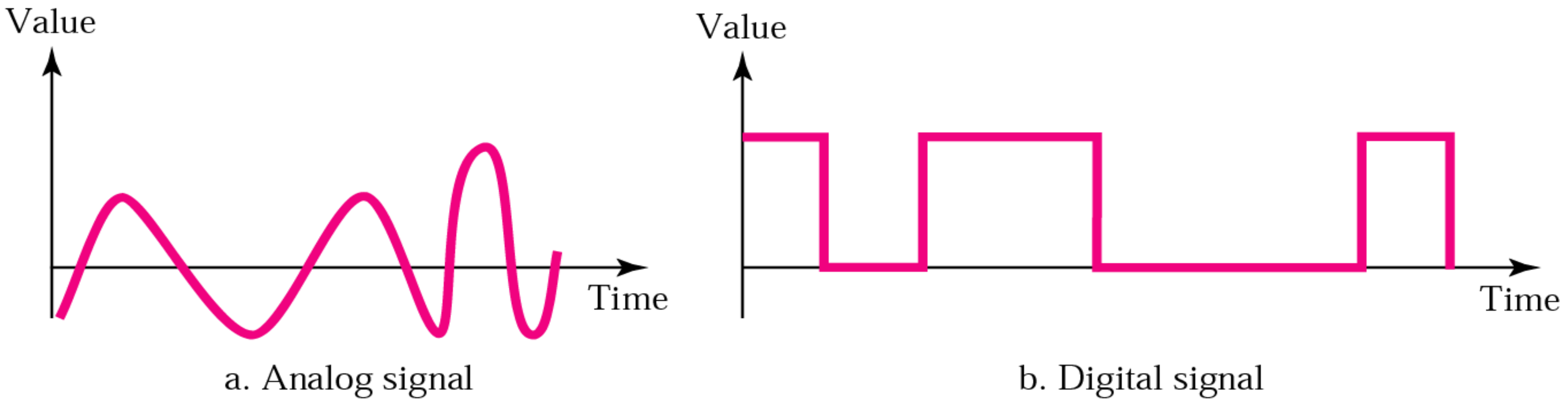
Signals

Analog/Digital, Fourier Transform, Modulation, Spread Spectrum

Slides based on the following texts:
"Data Communications and Networking" (Behrouz A. Forouzan)
"Wireless Comm. And Networking" (William Stallings)

Analog and Digital Signals



Signals can be analog or digital. Analog signals can have an infinite number of values in a range; digital signals can have only a limited number of values.

Note:

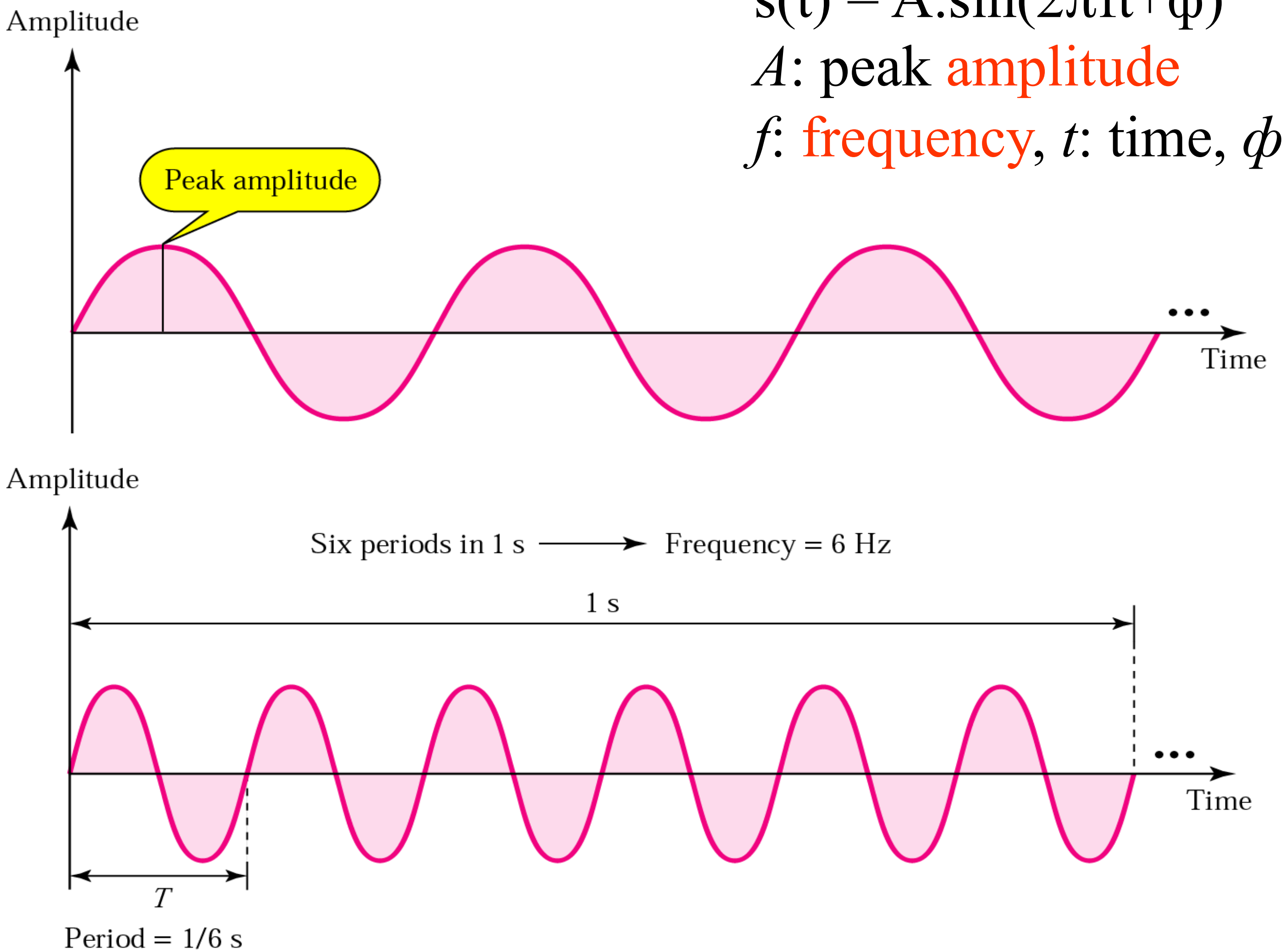
In data communications, we commonly use periodic analog signals and aperiodic digital signals.

Simple Analog Signals: Sine Waves

$s(t) = A.\sin(2\pi ft+\phi)$

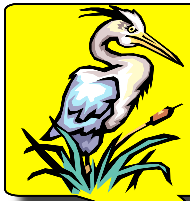
A: peak amplitude

f: frequency, *t*: time, ϕ: phase



Units of Frequency and Periods

Period	Equivalent	Frequency	Equivalent
Seconds (s)	1 s	hertz (Hz)	1 Hz
Milliseconds (ms)	10^{-3} s	kilohertz (KHz)	10^{3} Hz
Microseconds (ms)	10^{-6} s	megahertz (MHz)	10^{6} Hz
Nanoseconds (ns)	10^{-9} s	gigahertz (GHz)	10^{9} Hz
Picoseconds (ps)	10^{-12} s	terahertz (THz)	10^{12} Hz



Note:

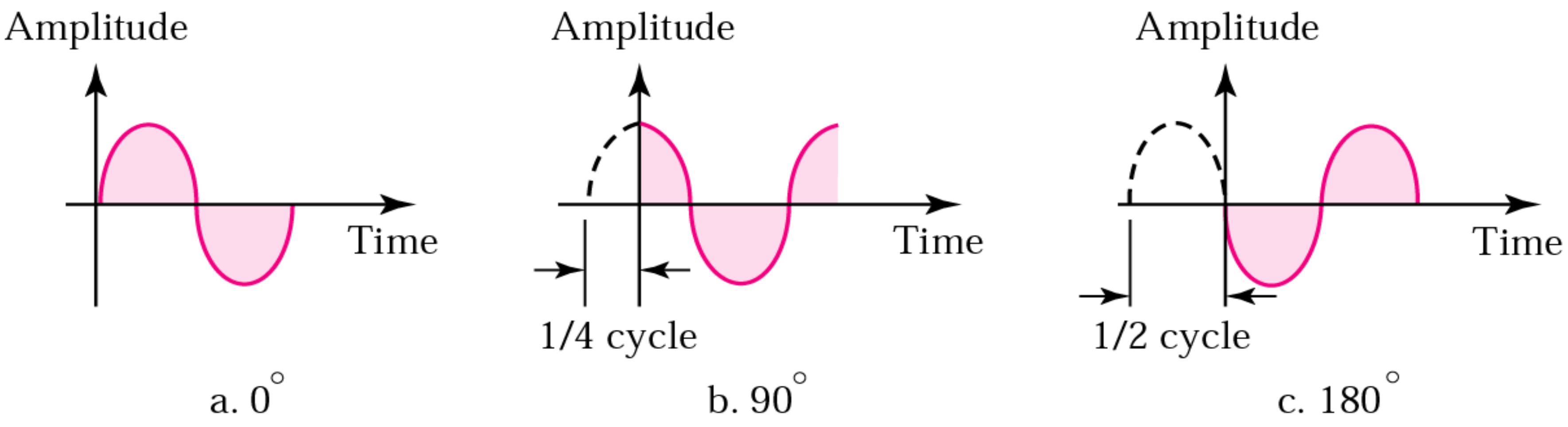
Frequency is the rate of change with respect to time. Change in a short span of time means high frequency. Change over a long span of time means low frequency.

If a signal does not change at all, its frequency is zero. If a signal changes instantaneously, its frequency is infinite.

Phase

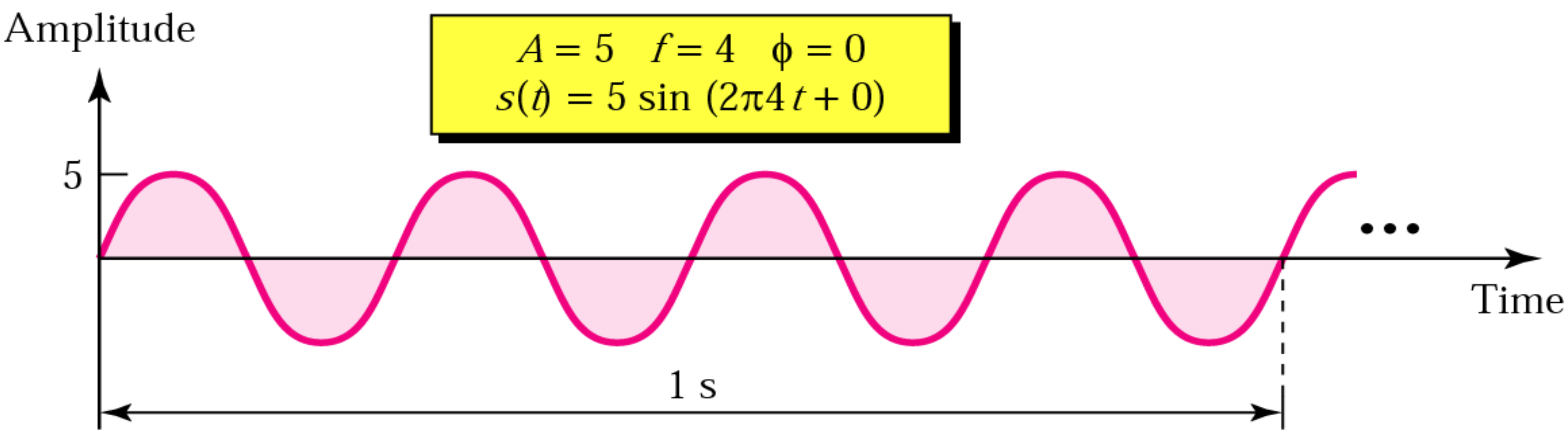
Phase describes the position of the waveform relative to time zero

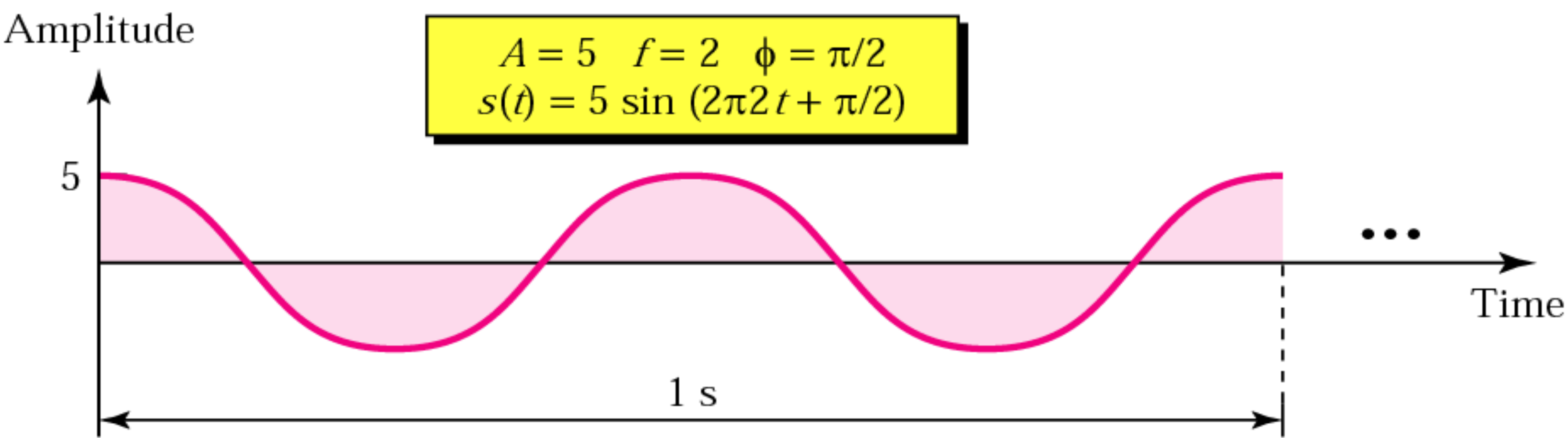
Phase is measured in radians or degrees: 360° means 1 cycle shifted



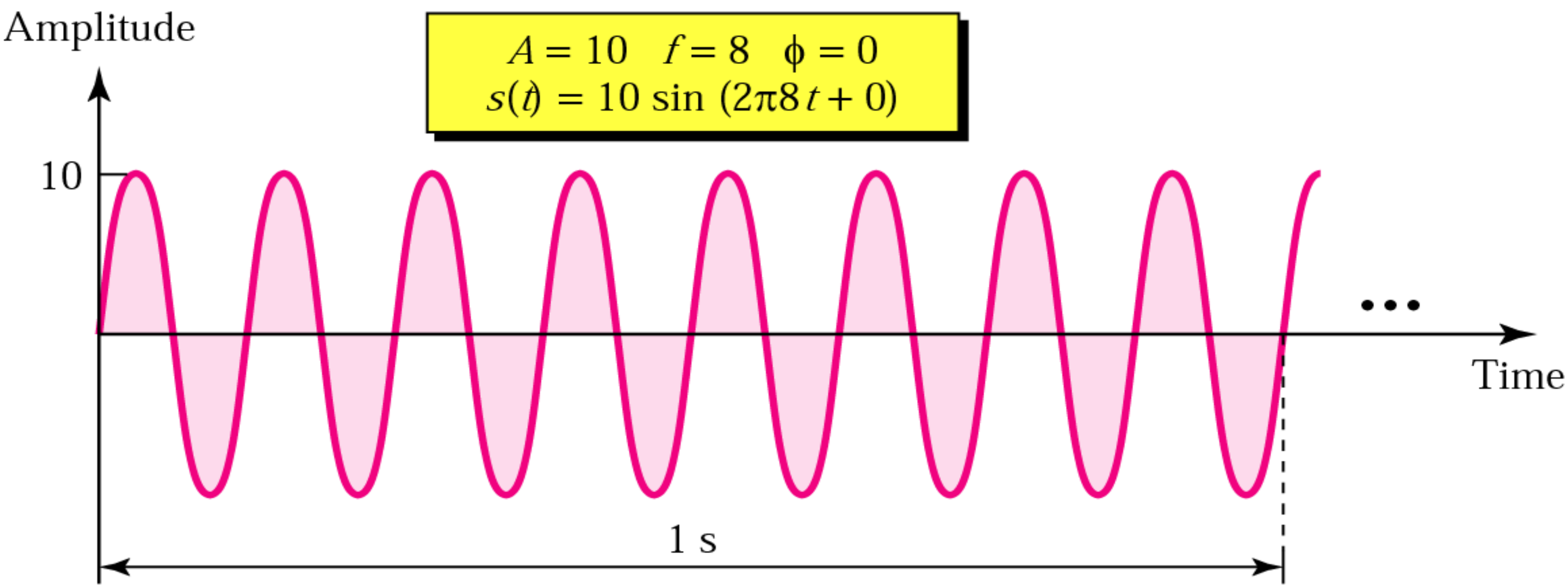
Question: A sine wave is offset one-sixth of a cycle with respect to time zero. What is its phase in degrees and radians???

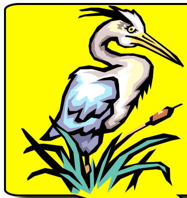
Sine Wave: Examples





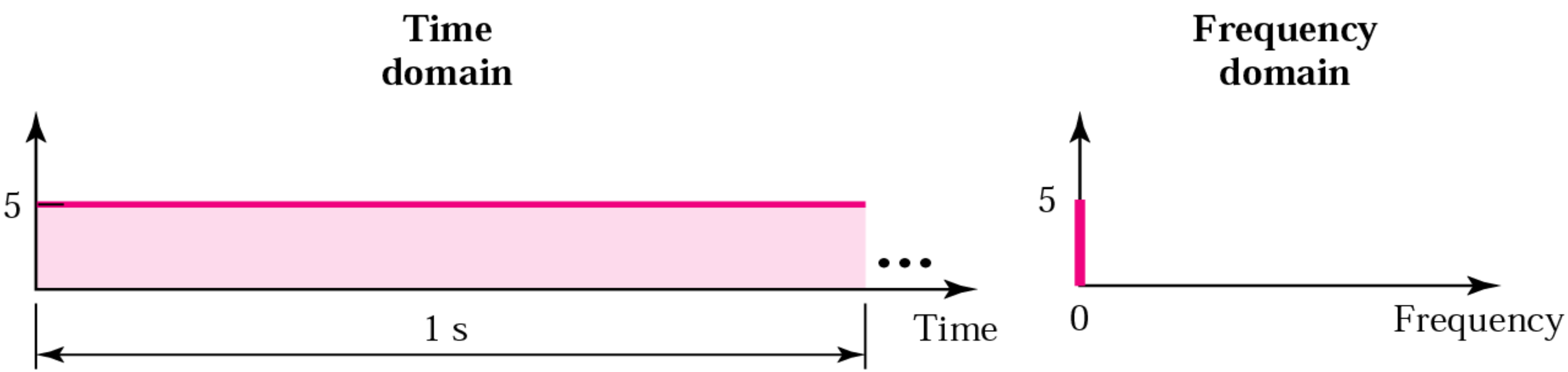
Sine Wave: One more example





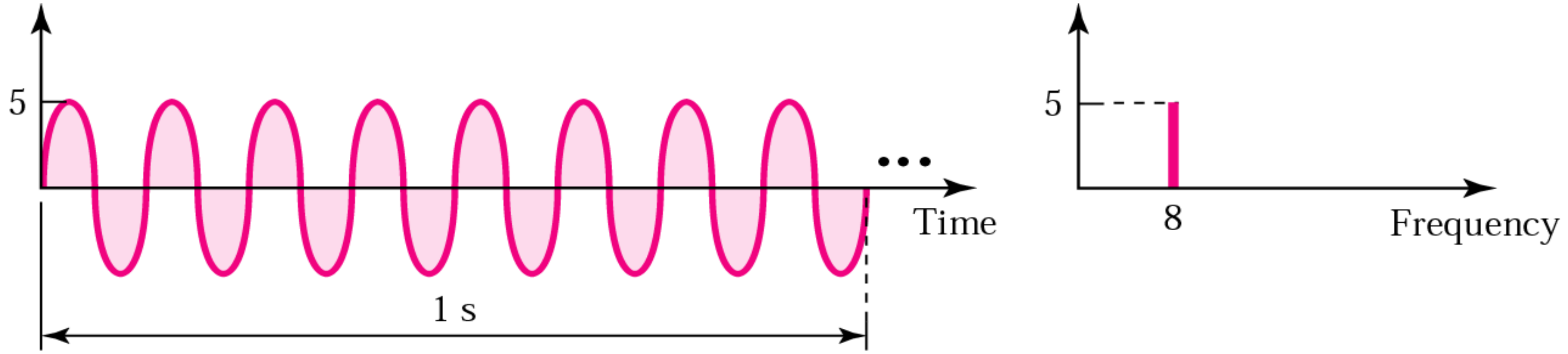
Note:

An analog signal is best represented in the frequency domain.

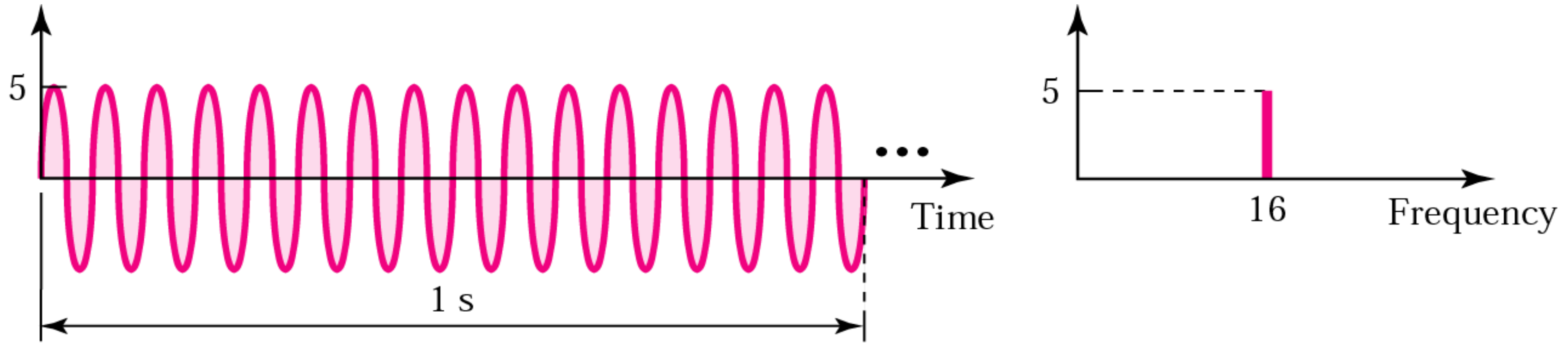


a. A signal with frequency 0

Frequency Domain



b. A signal with frequency 8



c. A signal with frequency 16

Use of Sine Waves

- A power company sends a single sine wave with frequency 60Hz to distribute electric energy to houses and businesses
- We can use a single sine wave to send an alarm to a security center
- But single sine waves are useless in data communications. WHY?
  - Think about phone conversation

Composite Analog Signals

Note:

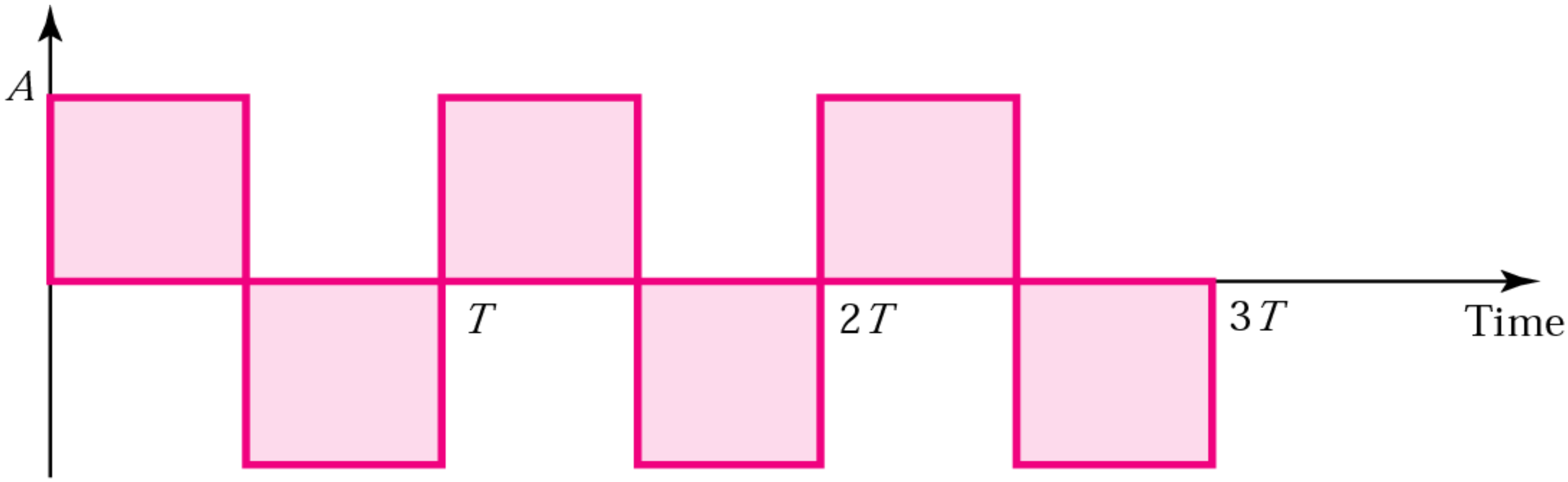
In reality, signals are more complicated than sine waves => ***can be represented as a combination of sine waves with different frequencies, amplitude, and phases***

(using Fourier transformation)

Fourier Transformation

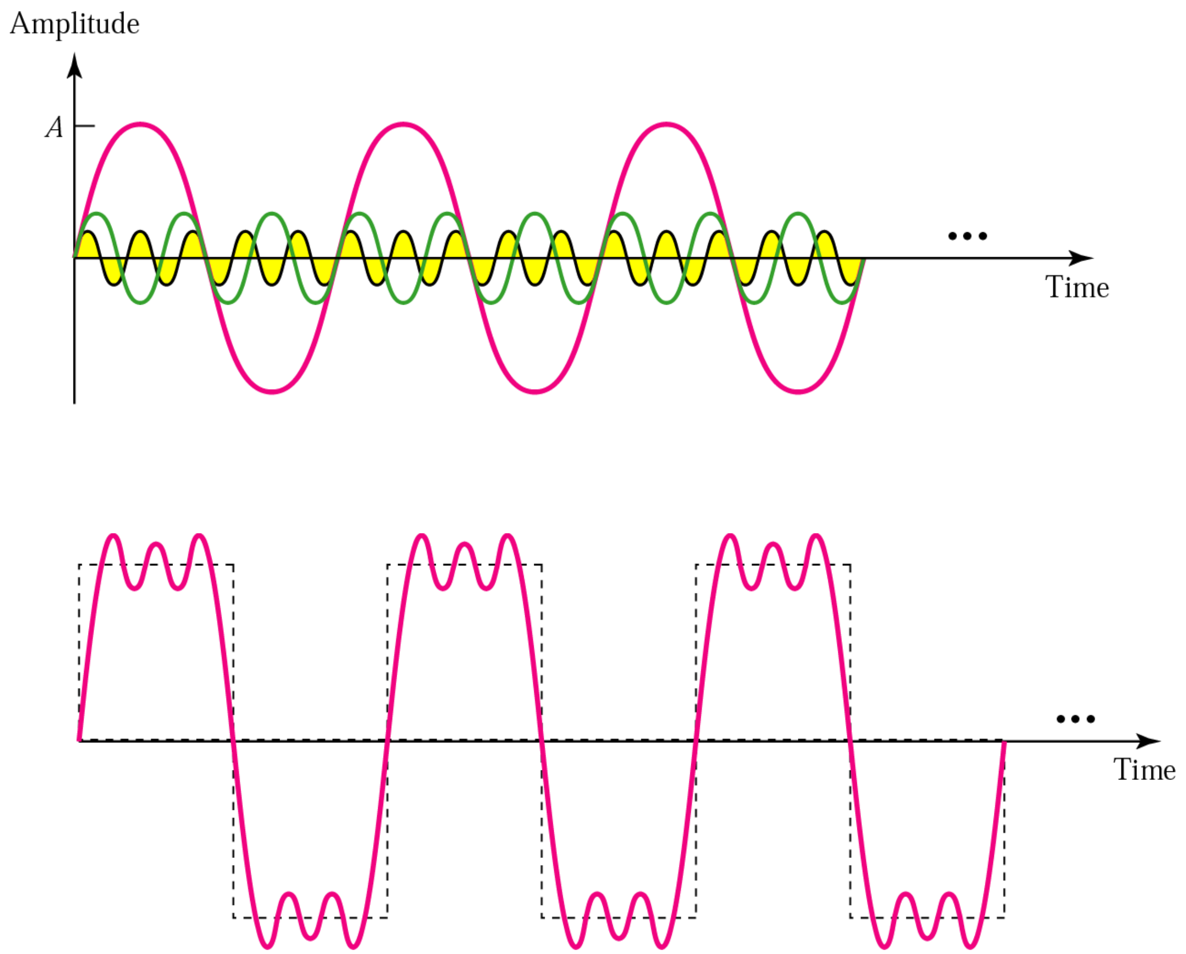
$$s(t)=A_1\sin(2\pi f_1 t+\phi_1) + A_2\sin(2\pi f_2 t+\phi_1) + A_3\sin(2\pi f_3 t+\phi_3) + \ldots$$

Found by the French mathematician Jean-Baptiste Fourier in the early 1900s



$$s(t)=(4A/\pi)\sin(2\pi ft) + (4A/3\pi)\sin(2\pi 3ft) + (4A/5\pi)\sin(2\pi 5ft) + \ldots$$

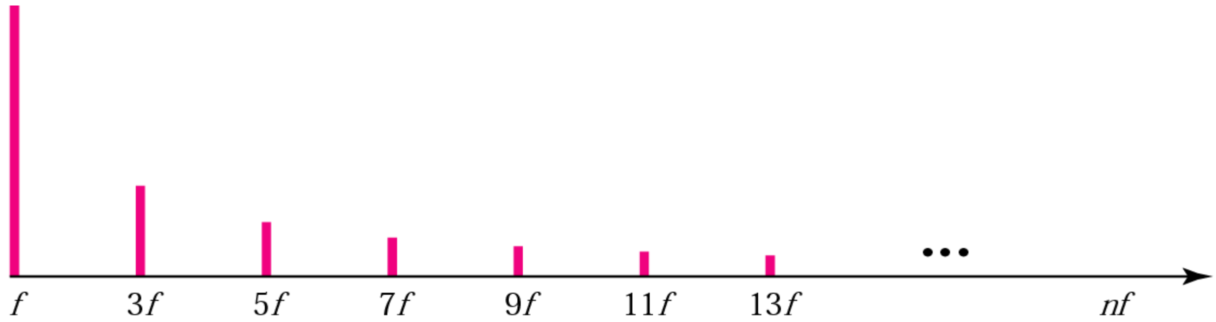
Combination of Single Sine Waves



Result of combination of only the first 3 harmonics

Frequency Spectrum

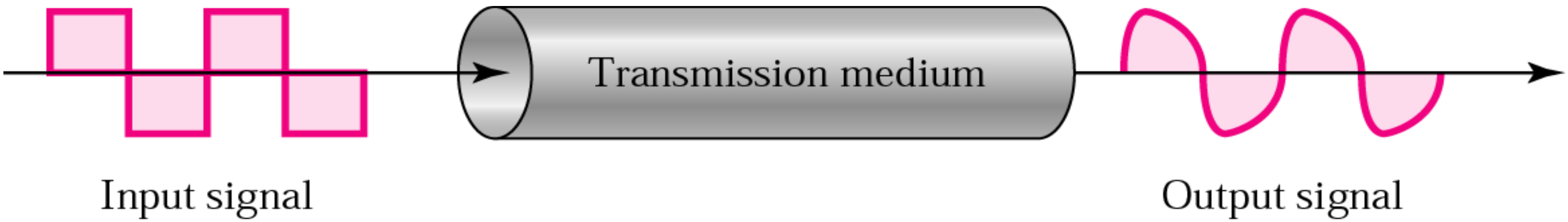
- The description of a signal using the frequency domain and containing all its sine-wave components is called the frequency spectrum of that signal



a. Frequency spectrum of a square wave

b. Frequency spectrum of an approximation with only three harmonics

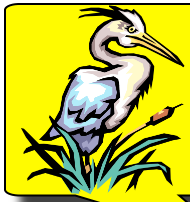
Signal Over Transmission Medium



Signal corruption: Transmission medium may block or weaken some frequencies. As a result, the output signal may be different from the input signal.

Perfect medium: preserve frequency, amplitude, and phase values

Bandwidth of Transmission Medium

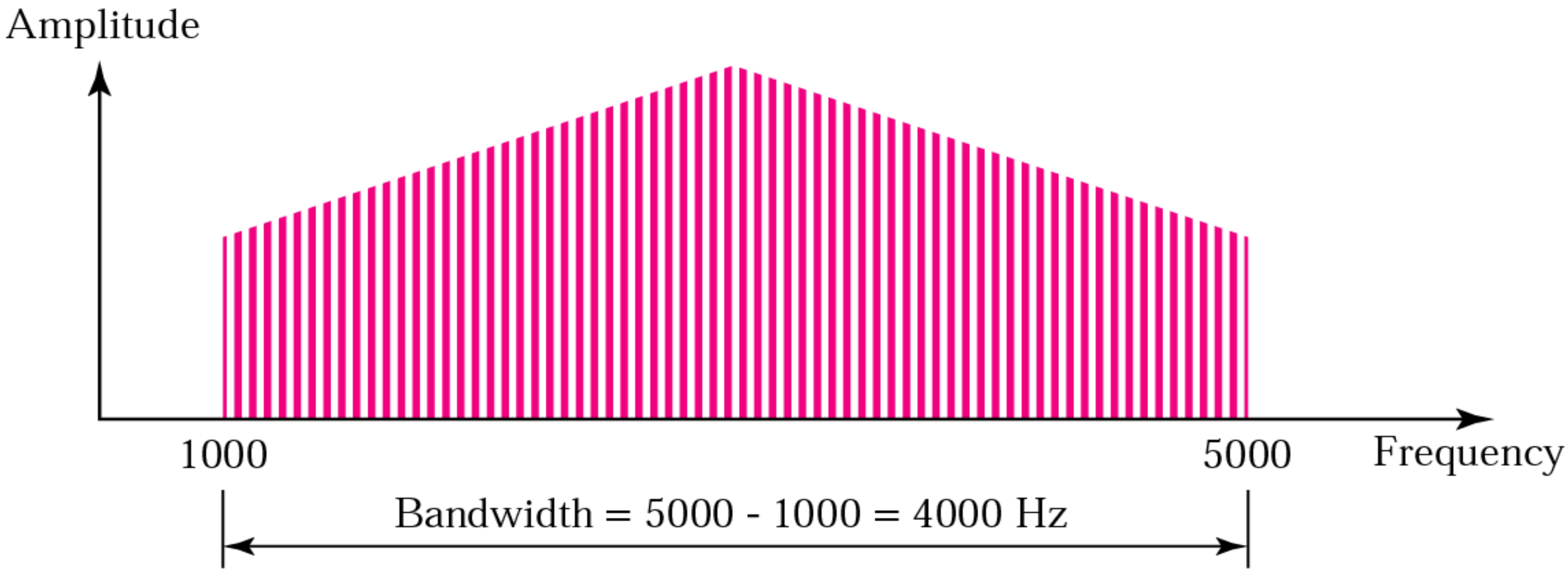


Note:

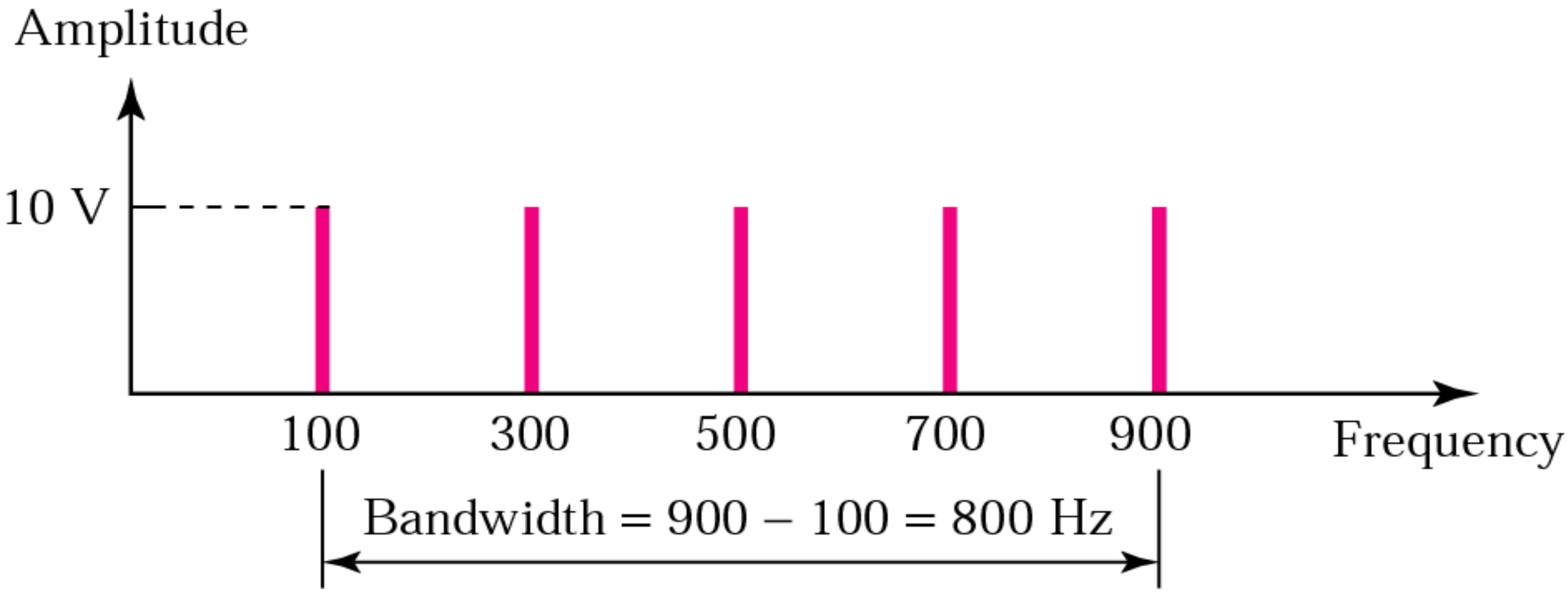
The bandwidth is a property of a medium: It is the difference between the highest and the lowest frequencies that the medium can satisfactorily pass.

Telephone line: Bandwidth between 3KHz and 4Khz

Analog Bandwidth

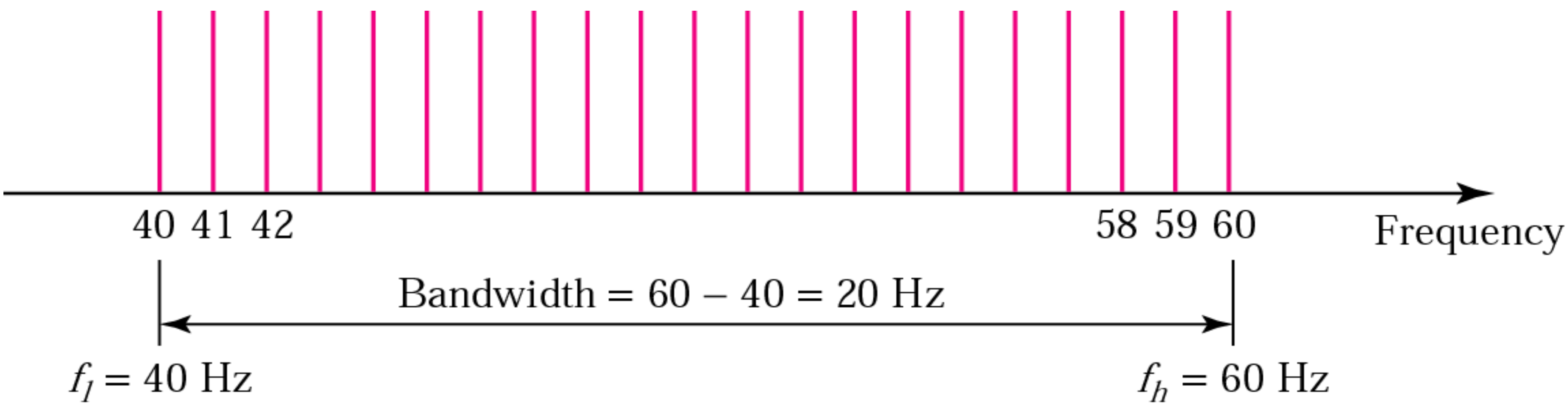


Analog Bandwidth: Example 1



Exercise: If a periodic signal is decomposed into five sine waves with frequencies of 100, 300, 500, 700, and 900 Hz, what is the bandwidth? Draw the spectrum, assuming all components have a maximum amplitude of 10V.

Analog Bandwidth: Example 2



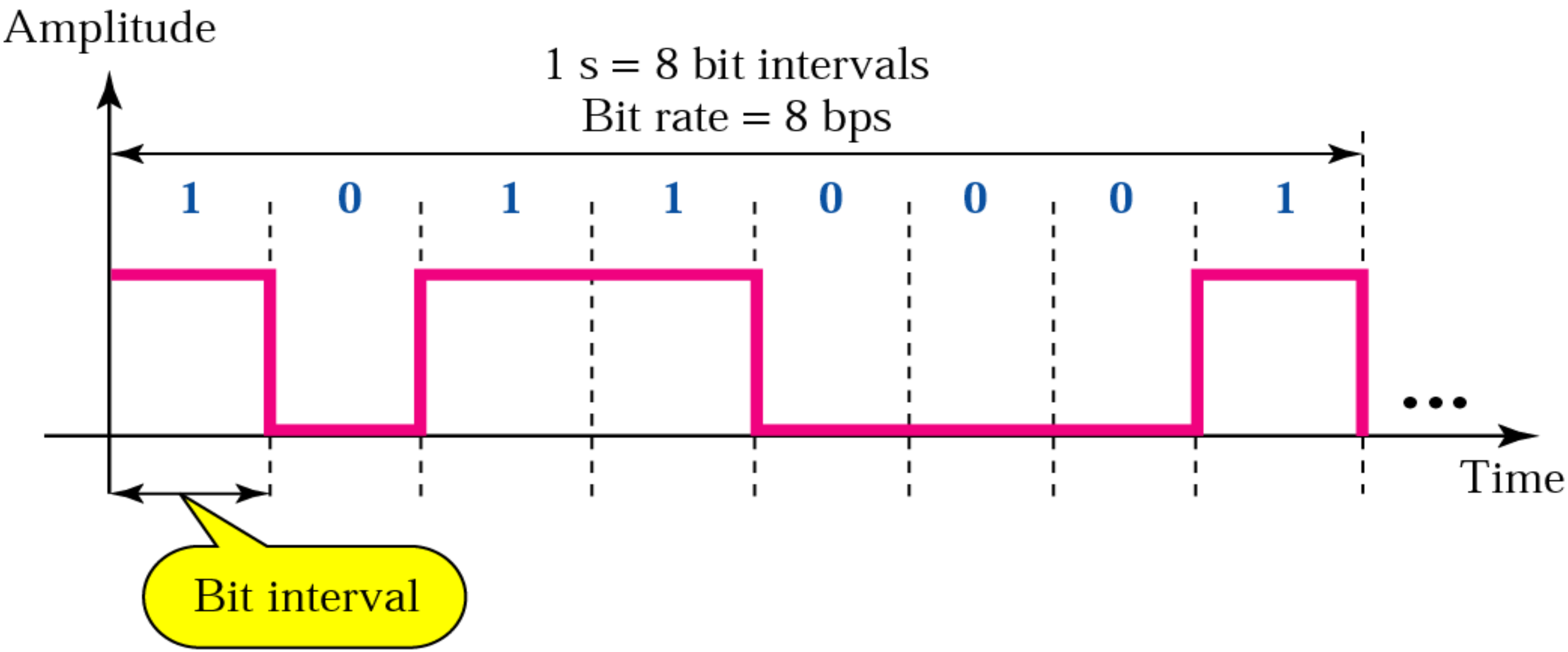
A signal has a bandwidth of 20 Hz. The highest frequency is 60 Hz. What is the lowest frequency? Draw the spectrum if the signal contains all integral frequencies of the same amplitude.

Analog Bandwidth: Example 3

A signal has a spectrum with frequencies between 1000 and 2000 Hz (bandwidth of 1000 Hz). A medium can pass frequencies from 3000 to 4000 Hz (a bandwidth of 1000 Hz).

Can this signal faithfully pass through this medium?

Digital Signals



Data can be represented as a digital signal: 1 as a positive voltage and 0 as a zero voltage

Most digital signals are aperiodic => frequency or period is irrelevant. Instead, we use the terms "bit rate" and "bit interval"

Digital Signal = Composite Analog Signal

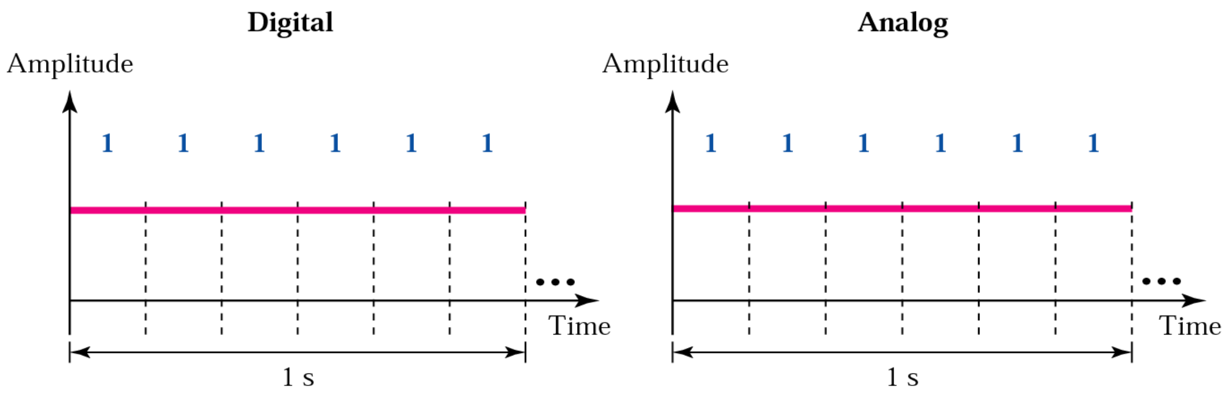
- Imagination: A digital signal can be considered as a composite analog signal with an infinite number of frequencies (using Fourier transformation).
  - Thus: the bandwidth of a digital signal is infinite

- *Question*: How to transmit digital signals over a transmission medium???
  - What is the minimum required bandwidth B in Hz of the transmission medium if we want to send a digital signal of n *bps?*

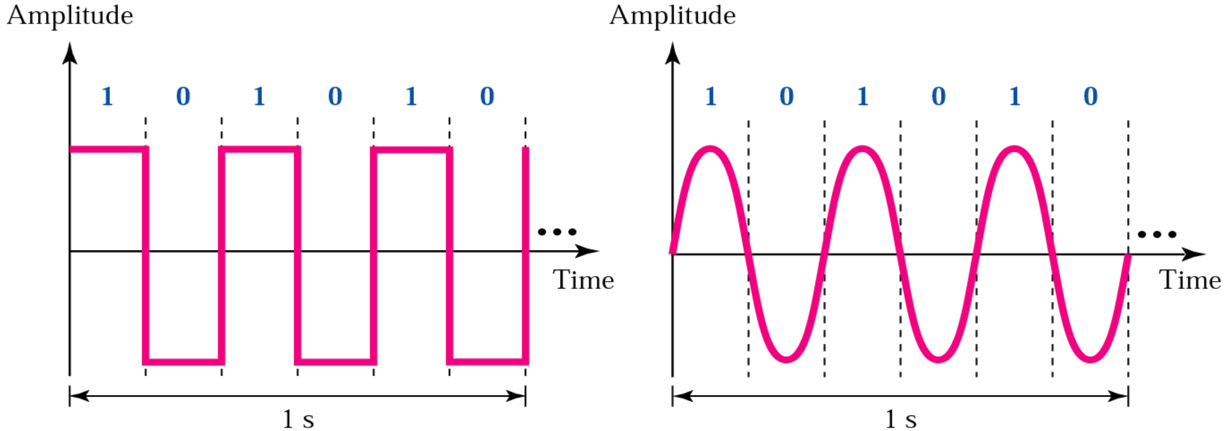
Bandwidth Requirement: Example

- Every second 6 bits are generated by the computer
  - E.g., 000000, 111111, 010110, 000011, etc.
- How to simulate these signals
  - Using a single-frequency analog signal?
  - Using a multi-frequency analog signal?

Example: Using One Harmonic



a. Best case, bit rate = 6, $f = 0$



b. Worst case, bit rate = 6, $f = 3$

Bandwidth requirement: 3Hz

Use More Harmonics

- N bits. The case where most changes occur is 0101010101…0101
- To get better quality, use Fourier transformation
- Fundamental freq n/2, the third-harmonic freq 3n/2, the fifth-harmonic freq 5n/2, …
- => B > n/2+3n/2+5n/2+…

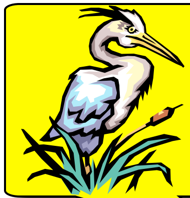
Medium Bandwidth Requirement

Bit Rate	Harmonic 1	Harmonics 1, 3	Harmonics 1, 3, 5	Harmonics 1, 3, 5, 7
1 Kbps	500 Hz	2 KHz	4.5 KHz	8 KHz
10 Kbps	5 KHz	20 KHz	45 KHz	80 KHz
100 Kbps	50 KHz	200 KHz	450 KHz	800 KHz

$$B = n/2+3n/2+5n/2+\ldots$$

The more harmonics, the better quality, the higher bandwidth required

Digital Bandwidth



Note:

The maximum bit rate that can be passed by the transmission medium

The analog bandwidth of a medium is expressed in hertz; the digital bandwidth, in bits per second.

I am so Confused ?!?!?!!!

B > n/2 => n < 2B => digital bandwidth must be smaller than 2B

BUT:

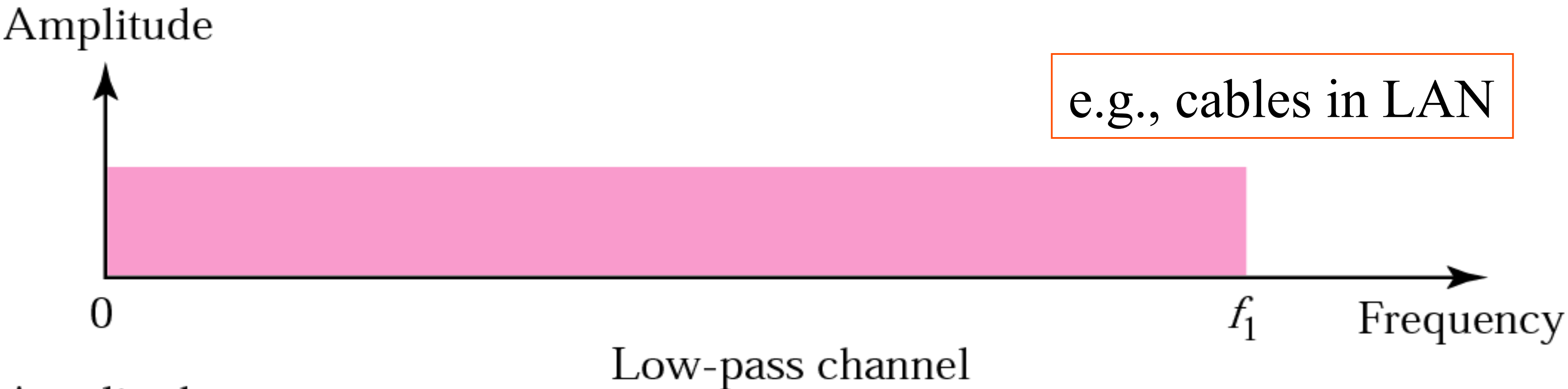
Analog bw of telephone lines: [3Khz, 4Khz]

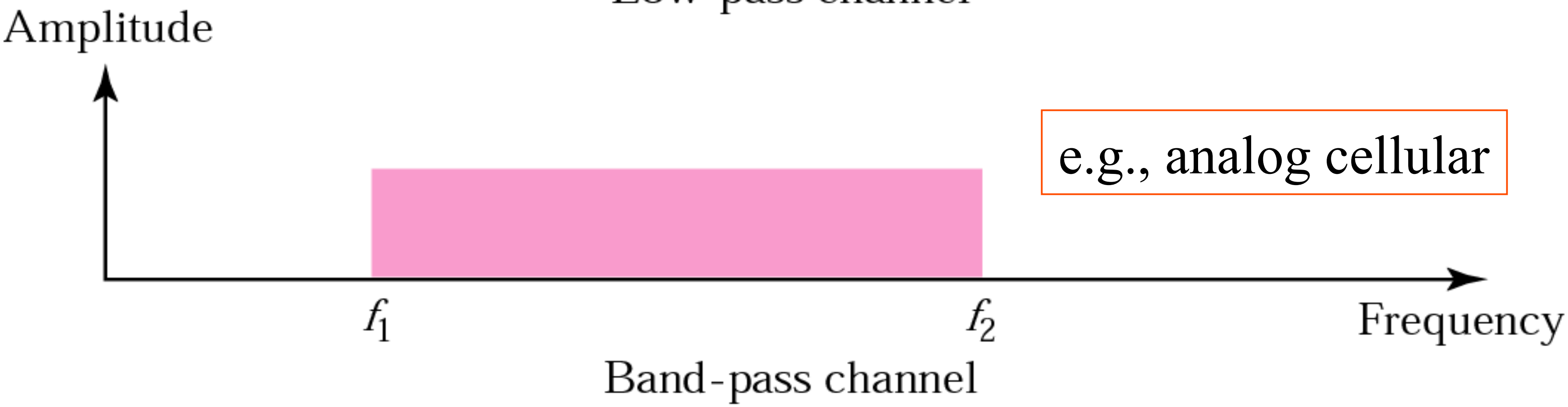
=> digital bandwidth must be at most 8Kbps

But, dial-up speed ~~ 30Kbps, how come????

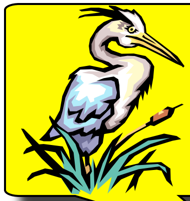
BECAUSE: modulation techniques allow to group multiple bits in one single period of an analog signal (TO BE DISCUSSED LATER)

Use Digital or Analog Signal?





There are two types of links: low-pass link and band-pass link



Note:

***Digital* transmission needs a *low-pass* channel.**

***Analog* transmission can use a *band-pass* channel.**

Question: can analog signals be transmitted in a low-pass link?

Digital vs. Analog

- Digital’s **advantage**:
  - Digital design less expensive and more reliable
  - Greater dynamic range and error detection and recovery by the use of coding
  - Many sources can be combine (voice, video, data) and sent over the same channel
- Digital’s **disadvantage**
  - More bandwidth needed

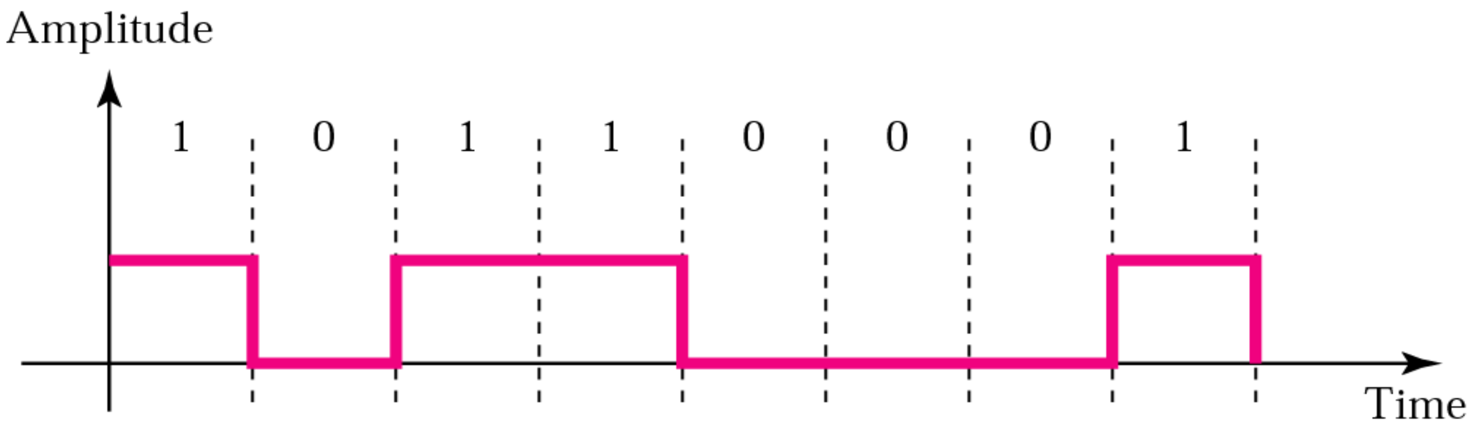
Baseband vs. Broadband Signals

- **Baseband signal**: frequency spectrum extends from 0 to some maximum frequency (similar to low-pass channel's property)
- **Broadband signal**: frequency spectrum belongs to a range between a min freq and a max freq (similar to band-pass channel's property)

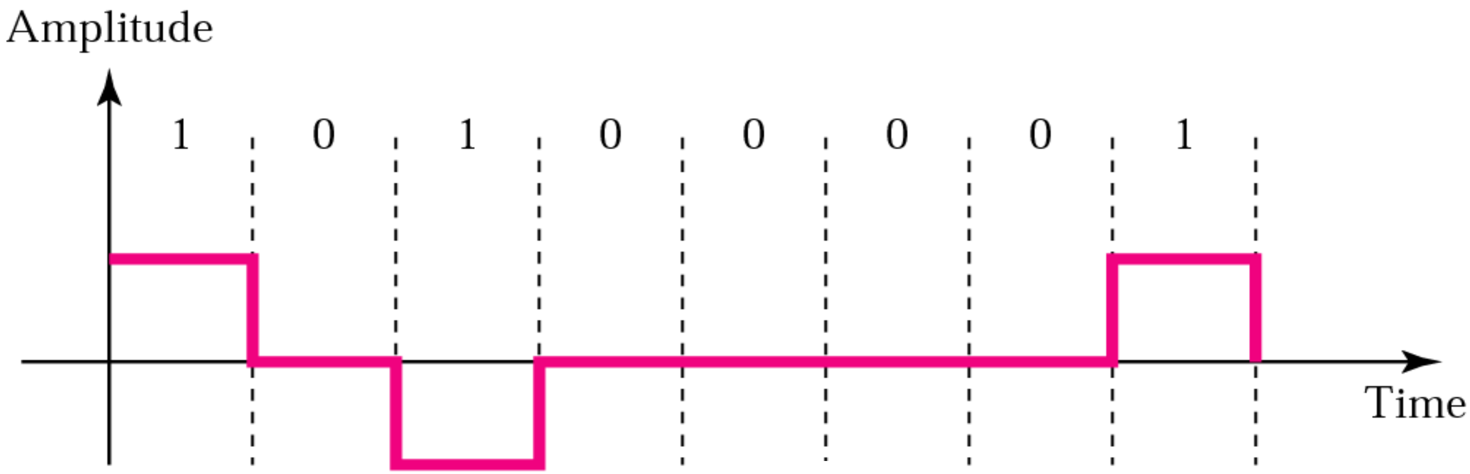
Data Rate Limits

- How fast can we send data (in bps) over a link?
- The answer depends on
  - Bandwidth available
  - Levels of signals we can use
  - Quality of channel (level of noise)

Signal Levels



a. Two signal levels, two data levels



b. Three signal levels, ı 2 data levels

Noiseless Channel: Nyquist Bitrate

- $bitRate = 2 \times Bandwidth \times \log_2 L$
  - L: the number of signal levels used to represent data
  - Bandwidth: analog channel bandwidth

Example: Consider a noiseless channel with a bandwidth of 3000 Hz transmitting a signal with two signal levels. The maximum bit rate can be calculated as

$$\text{Bit Rate} = 2 \times 3000 \times \log_2 2 = 6000 \text{ bps}$$

Noisy Channel: Shannon Capacity

- $channelCapacity = Bandwidth \times \log_2(1+SNR)$
  - SNR: signal to noise ratio – statistical ratio of the signal power and noise power
  - Bandwidth: analog channel bandwidth

Consider an extremely noisy channel with SNR is almost zero. In other words, the noise is so strong that the signal is faint. For this channel the capacity is calculated as

$$C = B \log_2 (1 + SNR) = B \log_2 (1 + 0)$$
$$= B \log_2 (1) = B \times 0 = 0$$

More Example

We have a channel with a 1 MHz bandwidth. The SNR for this channel is 63; what is the appropriate bit rate and signal level?

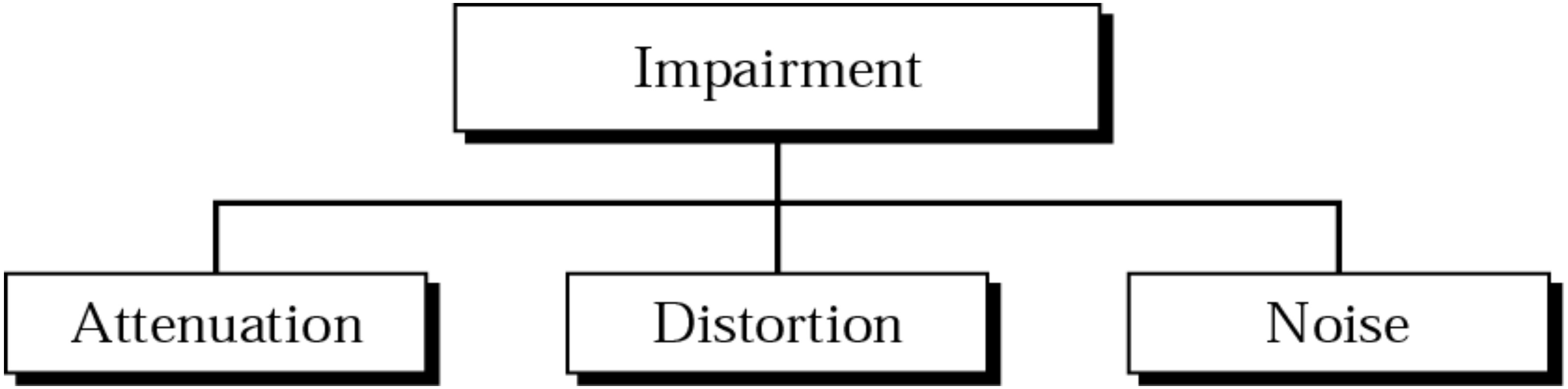
First, we use the Shannon formula to find our upper limit.

$$C = B \log_2 (1 + SNR) = 10^6 \log_2 (1 + 63) = 10^6 \log_2 (64) = 6 \text{ Mbps}$$

Then we use the Nyquist formula to find the number of signal levels.

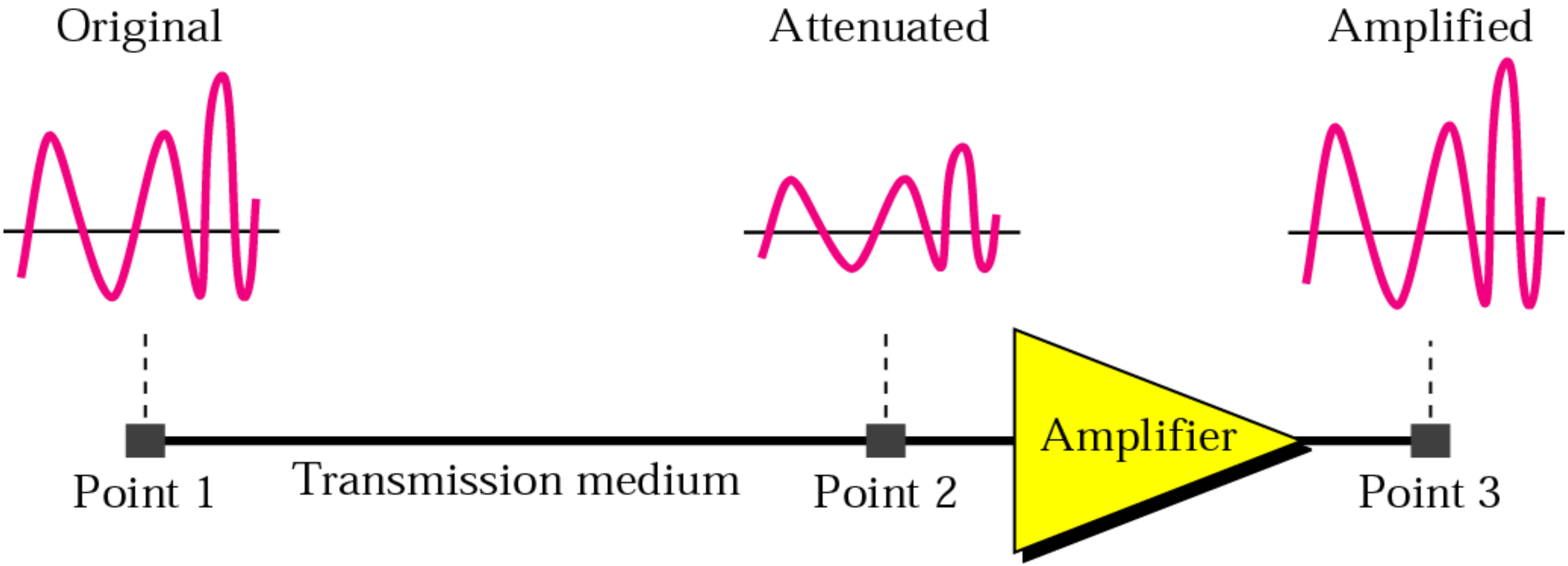
$$4 \text{ Mbps} = 2 \times 1 \text{ MHz} \times \log_2 L \rightarrow L = 4$$

Transmission Impairment



Transmission medium is not perfect => impairment in signal

Attenuation



The decibel (dB) measures the relative strengths of two signals or a signal at two different points

$dB = 10 \log_{10}(P_2/P_1)$

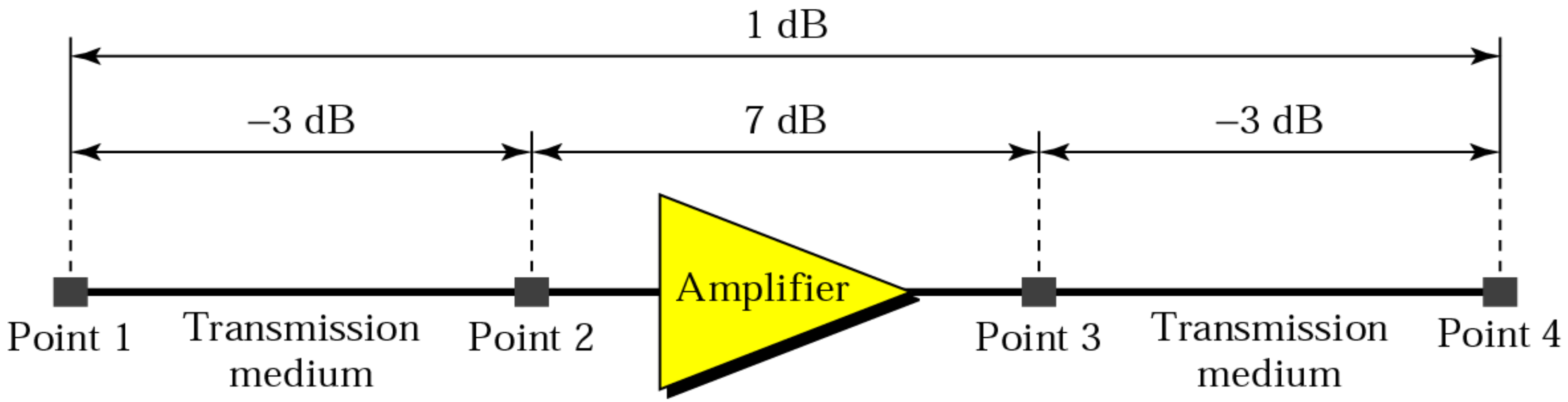
Attenuation: Example

Imagine a signal travels through a transmission medium and its power is reduced to half. This means that P2 = 1/2 P1. In this case, the attenuation (loss of power) can be calculated as

$$10 \log_{10} (P2/P1) = 10 \log_{10} (0.5P1/P1) = 10 \log_{10} (0.5)$$
$$= 10(-0.3) = -3 \text{ dB}$$

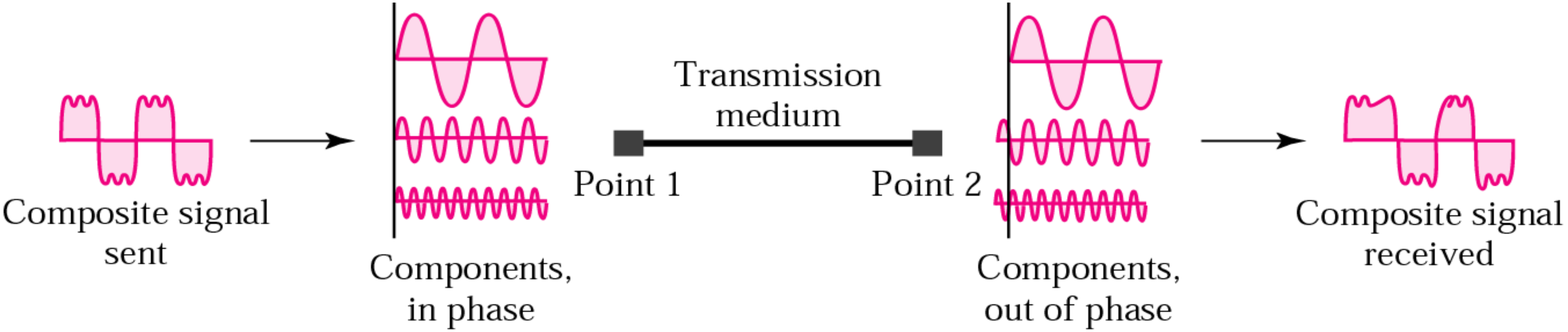
Why do We Use dB?

- What if we use the metrics dB = $10(P_2/P_1)$ instead of $10\log_{10}(P_2/P_1)$ to tell the difference between the two signals?



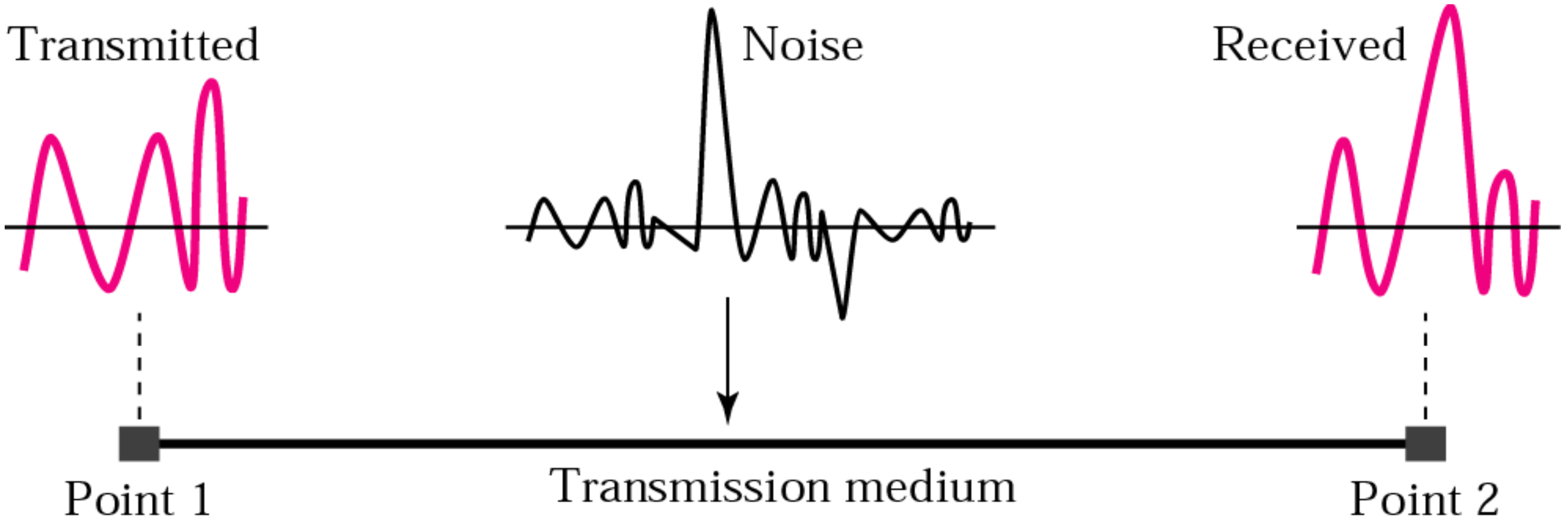
$$dB = -3 + 7 - 3 = +1$$

Distortion



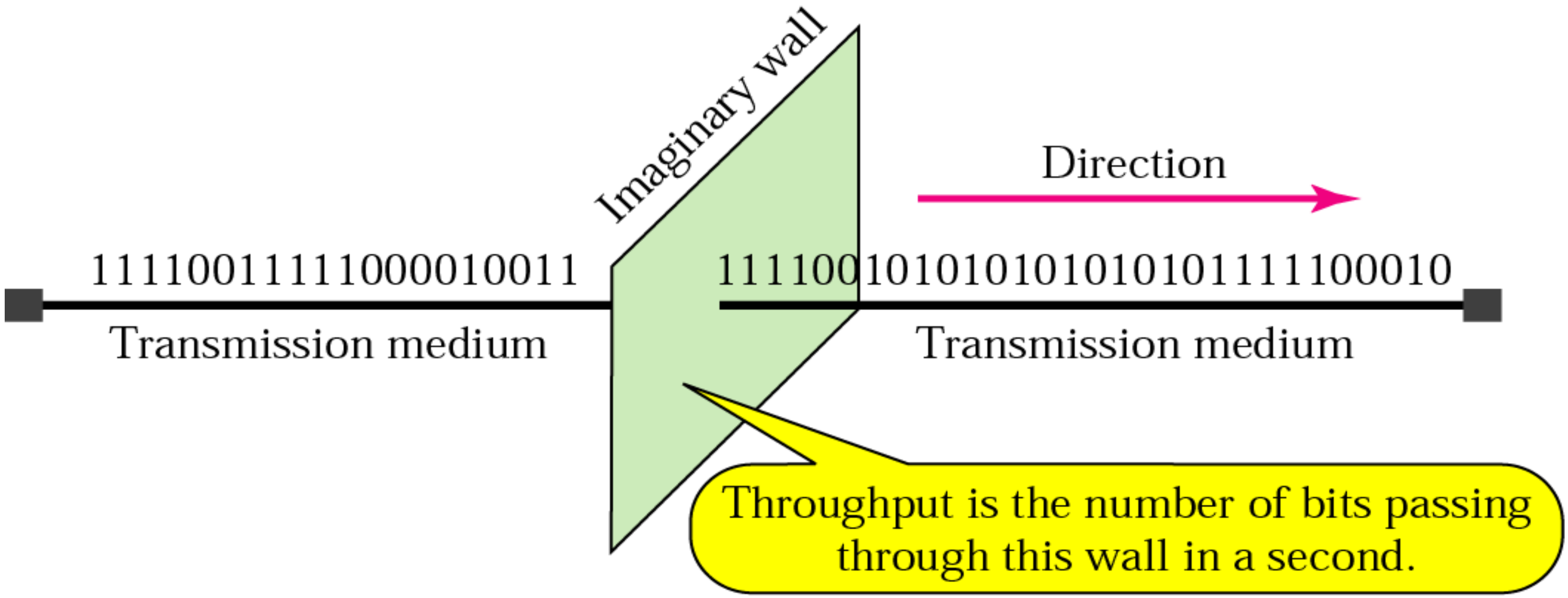
Composite signal
sent
Components,
in phase
Transmission
medium
Point 1
Point 2
Components,
out of phase
Composite signal
received

Noise

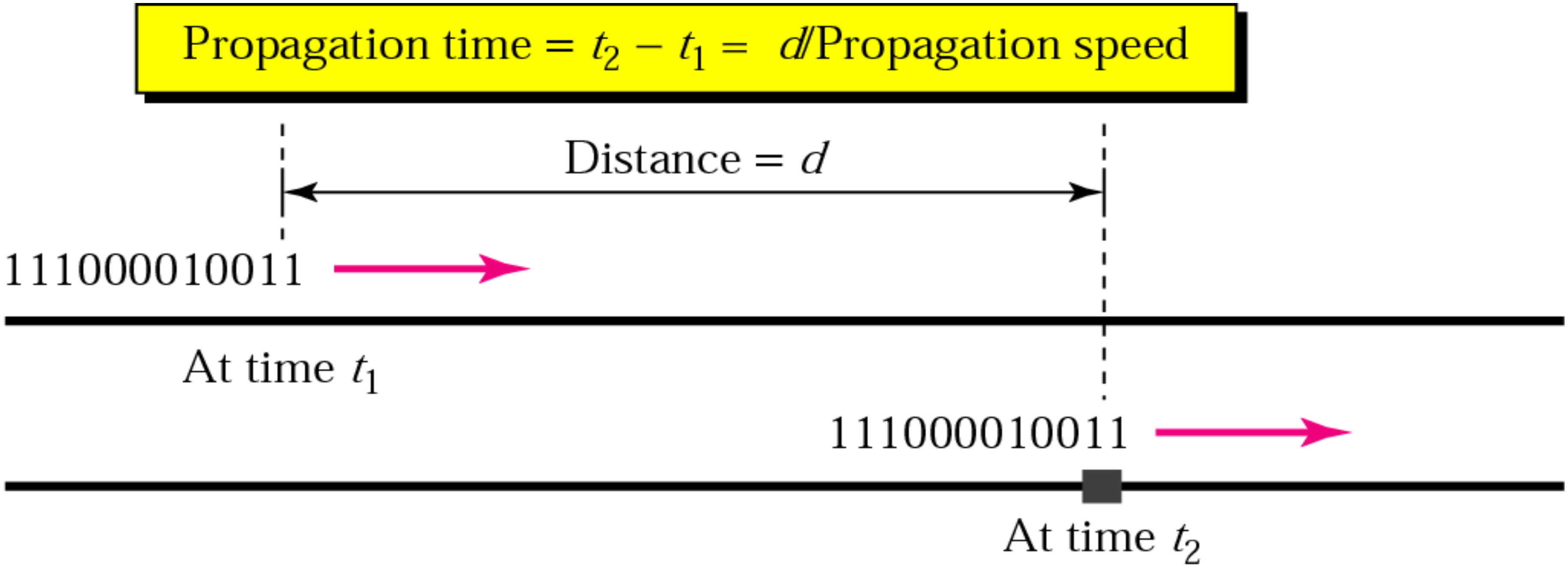


Transmitted
Noise
Received
Point 1
Transmission medium
Point 2

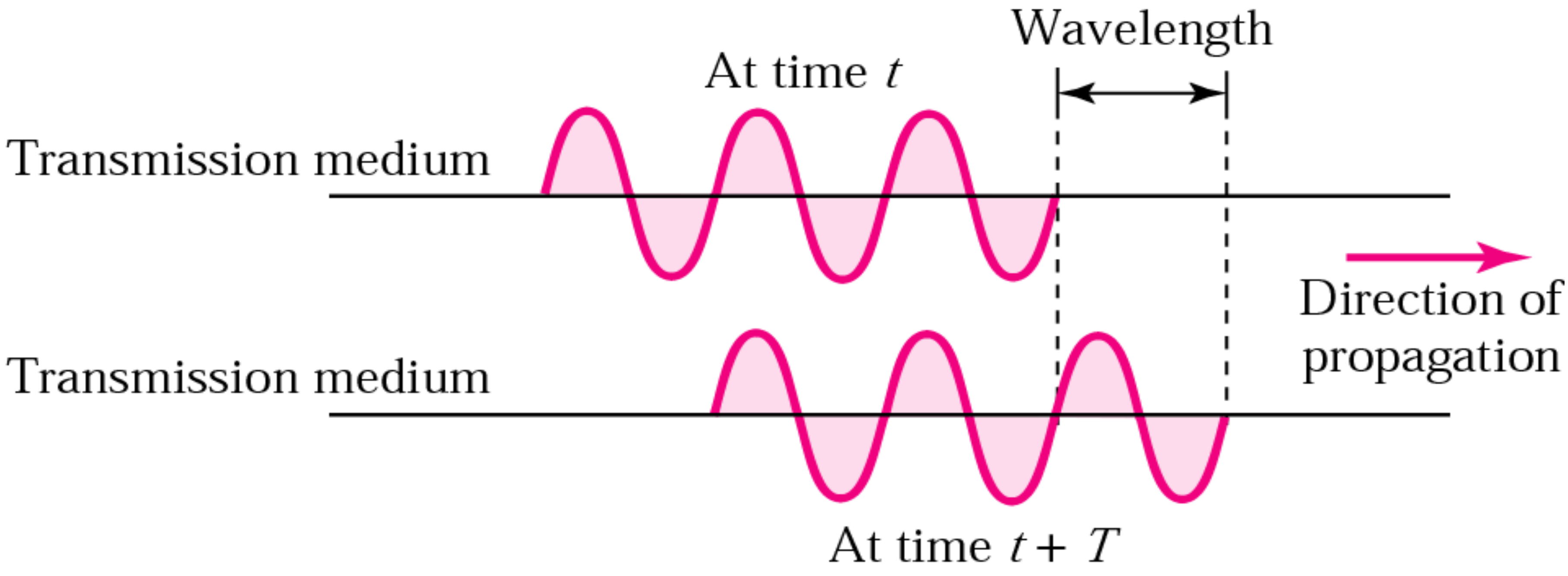
Throughput


Imaginary wall
Direction
11110011111000010011
111100101010101010101111100010
Transmission medium
Transmission medium
Throughput is the number of bits passing through this wall in a second.

Propagation Time



Wavelength



Wavelength (for electromagnetic signals)

= speed-of-light / frequency

= $3*10^8$ (m/s) / frequency

Common Wavelengths

Band	Approximate Center	Wavelength (m)
Voice	~ 1 Khz	300,000
Audiophile	~ 10 Khz	30,000
Broadcast AM	~ 1000 Khz	300
Broadcast FM	~ 100 Mhz	3
Satellite	~ 10 Ghz	0.03

Fact: Reception heard on FM radio is more sensible to mobility than that on AM radio

Dielectric Constant

- Ability of a material to resist the formation of an electric field within it

Wavelength = (1 / freq) * (Lightspeed / sqrt(dielectic))

Material	Dielectric constant
Free space	1.0
Air	1.0006
Metallic conductors	1.2-1.6
Rubbers	3.0
Glass	7.5

Exercise

- Consider an electromagnetic wave moving in a metallic conductor with a dielectric constant of 1.15
  - What is the propagation speed of this metallic conductor?
  - How much longer would it take the wave to travel 1000 miles than the same wave traveling in free space?

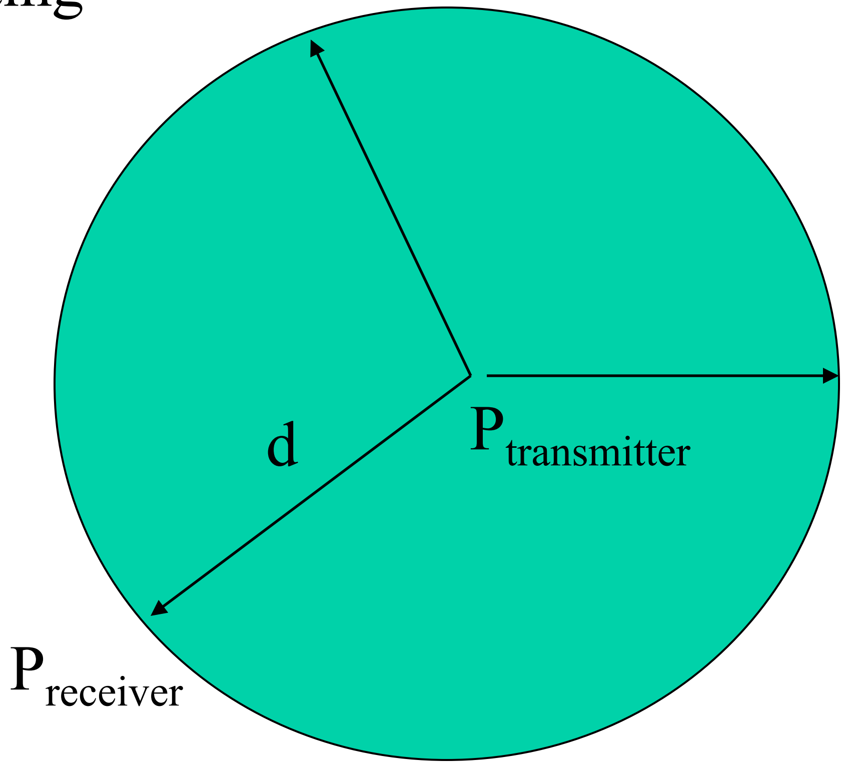
Radio Frequency Bands

Band name	Frequency, Wavelength	Example uses
ELF	**3–30 Hz, 100,000 km – 10,000 km**	
SLF	**30–300 Hz, 10,000 km – 1000 km**	Power line, lower end of human hearing
ULF	**300–3000 Hz, 1000 km – 100 km**	Human voice
VLF	**3–30 kHz, 100 km – 10 km**	Military communication, end of human hearing
LF	**30–300 kHz, 10 km – 1 km**	Navigation, time signals, AM longwave broadcasting
MF	**300–3000 kHz, 1 km – 100 m**	AM broadcasts
HF	**3–30 MHz, 100 m – 10 m**	Shortwave broadcasts and amateur radio
VHF	**30–300 MHz, 10 m – 1 m**	FM and television broadcasts
UHF	**300–3000 MHz, 1 m – 100 mm**	television broadcasts
SHF	**3–30 GHz, 100 mm – 10 mm**	microwave devices, mobile phones, wireless LAN
EHF	**30–300 GHz, 10 mm – 1 mm**	Next frontier for communications

Power Radiation

- How far can receiver receives a signal from transmitter?
  - Power radiates isotropically
  - Knowing power when transmitting
  - Knowing power received

$$P_{transmit} = 4\pi d^2 * P_{receive}$$



Modulation Techniques

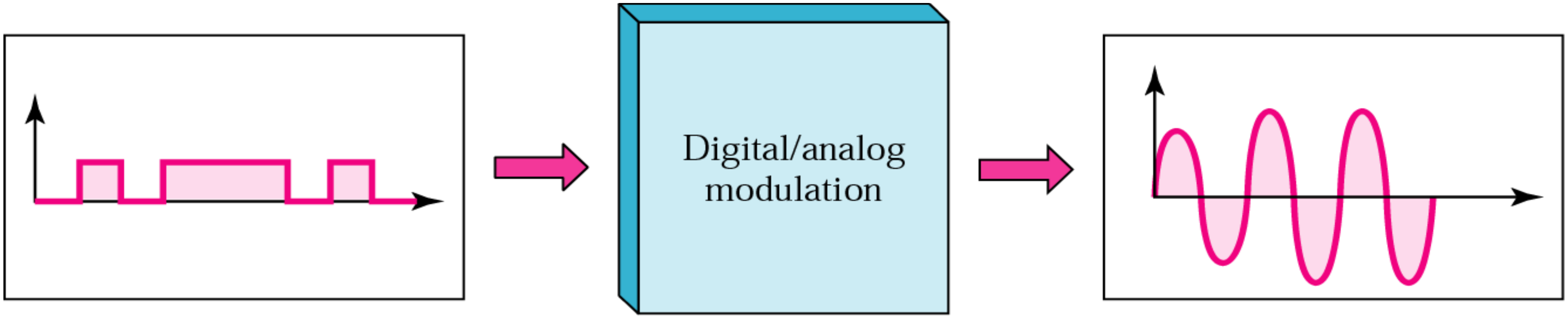
Digital to Analog Modulation

Modulation Devices

Analog to Analog Modulation

Analog to Digital Modulation

Digital to Analog Modulation



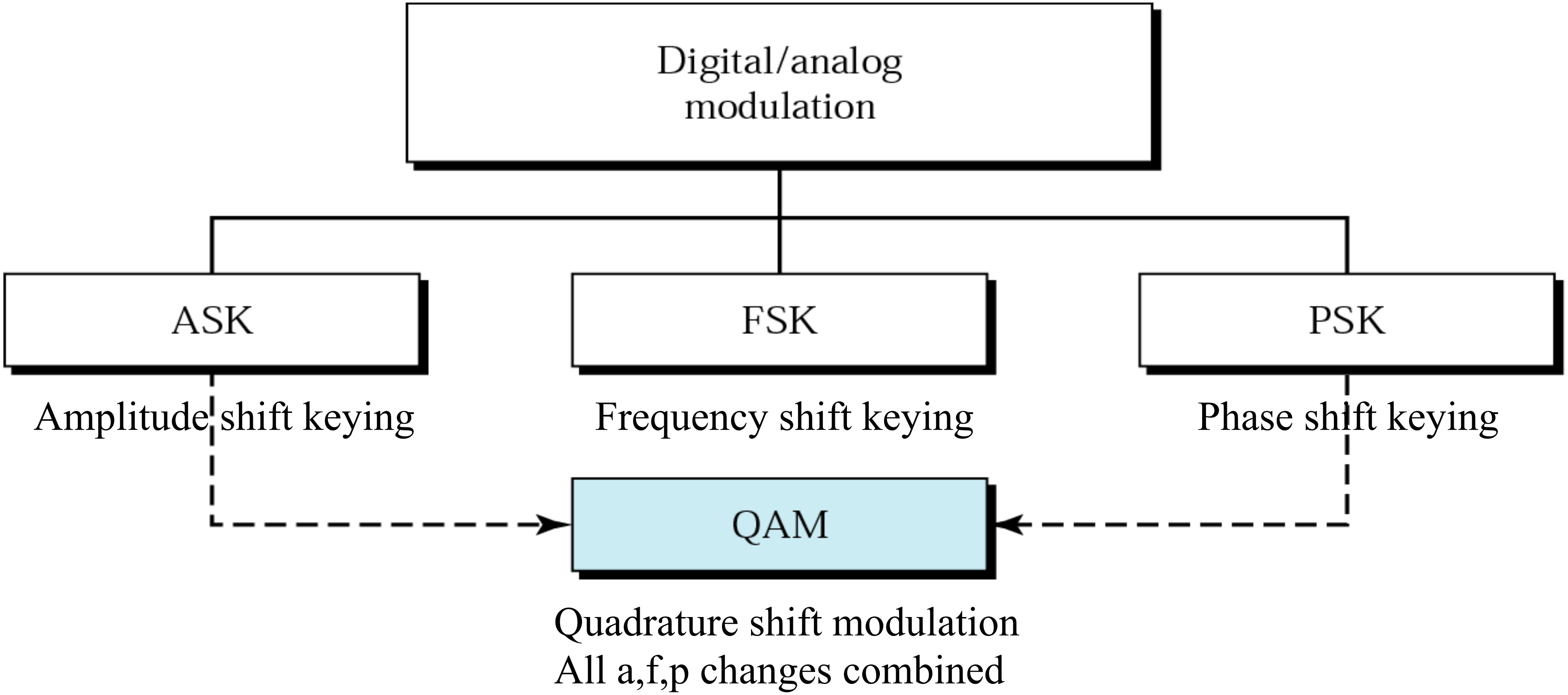
Digital-to-analog modulation: the process of changing one of the characteristics of an analog signal based on the information in a digital signal

"Forget me not": characteristics of a sine wave are amplitude, frequency, phase.

Carrier Signal

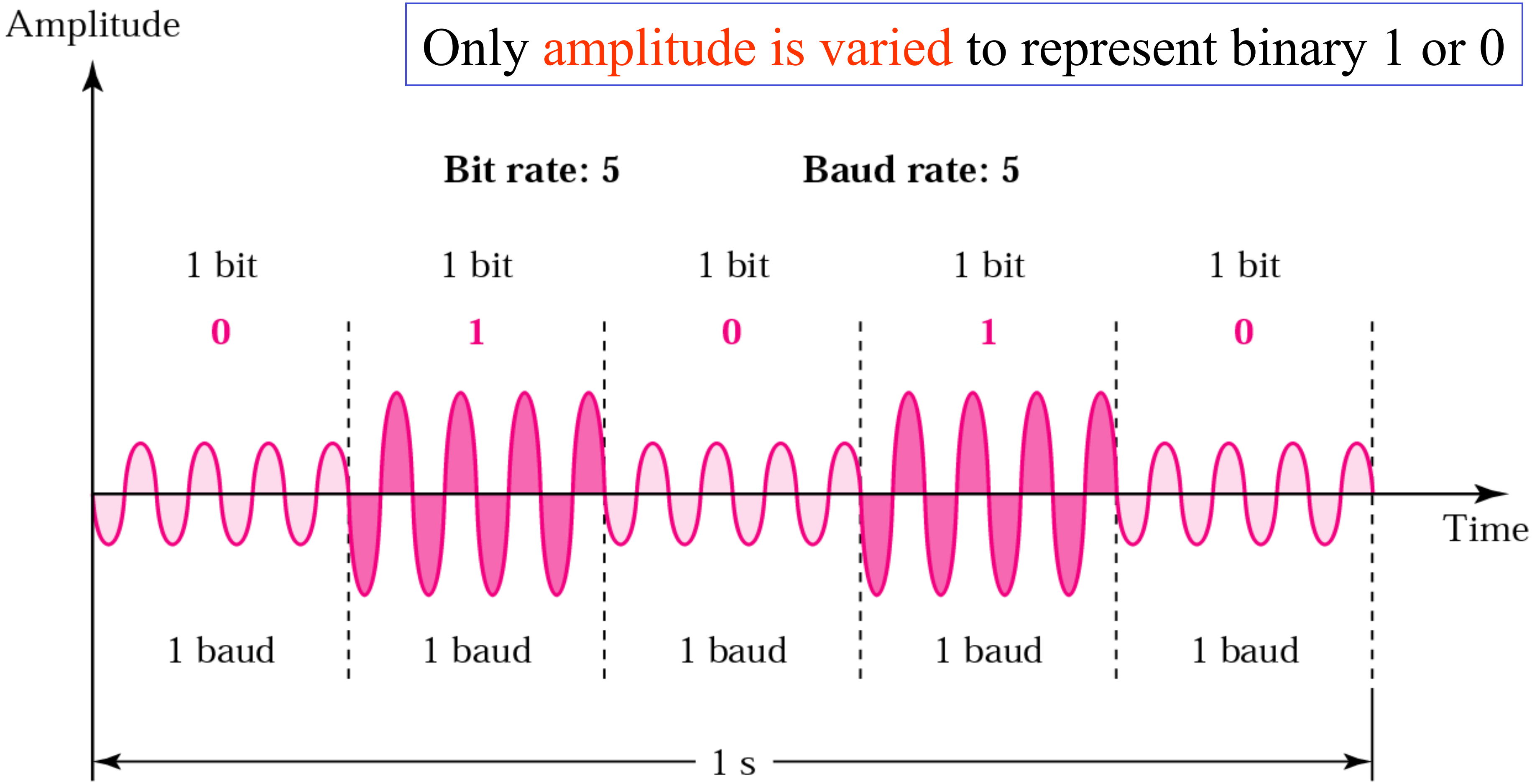
- Sender
  - Produce a high-frequency signal that acts as a basis for the information signal => carrier signal
  - Modulate the carrier signal to reflect the digital information. The information signal is called the modulating signal
- Receiver
  - Tune in the carrier frequency to receive

Digital-Analog Modulation Schemes



Amplitude Shift Keying (ASK)

Only amplitude is varied to represent binary 1 or 0



Peak amplitude during each bit duration is constant

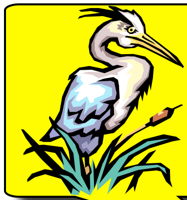
Amplitude-Shift Keying

- One binary digit represented by presence of carrier, at constant amplitude
- Other binary digit represented by absence of carrier

$$s(t) = \begin{cases} A\cos(2\pi f_c t) & \text{binary 1} \\ 0 & \text{binary 0} \end{cases}$$

where the carrier signal is $A\cos(2\pi f_c t)$

Bit Rate vs. Baud Rate



Note:

Bit rate ***is the number of bits per second***

- More important in speaking of computer efficiency

Baud rate ***is the number of*** ***signal units*** ***per second that are required to represent those bits***

-More important in speaking of data transmission

-Determine the bandwidth required to send the signal

Analogy in transportation: a baud is analogous to a car while a bit is analogous to a passenger (1: male, 0: female). The number of cars determines the traffic; that of passengers does not

Baud Rate Example

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

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

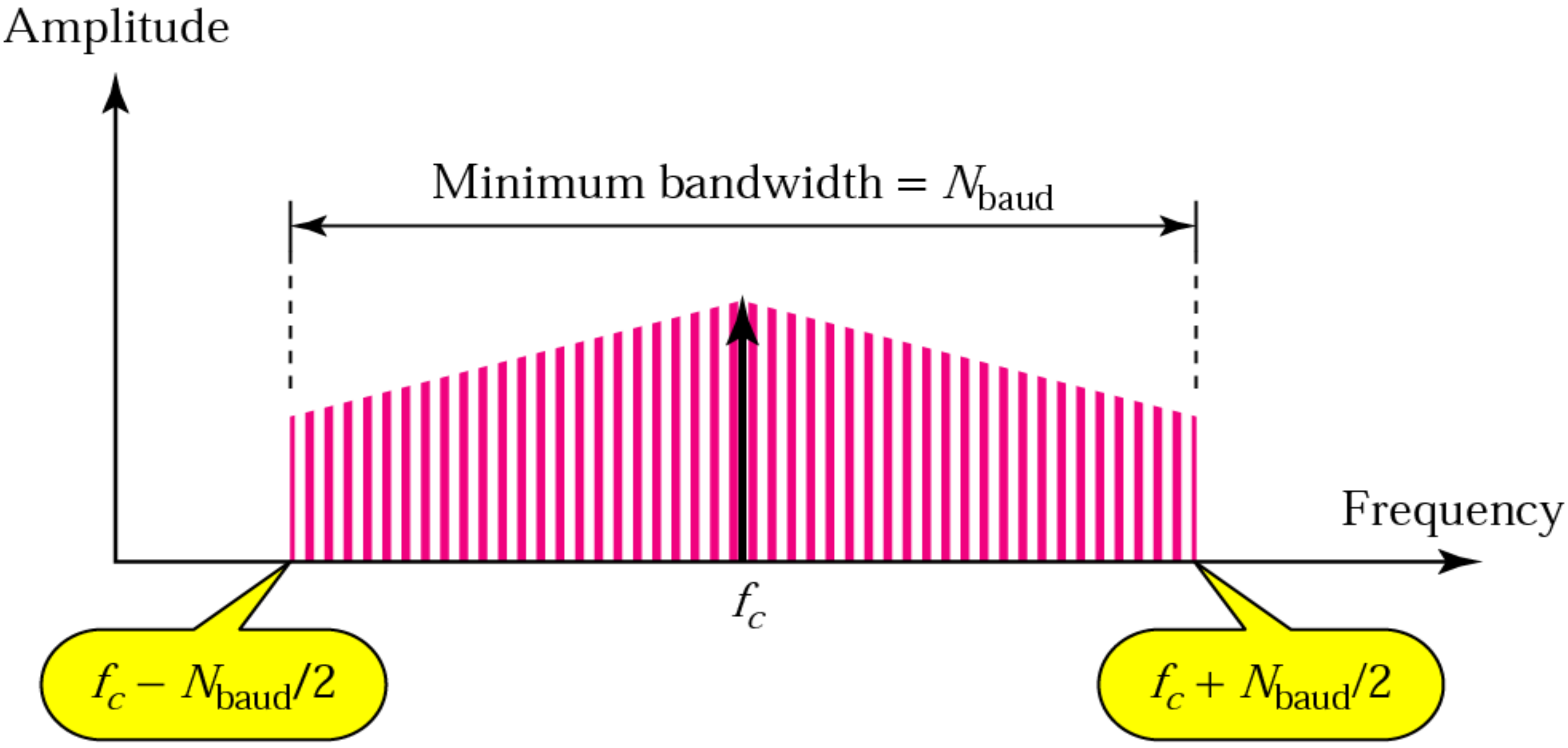
The bit rate of a signal is 3000. If each signal unit carries 6 bits, what is the baud rate?

Baud rate = 3000 / 6 = 500 baud/s

ASK (2)

- Disadvantage
  - Highly susceptible to noise interference because ASK relies on amplitude to differentiate between 1 and 0
    - Need a great gap between amplitude values so that noise can be detected and removed
- OOK (on/off keying)
  - A popular ASK technique
  - Zero voltage represent a bit value (e.g., 0)
  - Save energy in transmitting information
- On voice-grade line, up to 1200bps
- Used to transmit digital data over optical fiber

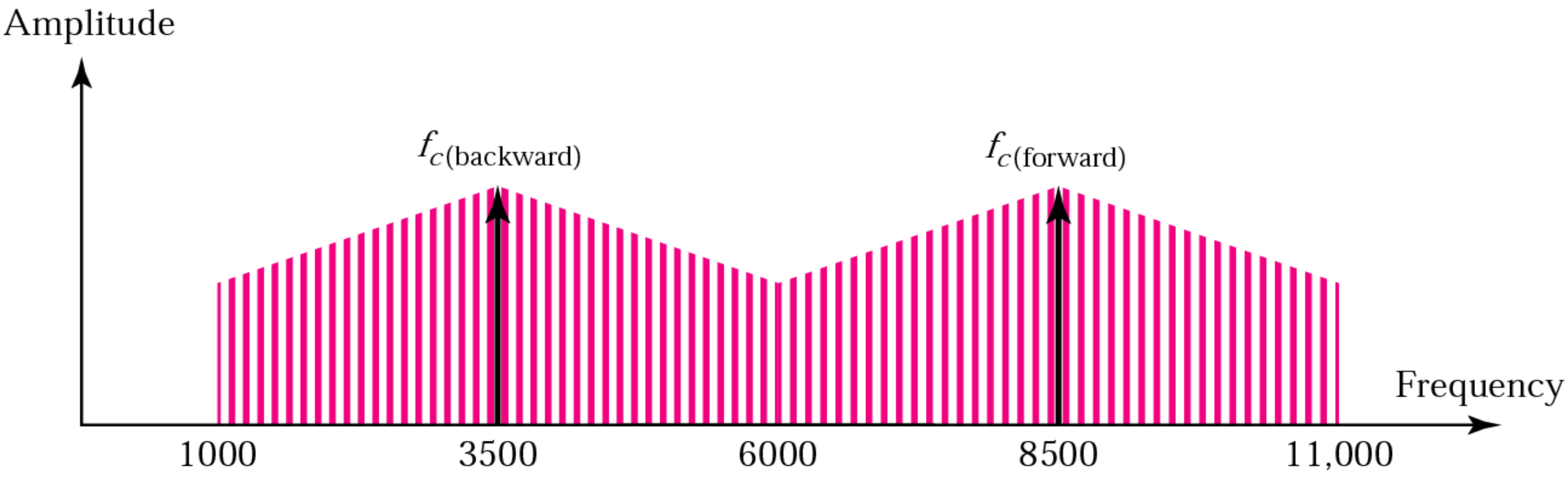
ASK: Bandwidth Requirement



Question: What is the min bw for an ASK signal transmitting at 2000 bps? The transmission mode is half-duplex.

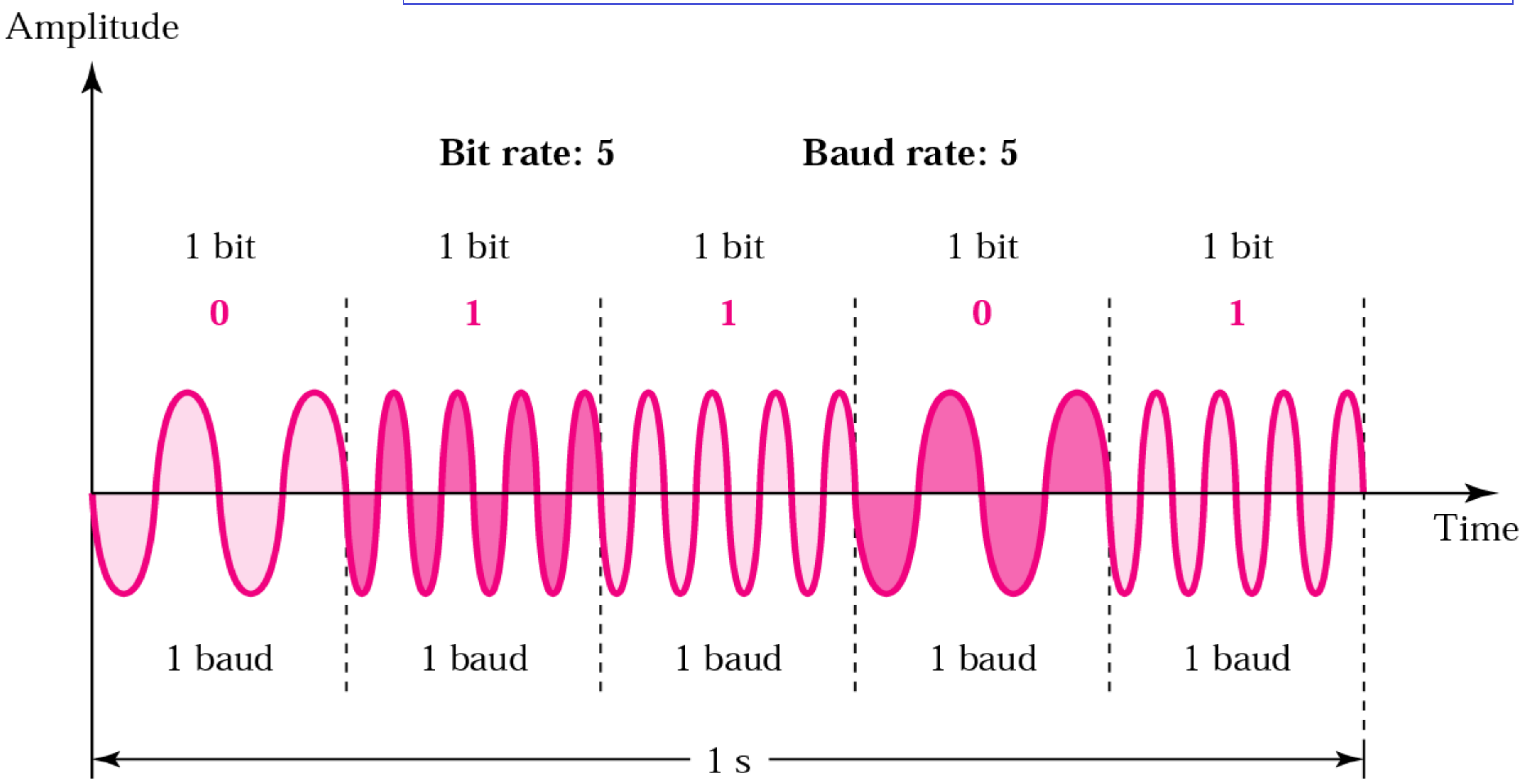
ASK: Example

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



Frequency Shift Keying (FSK)

Only frequency is varied to represent binary 1 or 0



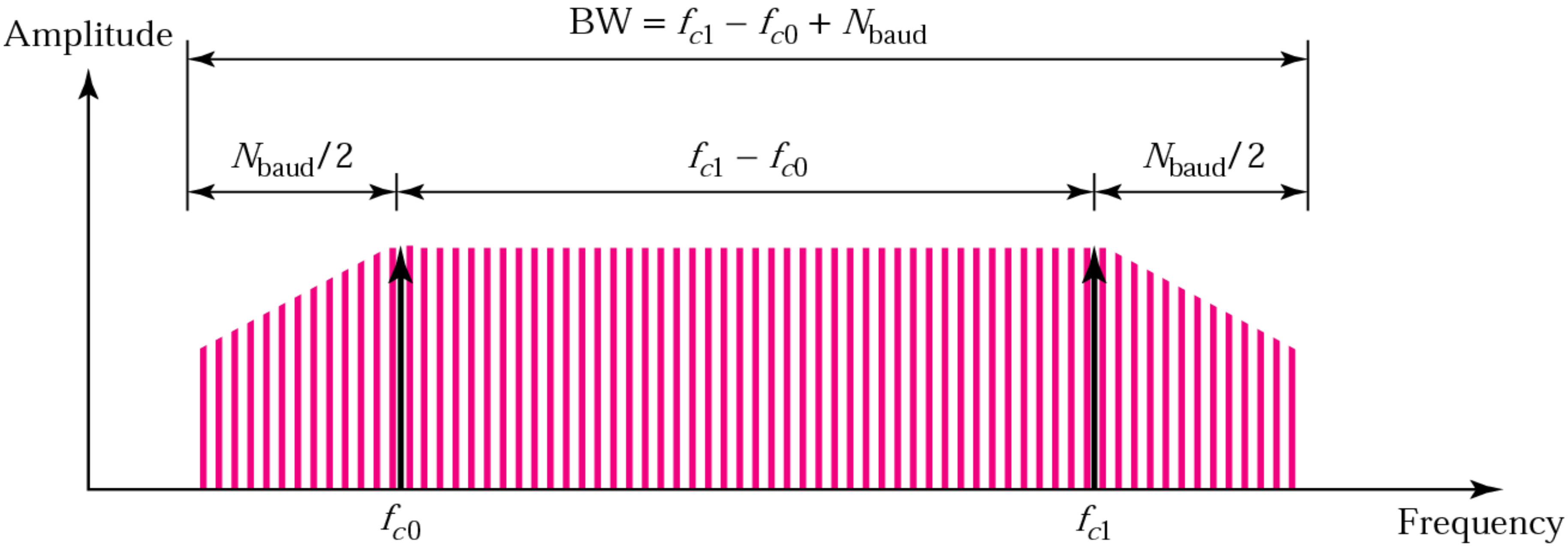
Binary Frequency-Shift Keying (BFSK)

- Two binary digits represented by two different frequencies near the carrier frequency

$$s(t) = \begin{cases} A\cos(2\pi f_1 t) & \text{binary 1} \\ A\cos(2\pi f_2 t) & \text{binary 0} \end{cases}$$

- where f_1 and f_2 are offset from carrier frequency f_c by equal but opposite amounts

FSK: Baud Rate and Bandwidth



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

Multiple Frequency-Shift Keying (MFSK)

- More than two frequencies are used
- More bandwidth efficient but more susceptible to error

$$s_i(t) = A\cos 2\pi f_i t \quad 1 \le i \le M$$

- $f_i = f_c + (2i - 1 - M)f_d$
- f_c = the carrier frequency
- f_d = the difference frequency
- M = number of different signal elements = 2^L
- L = number of bits per signal element

MFSK

- One signal element encodes L bits
- Element interval = $T_s = LT$ seconds
  - where T is the bit period (data rate = $1/T$)
- Total bandwidth required $2Mf_d$
- Minimum frequency separation required $2f_d = 1/T_s$

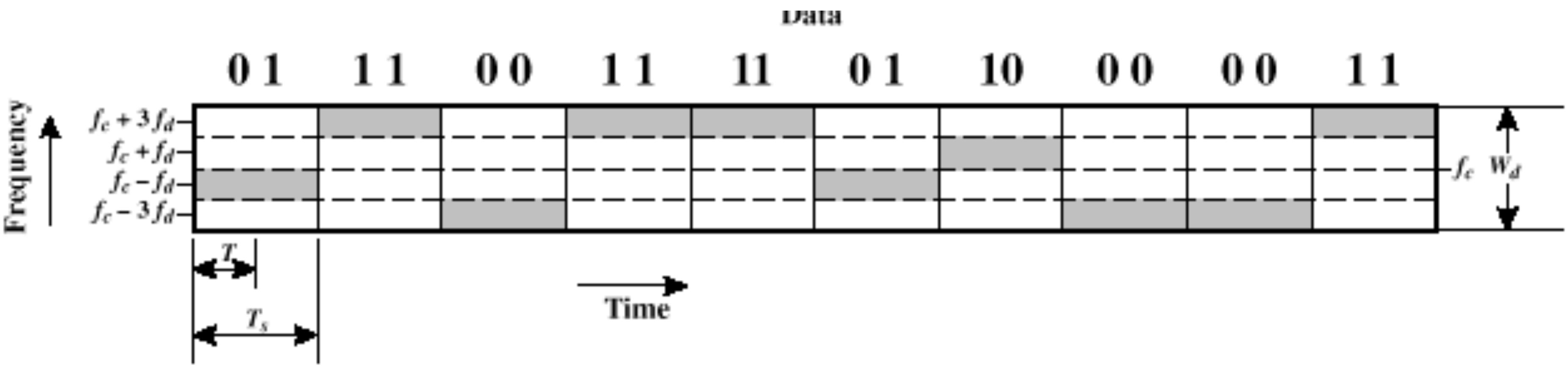


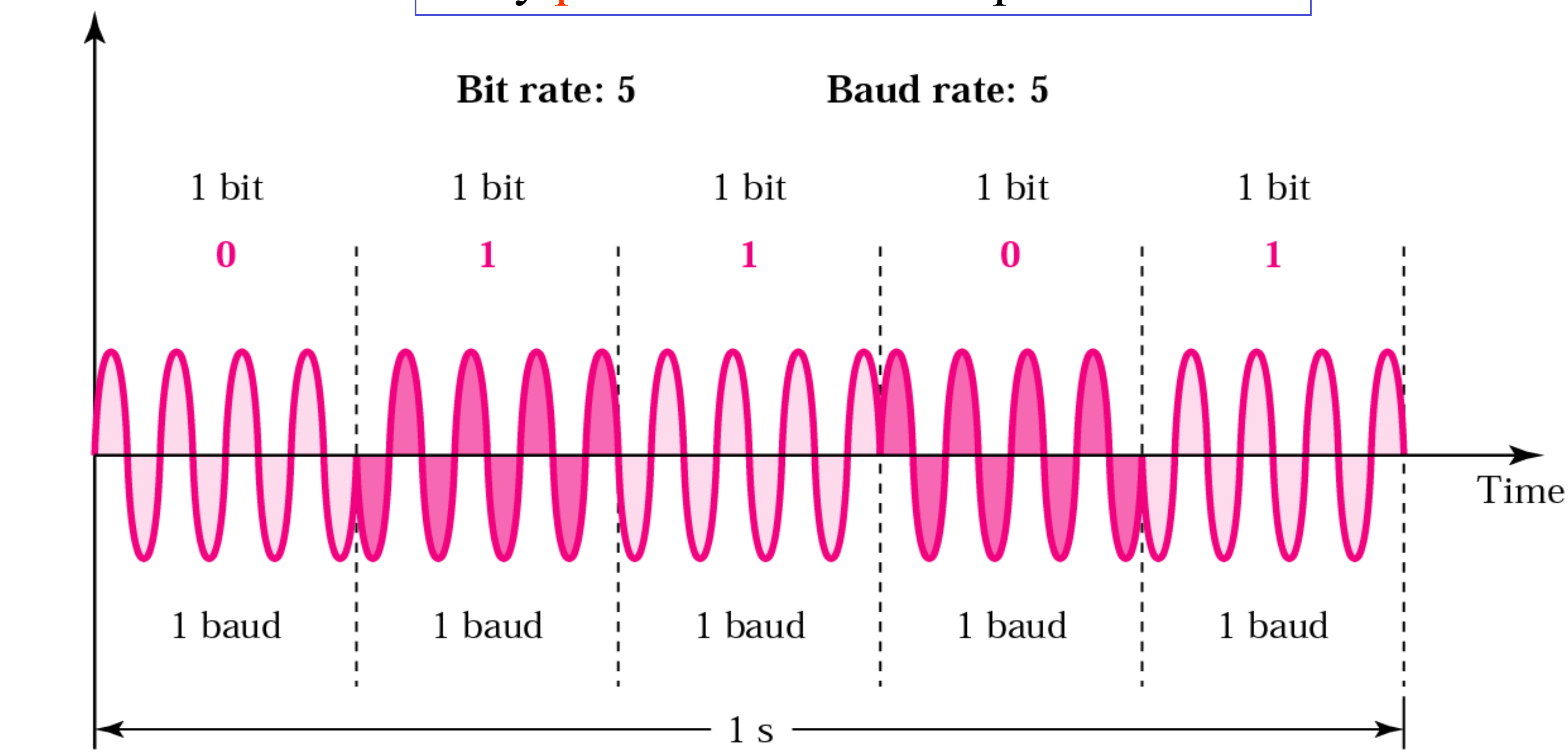
Figure 6.4 MFSK Frequency Use ($M = 4$)

FSK vs. ASK

- FSK
  - Less susceptible to error
  - On voice-grade lines, up to 1200bps
  - Commonly used for high-freq (3-30 Mhz) radio
  - Also used at even high freq on LANs that use coaxial cable

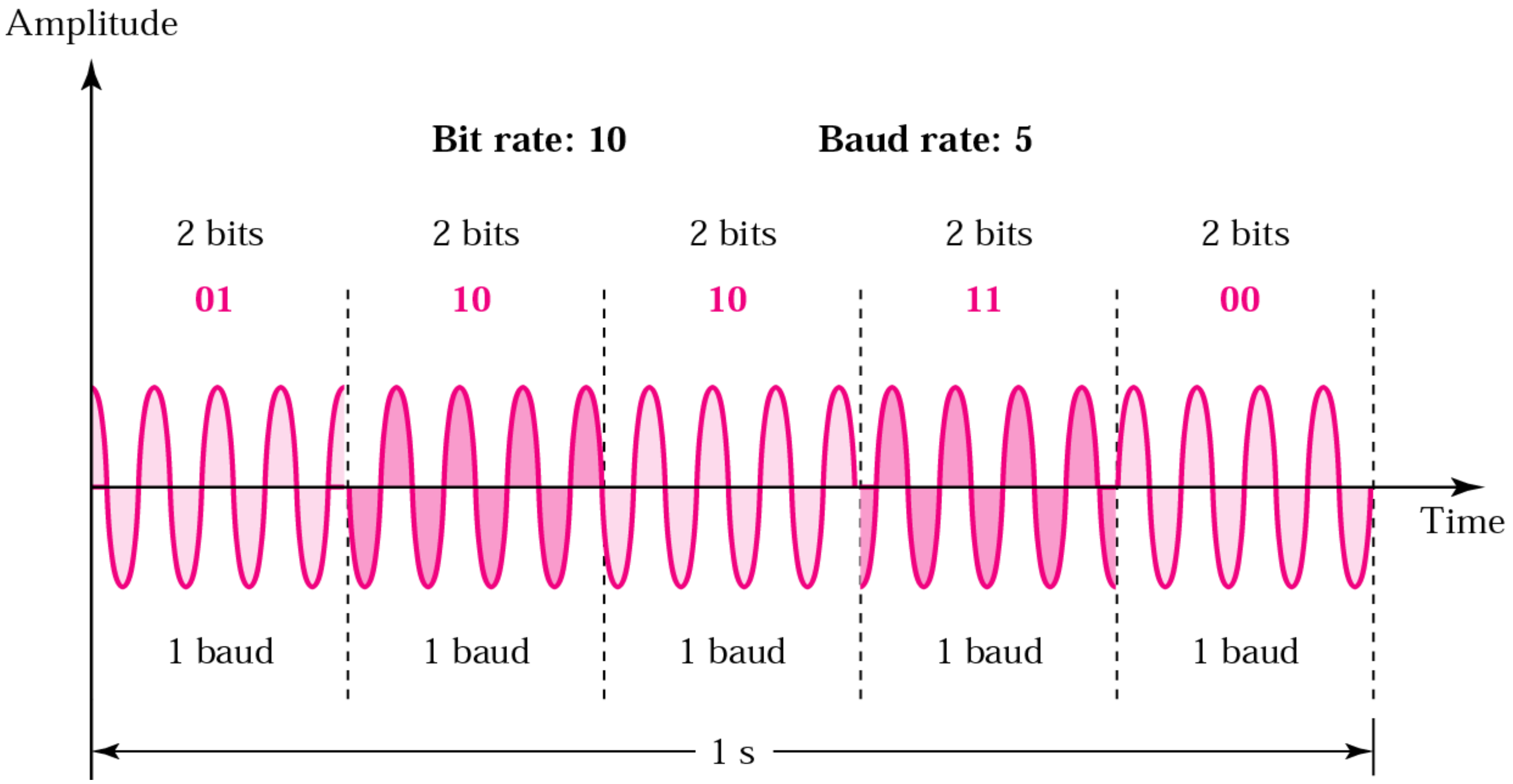
Phase Shift Keying (PSK)

Only phase is varied to represent 1 or 0



2-PSK: only 2 phase values are used, each for 1 or 0

4-PSK

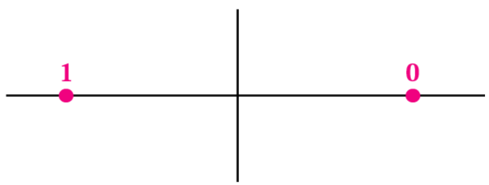


Amplitude
Bit rate: 10
Baud rate: 5
2 bits
2 bits
2 bits
2 bits
2 bits
01
10
10
11
00
Time
1 baud
1 baud
1 baud
1 baud
1 baud
1 s

Constellation (or Phase-State) Diagram

Bit	Phase
0	0
1	180

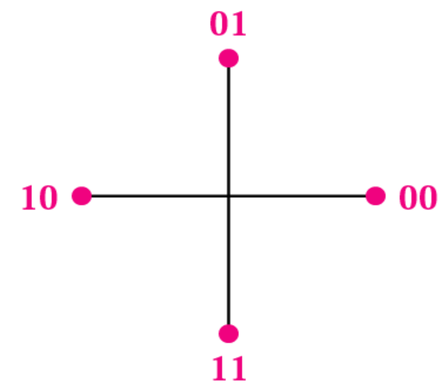
Bits



Constellation diagram

Dibit	Phase
00	0
01	90
10	180
11	270

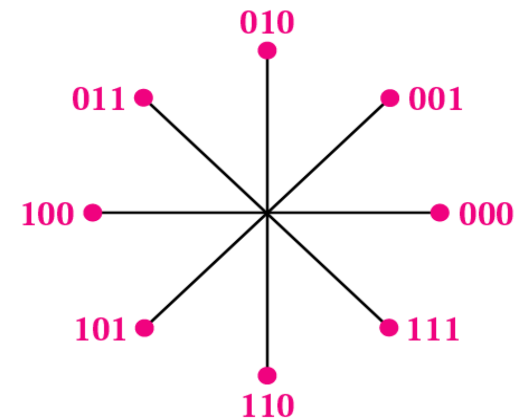
Dibit
(2 bits)



Constellation diagram

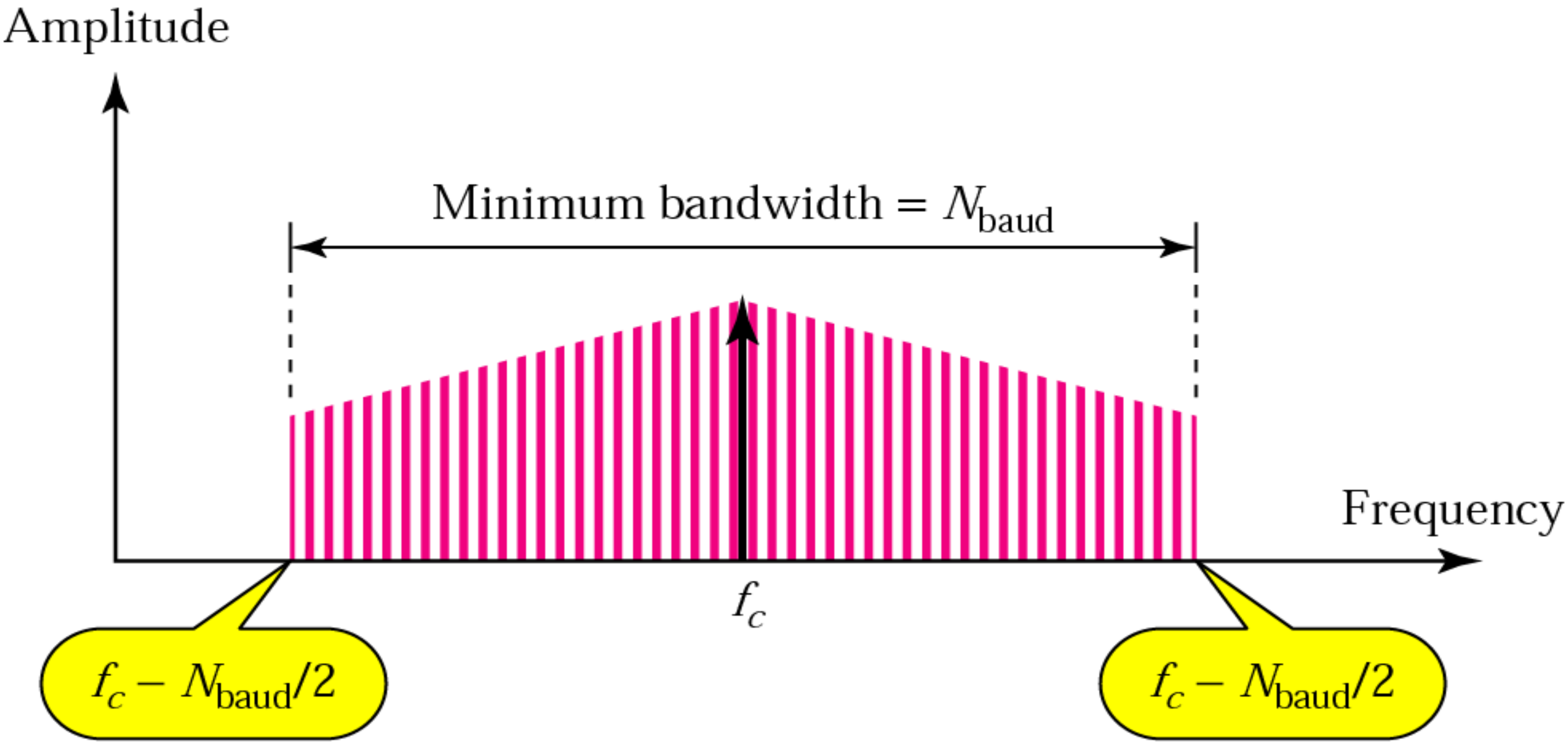
Tribit	Phase
000	0
001	45
010	90
011	135
100	180
101	225
110	270
111	315

Tribits
(3 bits)



Constellation diagram

PSK: Baud Rate and Bandwidth



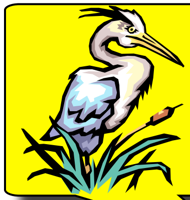
Same as in ASK, but can transmit more bps given same bandwidth

PSK: Questions

Given a bandwidth of 5000 Hz for an 8-PSK signal, what are the baud rate and bit rate? Transmission is in half-duplex mode.

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

PSK: Drawback



Note:

Modulation device is not able to distinguish small differences in phase => limit BitRate

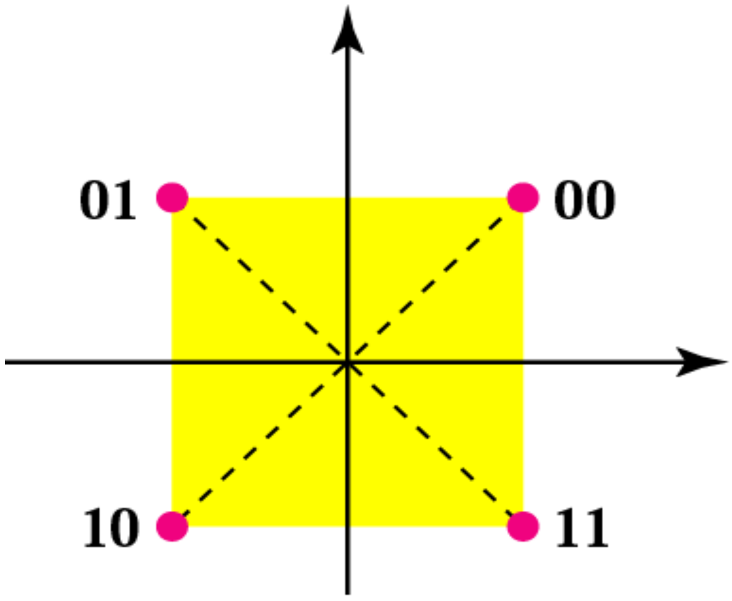
Why not combine PSK and ASK: **x** variations in phase with **y** variations in amplitude result in **xy** variations => increase bit rate

Quadrature Amplitude Modulation

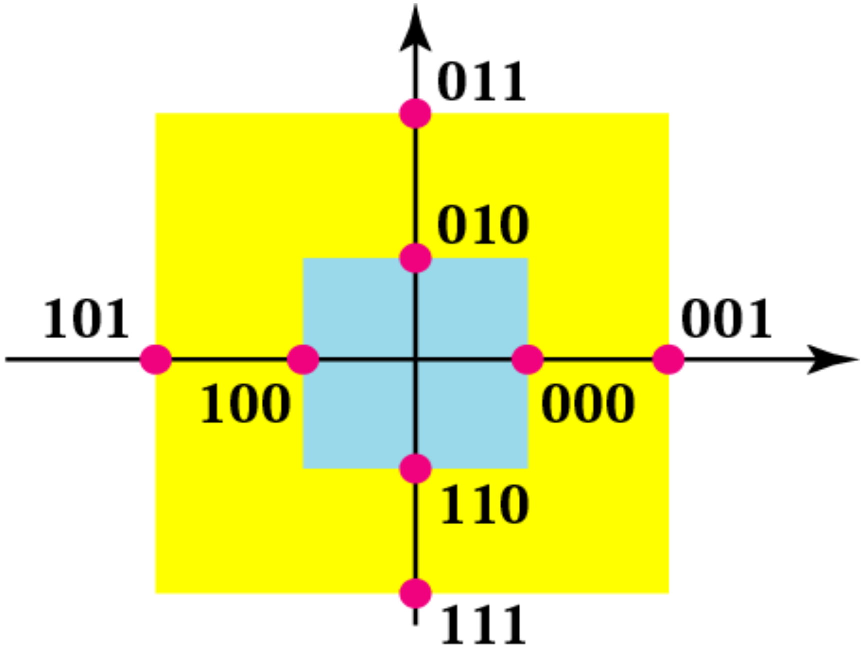
A combination of ASK and PSK: both phase and amplitude varied

#amplitude shifts << #phase shifts

Lower susceptible to noise than ASK, higher bit rate than PSK

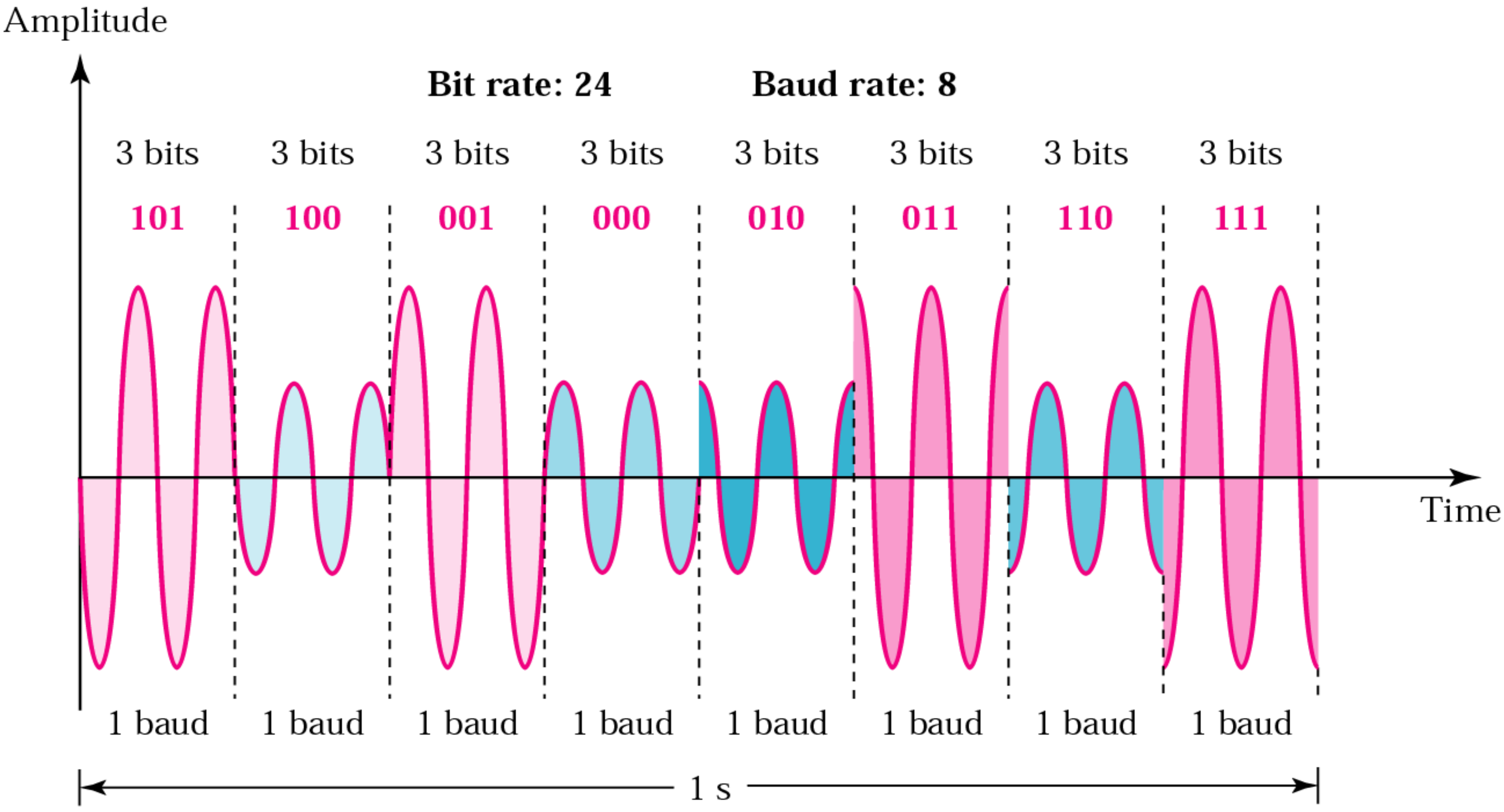


4-QAM
1 amplitude, 4 phases



8-QAM
2 amplitudes, 4 phases

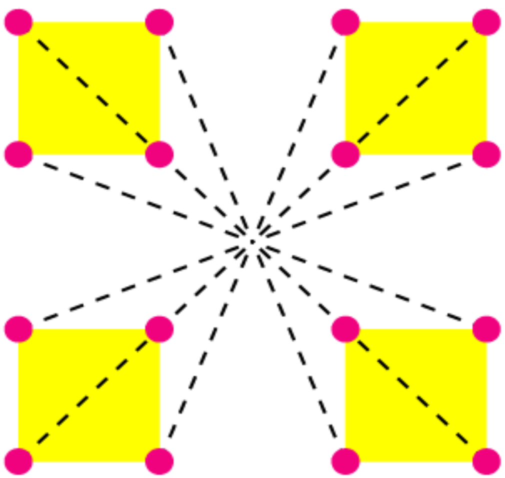
8-QAM



Amplitude
Bit rate: 24
Baud rate: 8
3 bits
3 bits
3 bits
3 bits
3 bits
3 bits
3 bits
3 bits
101
100
001
000
010
011
110
111
Time
1 baud
1 baud
1 baud
1 baud
1 baud
1 baud
1 baud
1 baud
1 s

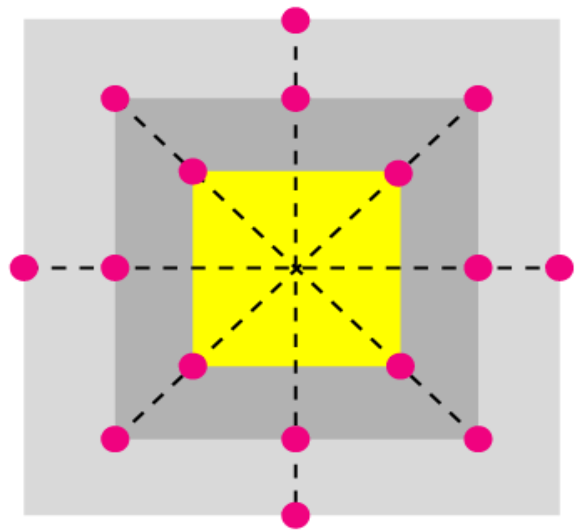
16-QAM

3 amplitudes, 12 phases



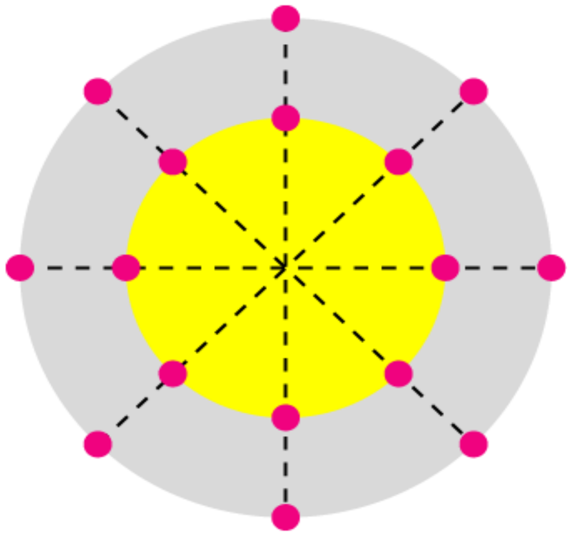
16-QAM

4 amplitudes, 8 phases



16-QAM

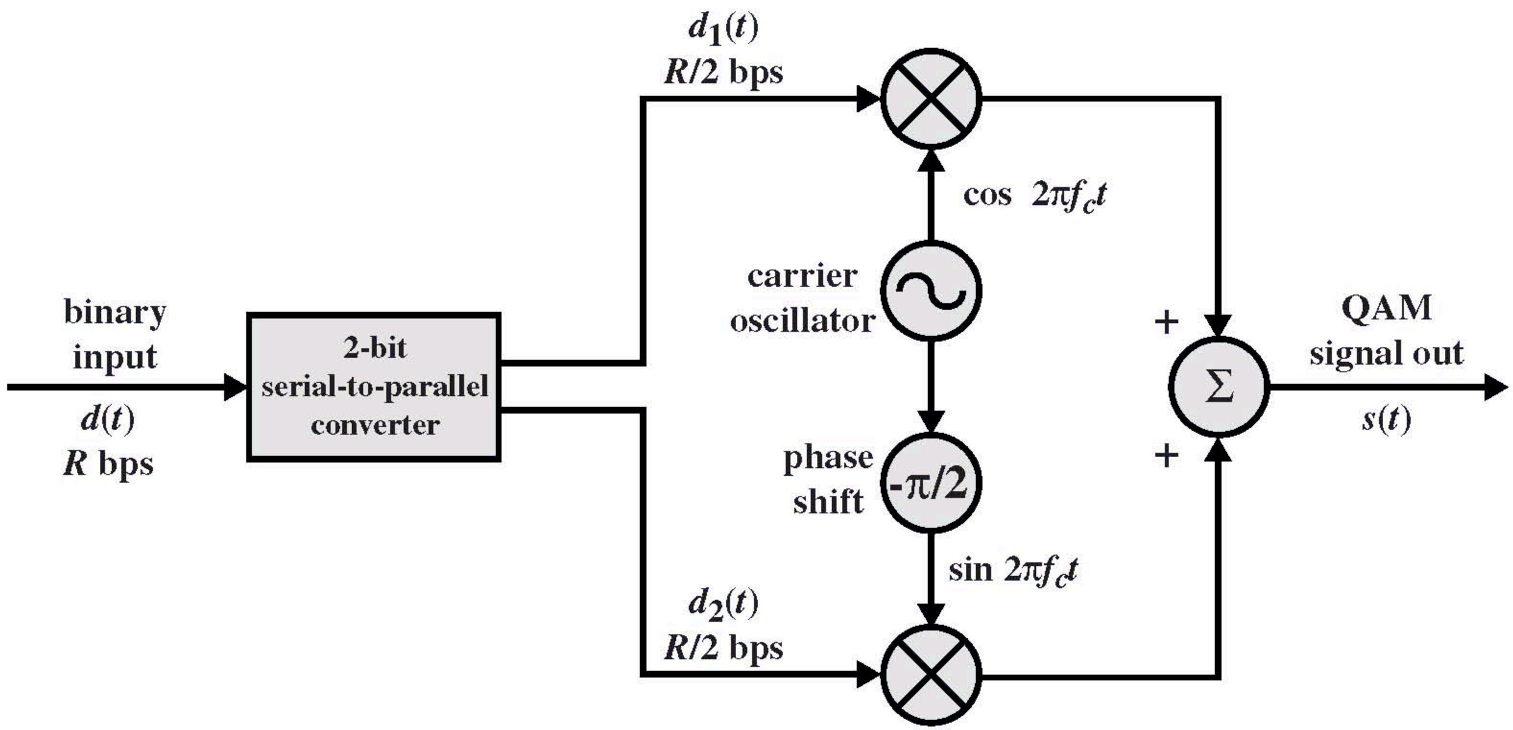
2 amplitudes, 8 phases



16-QAM

Better susceptible to noise because
-Not all possibilities are used
-Sometimes, Amp and Phase have a relationship

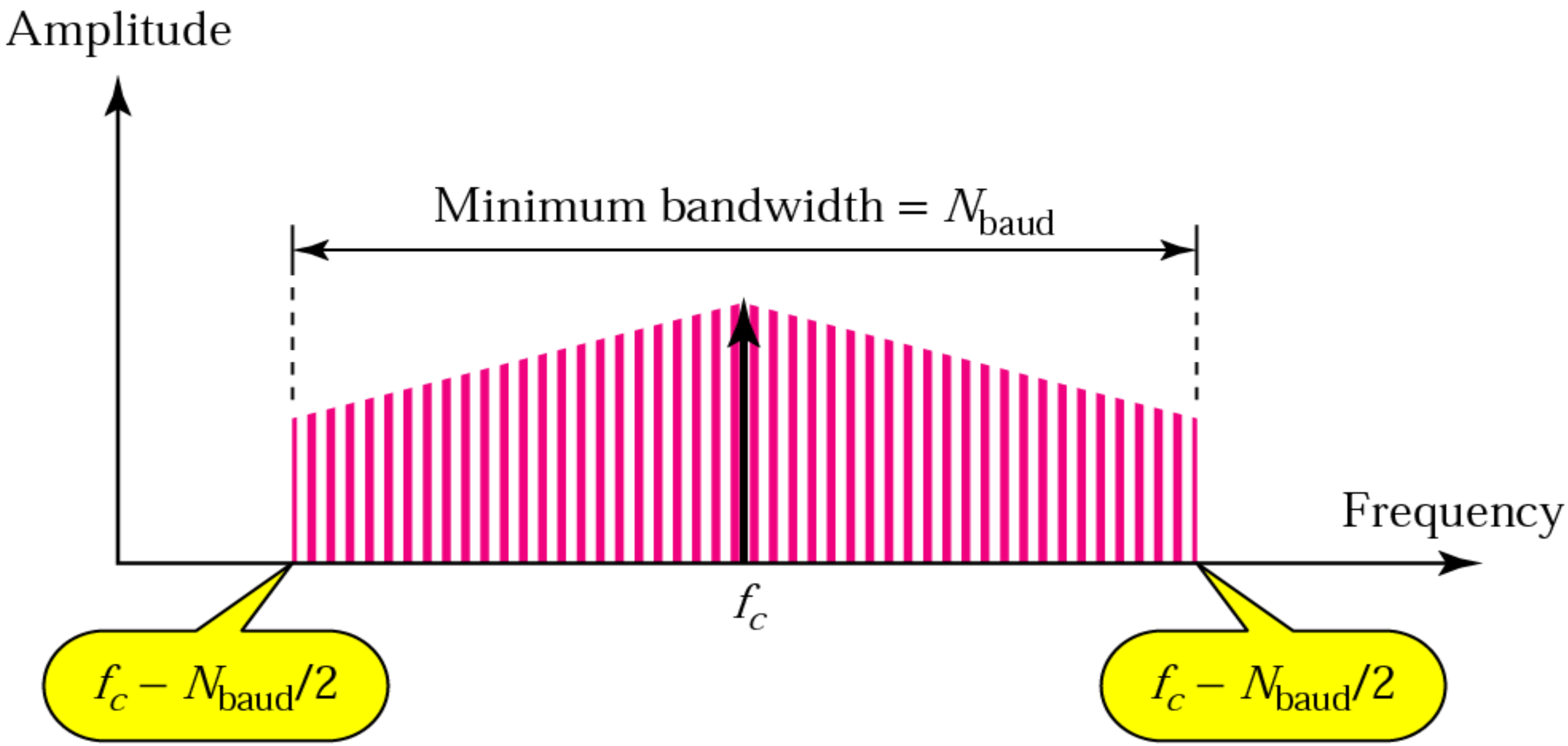
Example: QAM Modulator



$$s(t) = d_1(t)\cos(2\pi f_c t) + d_2(t)\sin(2\pi f_c t)$$

QAM: Bandwidth

Bandwidth requirement is the same as in ASK and PSK

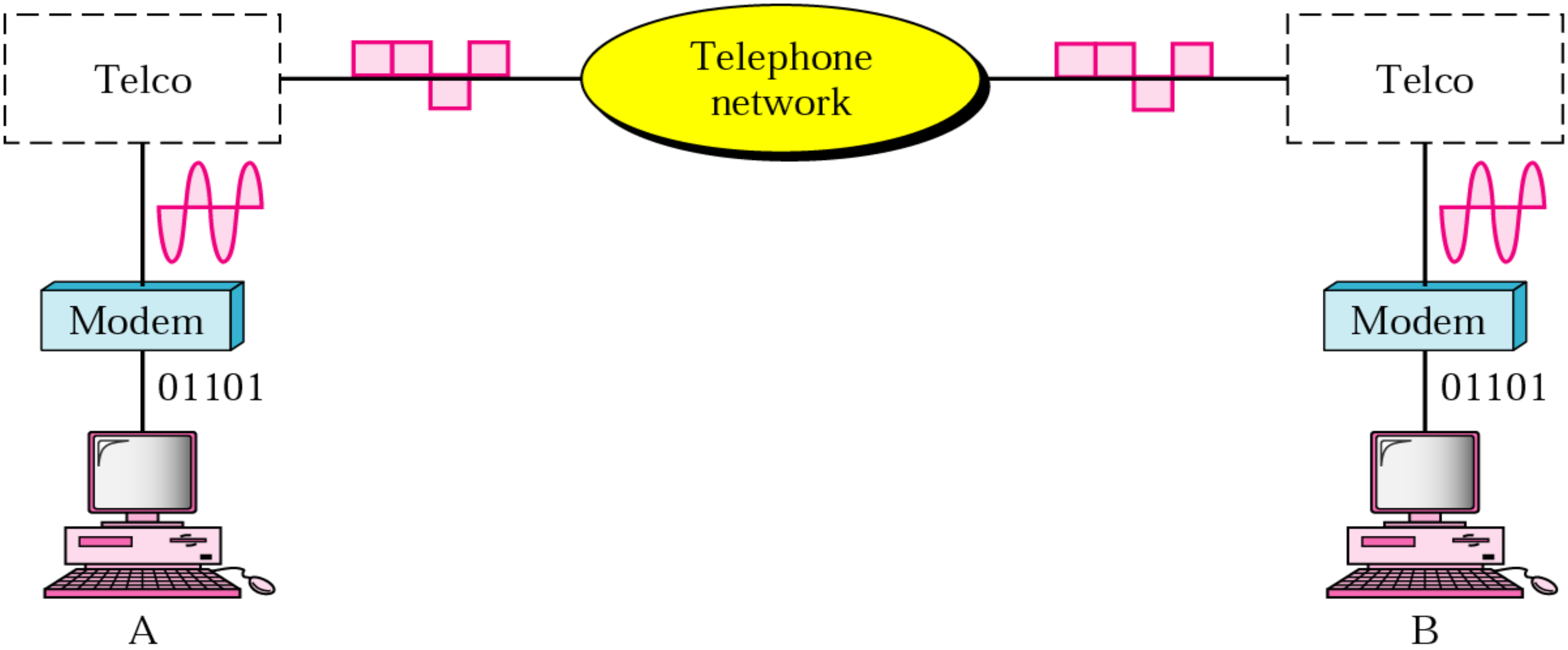


QAM: BitRate vs. Baud Rate

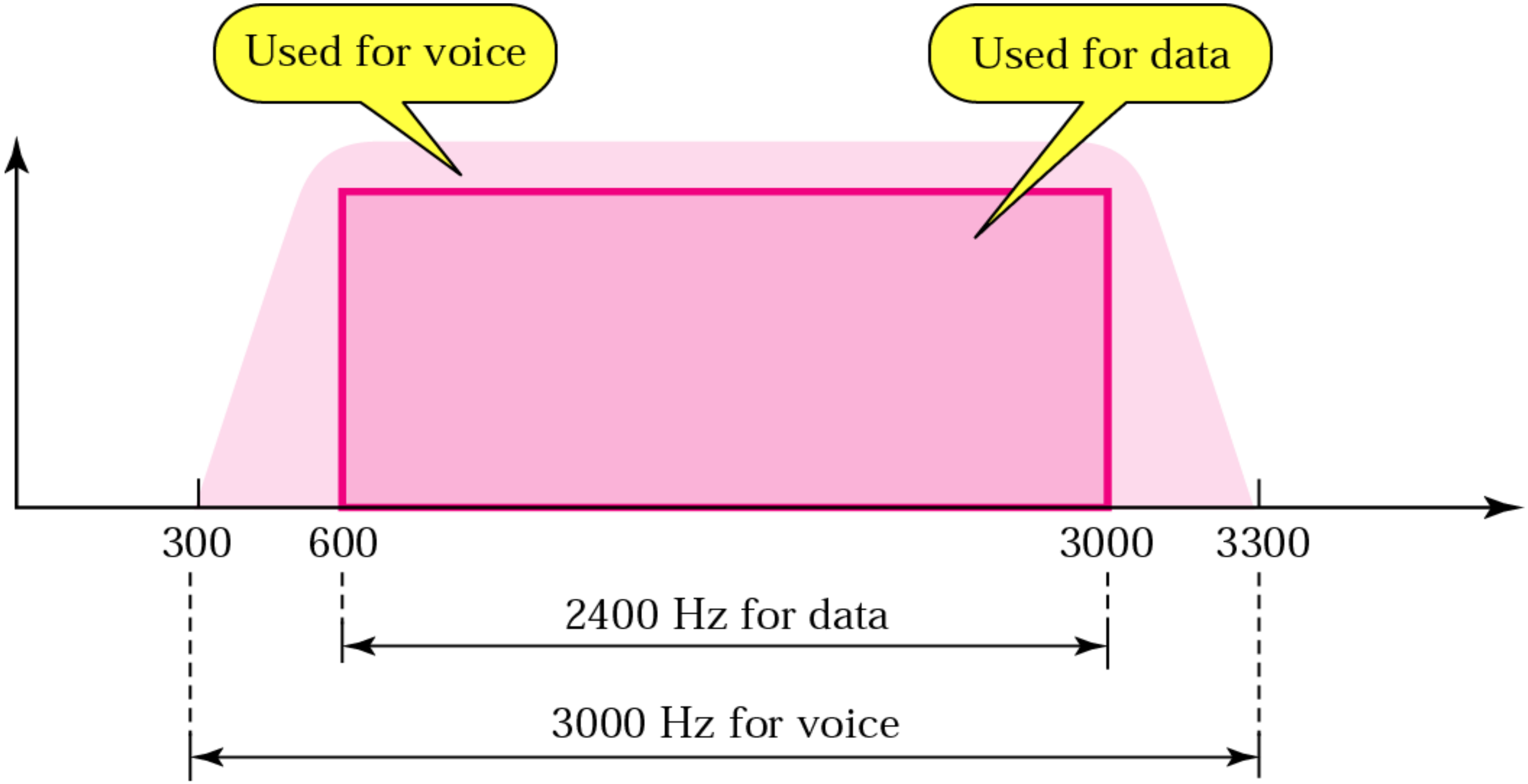
Modulation	Units	Bits/Baud	Baud rate	Bit Rate
ASK, FSK, 2-PSK	Bit	1	N	N
4-PSK, 4-QAM	Dibit	2	N	2N
8-PSK, 8-QAM	Tribit	3	N	3N
16-QAM	Quadbit	4	N	4N
32-QAM	Pentabit	5	N	5N
64-QAM	Hexabit	6	N	6N
128-QAM	Septabit	7	N	7N
256-QAM	Octabit	8	N	8N

Modem Standards

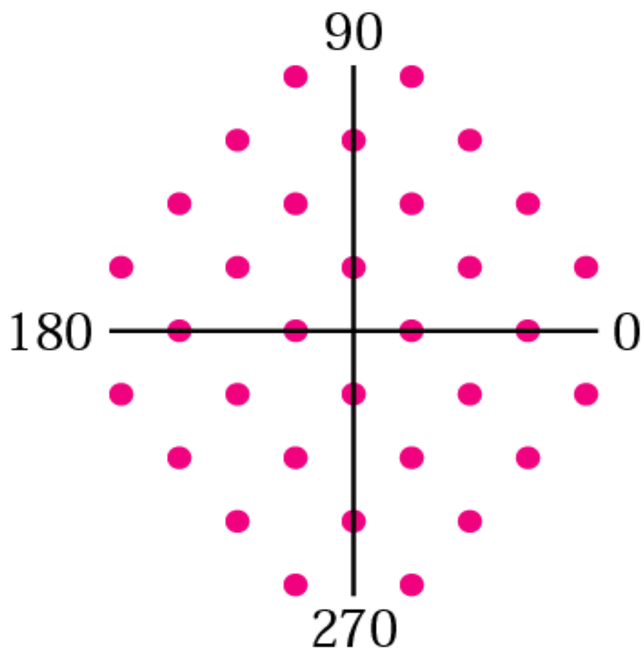
- Modem = Modulator/Demodulator
- Telephone modem:

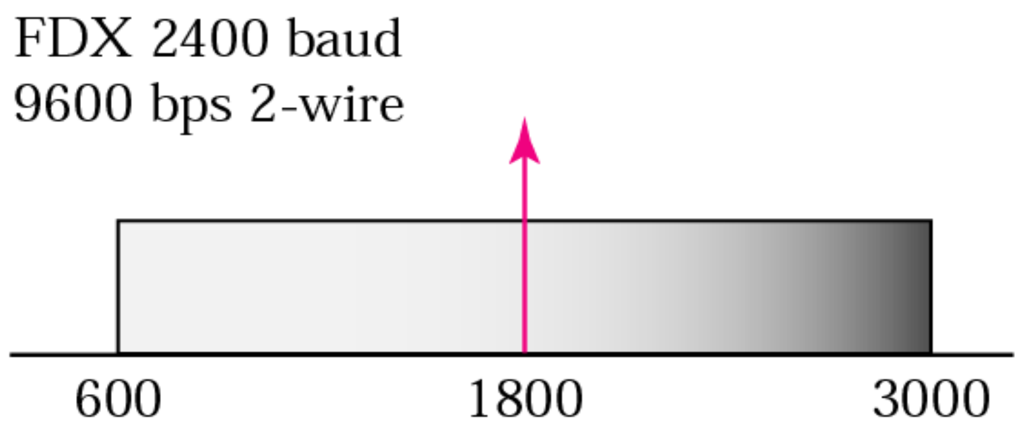


Telephone Line Bandwidth



V.32 Modem



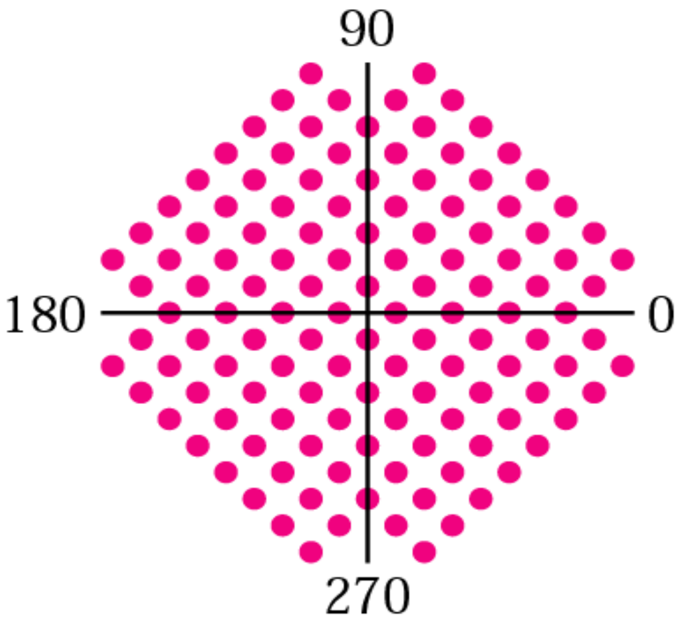


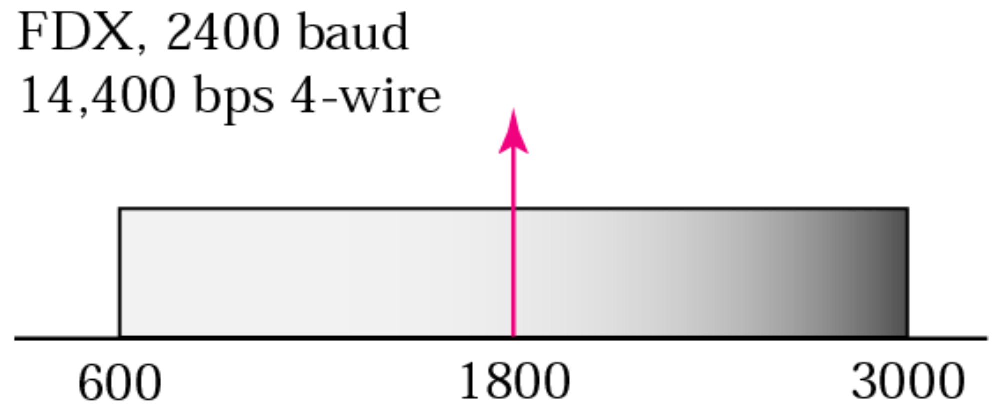
Use 32-QAM

Data is divided into 4-bit sections, each adding a redundant bit to form a 5-bit => reduce value density => reduce noise interference (how?)

baud rate = 2400 (why?)

V.32bis Modem





1st modem standard to support 14,400bps

Can adjust upstream or downstream speed depending on line or signal quality

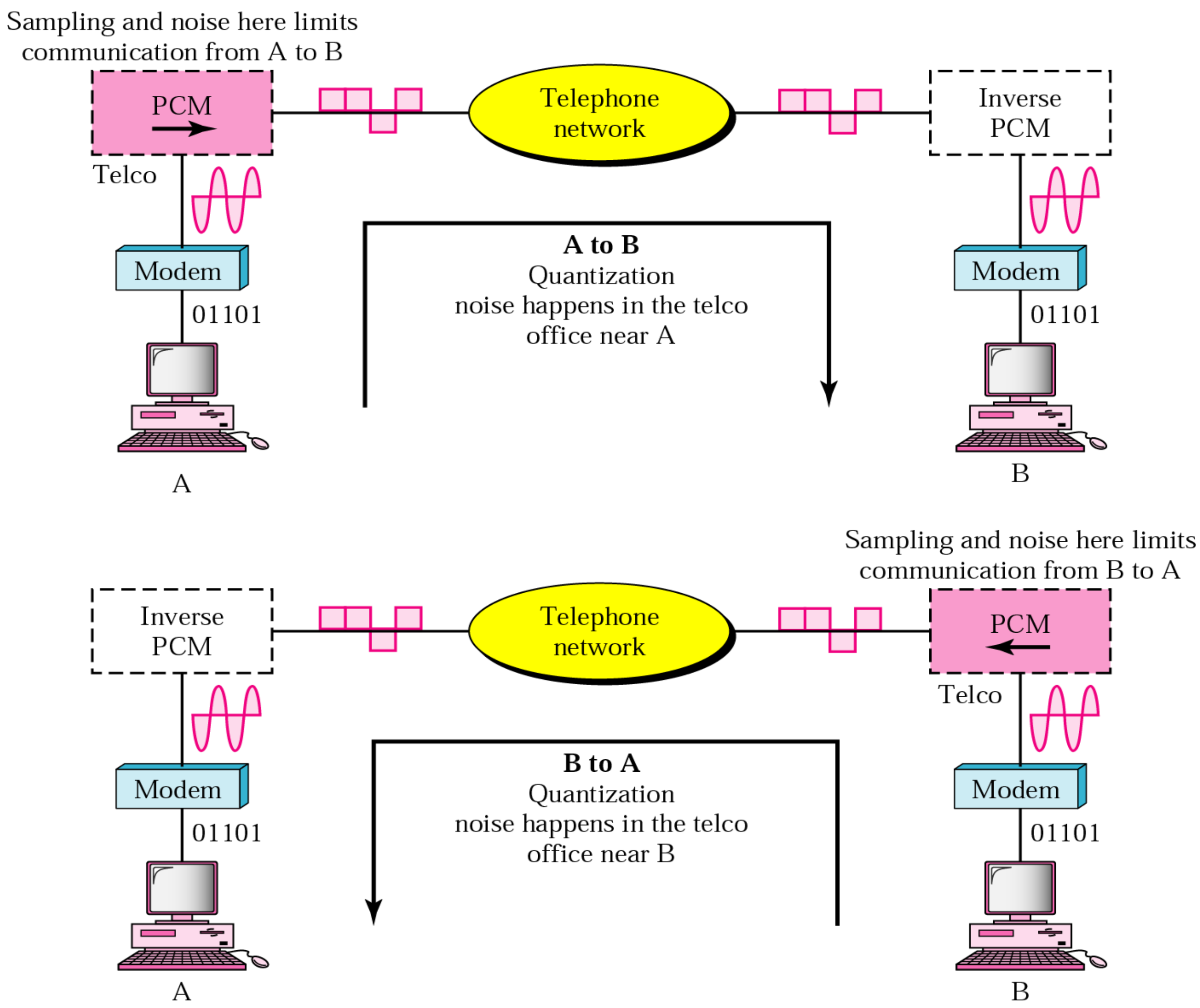
Use 128-QAM => 6-bit data => Bit rate = 14,400 bps

V.34bis Modem

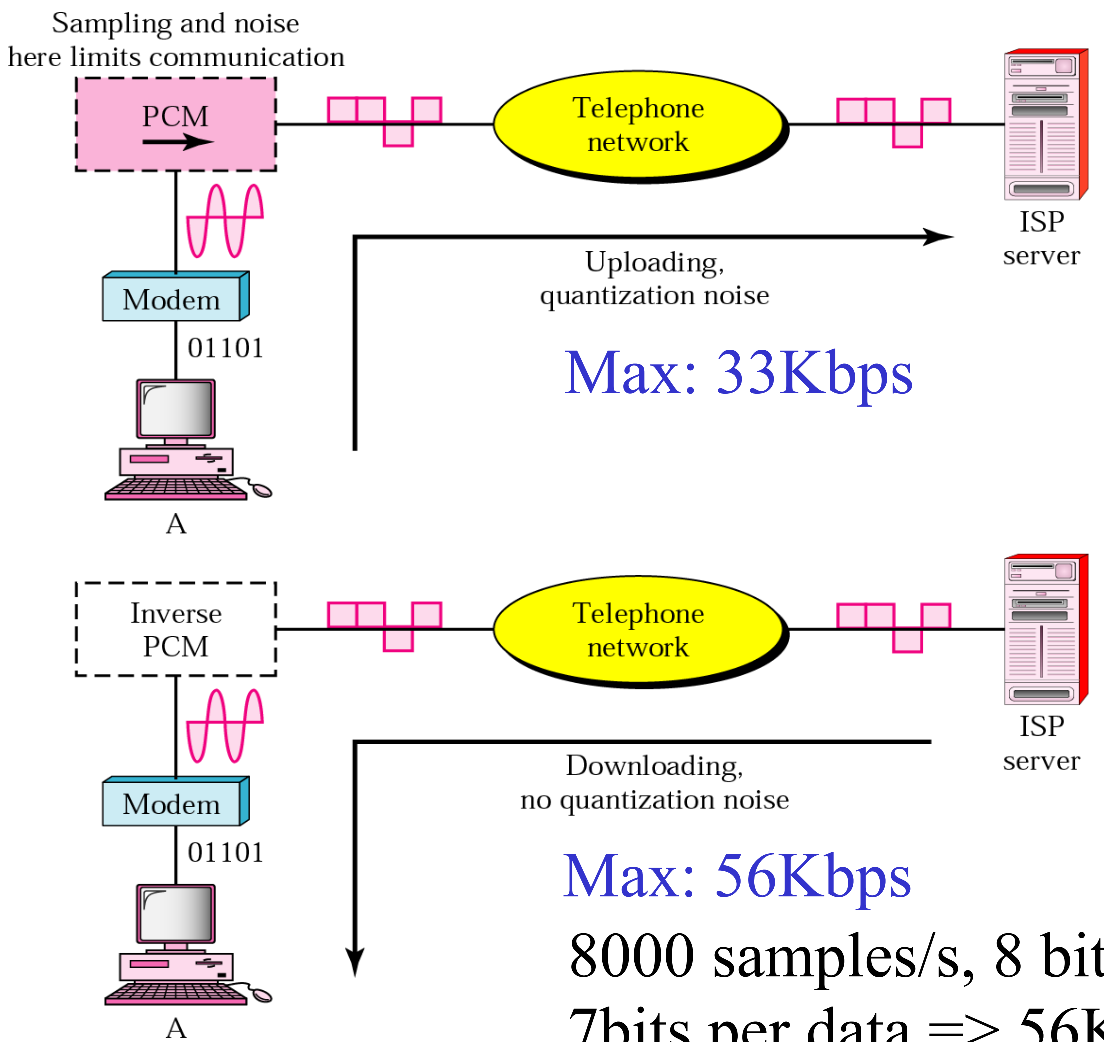
- 960-point constellation => bit rate = 28,800 bps
- 1664-point constellation => bit rate = 33,600 bps

- 33.6Kbps: max bit rate of traditional modems

Traditional Modems



56K Modem: V.90



Max: 33Kbps

Max: 56Kbps

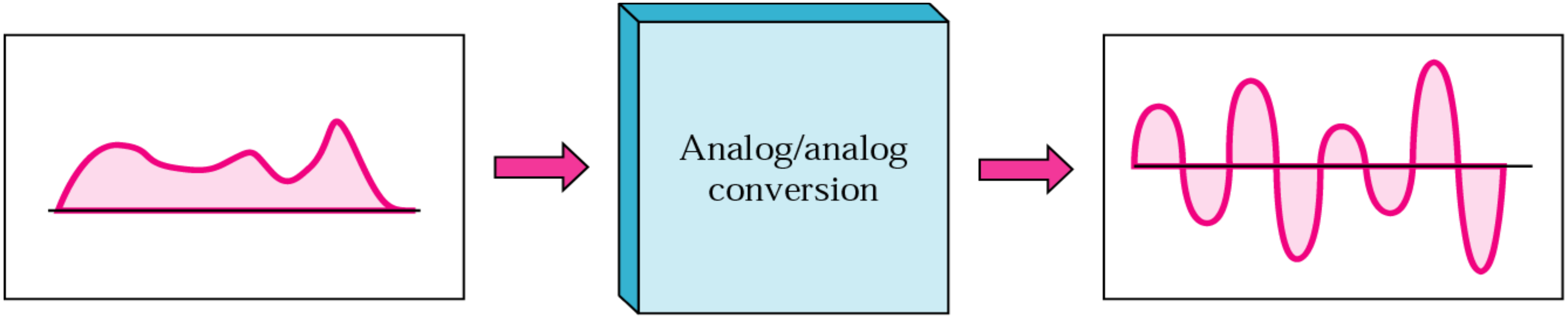
8000 samples/s, 8 bits/sample,
7bits per data => 56Kbps

56K Modem: V.92

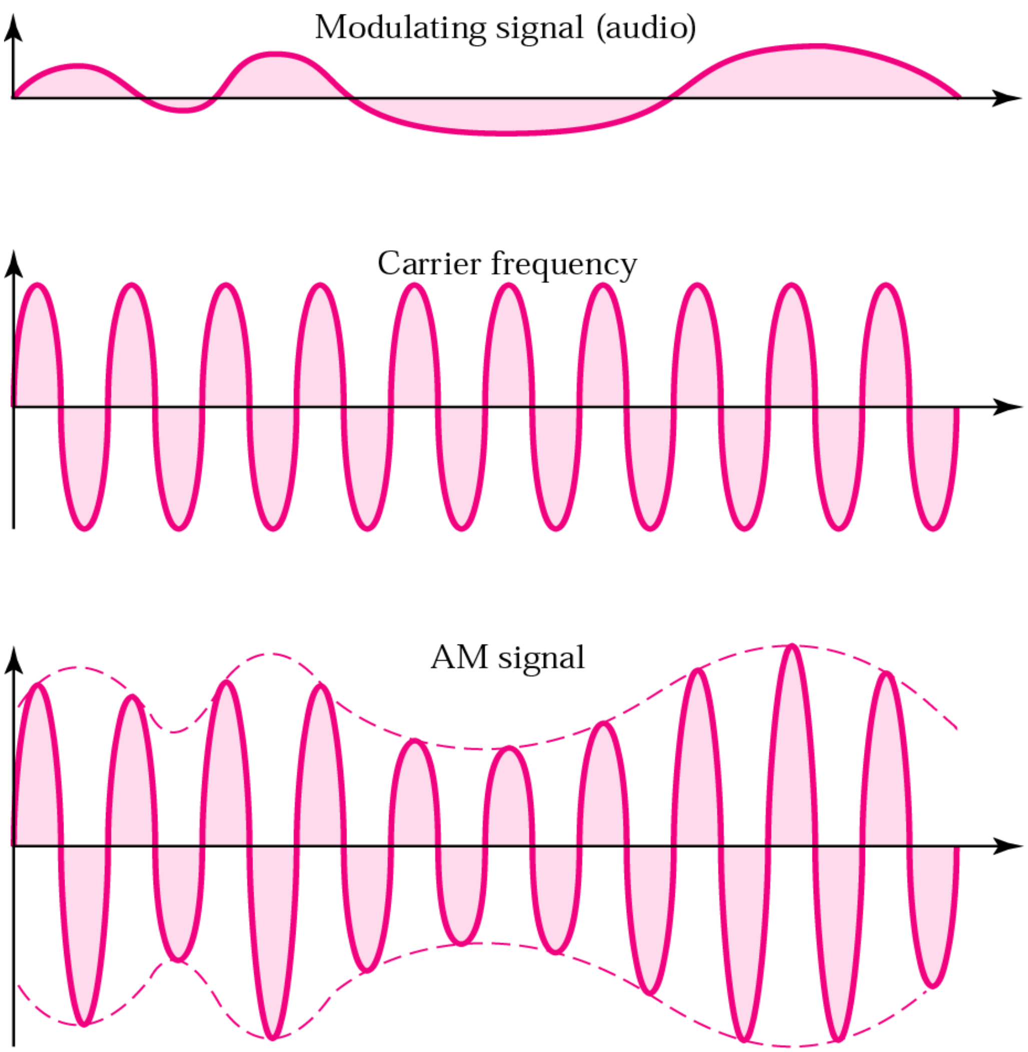
- Similar to V.90
  - Modem can adjust speed
  - If noise allows => upload max 48 Kbps, download still 56 Kbps
- V.92: can interrupt the Internet connection when there is an incoming call (if call-waiting service is installed)

Analog to Analog Modulation

- Representation of analog information by an analog signal
- Why do we need it? Analog is already analog!!!
  - Because we may have to use a band-pass channel
  - Think about radio…
- Schemes
  - Amplitude modulation (AM)
  - Frequency modulation (FM)
  - Phase modulation (PM)



Amplitude Modulation: AM



Carrier signal is modulated so that its amplitude varies with the changing amplitudes of the modulating signal

Freq, phase remain same

$$s(t) = (1+n_a x(t))\cos(2\pi f_c t)$$

Example: AM

- Let $x(t) = \cos(2\pi f_m t)$
- Derive an express for s(t)

Answer:

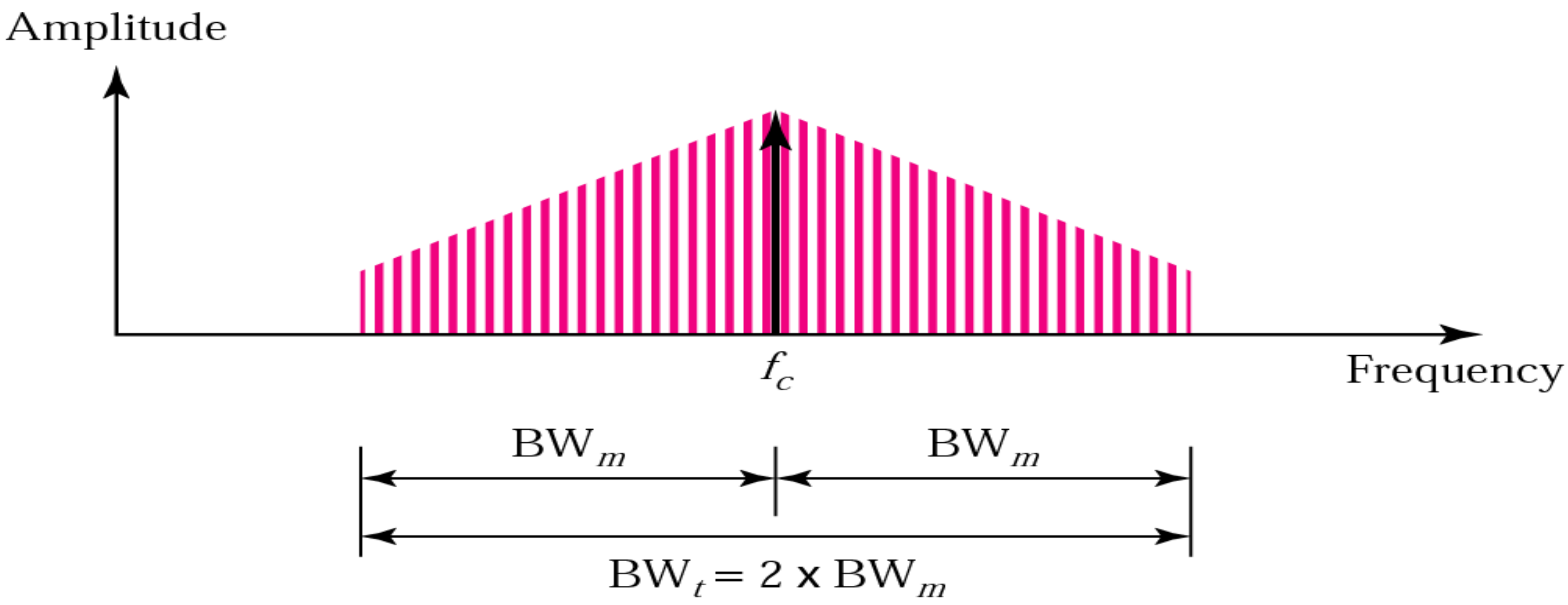
$s(t) = \cos(2\pi f_c t) + (n_a/2)\cos(2\pi(f_c - f_m)t) + (n_a/2)\cos(2\pi(f_c+f_m)t)$

AM: Bandwidth

BW_m = bandwidth of the modulating signal (audio)

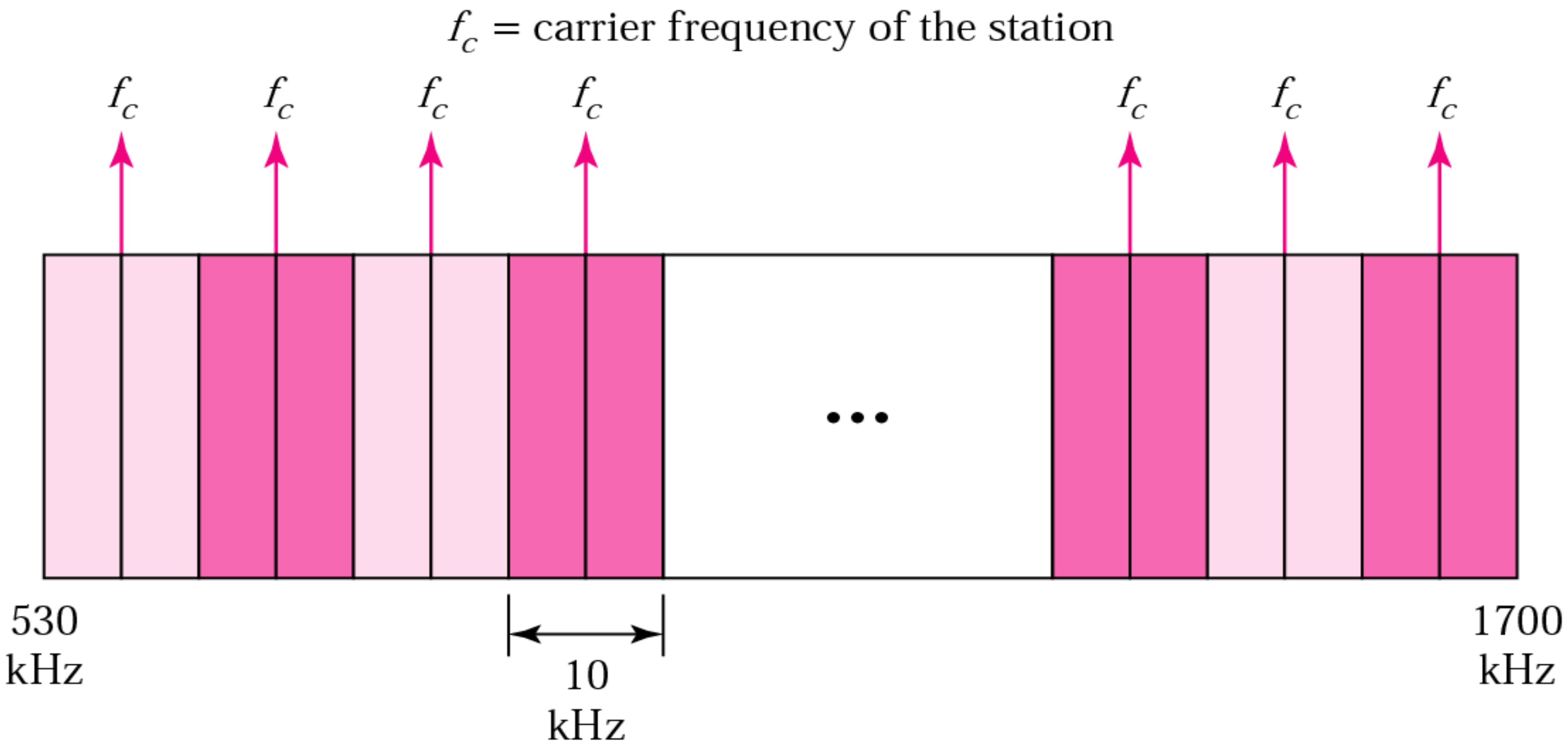
BW_t = total bandwidth (radio)

f_c = frequency of the carrier

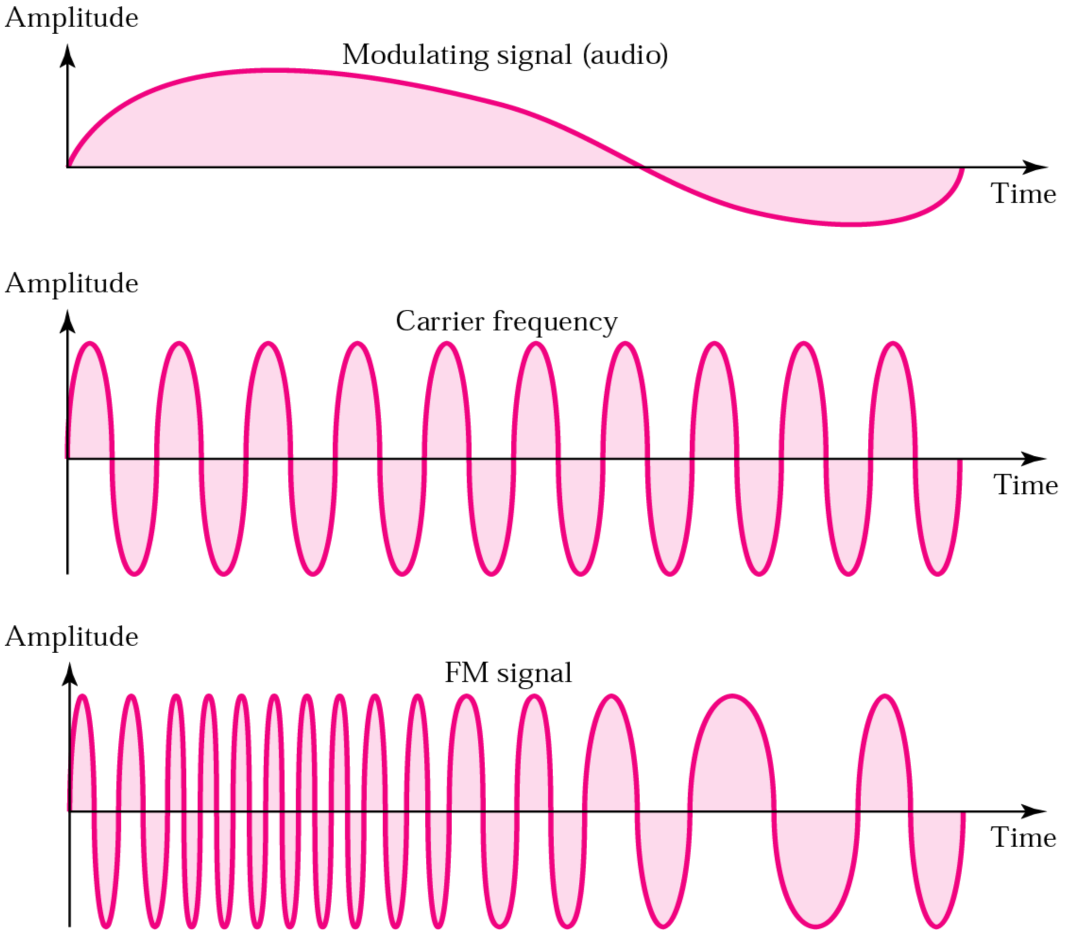


Audio signal bandwidth is ~5Khz => an AM radio station needs a minimum 10Khz

AM Band Allocation



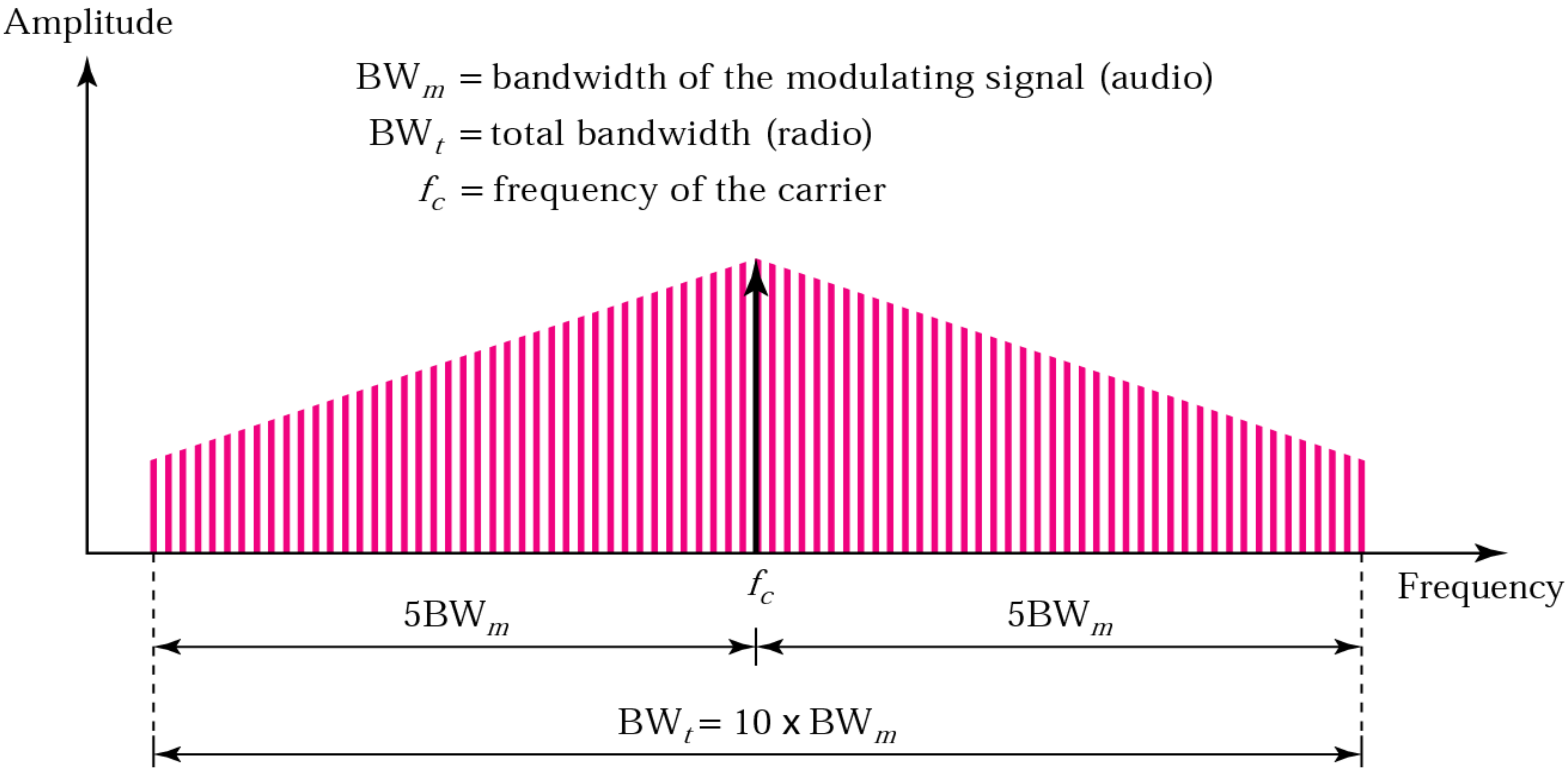
Frequency Modulation: FM



Freq. of carrier signal is modified to reflect the changing amplitudes of the modulating signal

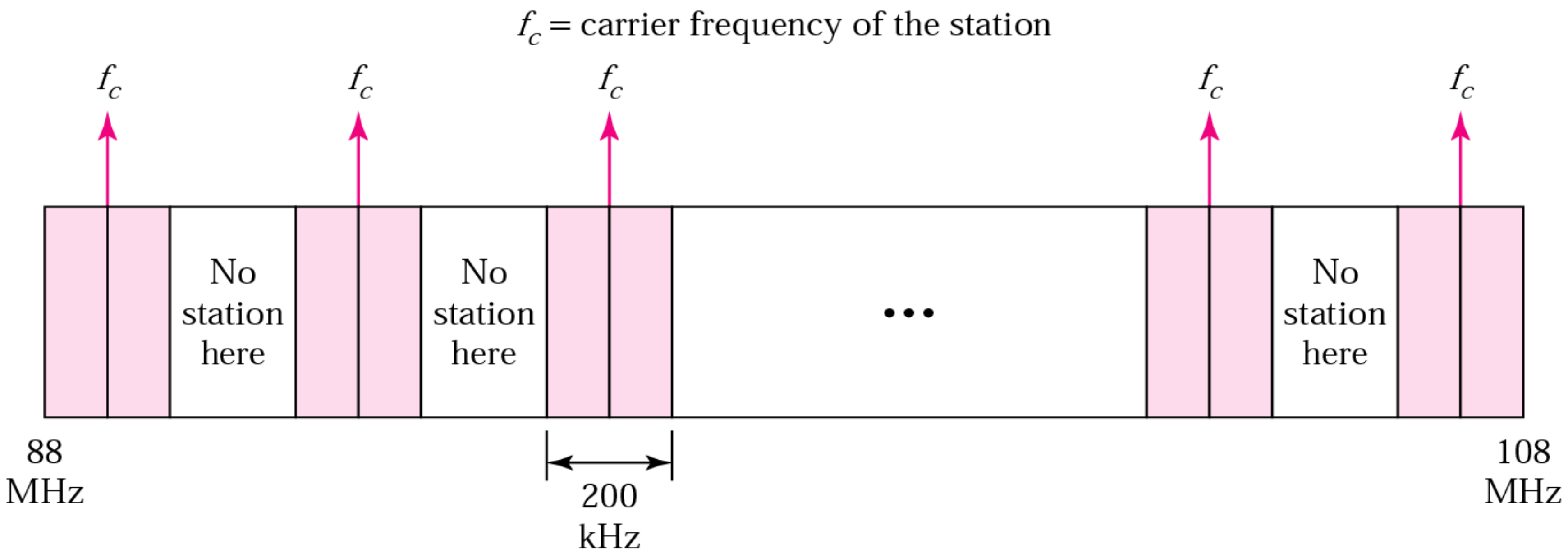
Amp., phase remain same

FM: Bandwidth



The bandwidth of a stereo audio signal is usually 15 KHz. Therefore, an FM station needs at least a bandwidth of 150 KHz. The FCC requires the minimum bandwidth to be at least 200 KHz (0.2 MHz).

FM Band Allocation



In some areas, FCC requires that only alternate bandwidth allocations be used

Question: how FM many stations can operate at any one time?

Phase Modulation: PM

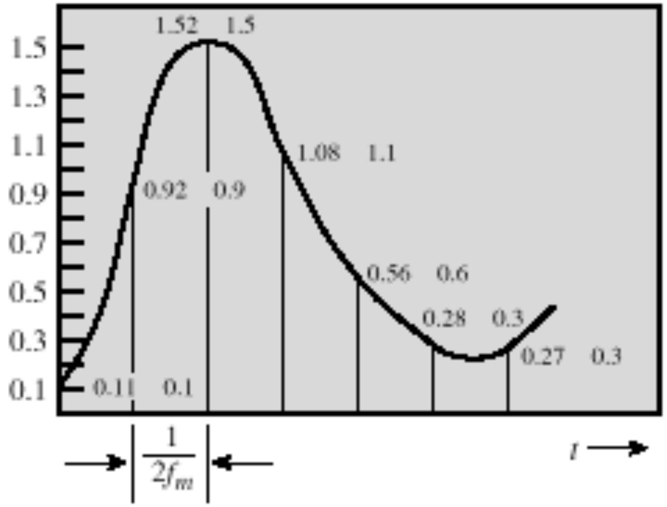
- Only phase is varied to reflect the change of amplitude in modulating signal
- Require simpler hardware than FM
  - Use in some systems as an alternative to FM

Analog Data to Digital Signal

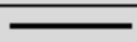
- Once analog data have been converted to digital signals, the digital data:
  - can be transmitted using NRZ-L
  - can be encoded as a digital signal using a code other than NRZ-L
  - can be converted to an analog signal, using previously discussed techniques

Pulse Code Modulation

- Based on the sampling theorem
- Each analog sample is assigned a binary code
  - Analog samples are referred to as pulse amplitude modulation (PAM) samples
- The digital signal consists of block of *n* bits, where each *n*-bit number is the amplitude of a PCM pulse



(a)

Digit	Binary Equivalent	PCM waveform
0	0000	
1	0001	
2	0010	
3	0011	
4	0100	
5	0101	
6	0110	
7	0111	

Digit	Binary Equivalent	PCM waveform
8	1000	
9	1001	
10	1010	
11	1011	
12	1100	
13	1101	
14	1110	
15	1111	

Figure 6.15 Pulse-Code Modulation

Pulse Code Modulation

- By quantizing the PAM pulse, original signal is only approximated
- Leads to quantizing noise
- Signal-to-noise ratio for quantizing noise

$$\mathrm{SNR}_{\mathrm{dB}} = 20\log 2^{n} + 1.76\ \mathrm{dB} = 6.02n + 1.76\ \mathrm{dB}$$

- Thus, each additional bit increases SNR by 6 dB, or a factor of 4

Delta Modulation

- Analog input is approximated by staircase function
  - Moves up or down by one quantization level (δ) at each sampling interval
- The bit stream approximates derivative of analog signal (rather than amplitude)
  - 1 is generated if function goes up
  - 0 otherwise

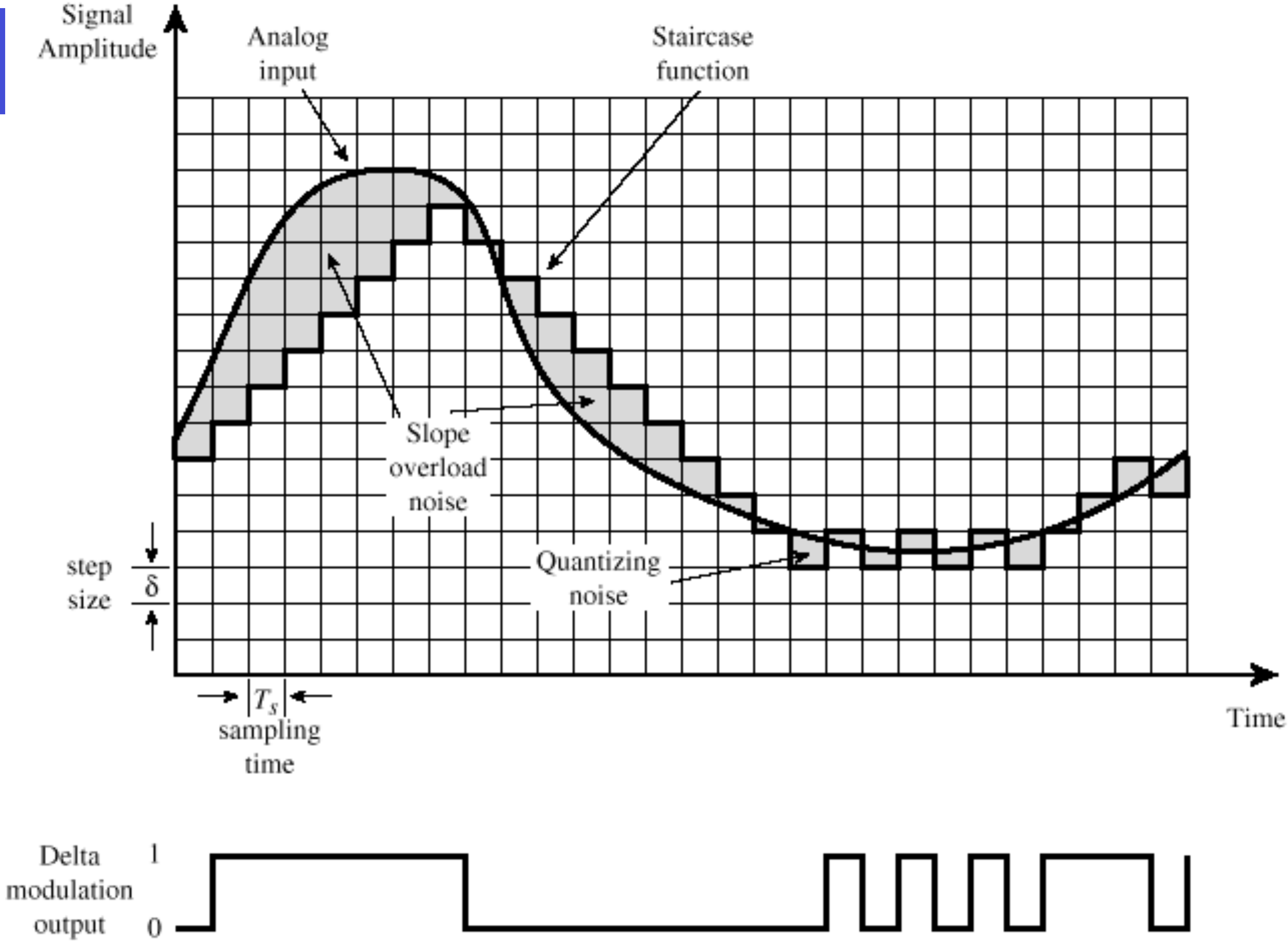


Figure 6.18 Example of Delta Modulation

Delta Modulation

- Two important parameters
  - Size of step assigned to each binary digit (δ)
  - Sampling rate
- Accuracy improved by increasing sampling rate
  - However, this increases the data rate
- Advantage of DM over PCM is the simplicity of its implementation

Reasons for Digital Techniques

- Growth in popularity of digital techniques for sending analog data
  - Repeaters are used instead of amplifiers
    - No additive noise
  - TDM is used instead of FDM
    - No intermodulation noise
  - Conversion to digital signaling allows use of more efficient digital switching techniques

Spread Spectrum

- Spread the information signal over a wider bandwidth to make jamming and interception more difficult
  - Initially purposed for military and intelligence requirements
- Can transmit either analog or digital data using an analog signal

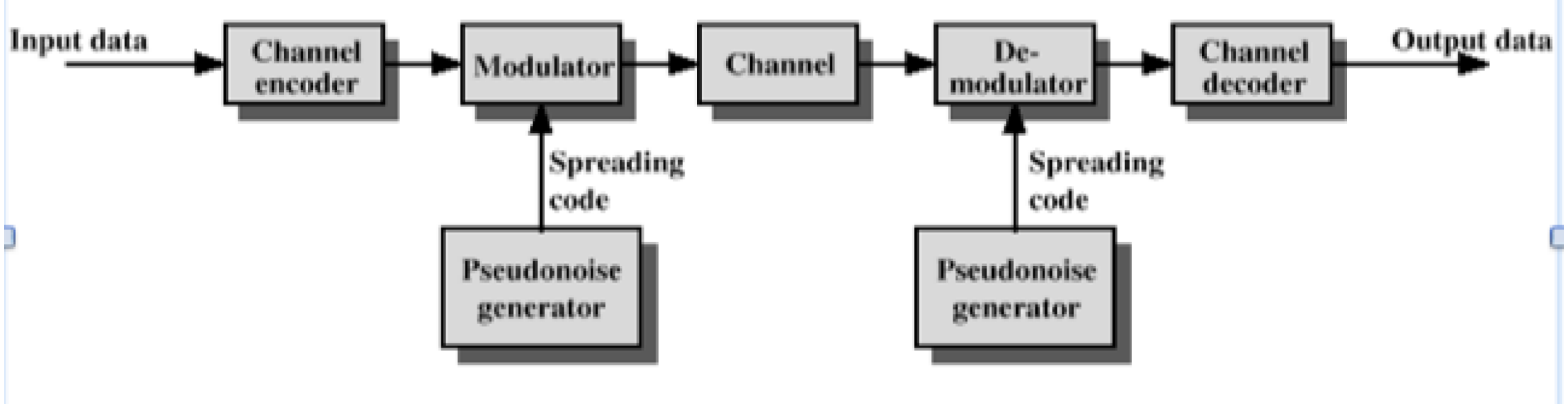
Spread Spectrum

<u>Sending</u>

- Feed signal into a channel encoder
  - To produce analog signal with narrow bandwidth around some center frequency
- Modulation using a sequence of digits
  - Spreading code or spreading sequence
  - Generated by pseudonoise, or pseudo-random number generator
  - <u>Purpose</u>: to increase bandwidth of signal to be transmitted

<u>Receiving</u>

- Digit sequence is used to demodulate the spread spectrum signal
- Signal is fed into a channel decoder to recover data



Why Waste of Spectrum?

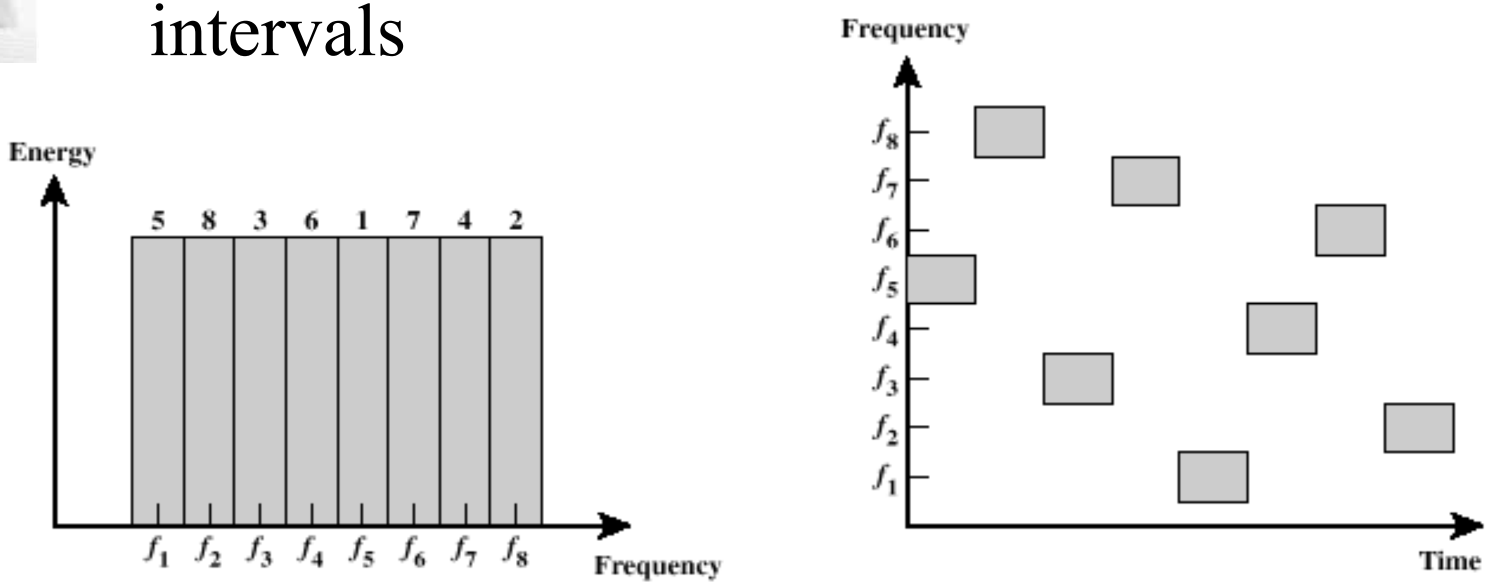
- Immunity from various kinds of noise and multipath distortion
- Can be used for hiding and encrypting signals
- Several users can independently use the same higher bandwidth with very little interference

UMASS BOSTON

Frequency Hopping Spread Spectrum (FHSS)

Hedy Lamarr
(1913-2000)

- Invented by actress Hedy Lamarr at age 26
- Signal is broadcast over seemingly random series of radio frequencies
- Signal hops from freq to freq at fixed intervals



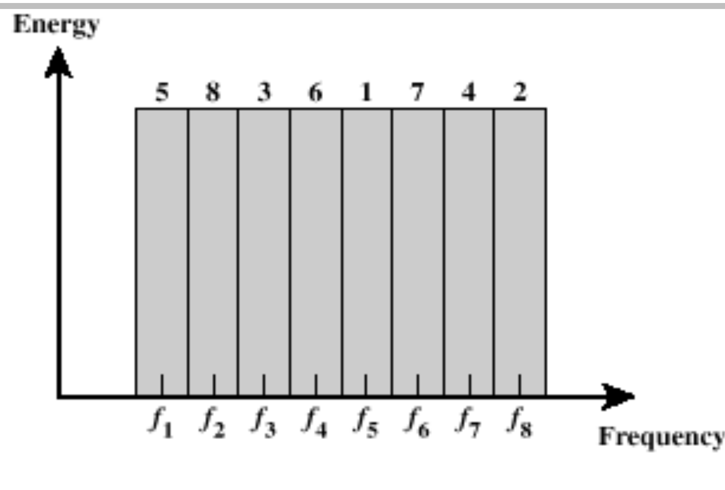
(a) Channel assignment

(b) Channel use

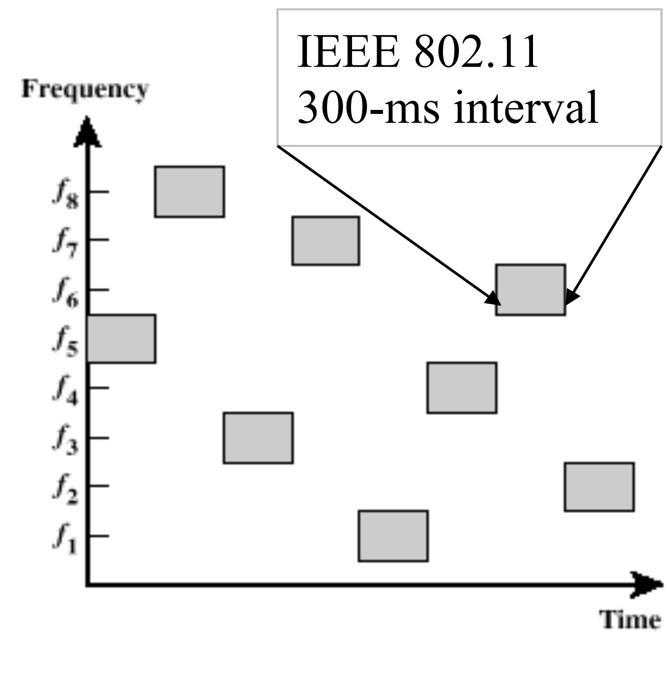
Frequency Hopping Spread Spectrum (FHSS)

- Channel sequence dictated by spreading code
- Receiver, hopping between frequencies in synchronization with transmitter, picks up message

- Eavesdroppers hear only unintelligible blips
- Attempts to jam signal on one frequency succeed only at knocking out a few bits



(a) Channel assignment



(b) Channel use

FHSS Using MFSK

- MFSK signal is translated to a new frequency every T_c seconds by modulating the MFSK signal with the FHSS carrier signal
- For data rate of *R:*
  - duration of a bit: $T = 1/R$ seconds
  - duration of signal element: $T_s = LT$ seconds
- $T_c \geq T_s$ - slow-frequency-hop spread spectrum
- $T_c < T_s$ - fast-frequency-hop spread spectrum

MFSK

- One signal element encodes L bits
- Element interval = $T_s = LT$ seconds
  - where T is the bit period (data rate = $1/T$)
- Total bandwidth required $2Mf_d$
- Minimum frequency separation required $2f_d = 1/T_s$

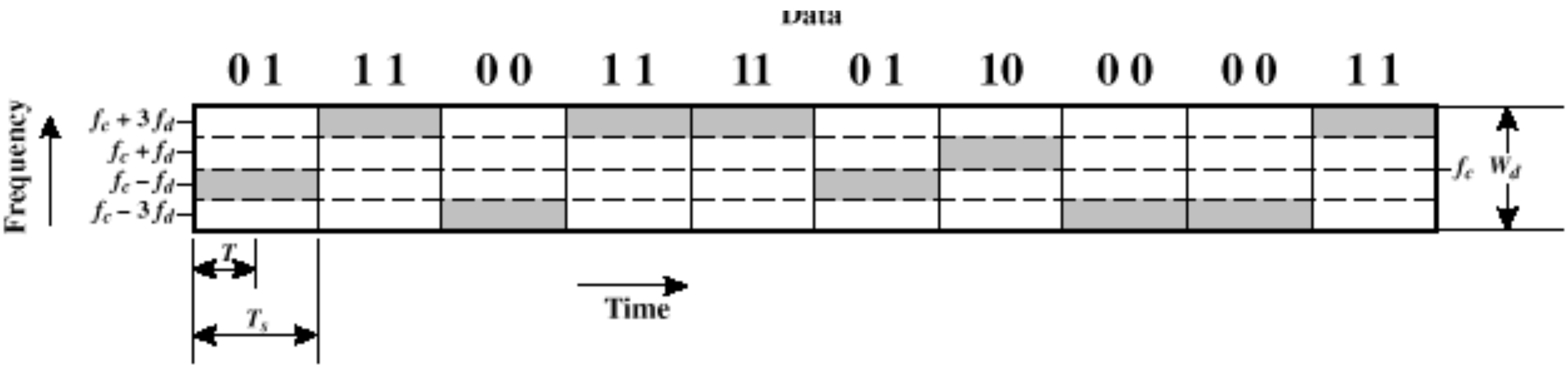
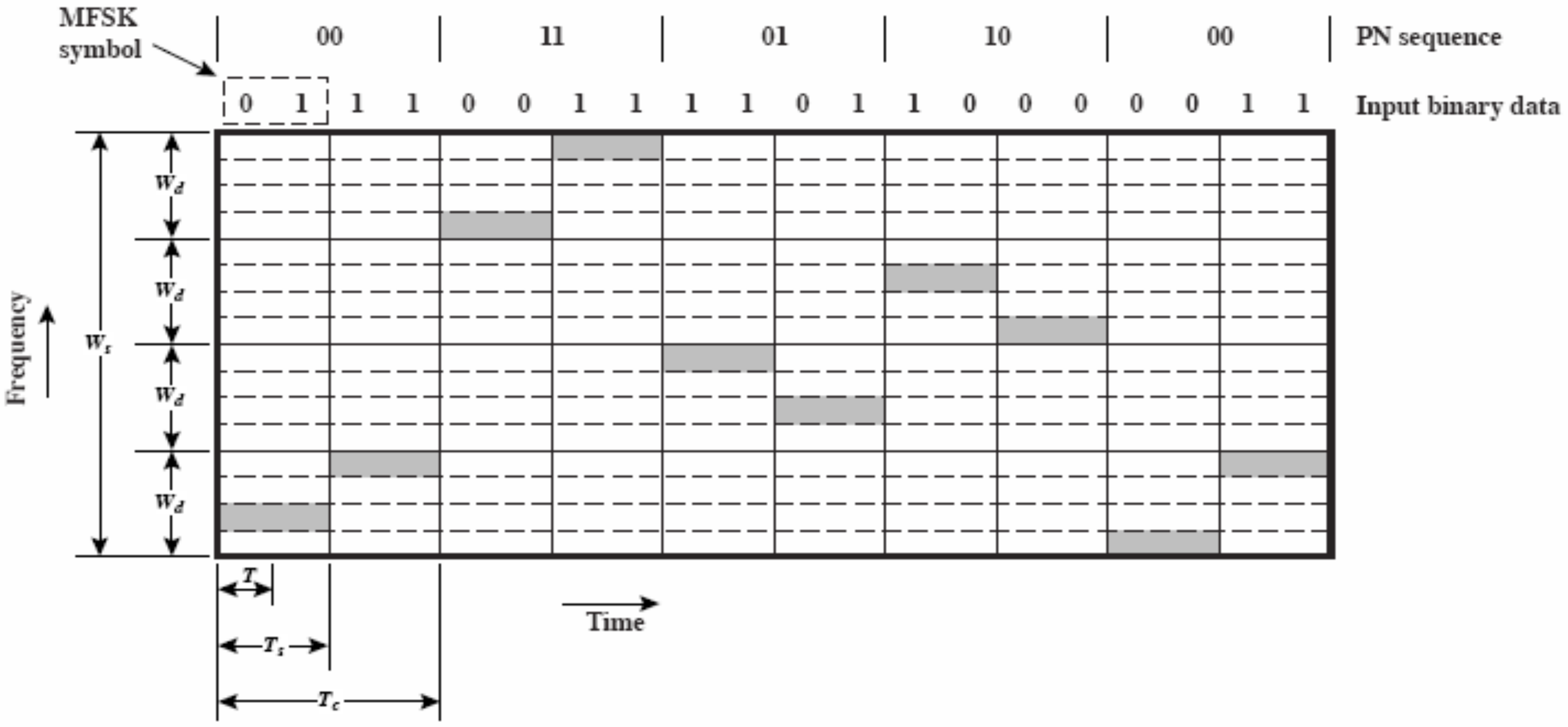


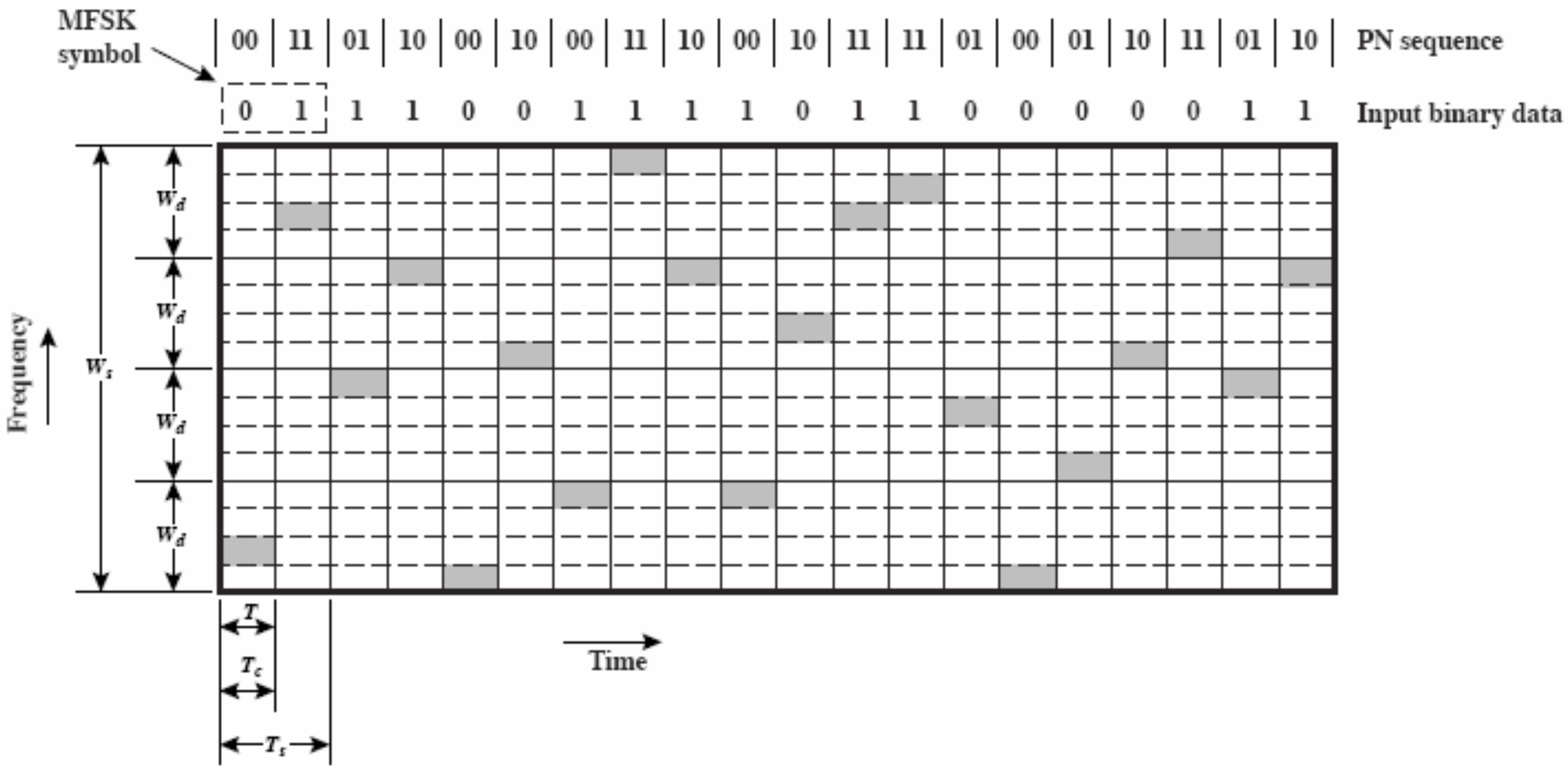
Figure 6.4 MFSK Frequency Use ($M = 4$)

FHSS + MFSK Example 1



Slow Frequency Hop Spread Spectrum Using MFSK ($M = 4$, $k = 2$)

FHSS + MFSK Example 2



Fast Frequency Hop Spread Spectrum Using MFSK ($M = 4$, $k = 2$)

FHSS Performance Considerations

- Large number of frequencies used
- Results in a system that is quite resistant to jamming
  - Jammer must jam all frequencies
  - With fixed power, this reduces the jamming power in any one frequency band

Direct Sequence Spread Spectrum (DSSS)

- Each bit in original signal is represented by multiple bits in the transmitted signal
- Spreading code spreads signal across a wider frequency band
  - Spread is in direct proportion to number of bits used
  - E.g., a 10-bit code spreads the signal to a band 10 times larger than a 1-bit code
- One technique combines digital information stream with the spreading code bit stream using exclusive-OR

DSSS: using XOR

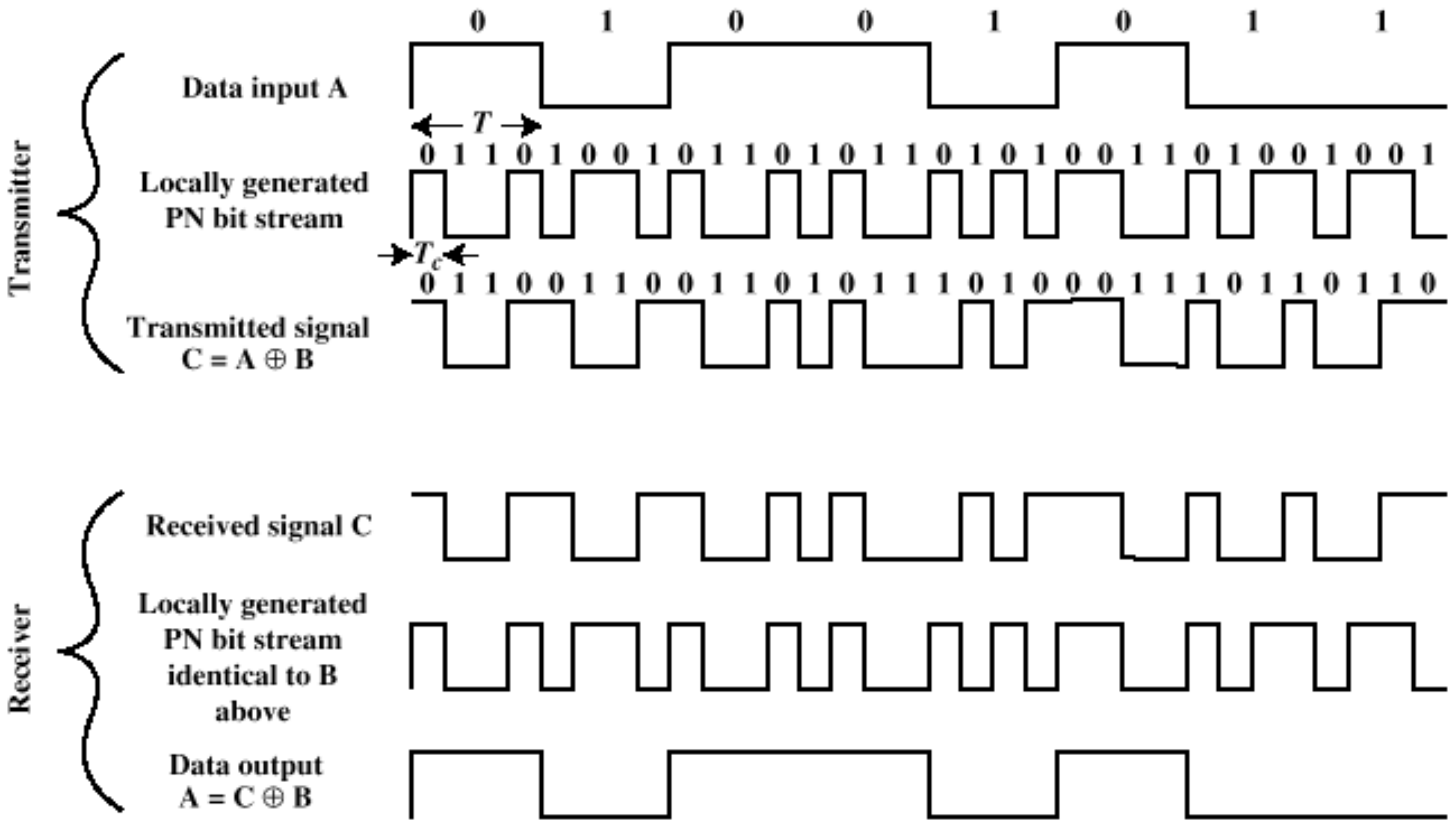


Figure 7.6 Example of Direct Sequence Spread Spectrum

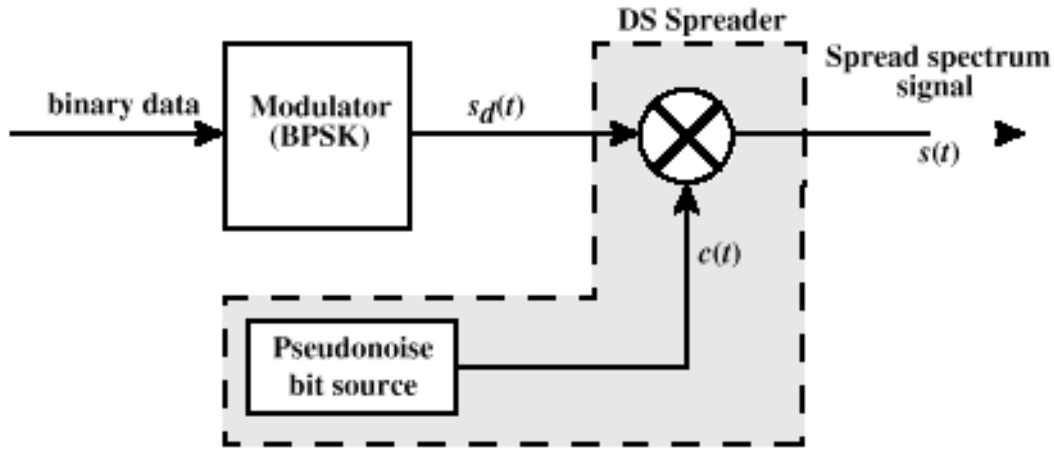
DSSS Using BPSK

- Information signal d(t) [sequence of +1 as 1 and -1 as 0]
- BPSK signal $s_d(t) = A\, d(t) \cos(2\pi f_c t)$
  - A = amplitude of signal
  - f_c = carrier frequency
  - d(t) = discrete function [+1, -1]
- PN sequence $c(t)$ [takes values +1, -1]

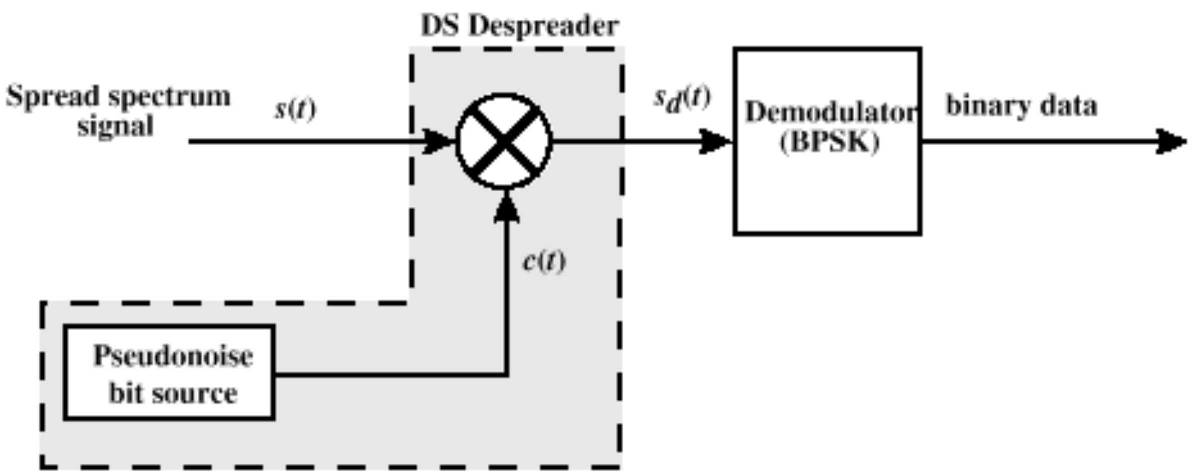
- At sender: $s(t) = s_d(t)\, c(t)$

- At receiver, multiply s(t) with c(t) to get original information

DSSS Using BPSK

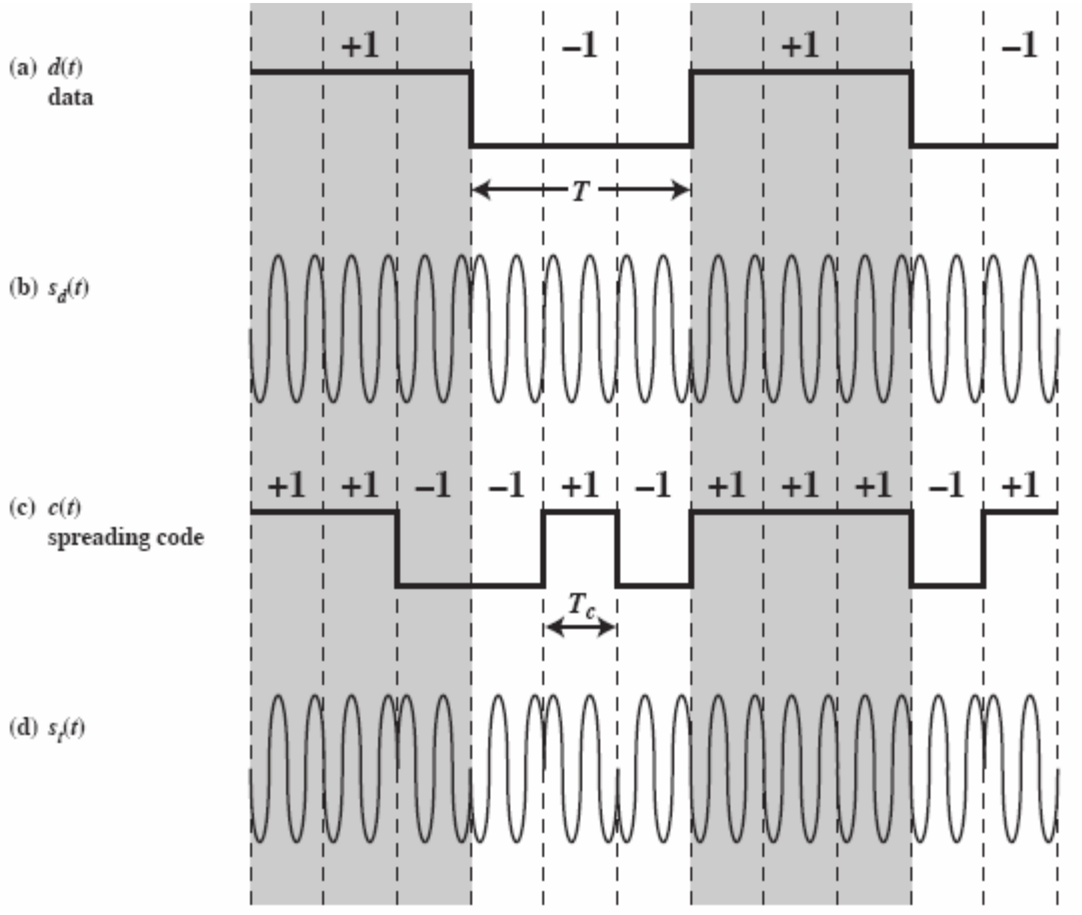


(a) Transmitter



(b) Receiver

DSSS+BPSK: Example



Example of Direct-Sequence Spread Spectrum Using BPSK

Code-Division Multiple Access (CDMA)

- Basic Principles of CDMA
  - D = rate of data signal
  - Break each bit into k *chips*
    - Chips are a user-specific fixed pattern
  - Chip data rate of new channel = kD

CDMA Example

- If *k*=6 and code is a sequence of 1s and -1s
  - For a '1' bit, A sends code as chip pattern
    - <c1, c2, c3, c4, c5, c6>
  - For a '0' bit, A sends complement of code
    - <-c1, -c2, -c3, -c4, -c5, -c6>
- Receiver knows sender's code and performs electronic decode function

$$S_u(d) = d1 \times c1 + d2 \times c2 + d3 \times c3 + d4 \times c4 + d5 \times c5 + d6 \times c6$$

- <d1, d2, d3, d4, d5, d6> = received chip pattern
- <c1, c2, c3, c4, c5, c6> = sender's code

CDMA Example

- User A code = <1, –1, –1, 1, –1, 1>
  - To send a 1 bit = <1, –1, –1, 1, –1, 1>
  - To send a 0 bit = <–1, 1, 1, –1, 1, –1>
- User B code = <1, 1, –1, – 1, 1, 1>
  - To send a 1 bit = <1, 1, –1, –1, 1, 1>
- Receiver receiving with A's code
  - (A's code) x (received chip pattern)
    - User A '1' bit: 6 -> 1
    - User A '0' bit: -6 -> 0
    - User B '1' bit: 0 -> unwanted signal ignored

Orthogonal Codes

- Orthogonal codes
  - All pairwise cross correlations are zero
  - Fixed- and variable-length codes used in CDMA systems
  - For CDMA application, each mobile user uses one sequence in the set as a spreading code
    - Provides zero cross correlation among all users
- Types
  - Walsh codes
  - Variable-Length Orthogonal codes

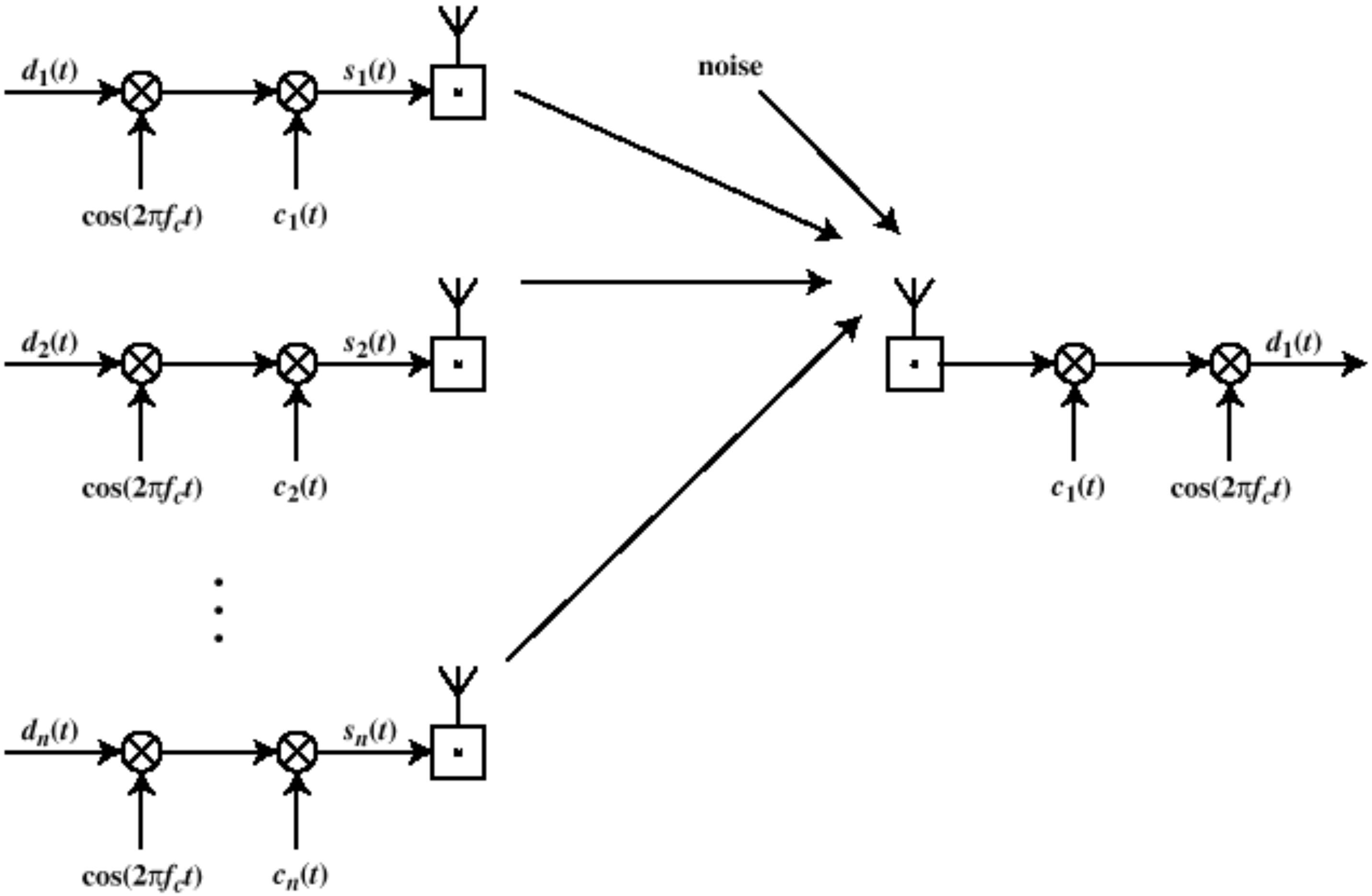
Walsh Codes

- Set of Walsh codes of length *n* consists of the n rows of an *n* ´ *n* Walsh matrix:
  - $W_1 = (0)$

$$W_{2n} = \begin{pmatrix} W_n & W_{2n} \\ W_n & \overline{W_n} \end{pmatrix}$$

    - n = dimension of the matrix
  - Every row is orthogonal to every other row and to the logical not of every other row
  - Requires tight synchronization
    - Cross correlation between different shifts of Walsh sequences is not zero

CDMA for Direct Sequence Spread Spectrum



CDMA in a DSSS Environment

UMASS BOSTON

Typical Multiple Spreading Approach

- Spread data rate by an orthogonal code (channelization code)
  - Provides mutual orthogonality among all users in the same cell
- Further spread result by a PN sequence (scrambling code)
  - Provides mutual randomness (low cross correlation) between users in different cells