

Data Communications and Networking

Chapter 5 Signal Encoding Techniques

References:

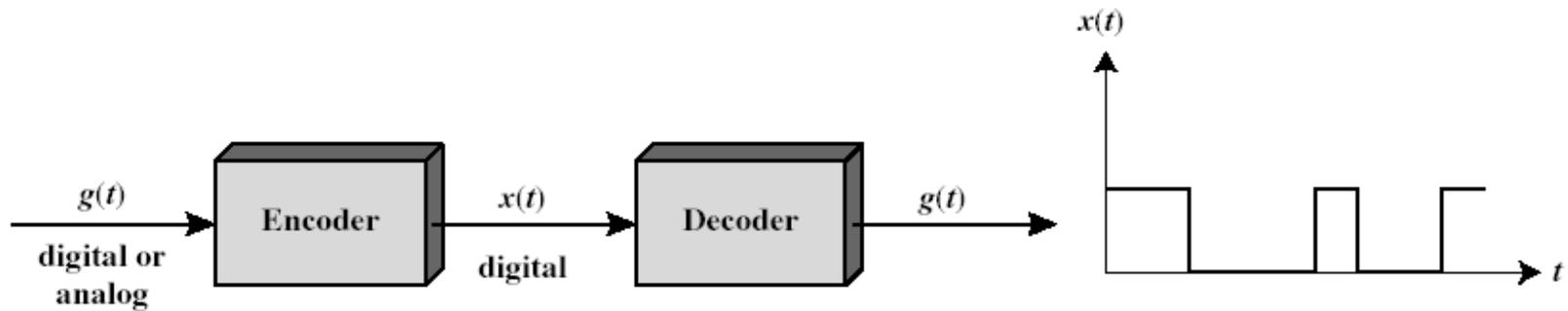
Book Chapter 5

***Data and Computer Communications, 8th
edition, by William Stallings***

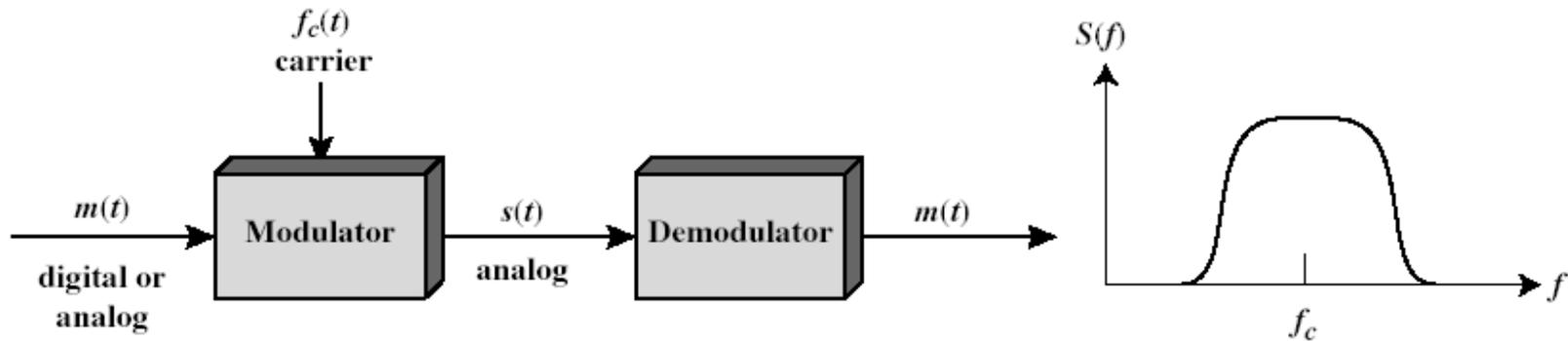
Outline

- Overview
 - Encoding and Modulation
- Digital data, digital signal
- Digital data, analog signal
- Analog data, digital signal
- Analog data, analog signal

Encoding and Modulation



(a) Encoding onto a digital signal



(b) Modulation onto an analog signal

Modulation

- Modulation is the process of encoding source data onto a **carrier signal** with frequency f_c .
 - The frequency of the carrier signal is chosen to be compatible with the transmission medium being used.
 - Modulation techniques involve operation on one or more of the three parameters: ***amplitude, frequency, and phase***
- According to the input source signal $m(t)$ (either analog or digital), which is called **baseband signal (or modulating signal)**, the carrier signal $f_c(t)$ will be modulated into **modulated signal** $s(t)$.

Encoding/modulation Techniques

- **Digital data, digital signal**
 - The equipment for encoding digital data into a digital signal is less complex and less expensive than digital-to-analog modulation equipment.
- **Analog data, digital signal**
 - Conversion of analog data (e.g., voice, video) to digital form permits the use of modern digital transmission & switching.
- **Digital data, analog signal**
 - Optical system and unguided media (wireless system) only propagate analog signals.
- **Analog data, analog signal**
 - Baseband: easy and cheap, e.g., in voice-grade telephone lines, voice signals are transmitted over telephone lines at their original spectrum
 - Modulation permits frequency division multiplexing, e.g., AM/FM radios

(I) Digital Data, Digital Signal

- Digital signal is a sequence of discrete, discontinuous **voltage pulses**.
- Each pulse is a **signal element**.
- Binary data are transmitted by encoding the bit stream into signal elements.
- In the simplest case, one bit is represented by one signal element.
 - E.g., 1 is represented by a lower voltage level, and 0 is represented by a higher voltage level

Terminologies

- Unipolar
 - If all signal elements have the same algebraic sign (all positive or all negative), then the signal is unipolar.
- Polar
 - One logic state represented by positive voltage, the other by negative voltage
- Data rate
 - Rate of data transmission measured in **bps**: **bits per second**
- Duration or length of a bit
 - Time taken for transmitter to emit the bit
- Modulation rate
 - Rate at which the signal level changes
 - Measured in **baud**: **signal elements per second**
- Mark and Space
 - Mark: Binary 1
 - Space: Binary 0

How are they related?

Interpreting Signals at the Receiver

- The receiver needs to know
 - The timing of each signal element, i.e., when a signal element begins and ends
 - signal levels
 - These tasks are performed by sampling each element position in the middle of the interval and comparing the value to a threshold.
- Factors affecting successful interpreting of signals
 - Signal-to-noise ratio (SNR)
 - Data rate
 - Bandwidth
- Some principles:
 - An increase in data rate increases bit error rate (BER)
 - An increase in SNR decreases BER
 - An increase in bandwidth allows an increase in data rate
- Another factor that can improve performance:
 - **Encoding scheme**: the mapping from data bits to signal elements

Evaluation of Encoding Schemes (1)

- Signal Spectrum
 - Lack of high frequencies reduces required bandwidth
 - Lack of dc component allows ac coupling via transformer, providing electrical isolation and reducing interference
 - Concentrate power in the middle of the bandwidth
- Clocking
 - Need to determine the beginning and end of each bit
 - Synchronizing transmitter and receiver
 1. Use external clock, which is expensive; or
 2. Synchronization mechanism based on the transmitted signal

Comparison of Encoding Schemes (2)

- Error detection
 - Various error-detection techniques will be covered in Chapter 9
 - Some error detection capability can be built into signal encoding scheme
- Signal interference and noise immunity
 - Some codes are better than others in the presence of noise
 - Performance is usually expressed in terms of BER
- Cost and complexity
 - Higher signal rate (thus data rate) leads to higher cost
 - Some codes require a signal rate greater than the actual data rate

Encoding Schemes

- Nonreturn to Zero (NRZ)
 - Nonreturn to Zero-Level (NRZ-L)
 - Nonreturn to Zero Inverted (NRZI)
- Multilevel Binary
 - Bipolar-AMI
 - Pseudoternary
- Biphasic
 - Manchester
 - Differential Manchester
- Scrambling techniques
 - B8ZS
 - HDB3

Table 5.2 Definition of Digital Signal Encoding Formats

Nonreturn to Zero-Level (NRZ-L)

0 = high level

1 = low level

Nonreturn to Zero Inverted (NRZI)

0 = no transition at beginning of interval (one bit time)

1 = transition at beginning of interval

Bipolar-AMI

0 = no line signal

1 = positive or negative level, alternating for successive ones

Pseudoternary

0 = positive or negative level, alternating for successive zeros

1 = no line signal

Manchester

0 = transition from high to low in middle of interval

1 = transition from low to high in middle of interval

Differential Manchester

Always a transition in middle of interval

0 = transition at beginning of interval

1 = no transition at beginning of interval

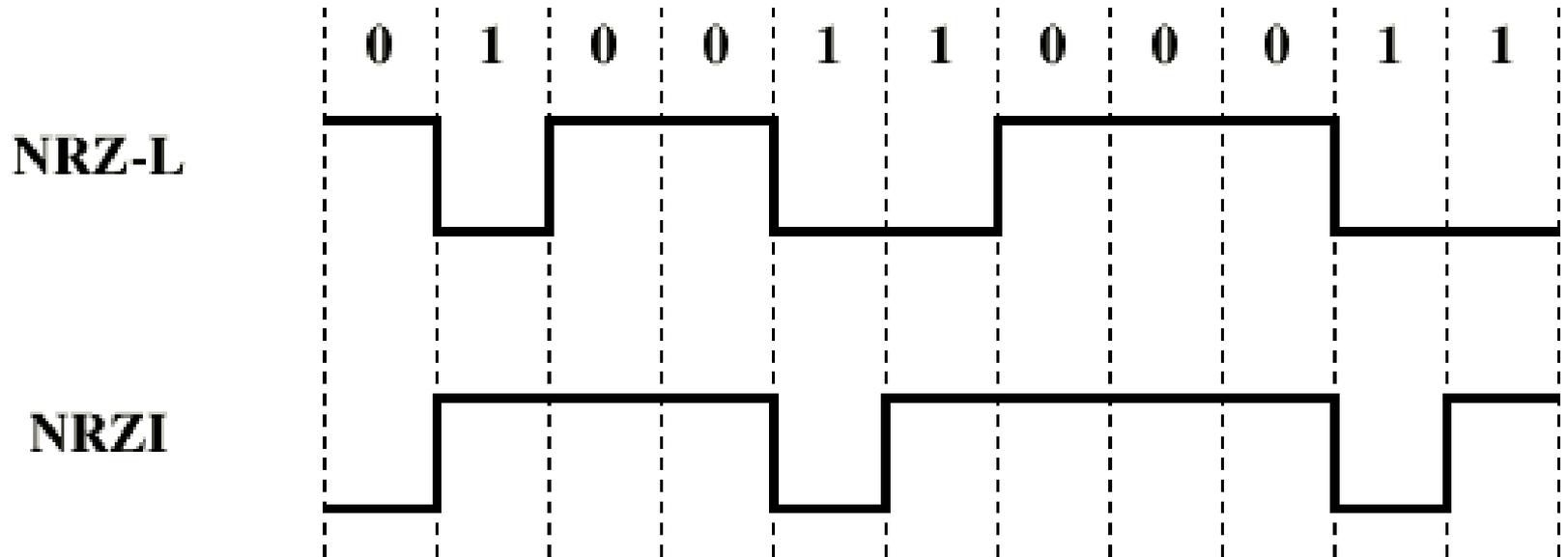
B8ZS

Same as bipolar AMI, except that any string of eight zeros is replaced by a string with two code violations

HDB3

Same as bipolar AMI, except that any string of four zeros is replaced by a string with one code violation

NRZ



Nonreturn to Zero-Level (NRZ-L)

- Two different voltages for 0 and 1 bits
- Voltage is constant during a bit interval
 - no transition, i.e. no return to zero voltage
- E.g. absence of voltage for zero, constant positive voltage for one
- More often, negative voltage for one value and positive for the other
- This is known as **NRZ-L**

Nonreturn to Zero Inverted

- **NRZI:** Nonreturn to zero, invert on ones
- Constant voltage pulse for duration of bit
- Data are encoded as presence or absence of **signal transition** at the beginning of the bit time
- A transition (low to high or high to low) denotes a binary 1
- No transition denotes binary 0
- NRZI is an example of **differential encoding** technique

Differential Encoding

- Data are represented in terms of **the changes between successive signal elements**, rather than the signal elements themselves.
- It is more reliable to detect a transition in the presence of noise than to compare a value to a threshold.
- With a complex transmission layouts, it is easy to lose the sense of the polarity of the signal.

NRZ pros and cons

- Pros
 - Easy to engineer
 - Make efficient use of bandwidth
- Cons
 - The presence of dc component
 - The lack of synchronization capability
- NRZ codes are commonly used for digital magnetic recording, but not often used for signal transmission.

Multilevel Binary

- Use more than two levels
- Bipolar-AMI: alternate mark inversion
 - zero represented by no line signal
 - one represented by a positive or negative pulse
 - one pulses must alternate in polarity
 - Advantages:
 - No loss of synchronization if a long string of 1s occurs (0s still be a problem)
 - No net dc component
 - Provides a simple means of error detection

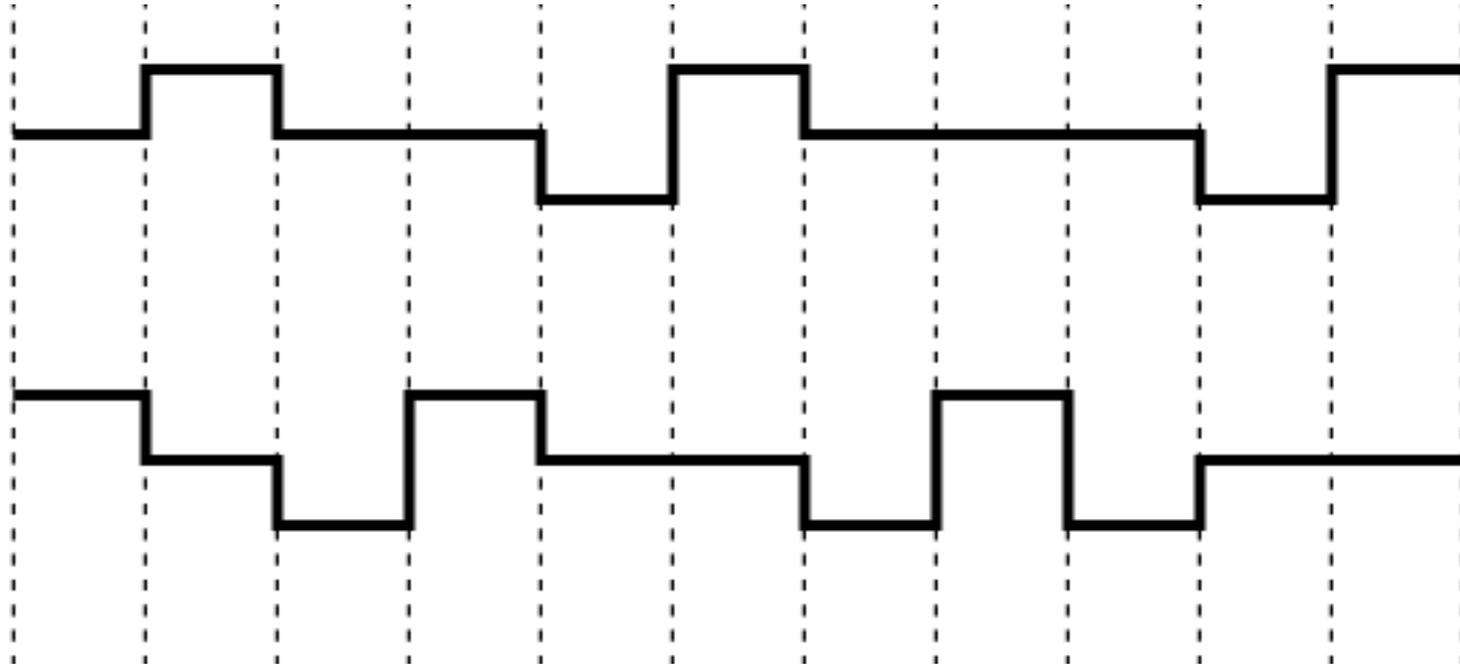
Pseudoternary

- 1 represented by the absence of line signal
- 0 represented by alternating positive and negative pulses
- No advantage or disadvantage over bipolar-AMI

Bipolar-AMI and Pseudoternary

0 1 0 0 1 1 0 0 0 1 1

Bipolar-AMI
(most recent
preceding 1 bit has
negative voltage)



Pseudoternary
(most recent
preceding 0 bit has
negative voltage)

Trade-off for Multilevel Binary

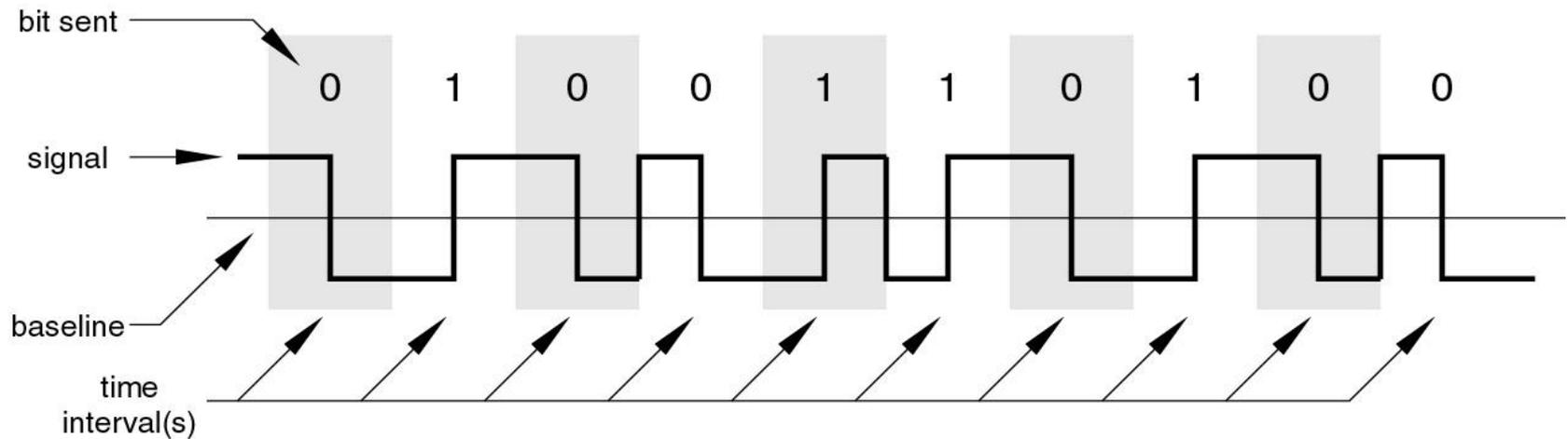
- Not as efficient as NRZ
 - In a 3 level system, each signal element could represent $\log_2 3 = 1.58$ bits
 - However, in bipolar-AMI & pseudoternary, each signal element only represents one bit
 - Receiver must distinguish between three levels (+A, -A, 0)
 - Requires approx. 3dB more signal power for same probability of bit error, or
 - The BER for NRZ codes, at a given SNR, is significantly less than for multilevel binary.

Biphase

- Manchester
 - There is a transition at the middle of each bit period.
 - The **midbit transition** serves as **a clock mechanism** and also as data: low to high represents 1, high to low represents 0
 - Used by IEEE 802.3 Ethernet LAN
- Differential Manchester
 - The midbit transition is used only to provide clocking.
 - 0 is represented by the presence of a transition at the beginning of a bit period.
 - 1 is represented by the absence of a transition at the beginning of a bit period.
 - Note: this is a differential encoding scheme
 - Used by IEEE 802.5 token ring LAN

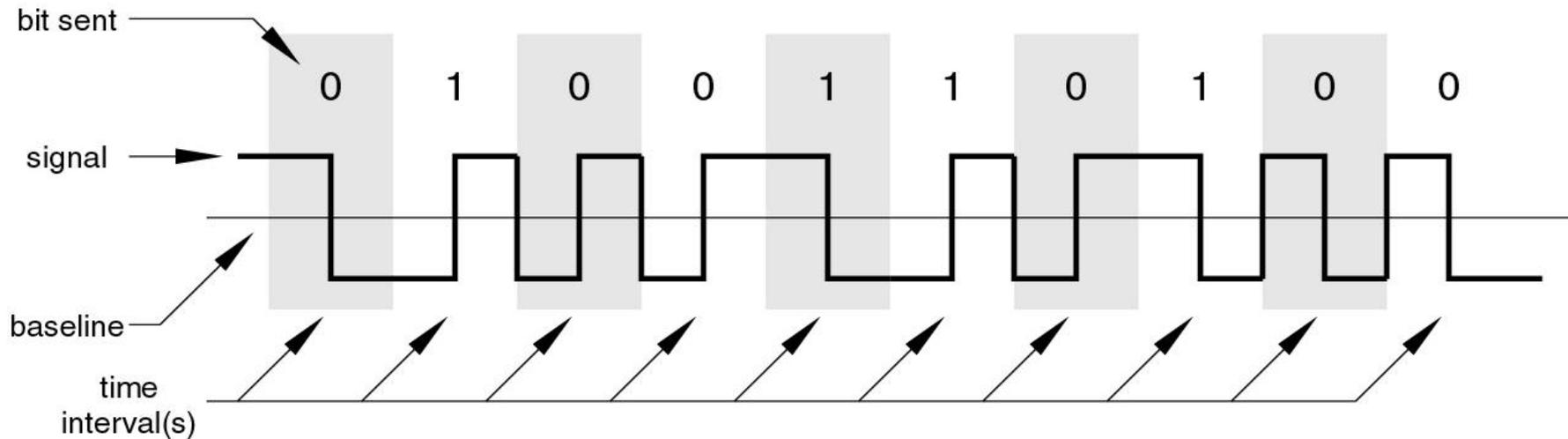
Manchester Encoding

Manchester Encoding



Differential Manchester Encoding

Differential Manchester Encoding



Biphase Pros and Cons

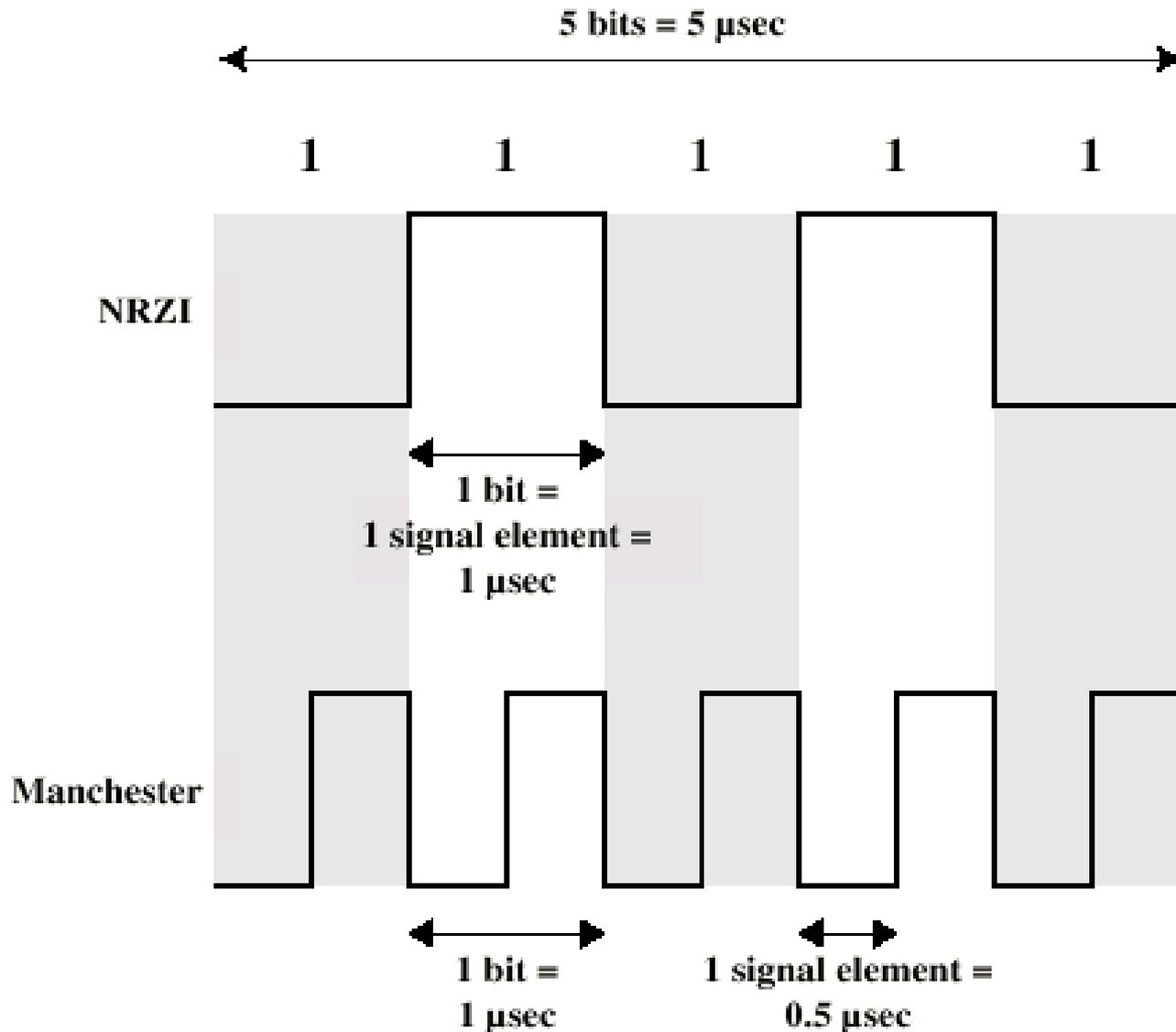
- Pros

- **Self-clocking**: Because there is a predictable transition during each bit time, the receiver can synchronize on that transition.
- No dc component
- Error detection: the absence of an expected transition can be used to detect errors

- Con

- Requires at least one transition per bit time and may have as many as two transitions, thus,
- The maximum modulation rate is twice that for NRZ
- Requires more bandwidth

Modulation Rate



Scrambling

- Use scrambling to replace sequences that would produce constant voltage
- Main idea:
 - Sequences that would result in a constant voltage are replaced by **filling sequences** that will provide sufficient transitions for the receiver's clock to maintain synchronization.
 - Filling sequences must be recognized by receiver and replaced with original data sequence.
 - Filling sequence is the same length as original sequence.
- Design goals:
 - No dc component
 - No long sequences of zero-level line signals
 - No reduction in data rate
 - Error detection capability

B8ZS

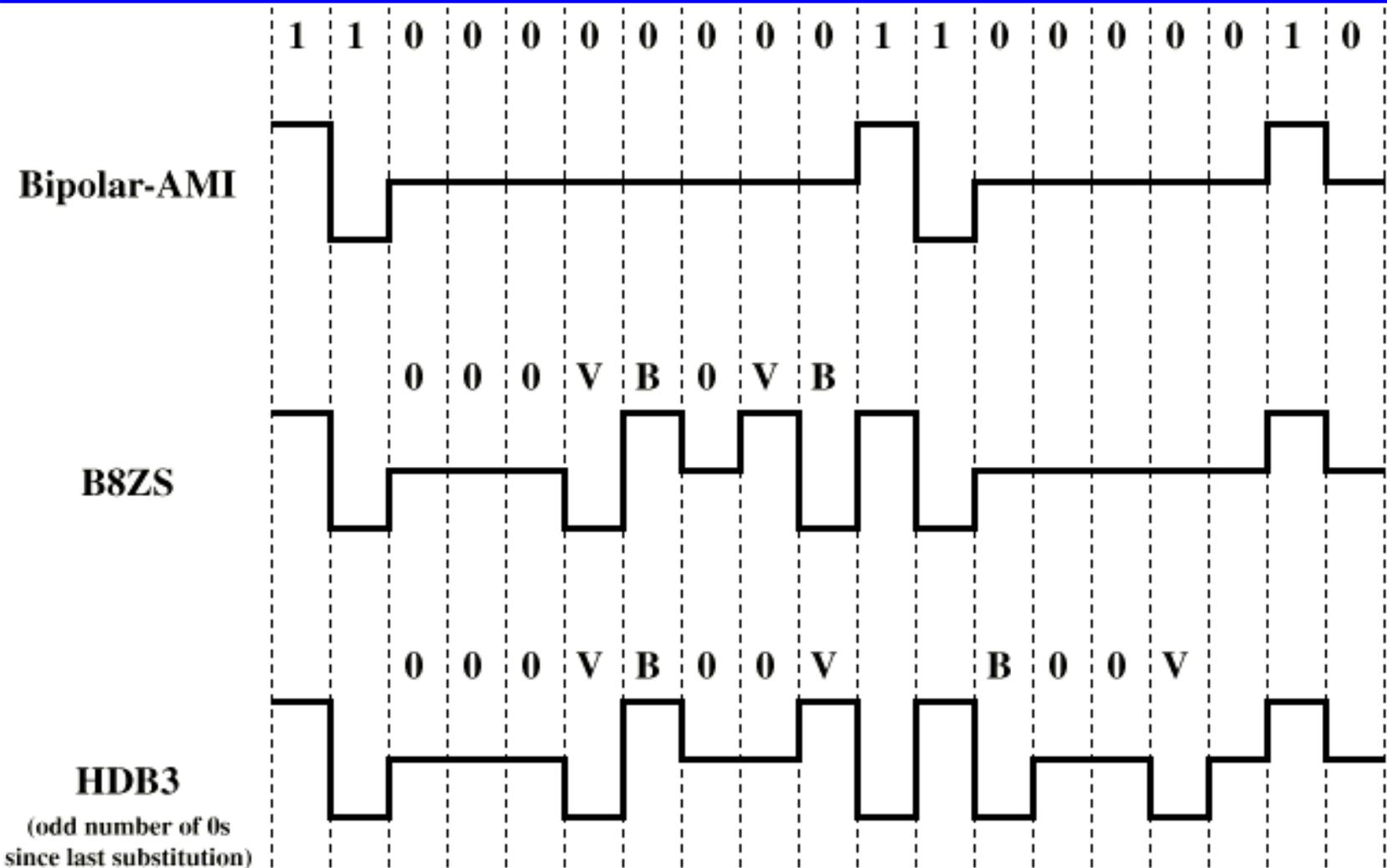
- Bipolar With 8-Zeros Substitution
- Based on bipolar-AMI, whose drawback is a long string of zeros may result in loss of synchronization.
- If **octet of all zeros** occurs and the last voltage pulse preceding this octet was positive, encode as 000+-0-+
- If **octet of all zeros** occurs and the last voltage pulse preceding this octet was negative, encode as 000-+0+-
- Causes two violations of AMI code
- Unlikely to occur as a result of noise
- Receiver recognizes the pattern and interprets the octet as consisting of all zeros.

HDB3

- High-Density Bipolar-3 Zeros
- Based on bipolar-AMI
- **String of four zeros** is replaced with sequences containing one or two pulses.

	Number of Bipolar Pulses since last substitution	
Polarity of Preceding Pulse	Odd	Even
-	000-	+00+
+	000+	-00-

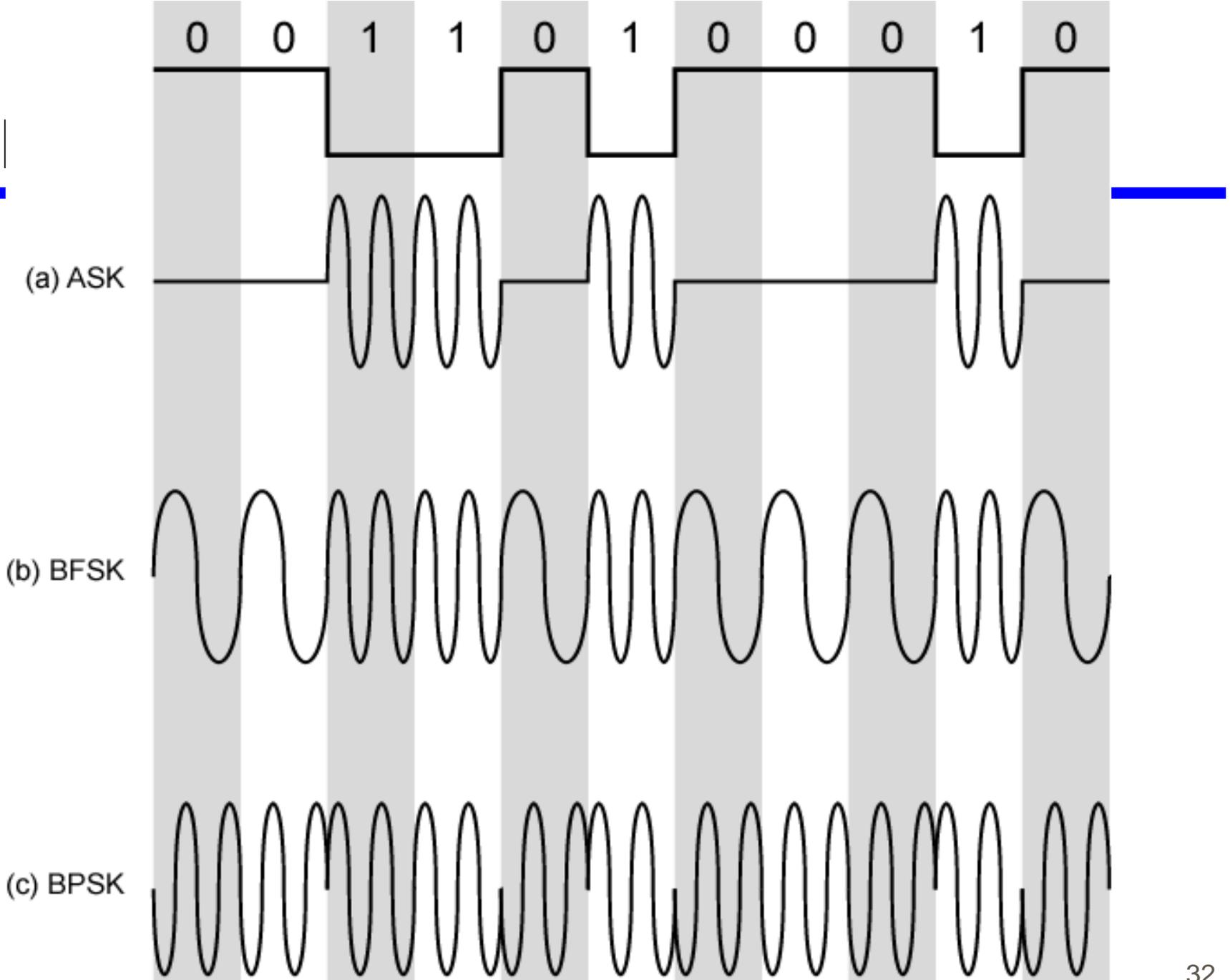
B8ZS and HDB3



B = Valid bipolar signal
 V = Bipolar violation

(II) Digital Data, Analog Signal

- E.g., Public telephone system
 - Designed to transmit **analog signals** in 300Hz to 3400Hz (limited by the central office, not the twisted pair cable)
 - Use **modem** for digital data (modulator-demodulator)
- Modulation involves operation on **one or more** of the three characteristics of a **carrier signal**
 - Amplitude shift keying (ASK)
 - Frequency shift keying (FSK)
 - Binary FSK (BFSK)
 - Multiple FSK (MFSK)
 - Phase shift keying (PSK)
 - Binary PSK (BPSK)
 - Four-level PSK (QPSK)
 - Multilevel PSK (MPSK)
- QAM: a combination of ASK and PSK



Amplitude Shift Keying

- Values are represented by different amplitudes of the carrier frequency
- Usually, one amplitude is zero
 - i.e. presence and absence of carrier is used
- Inefficient: up to 1200bps on voice grade lines
- ASK is used to transmit digital data over optical fiber.

Binary Frequency Shift Keying

- The most common form of FSK is **binary FSK** (BFSK)
- Two binary values represented by two different frequencies (near carrier frequency)
- BFSK is less susceptible to error than ASK.
- Up to 1200bps on voice grade lines
- Also used for high frequency (3 to 30MHz) radio

Multiple FSK

- MFSK: More than two frequencies are used
- Each signalling element represents more than one bit
- More bandwidth efficient
- But more prone to error!

FSK on Voice Grade Line

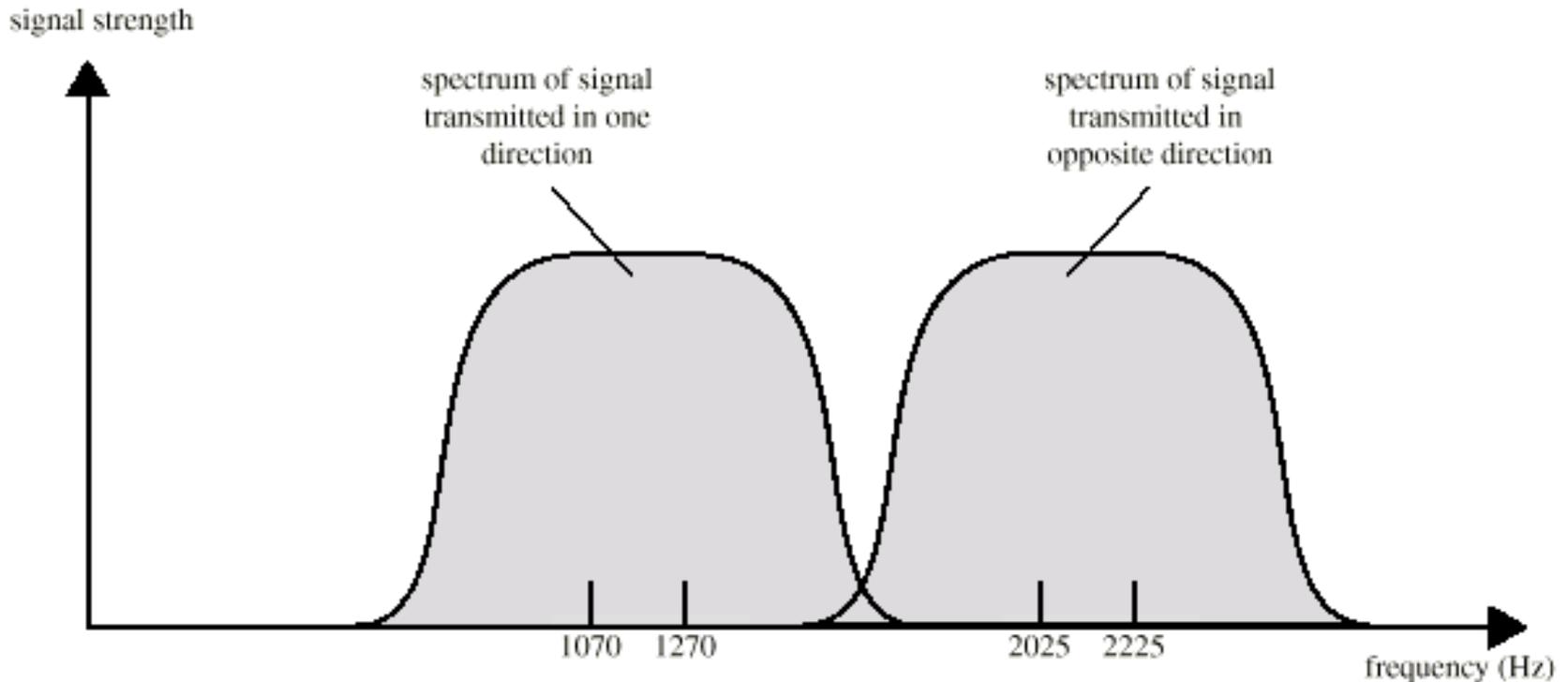
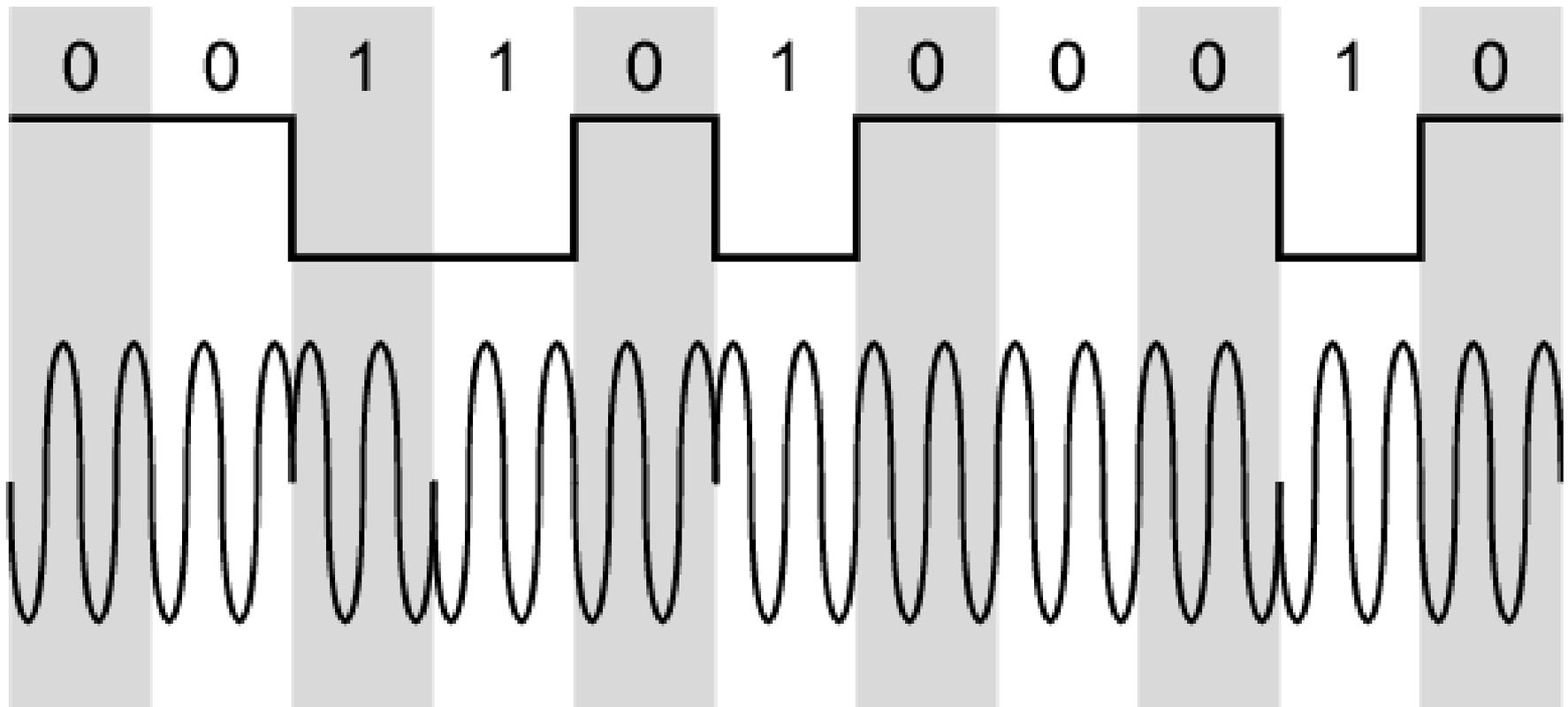


Figure 5.8 Full-Duplex FSK Transmission on a Voice-Grade Line

Phase Shift Keying

- In PSK, the phase of the carrier signal is shifted to represent data.
- Binary PSK
 - Two phases represent two binary digits
- Differential PSK
 - Phase shifted relative to previous transmission rather than some constant reference signal

Differential PSK



Multilevel PSK

- More efficient use of bandwidth
- Each signal element represents more than one bit
- QPSK: quadrature PSK
 - shifts of $\pi/2$ (90°), i.e. 4 different phases
 - Each signal element represents 2 bits
- Multilevel PSK
 - Can use 8 or more phase angles, and each phase can have more than one amplitude
 - 9600bps modem use 12 angles, four of which have two amplitudes, in total 16 different signal elements

Quadrature Amplitude Modulation

- QAM is used in the **asymmetric digital subscriber line** (ADSL) and some wireless standards.
- Combination of ASK and PSK
- A logical extension of QPSK
- Send two different signals simultaneously on the same carrier frequency
 - Use two copies of the carrier, one shifted by 90°
 - Each carrier is ASK modulated
 - Two independent signals over same medium
 - Demodulate and combine for original binary output

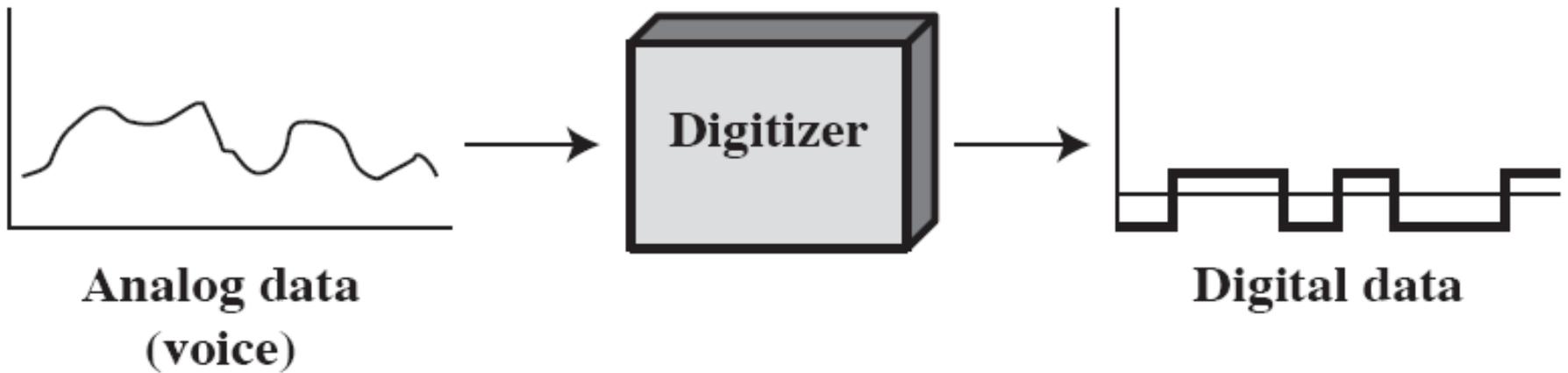
QAM Levels

- Two level ASK
 - Each of two streams in one of two states
 - Four state system
 - Essentially QPSK
- Four level ASK
 - Combined stream in one of 16 states
- 64 and 256 state systems have been implemented
- Improved data rate for given bandwidth
 - Increased potential error rate

(III) Analog Data, Digital Signal

- Digitization
 - Conversion of analog data into digital data
 - Digital data can then be transmitted using NRZ-L
 - Digital data can then be transmitted using code other than NRZ-L
 - Digital data can then be converted to analog signal
 - Analog to digital conversion done using a **codec** (coder-decoder)
 - Two principle codec techniques
 - Pulse Code Modulation
 - Delta modulation

Digitizing Analog Data



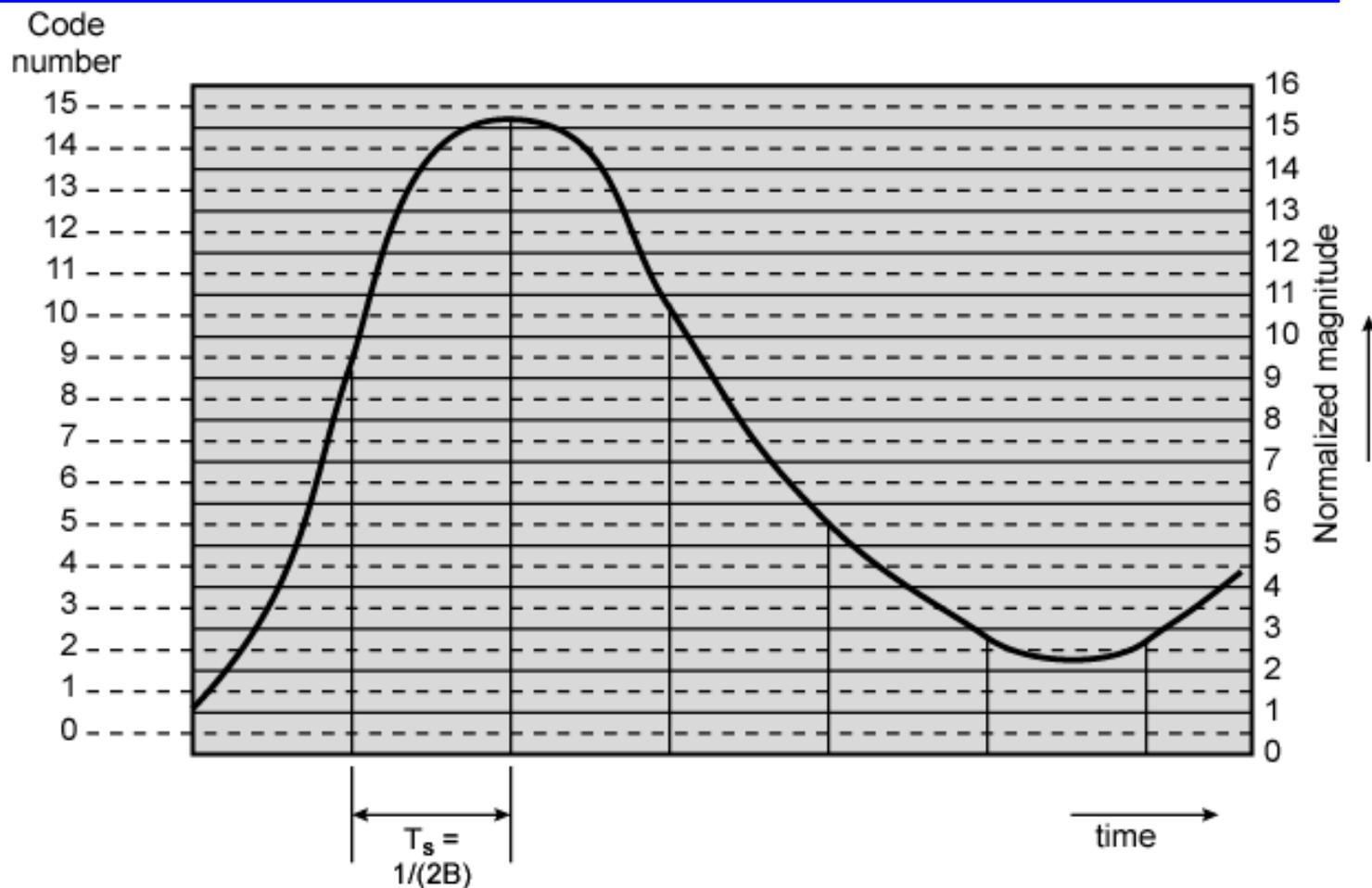
Pulse Code Modulation

- **Sampling Theorem**: If a signal is sampled at regular intervals of time and at a rate higher than twice the highest signal frequency, then the samples contain all the information of the original signal.
- For example, voice data are limited to below 4000Hz
 - **8000 samples per second** is sufficient to characterize the voice signal.
- Samples are analog samples, called **Pulse Amplitude Modulation** (PAM) samples.
- To convert to digital, each analog sample must be assigned a binary code.

Pulse Code Modulation

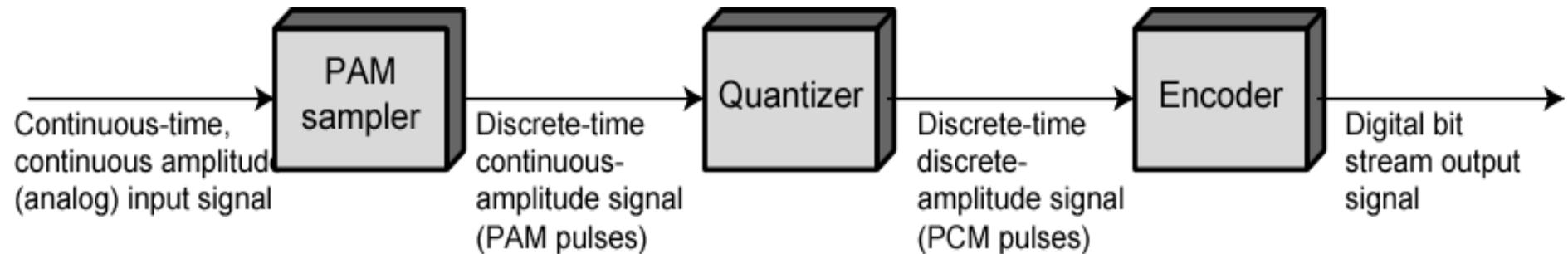
- Each sample is quantized into some level
 - The original signal is now only approximated and cannot be recovered exactly
 - This effect is called **quantizing error** or **quantizing noise**
- For example, 8 bit sample gives 256 levels
- **8000 samples per second and 8 bits per sample gives 64kbps, for a single voice signal.**

PCM Example



PAM value	1.1	9.2	15.2	10.8	5.6	2.8	2.7
quantized code number	1	9	15	10	5	2	2
PCM code	0001	1001	1111	1010	0101	0010	0010

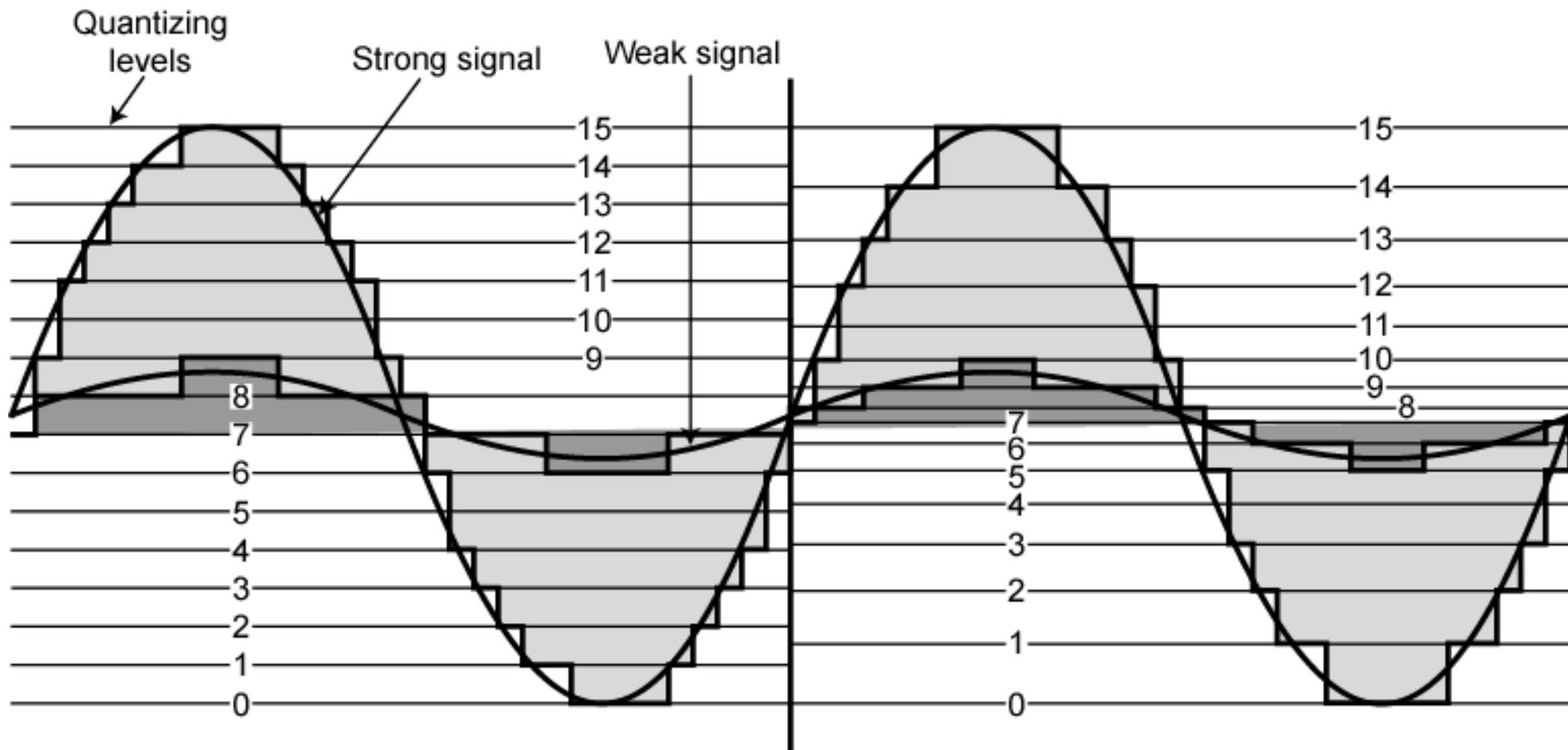
PCM Block Diagram



Nonlinear Encoding

- Typically, PCM scheme is refined using **nonlinear encoding**.
- Quantization levels are not equally spaced.
- The problem of equal spacing:
 - The mean absolute error for each sample is regardless of signal level.
 - Lower amplitude values are relatively more distorted.
- Nonlinear encoding:
 - Use a greater number of quantizing steps for signals of low amplitude, and a smaller number of quantizing steps for signals of large amplitude
 - Reduces overall signal distortion

Effect of Non-Linear Coding

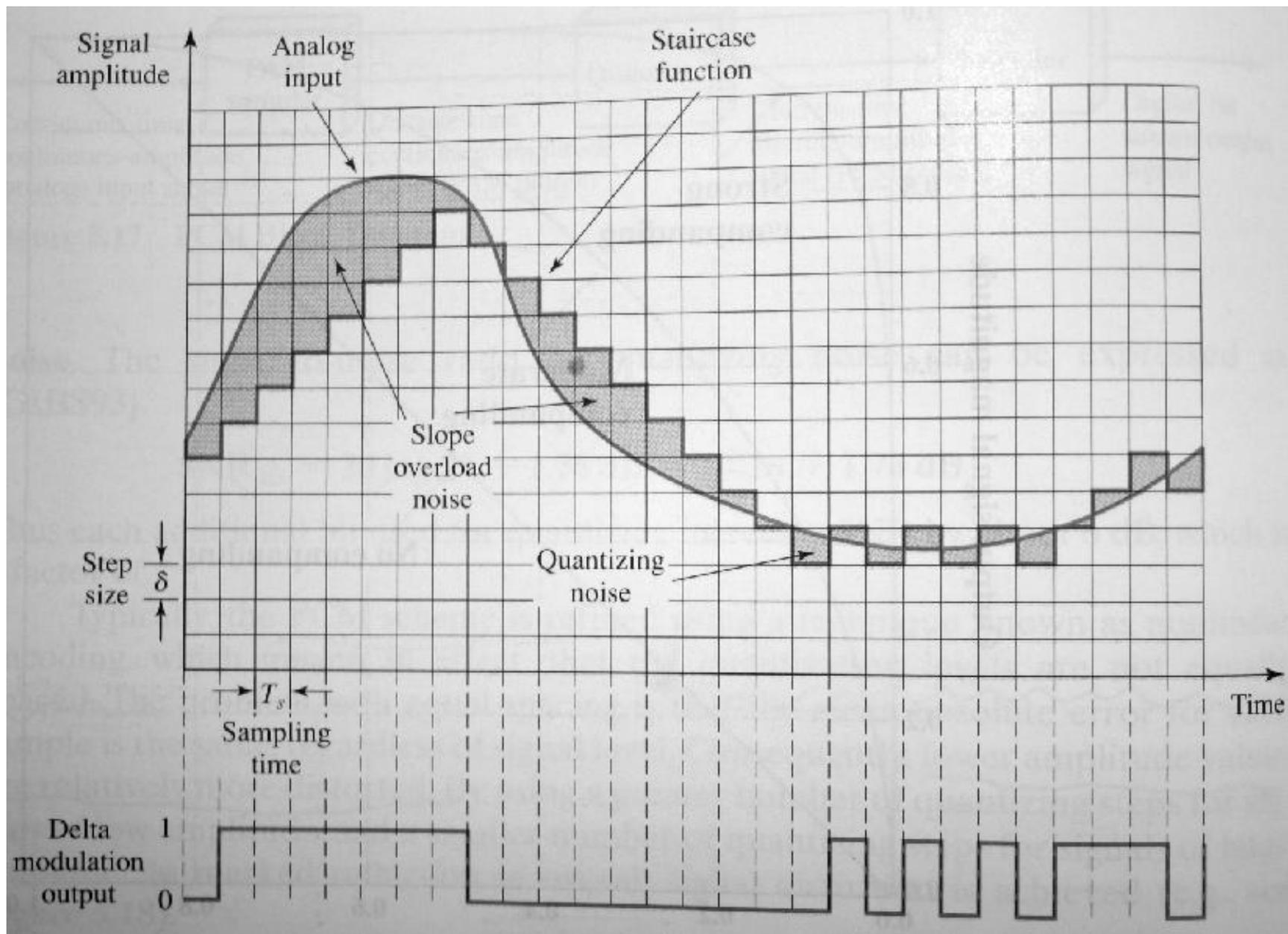


(a) Without nonlinear encoding

(b) With nonlinear encoding

Delta Modulation

- Modulation:
 - An analog signal is approximated by a staircase function that moves up or down by quantization level at each sampling interval.
 - If the value of the sampled waveform exceeds that of the staircase function, 1 is generated, otherwise, 0 is generated.
- Two important parameters:
 - The size of the step.
 - The sampling rate.



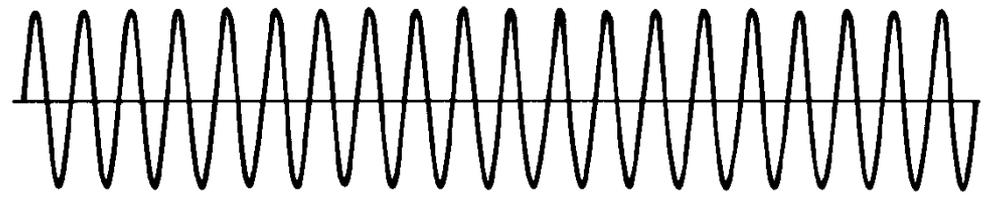
Delta Modulation

- Noise
 - Slope overload noise (when the analog waveform is changing rapidly than the staircase can follow)
 - Quantizing noise (when the analog waveform is changing slowly)
- Trade-off
 - The quantizing noise increases as the size of the step increases.
 - The slope overload noise increases as the size of the step decreases.

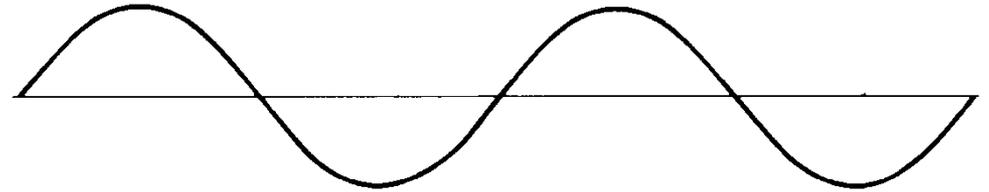
(IV) Analog Data, Analog Signals

- Modulation:
 - Combine an input signal $m(t)$ and a carrier frequency f_c to produce a signal $s(t)$ whose bandwidth is usually centered on f_c
- E.g., voice signals are transmitted over telephone lines at their original spectrum.
- Types of modulation
 - Amplitude modulation: AM
 - Angle Modulation
 - Frequency modulation: FM
 - Phase modulation: PM

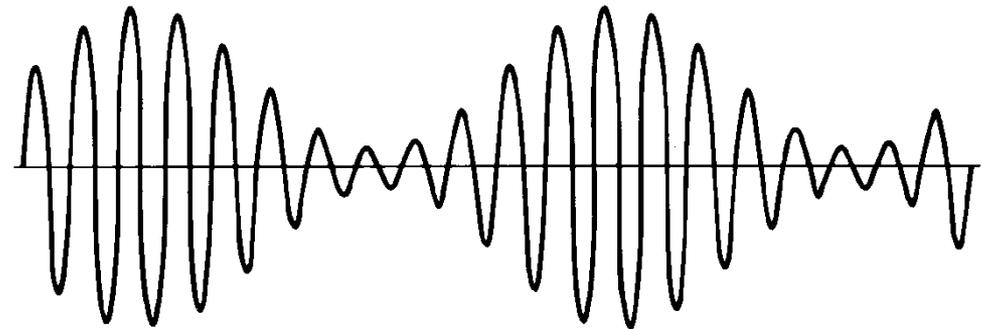
Analog Modulation



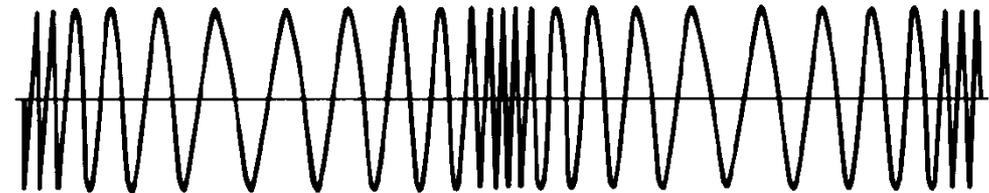
Carrier



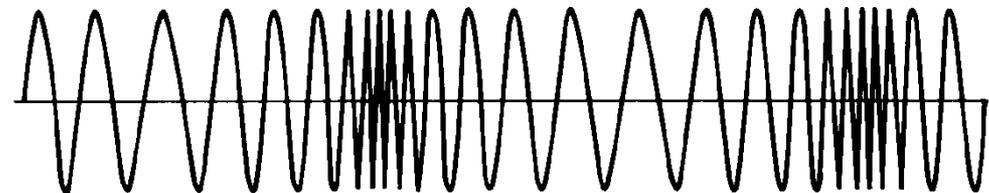
Modulating sine-wave signal



Amplitude-modulated (DSB-TC) wave



Phase-modulated wave



Frequency-modulated wave

KEY POINTS

- Both analog and digital information can be encoded as either analog or digital signals. The particular **encoding** that is chosen depends on the specific requirements to be met and the media and communications facilities available.
- **Digital data, digital signal**: The simplest form of digital encoding of digital data is to assign one voltage level to binary one and another to binary zero. More complex encoding schemes are used to improve performance, by altering the spectrum of the signal and providing synchronization capability.
- **Digital data, analog signal**: A modem converts digital data to an analog signal so that it can be transmitted over an analog line. The basic techniques are **ASK, FSK,** and **PSK**.

KEY POINTS

- **Analog data, digital signals:** Analog data, such as voice and video, are often digitized to be able to use digital transmission facilities. The simplest technique is **PCM (Pulse Code Modulation)**, which involve **sampling** the analog data periodically and **quantizing** the samples. Another technique is **Delta Modulation**.
- **Analog data, analog signals:** Analog data are modulated by a carrier frequency to produce an analog signal in a different frequency band, which can be utilized on an analog transmission system. The basic techniques are **AM (Amplitude Modulation)**, **FM (Frequency Modulation)**, and **PM (Phase Modulation)**.