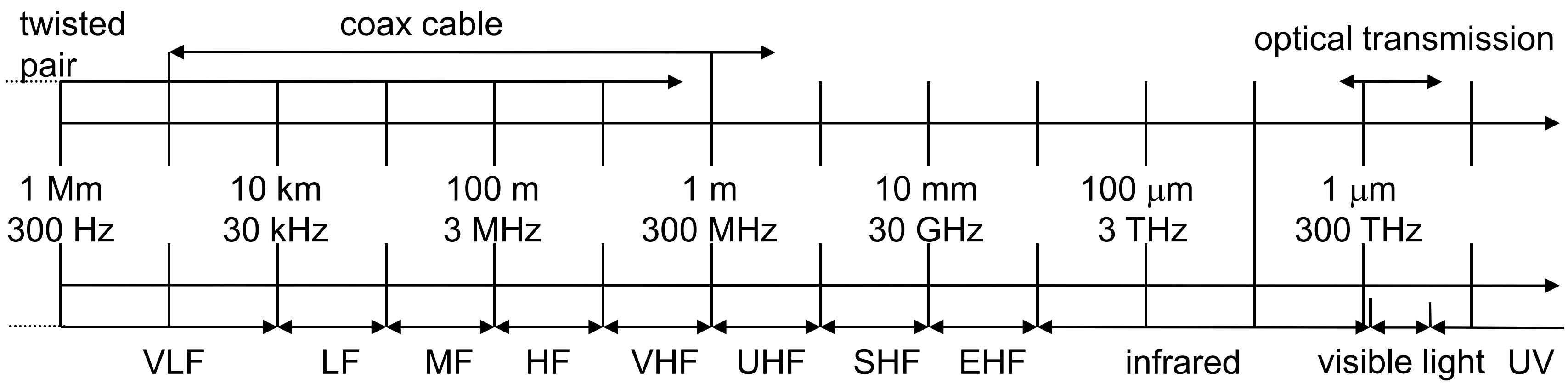
Wireless Transmission

- Frequencies
- Signals
- Antenna
- Signal propagation
- Multiplexing
- Spread spectrum
- Modulation

Frequencies for communication



VLF = Very Low Frequency

LF = Low Frequency

MF = Medium Frequency

HF = High Frequency

VHF = Very High Frequency

UHF = Ultra High Frequency

SHF = Super High Frequency

EHF = Extra High Frequency

UV = Ultraviolet Light

Frequency and wave length:

$\lambda = c/f$

wave length λ, speed of light $c \cong 3 \times 10^8$ m/s, frequency f

Frequencies for mobile communication

- VHF-/UHF-ranges for mobile radio
  - simple, small antenna for cars
  - deterministic propagation characteristics, reliable connections
- SHF and higher for directed radio links, satellite communication
  - small antenna, focusing
  - large bandwidth available
- **Wireless LANs use frequencies in UHF to SHF spectrum**
  - **some systems planned up to EHF**
  - **limitations due to absorption by water and oxygen molecules (resonance frequencies)**
    - **weather dependent fading, signal loss caused by heavy rainfall etc.**

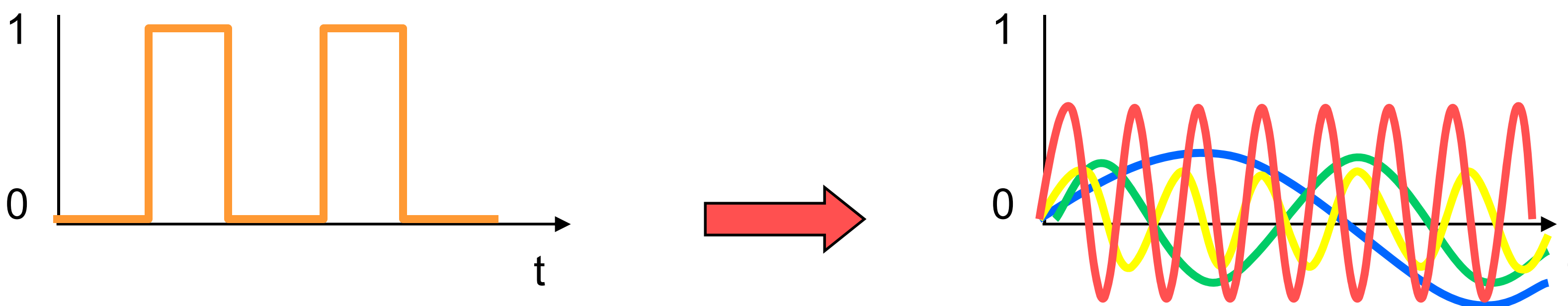
Signals I

- physical representation of data
- function of time and location
- signal parameters: parameters representing the value of data
- classification
  - continuous time/discrete time
  - continuous values/discrete values
  - analog signal = continuous time and continuous values
  - digital signal = discrete time and discrete values
- signal parameters of periodic signals:
  period T, frequency f=1/T, amplitude A, phase shift φ
  - sine wave as special periodic signal for a carrier:

$$s(t) = A_t \sin(2 \pi f_t t + \varphi_t)$$

Fourier representation of periodic signals

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi n f t) + \sum_{n=1}^{\infty} b_n \cos(2\pi n f t)$$

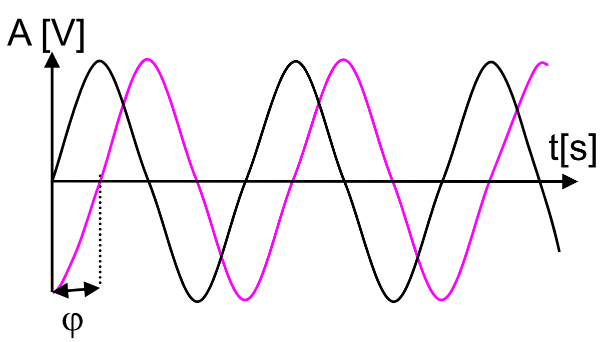


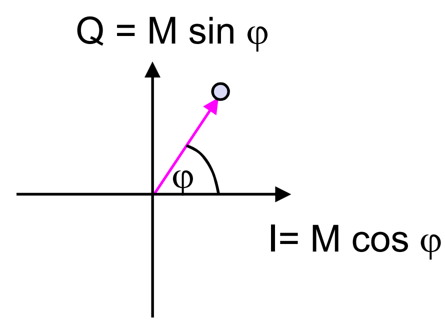
ideal periodic signal

real composition
(based on harmonics)

Signals II

- Different representations of signals
  - amplitude (amplitude domain)
  - frequency spectrum (frequency domain)
  - phase state diagram (amplitude M and phase φ in polar coordinates)

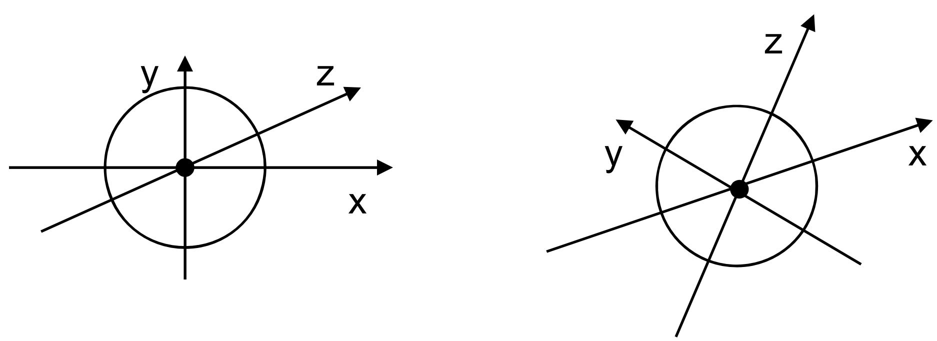




- Composed signals transferred into frequency domain using Fourier transformation
- Digital signals need
  - infinite frequencies for perfect transmission
  - modulation with a carrier frequency for transmission (analog signal!)

Antennas: isotropic radiator

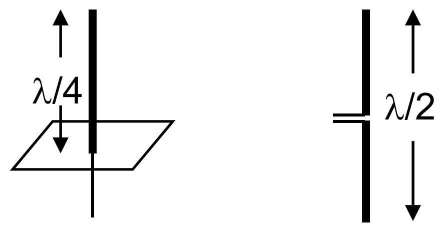
- Radiation and reception of electromagnetic waves, coupling of wires to space for radio transmission
- Isotropic radiator: equal radiation in all directions (three dimensional) - only a theoretical reference antenna
- Real antennas always have directive effects (vertically and/or horizontally)
- Radiation pattern: measurement of radiation around an antenna



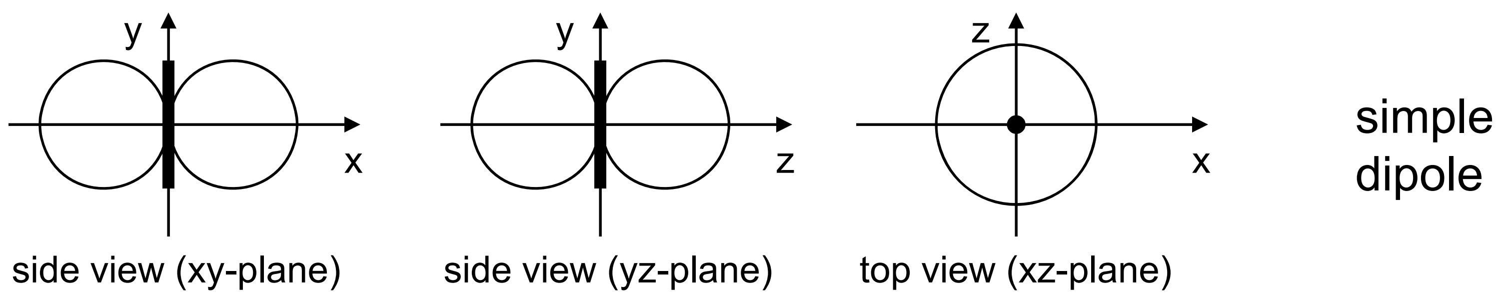
ideal
isotropic
radiator

Antennas: simple dipoles

- Real antennas are not isotropic radiators but, e.g., dipoles with lengths λ/4 on car roofs or λ/2 as Hertzian dipole
  ➔ shape of antenna proportional to wavelength



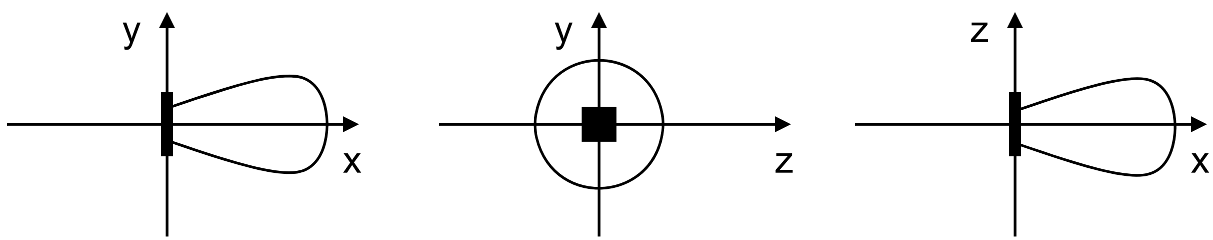
- Example: Radiation pattern of a simple Hertzian dipole



- Gain: maximum power in the direction of the main lobe compared to the power of an isotropic radiator (with the same average power)

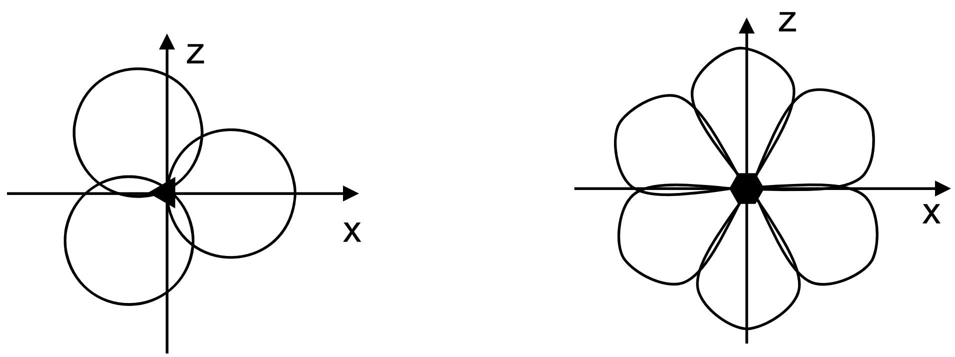
Antennas: directed and sectorized

Often used for microwave connections or base stations for mobile phones (e.g., radio coverage of a valley)



side view (xy-plane) side view (yz-plane) top view (xz-plane)

directed antenna

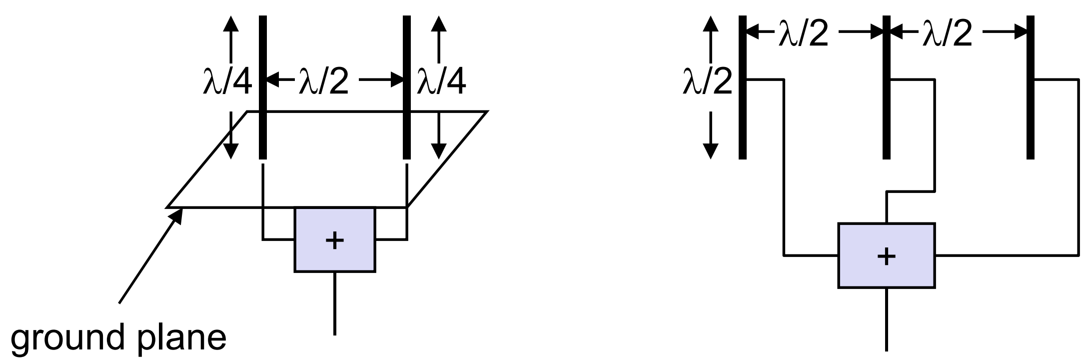


top view, 3 sector top view, 6 sector

sectorized antenna

Antennas: diversity

- Grouping of 2 or more antennas
  - multi-element antenna arrays
- Antenna diversity
  - switched diversity, selection diversity
    - receiver chooses antenna with largest output
  - diversity combining
    - combine output power to produce gain
    - cophasing needed to avoid cancellation

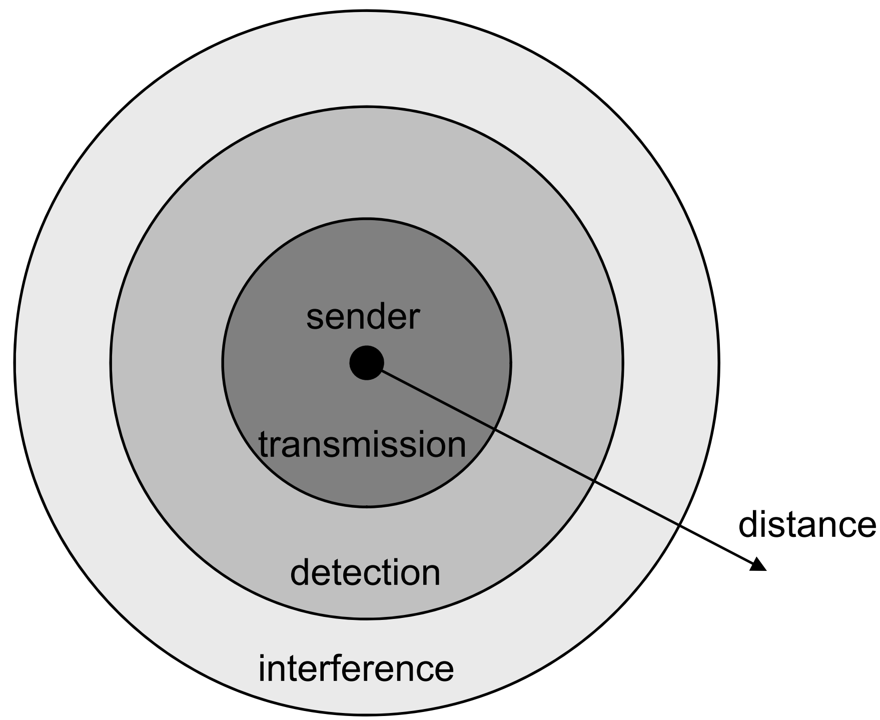


Signal propagation ranges

Transmission range
- communication possible
- low error rate

Detection range
- detection of the signal possible
- no communication possible

Interference range
- signal may not be detected
- signal adds to the background noise



Signal propagation

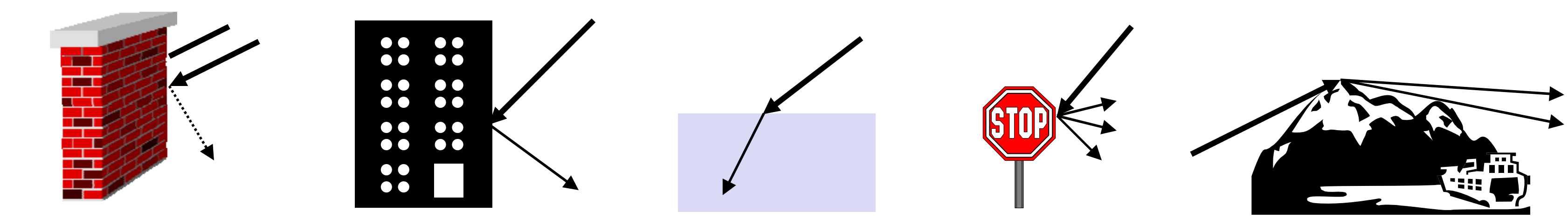
Propagation in free space always like light (straight line)

Receiving power proportional to $1/d^2$

(d = distance between sender and receiver)

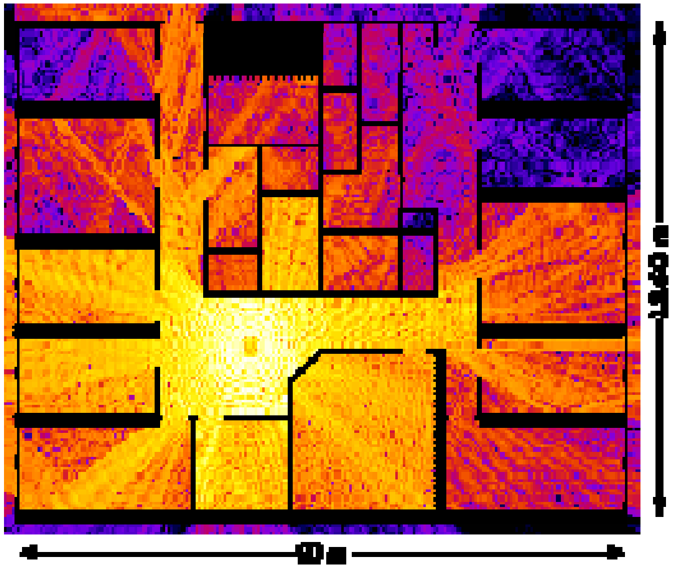
Receiving power additionally influenced by

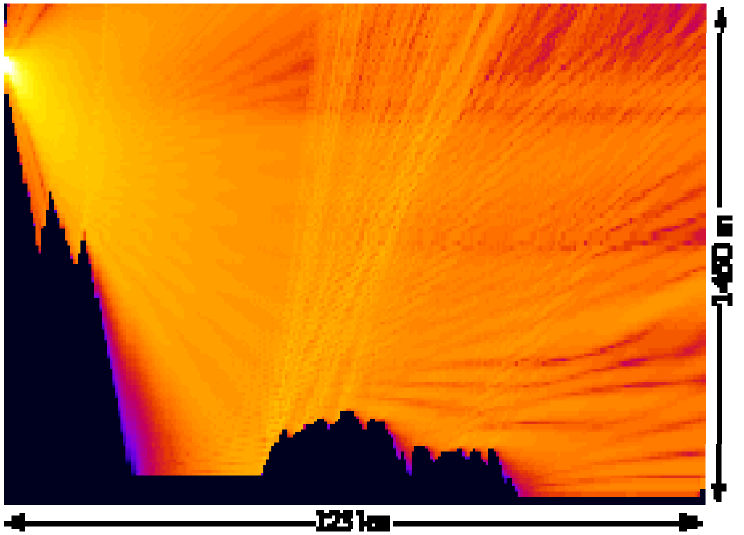
- fading (frequency dependent)
- shadowing
- reflection at large obstacles
- refraction depending on the density of a medium
- scattering at small obstacles
- diffraction at edges

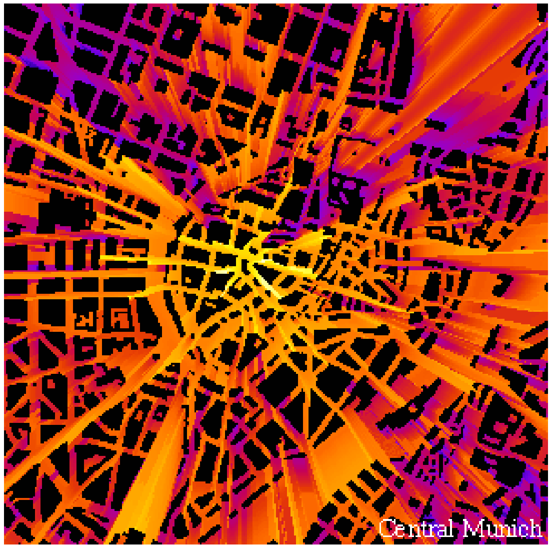


shadowing reflection refraction scattering diffraction

Real world example

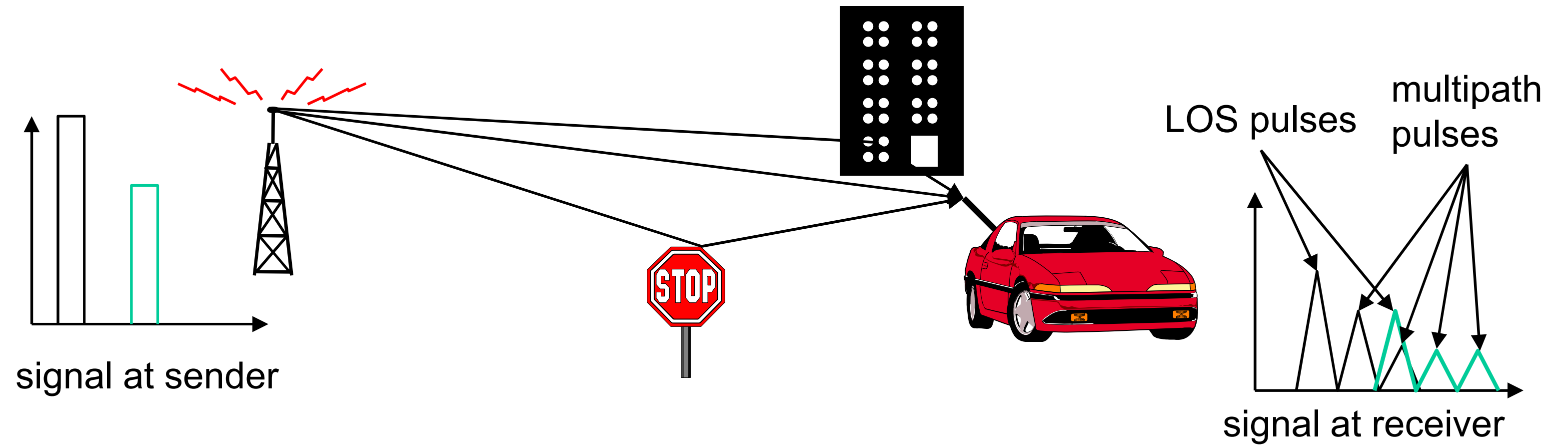






Multipath propagation

Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction



Time dispersion: signal is dispersed over time

➔ interference with “neighbor” symbols, Inter Symbol Interference (ISI)

The signal reaches a receiver directly and phase shifted

➔ distorted signal depending on the phases of the different parts

Effects of mobility

Channel characteristics change over time and location

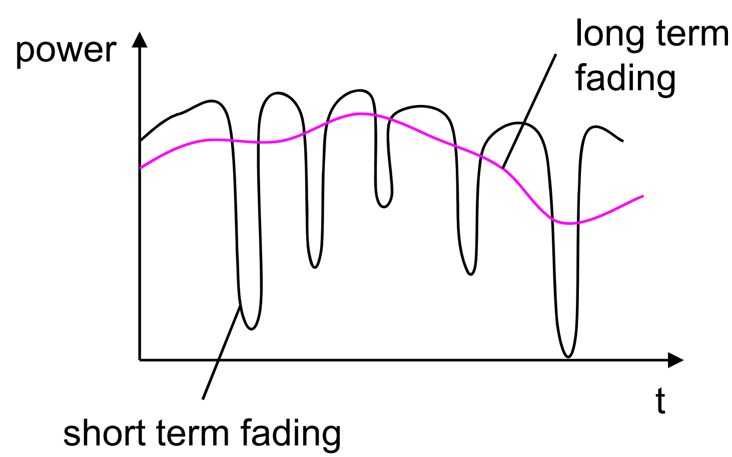
- signal paths change
- different delay variations of different signal parts
- different phases of signal parts

➔ quick changes in the power received (short term fading)

Additional changes in

- distance to sender
- obstacles further away

➔ slow changes in the average power received (long term fading)



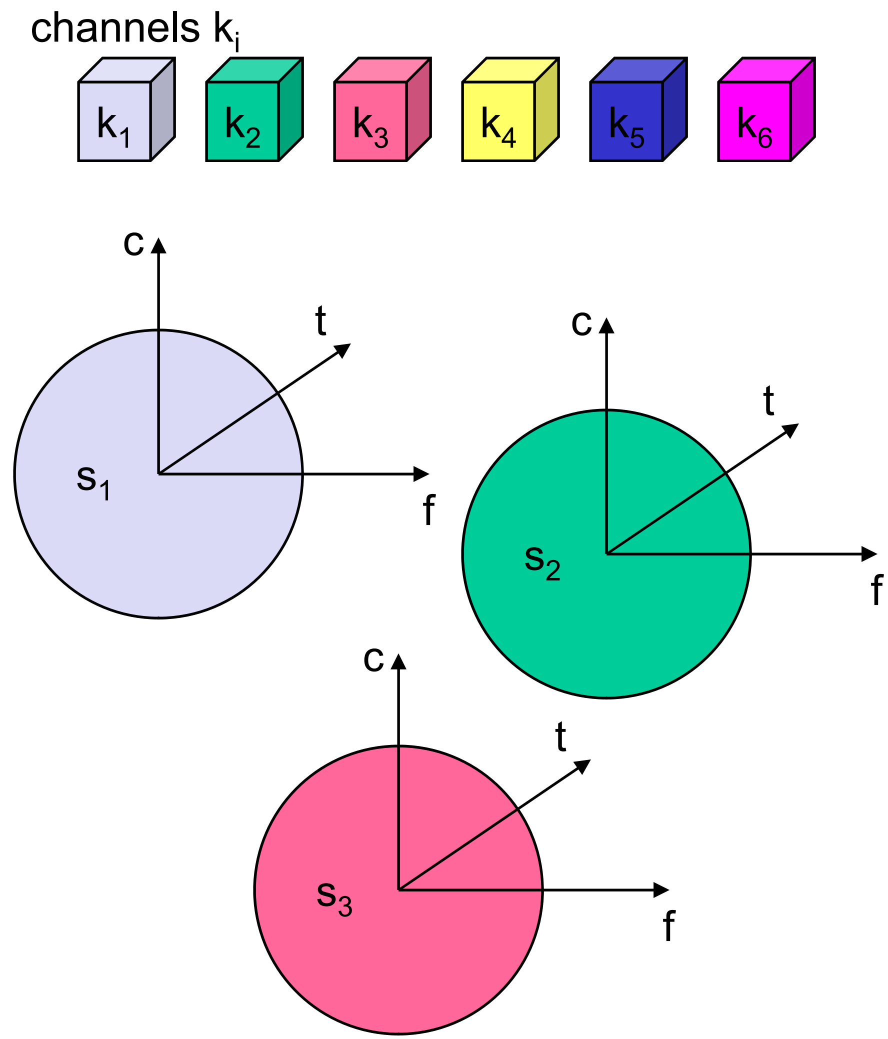
Multiplexing

Multiplexing in 4 dimensions

- space (s_i)
- time (t)
- frequency (f)
- code (c)

Goal: multiple use
of a shared medium

Important: guard spaces needed!



Frequency multiplex

Separation of the whole spectrum into smaller frequency bands

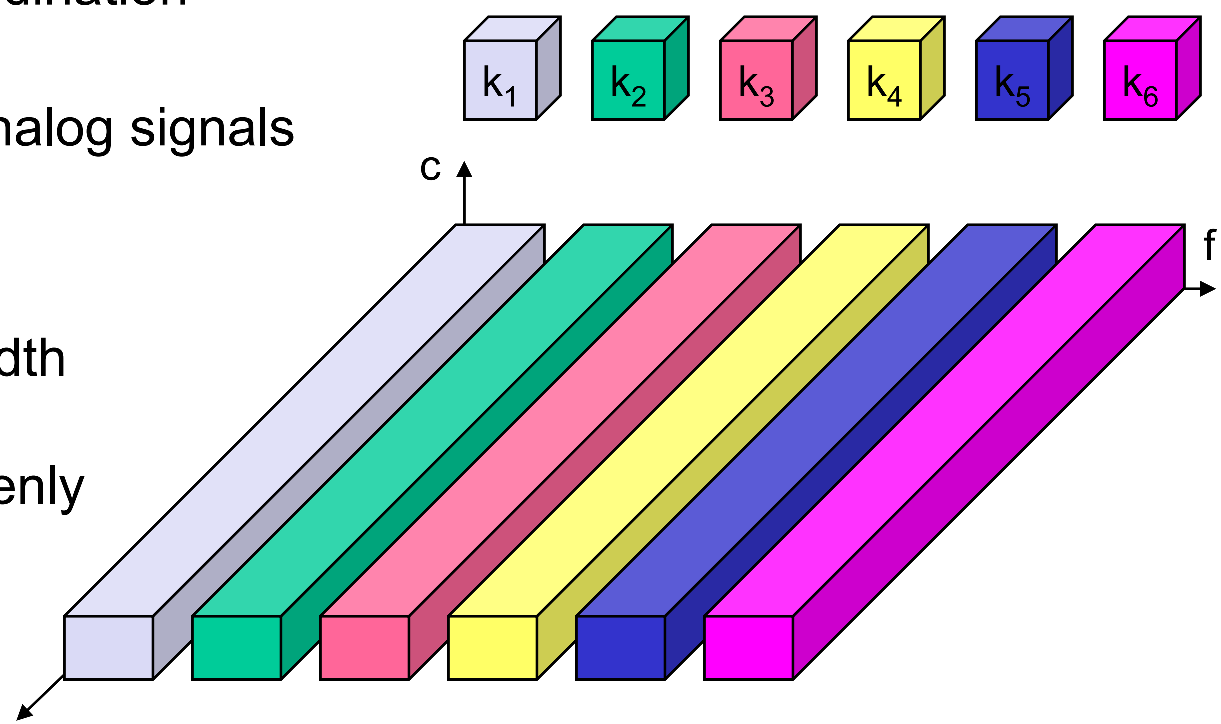
A channel gets a certain band of the spectrum for the whole time

Advantages:

- no dynamic coordination necessary
- works also for analog signals

Disadvantages:

- waste of bandwidth if the traffic is distributed unevenly
- inflexible
- guard spaces



Time multiplex

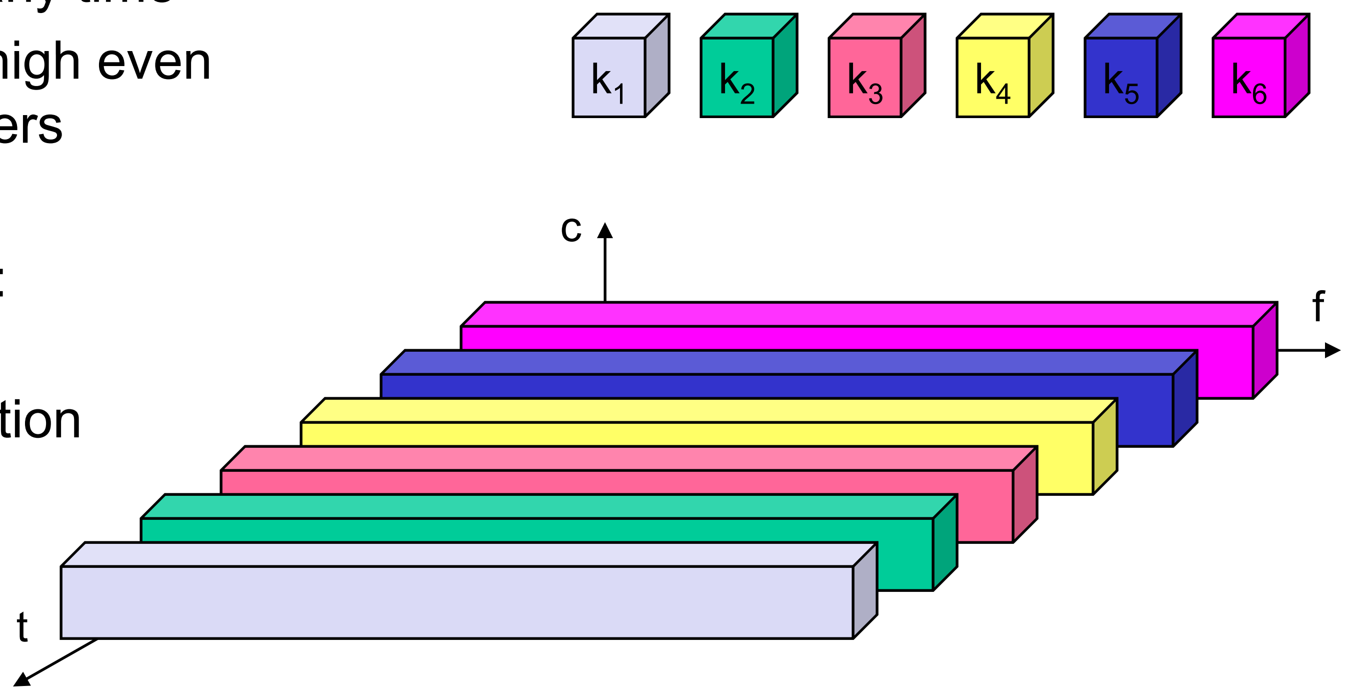
A channel gets the whole spectrum for a certain amount of time

Advantages:

- only one carrier in the medium at any time
- throughput high even for many users

Disadvantages:

- precise synchronization necessary



Time and frequency multiplex

Combination of both methods

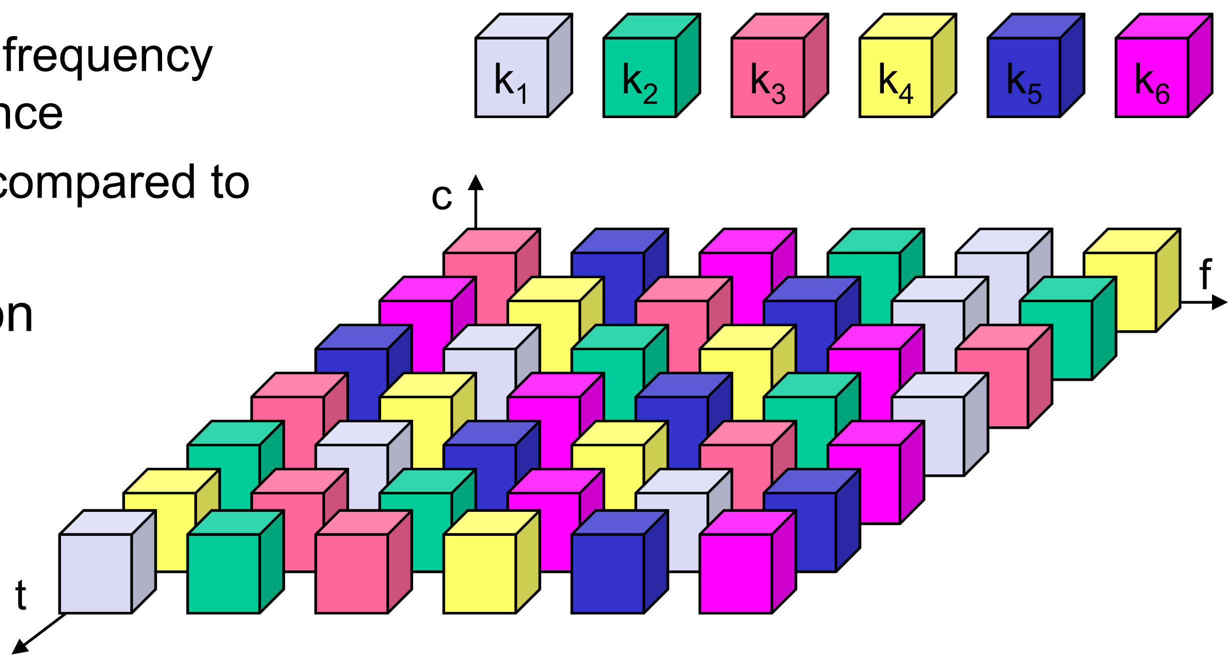
A channel gets a certain frequency band for a certain amount of time

Example: GSM

Advantages:

- better protection against tapping
- protection against frequency selective interference
- higher data rates compared to code multiplex

but: precise coordination required



Code multiplex

Each channel has a unique code

All channels use the same spectrum at the same time

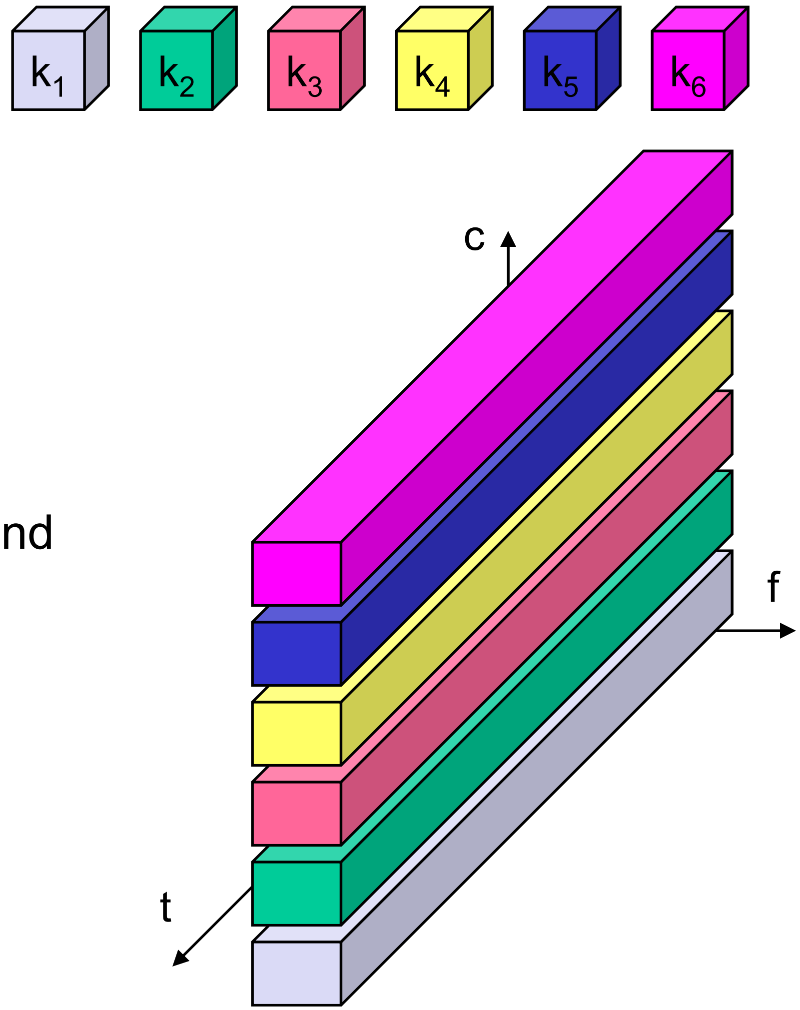
Advantages:

- bandwidth efficient
- no coordination and synchronization necessary
- good protection against interference and tapping

Disadvantages:

- lower user data rates
- more complex signal regeneration

Implemented using spread spectrum technology



Modulation

Digital modulation

- digital data is translated into an analog signal (baseband)
- ASK, FSK, PSK - main focus in this chapter
- differences in spectral efficiency, power efficiency, robustness

Analog modulation

- shifts center frequency of baseband signal up to the radio carrier

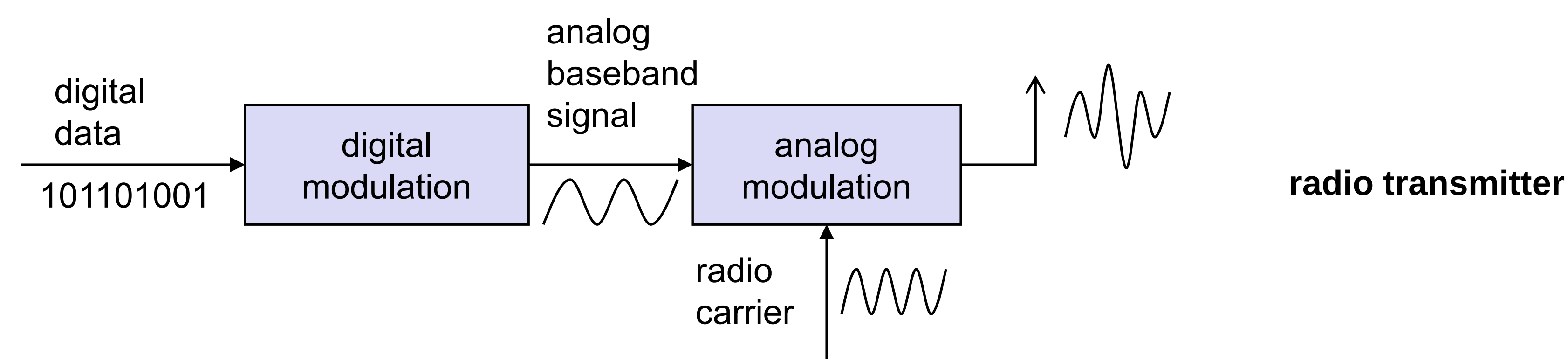
Motivation

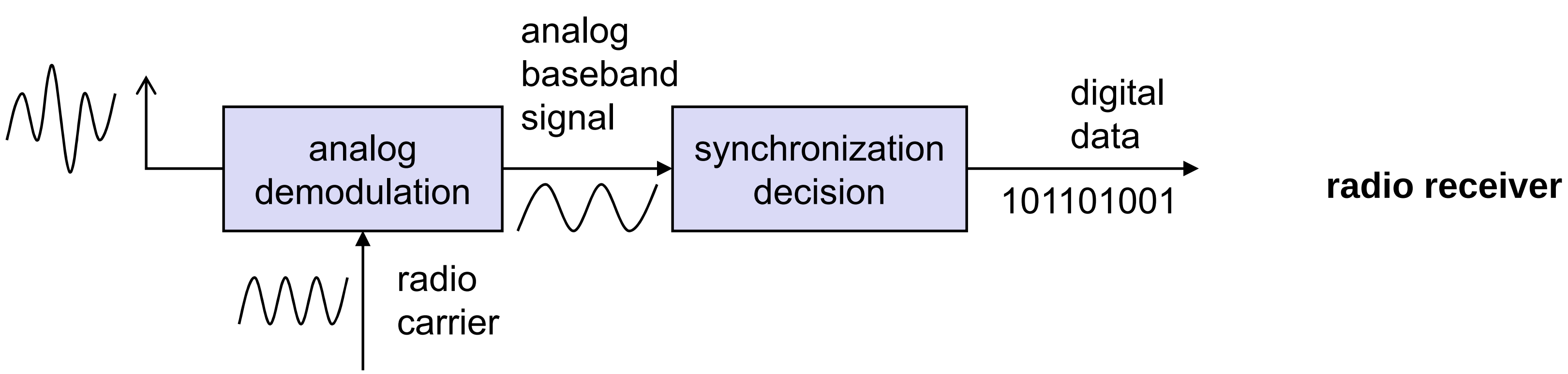
- smaller antennas (e.g., $\lambda/4$)
- Frequency Division Multiplexing
- medium characteristics

Basic schemes

- Amplitude Modulation (AM)
- Frequency Modulation (FM)
- Phase Modulation (PM)

Modulation and demodulation

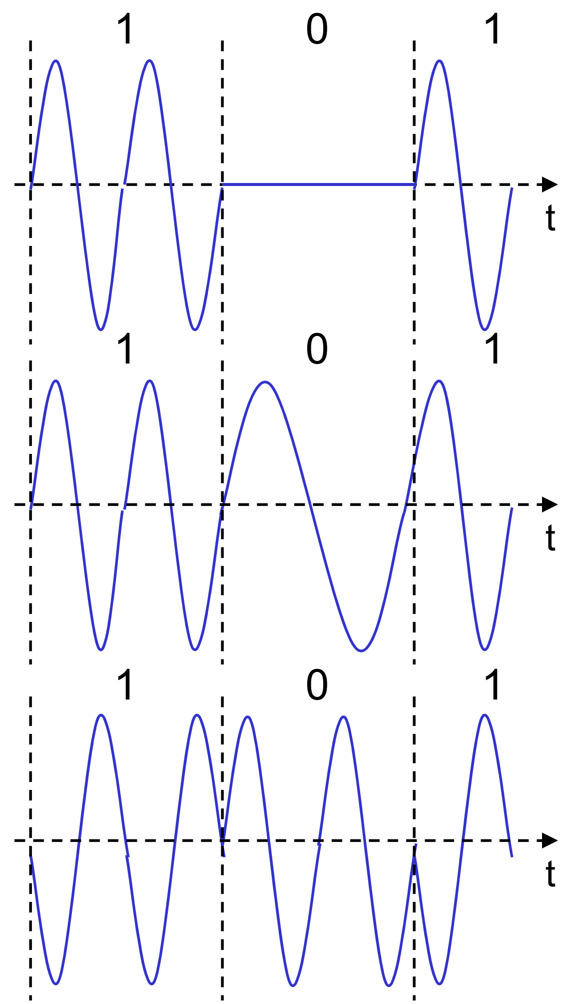




Digital modulation

Modulation of digital signals known as Shift Keying

- Amplitude Shift Keying (ASK):
  - very simple
  - low bandwidth requirements
  - very susceptible to interference
- Frequency Shift Keying (FSK):
  - needs larger bandwidth
- Phase Shift Keying (PSK):
  - more complex
  - robust against interference

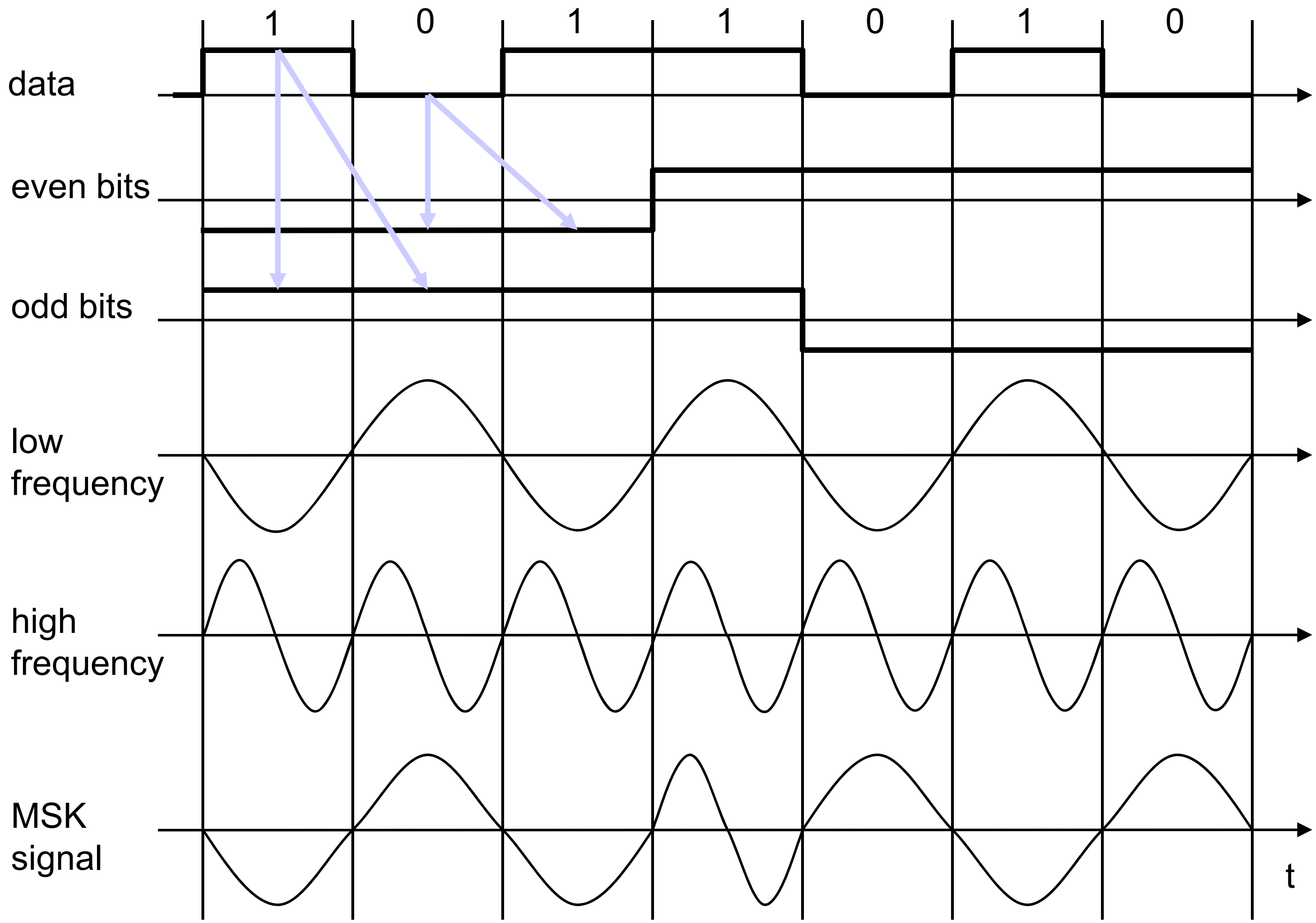


Advanced Frequency Shift Keying

- bandwidth needed for FSK depends on the distance between the carrier frequencies
- special pre-computation avoids sudden phase shifts
  ➔ MSK (Minimum Shift Keying)
- bit separated into even and odd bits, the duration of each bit is doubled
- depending on the bit values (even, odd) the higher or lower frequency, original or inverted is chosen
- the frequency of one carrier is twice the frequency of the other
- Equivalent to offset QPSK

- even higher bandwidth efficiency using a Gaussian low-pass filter ➔ GMSK (Gaussian MSK), used in GSM

Example of MSK



bit	
even	0 1 0 1
odd	0 0 1 1
signal value	h n n h - - + +

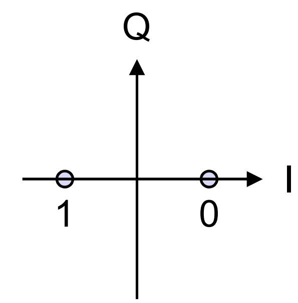
h: high frequency
n: low frequency
+: original signal
-: inverted signal

No phase shifts!

Advanced Phase Shift Keying

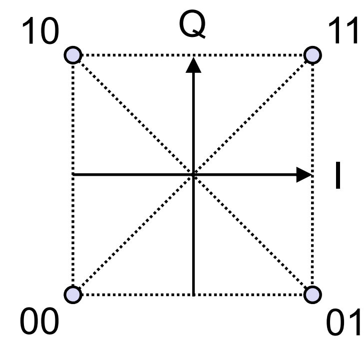
BPSK (Binary Phase Shift Keying):

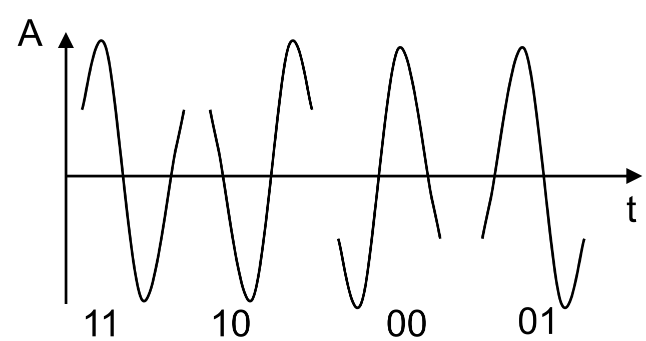
- bit value 0: sine wave
- bit value 1: inverted sine wave
- very simple PSK
- low spectral efficiency
- robust, used e.g. in satellite systems



QPSK (Quadrature Phase Shift Keying):

- 2 bits coded as one symbol
- symbol determines shift of sine wave
- needs less bandwidth compared to BPSK
- more complex



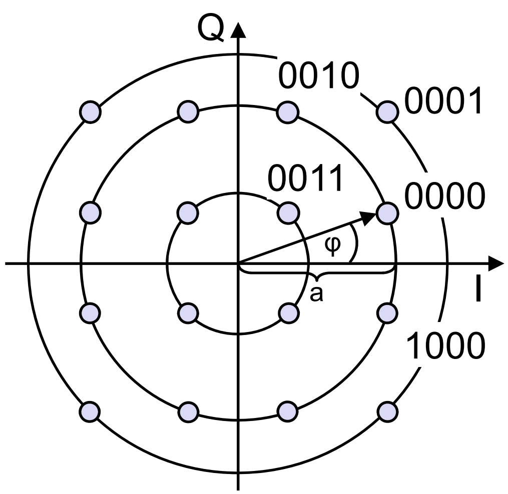


Often also transmission of relative, not absolute phase shift: DQPSK - Differential QPSK (IS-136, PHS)

Quadrature Amplitude Modulation

Quadrature Amplitude Modulation (QAM): combines amplitude and phase modulation

- it is possible to code n bits using one symbol
- 2^n discrete levels, n=2 identical to QPSK
- bit error rate increases with n, but less errors compared to comparable PSK schemes



Example: 16-QAM (4 bits = 1 symbol)

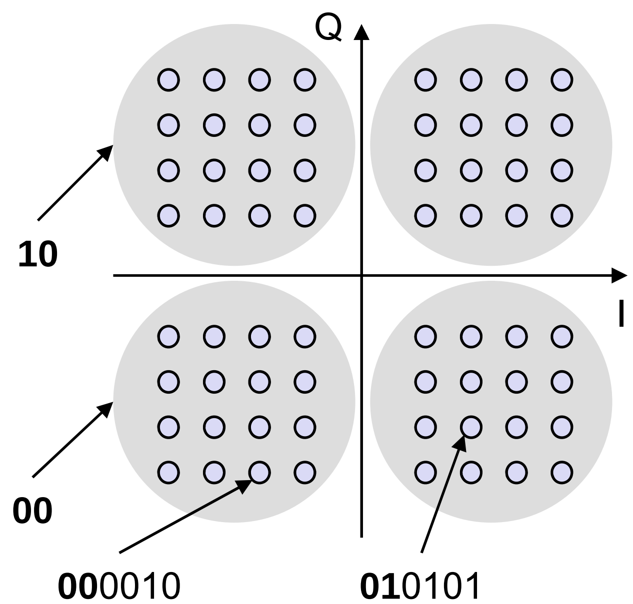
Symbols 0011 and 0001 have the same phase φ, but different amplitude *a*. 0000 and 1000 have different phase, but same amplitude.

➔ used in standard 9600 bit/s modems

Hierarchical Modulation

DVB-T modulates two separate data streams onto a single DVB-T stream

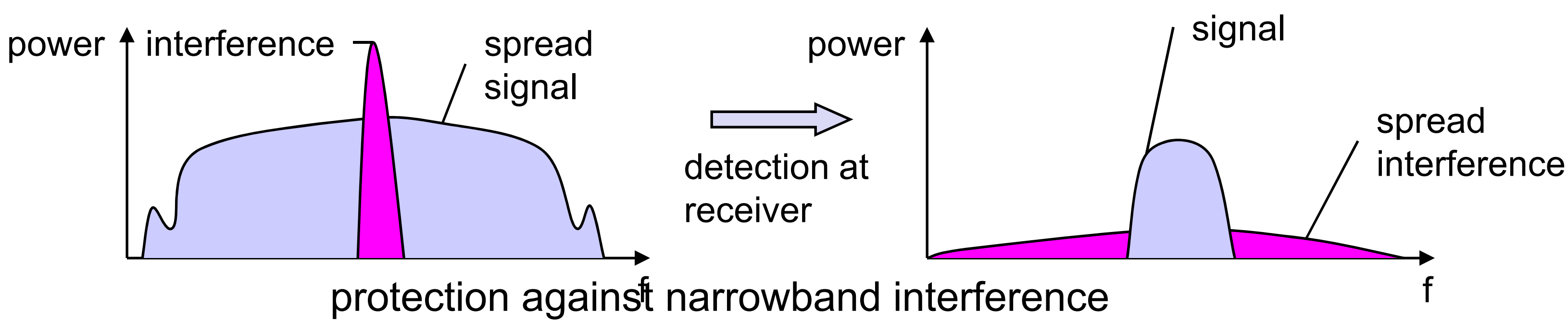
- High Priority (HP) embedded within a Low Priority (LP) stream
- Multi carrier system, about 2000 or 8000 carriers
- QPSK, 16 QAM, 64QAM
- Example: 64QAM
  - good reception: resolve the entire 64QAM constellation
  - poor reception, mobile reception: resolve only QPSK portion
  - 6 bit per QAM symbol, 2 most significant determine QPSK
  - HP service coded in QPSK (2 bit), LP uses remaining 4 bit



Spread spectrum technology

Problem of radio transmission: frequency dependent fading can wipe out narrow band signals for duration of the interference

Solution: spread narrow band signal into broad band signal using special code



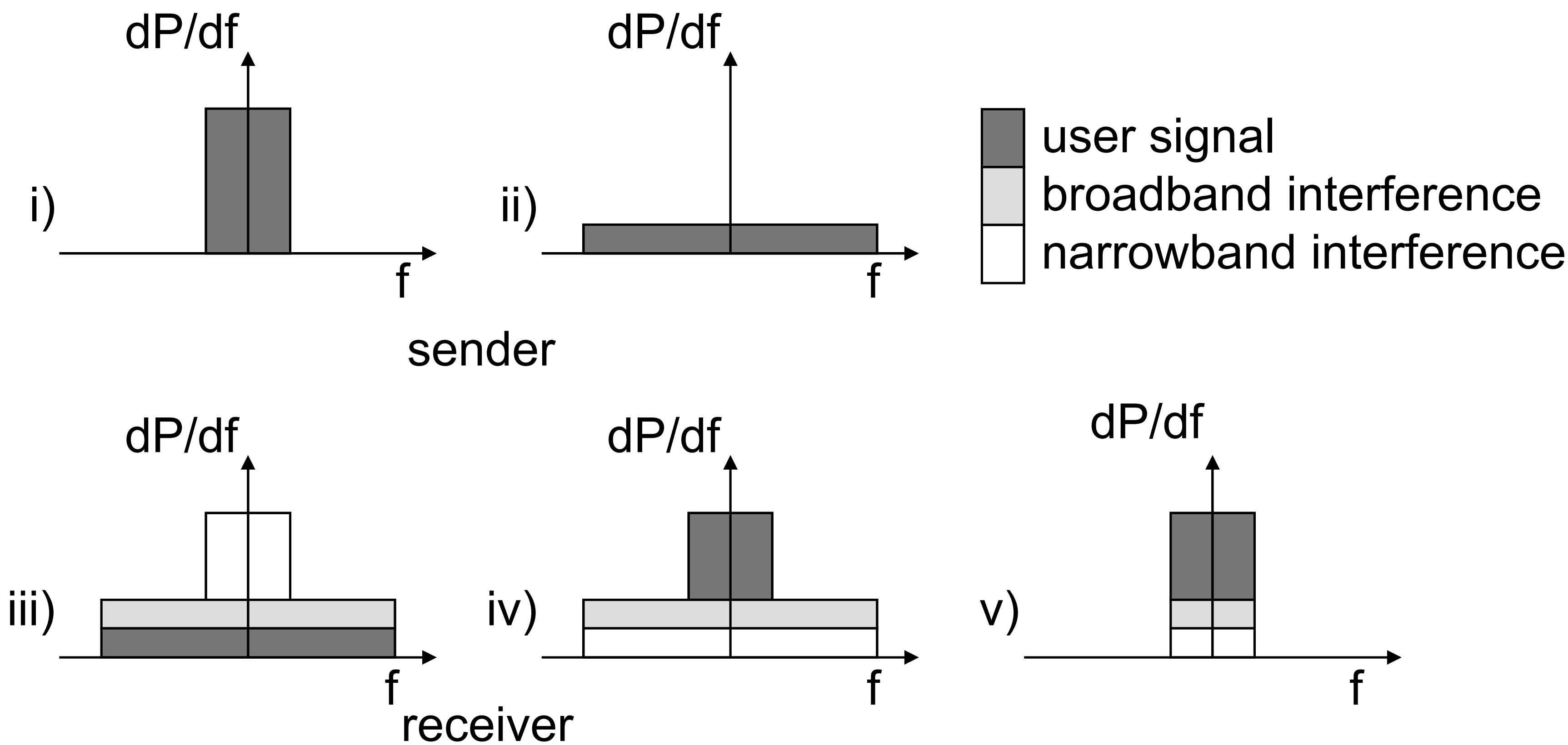
protection against narrowband interference

Side effects:

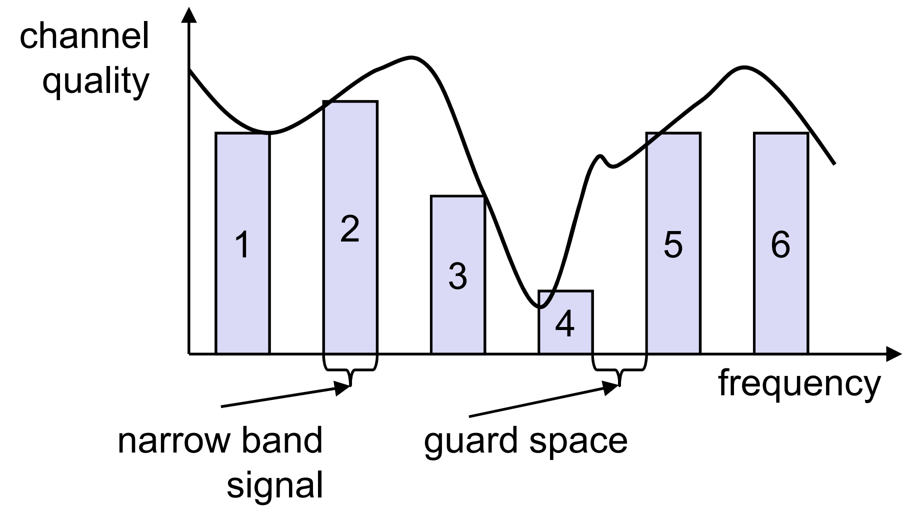
- coexistence of several signals without dynamic coordination
- tap-proof

Alternatives: Direct Sequence, Frequency Hopping

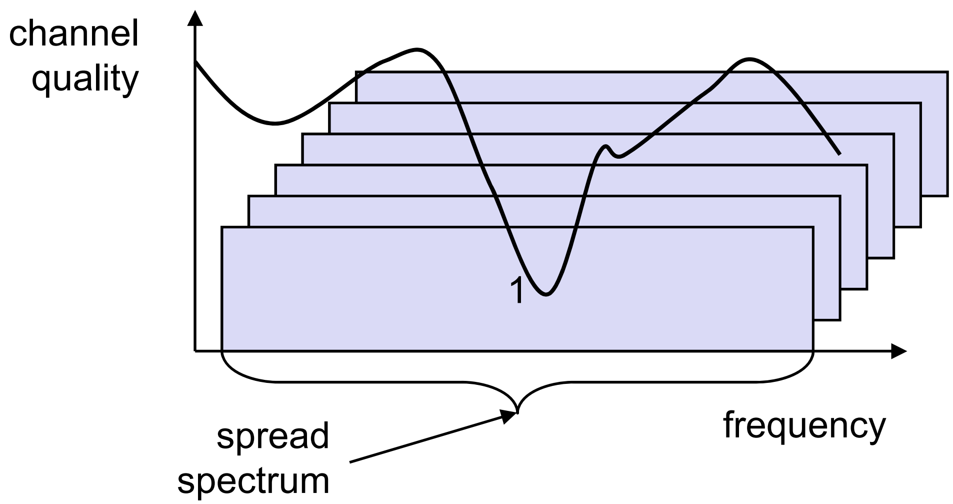
Effects of spreading and interference



Spreading and frequency selective fading



narrowband channels



spread spectrum channels

DSSS (Direct Sequence Spread Spectrum) I

XOR of the signal with pseudo-random number (chipping sequence)

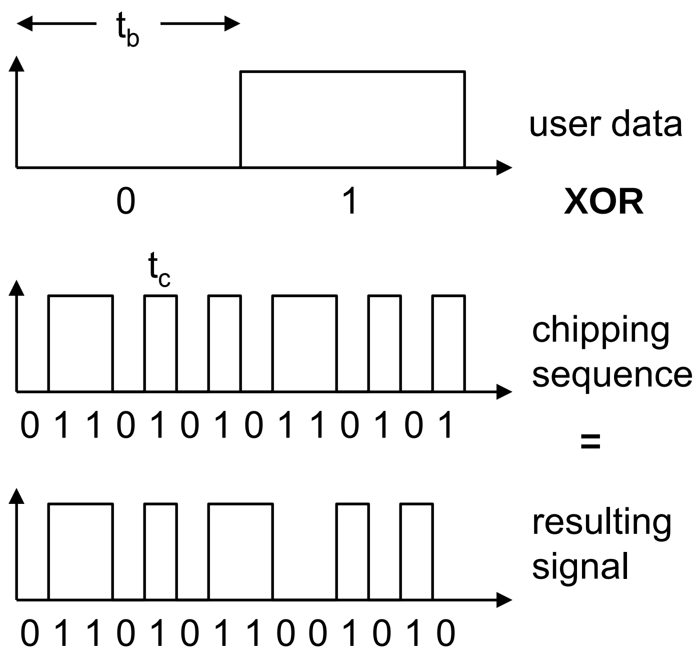
- many chips per bit (e.g., 128) result in higher bandwidth of the signal

Advantages

- reduces frequency selective fading
- in cellular networks
  - base stations can use the same frequency range
  - several base stations can detect and recover the signal
  - soft handover

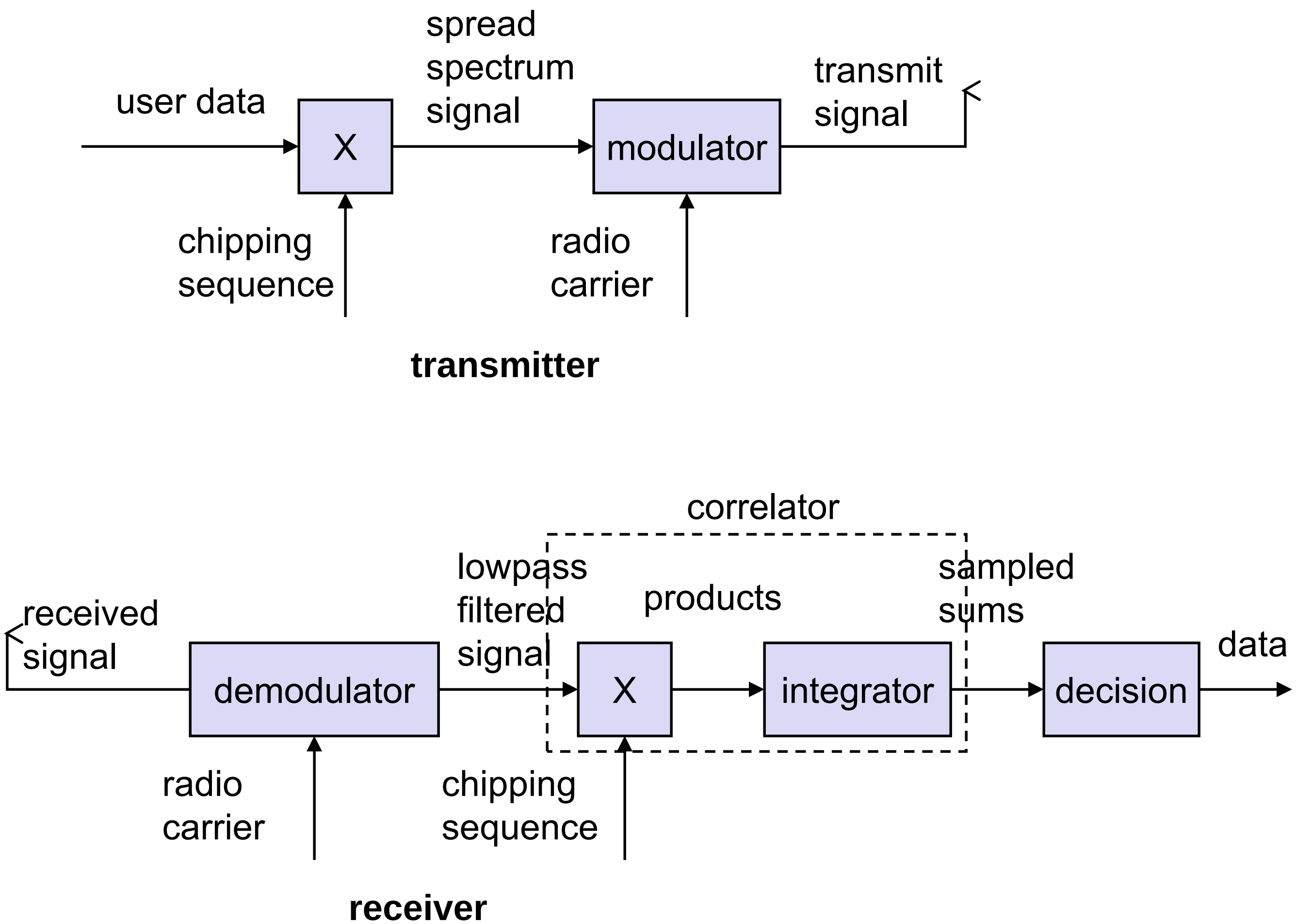
Disadvantages

- precise power control necessary



t_b: bit period
t_c: chip period

DSSS (Direct Sequence Spread Spectrum) II



FHSS (Frequency Hopping Spread Spectrum) I

Discrete changes of carrier frequency

- sequence of frequency changes determined via pseudo random number sequence

Two versions

- Fast Hopping:
  several frequencies per user bit
- Slow Hopping:
  several user bits per frequency

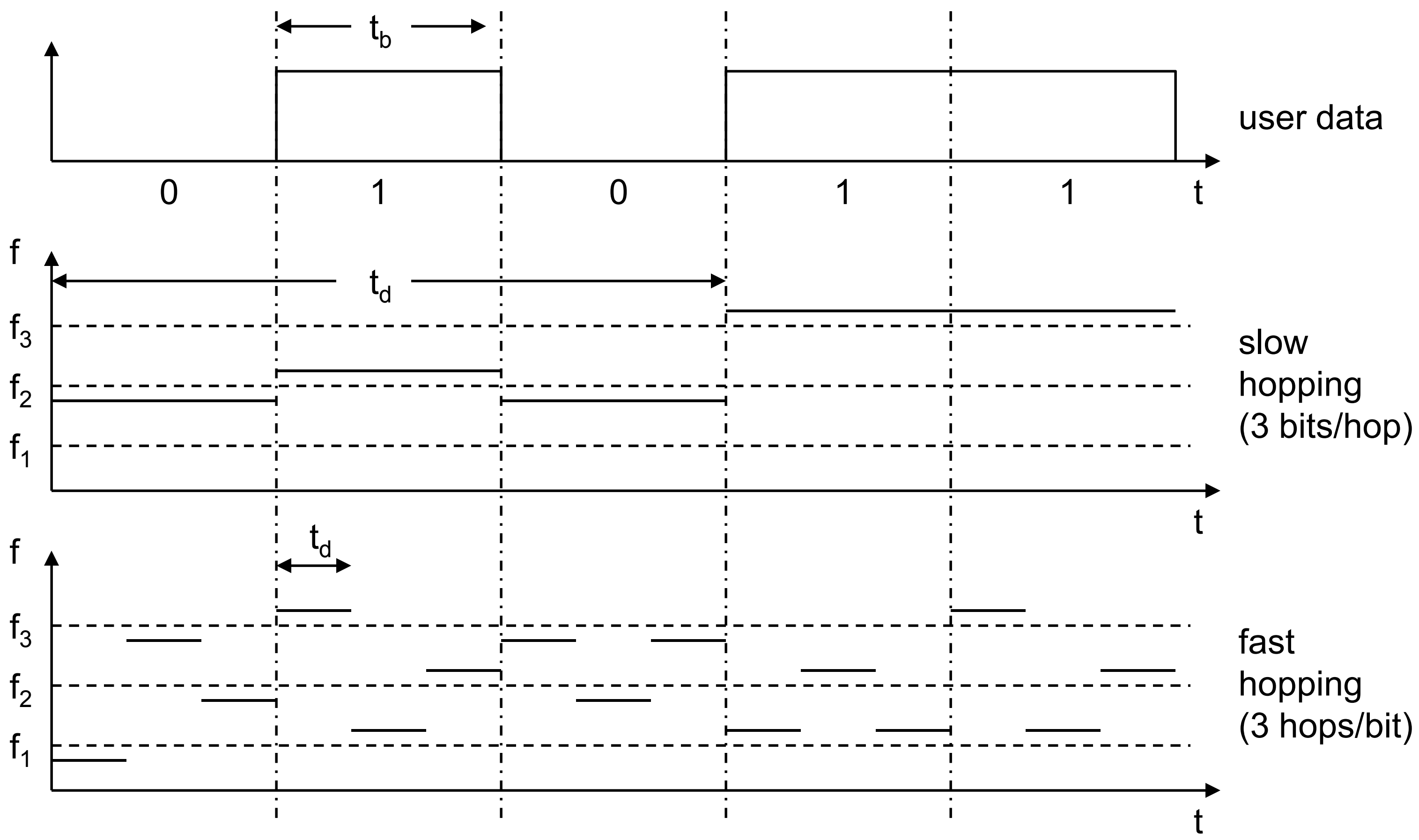
Advantages

- frequency selective fading and interference limited to short period
- simple implementation
- uses only small portion of spectrum at any time

Disadvantages

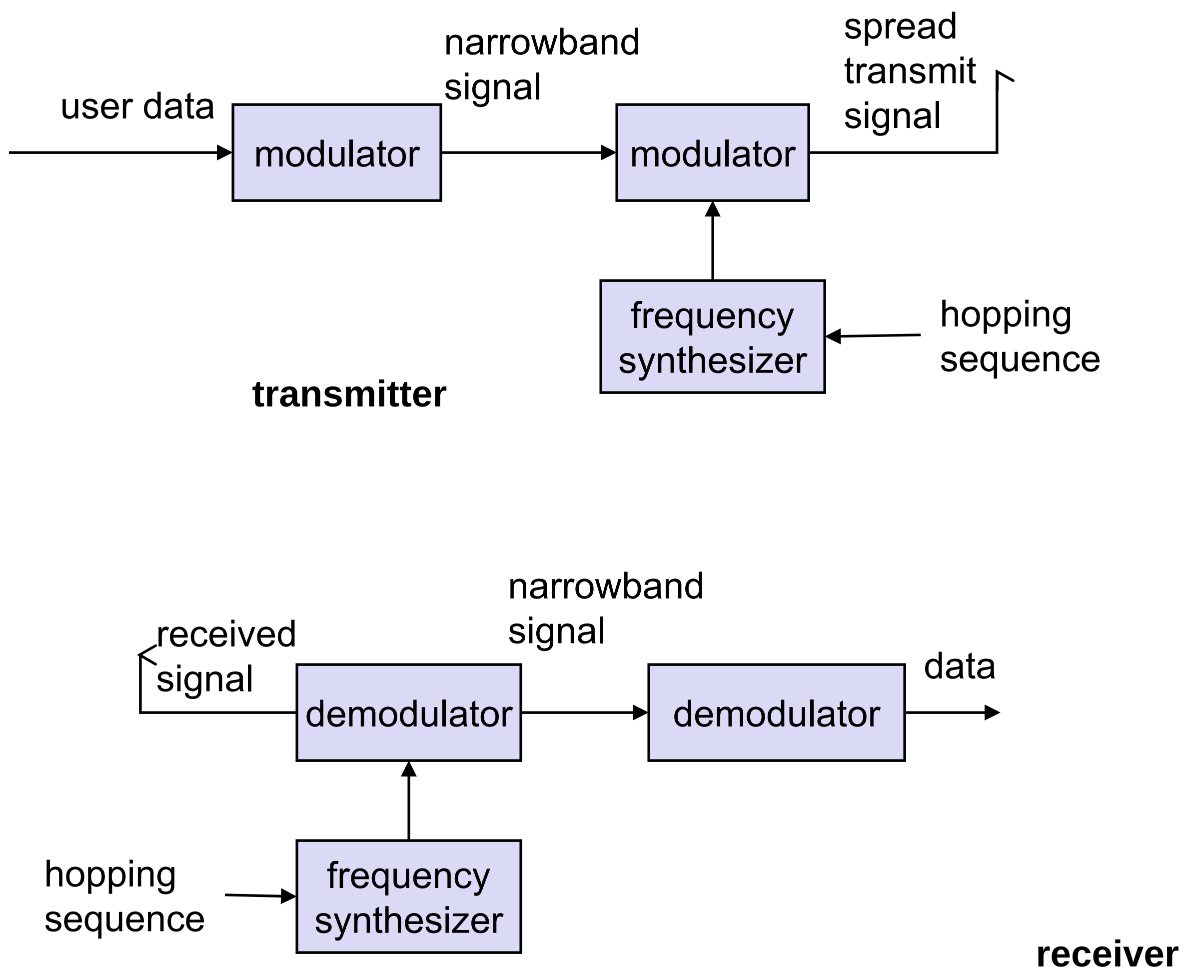
- not as robust as DSSS
- simpler to detect

FHSS (Frequency Hopping Spread Spectrum) II



t_b: bit period t_d: dwell time

FHSS (Frequency Hopping Spread Spectrum) III



Physical layer

Receiver: Demodulation

The receiver looks at the received wave form and matches it with the data bit that caused the transmitter to generate this wave form

- Necessary: one-to-one mapping between data and wave form
- Because of channel imperfections, this is at best possible for digital signals, but not for analog signals

Problems caused by

- Carrier synchronization: frequency can vary between sender and receiver (drift, temperature changes, aging, …)
- Bit synchronization (actually: symbol synchronization): When does symbol representing a certain bit start/end?
- Frame synchronization: When does a packet start/end?
- Biggest problem: Received signal is ***not*** the transmitted signal!

Attenuation results in path loss

Effect of attenuation: received signal strength is a function of the distance *d* between sender and transmitter

Captured by ***Friis free-space equation***

- Describes signal strength at distance d relative to some reference distance $d_0 < d$ for which strength is known
- d_0 is ***far-field distance,*** depends on antenna technology

$$P_{\text{recv}}(d) = \frac{P_{\text{tx}} \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 \cdot d^2 \cdot L}$$

$$= \frac{P_{\text{tx}} \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2 \cdot d_0^2 \cdot L} \cdot \left(\frac{d_0}{d}\right)^2 = P_{\text{recv}}(d_0) \cdot \left(\frac{d_0}{d}\right)^2$$

Generalizing the attenuation formula

To take into account stronger attenuation than only caused by distance (e.g., walls, …), use a larger exponent $\gamma > 2$

- γ is the ***path-loss exponent***

$$P_{\text{recv}}(d) = P_{\text{recv}}(d_0) \cdot \left(\frac{d_0}{d}\right)^{\gamma}$$

- Rewrite in logarithmic form (in dB):

$$\text{PL}(d)[\text{dB}] \; = \; \text{PL}(d_0)[\text{dB}] \; + 10\gamma \log_{10}\left(\frac{d}{d_0}\right)$$

Take obstacles into account by a random variation

- Add a Gaussian random variable with 0 mean, variance σ^2 to dB representation
- Equivalent to multiplying with a lognormal distributed r.v. in metric units ! ***lognormal fading***

$$\text{PL}(d)[\text{dB}] \; = \; \text{PL}(d_0)[\text{dB}] + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + X_{\sigma}[\text{dB}]$$

Noise and interference

So far: only a single transmitter assumed

- Only disturbance: self-interference of a signal with multi-path “copies” of itself

In reality, two further disturbances

- ***Noise*** – due to effects in receiver electronics, depends on temperature
  - Typical model: an additive Gaussian variable, mean 0, no correlation in time
- ***Interference*** from third parties
  - Co-channel interference: another sender uses the same spectrum
  - Adjacent-channel interference: another sender uses some other part of the radio spectrum, but receiver filters are not good enough to fully suppress it

Effect: Received signal is distorted by channel, corrupted by noise and interference

- What is the result on the received bits?

Symbols and bit errors

Extracting symbols out of a distorted/corrupted wave form is fraught with errors

- Depends essentially on strength of the received signal compared to the corruption
- Captured by ***signal to noise and interference ratio (SINR)***

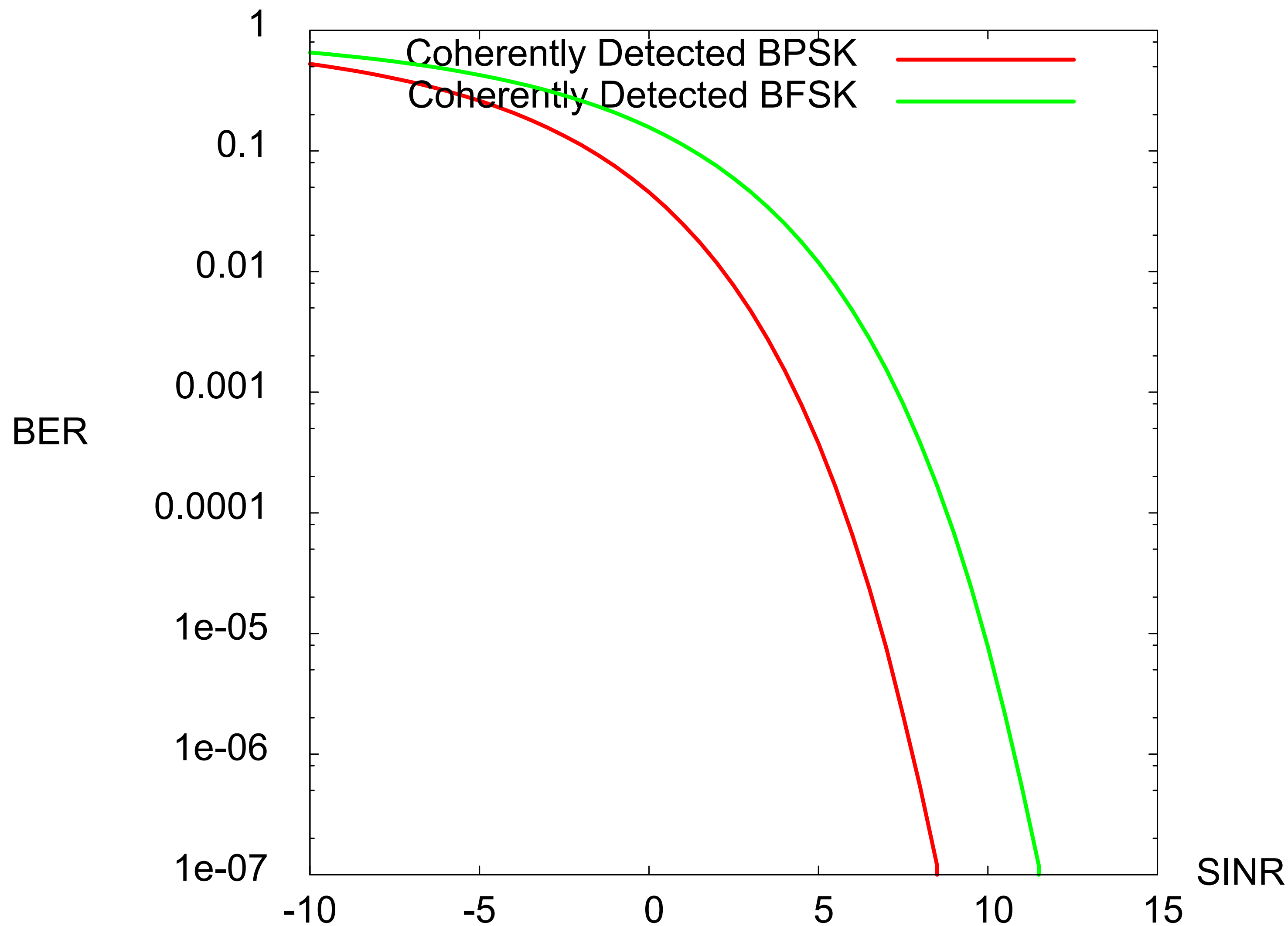
$$\text{SINR} = 10 \log_{10} \left(\frac{P_{\text{recv}}}{N_0 + \sum_{i=1}^{k} I_i} \right)$$

SINR allows to compute ***bit error rate*** (***BER***) for a given modulation

- Also depends on data rate (# bits/symbol) of modulation
- E.g., for simple DPSK, data rate corresponding to bandwidth:

$$\text{BER}(\text{SINR}) = 0.5 e^{-\frac{E_b}{N_0}}$$
$$E_b/N_0 = \text{SINR} \cdot \frac{1}{R}$$

Examples for SINR → BER mappings



Channel models – analog

How to stochastically capture the behavior of a wireless channel

- Main options: model the SNR or directly the bit errors

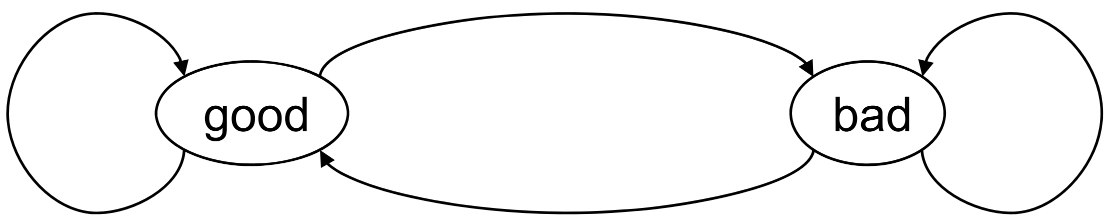
Signal models

- Simplest model: assume transmission power and attenuation are constant, noise an uncorrelated Gaussian variable
  - ***Additive White Gaussian Noise*** model, results in constant SNR
- Situation with no line-of-sight path, but many indirect paths: Amplitude of resulting signal has a ***Rayleigh*** distribution (***Rayleigh fading)***
- One dominant line-of-sight plus many indirect paths: Signal has a ***Rice*** distribution (***Rice fading***)

Channel models – digital

Directly model the resulting bit error behavior

- ❑ Each bit is erroneous with constant probability, independent of the other bits → ***binary symmetric channel (BSC)***
- ❑ Capture fading models' property that channel be in different states → Markov models – states with different BERs
  - Example: Gilbert-Elliot model with "bad" and "good" channel states and high/low bit error rates



- ❑ Fractal channel models describe number of (in-)correct bits in a row by a heavy-tailed distribution

WSN-specific channel models

Typical WSN properties

- Small transmission range
- Implies small delay spread (nanoseconds, compared to micro/milliseconds for symbol duration)

→ Frequency-non-selective fading, low to negligible inter-symbol interference

- Coherence bandwidth often > 50 MHz

Some example measurements

- γ path loss exponent
- Shadowing variance σ^2
- Reference path loss at 1 m

Location	Average of γ	Average of σ^2[dB]	Range of PL(1m)[dB]
Engineering Building	1.9	5.7	$[-50.5, -39.0]$
Apartment Hallway	2.0	8.0	$[-38.2, -35.0]$
Parking Structure	3.0	7.9	$[-36.0, -32.7]$
One-sided Corridor	1.9	8.0	$[-44.2, -33.5]$
One-sided patio	3.2	3.7	$[-39.0, -34.2]$
Concrete canyon	2.7	10.2	$[-48.7, -44.0]$
Plant fence	4.9	9.4	$[-38.2, -34.5]$
Small boulders	3.5	12.8	$[-41.5, -37.2]$
Sandy flat beach	4.2	4.0	$[-40.8, -37.5]$
Dense bamboo	5.0	11.6	$[-38.2, -35.2]$
Dry tall underbrush	3.6	8.4	$[-36.4, -33.2]$

Wireless channel quality – summary

Wireless channels are substantially worse than wired channels

- In throughput, bit error characteristics, energy consumption, …

Wireless channels are extremely diverse

- There is no such thing as THE typical wireless channel

Various schemes for quality improvement exist

- Some of them geared towards high-performance wireless communication – not necessarily suitable for WSN, ok for MANET
  - Diversity, equalization, …
- Some of them general-purpose (ARQ, FEC)
- Energy issues need to be taken into account!

Some transceiver design considerations

Strive for good power efficiency at low transmission power

- Some amplifiers are optimized for efficiency at high output power
- To radiate 1 mW, typical designs need 30-100 mW to operate the transmitter
  - WSN nodes: 20 mW (mica motes)
- Receiver can use as much or more power as transmitter at these power levels

  ! Sleep state is important

Startup energy/time penalty can be high

- Examples take 0.5 ms and ¼ 60 mW to wake up

Exploit communication/computation tradeoffs

- Might payoff to invest in rather complicated coding/compression schemes

Choice of modulation

One exemplary design point: which modulation to use?

- Consider: required data rate, available symbol rate, implementation complexity, required BER, channel characteristics, …
- Tradeoffs: the faster one sends, the longer one can sleep
  - Power consumption can depend on modulation scheme
- Tradeoffs: symbol rate (high?) versus data rate (low)
  - Use m-ary transmission to get a transmission over with ASAP
  - But: startup costs can easily void any time saving effects
  - For details: see example in exercise!

Adapt modulation choice to operation conditions

- Akin to dynamic voltage scaling, introduce ***Dynamic Modulation Scaling***

Summary

Wireless radio communication introduces many uncertainties and vagaries into a communication system

Handling the unavoidable errors will be a major challenge for the communication protocols

Dealing with limited bandwidth in an energy-efficient manner is the main challenge

MANET and WSN are pretty similar here

- Main differences are in required data rates and resulting transceiver complexities (higher bandwidth, spread spectrum techniques)

Wireless Communications

Principles and Practice

Mobile Radio Propagation: Large-Scale Path Loss

Co-channel and Adjacent Channel Interference, Propagation

Small-scale and large-scale fading

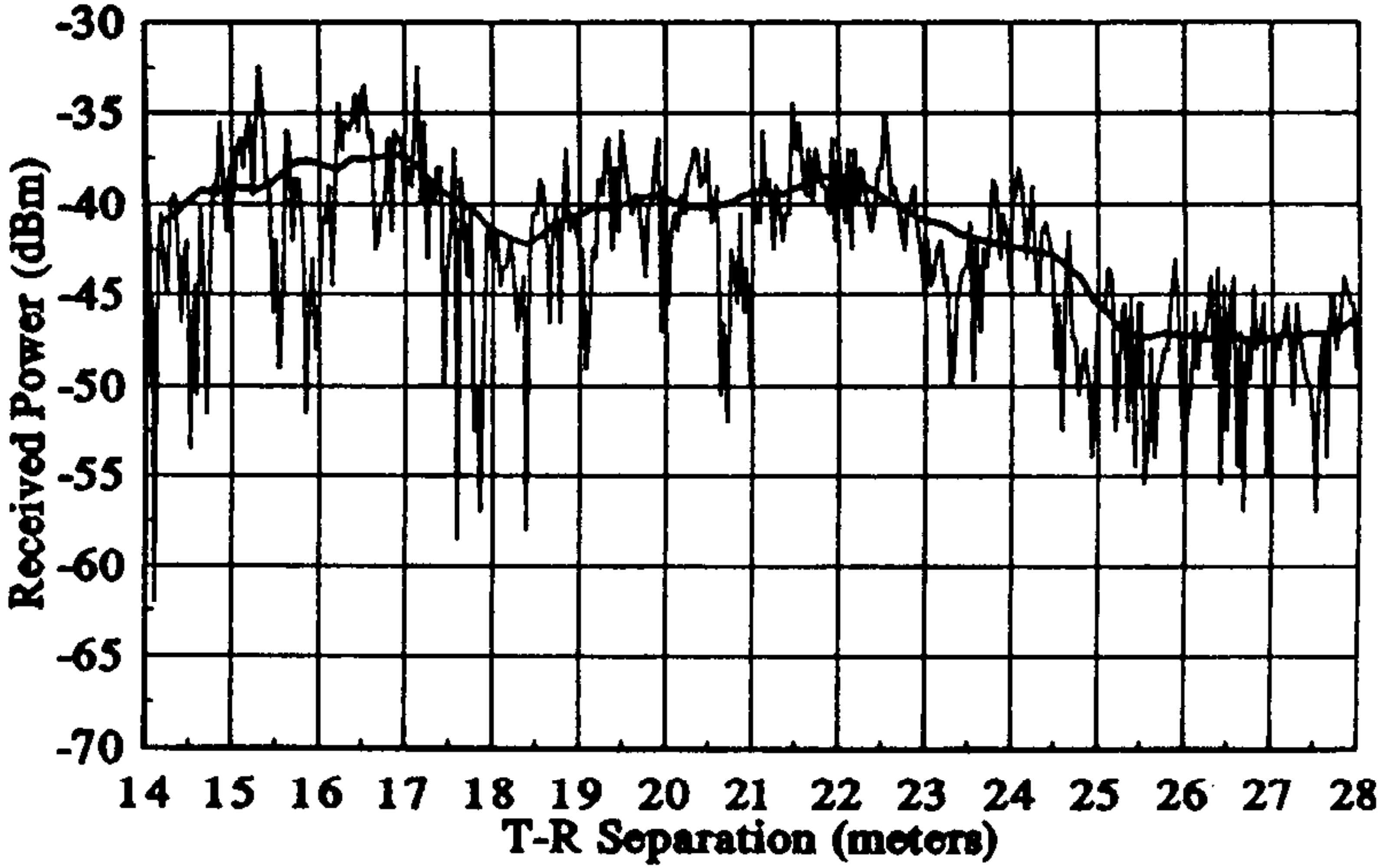


Figure 4.1 Small-scale and large-scale fading.

Typical electromagnetic properties

Table 4.1 Material Parameters at Various Frequencies

Material	Relative Permittivity ε_r	Conductivity σ (s/m)	Frequency (MHz)
Poor Ground	4	0.001	100
Typical Ground	15	0.005	100
Good Ground	25	0.02	100
Sea Water	81	5.0	100
Fresh Water	81	0.001	100
Brick	4.44	0.001	4000
Limestone	7.51	0.028	4000
Glass, Corning 707	4	0.00000018	1
Glass, Corning 707	4	0.000027	100
Glass, Corning 707	4	0.005	10000

Typical large-scale path loss

Table 4.2 Path Loss Exponents for Different Environments

Environment	Path Loss Exponent, *n*
Free space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Measured large-scale path loss

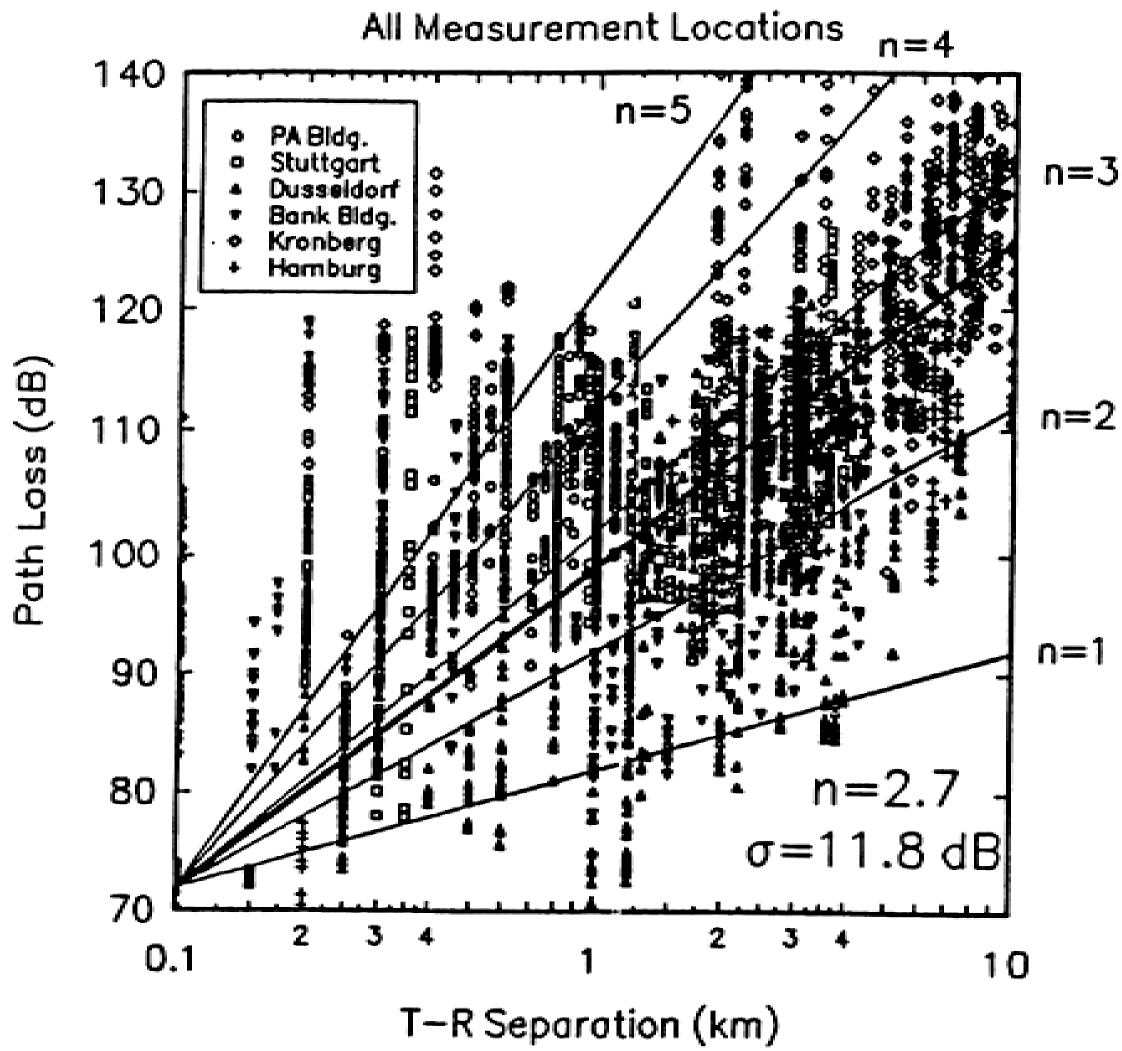


Figure 4.17 Scatter plot of measured data and corresponding MMSE path loss model for many cities in Germany. For this data, $n = 2.7$ and $\sigma = 11.8$ dB [from [Sei91] © IEEE].

Partition losses

Table 4.3 Average Signal Loss Measurements Reported by Various Researchers for Radio Paths Obstructed by Common Building Material

Material Type	Loss (dB)	Frequency	Reference
All metal	26	815 MHz	[Cox83b]
Aluminum siding	20.4	815 MHz	[Cox83b]
Foil insulation	3.9	815 MHz	[Cox83b]
Concrete block wall	13	1300 MHz	[Rap91c]
Loss from one floor	20-30	1300 MHz	[Rap91c]
Loss from one floor and one wall	40-50	1300 MHz	[Rap91c]
Fade observed when transmitter turned a right angle corner in a corridor	10-15	1300 MHz	[Rap91c]
Light textile inventory	3-5	1300 MHz	[Rap91c]
Chain-like fenced in area 20 ft high containing tools, inventory, and people	5-12	1300 MHz	[Rap91c]
Metal blanket — 12 sq ft	4-7	1300 MHz	[Rap91c]
Metallic hoppers which hold scrap metal for recycling — 10 sq ft	3-6	1300 MHz	[Rap91c]
Small metal pole — 6" diameter	3	1300 MHz	[Rap91c]
Metal pulley system used to hoist metal inventory — 4 sq ft	6	1300 MHz	[Rap91c]
Light machinery < 10 sq ft	1-4	1300 MHz	[Rap91c]
General machinery — 10 - 20 sq ft	5-10	1300 MHz	[Rap91c]
Heavy machinery > 20 sq ft	10-12	1300 MHz	[Rap91c]
Metal catwalk/stairs	5	1300 MHz	[Rap91c]
Light textile	3-5	1300 MHz	[Rap91c]
Heavy textile inventory	8-11	1300 MHz	[Rap91c]
Area where workers inspect metal finished products for defects	3-12	1300 MHz	[Rap91c]
Metallic inventory	4-7	1300 MHz	[Rap91c]
Large I-beam — 16 - 20"	8-10	1300 MHz	[Rap91c]
Metallic inventory racks — 8 sq ft	4-9	1300 MHz	[Rap91c]
Empty cardboard inventory boxes	3-6	1300 MHz	[Rap91c]
Concrete block wall	13-20	1300 MHz	[Rap91c]
Ceiling duct	1-8	1300 MHz	[Rap91c]
2.5 m storage rack with small metal parts (loosely packed)	4-6	1300 MHz	[Rap91c]
4 m metal box storage	10-12	1300 MHz	[Rap91c]

Table 4.3 Average Signal Loss Measurements Reported by Various Researchers for Radio Paths Obstructed by Common Building Material (Continued)

Material Type	Loss (dB)	Frequency	Reference
5 m storage rack with paper products (loosely packed)	2-4	1300 MHz	[Rap91c]
5 m storage rack with large paper products (tightly packed)	6	1300 MHz	[Rap91c]
5 m storage rack with large metal parts (tightly packed)	20	1300 MHz	[Rap91c]
Typical N/C machine	8-10	1300 MHz	[Rap91c]
Semi-automated assembly line	5-7	1300 MHz	[Rap91c]
0.6 m square reinforced concrete pillar	12-14	1300 MHz	[Rap91c]
Stainless steel piping for cook-cool process	15	1300 MHz	[Rap91c]
Concrete wall	8-15	1300 MHz	[Rap91c]
Concrete floor	10	1300 MHz	[Rap91c]
Commercial absorber	38	9.6 GHz	[Vio88]
Commercial absorber	51	28.8 GHz	[Vio88]
Commercial absorber	59	57.6 GHz	[Vio88]
Sheetrock (3/8 in) — 2 sheets	2	9.6 GHz	[Vio88]
Sheetrock (3/8 in) — 2 sheets	2	28.8 GHz	[Vio88]
Sheetrock (3/8 in) — 2 sheets	5	57.6 GHz	[Vio88]
Dry plywood (3/4 in) — 1 sheet	1	9.6 GHz	[Vio88]
Dry plywood (3/4 in) — 1 sheet	4	28.8 GHz	[Vio88]
Dry plywood (3/4 in) — 1 sheet	8	57.6 GHz	[Vio88]
Dry plywood (3/4 in) — 2 sheets	4	9.6 GHz	[Vio88]
Dry plywood (3/4 in) — 2 sheets	6	28.8 GHz	[Vio88]
Dry plywood (3/4 in) — 2 sheets	14	57.6 GHz	[Vio88]
Wet plywood (3/4 in) — 1 sheet	19	9.6 GHz	[Vio88]
Wet plywood (3/4 in) — 1 sheet	32	28.8 GHz	[Vio88]
Wet plywood (3/4 in) — 1 sheet	59	57.6 GHz	[Vio88]
Wet plywood (3/4 in) — 2 sheets	39	9.6 GHz	[Vio88]
Wet plywood (3/4 in) — 2 sheets	46	28.8 GHz	[Vio88]
Wet plywood (3/4 in) — 2 sheets	57	57.6 GHz	[Vio88]
Aluminum (1/8 in) — 1 sheet	47	9.6 GHz	[Vio88]
Aluminum (1/8 in) — 1 sheet	46	28.8 GHz	[Vio88]
Aluminum (1/8 in) — 1 sheet	53	57.6 GHz	[Vio88]

Partition losses

Table 4.4 Total Floor Attenuation Factor and Standard Deviation σ (dB) for Three Buildings. Each Point Represents the Average Path Loss Over a 20λ Measurement Track [Sei92a]

Building	915 MHz FAF (dB)	σ (dB)	Number of locations	1900 MHz FAF (dB)	σ (dB)	Number of locations
Walnut Creek						
One Floor	33.6	3.2	25	31.3	4.6	110
Two Floors	44.0	4.8	39	38.5	4.0	29
SF PacBell						
One Floor	13.2	9.2	16	26.2	10.5	21
Two Floors	18.1	8.0	10	33.4	9.9	21
Three Floors	24.0	5.6	10	35.2	5.9	20
Four Floors	27.0	6.8	10	38.4	3.4	20
Five Floors	27.1	6.3	10	46.4	3.9	17
San Ramon						
One Floor	29.1	5.8	93	35.4	6.4	74
Two Floors	36.6	6.0	81	35.6	5.9	41
Three Floors	39.6	6.0	70	35.2	3.9	27

Partition losses

Table 4.5 Average Floor Attenuation Factor in dB for One, Two, Three, and Four Floors in Two Office Buildings [Sei92b]

Building	FAF (dB)	σ (dB)	Number of locations
Office Building 1:			
Through One Floor	12.9	7.0	52
Through Two Floors	18.7	2.8	9
Through Three Floors	24.4	1.7	9
Through Four Floors	27.0	1.5	9
Office Building 2:			
Through One Floor	16.2	2.9	21
Through Two Floors	27.5	5.4	21
Through Three Floors	31.6	7.2	21

Wireless Communications

Principles and Practice

Mobile Radio Propagation: Small-Scale Fading and Multipath as it applies to Modulation Techniques

Channel Sounder: Pulse type

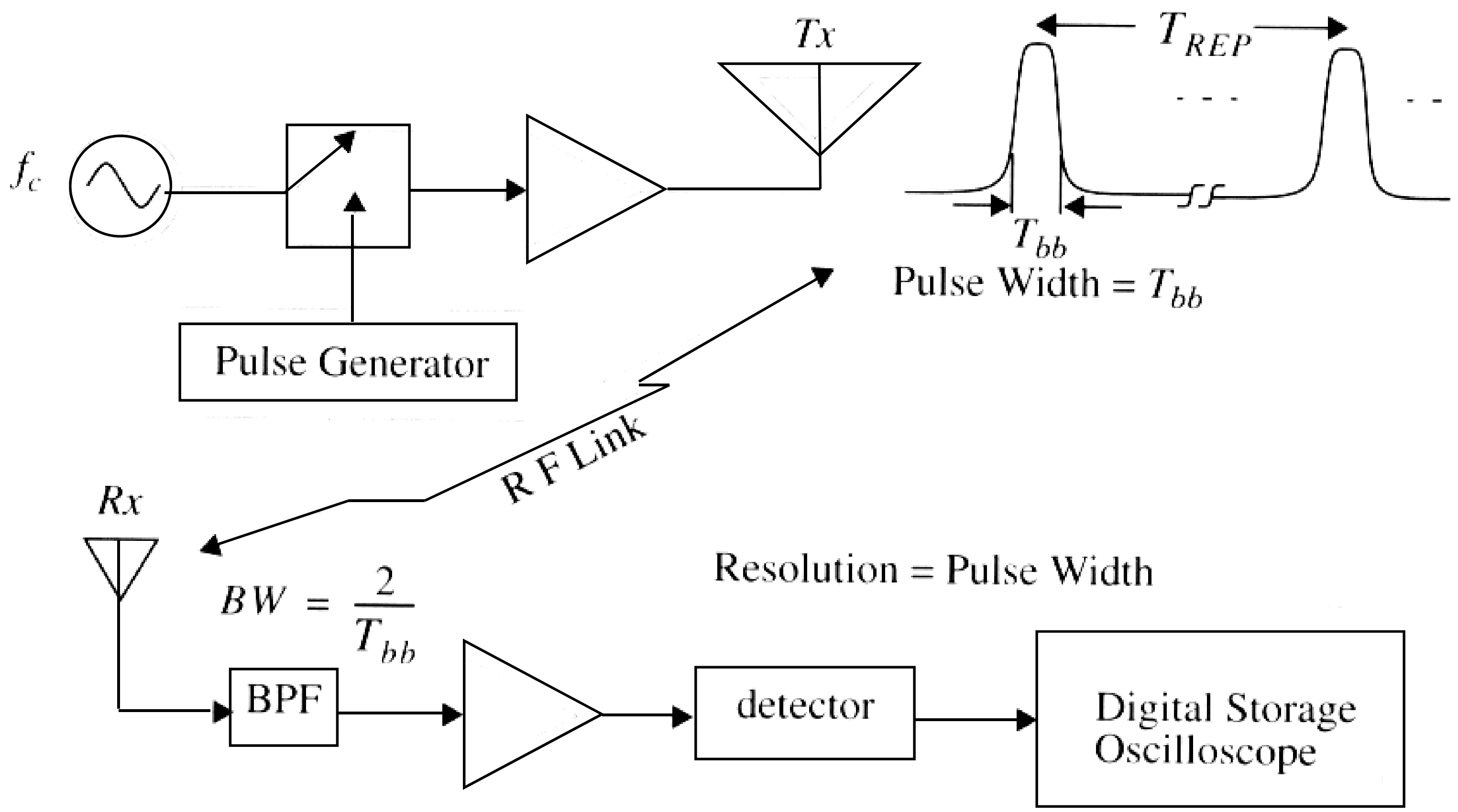


Figure 5.6 Direct RF channel impulse response measurement system.

Channel Sounder: PN Type

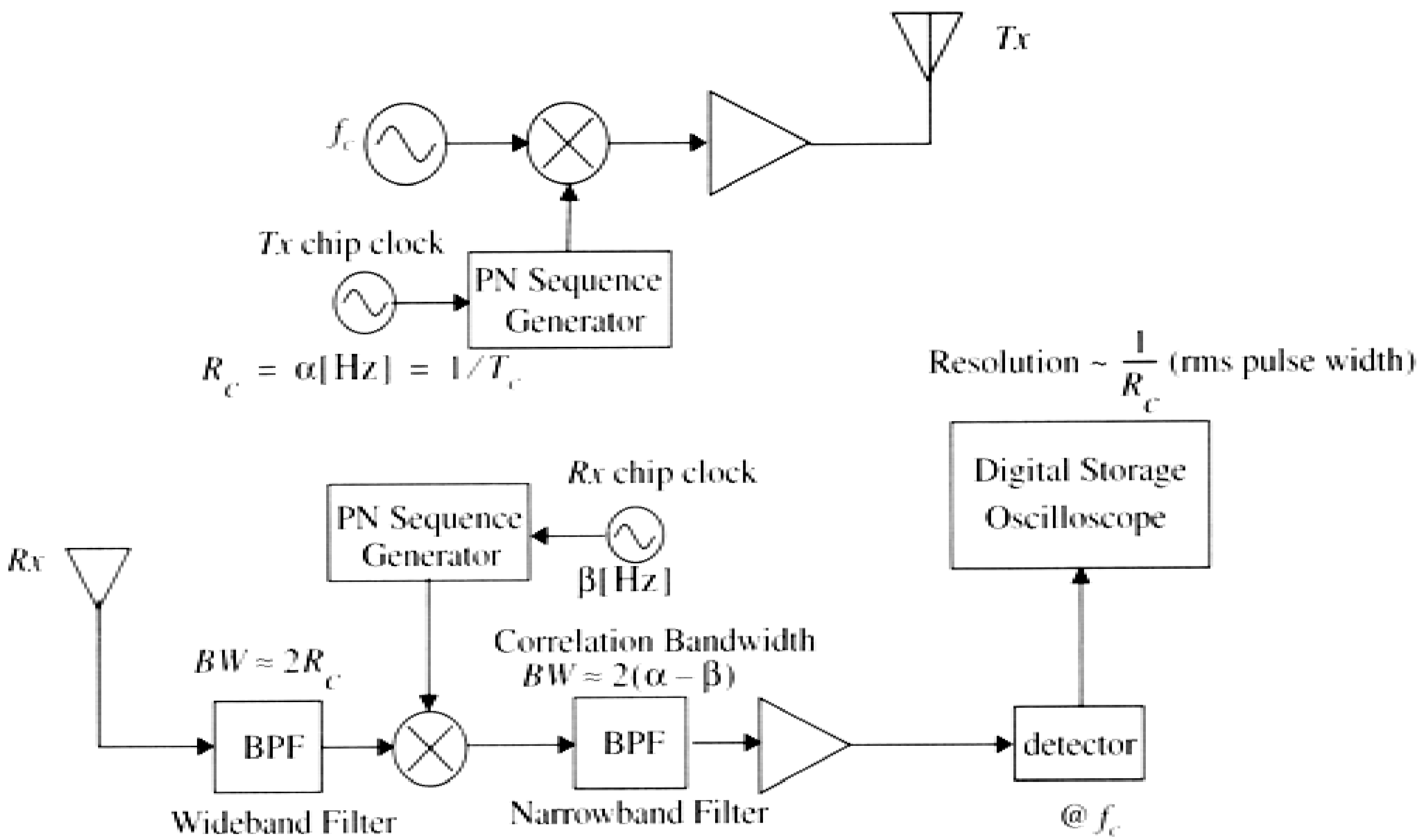


Figure 5.7 Spread spectrum channel impulse response measurement system.

Typical RMS delay spreads

Table 5.1 Typical Measured Values of RMS Delay Spread

Environment	Frequency (MHz)	RMS Delay Spread (σ_τ)	Notes	Reference
Urban	910	1300 ns avg. 600 ns st. dev. 3500 ns max.	New York City	[Cox75]
Urban	892	10–25 μs	Worst case San Francisco	[Rap90]
Suburban	910	200–310 ns	Averaged typical case	[Cox72]
Suburban	910	1960–2110 ns	Averaged extreme case	[Cox72]
Indoor	1500	10–50 ns 25 ns median	Office building	[Sal87]
Indoor	850	270 ns max.	Office building	[Dev90a]
Indoor	1900	70–94 ns avg. 1470 ns max.	Three San Francisco buildings	[Sei92a]

Two independent fading issues

Small-Scale Fading
(Based on multipath time delay spread)

Flat Fading
1. BW of signal < BW of channel
2. Delay spread < Symbol period

Frequency Selective Fading
1. BW of signal > BW of channel
2. Delay spread > Symbol period

Small-Scale Fading
(Based on Doppler spread)

Fast Fading
1. High Doppler spread
2. Coherence time < Symbol period
3. Channel variations faster than baseband signal variations

Slow Fading
1. Low Doppler spread
2. Coherence time > Symbol period
3. Channel variations slower than baseband signal variations

Figure 5.11 Types of small-scale fading.

Flat-fading (non-freq. Selective)

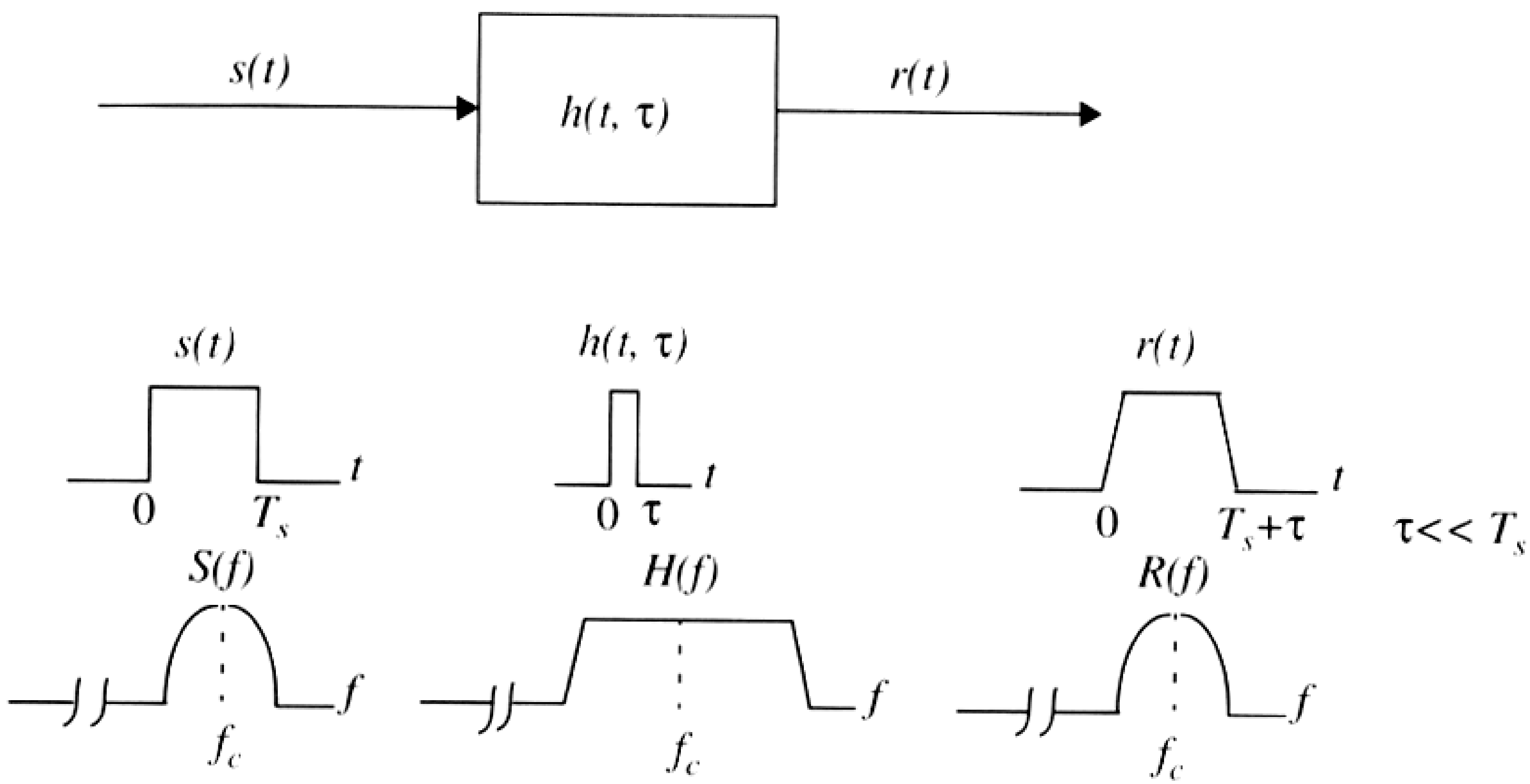


Figure 5.12 Flat fading channel characteristics.

Frequency selective fading

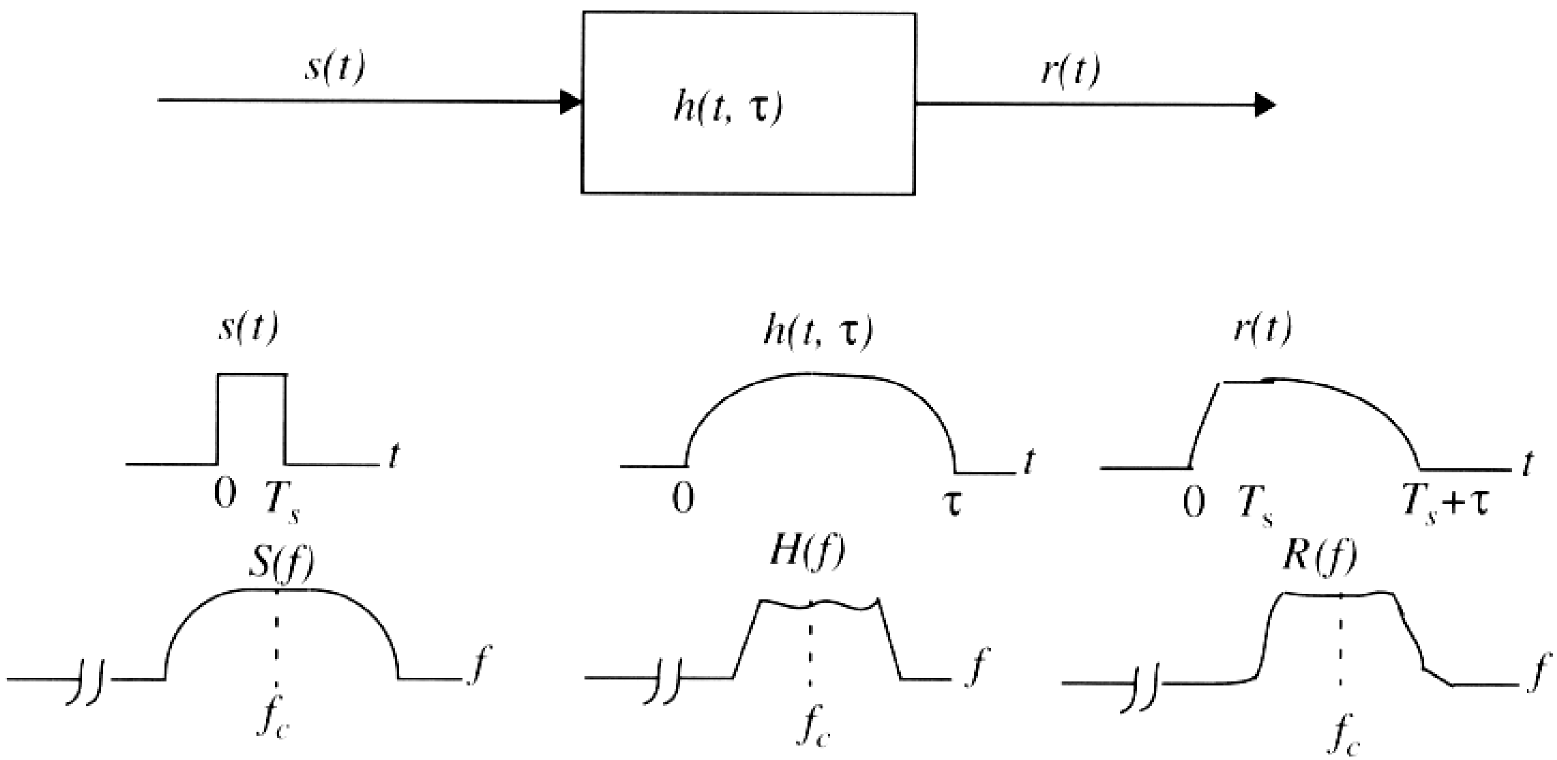


Figure 5.13 Frequency selective fading channel characteristics.

Two independent fading issues

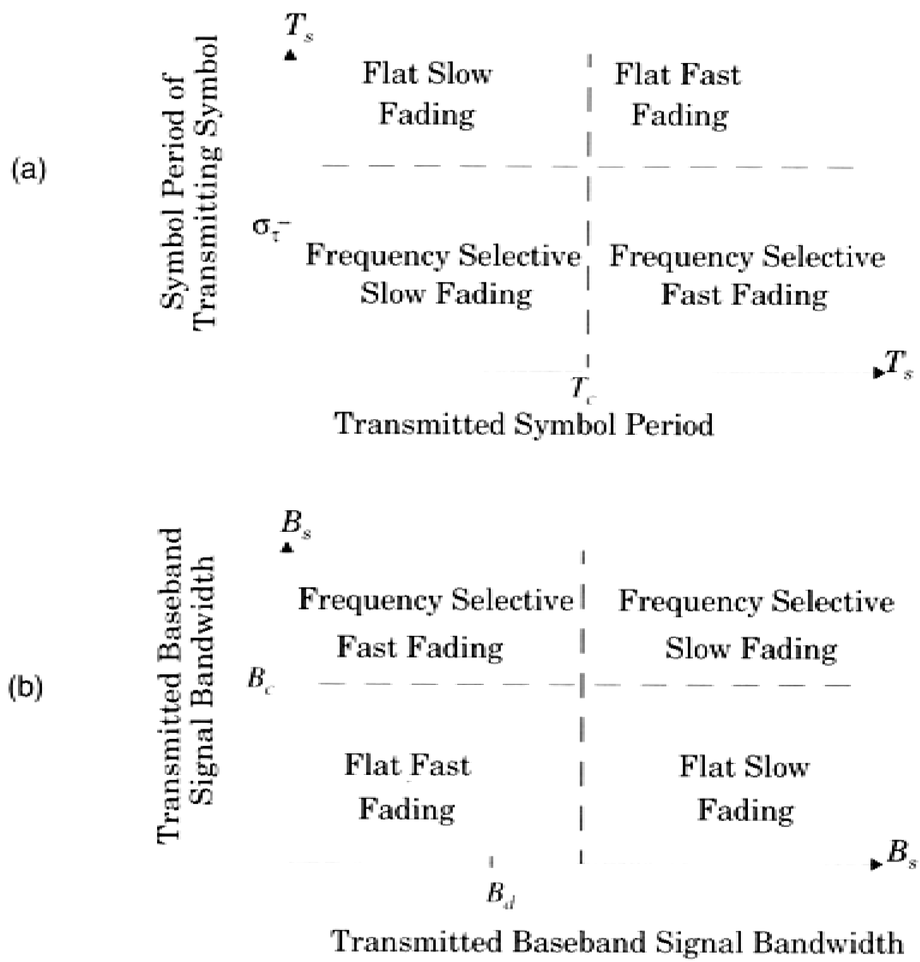


Figure 5.14 Matrix illustrating type of fading experienced by a signal as a function of: (a) symbol period; and (b) baseband signal bandwidth.

Rayleigh fading

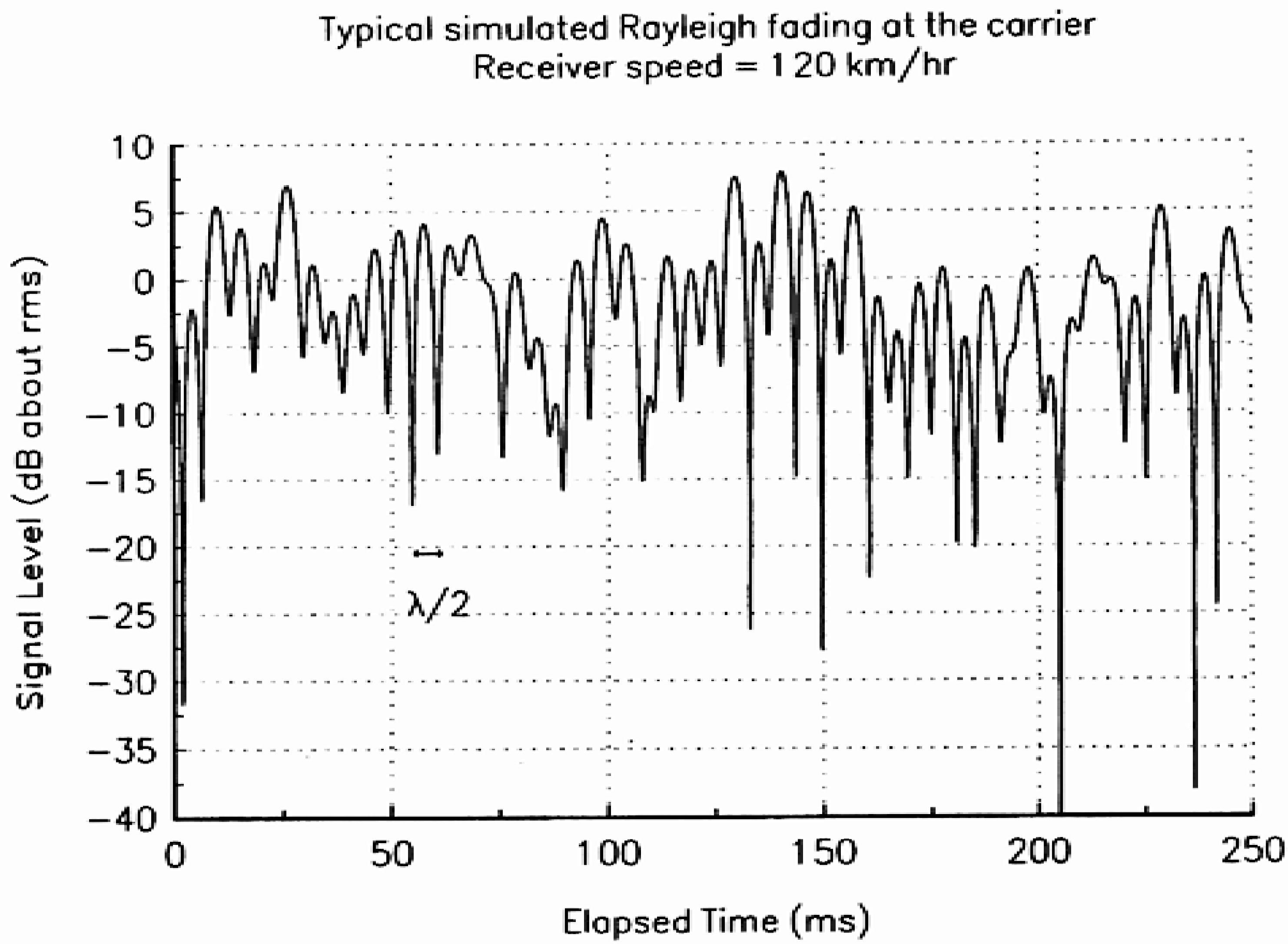


Figure 5.15 A typical Rayleigh fading envelope at 900 MHz [from [Fun93] © IEEE].

Small-scale envelope distributions

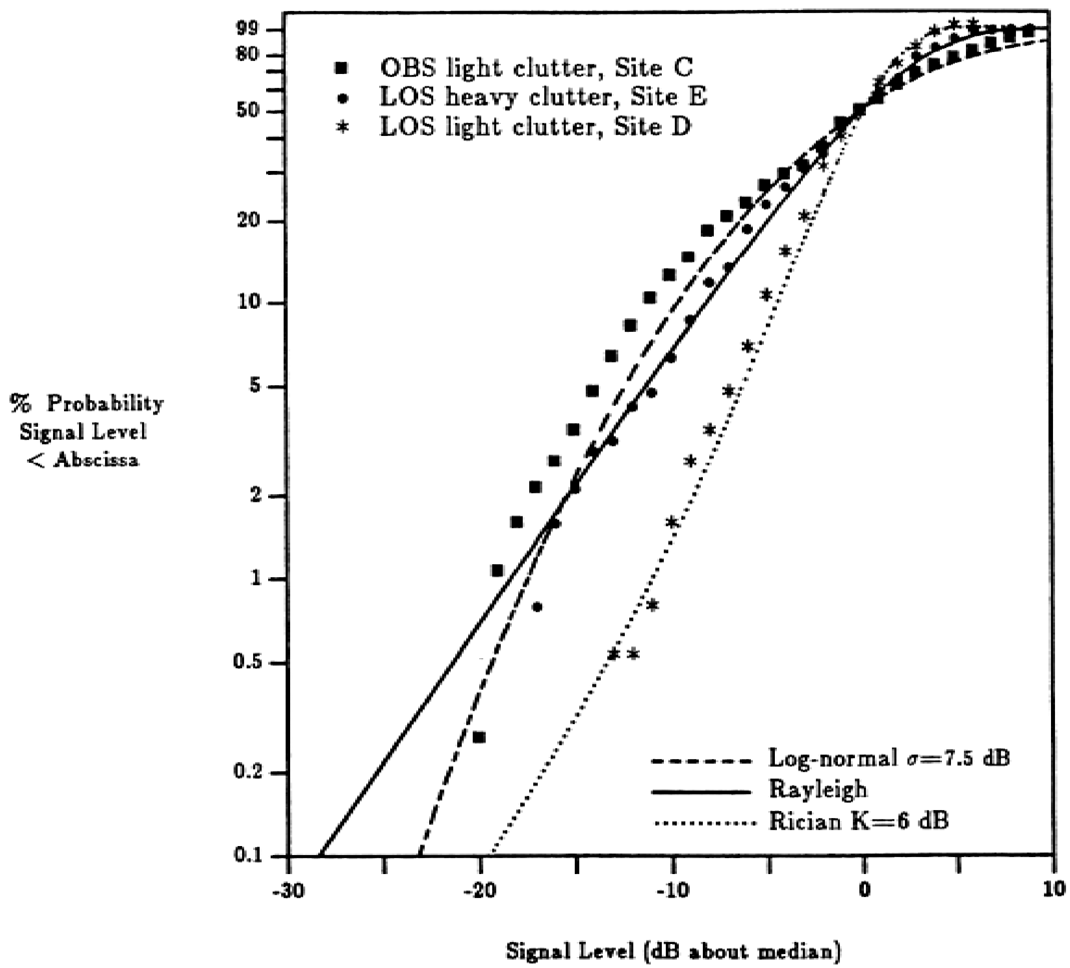


Figure 5.17 Cumulative distribution for three small-scale fading measurements and their fit to Rayleigh, Ricean, and log-normal distributions [from [Rap89] © IEEE].

Ricean and Rayleigh fading distributions

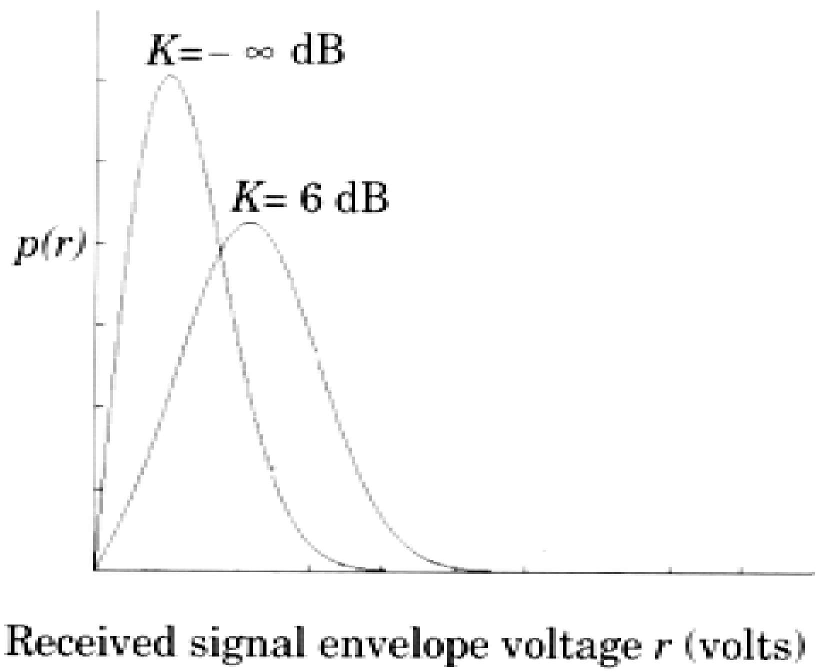


Figure 5.18 Probability density function of Ricean distributions: $K = -\infty$ dB (Rayleigh) and $K = 6$ dB. For K >> 1, the Ricean pdf is approximately Gaussian about the mean.

Wireless Communications

Principles and Practice

Modulation Techniques for Mobile Radio

Amplitude Modulation

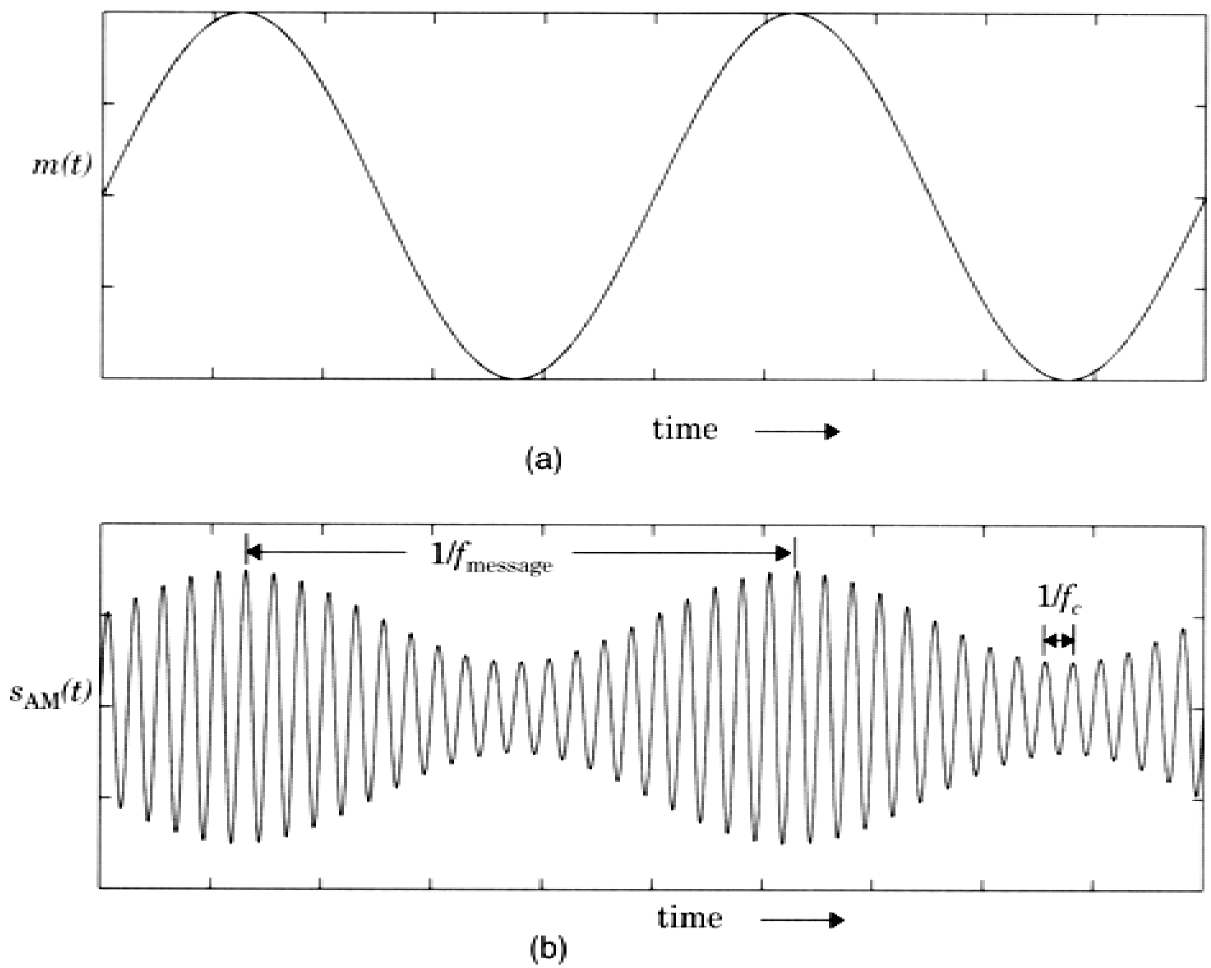


Figure 6.1 (a) A sinusoidal modulating signal and (b) the corresponding AM signal with modulation index 0.5.

Double Sideband Spectrum

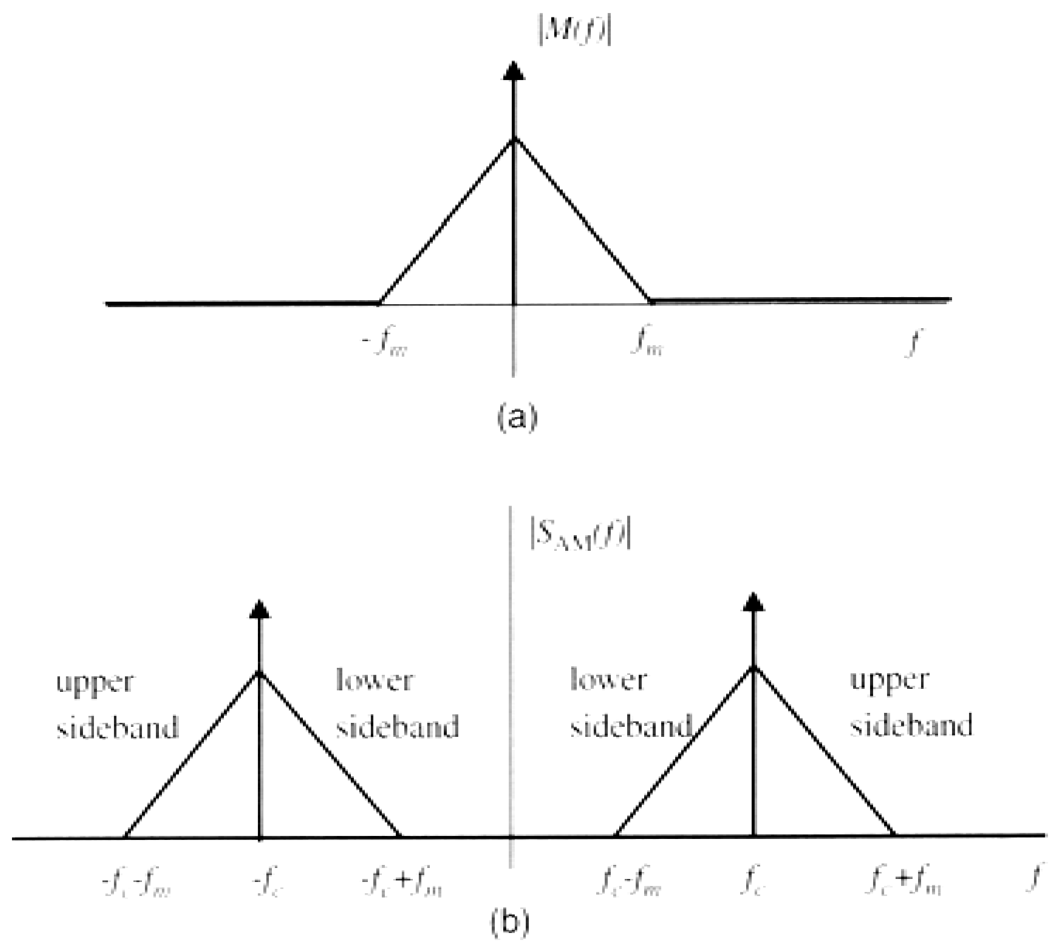


Figure 6.2 (a) Spectrum of a message signal; (b) spectrum of the corresponding AM signal.

SSB Modulators

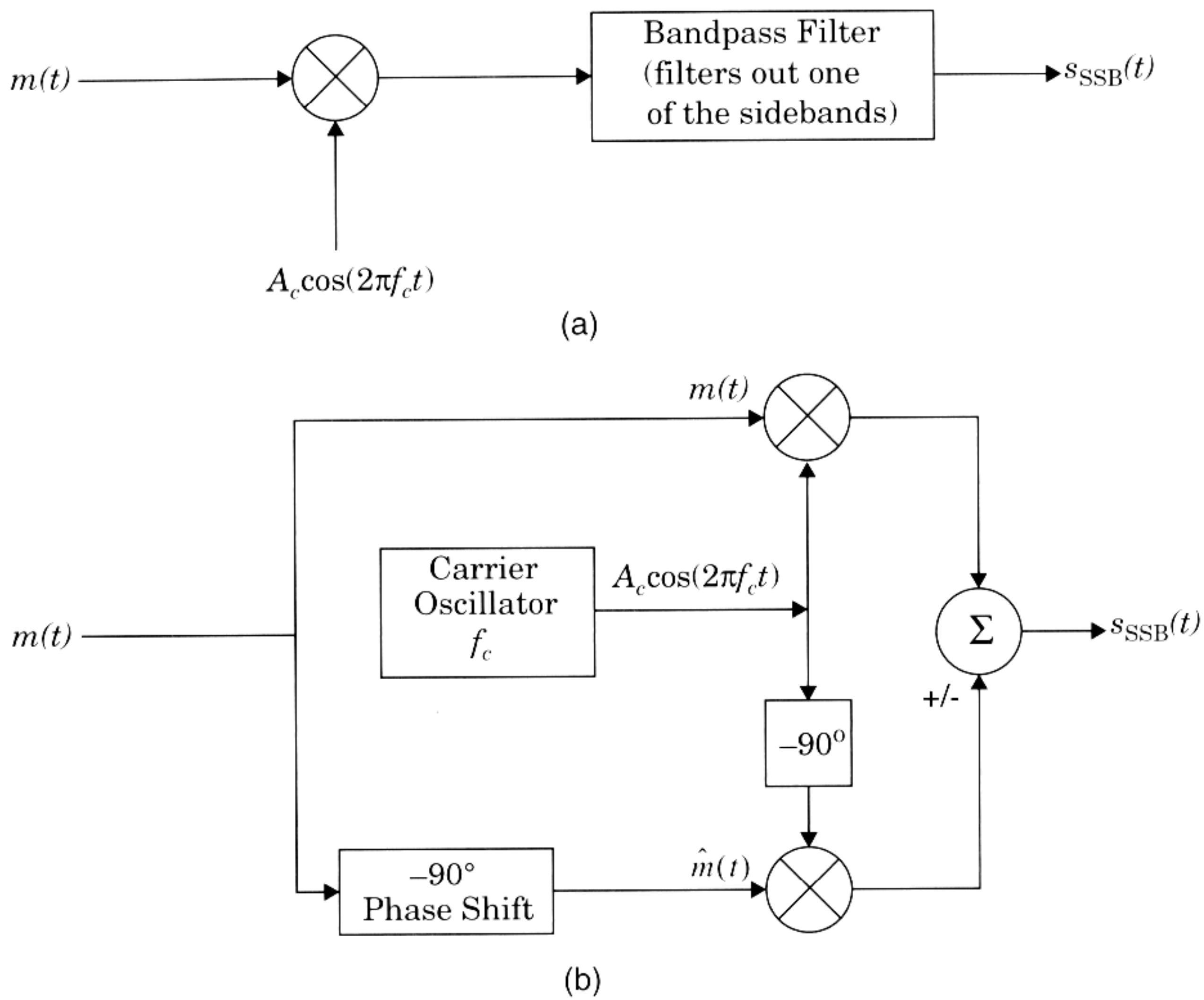


Figure 6.3 Generation of SSB using (a) a sideband filter and (b) a balanced modulator.

Tone-in Band SSB

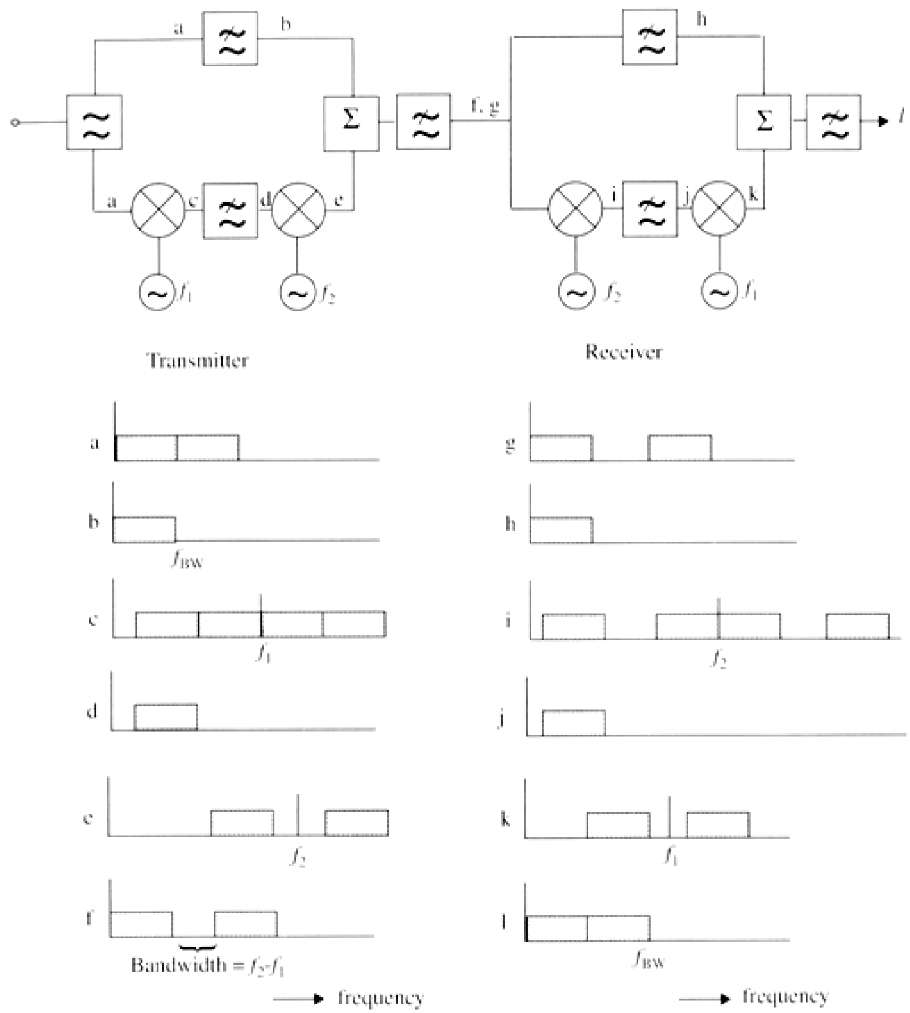


Figure 6.4 Illustration of transparent tone-in-band system [from [McG84] © IEEE]. Only positive frequencies are shown, and the two different cross-hatchings denote different spectral bands.

Product Detection

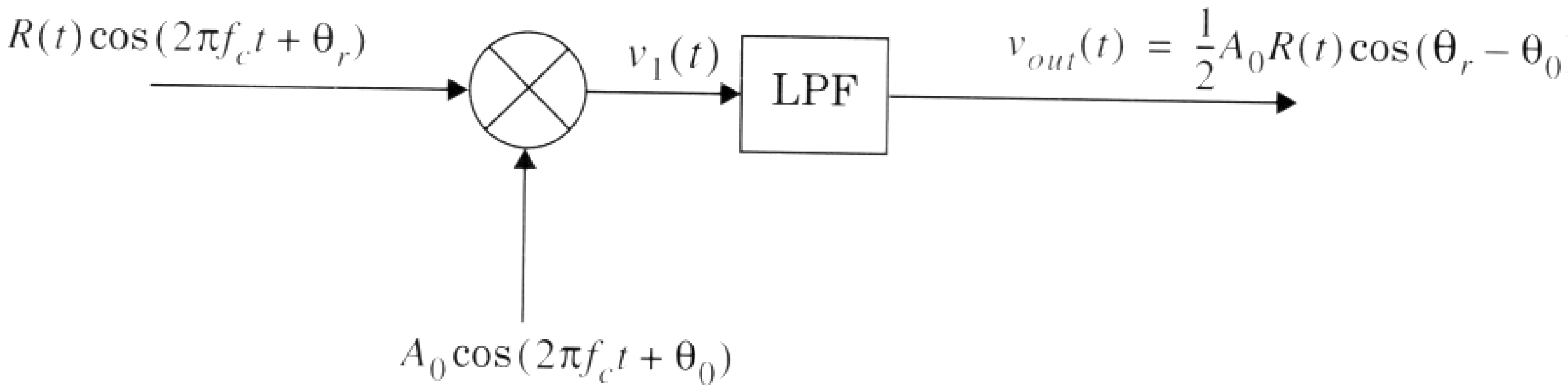


Figure 6.5 Block diagram of a product detector.

VCO circuit

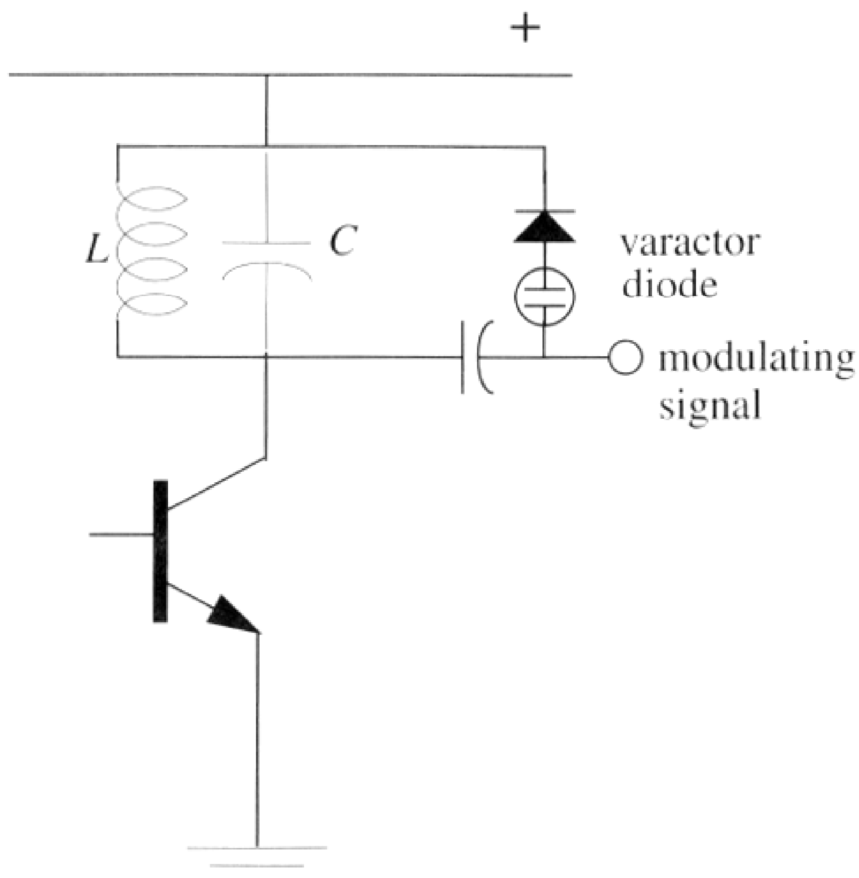


Figure 6.6 A simple reactance modulator in which the capacitance of a varactor diode is changed to vary the frequency of a simple oscillator. This circuit serves as a VCO.

Wideband FM generation

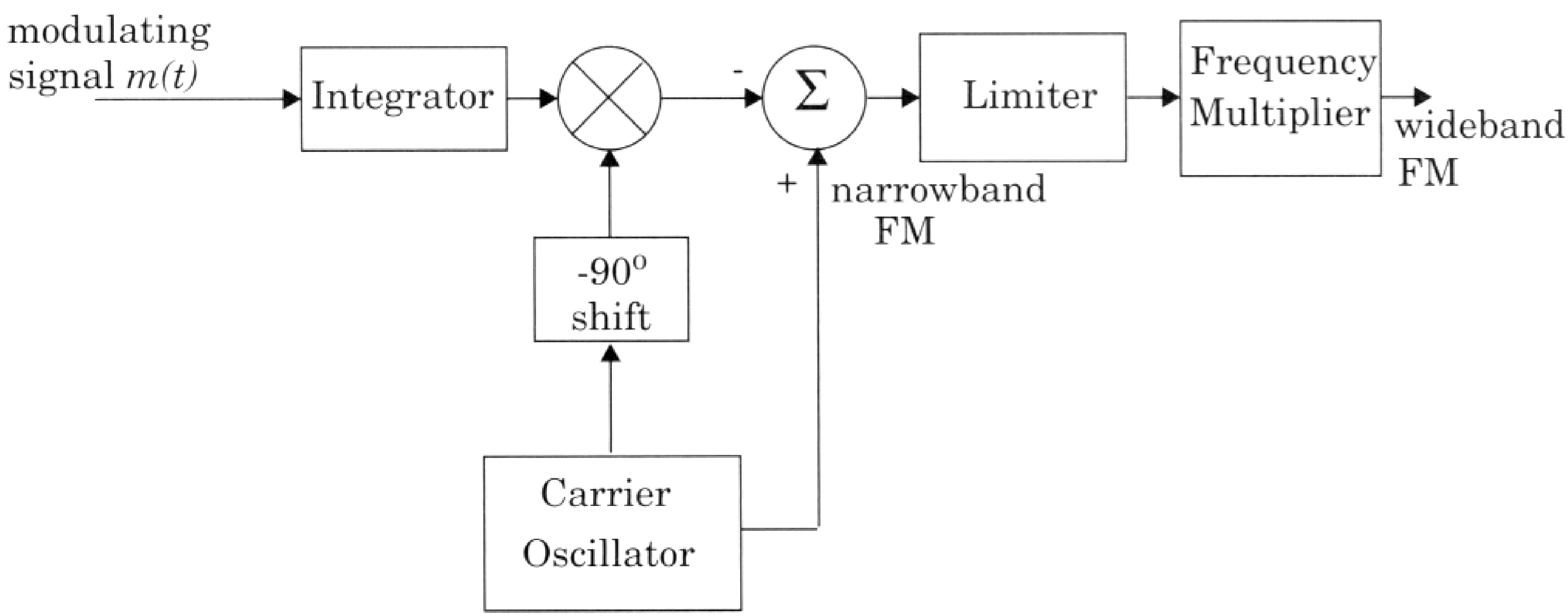


Figure 6.7 Indirect method for generating a wideband FM signal. A narrowband FM signal is generated using a balanced modulator and then frequency multiplied to generate a wideband FM signal.

Slope Detector for FM

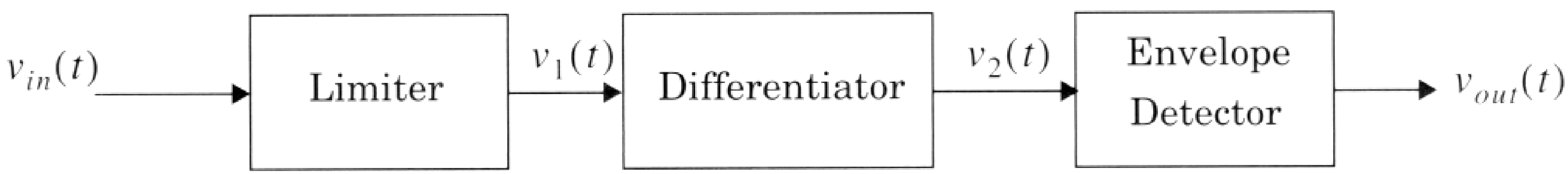


Figure 6.8 Block diagram of a slope detector type FM demodulator.

Digital Demod for FM

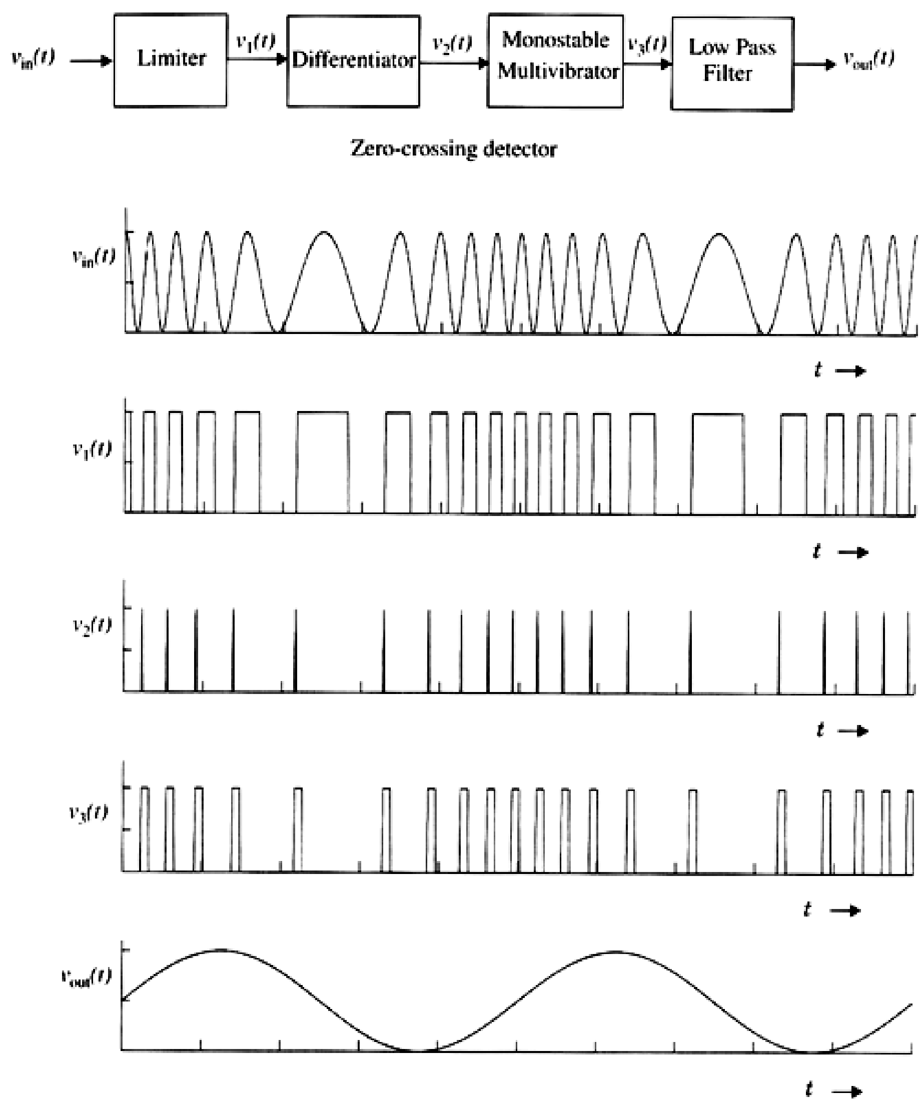


Figure 6.9 Block diagram of a zero-crossing detector and associated waveforms.

PLL Demod for FM

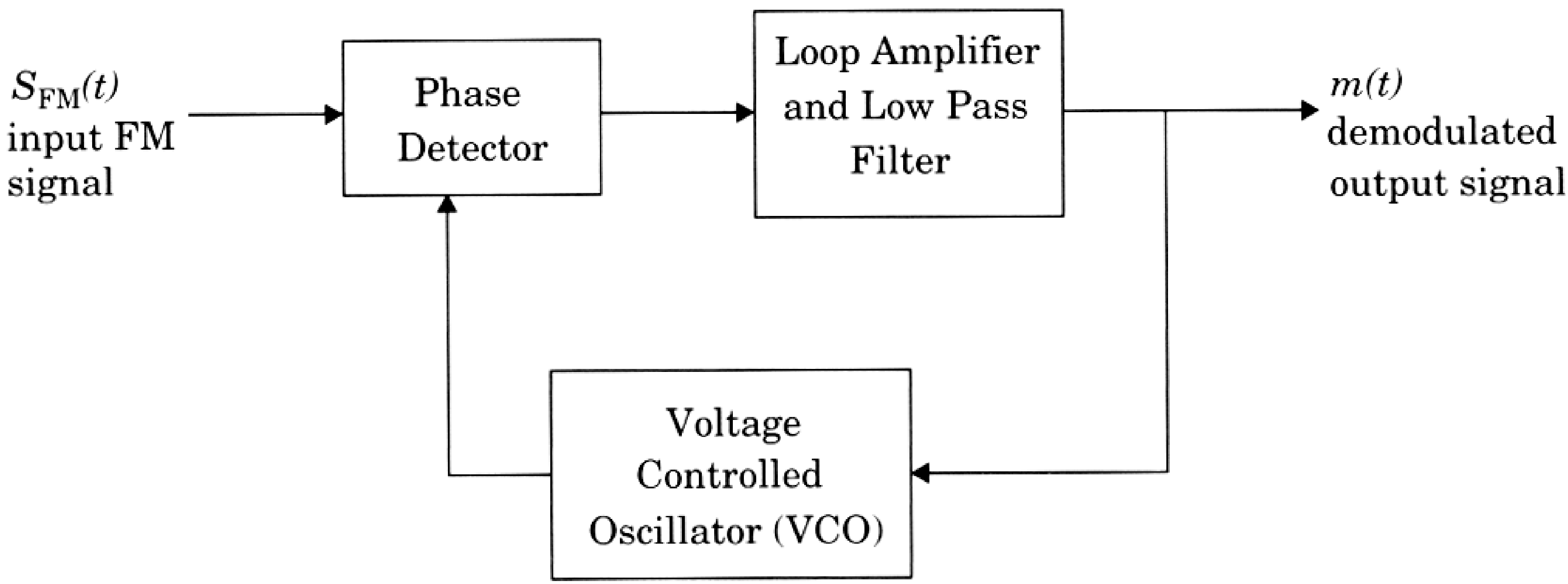


Figure 6.10 Block diagram of a PLL used as a frequency demodulator.

Phase-shift quadrature FM demod

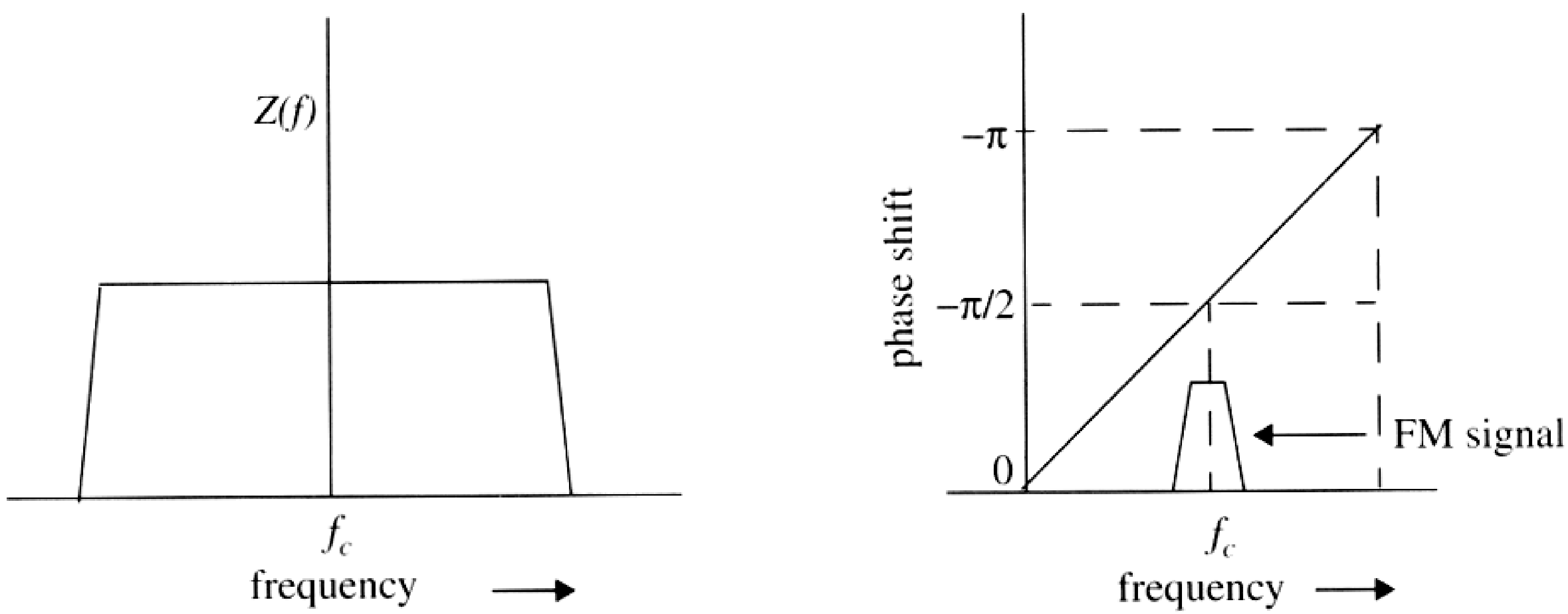


Figure 6.11 Characteristics of the phase-shift network with constant gain and linear phase.

FM Demod circuit

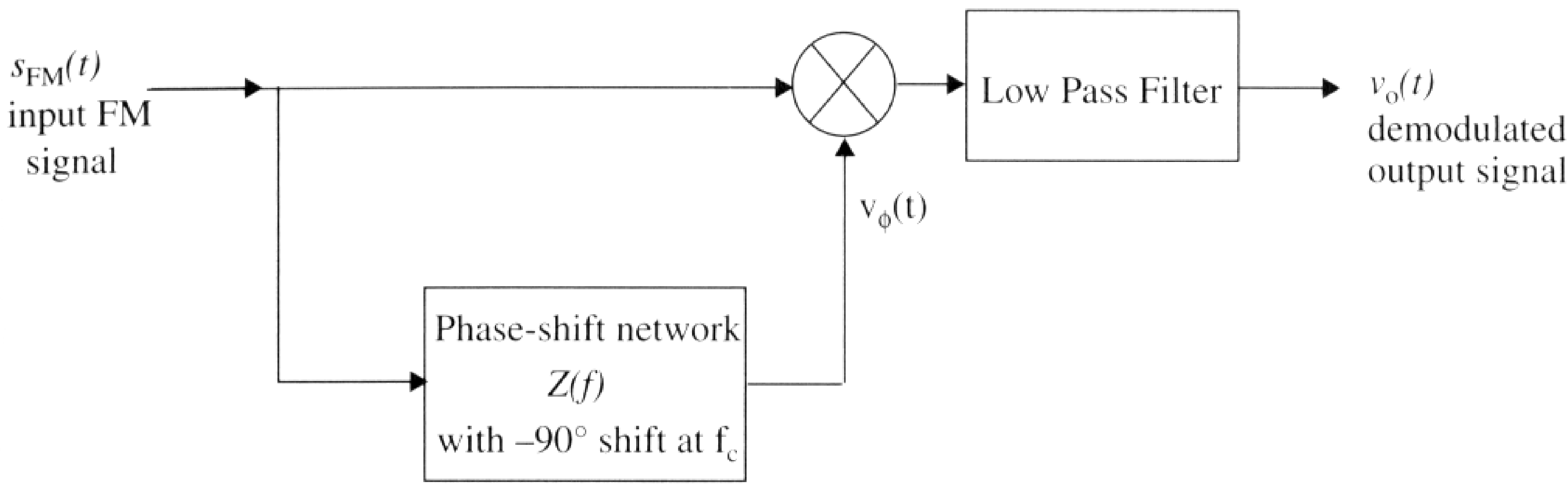


Figure 6.12 Block diagram of a quadrature detector.

Line Coding spectra

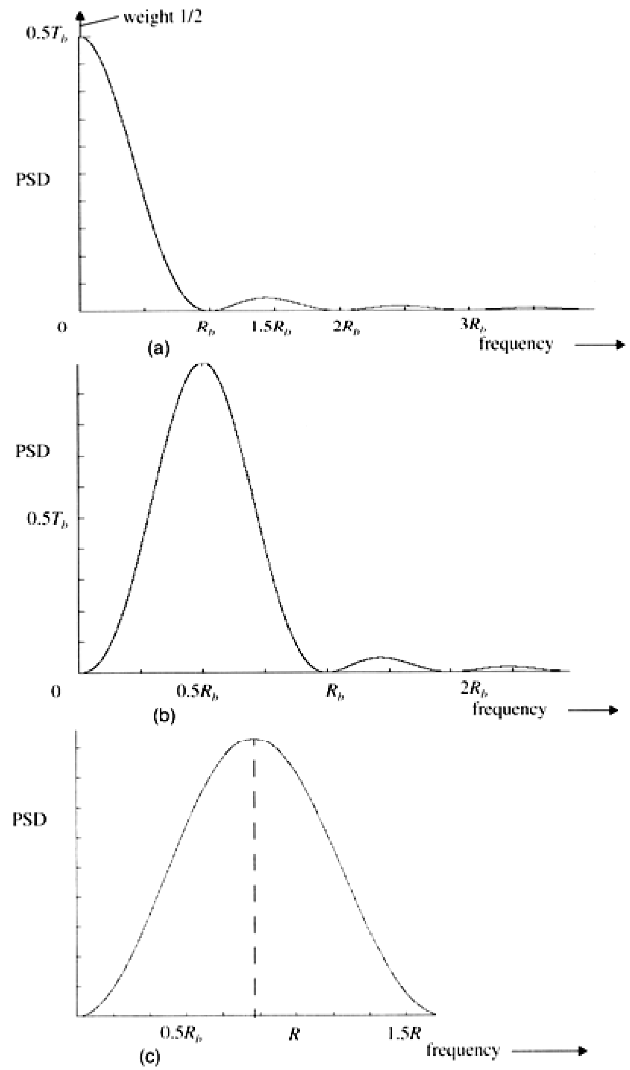


Figure 6.13 Power spectral density of (a) unipolar NRZ, (b) bipolar RZ, and (c) Manchester NRZ line codes.

RZ and NRZ Line Codes

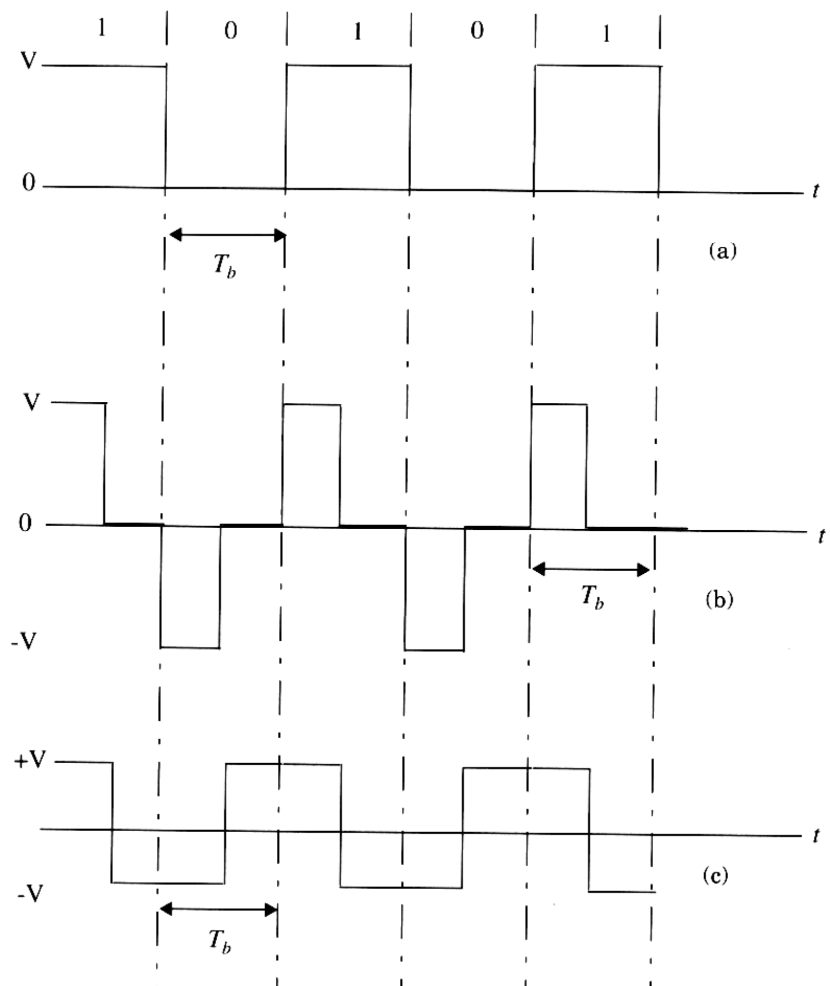


Figure 6.14 Time waveforms of binary line codes: (a) unipolar NRZ; (b) bipolar RZ; (c) Manchester NRZ.

Nyquist Pulses for zero-ISI

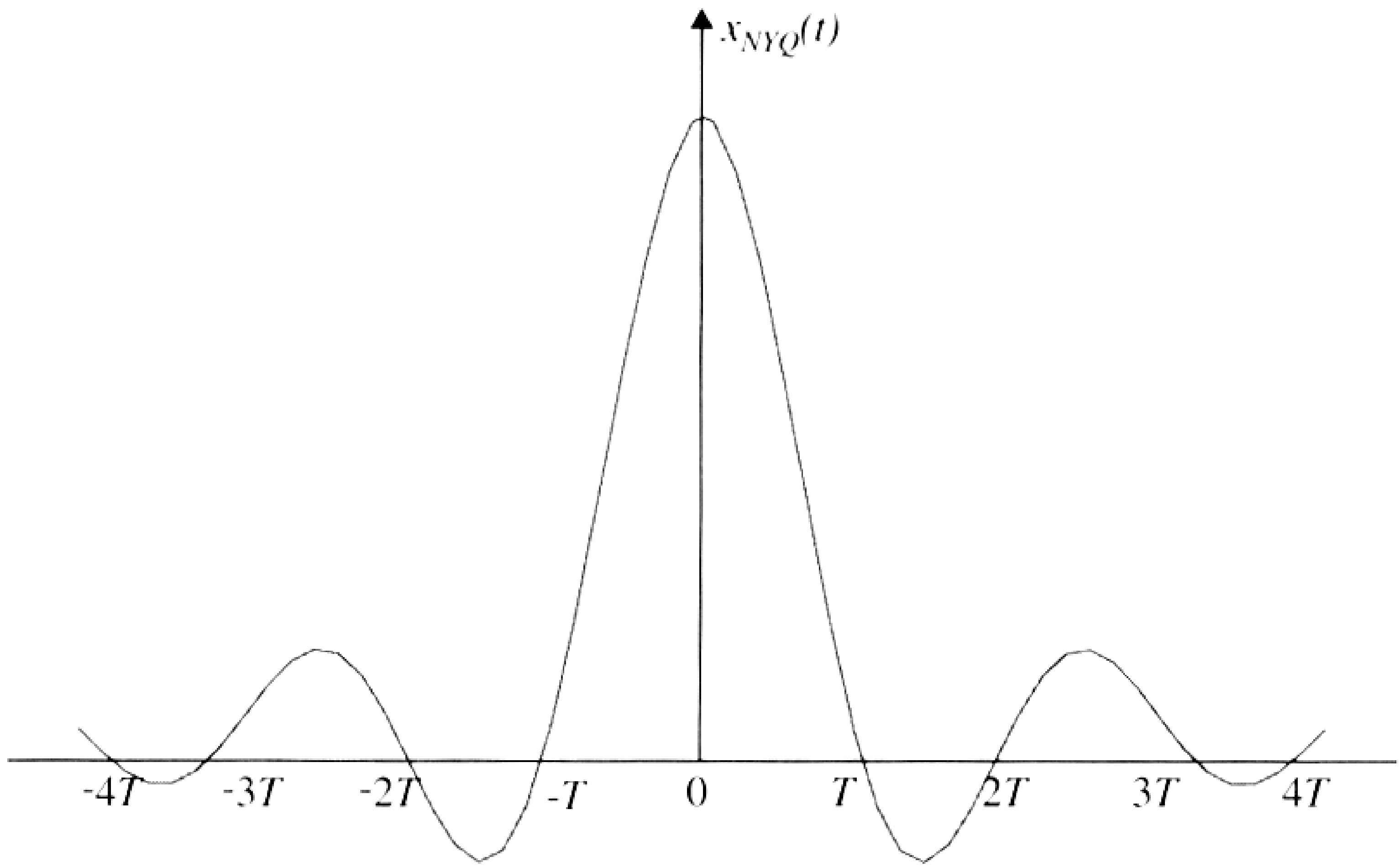


Figure 6.15 Nyquist ideal pulse shape for zero intersymbol interference.

Raised Cosine Spectrum

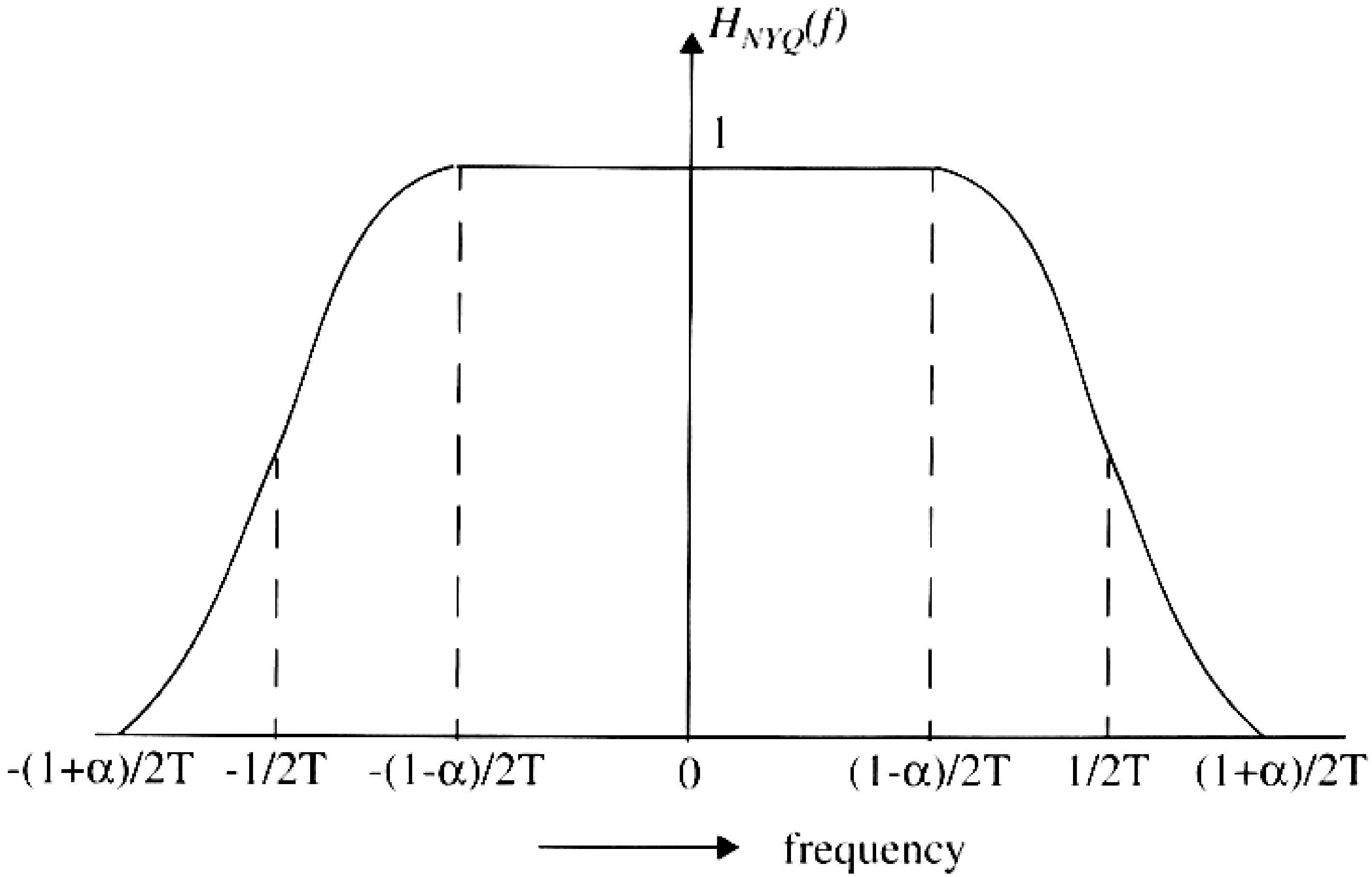


Figure 6.16 Transfer function of a Nyquist pulse-shaping filter at baseband.

Spectrum of Raised Cosine pulse

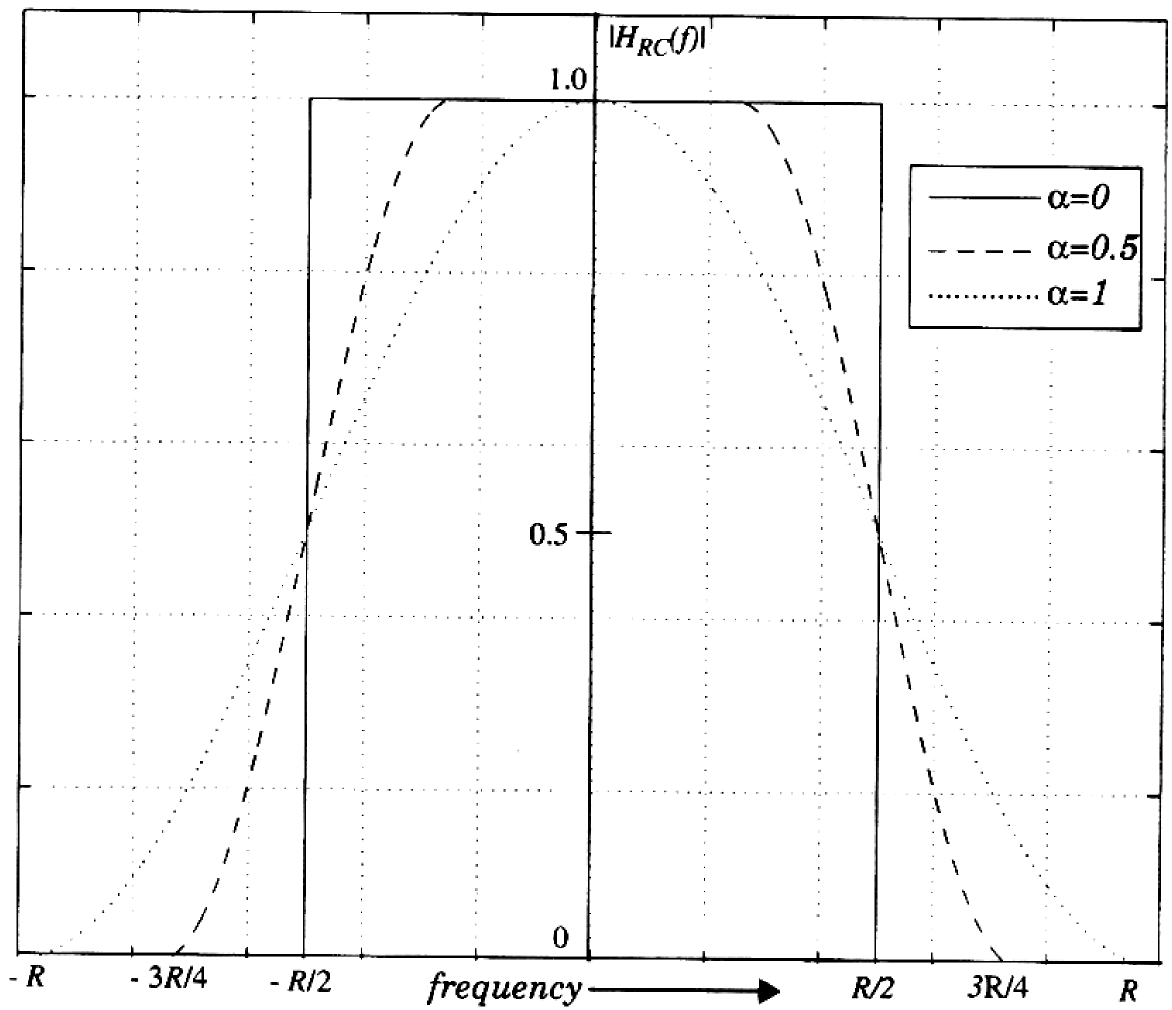


Figure 6.17 Magnitude transfer function of a raised cosine filter at baseband.

Raised Cosine pulses

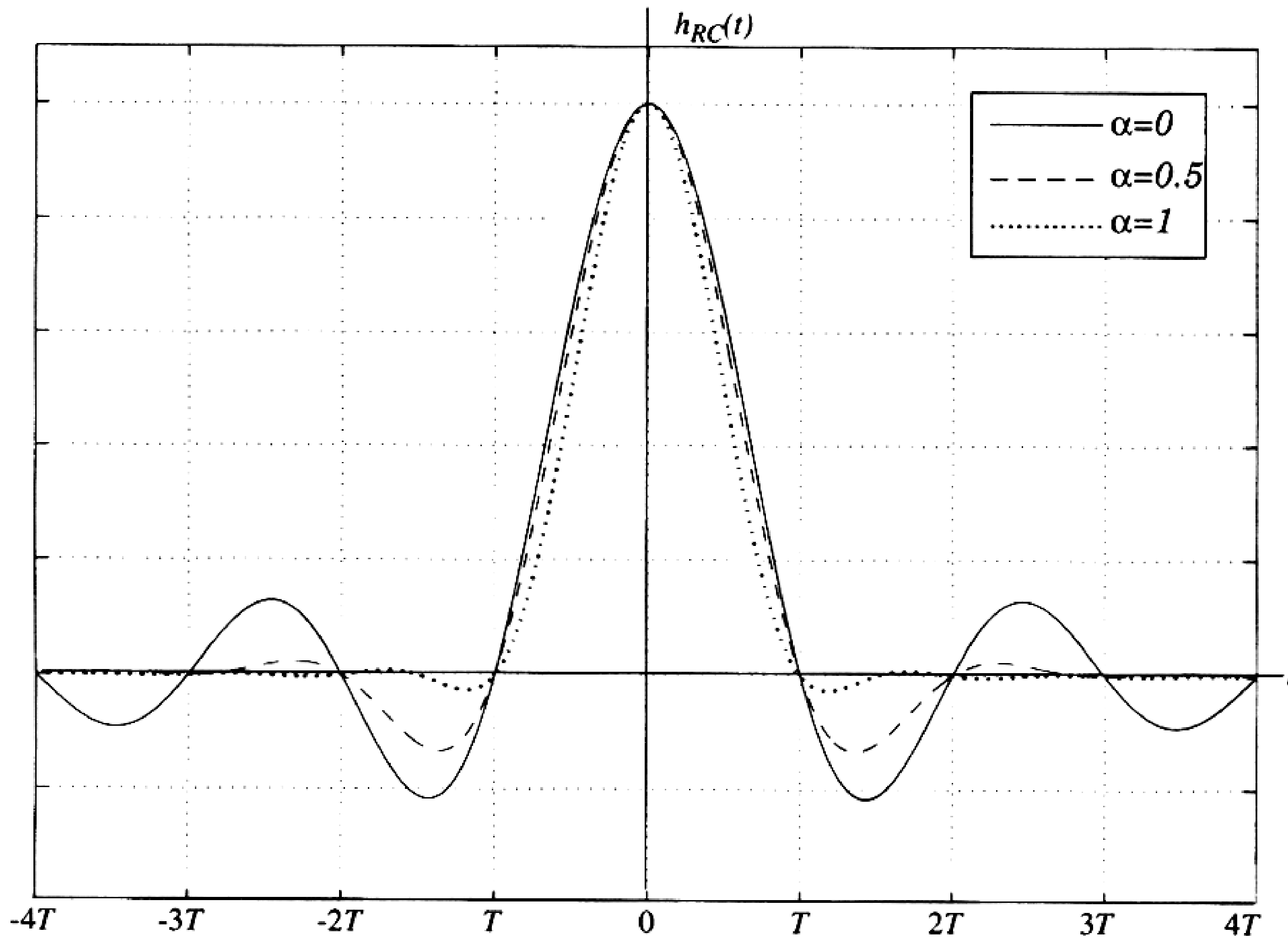


Figure 6.18 Impulse response of a raised cosine rolloff filter at baseband.

RF signal usig Raised Cosine

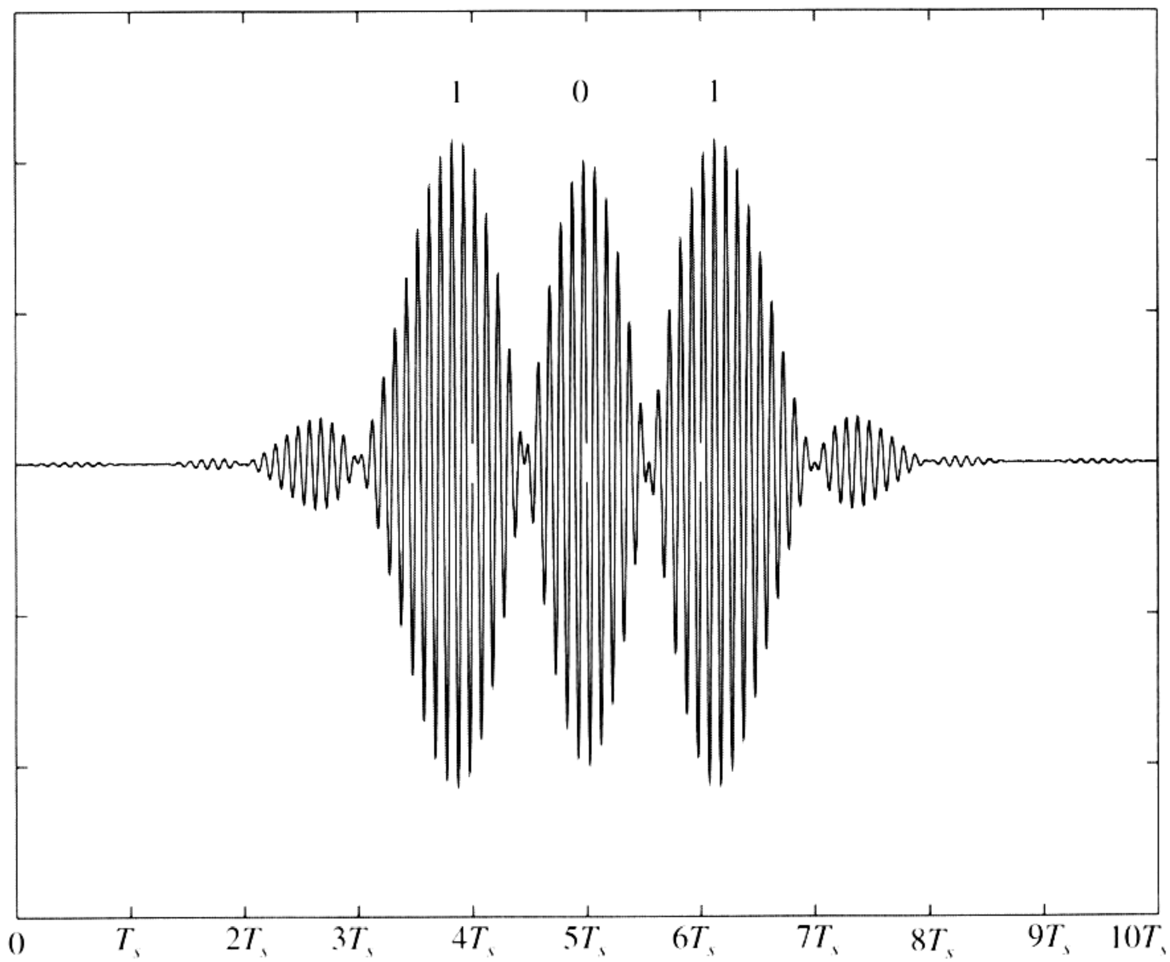


Figure 6.19 Raised cosine filtered (α = 0.5) pulses corresponding to 1, 0, 1 data stream for a BPSK signal. Notice that the decision points (at $4T_s$, $5T_s$, $6T_s$) do not always correspond to the maximum values of the RF waveform.

Gaussian pulse-shapes

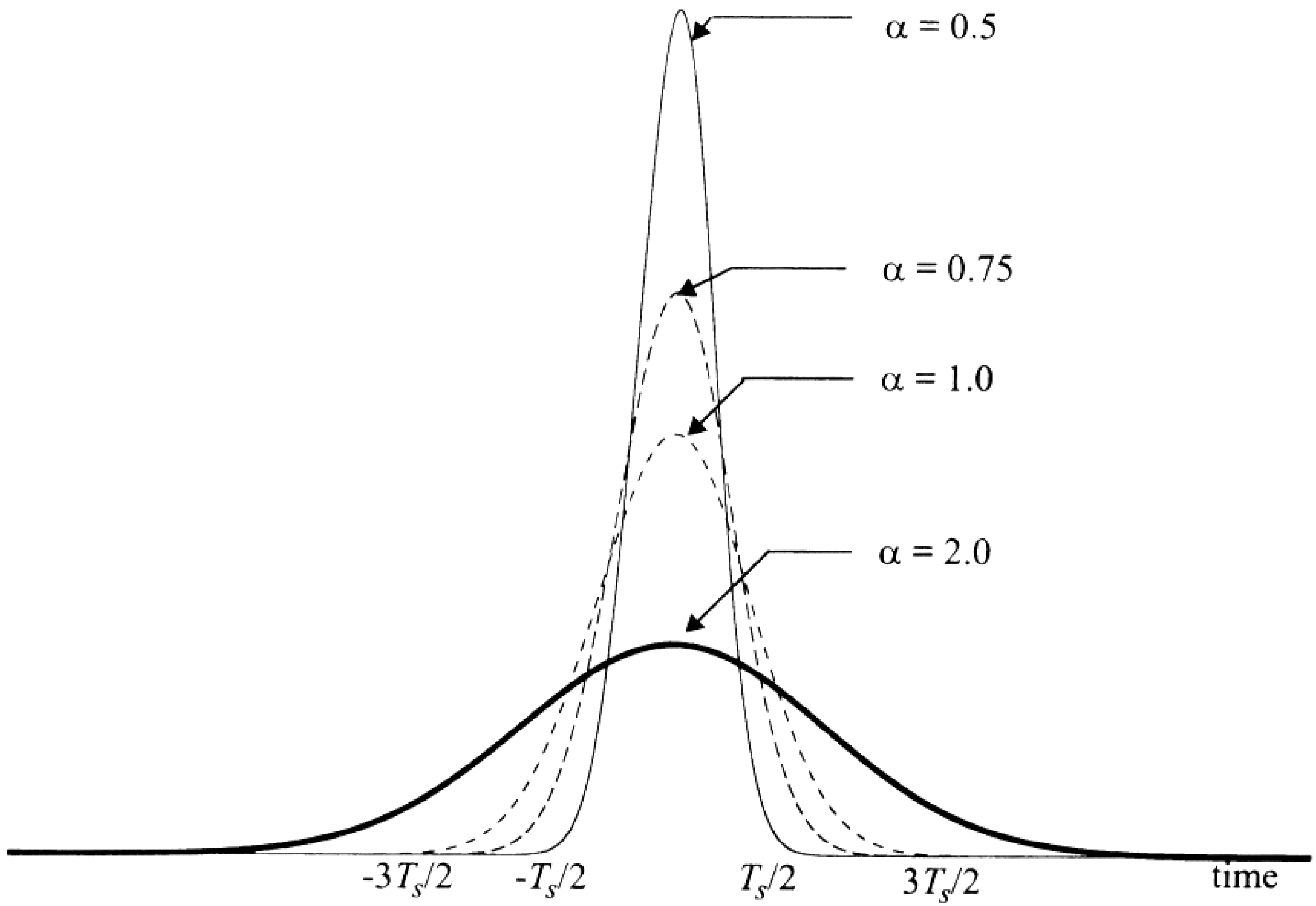


Figure 6.20 Impulse response of a Gaussian pulse-shaping filter.

BPSK constellation

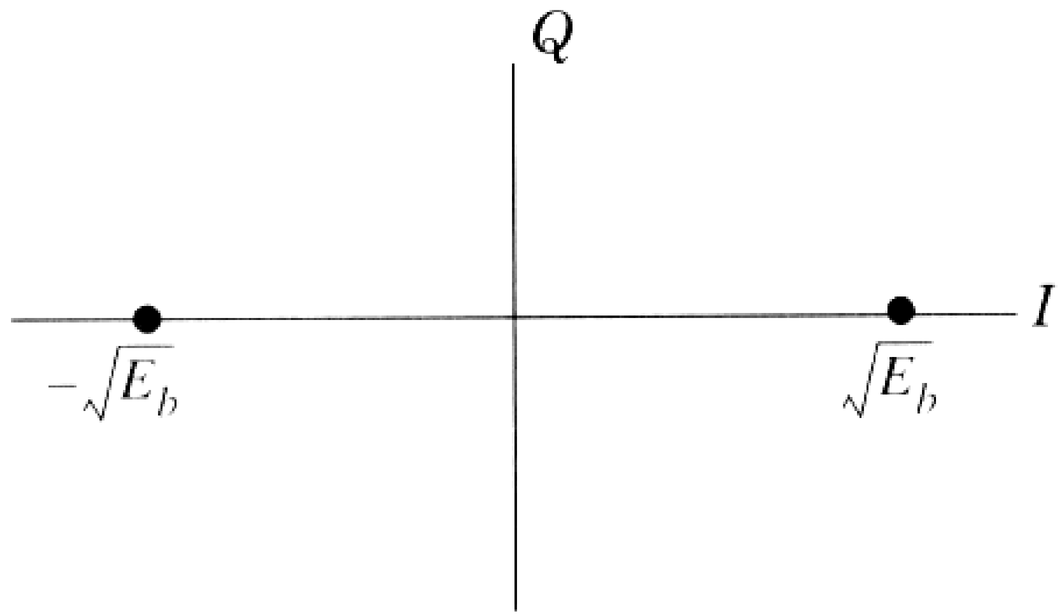


Figure 6.21 BPSK constellation diagram.

Virtue of pulse shaping

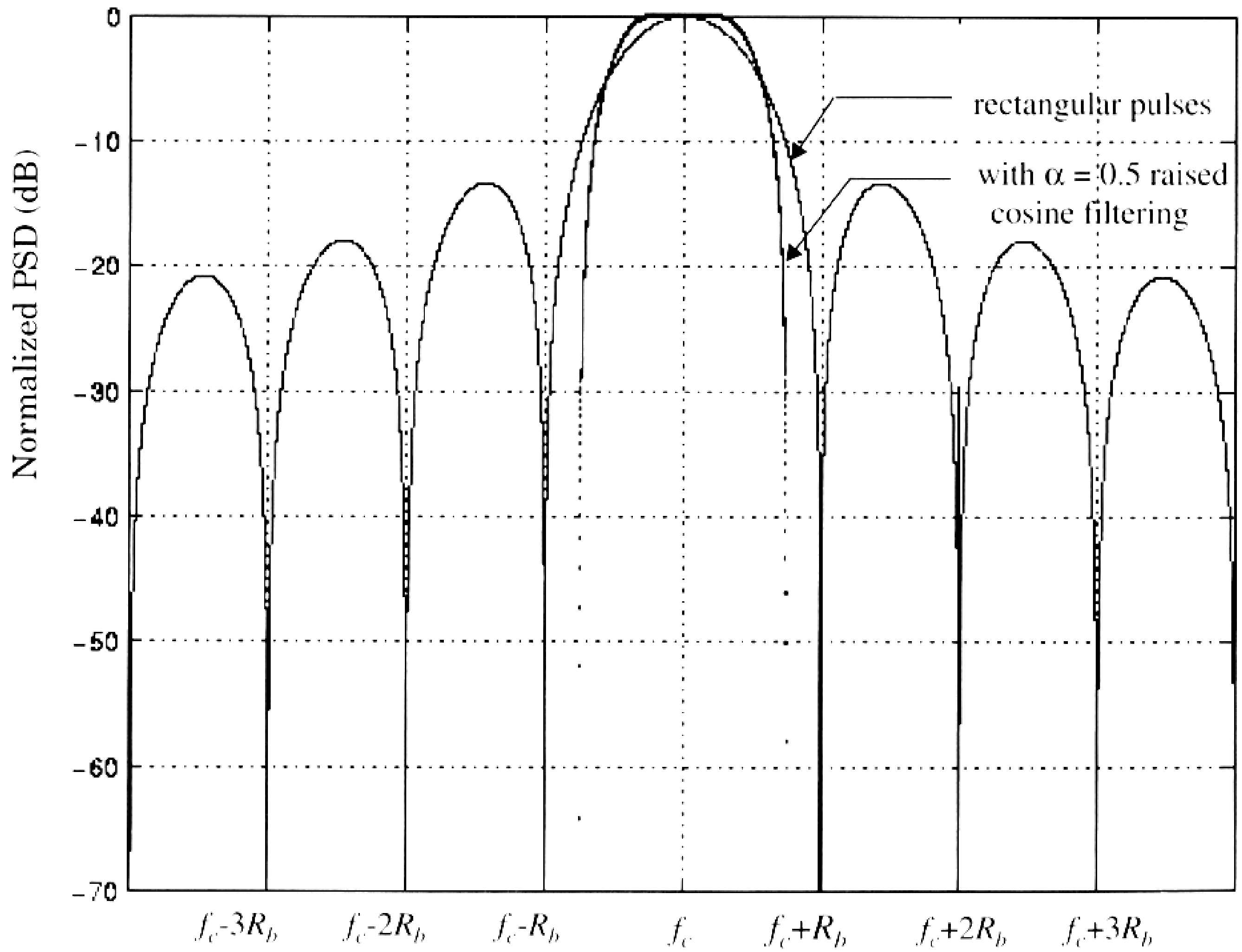


Figure 6.22 Power spectral density (PSD) of a BPSK signal.

BPSK Coherent demodulator

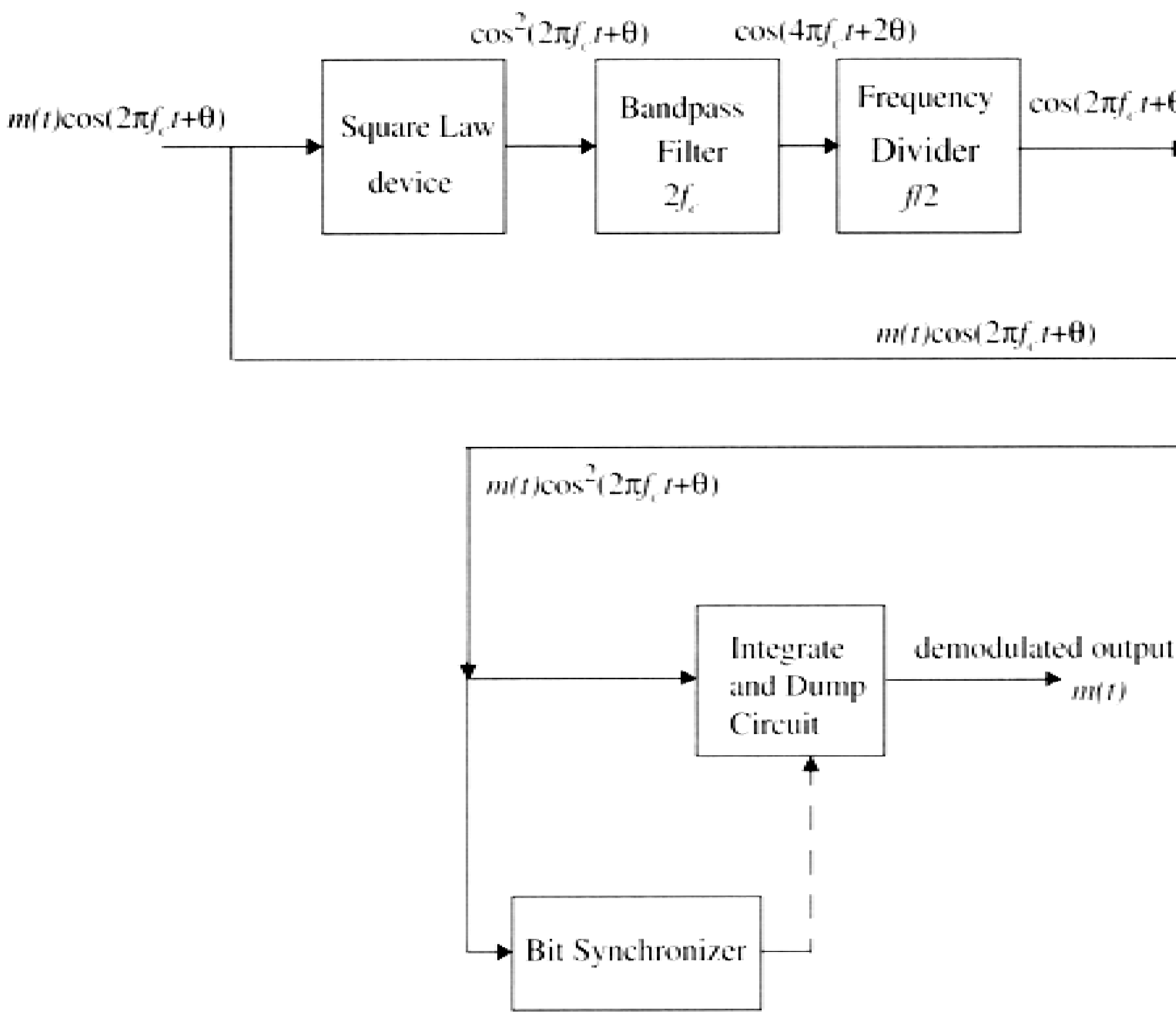


Figure 6.23 BPSK receiver with carrier recovery circuits.

Differential PSK encoding

Table 6.1 Illustration of the Differential Encoding Process

$\{m_k\}$		1	0	0	1	0	1	1	0
$\{d_{k-1}\}$		1	1	0	1	1	0	0	0
$\{d_k\}$	1	1	0	1	1	0	0	0	1

DPSK modulation

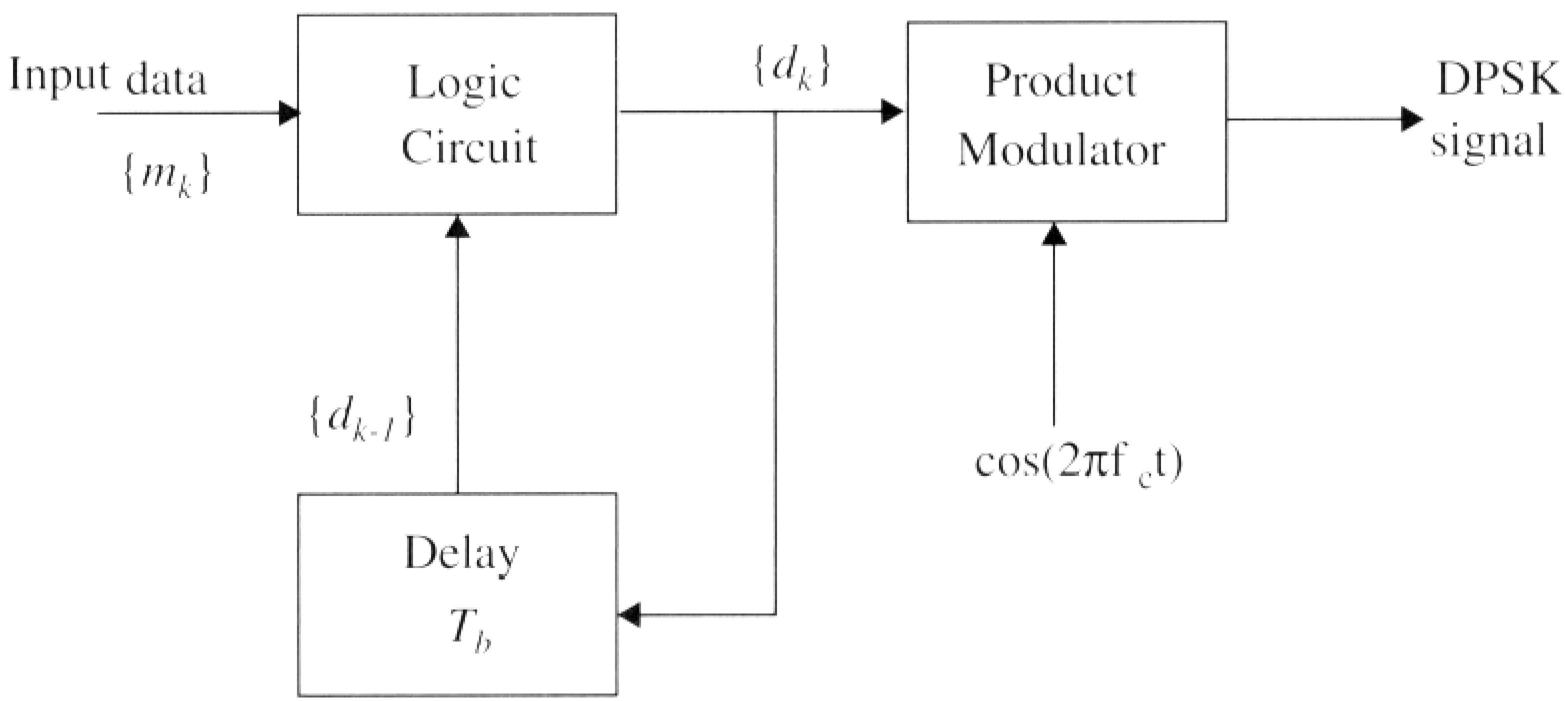


Figure 6.24 Block diagram of a DPSK transmitter.

DPSK receiver

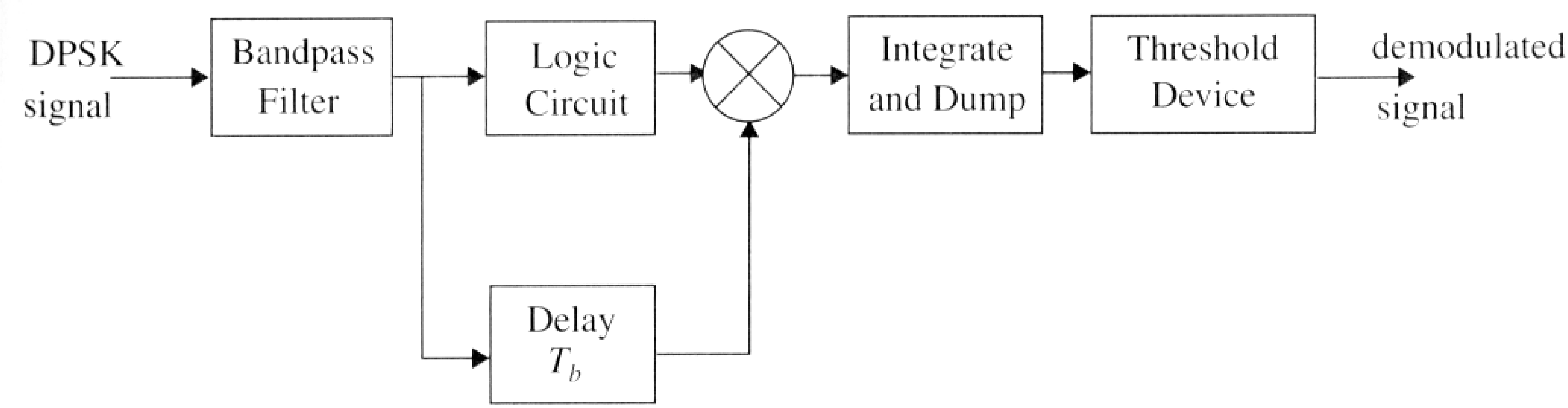
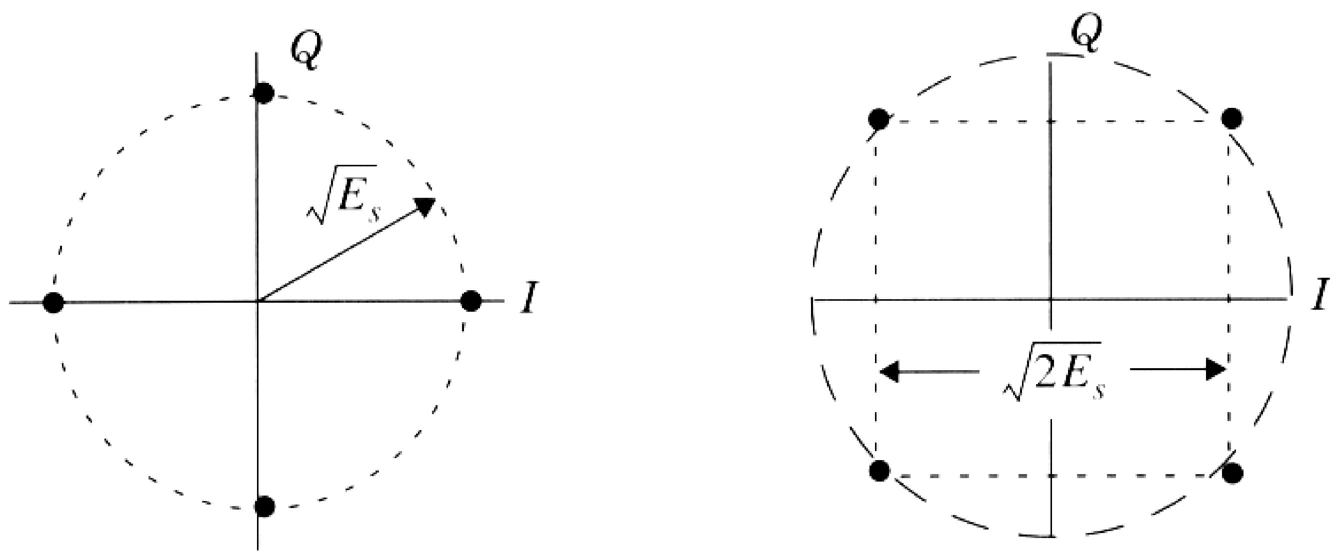


Figure 6.25 Block diagram of DPSK receiver.

QPSK constellation diagrams



(a) (b)

Figure 6.26 (a) QPSK constellation where the carrier phases are 0, $\pi/2$, π, $3\pi/2$; (b) QPSK constellation where the carrier phases are $\pi/4$, $3\pi/4$, $5\pi/4$, $7\pi/4$.

Virtues of Pulse Shaping

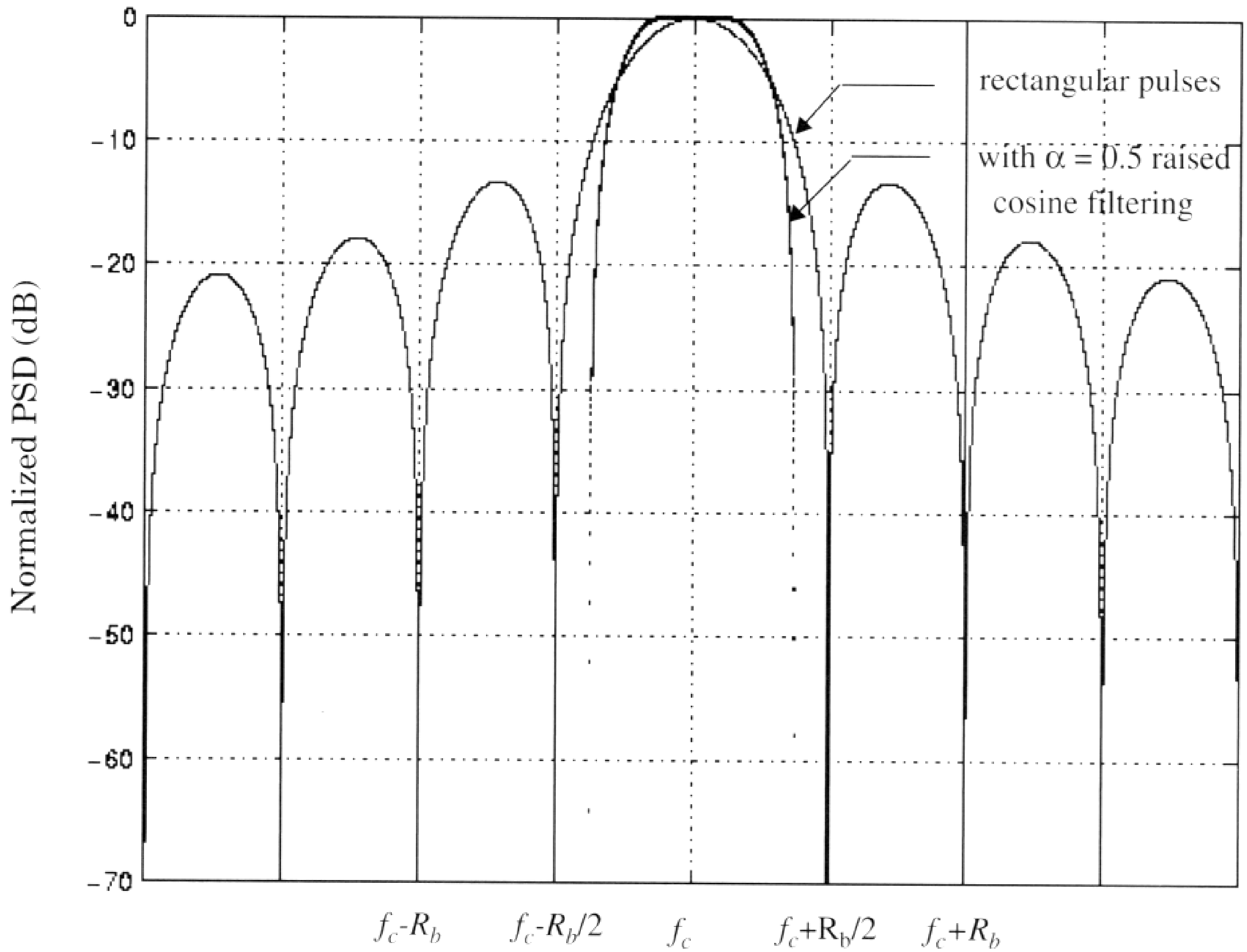


Figure 6.27 Power spectral density of a QPSK signal.

QPSK modulation

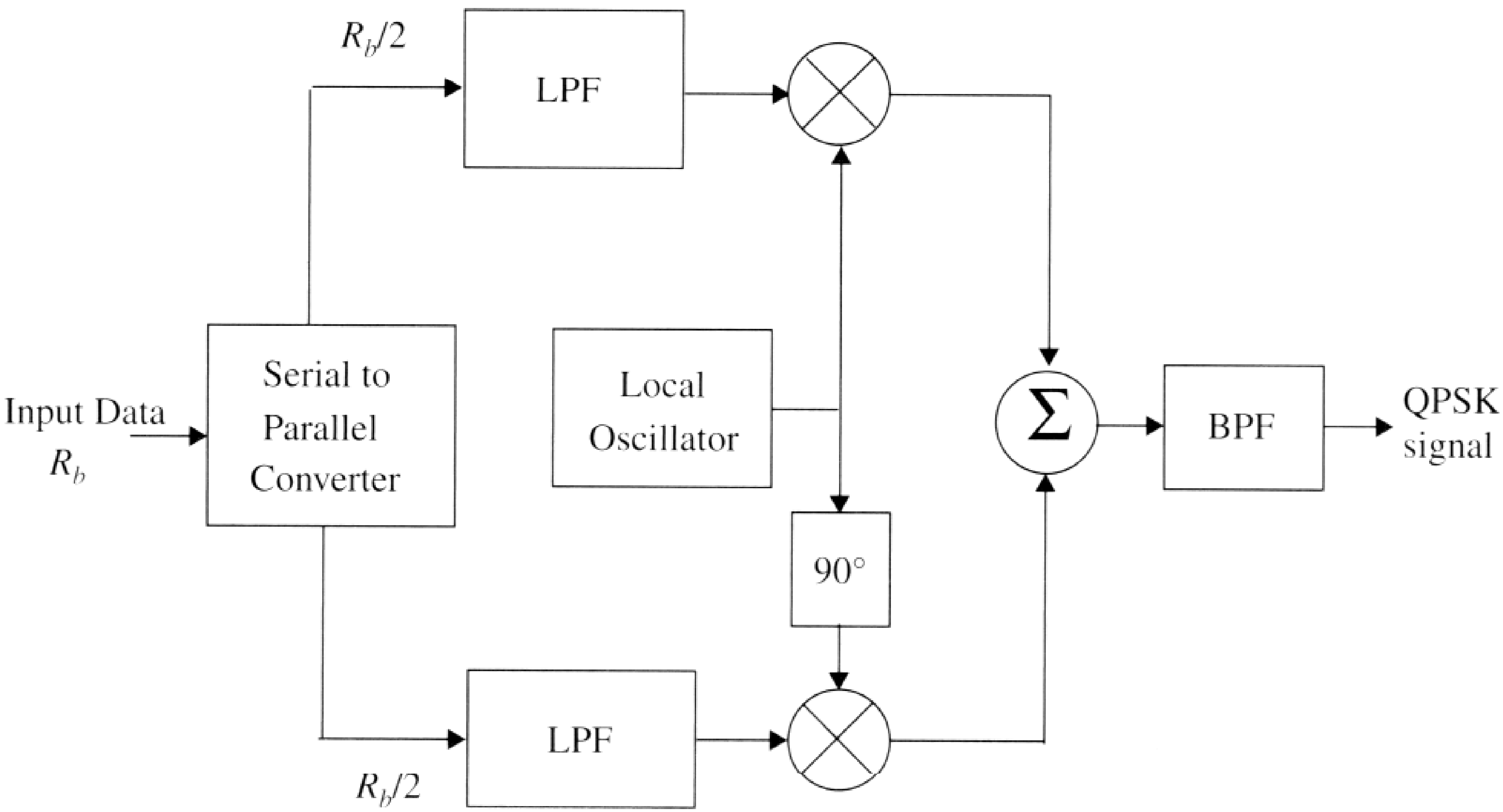


Figure 6.28 Block diagram of a QPSK transmitter.

QPSK receiver

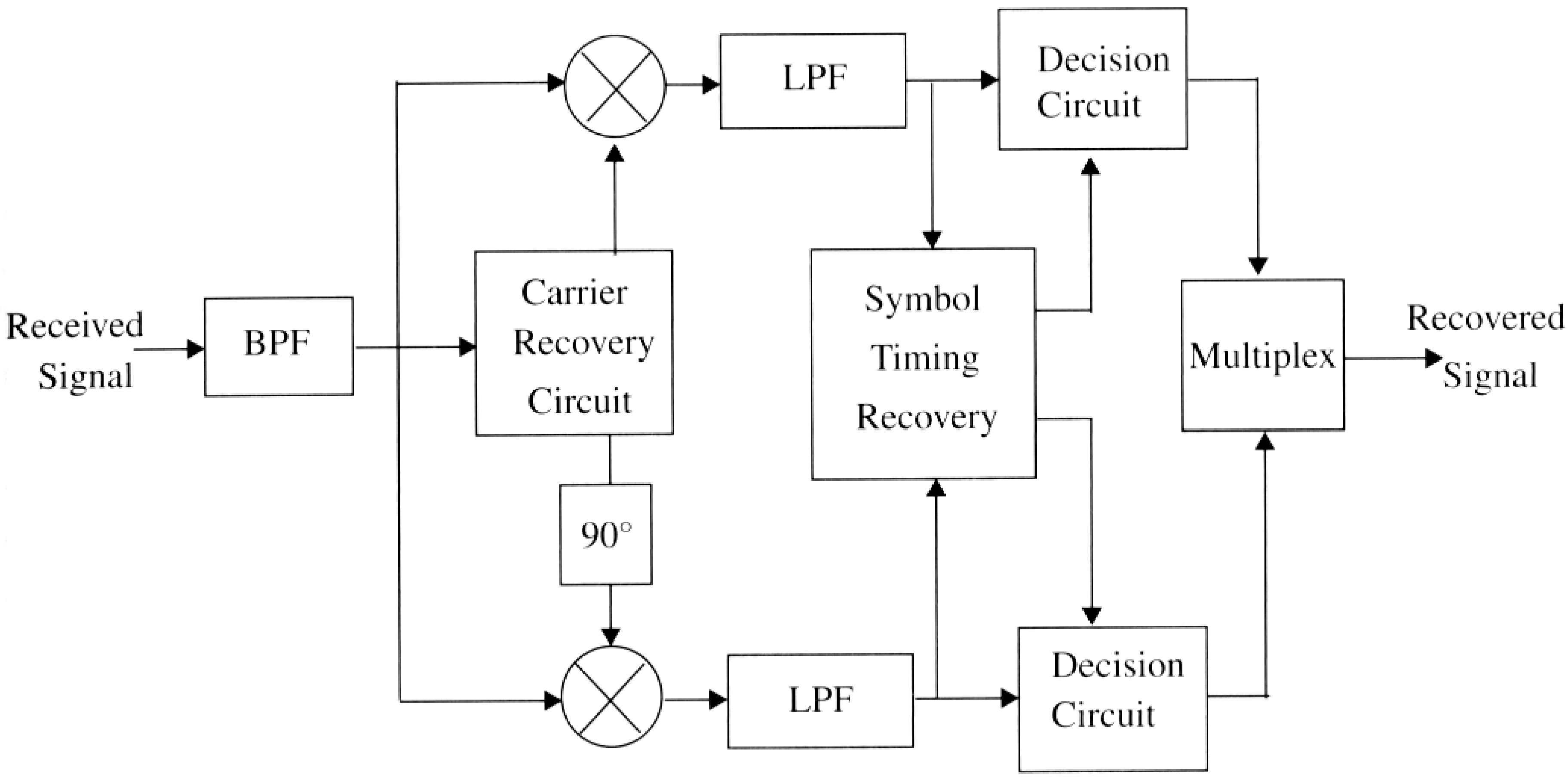


Figure 6.29 Block diagram of a QPSK receiver.

Offset QPSK waveforms

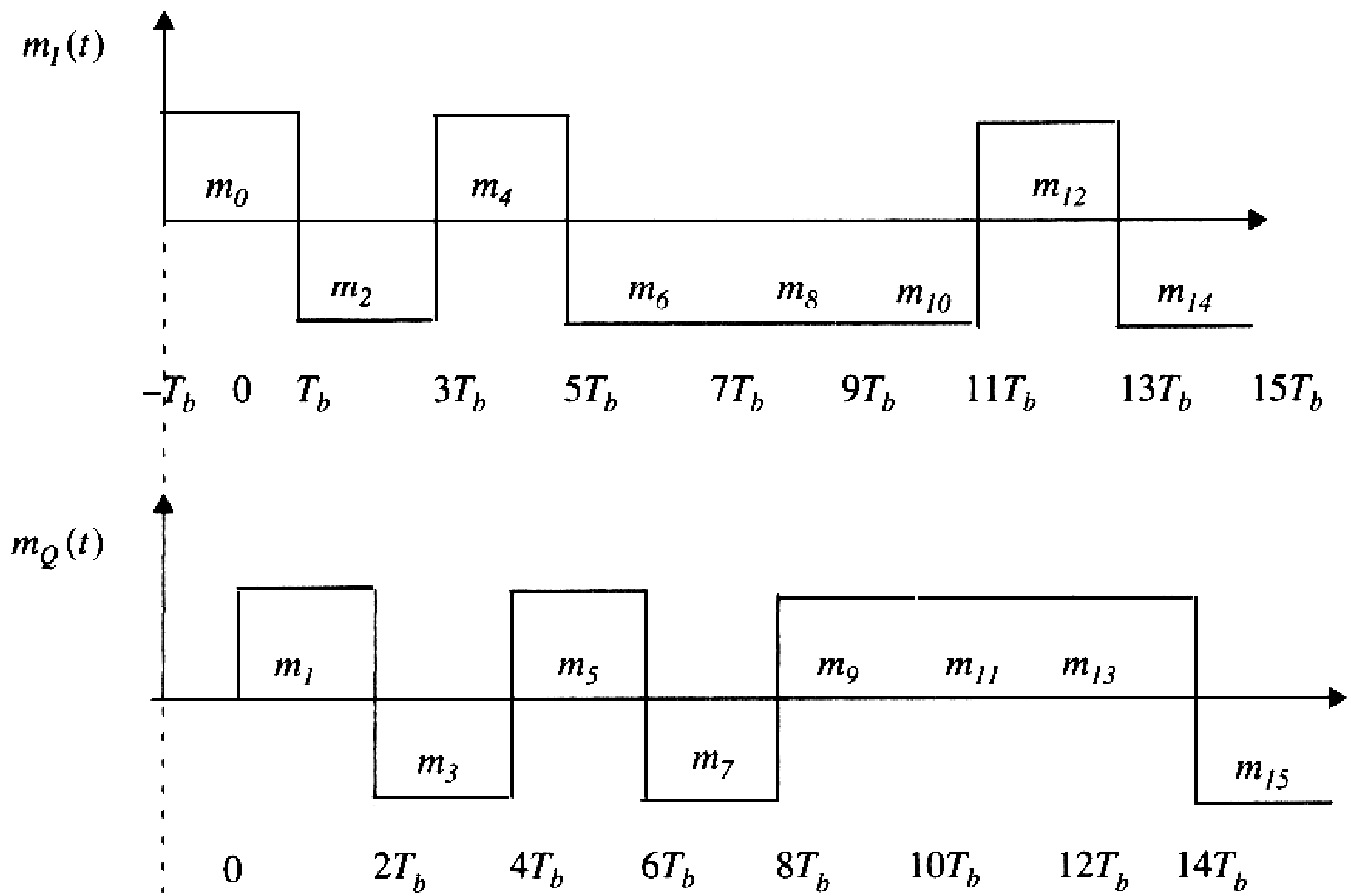


Figure 6.30 The time offset waveforms that are applied to the in-phase and quadrature arms of an OQPSK modulator. Notice that a half-symbol offset is used.

Pi/4 QPSK signaling

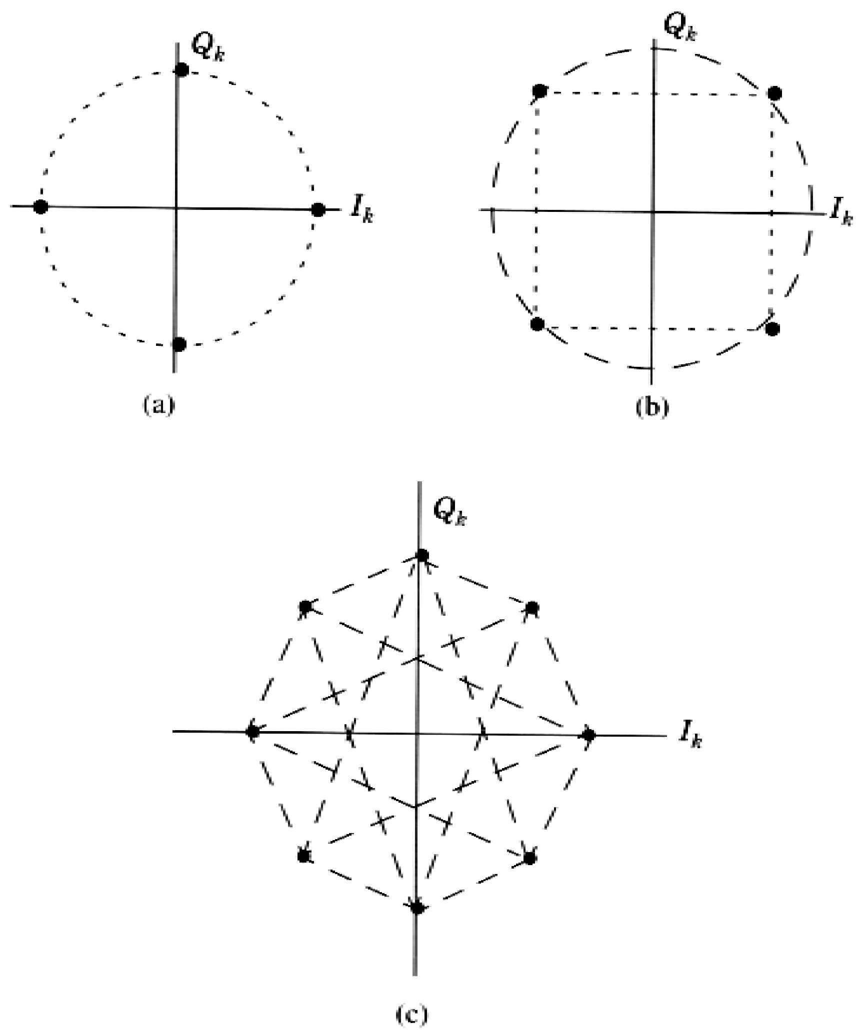


Figure 6.31 Constellation diagram of a $\pi/4$ QPSK signal: (a) possible states for θ_k when $\theta_{k-1} = n\pi/4$; (b) possible states when $\theta_{k-1} = n\pi/2$; (c) all possible states.

Pi/4 QPSK phase shifts

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

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

Pi/4 QPSK transmitter

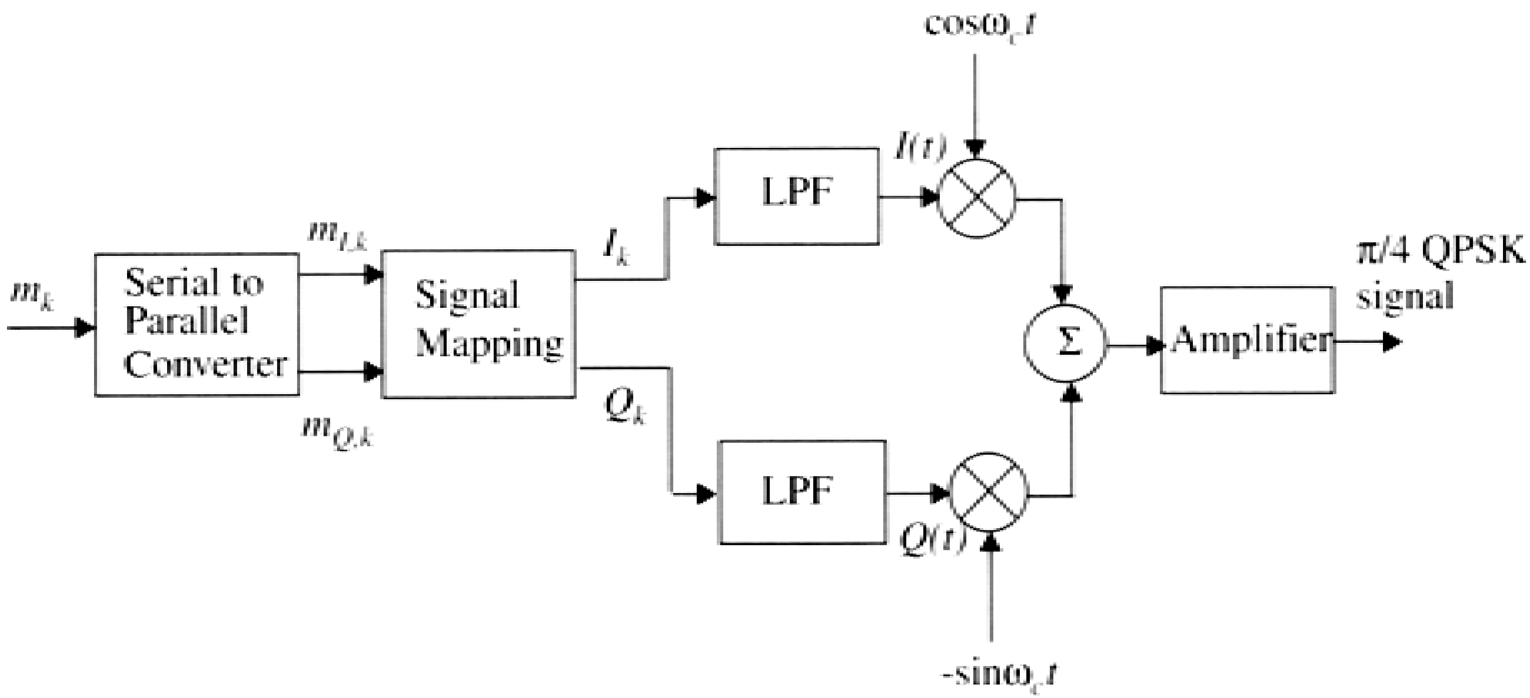


Figure 6.32 Generic π/4 QPSK transmitter.

Differential detection of pi/4 QPSK

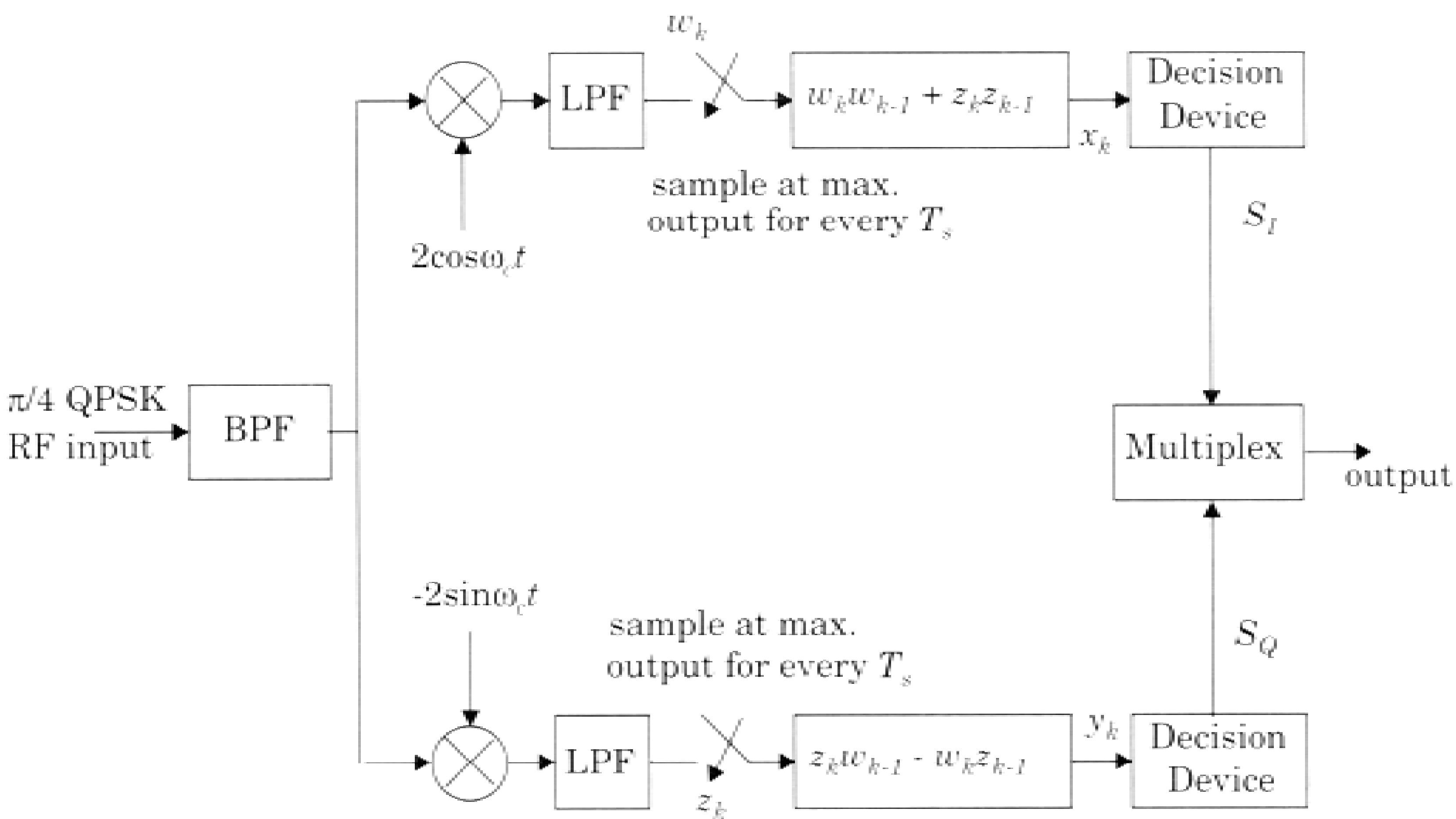


Figure 6.33 Block diagram of a baseband differential detector [from [Feh91] © IEEE].

IF Differential Detection

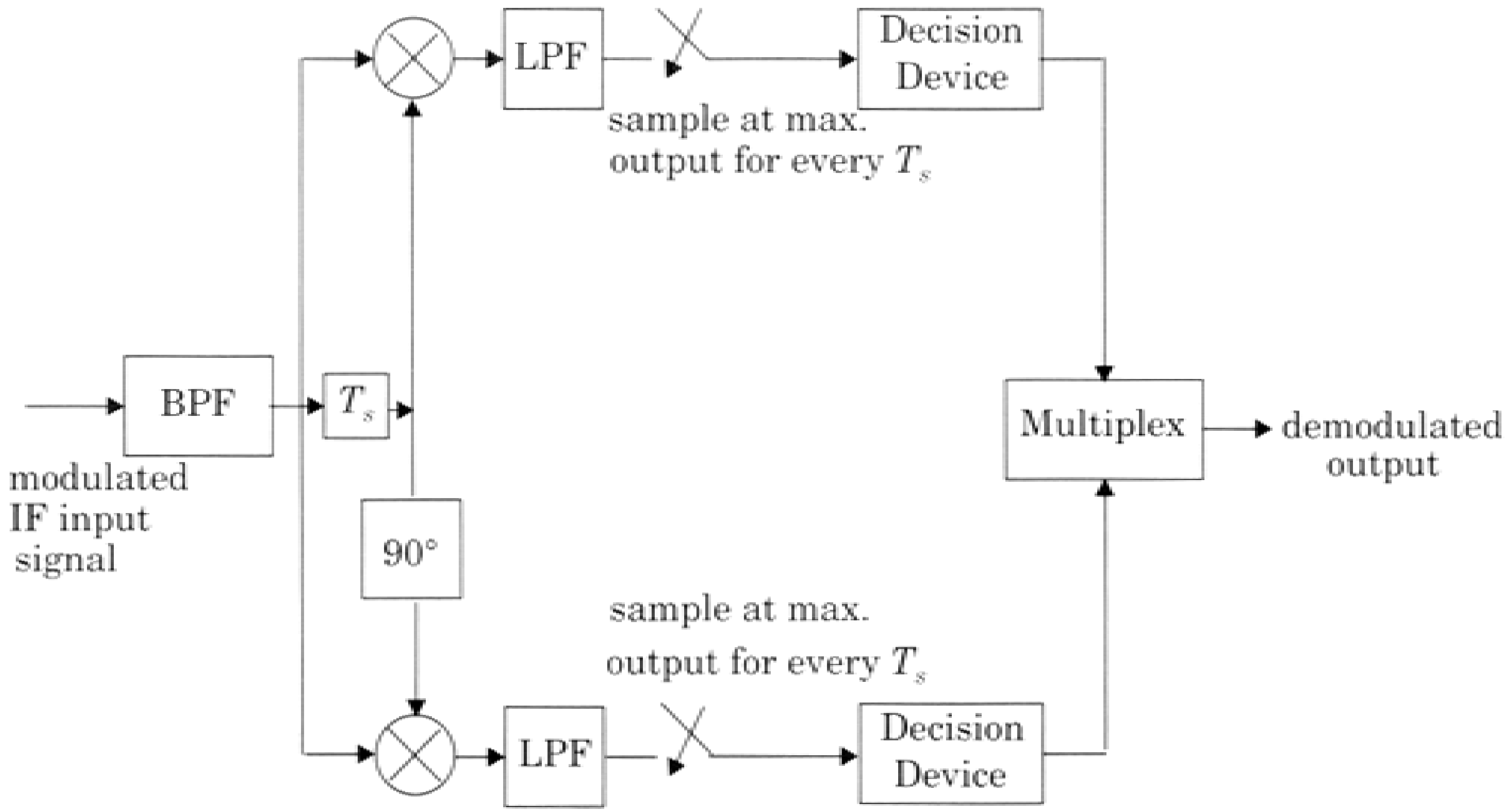


Figure 6.34 Block diagram of an IF differential detector for π/4 QPSK.

FM Discriminator detector

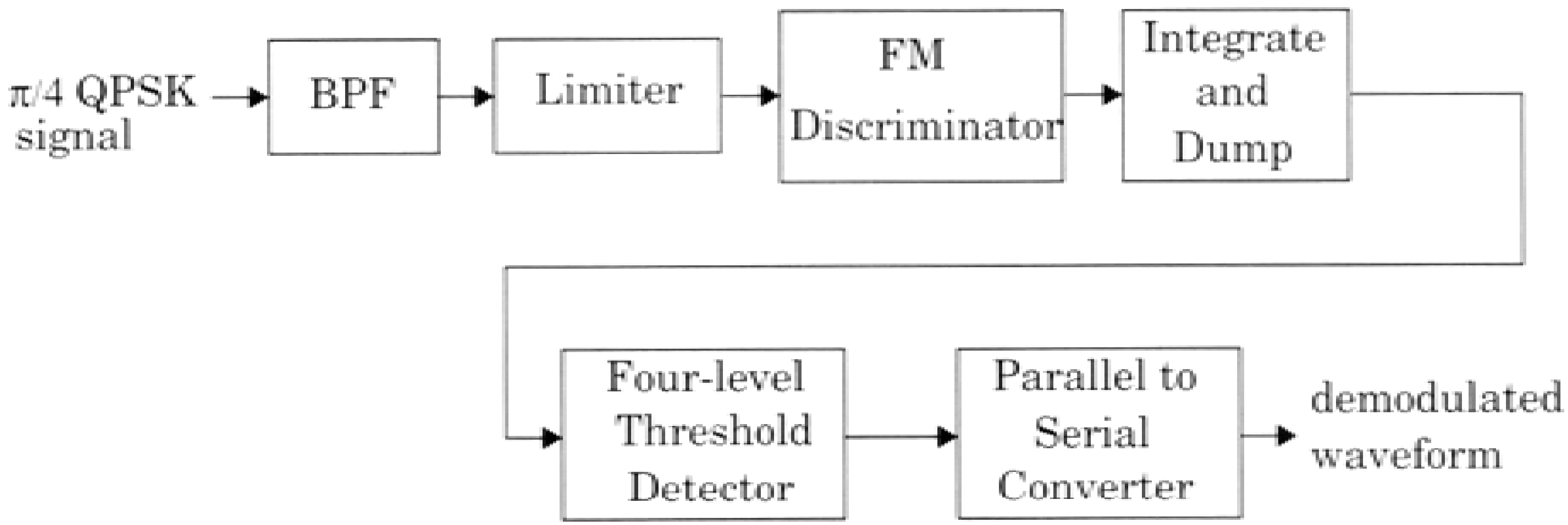


Figure 6.35 FM discriminator detector for π/4 DQPSK demodulation.

FSK Coherent Detection

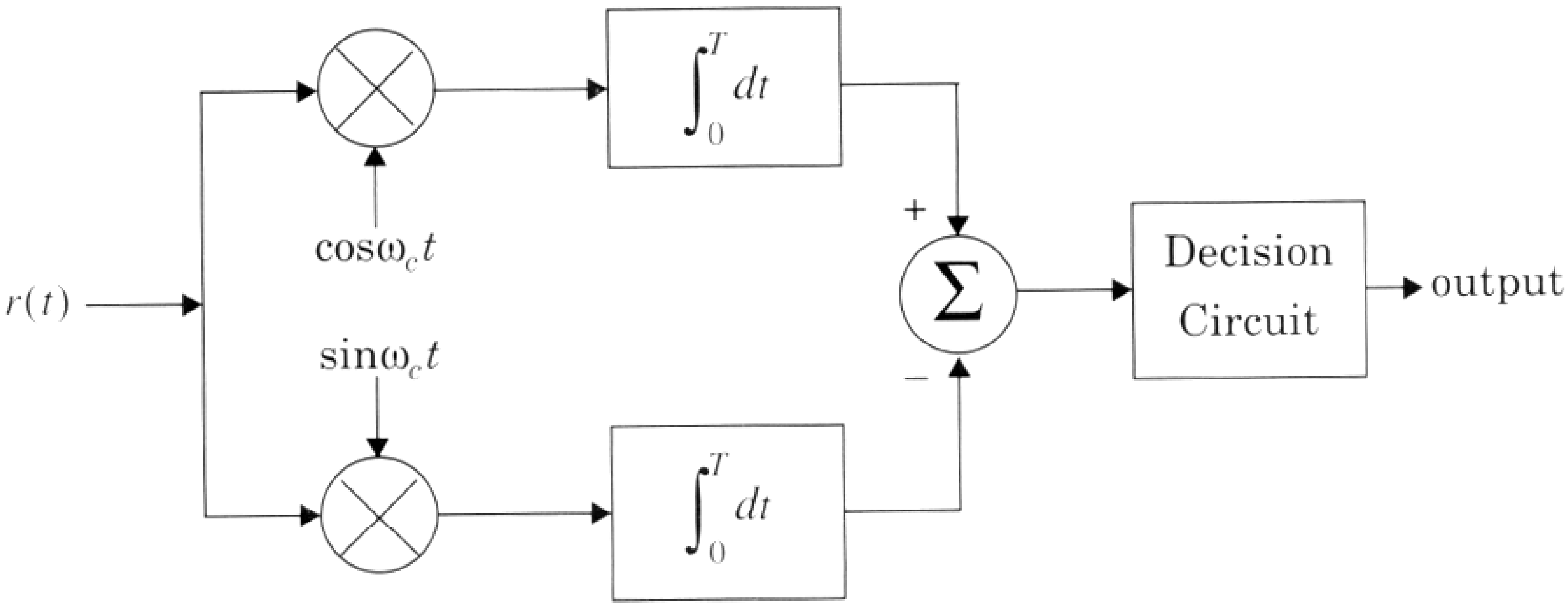


Figure 6.36 Coherent detection of FSK signals.

Noncoherent FSK

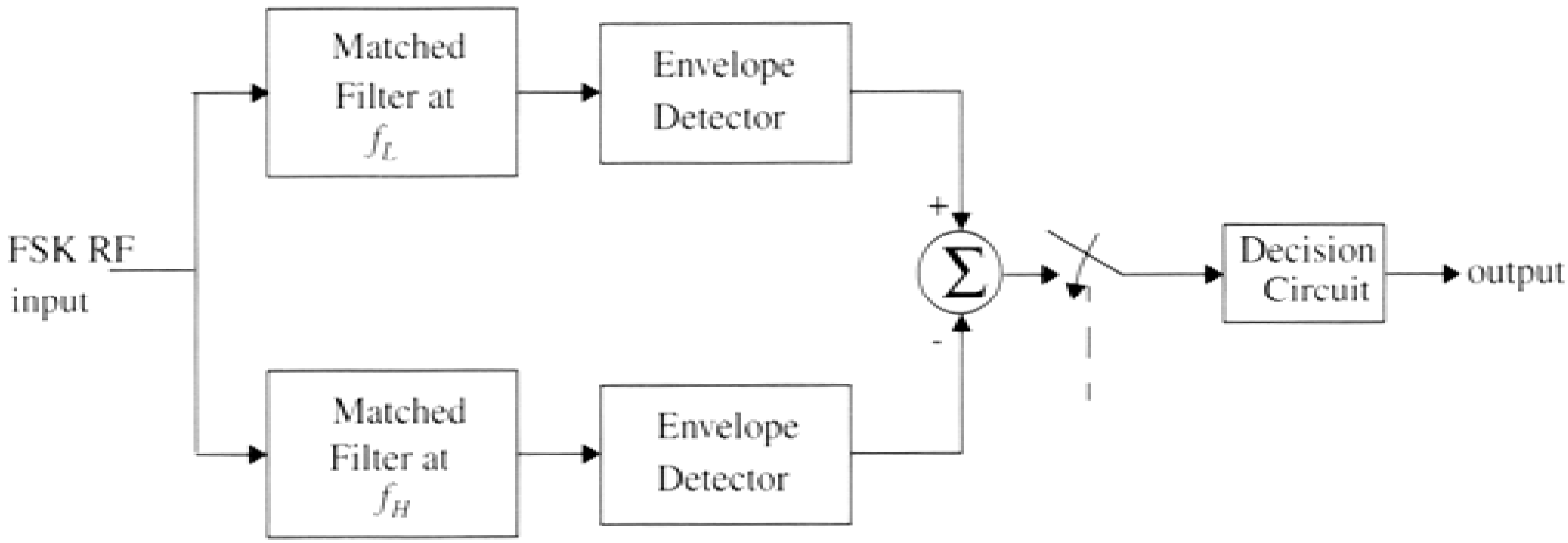


Figure 6.37 Block diagram of noncoherent FSK receiver.

Minimum Shift Keying spectra

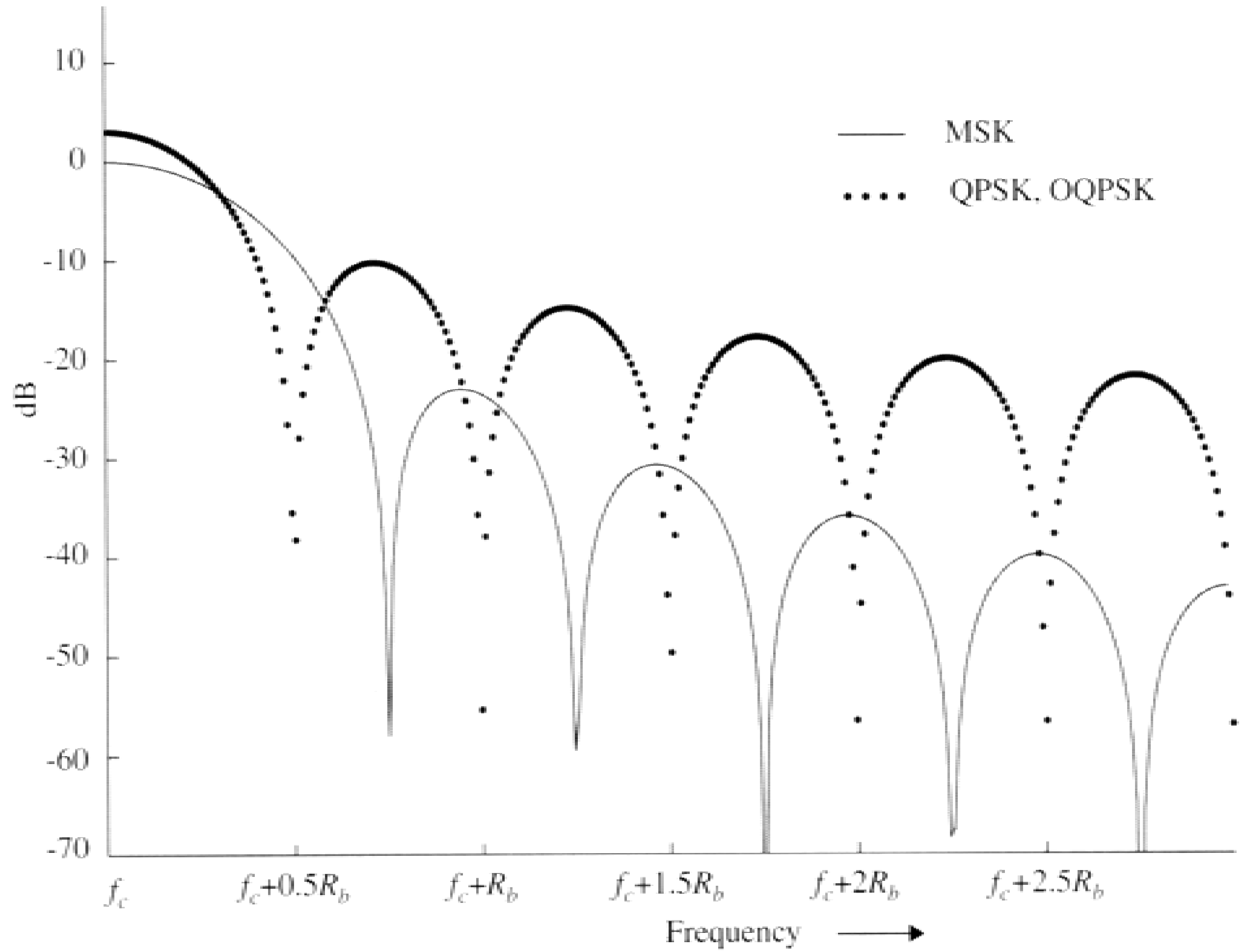


Figure 6.38 Power spectral density of MSK signals as compared to QPSK and OQPSK signals.

MSK modulation

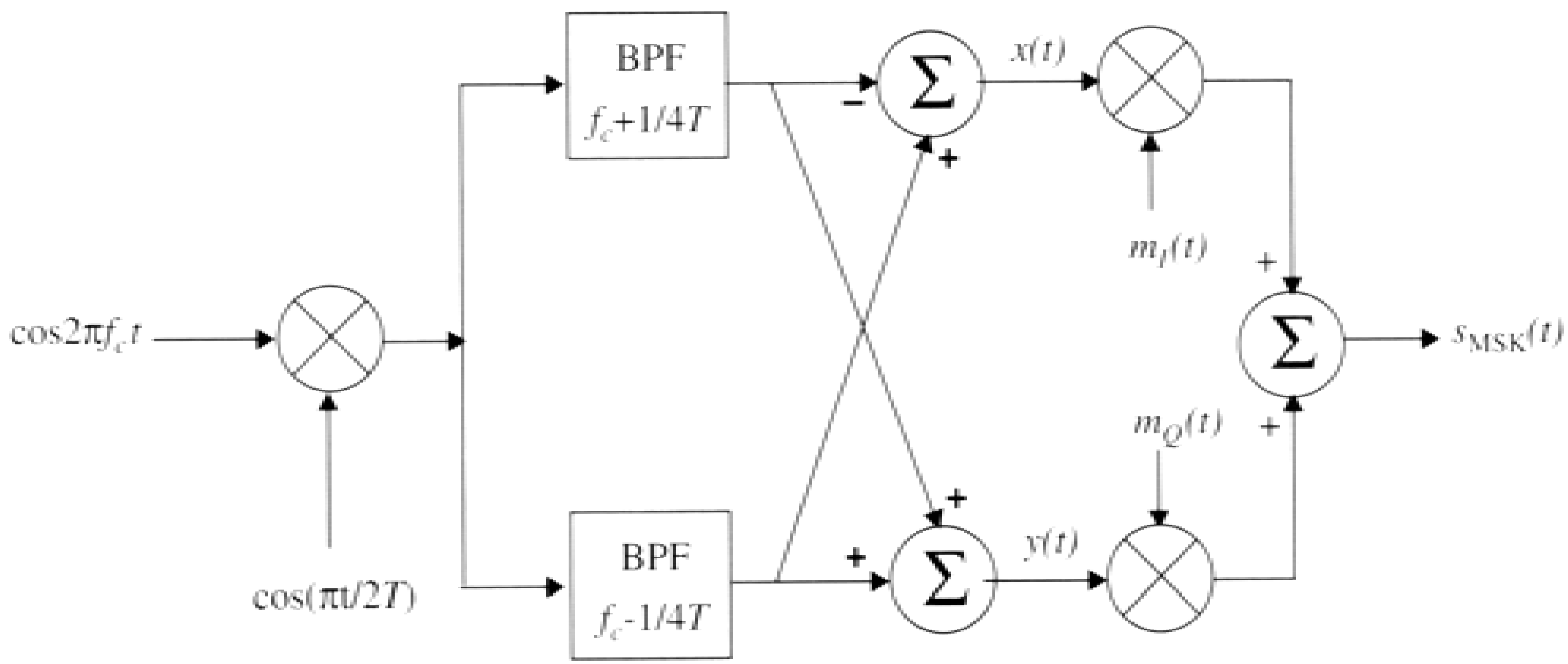


Figure 6.39 Block diagram of an MSK transmitter. Note that $m_I(t)$ and $m_Q(t)$ are offset by T_b.

MSK reception

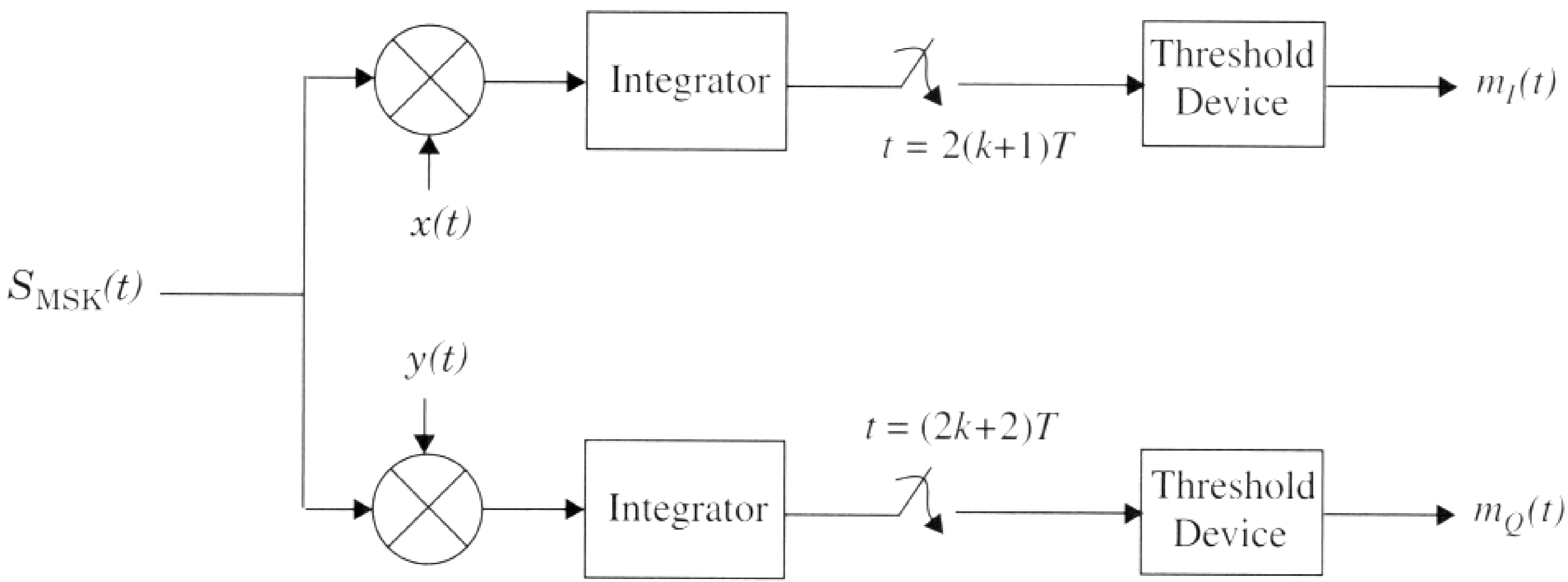


Figure 6.40 Block diagram of an MSK receiver.

GMSK spectral shaping

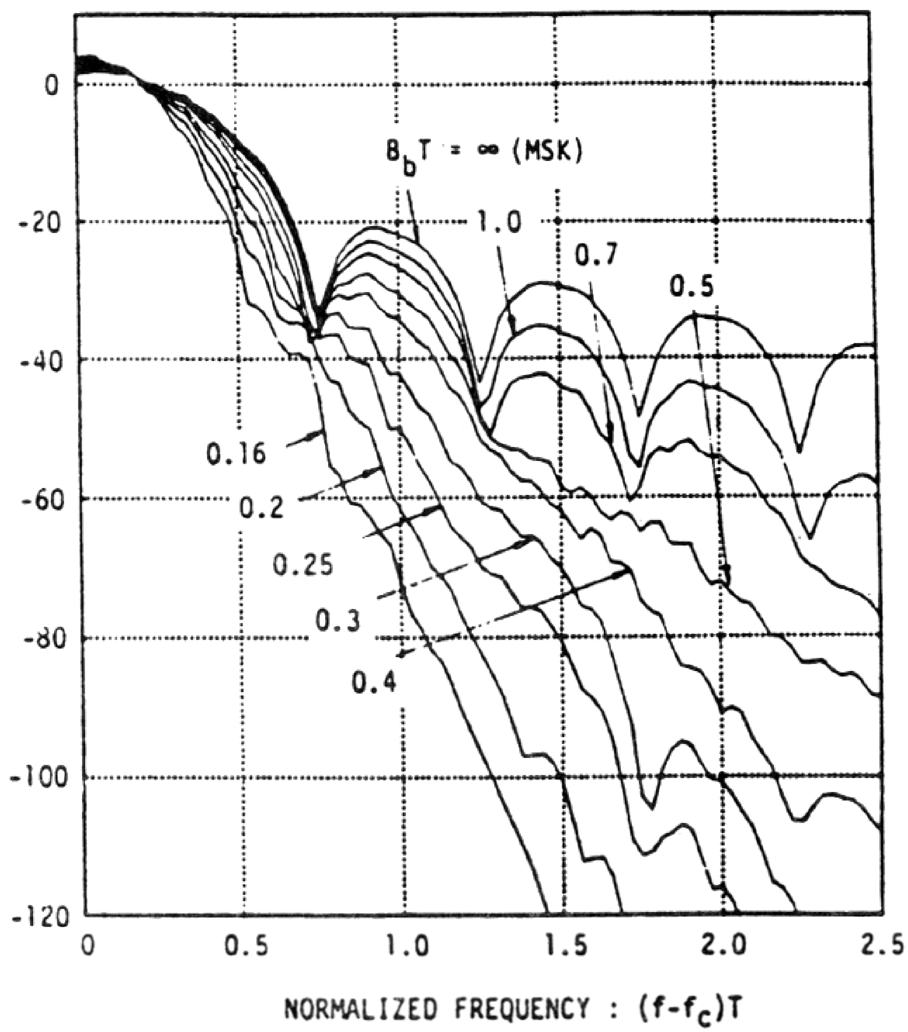


Figure 6.41 Power spectral density of a GMSK signal [from [Mur81] © IEEE].

GMSK spectra shaping

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

Simple GMSK generation

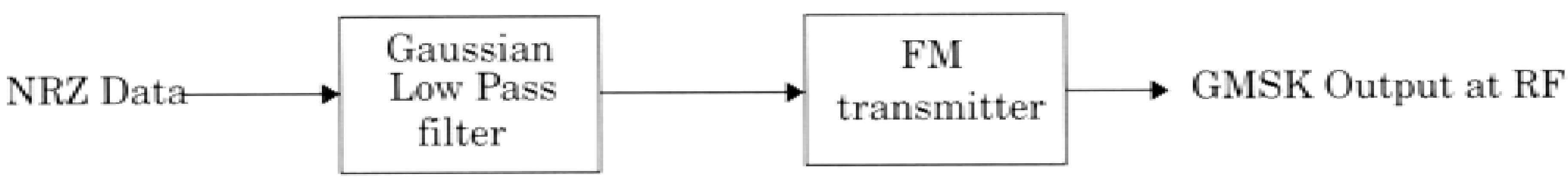


Figure 6.42 Block diagram of a GMSK transmitter using direct FM generation.

GMSK Demodulator

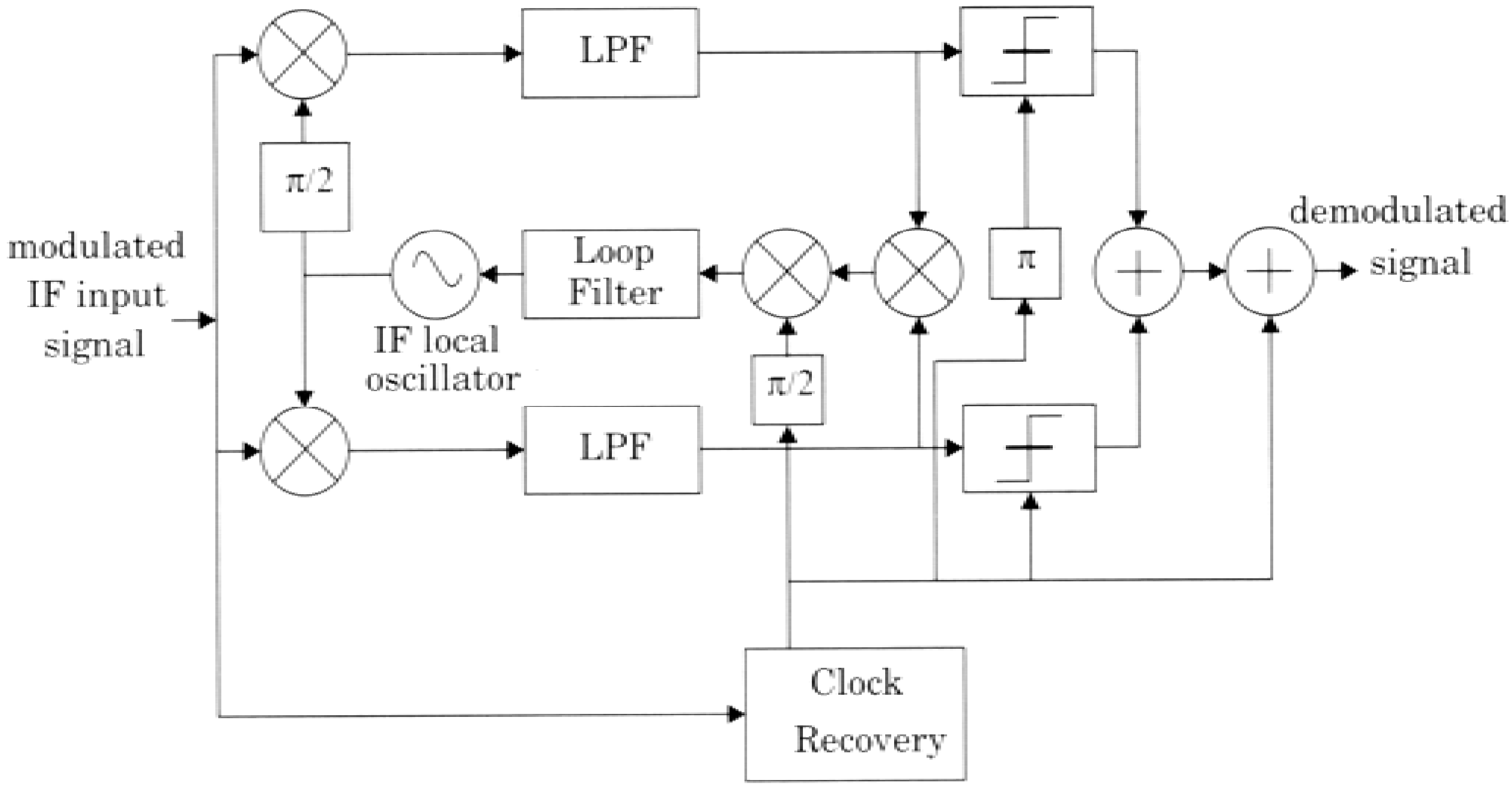


Figure 6.43 Block diagram of a GMSK receiver.

Digital GMSK demodulator

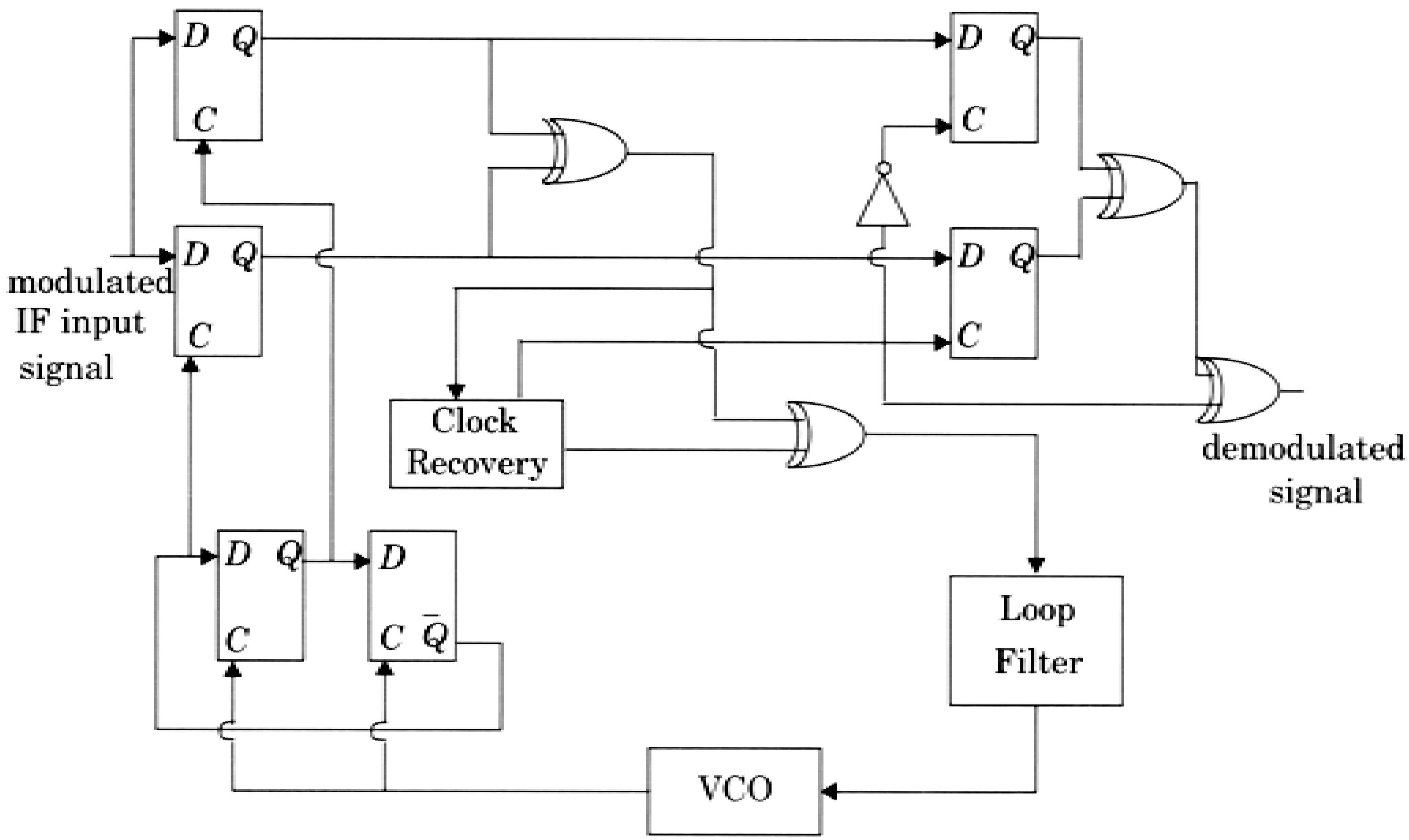


Figure 6.44 Digital logic circuit for GMSK demodulation [from [deB72] © IEEE].

8-PSK Signal Constellation

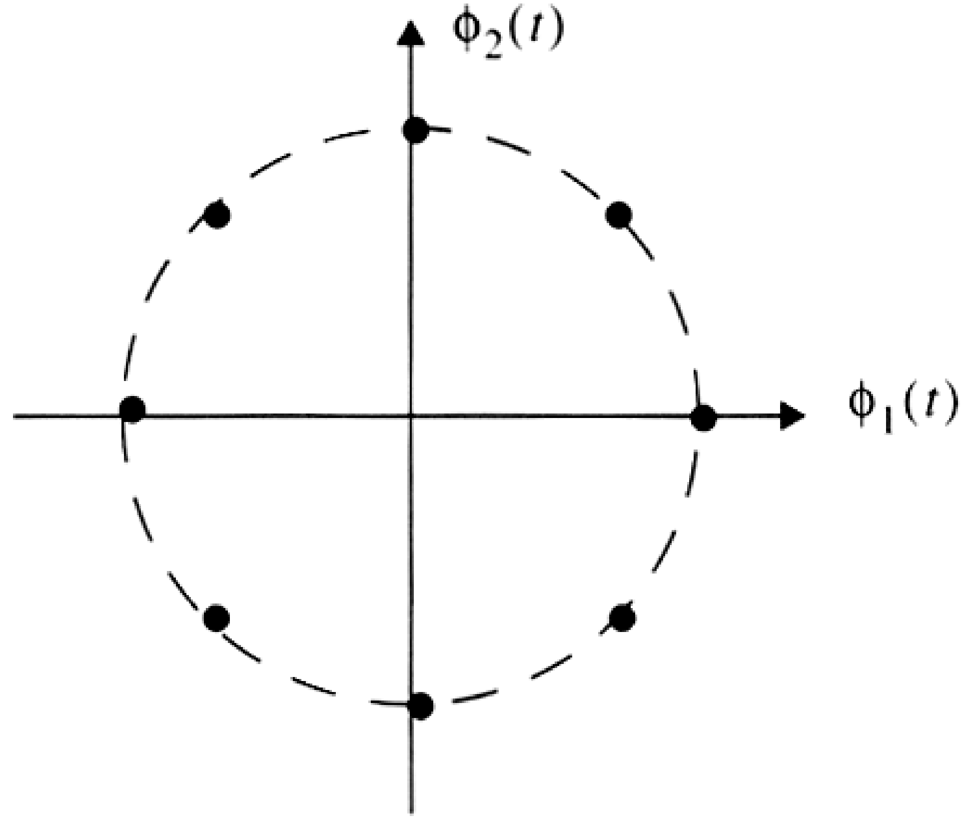


Figure 6.45 Constellation diagram of an M-ary PSK system ($M = 8$).

Bandwidth vs. Power Efficiency

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

Pulse Shaped M-PSK

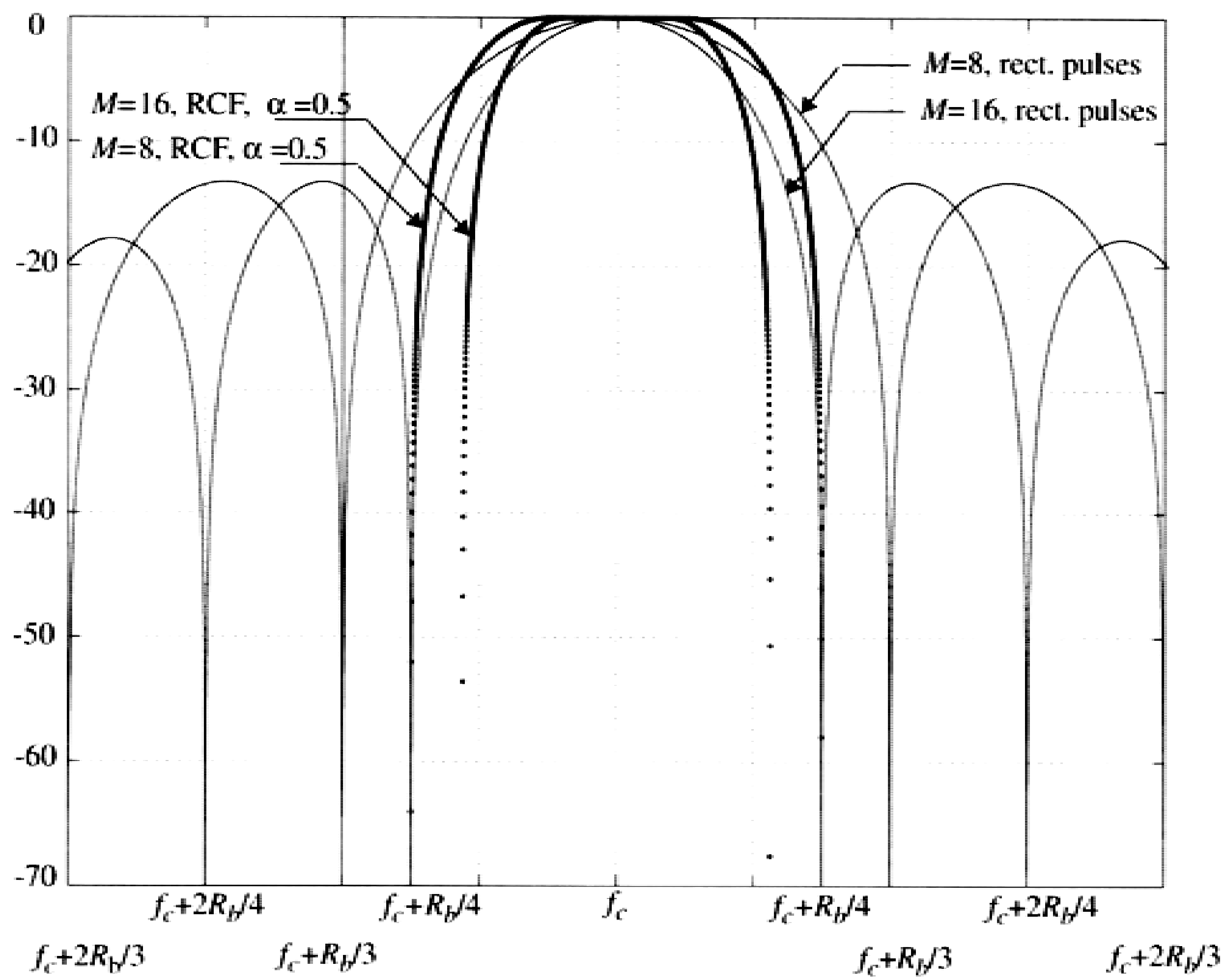


Figure 6.46 M-ary PSK power spectral density, for M = 8, 16 (PSD for both rectangular and raised cosine filtered pulses are shown for fixed R_b).

16-QAM Signal Constellation

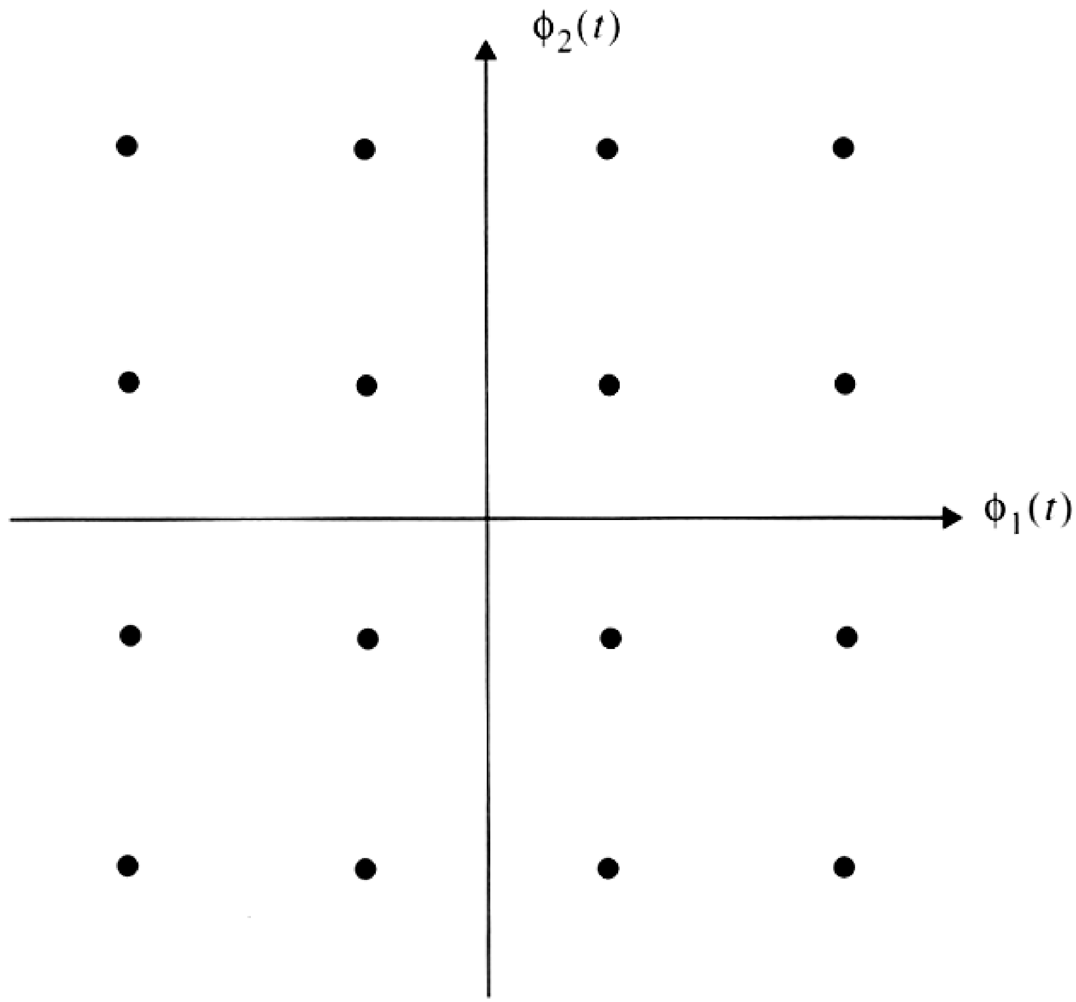


Figure 6.47 Constellation diagram of an M-ary QAM ($M = 16$) signal set.

QAM efficiencies

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

M-ary FSK efficiencies

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

PN Sequence Generator

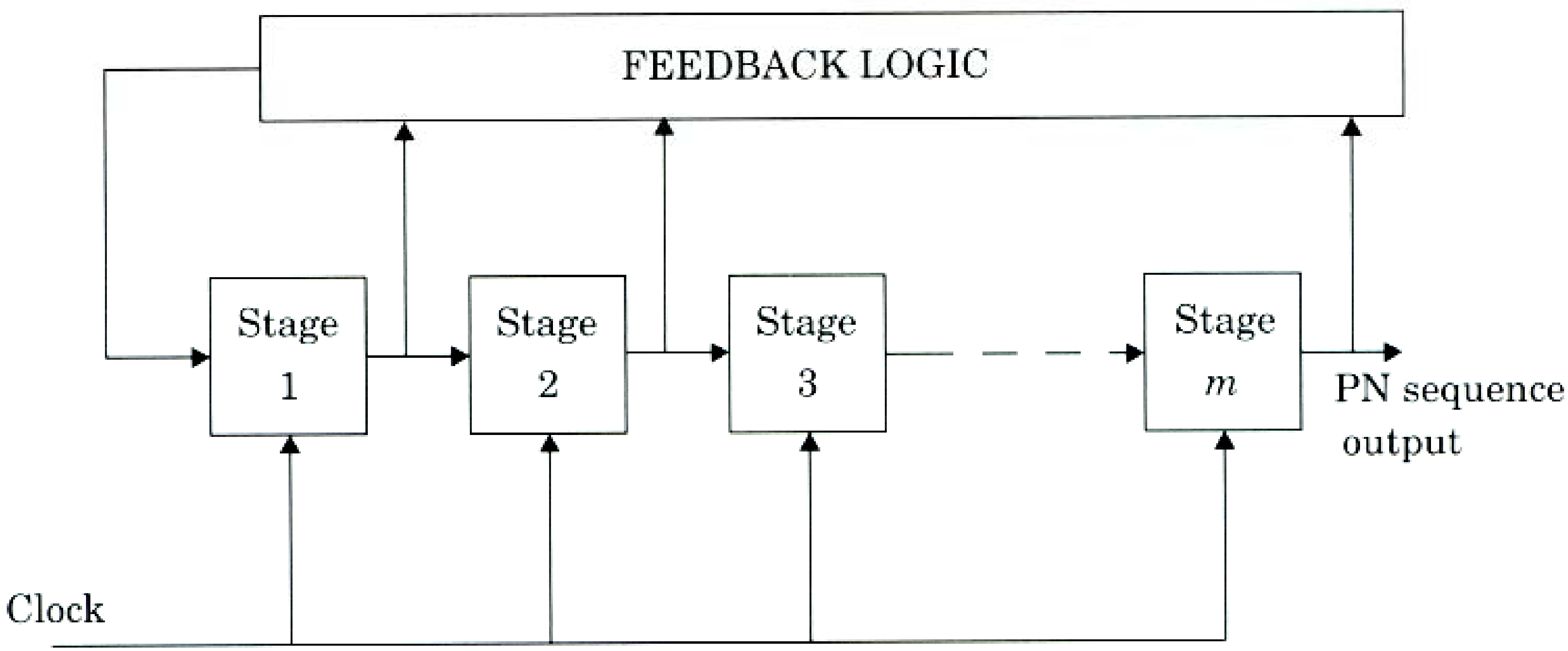


Figure 6.48 Block diagram of a generalized feedback shift register with *m* stages.

Direct Sequence Spread Spectrum

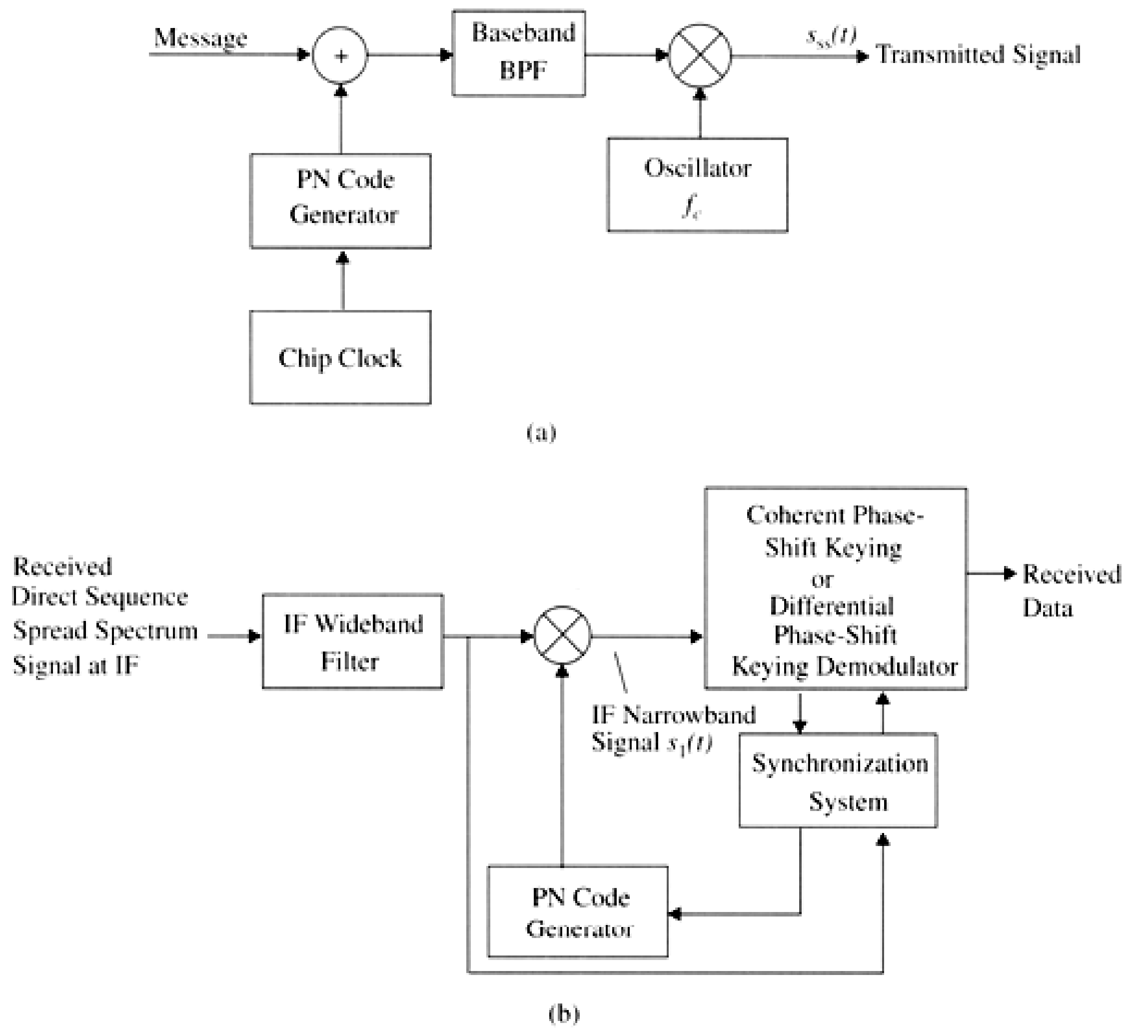


Figure 6.49 Block diagram of a DS–SS system with binary phase modulation: (a) transmitter; and (b) receiver.

Direct Sequence Spreading

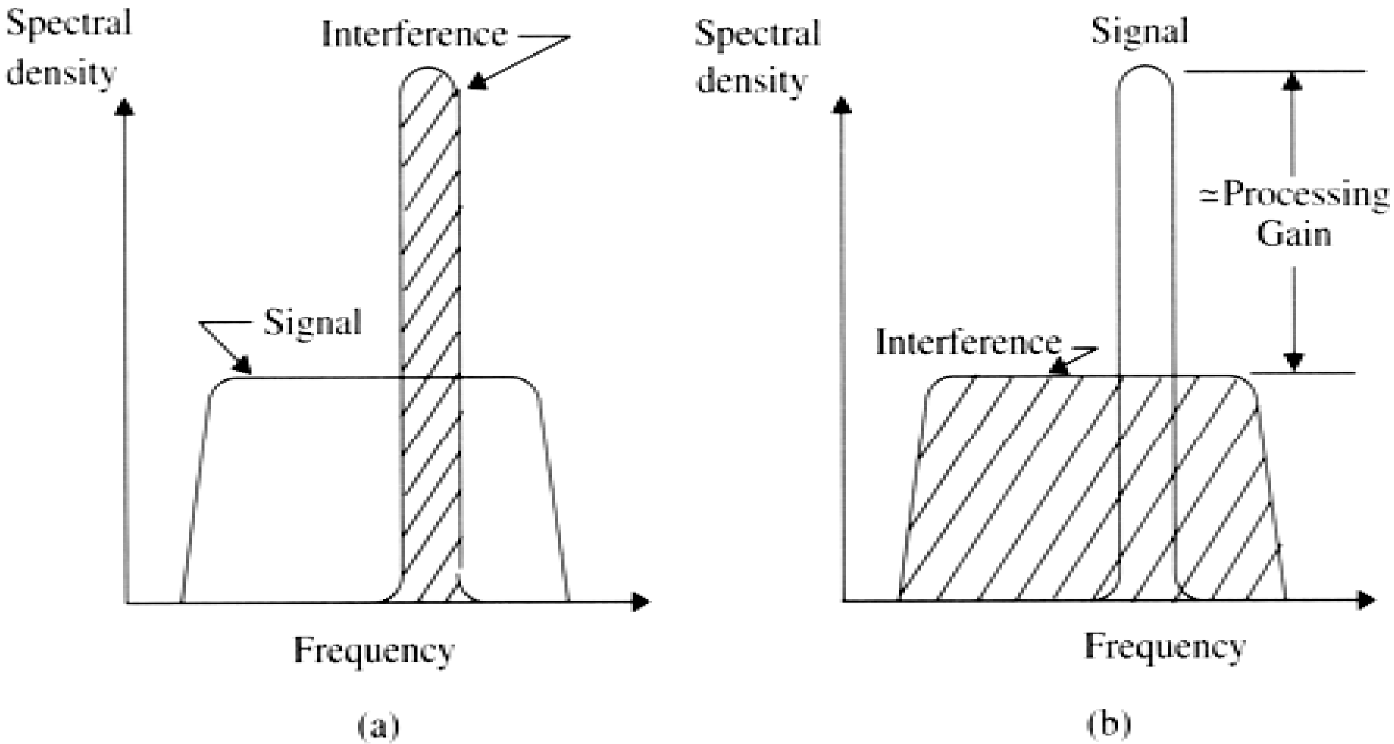


Figure 6.50 Spectra of desired received signal with interference: (a) wideband filter output and (b) correlator output after despreading.

Frequency Hopping Spread Spectrum

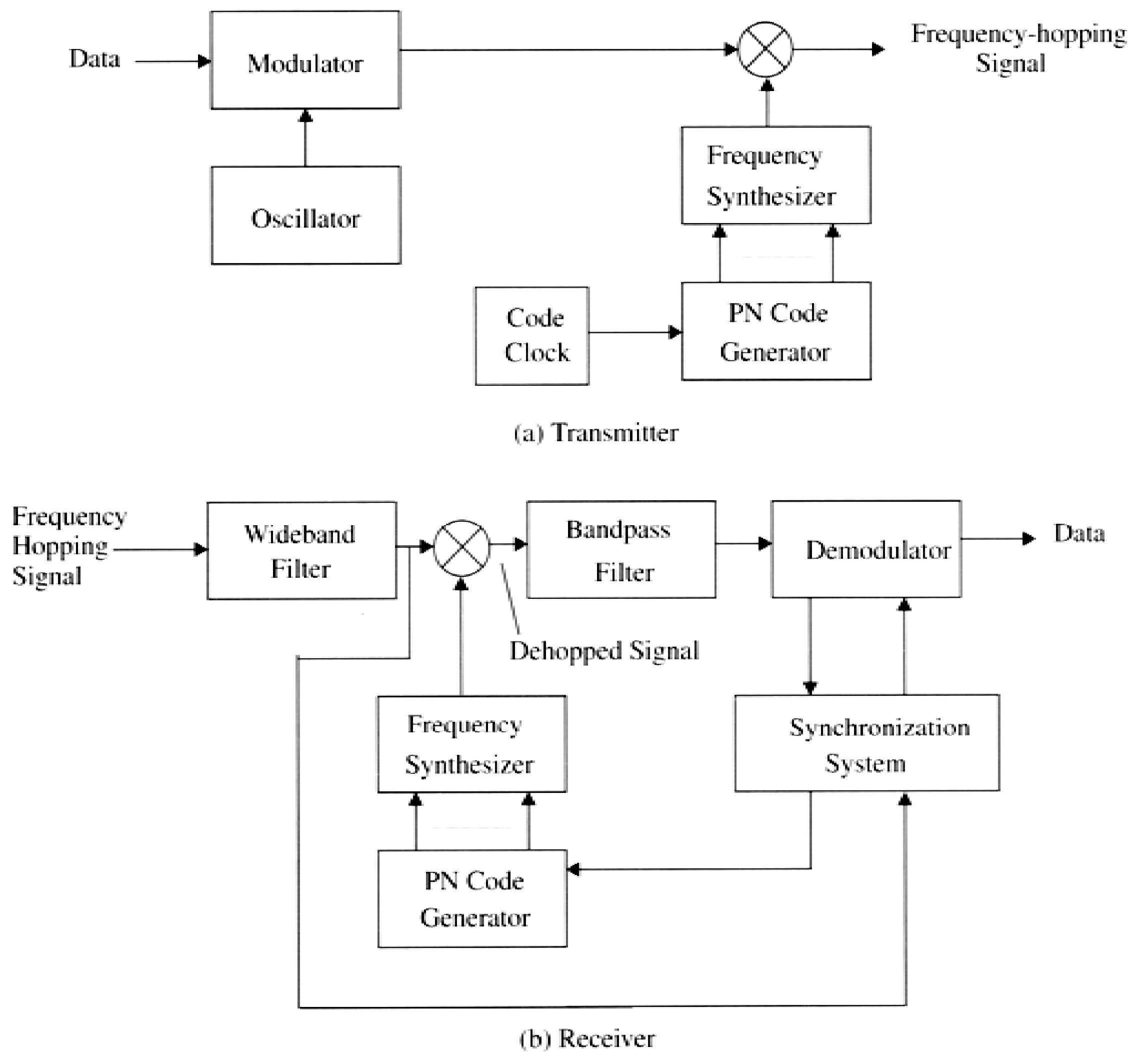


Figure 6.51 Block diagram of frequency hopping (FH) system with single channel modulation.

CDMA – Multiple Users

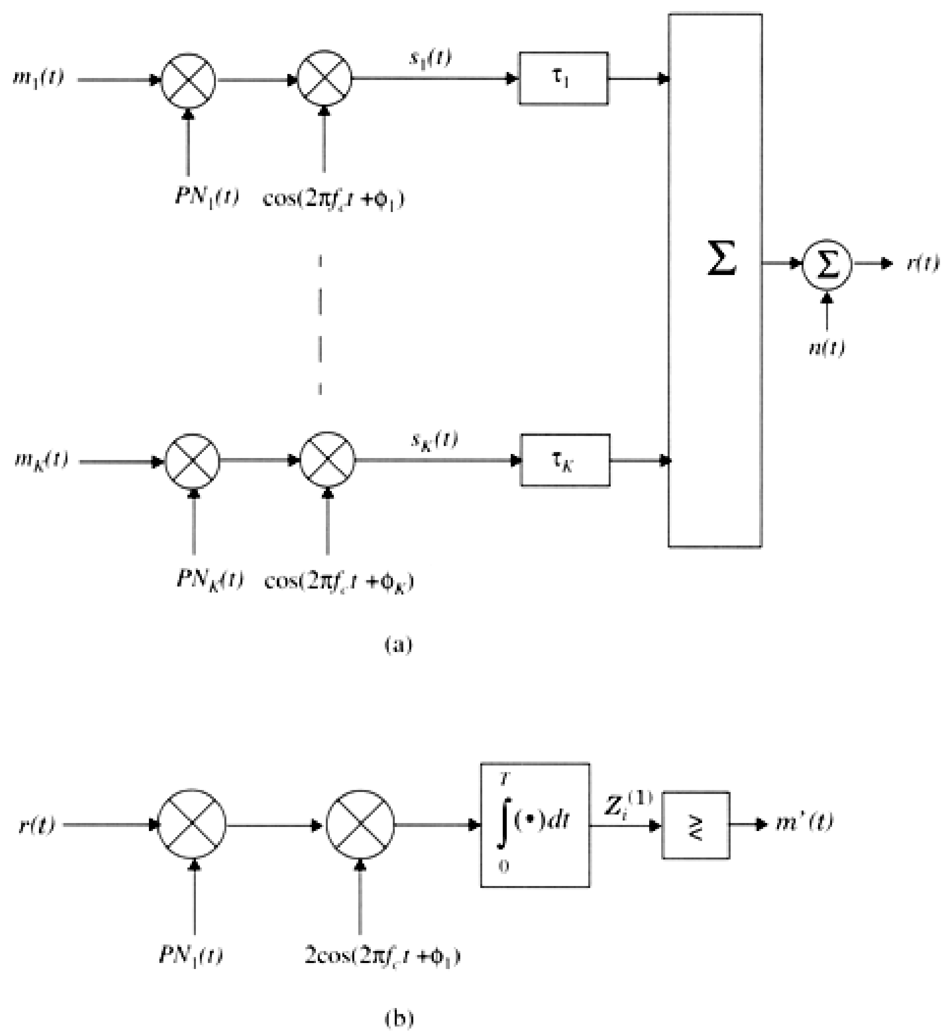


Figure 6.52 A simplified diagram of a DS–SS system with K users. (a) Model of K users in a CDMA spread spectrum system; (b) receiver structure for User 1.

Effects of Fading

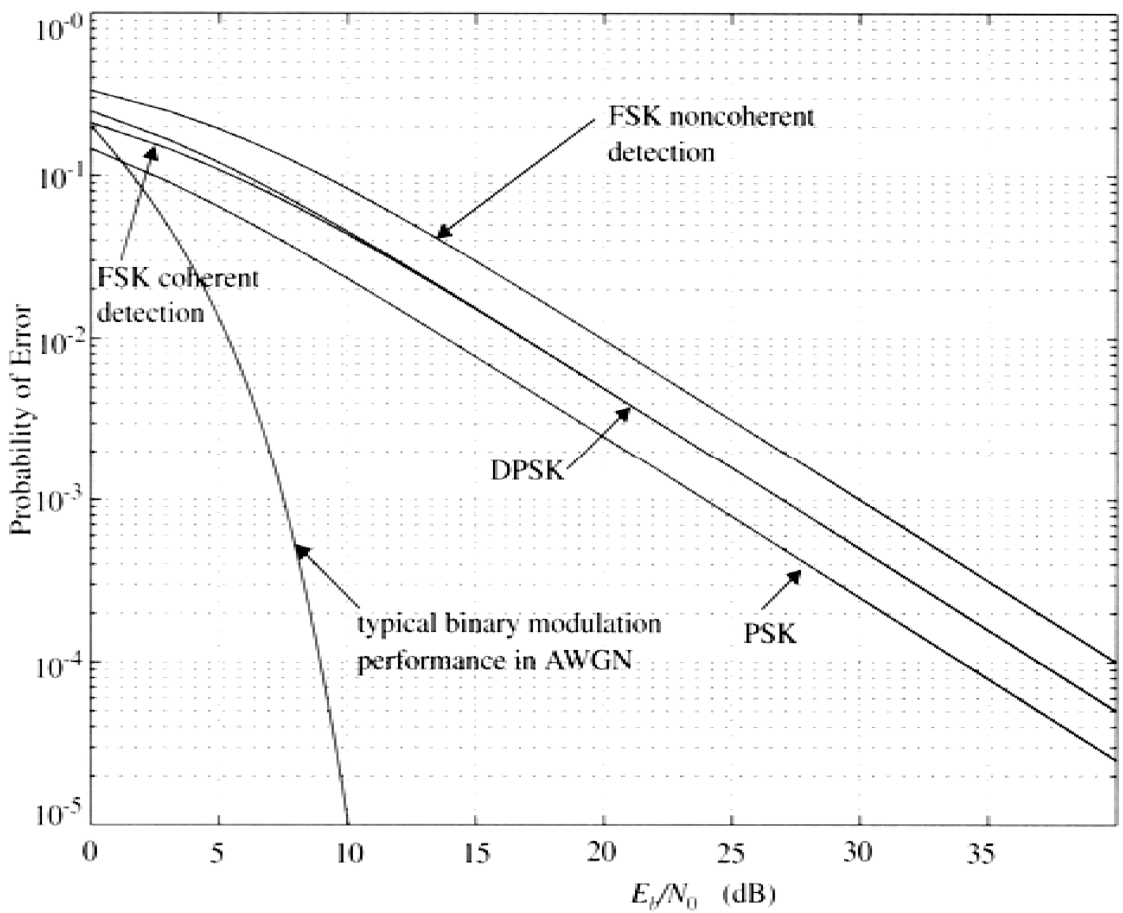


Figure 6.53 Bit error rate performance of binary modulation schemes in a Rayleigh flat-fading channel as compared to a typical performance curve in AWGN.

Irreducible Bit Error Rate due to multipath

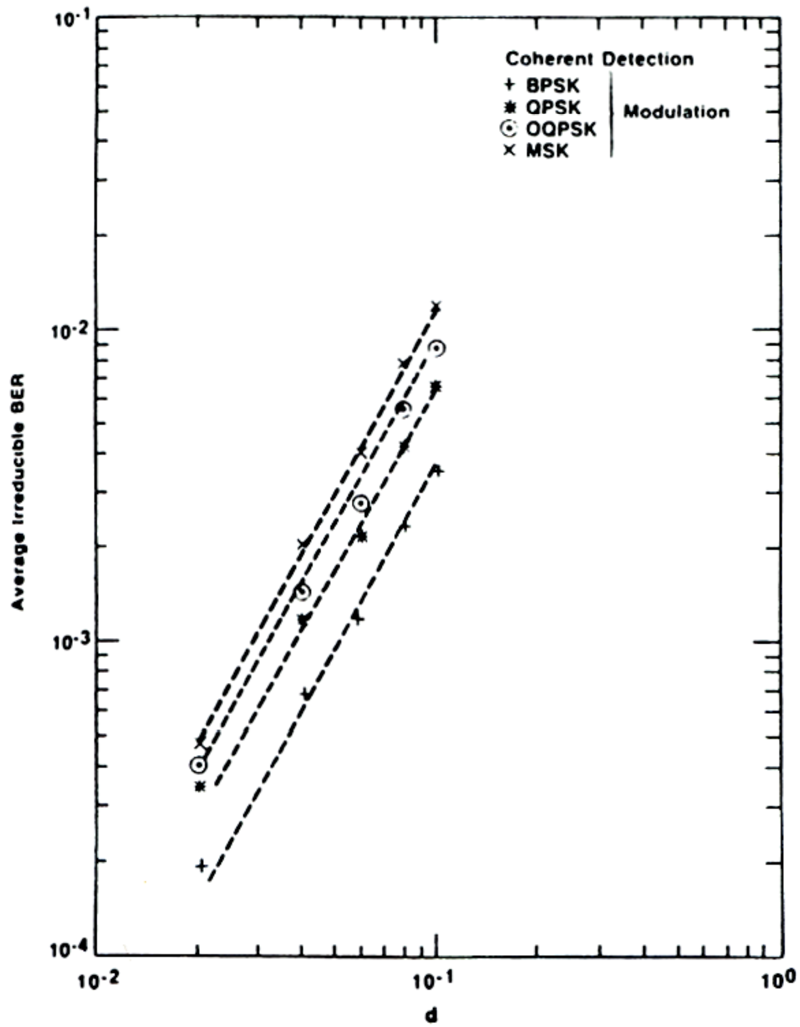


Figure 6.54 The irreducible BER performance for different modulations with coherent detection for a channel with a Gaussian shaped power delay profile. The parameter *d* is the rms delay spread normalized by the symbol period [from [Chu87] © IEEE].

Irreducible Bit Error Rate due to multipath

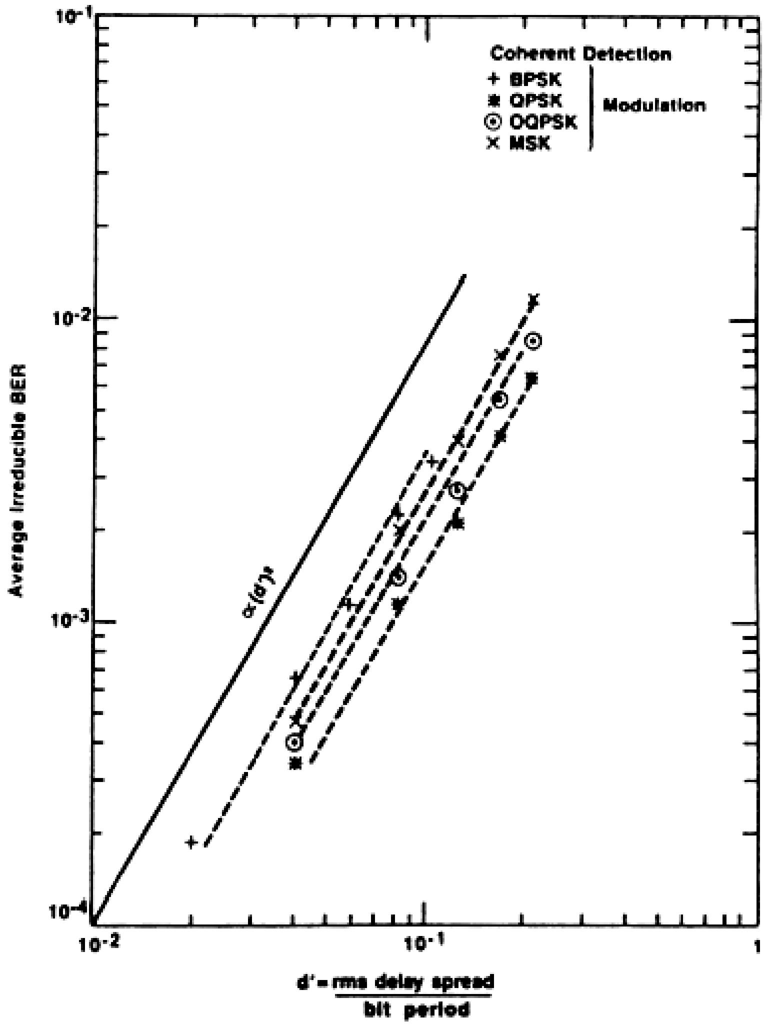


Figure 6.55 The same set of curves as plotted in Figure 6.54 plotted as a function of rms delay spread normalized by bit period [from [Chu87] © IEEE].

Simulation of Fading and Multipath

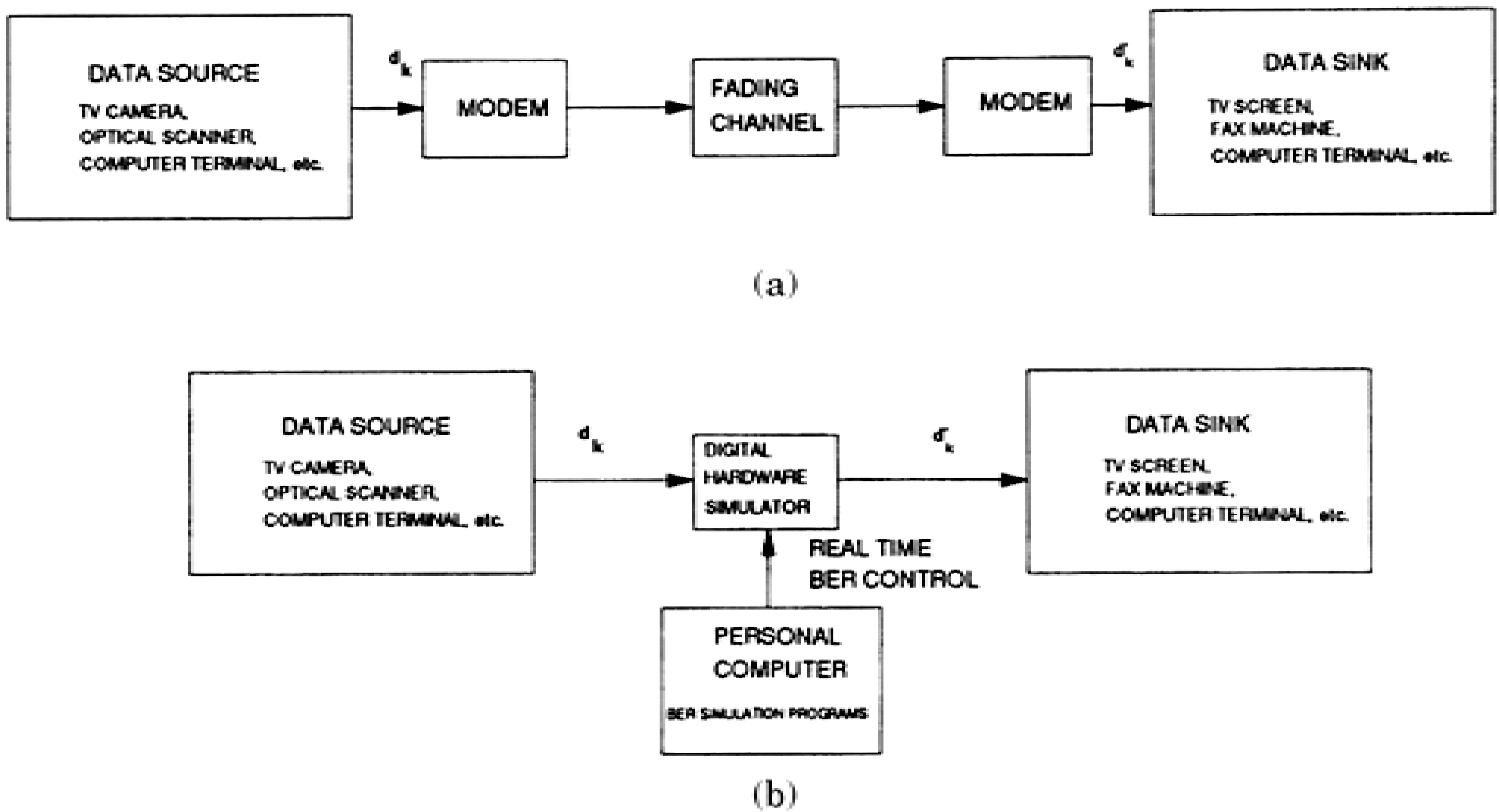


Figure 6.56 The BERSIM concept: (a) Block diagram of actual digital communication system; (b) block diagram of BERSIM using a baseband digital hardware simulator with software simulation as a driver for real-time BER control (US Patent 5,233,628).

Irreducible BER due to fading

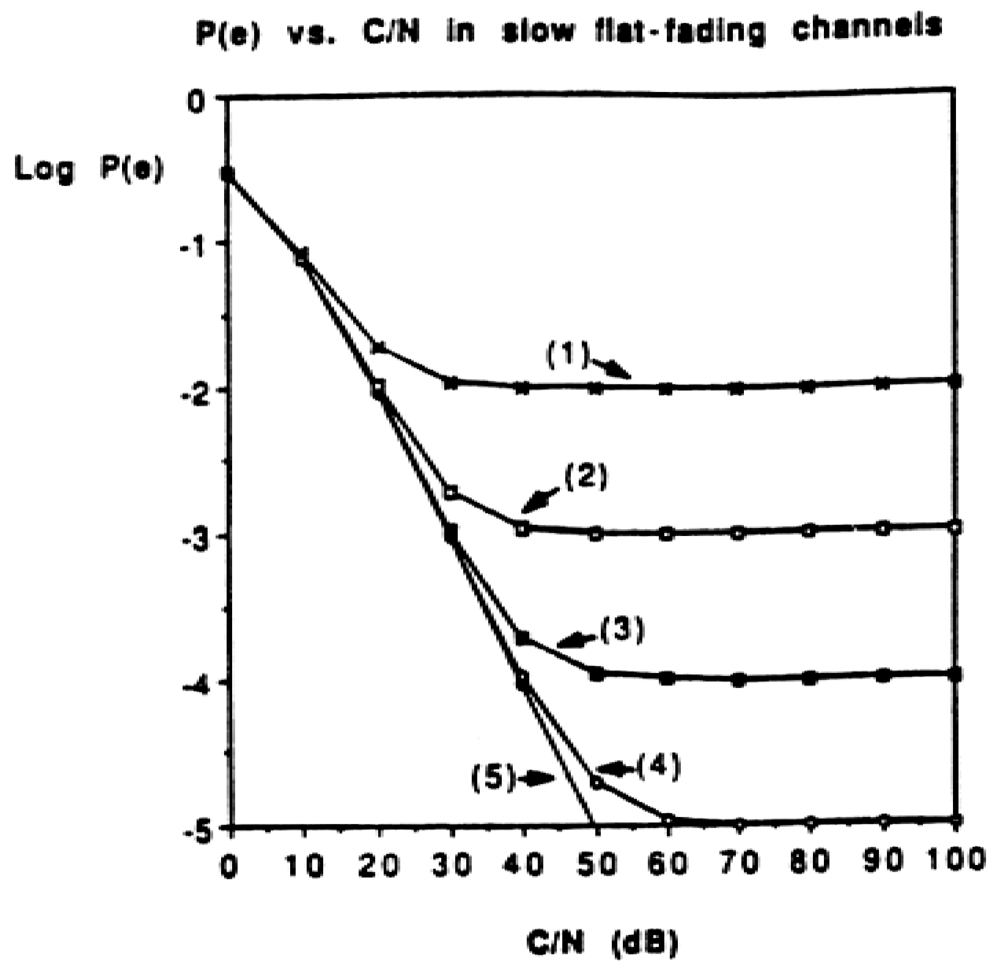


Figure 6.57 BER performance of π/4 DQPSK in a slow flat-fading channel corrupted by CCI and AWGN. f_c = 850 MHz, f_s = 24 ksps raised cosine roll-off factor = 0.2, C/I = (1) 20 dB, (2) 30 dB, (3) 40 dB, (4) 50 dB, (5) infinity [from [Liu91] © IEEE].

Irreducible BER due to fading

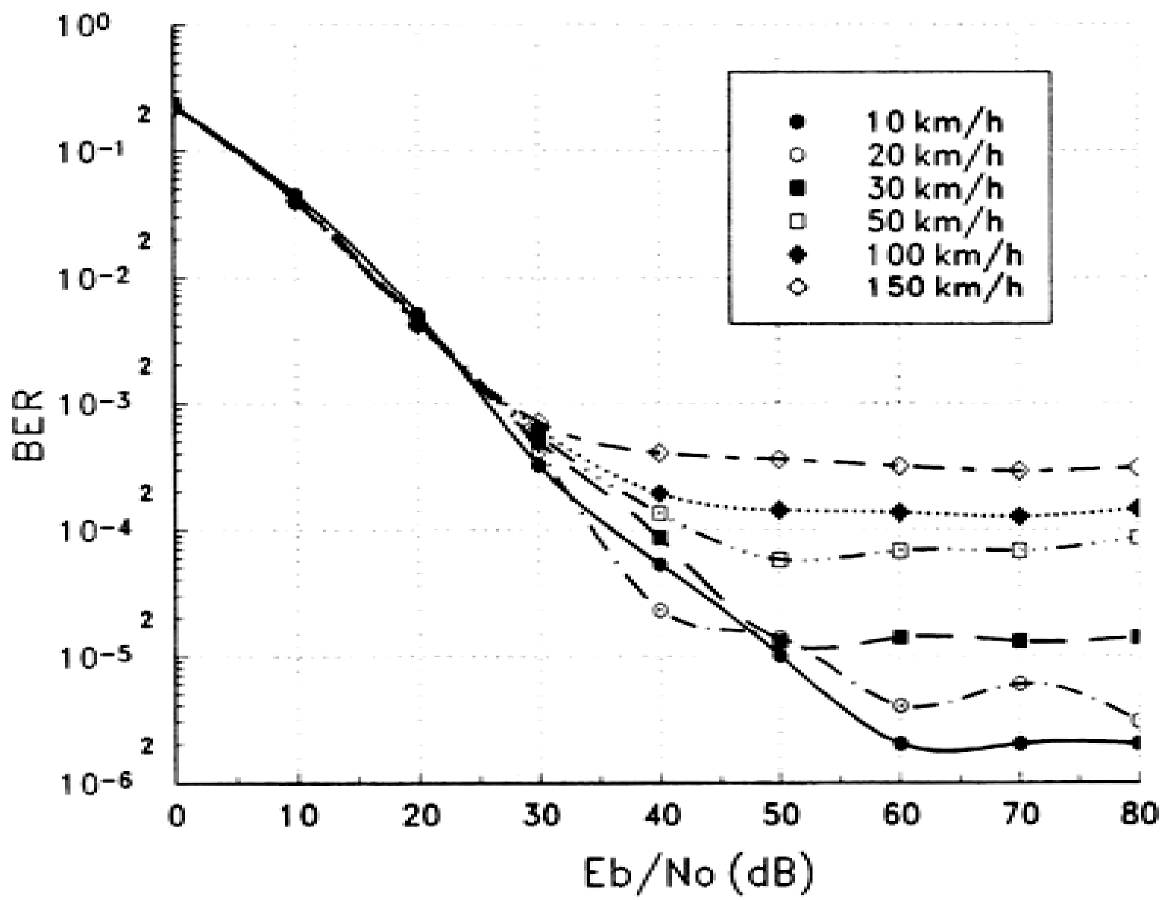


Figure 6.58 BER performance versus E_b / N_0 for $\pi/4$ DQPSK in a Raleigh flat-fading channel for various mobile speeds: f_c = 850 MHz, f_s = 24 ksps, raised cosine rolloff factor is 0.2, C/I = 100 dB. Generated by BERSIM [from [Fun93] © IEEE].

BER due to fading & multipath

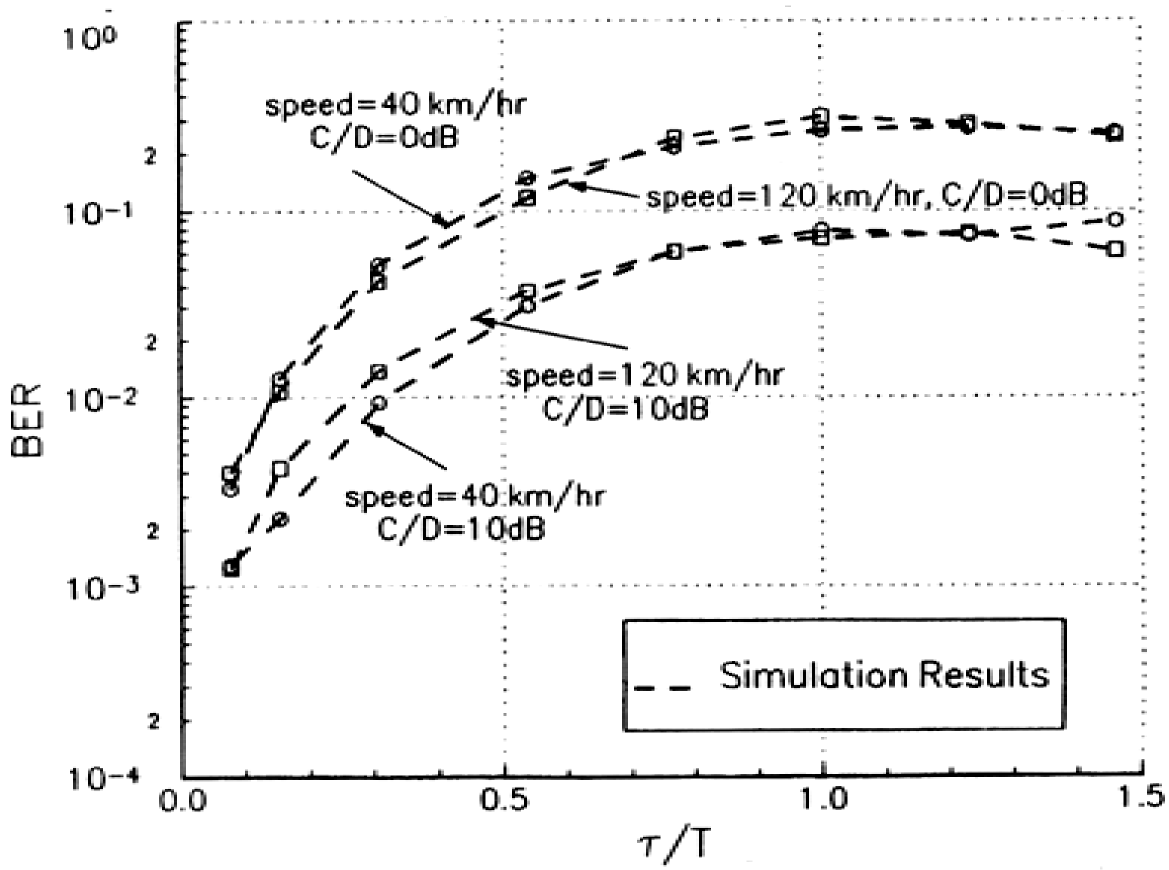
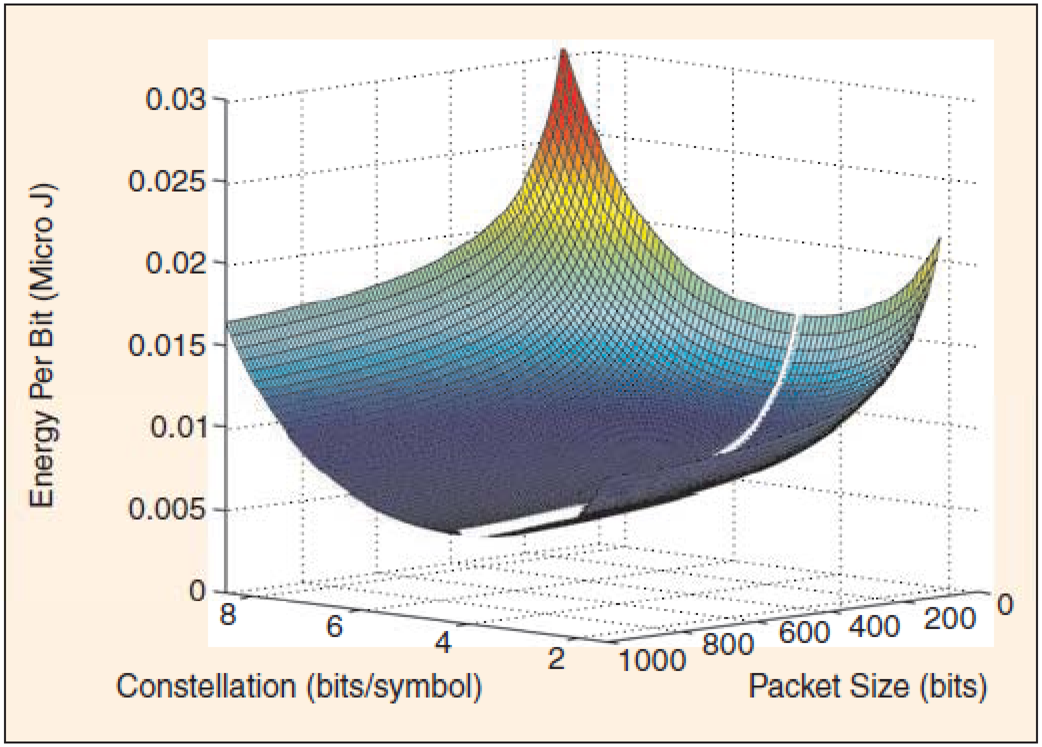


Figure 6.59 BER performance of π/4 DQPSK in a two-ray Rayleigh fading channel, where the time delay τ, and the power ratio *C/D* between the first and second ray are varied. f_c = 850 MHz, f_s = 24 ksps, raised cosine rolloff rate is 0.2, *v* = 40 km/hr, 120 km/hr E_b/N_0 = 100 dB. Produced by BERSIM [from [Fun93] © IEEE].

- Energy per bit as a function of modulation and packet size (Raghunathan et al)



Shannon's Capacity Theorem

- States the theoretical maximum rate at which an error-free bit can be transmitted over a noisy channel

***C*: the channel capacity in bits per second**

***B*: the bandwidth in hertz**

***SNR*: the ratio of signal power to noise power**

- Channel capacity depends on channel bandwidth and system SNR

Shannon's Theorem: Example

- For SNR of 0, 10, 20, 30 dB, one can achieve C/B of 1, 3.46, 6.66, 9.97 bps/Hz, respectively

- Example:
  - Consider the operation of a modem on an ordinary telephone line. The SNR is usually about 1000. The bandwidth is 3.4 KHz. Therefore:

$$C = 3400 \text{ X } \log_2(1 + 1000)$$
$$= (3400)(9.97)$$
$$\approx 34 \text{ kbps}$$

Bit Error Rate

- BER = Errors / Total number of bits
  - Error means the reception of a “1” when a “0” was transmitted or vice versa.

- Noise is the main factor of BER performance – signal path loss, circuit noise, …

Thermal Noise

- Thermal Noise
  - white noise since it contains the same level of power at all frequencies
  - *kTB*, where
    - *k* is the Boltzmann's constant = 1.381e-21 *W* / K / Hz,
    - *T* is the absolute temperature in Kelvin, and
    - *B* is the bandwidth.

- At room temperature, *T* = 290*K*, the thermal noise power spectral density,
  - *kT* = 4.005e-21 W/Hz or

    –174 dBm/Hz

Receiver Sensitivity

- The minimum input signal power needed at receiver input to provide adequate SNR at receiver output to do data demodulation

- SNR depends on
  - Received signal power
  - Background thermal noise at antenna (N_a)
  - Noise added by the receiver (N_r)

- $P_{min} = SNR_{min} \times (N_a + N_r)$

Noise Figure

- Noise Figure (F) quantifies the increase in noise caused by the noise source in the receiver relative to input noise

$$F = SNR_{input}/SNR_{output} = (N_a + N_r)/N_a$$

$$P_{min} = SNR_{min} \times (N_a + Nr) = SNR_{min} \times F \times N_a$$

Example: if $SNR_{min} = 10$ dB, F = 4 dB, BW = 1 MHz $P_{min} = 10 + 4 - 174 + 10 \times \log(10^6) = -100$ dBm

802.15.4 - Modulation Scheme

- 2.4 GHz PHY
  - 250 kb/s (4 bits/symbol, 62.5 kBaud)
  - Data modulation is 16-ary orthogonal O-QPSK
  - 16 symbols are ~orthogonal set of 32-chip PN codes

- 868 MHz/915 MHz PHY
  - Symbol rate
    - 868 MHz band: 20 kbps (1bit/symbol, 20 Kbaud)
    - 915 MHz band: 40 kbps (1bit/symbol, 40 Kbaud)
  - Spreading code is 15-chip
  - Data modulation is BPSK
    - 868 MHz: 300 Kchips/s
    - 915 MHz: 600 Kchips/s

802.15.4 - PHY Communication Parameters

- Transmit power
  - Capable of at least 0.5 mW
- Transmit center frequency tolerance
  - ±40 ppm
- Receiver sensitivity **(packet error rate < 1%)**
  - −85 dBm @ 2.4 GHz band
  - −92 dBm @ 868/915 MHz band
- Receiver Selectivity
  - 2.4 GHz: 5 MHz channel spacing, 0 dB adjacent channel requirement
- Channel Selectivity and Blocking
  - 915 MHz and 2.4 GHz band: 0 dB rejection of interference from adjacent channel
  - 30 dB rejection of interference from alternate channel
- Rx Signal Strength Indication Measurements
  - Packet strength indication
  - Clear channel assessment
  - Dynamic channel selection

802.15.4: Receiver Noise Figure Calculation

- Channel Noise bandwidth is 1.5 MHz
- Transmit Power is 1mW or 0 dBm
- Thermal noise floor is –174 dBm/Hz X 1.5 MHz = –112 dBm
- Total SNR budget is 0 dBm –(–112 dBm) = 112 dBm
- To cover ~100 ft. at 2.4 GHz results in a path loss of 40 dB
  - i.e. Receiver sensitivity is –85 dBm

- Required SNR for QPSK is 12.5 dB
  - 802.15.4 packet length is 1Kb
  - Worst packet loss < 1%, $(1 - BER)^{1024} = 1 - 1\%$, $BER = 10^{-5}$

- Receiver noise figure requirement
  - NF = Transmit Power – Path Loss – Required SNR – Noise floor

    = 0 + 112 –40 –12.5 = 59.5 dB
- The design spec is very relaxed
- Low transmit power enables CMOS single chip solution at low cost and power!