tradeoff: Better bandwidth efficiency at the expense of power efficiency
  - More bits per symbol time → better use of constrained bandwidth
  - Need much more power to keep constellation points far enough apart for acceptable bit error rates.
    - need a large circle for M-ary PSK
    - symbols at corners (extreme points) of QAM constellation use a lot of power.

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

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M-ary FSK

- M-ary FSK
  - Frequencies are chosen in a special way so that they are easily separated at the demodulator (orthogonality principle).
  - M-ary FSK transmitted signals:

$$s_i(t) = \sqrt{\frac{2E_s}{T_s}} \cos\left[\frac{\pi}{T_s}(n_c + i)t\right] \qquad 0 \le t \le T_s \quad i = 0,1,\ldots,M$$

- $f_c = n_c / 2T_s$ for some integer n_c
- The M transmitted signals are of equal energy and equal duration
- The signal frequencies are separated by $1/2T_s$ Hz, making the signals orthogonal to one another

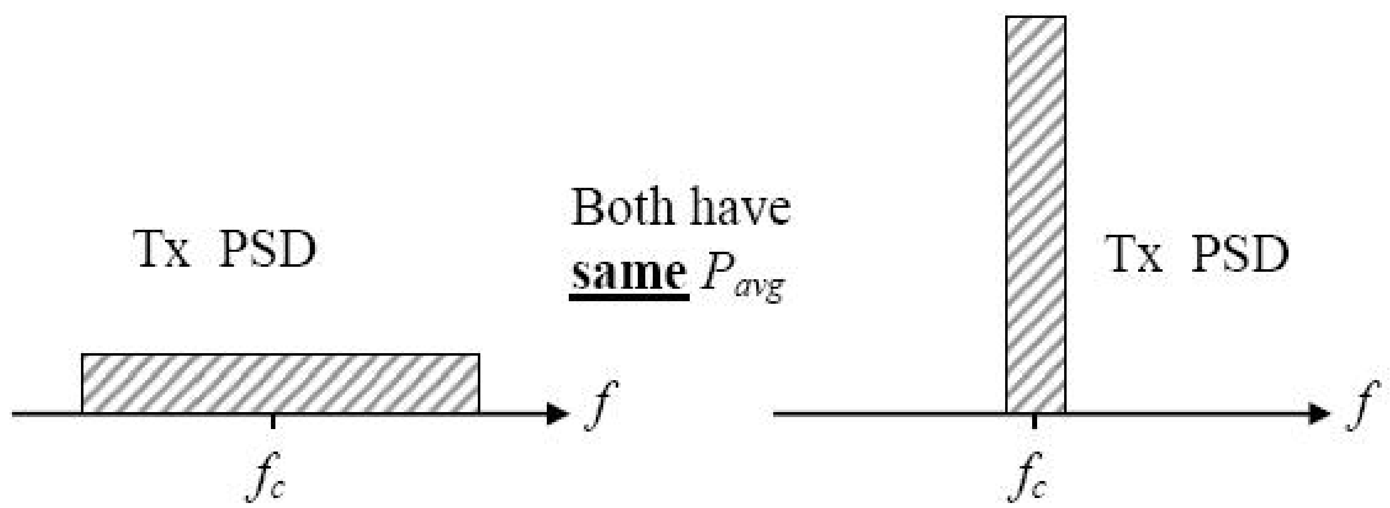
- The bandwidth efficiency of an M-ary FSK signal ↓ with M↑
- Power efficiency ↑ with M↑
  - Since M signals are orthogonal, there is no crowding in the signal space

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

Spread Spectrum Modulation (SSM)

- Tx expands (spreads) signal BW **many** times with a special code and the signal is then collapsed (despread) in Rx with the same code
- Other signals created with other codes just appear at the Rx as random noise.
- Trade BW for signal power like with FM



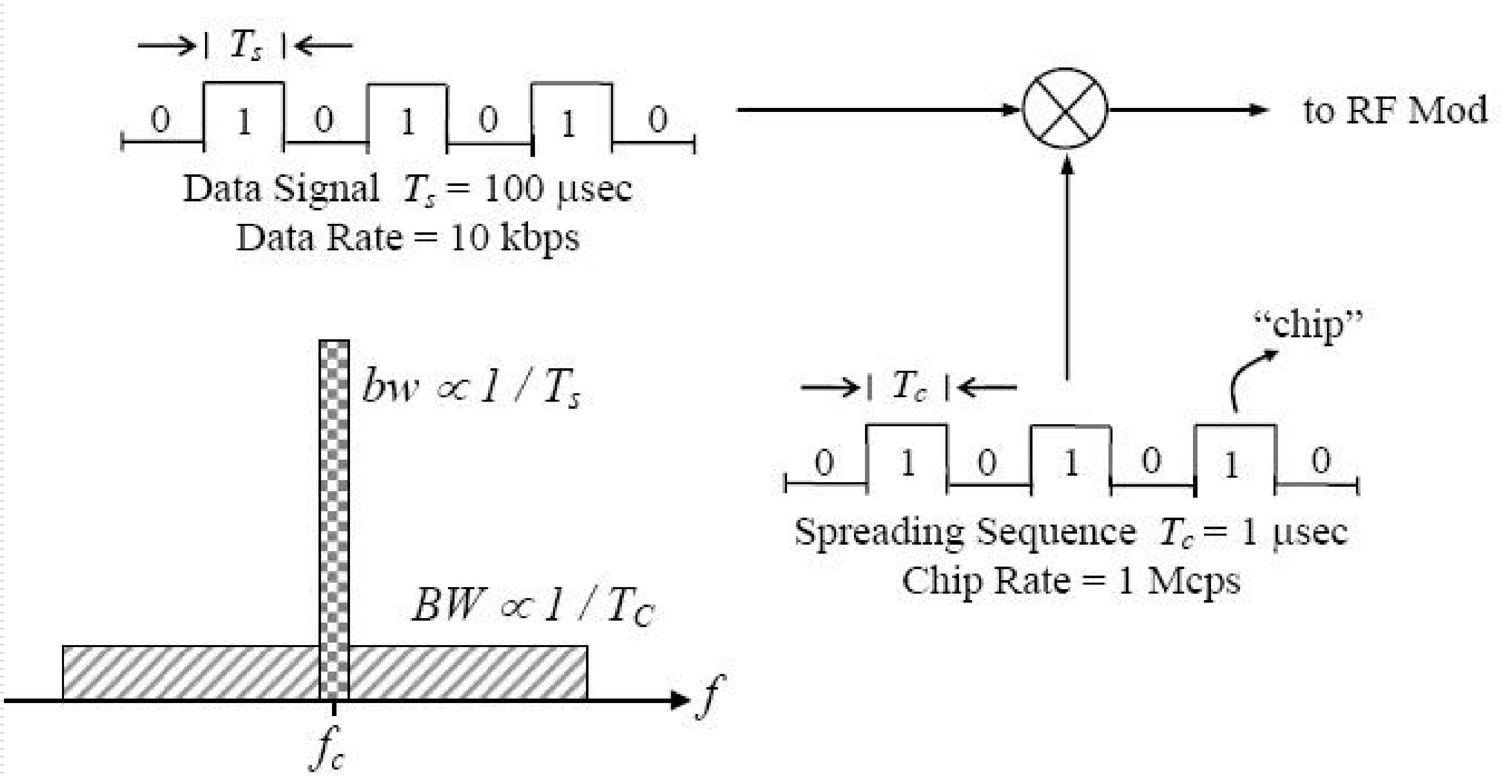
- Advantages
  1) Resistant to narrowband interference – interference can only realistically affect part of the signal.
  2) Allows multiple users with different codes to share same the MRC
     - no frequency reuse needed
     - rejects interference from other users

3) Combats multipath fading → if a multipath signal is received with enough delay (more than one chip duration), it also appears like noise.

4) Can even use shifted versions of codes to isolate and receive different multipath components (RAKE receiver which we will see later)

5) As # simultaneous users ↑ the bandwidth efficiency↑

- Signal spreading is done by multiplying the data signal by a pseudo-noise (PN) code or sequence
  - the pseudo-noise signal looks like noise to all except those who know how to recreate the sequence.



PN Codes

- Binary sequence with random properties → noise-like (called "pseudo-noise" because they technically are not noise)
- ≈ equal #’s of 1’s and 0’s
- Very low correlation between time-shifted versions of **same** sequence

- Very low cross-correlation between **different** codes
  - each user assigned unique code that is approximately orthogonal to all other codes
  - the other users' signals appear like random noise!

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- Exactly 2^m-1 nonzero states for an *m*-stage feedback shift register
- The period of a PN sequence can not exceed 2^m-1 symbols (*maximal length*)

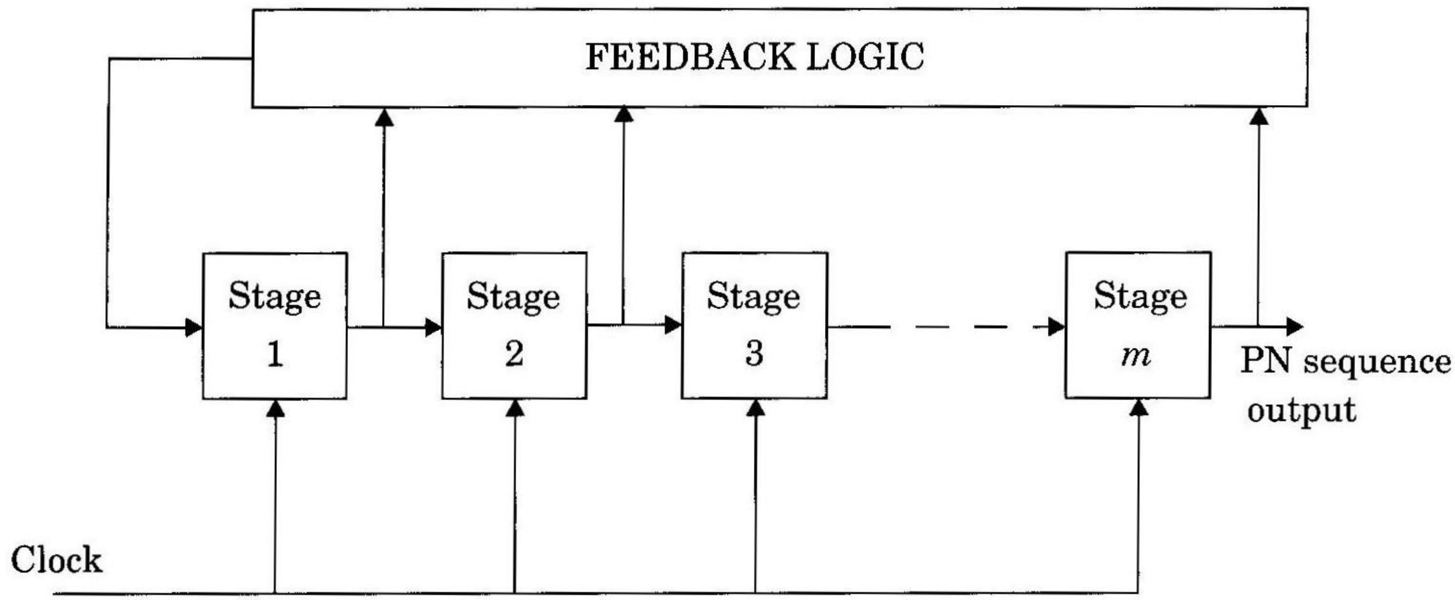

Figure 6.48 Block diagram of a generalized feedback shift register with *m* stages.

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- Spreading codes

Example: 0 0 0 1 1 0 1 → let "0" = – & "1" = +

$- \; - \; - \; + \; + \; - \; +$

Matched

$$\begin{array}{ccccccc} - & - & - & + & + & - & + \\ - & - & - & + & + & - & + \\ \hline 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{array} \rightarrow \Sigma = 7$$

Time shifted by 1

$$\begin{array}{cccccccc} - & - & - & + & + & - & + & \\ & - & - & - & + & + & - & + \\ \hline 0 & 1 & 1 & -1 & 1 & -1 & -1 & 0 \end{array} \rightarrow \Sigma = 1 \;!$$

- The correlation properties of PN codes are such that this slight delay causes the multipath to appear uncorrelated with the intended signal
  - Multipath contributions appear invisible the desired Rx signal

Direct Sequence (DS)

- Two types of SSM – DS & FH

  1) Direct Sequence (DS)

  - Multiply baseband data by PN code (same as diagram above)
  - Spread the baseband spectrum over a wide range.
  - The Rx spread spectrum signal

$$s_i(t) = \sqrt{\frac{2E_s}{T_s}} m(t)\, p(t) \cos\left(2\pi f_c t + \theta\right)$$

- $m(t)$: the data sequence
- $p(t)$: The PN sequence

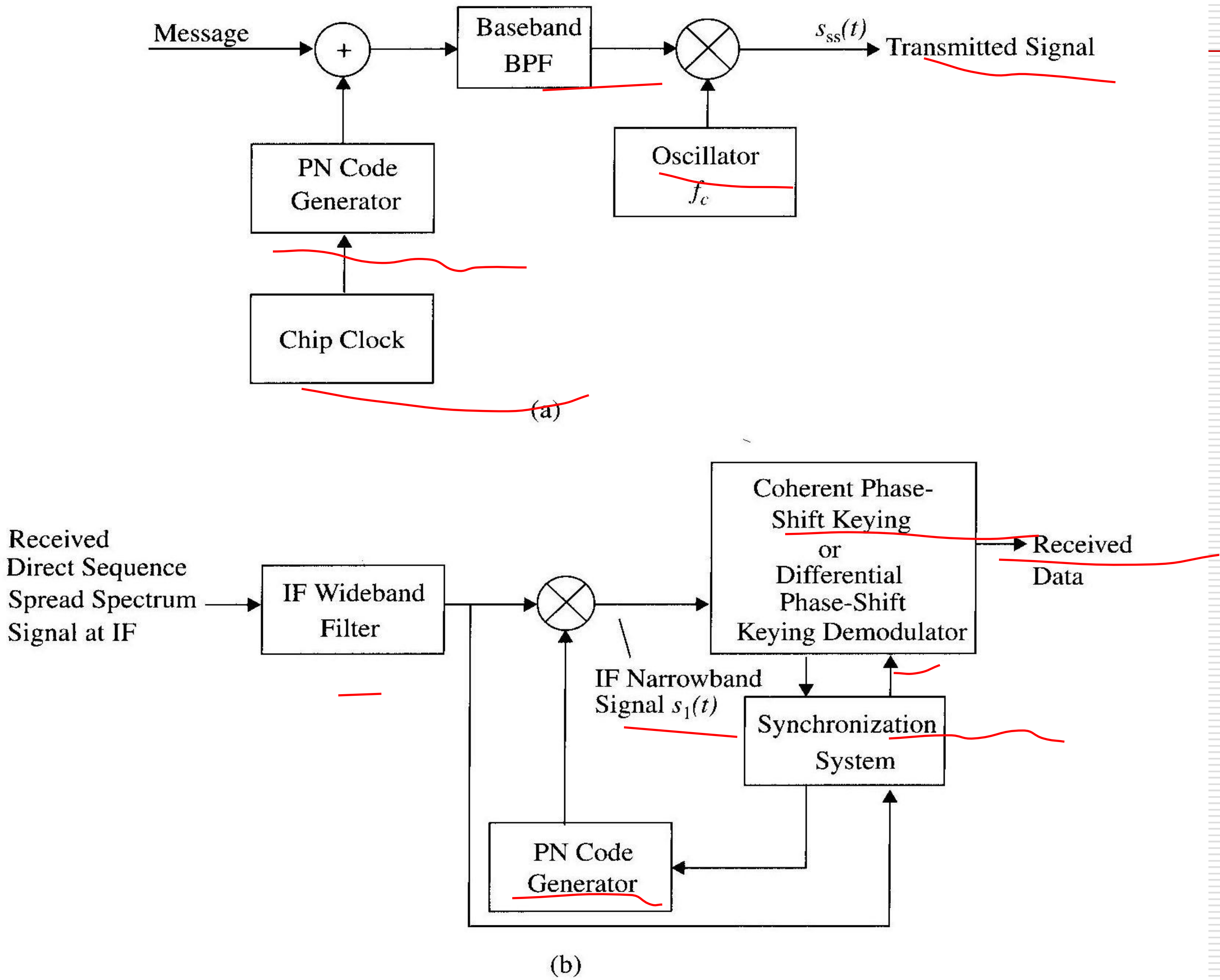

Figure 6.49 Block diagram of a DS–SS system with binary phase modulation: (a) transmitter; and (b) receiver.

Frequency Hopping (FH)

2) Frequency Hopping (FH)

- Randomly change f_c with time
- Spread the frequency values that are used over a wide range.
- In effect, this signal stays narrowband but moves around a lot to use a wide band of frequencies over time.

- *Hopset* : the set of possible carrier frequencies
- *Hop duration*: the time during between hops
- Classified as *fast* FH or *slow* FH
  - ***fast* FH**: more than one frequency hop during each Tx symbol
  - ***slow* FH** : one or more symbol are Tx in the time interval between frequency hops.

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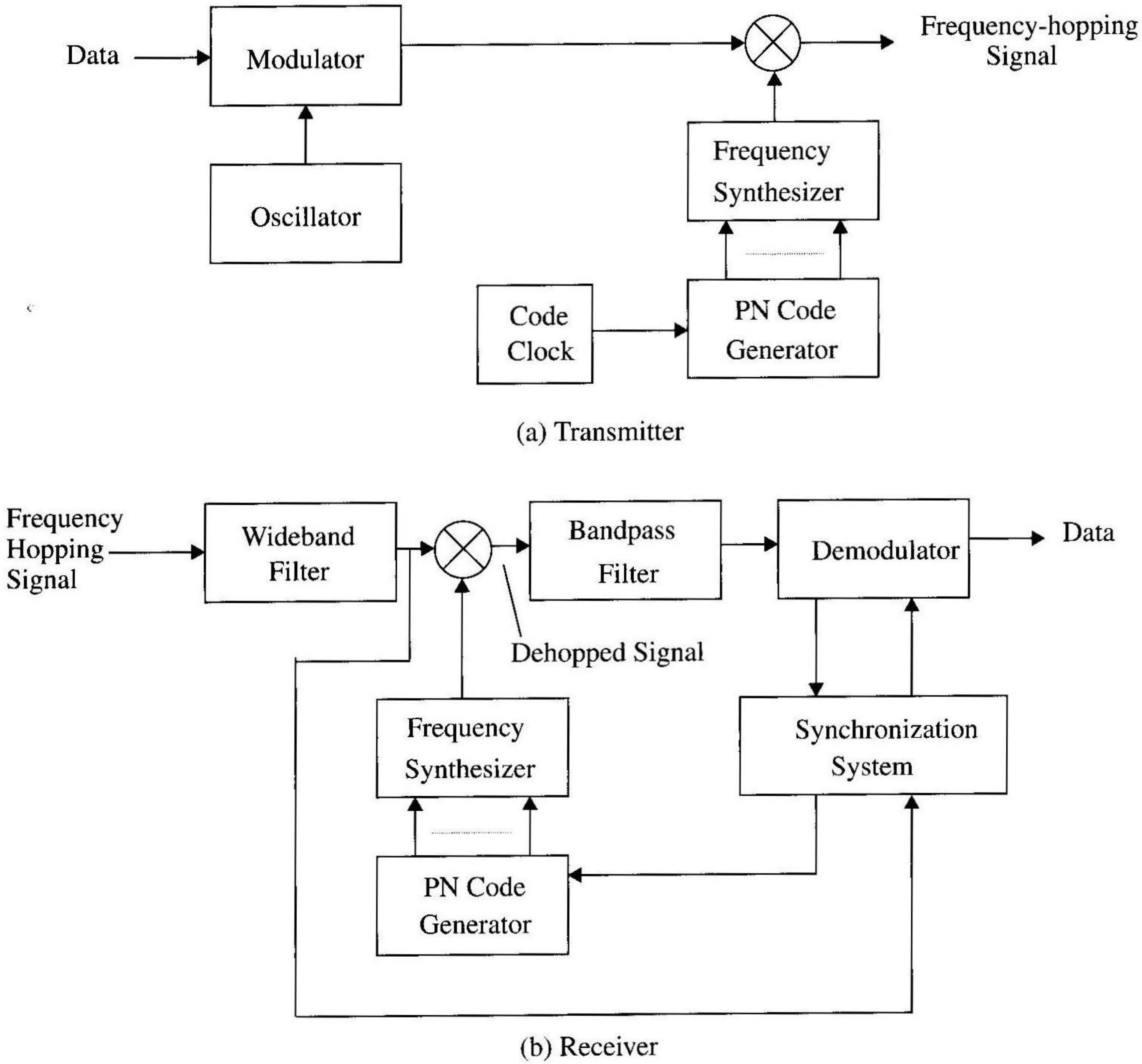

Figure 6.51 Block diagram of frequency hopping (FH) system with single channel modulation.

- Bluetooth uses FH because it is an ad-hoc network. DS would require more precise bit timing coordination (because of the high data rate signal), which is hard to do among an ad hoc collection of devices.
- Bluetooth uses frequency hopping with a dwell time of 625 µs (1600 frequency hops per second) over 79 different frequencies

- Processing Gain = *PG*
  - SSM is resistant to narrowband interfering signals

- Part (a) shows how an interfering source can only affect a small part of the spectrum of the signal.
- Part (b) shows how the despreading process shrinks the signal spectrum and spreads out the interference energy.

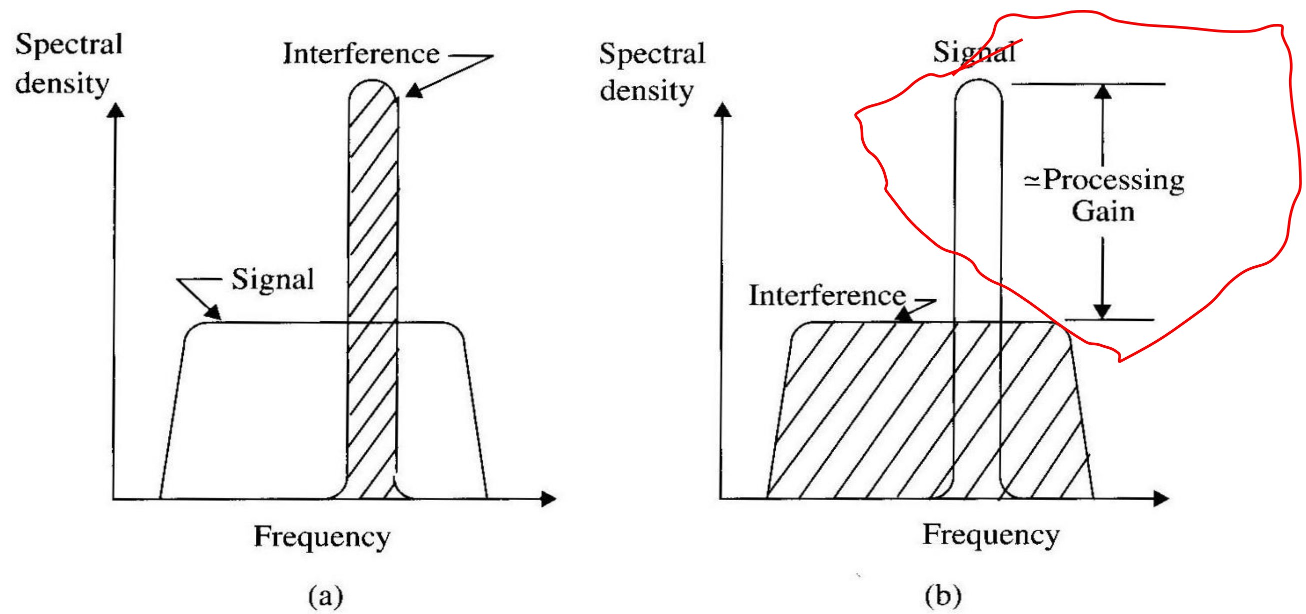

Figure 6.50 Spectra of desired received signal with interference: (a) wideband filter output and (b) correlator output after despreading.

- Most of interfering energy will be outside of signal bandwidth and will be removed with Low Pass Filtering

$$PG = \frac{T_s}{T_c} = \frac{R_c}{R_s} = \frac{W_{ss}}{B}$$

$$\text{where } W_{ss} = \text{SS BW} \quad \text{and } \text{B} = \text{signal BW}$$

- The larger the PG, the greater the ability to suppress in-band interference.

Performance of DS spread spectrum

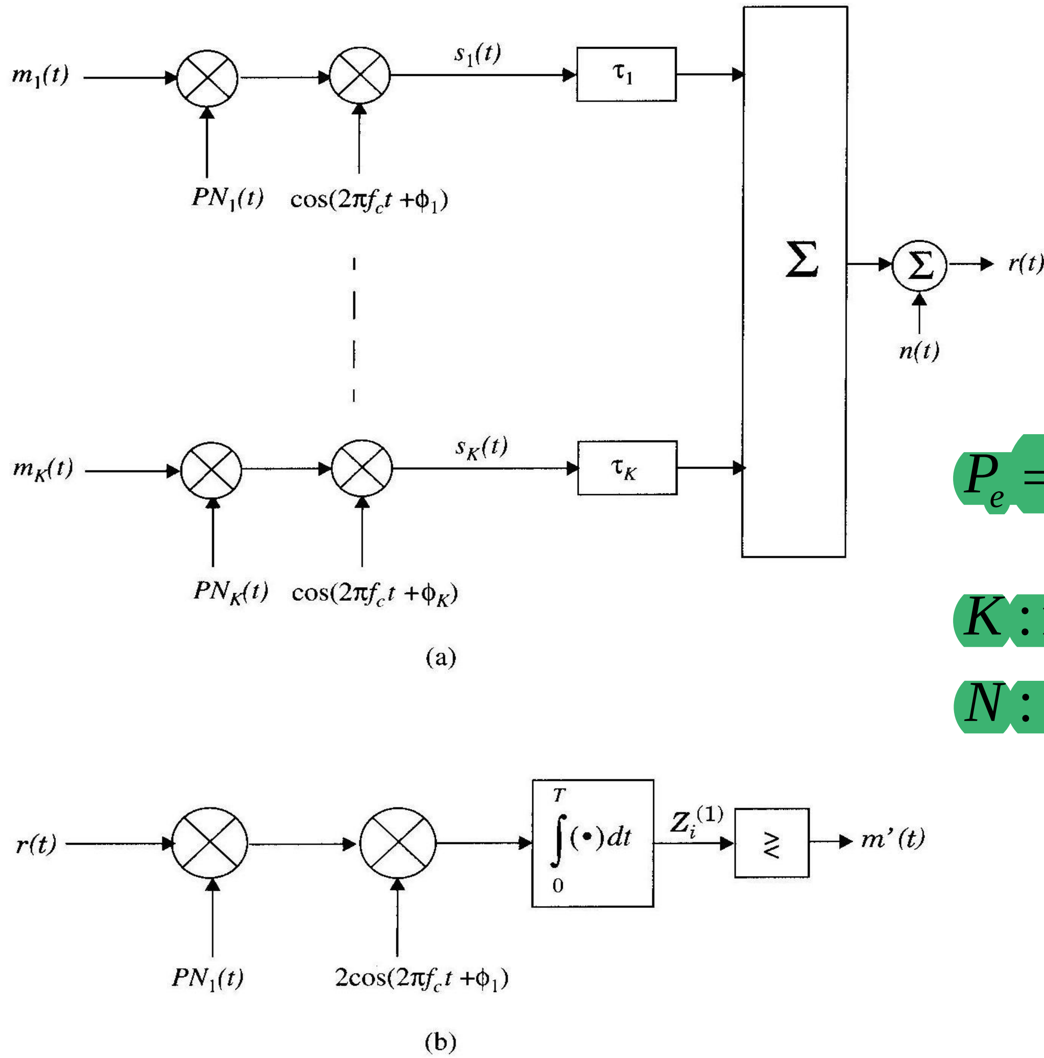

Figure 6.52 A simplified diagram of a DS–SS system with K users. (a) Model of K users in a CDMA spread spectrum system; (b) receiver structure for User 1.

$$P_e = Q\left(\sqrt{\frac{3N}{K-1}}\right)$$

K : multiple acess users

N : Chips

Performance of FH spread spectrum

- Error rate due to multiple access interference

$$\lim_{\frac{E_b}{N_0}\to\infty} (P_e) = \frac{1}{2}\left[\frac{K-1}{M}\right]$$

K : multiple acess users

M : Hopping channel

- To combat the occasional hits
  - Applying Reed-Solomon or other burst error correcting codes
- Not as susceptible to the near-far problem

- With Spread Spectrum Modulation, users are able to share a common band of frequencies
  - a multiple access technique
    - TDMA: Users share a band of frequencies, but use a different time slot
    - FDMA: Users share a band of frequencies, but use a different slice of frequency
    - SSM enables CDMA (Code Division Multiple Access): Users share a band of frequencies, but each use a different spreading code.

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- Sprint PCS, Cingular, and AT&T Wirless → DS-SSM
  - Sprint PCS was the first nationwide deployment of a CDMA system
  - Technology started by Qualcomm
- The main disadvantage of DS-SSM is that very good power control of mobiles is required
  - Near/far problem
  - Discussed in Chapter 8

Performance of digital modulation in slow flat-fading channel

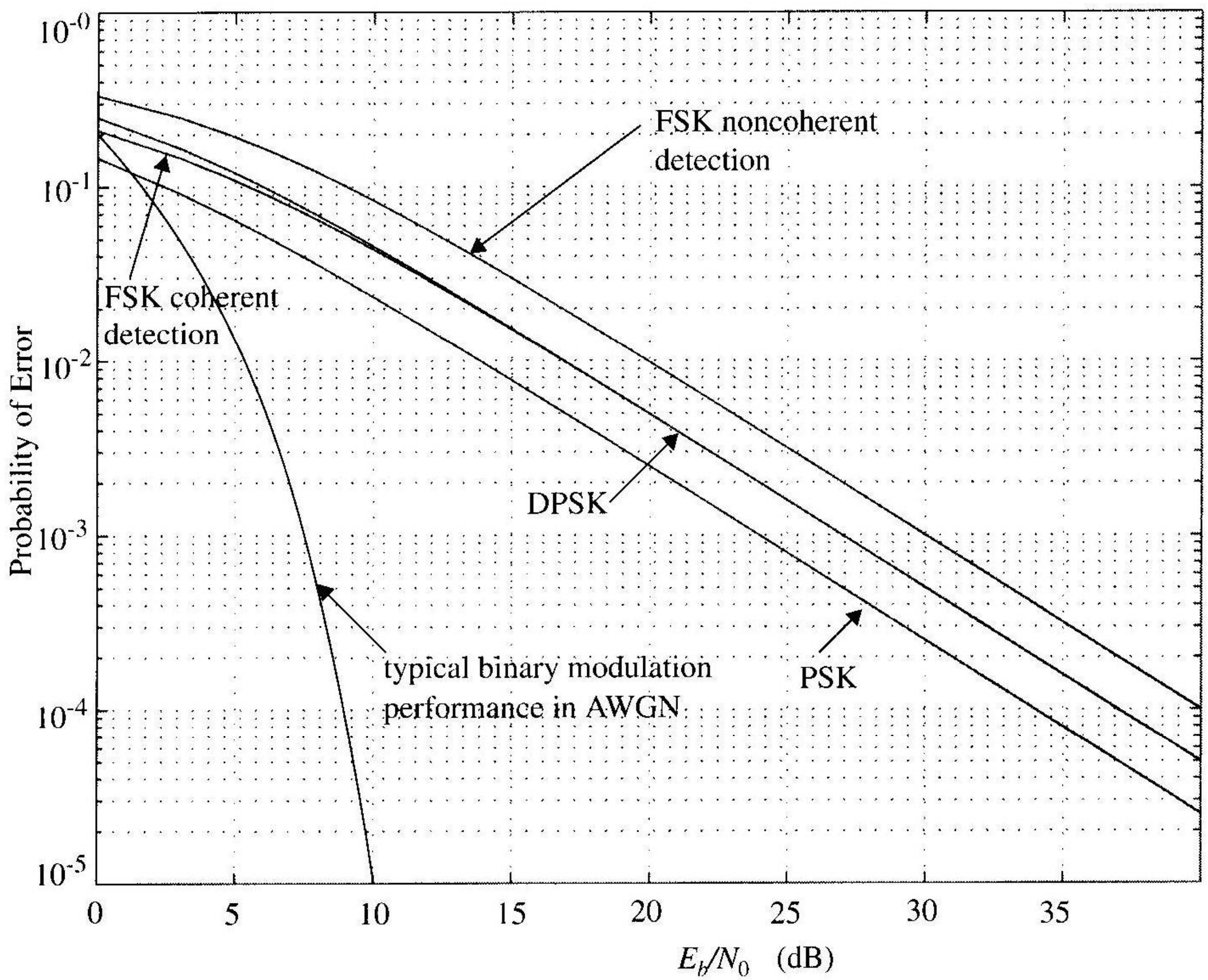

Figure 6.53 Bit error rate performance of binary modulation schemes in a Rayleigh flat-fading channel as compared to a typical performance curve in AWGN.

Performance of digital modulation in frequency selective channel

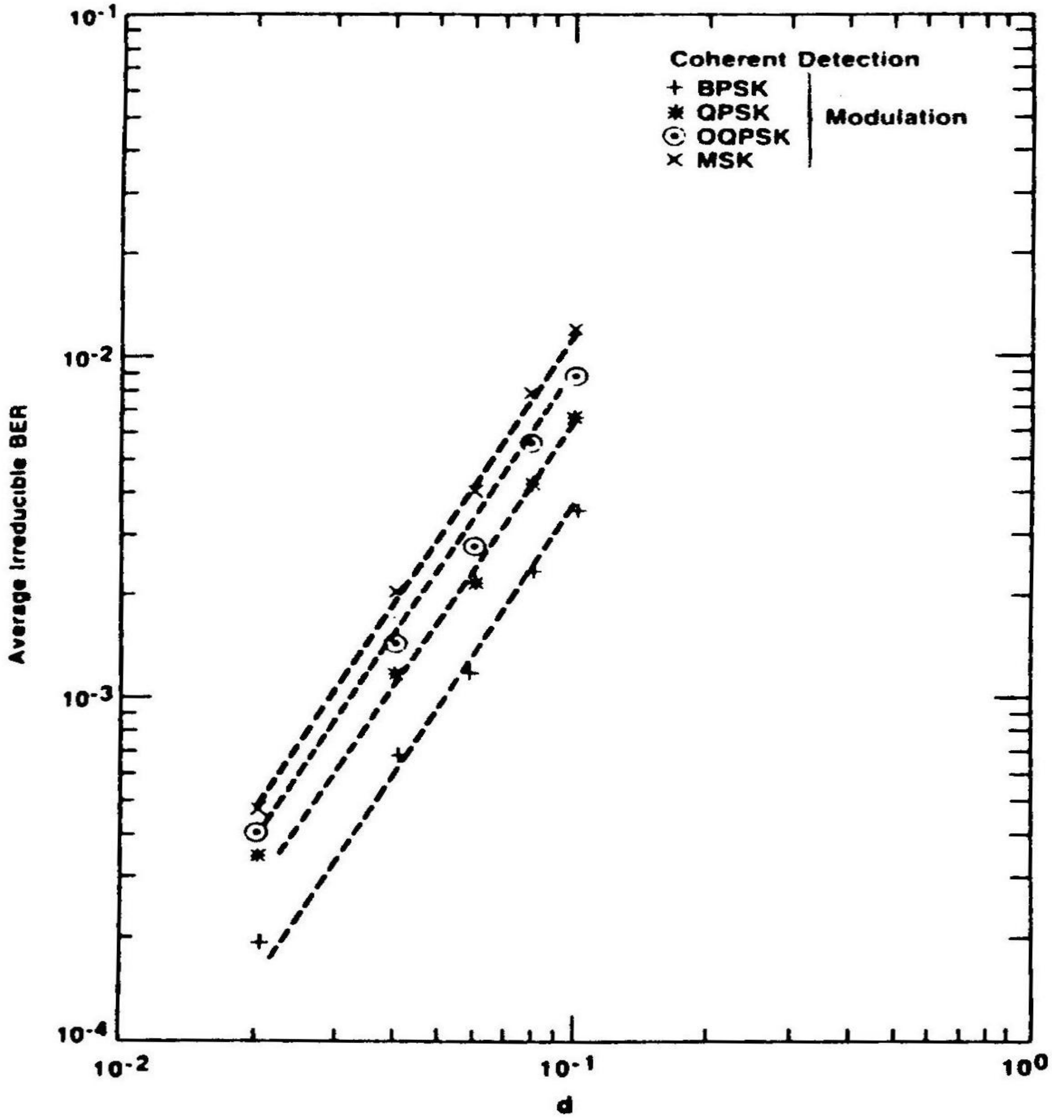

Figure 6.54 The irreducible BER performance for different modulations with coherent detection for a channel with a Gaussian shaped power delay profile. The parameter *d* is the rms delay spread normalized by the symbol period [from [Chu87] © IEEE].

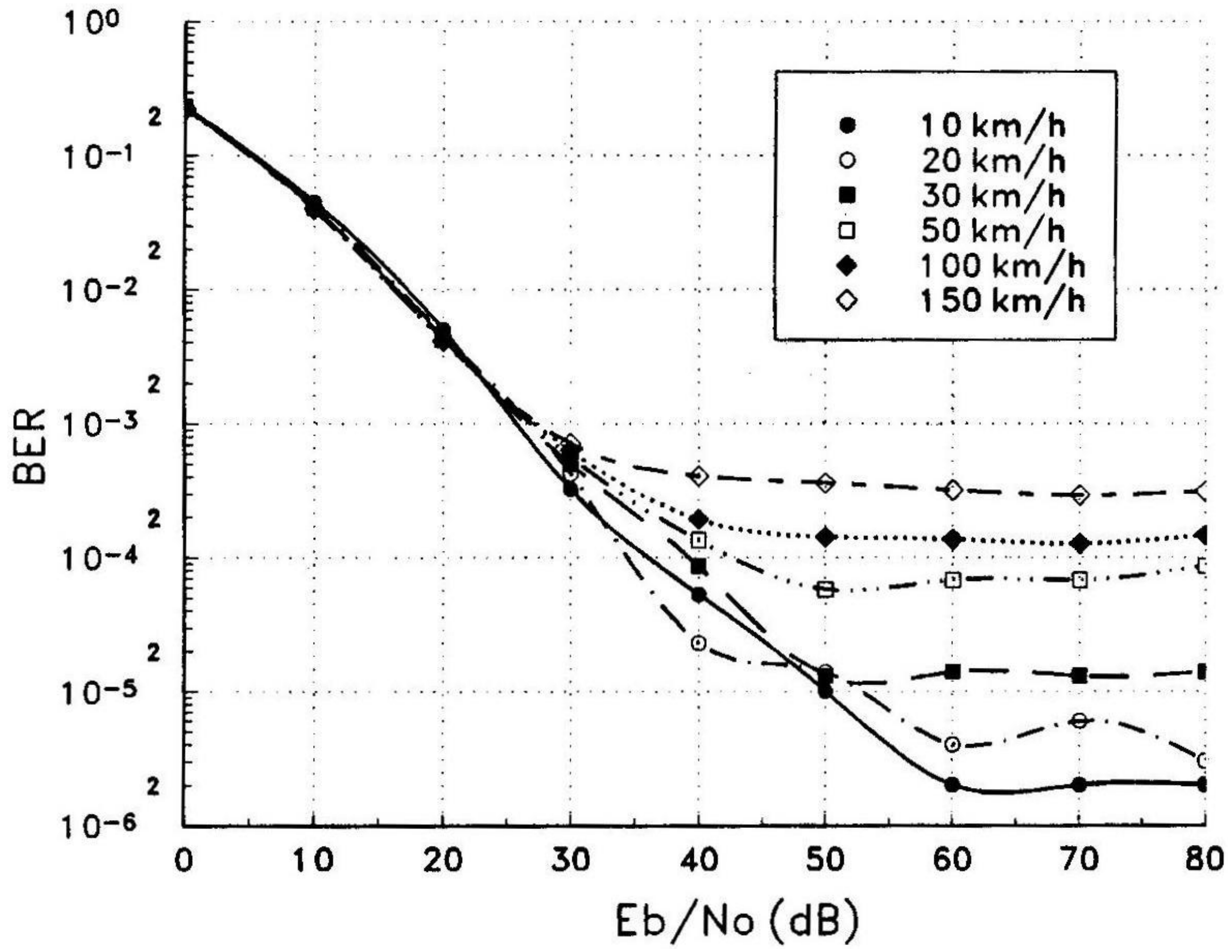

Figure 6.58 BER performance versus E_b / N_0 for $\pi/4$ DQPSK in a Raleigh flat-fading channel for various mobile speeds: $f_c = 850$ MHz, $f_s = 24$ ksps, raised cosine rolloff factor is 0.2, $C/I = 100$ dB. Generated by BERSIM [from [Fun93] © IEEE].

- Next lectures: Using the concept of redundancy to improve wireless signal quality.
  - Redundant antennas →
    diversity to overcome fading.
  - Redundant data bits →
    error control codes to detect and correct errors.