Lecture 2
Basic Communication Principles

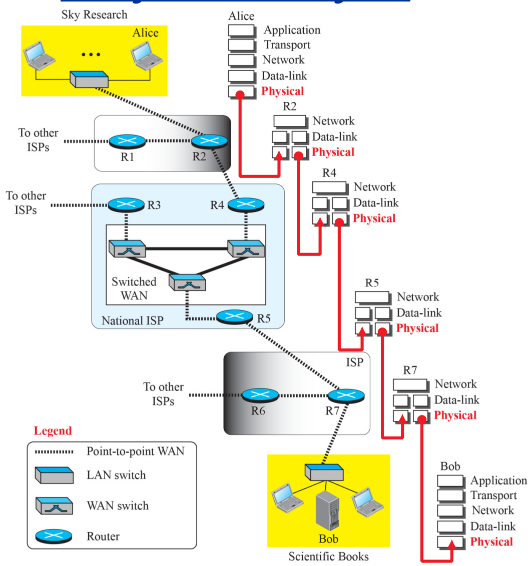
Textbook: Ch.3 and Ch.4

Main Topics

Ch 3. Physical Layer
- 3.1 Data and Signal
- 3.2 Periodic Analogue Signals
- 3.3 Digital Signals
- 3.4 Transmission Impairment
- 3.5 Data rate limit
- 3.6 Performance

Ch 4. Digital Transmission
- Analog-to-digital Conversion (PCM)

Physical layer



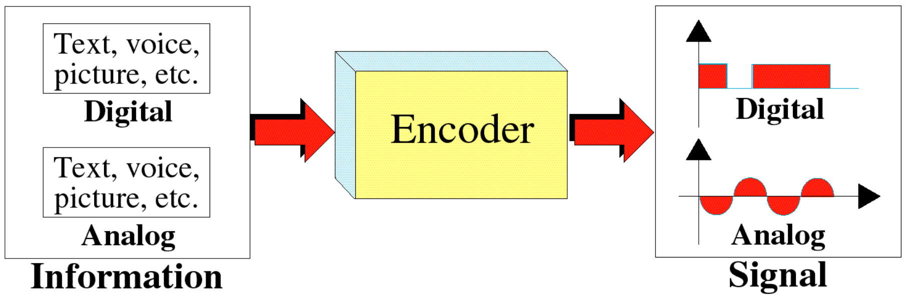
1.3

Figure 3.1: Communication at the physical layer

3.1 Data and Signal

Transformation of Information to Signals

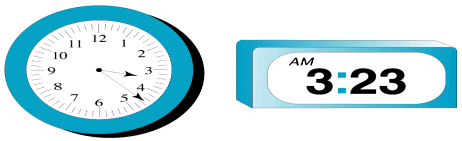
- To be transmitted, data must be transformed to electromagnetic signals



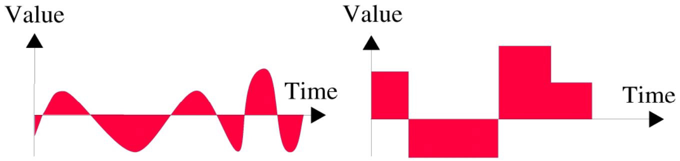
WCB/McGraw-Hill

Analog and Digital

- **Analog signals** can have any value in a range (continuous values)
- **Digital signals** can have only a limited number of values (discrete values)



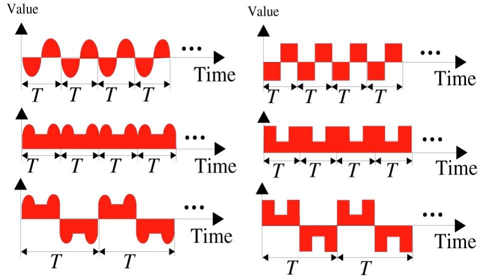
a. Analog b. Digital



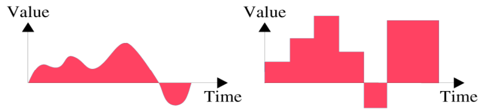
a. Analog signal b. Digital signal

3.2 Periodic Analogue Signals

Periodic Signals consists of a continuously repeated pattern

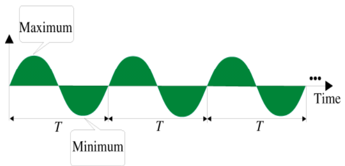


Aperiodic Signals has no repetitive pattern



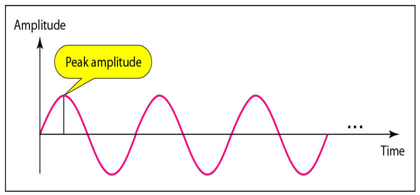
Periodic Analog Signals

- The **sine wave** is the most fundamental form of a periodic signal
- A periodic signal can be decomposed into a set of sine waves

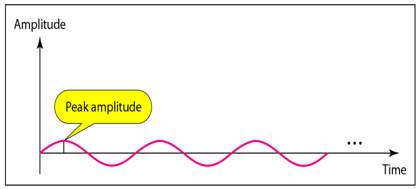


- Characteristics of a sine wave:
  - Amplitude – the instantaneous height
  - Frequency – the no. of cycles per second (Hz)
    - Frequency and period are the inverse of each other $f = \frac{1}{T}$ and $T = \frac{1}{f}$
  - Phase – the shift of the wave along the time axis (relative to time zero) measured in degrees or radians

Different Amplitudes

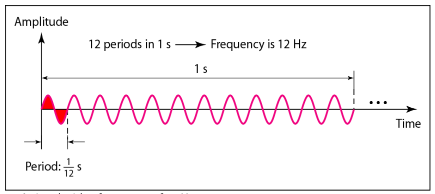


a. A signal with high peak amplitude

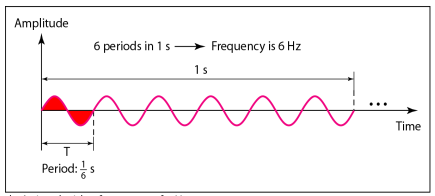


b. A signal with low peak amplitude

Different Frequencies

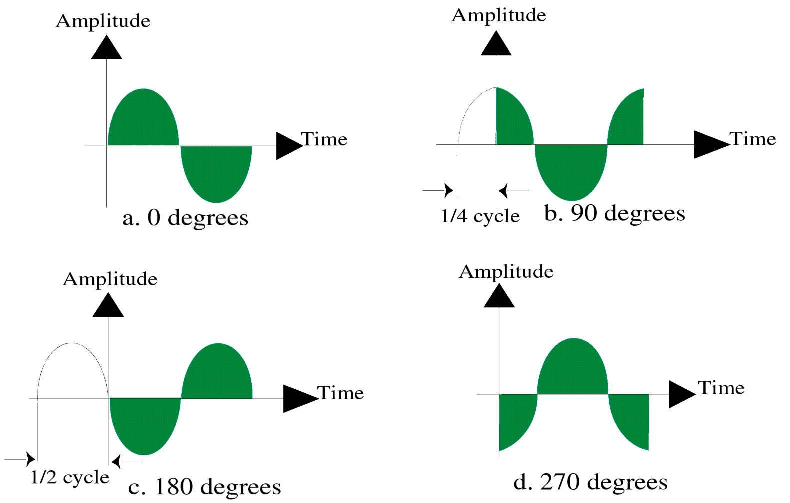


a. A signal with a frequency of 12 Hz



b. A signal with a frequency of 6 Hz

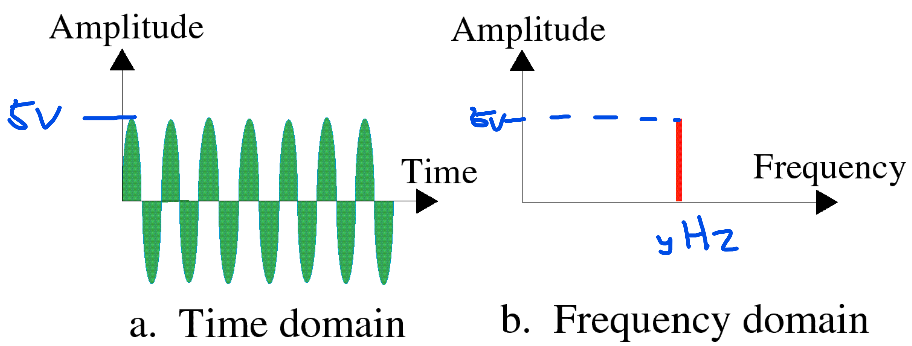
Different Phases



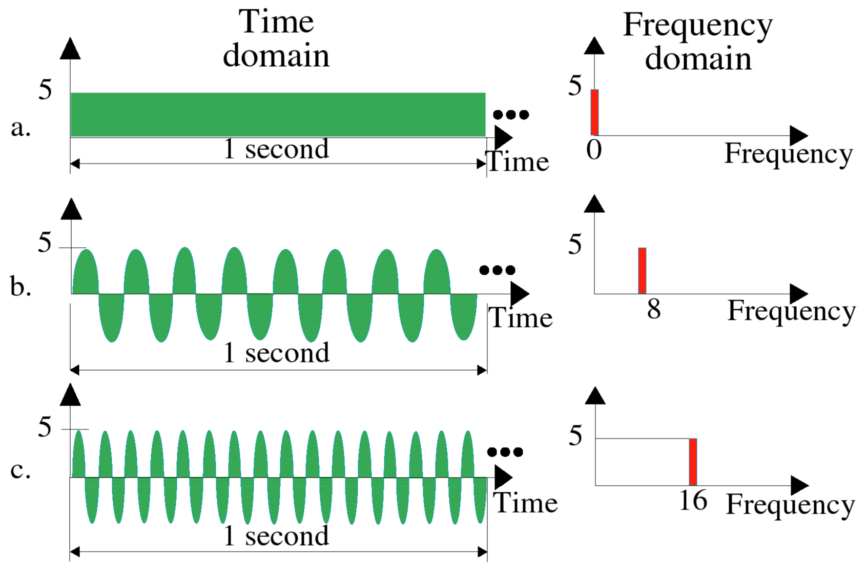
Time and Frequency Domains

- A time-domain graph plots amplitude as a function of time
- A frequency-domain graph plots each sine wave's peak amplitude against its frequency

Time and Frequency Domain

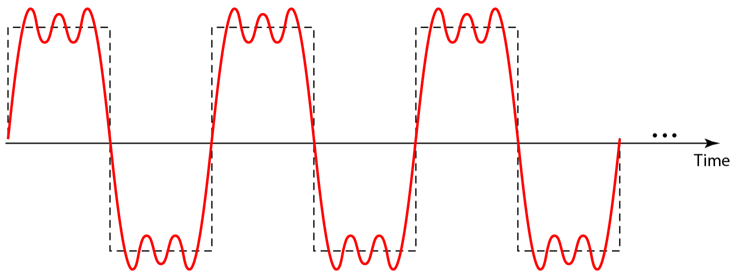


Examples

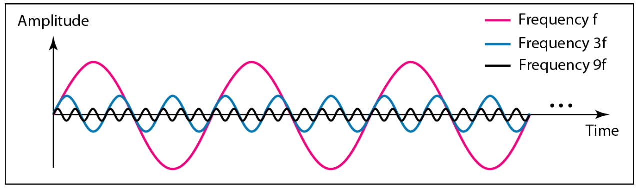


Composite Signals

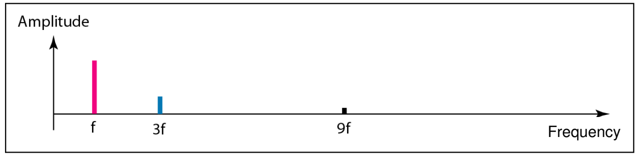
- Periodic signal can be decomposed into a set of sine waves (called **components**)
  - each has its own amplitude, frequency, and phase



Decomposition of the signal



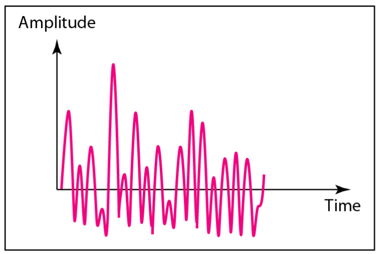
a. Time-domain decomposition of a composite signal



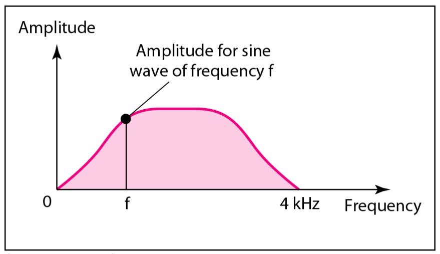
b. Frequency-domain decomposition of the composite signal

Bandwidth of a Signal

- The bandwidth of a composite signal is the **difference** between the **highest** and the **lowest** frequencies contained in that signal.



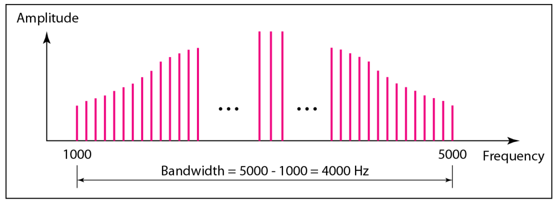
a. Time domain



b. Frequency domain

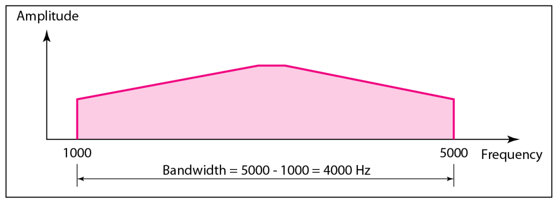
Bandwidth of periodic and aperiodic signals

Periodic Signal contains discrete frequencies



a. Bandwidth of a periodic signal

Aperiodic Signal with continuous frequencies



b. Bandwidth of a nonperiodic signal

Example

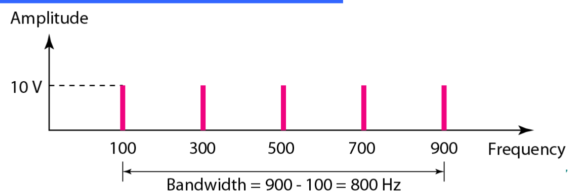
If a periodic signal is decomposed into five sine waves with frequencies of 100, 300, 500, 700, and 900 Hz, what is its bandwidth? Draw the spectrum, assuming all components have a maximum amplitude of 10 V.

Solution

Let f_h be the highest frequency, f_l the lowest frequency, and B the bandwidth. Then

$$\boxed{B = f_h - f_l = 900 - 100 = 800 \text{ Hz}}$$

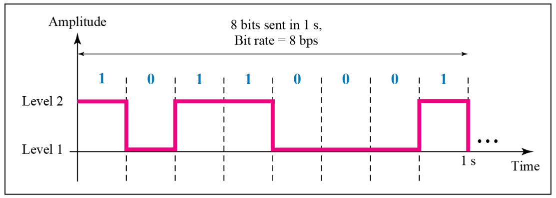
The spectrum has only five spikes, at 100, 300, 500, 700, and 900 Hz



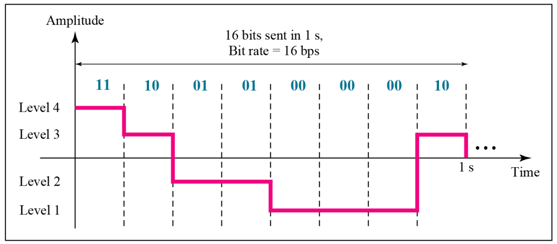
3.3 Digital Signals

- **In addition to being represented by an analog signal, information can also be represented by a digital signal**
- **For example, a 1 can be encoded as a positive voltage and a 0 as zero voltage. A digital signal can have more than two levels. In this case, we can send more than 1 bit for each level.**

Digital signal can have more than two levels, in this case, more bits can be sent in each level.



a. A digital signal with two levels



b. A digital signal with four levels

Example

A digital signal has eight levels. How many bits are needed per level?

Solution

We calculate the number of bits from the formula

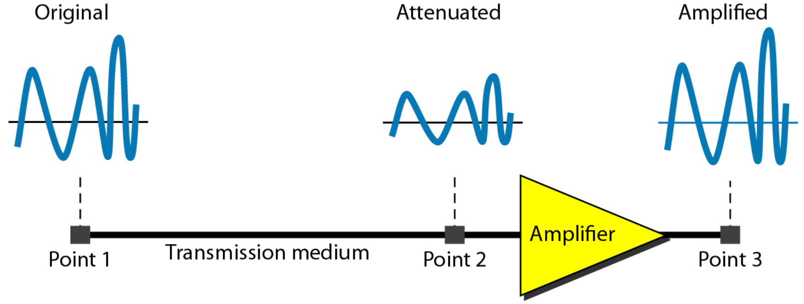
$$\boxed{\text{Number of bits per level} = \log_2 8 = 3}$$

Each signal level is represented by 3 bits.

3.4 TRANSMISSION IMPAIRMENT

- **Signals travel through transmission media, which are not perfect. The imperfection causes signal impairment.**
- **The signal at the beginning of the medium is not the same as the signal at the end of the medium.**
  - **What is sent is not what is received.**
- **Three causes of impairment are**
  - **Attenuation**
  - **Distortion**
  - **Noise**

Attenuation



- ***Attenuation** means a loss of energy.*
- *Measured by **decibel (dB) =*** $10 \log_{10} \frac{P_2}{P_1}$

Example

Suppose a signal travels through a transmission medium and its power is reduced to one-half. This means that P_2 is $(1/2)P_1$. In this case, the attenuation (loss of power) can be calculated as

$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{0.5P_1}{P_1} = 10 \log_{10} 0.5 = 10(-0.3) = -3 \text{ dB}$$

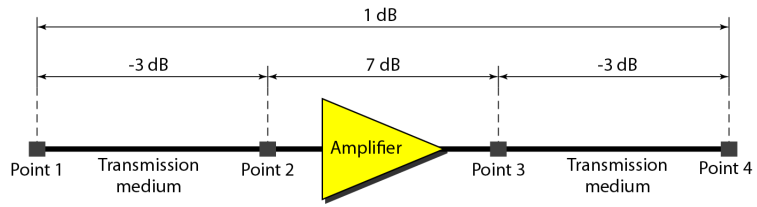
A loss of 3 dB (–3 dB) is equivalent to losing one-half the power.

Reason for using dB

Decibel numbers can be added (or subtracted) when we are measuring several points (cascading) instead of just two.

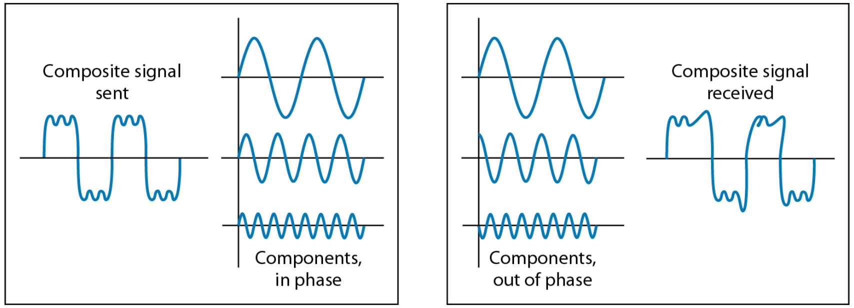
Example: ***A signal travels from point 1 to point 4. In this case, the decibel value can be calculated as***

$$\text{dB} = -3 + 7 - 3 = +1$$



Distortion

- ***Distortion** means that the signal **changes its form** or shape.*
- *Main cause: **Difference** in **delay** of different **frequency** components.*



At the sender | At the receiver

Noise

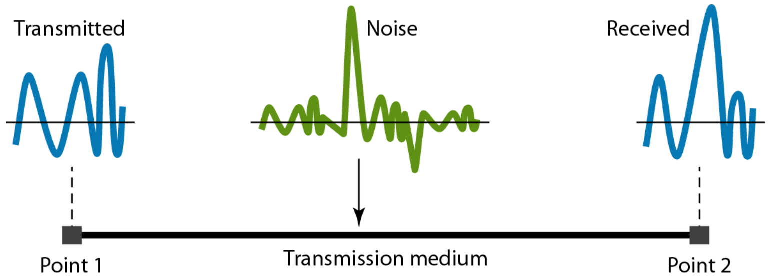
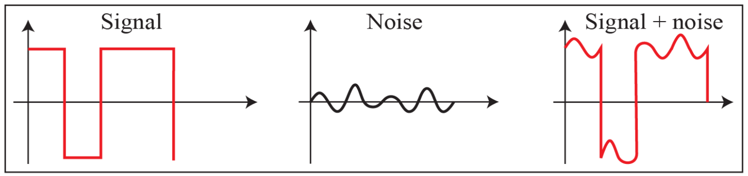


Figure 3.29

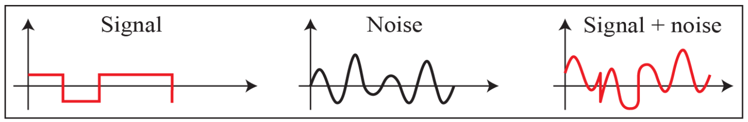
- Noise includes thermal noise, induced noise, crosstalk, and impulse noise, etc.
- Measured by **Signal-to-noise ratio (SNR)**:

$$\text{SNR} = \frac{\text{Average signal power}}{\text{Average noise power}}$$

Two cases of SNR: a high SNR and a low SNR



a. High SNR



b. Low SNR

Example

The power of a signal is 10 mW and the power of the noise is 1 μW. What are the values of SNR and SNR_{dB} ?

Solution

The values of SNR and SNR_{dB} can be calculated as follows:

$$\text{SNR} = \frac{10{,}000\ \mu\text{W}}{1\ \mu\text{W}} = 10{,}000$$

$$\text{SNR}_{\text{dB}} = 10 \log_{10} 10{,}000 = 10 \log_{10} 10^4 = 40$$

3.5 DATA RATE LIMITS

A very important consideration in data communications is how fast we can send data, in bits per second, over a channel.

Data rate depends on three factors:

1. *The bandwidth available*
2. *The level of the signals we use*
3. *The quality of the channel (the level of noise)*

Noiseless Channel: Nyquist Bit Rate

- For a noiseless Channel, the **Nyquist bit rate** formula defines the theoretical maximum bit rate:

$$\text{BitRate} = 2 \times \text{bandwidth} \times \log_2 L$$

Note

Increasing the levels of a signal may reduce the reliability of the system.

- Receiver becomes difficult to distinguish different levels

Examples on Nyquist Bit Rate

- *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*

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

- *Consider the same noiseless channel transmitting a signal with **four signal** levels (for each level, we send 2 bits). The maximum bit rate can be calculated as*

$$\text{BitRate} = 2 \times 3000 \times \log_2 4 = 12{,}000 \text{ bps}$$

Noisy Channel: Shannon Capacity

- In reality, we cannot have a noiseless channel; the channel is always noisy. In 1944, Claude Shannon introduced a formula, called the Shannon capacity.
- The theoretical maximum data rate of a noisy channel is related to SNR

$$C = B \log_2 (1 + \text{SNR}) \text{ bps}$$

  - B – bandwidth of the channel (in Hz)
  - C – (Shannon) Capacity of the channel (in bps)
- Actual data rate usually is smaller
- Regardless to number of signal levels

Example on Shannon Capacity

We can calculate the theoretical highest bit rate of a regular telephone line. A telephone line normally has a bandwidth of 3000. The signal-to-noise ratio is usually 3162. For this channel the capacity is calculated as

$$C = B \log_2 (1 + \text{SNR}) = 3000 \log_2 (1 + 3162) = 3000 \log_2 3163$$
$$= 3000 \times 11.62 = 34{,}860 \text{ bps}$$

This means that the highest bit rate for a telephone line is 34.860 kbps. If we want to send data faster than this, we can either increase the bandwidth of the line or improve the signal-to-noise ratio.

3.6. Performance Throughput

- The ***throughput*** is a measure of how fast we can actually send data through a network.
- Although, at first glance, bandwidth in bits per second and throughput seem the same, they are different.
- A link may have a bandwidth of B bps, but we can only send T bps, but

T always less than B.

Throughput Example

A network with bandwidth of 10 Mbps can pass only an average of 12,000 frames per minute with each frame carrying an average of 10,000 bits. What is the throughput of this network?

Solution

We can calculate the throughput as

$$\textbf{Throughput} = (12{,}000 \times 10{,}000) / 60 = 2 \text{ Mbps}$$

The throughput is almost one-fifth of the bandwidth in this case.

Latency or Delay

- The latency or delay defines how long it takes for an entire message to completely arrive at the destination from the time the first bit is sent out from the source.
- We can say that latency is made of four components:
  - propagation time,
  - transmission time,
  - queuing time, and
  - processing delay.

$$\textbf{Latency} = \text{propagation time} + \text{transmission time} + \text{queuing time} + \text{processing delay}$$

Propagation Time and Transmission Time

- Propagation Time
  - Measures the time required for a bit to travel from the source to the destination. The propagation time is calculated by dividing distance by the propagation speed.

    Propagation Time = Distance / (Propagation Speed)

  - We will use T_p as the short form for Propagation Time.
- Transmission Time
  - Measures the time between the first bit and the last bit leaving the sender. The Transmission time depends on the size of the message and the bandwidth of the channel.

    Transmission Time = (Message Size) / Bandwidth

  - We will use T_x as the short form for Transmission Time.

Example 3.45

Propagation time Example

What is the propagation time if the distance between the two points is 12,000 km? Assume the propagation speed to be 2.4×10^8 m/s in cable.

Solution

We can calculate the propagation time as

Propagation time = (12,000 x 1,000) / (2.4 x10^8) = 50 ms

The example shows that a bit can go over the Atlantic Ocean in only 50 ms if there is a direct cable between the source and the destination.

Example 3.46

What are the propagation time and the transmission time for a 2.5-KB (kilobyte) message if the bandwidth of the network is 1 Gbps? Assume that the distance between the sender and the receiver is 12,000 km and that light travels at 2.4×10^8 m/s.

Solution

We can calculate the propagation and transmission time as

Propagation time = $(12{,}000 \times 1000) / (2.4 \times 10^8) = 50$ ms

Transmission time = $(2500 \times 8) / 10^9 = 0.020$ ms

Note that in this case, because the message is short and the bandwidth is high, the dominant factor is the propagation time, not the transmission time.

Example 3.47

Assume that the distance between the sender and the receiver is 12,000 km and that light travels at 2.4×10^8 m/s. What are the propagation time and the transmission time for a 5-MB (megabyte) message (an image) if the bandwidth of the network is 1 Mbps?

Solution

We can calculate the propagation and transmission times as

Propagation time = $(12{,}000 \times 1000) / (2.4 \times 10^8) = 50$ ms

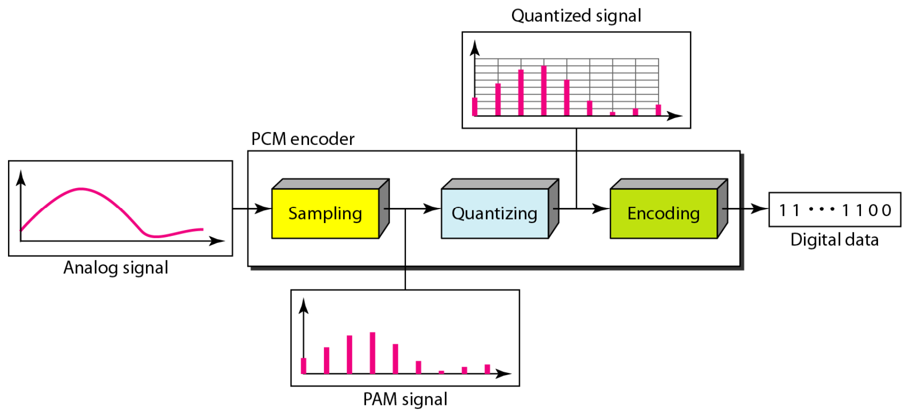
Transmission time = $(5{,}000{,}000 \times 8) / 10^6 = 40$ s

The dominant factor is transmission time now.

4. Analog-to-digital Conversion

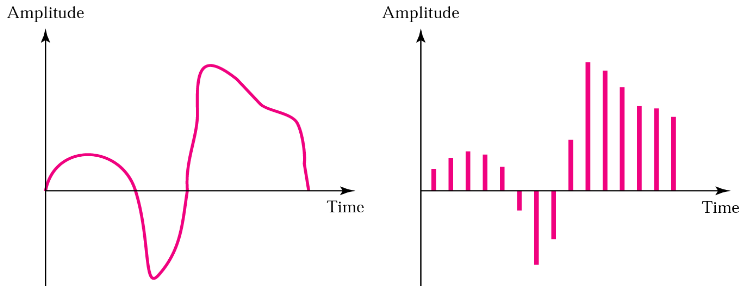
- Nowadays systems process digital data
- However, we may receive analog signal
  - Microphone, Camera, etc.
- Convert analog signal to digital data
  - Pulse Code Modulation (PCM)

Components of PCM encoder

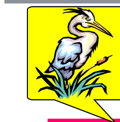


Sampling - Pulse Amplitude Modulation (PAM)

- Analog signal is sampled every T_s
  - T_s is the sample interval
  - $f_s = 1/T_s$ is the sampling rate (or sampling frequency)



a. Analog signal b. PAM signal



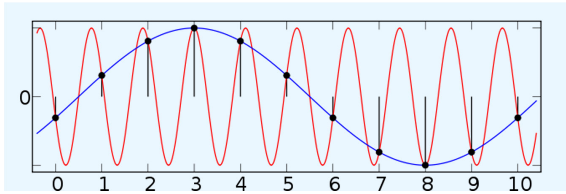
Note: How many samples are sufficient?

According to the Nyquist theorem, the sampling rate must be at least 2 times the highest frequency contained in the signal

Nyquist rate = $2 \times f_{max}$

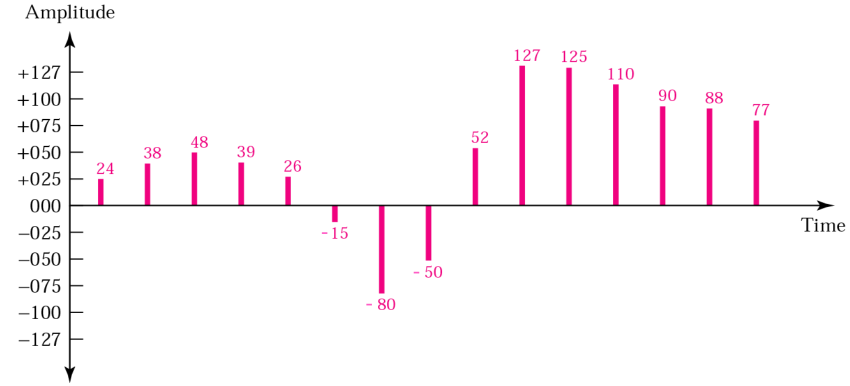
(to ensure the accurate reproduction of the original signal)

Undersampling *will reproduce another signal with lower frequency*



Quantization

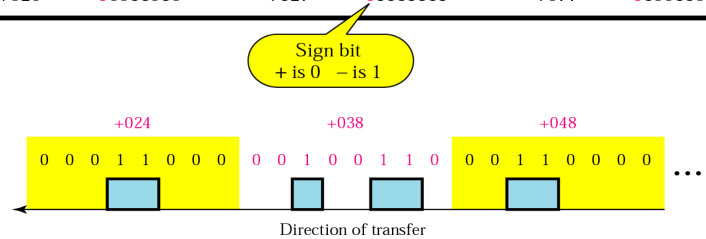
- Assign quantized values to quantization levels
- Approximate the sample amplitude to the quantized values



Represent the quantized samples by bits

- How many bits are required per sample?
  - $n_b = \log_2 L$ (L is the number of quantization levels)

+024	00011000	−015	10001111	+125	01111101
+038	00100110	−080	11010000	+110	01101110
+048	00110000	−050	10110010	+090	01011010
+039	00100111	+052	00110110	+088	01011000
+026	00011010	+127	01111111	+077	01001101



Quantization Error

- Quantization is an approximation process.
- The value of the difference of the actual value and the quantized value is the quantization error.
- This error is regarded as a noise.

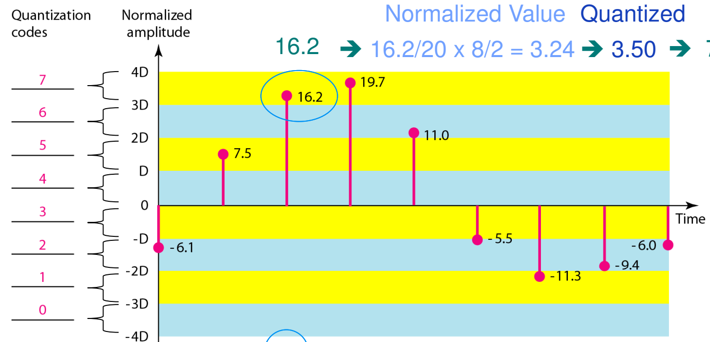
- The signal-to-noise (in dB) ratio depends on the number of bits per sample (n_b), which is calculated in the following formula:

$$SNR_{dB} = 6.02n_b + 1.76 \text{ dB}$$

Quantization and encoding of a sampled signal

Normalized Value Quantized

16.2 → 16.2/20 x 8/2 = 3.24 → 3.50 → 7



Normalized PAM values	-1.22	1.50	3.24	3.94	2.20	-1.10	-2.26	-1.88	-1.20
Normalized quantized values	-1.50	1.50	3.50	3.50	2.50	-1.50	-2.50	-1.50	-1.50
Normalized error	-0.38	0	+0.26	-0.44	+0.30	-0.40	-0.24	+0.38	-0.30
Quantization code	2	5	7	7	6	2	1	2	2
Encoded words	010	101	111	111	110	010	001	010	010

Example

What is the quantization error (SNR_{dB}) in the previous slide?

Solution

We can use the formula to find the quantization. We have eight levels and 3 bits per sample, so

$$SNR_{dB} = 6.02(3) + 1.76 = 19.82 \text{ dB}$$

Increasing the number of levels increases the SNR.

Example

We want to digitize the human voice. Assuming 8 bits per sample, what is the bit rate?

Solution

The human voice normally contains frequencies from 0 to 4000 Hz.

Sampling rate = 2 x 4000 = 8000 samples/s

Bit rate = sampling rate x number of bits per sample
= 8000 x 8 = 64,000 bps = 64 Kbps

Summary

- **Analog Signal and Digital Signal**
  - **Periodic and aperiodic**
  - **Time domain and frequency domain**
- **Transmission Impairment**
  - **Attenuation, Distortion, Noise**
- **Data rate limit**
  - **Nyquist bit rate (for noiseless channel)**
  - **Shannon capacity (for noisy channel)**
- **Analog-to-digital Conversion (PCM)**
  - **Sampling, quantization**
- **Revision Quiz**
  - http://highered.mheducation.com/sites/0073376221/student_view0/chapter3/quizzes.html