DATA AND SIGNALS

Analog and Digital Data

-analog data refers to information that is continuous;

For example, the sounds made by a human voice, take on continuous values.

-digital data refers to information that has discrete states.

For example, data are stored in computer memory in the form of 0s and 1s (take on discrete values).

Analog and Digital Signals

Like the data they represent, signals can be either analog or digital.

-An analog signal has infinitely many levels of intensity over a period of time.

-A digital signal, can have only a limited number of defined values. Although each value can be any number, it is often as simple as 1 and 0.

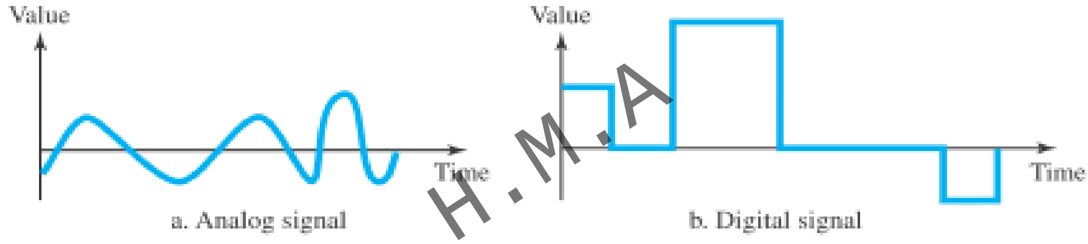

Figure 3.1 Comparison of analog and digital signals

Periodic and Nonperiodic

Both analog and digital signals can take one of two forms: periodic or nonperiodic(aperiodic)

-A periodic signal completes a pattern within a measurable time frame, called a period, and repeats that pattern over subsequent identical periods.

The completion of one full pattern is called a cycle.

-A nonperiodic signal changes without exhibiting a pattern or cycle that repeats over time.

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

PERIODIC ANALOG SIGNALS

Periodic analog signals can be classified as simple or composite.

-A simple periodic analog signal, a sine wave, cannot be decomposed into simpler signals.

-A composite periodic analog signal is composed of multiple sine waves.

Sine Wave

The sine wave is the most fundamental form of a periodic analog signal.

Figure 3.2 shows a sine wave. Each cycle consists of a single arc above the time axis followed by a single arc below it.

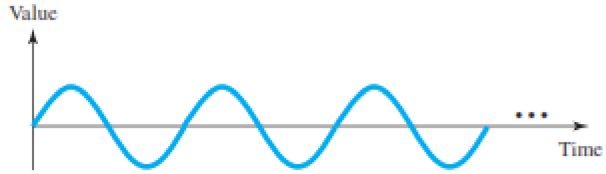

Figure 3.2sine wave

A sine wave can be represented by three parameters: the peak amplitude, the frequency, and the phase. These three parameters fully describe a sine wave.

Peak Amplitude

The peak amplitude of a signal is the absolute value of its highest intensity, proportional to the energy it carries. For electric signals, peak amplitude is normally measured in volts. Figure 2.3 shows two signals and their peak amplitudes.

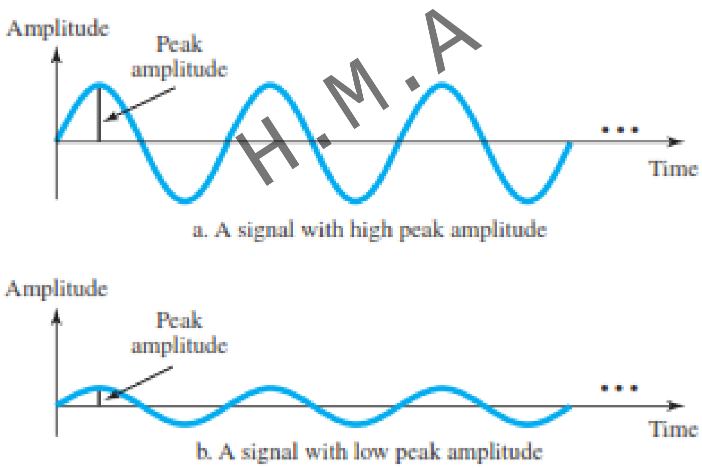

Figure 3.3 Two signals with the same phase and frequency, but different amplitudes

Period and Frequency

-Period refers to the amount of time, in seconds, a signal needs to complete 1 cycle.

-Frequency refers to the number of periods in 1 s. Note that period and frequency are just

one characteristic defined in two ways. Period is the inverse of frequency, and frequency is the inverse of period, as the following formulas show.

$f=1/T$ and $T=1/f$

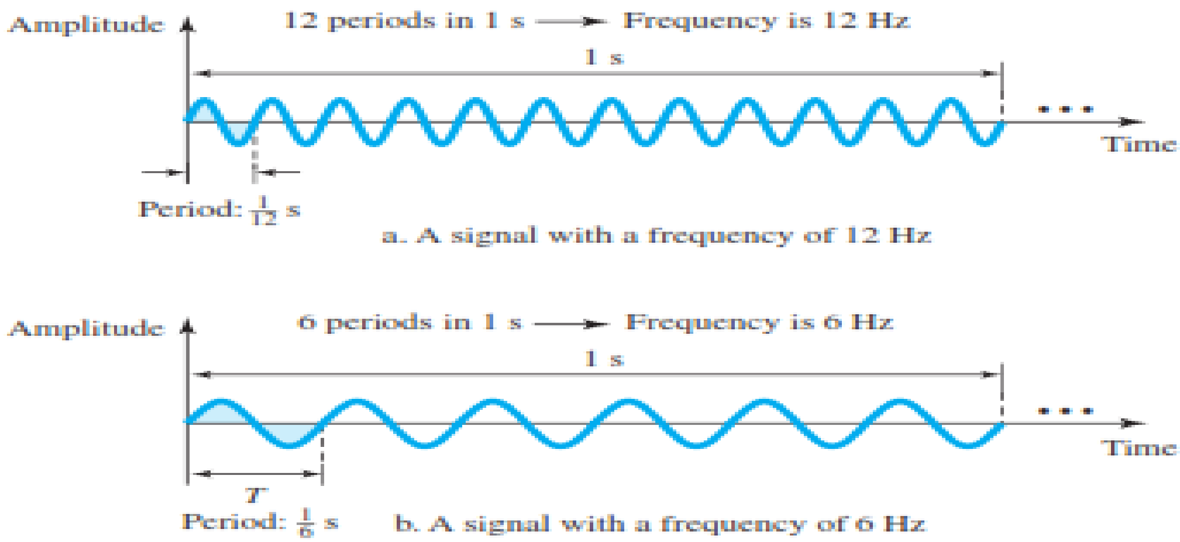

Figure 3.4 Two signals with the same amplitude and phase, but different frequencies

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

The term phase, or phase shift, describes the position of the waveform relative to time 0.

Phase is measured in degrees or radians [360º is 2π rad; 1º is 2π/360 rad, and 1 rad is 360/(2π)].

a. A sine wave with a phase of 0° is not shifted.

b. A sine wave with a phase of 90° is shifted to the left by cycle. However, note that the signal does not really exist before time 0.

c. A sine wave with a phase of 180° is shifted to the left by cycle. However, note that the signal does not really exist before time 0.

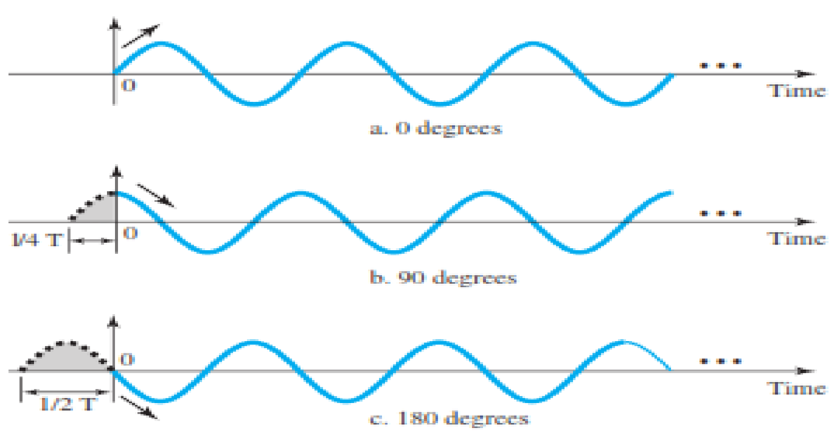

Figure 3.5 Three sine waves with the same amplitude and frequency, but different phases

Wavelength

Wavelength is another characteristic of a signal traveling through a transmission medium. Wavelength binds the period or the frequency of a simple sine wave to the propagation speed of the medium (see Figure 3.6).

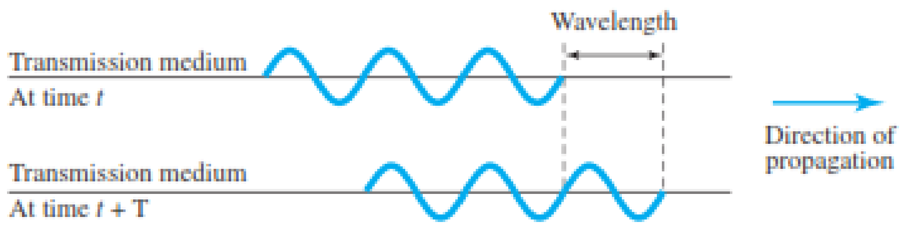

Figure 3.6 Wavelength and period

Wavelength = (propagation speed) × period= propagation speed/ frequency

$\lambda = c/f$

Time and Frequency Domains

-The time-domain plot shows changes in signal amplitude with respect to time

- A frequency-domain plot is concerned with only the peak value and the frequency.

- The advantage of the frequency domain is that we can immediately see the values of the frequency and peak amplitude.

- A complete sine wave in the time domain can be represented

by one single spike in the frequency domain..

- The position of the spike shows the frequency; its height shows the peak amplitude.

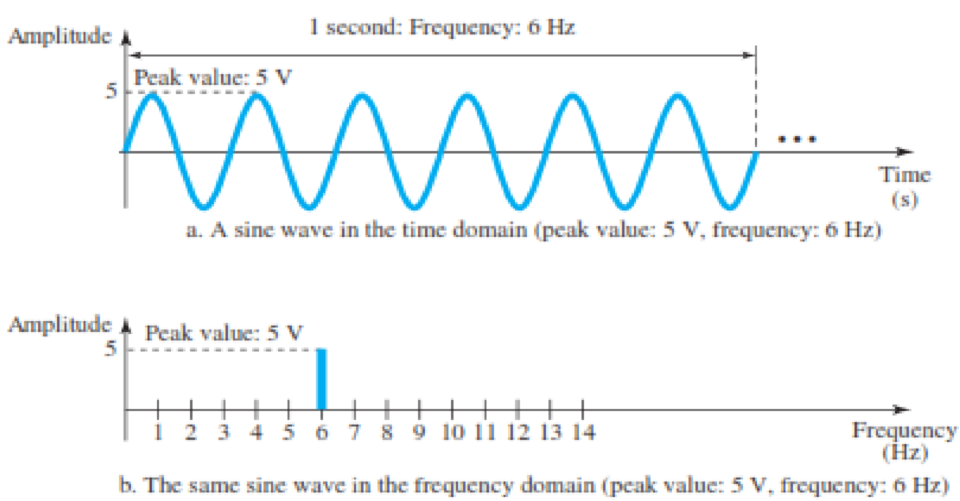

Figure 3.7 The time-domain and frequency-domain plots of a sine wave

Composite Signals

A composite signal is made of many simple sine waves.

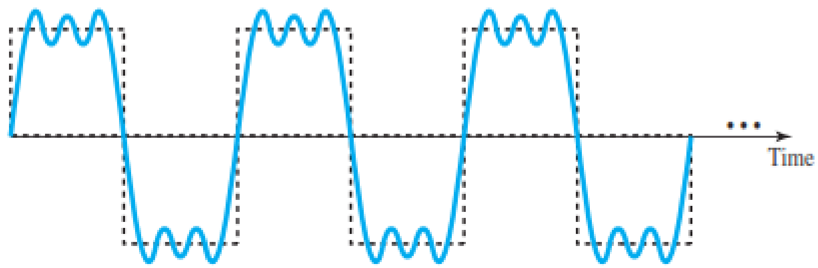

Figure 3.9 A composite periodic signal

- single-frequency sine wave is not useful in data communications;

we need to send a composite signal, a signal made of many simple sine waves.

- A composite signal can be periodic or nonperiodic.

- If the composite signal is periodic, the decomposition gives a series of signals with discrete frequencies;

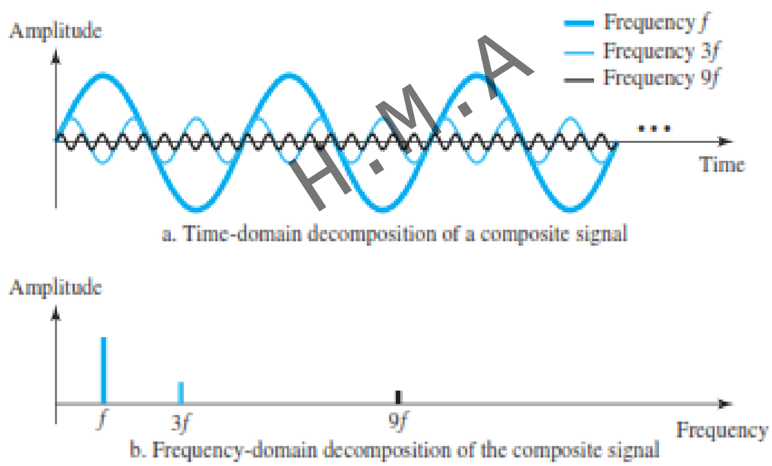

Figure 3.10 Decomposition of a composite periodic signal in the time and frequency domains

-if the composite signal is nonperiodic, the decomposition

gives a combination of sine waves with continuous frequencies.

Bandwidth

The bandwidth of a composite signal is the difference between the

highest and the lowest frequencies contained in that signal.

For example, if a composite signal contains frequencies between 1000 and 5000, its bandwidth is 5000 − 1000, or 4000.

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

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

DIGITAL SIGNALS

Bit Rate

-Most digital signals are nonperiodic, and thus period and frequency are not appropriate characteristics. Another term—bit rate (instead of frequency) is used to describe digital signals.

The bit rate is the number of bits sent in 1s, expressed in bits per second (bps).

Example

Assume we need to download text documents at the rate of 100 pages per second. What is the required bit rate of the channel?

Solution

A page is an average of 24 lines with 80 characters in each line. If we assume that one character requires 8 bits, the bit rate is

$100 \times 24 \times 80 \times 8 = 1{,}536{,}000$ bps = 1.536 Mbps

Bit Length

The bit length is the distance one bit occupies on the transmission medium.

Bit length = propagation speed × bit duration

TRANSMISSION IMPAIRMENT

Signals travel through transmission media, which are not perfect. The imperfection causes signal impairment. This means that 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, and noise

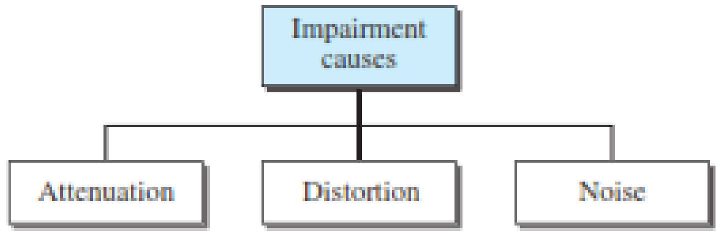

Figure 3.11Causes of impairment

Attenuation

Attenuation means a loss of energy. When a signal, simple or composite, travels through a medium, it loses some of its energy in overcoming the resistance of the medium. That is why a wire carrying electric signals gets warm, if not hot, after a while. Some of the electrical energy in the signal is converted to heat. To compensate for this loss, amplifiers are used to amplify the signal. Figure 3.12 shows the effect of attenuation and amplification

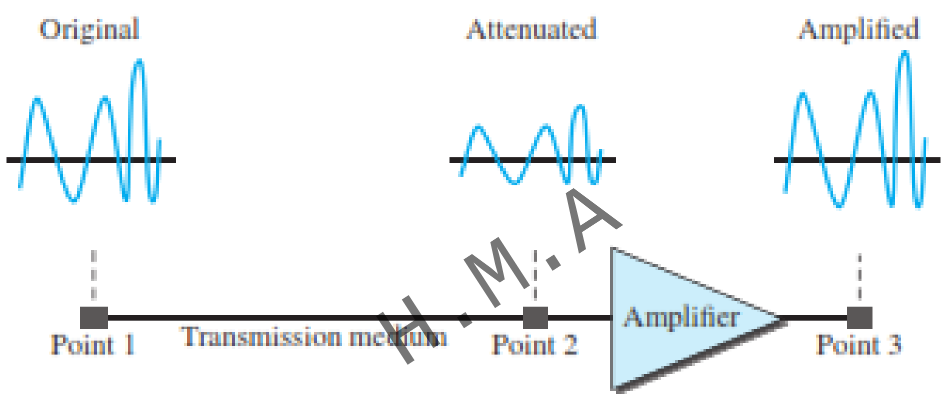

Figure 3.12 Attenuation

Decibel

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

Note that the decibel is negative if a signal is attenuated and positive if a signal is amplified.

dB= $10 \log_{10} P_2/P_1$ Variables P_1 and P_2 are the powers of a signal at points 1 and 2, respectively.

Distortion

Distortion means that the signal changes its form or shape. Distortion can occur in a composite signal made of different frequencies. Each signal component has its own propagation speed through a medium and, therefore, its own delay in arriving at the final destination. Differences in delay may create a difference in phase if the delay is not exactly the same as the period duration. In other words, signal components at the receiver have phases different from what they had at the sender. The shape of the composite signal is therefore not the same. Figure 3.13 shows the effect of distortion on a composite signal.

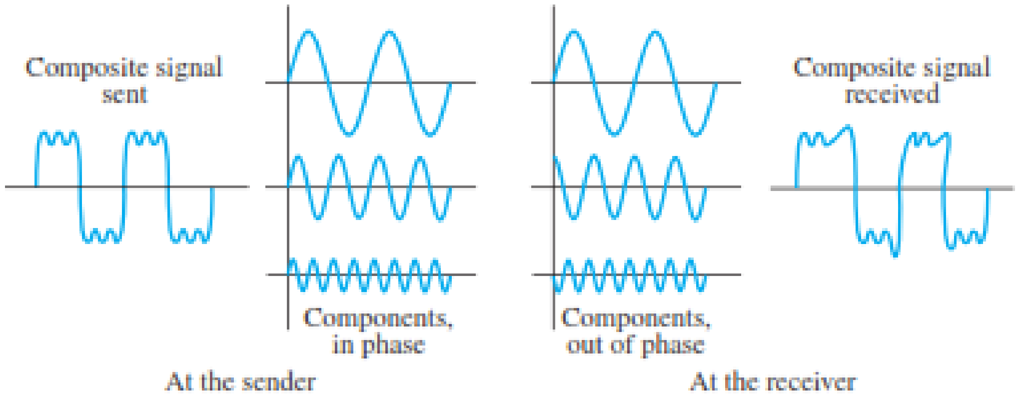

Figure 3.13 Distortion

Noise

Noise is another cause of impairment. Several types of noise, such as thermal noise, induced noise, crosstalk, and impulse noise, may corrupt the signal.

-Thermal noise is the random motion of electrons in a wire, which creates an extra signal not originally sent by the transmitter.

-Induced noise comes from sources such as motors and appliances. These devices act as a sending antenna, and the transmission medium acts as the receiving antenna.

-Crosstalk is the effect of one wire on the other. One wire acts as a sending antenna and the other as the receiving antenna.

-Impulse noise is a spike (a signal with high energy in a very short time) that comes from power lines, lightning, and so on. Figure below shows the effect of noise on a signal.

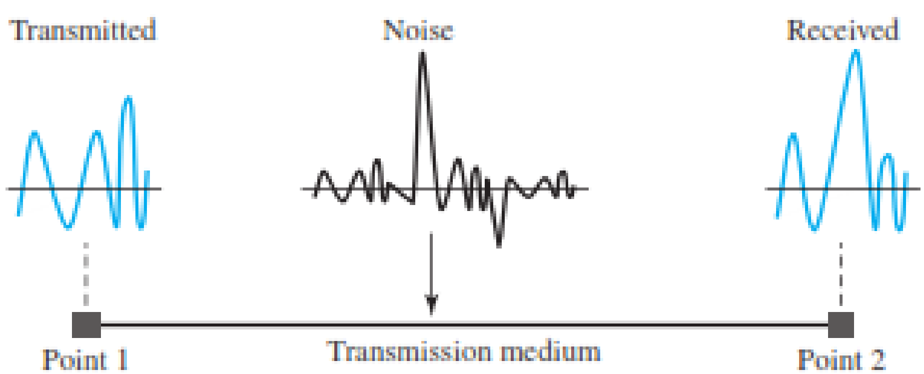

Figure 3.14 Noise

Signal-to-Noise Ratio (SNR)

The signal-to-noise ratio is defined as SNR =average signal power/ average noise power

* A high SNR means the signal is less corrupted by noise; a low SNR means the signal is more corrupted by noise.

* Because SNR is the ratio of two powers, it is often described in decibel units, SNR_{dB}, defined as $SNR_{dB} = 10 \log_{10} SNR$

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:

$SNR = (10{,}000\ \mu w) / (1\ \mu w) = 10{,}000$ $SNR_{dB} = 10 \log_{10} 10{,}000 = 10 \log_{10} 10^4 = 40$

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)

*Two theoretical formulas were developed to calculate the data rate: one by **Nyquist** for a noiseless channel, another by **Shannon** for a noisy channel.

Noiseless Channel: Nyquist Bit Rate

For a noiseless channel, the Nyquist bit rate formula defines the theoretical maximum bit rate

$BitRate = 2 \times bandwidth \times \log_2 L$

In this formula, bandwidth is the bandwidth of the channel, L is the number of signal levels used to represent data, and BitRate is the bit rate in bits per second.

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

Example

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

$\text{BitRate} = 2 \times 3000 \times \log_2 4 = 12{,}000$ 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, to determine the theoretical highest data rate for a noisy channel: $\text{Capacity} = \text{bandwidth} \times \log_2(1 + \text{SNR})$

* the formula defines a characteristic of the channel, not the method of transmission.

Example

The signal-to-noise ratio is often given in decibels. Assume that $SNR_{dB} = 36$ and the channel bandwidth is 2 MHz. The theoretical channel capacity can be calculated as

$SNR_{dB} = 10 \log_{10} SNR$ $\quad SNR = 10^{SNRdB/10}$ $\quad SNR = 10^{3.6} = 3981$

$C = B \log_2(1 + SNR) = 2 \times 10^6 \times \log_2 3982 = 24$ Mbps

Using Both Limits

In practice, we need to use both methods to find the limits and signal levels. Let us show this with an example.

Example

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

Solution

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

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

The Shannon formula gives us 6 Mbps, the upper limit. For better performance we choose something lower, 4 Mbps, for example. Then we use the Nyquist formula to find the number of signal levels.

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

* The Shannon capacity gives us the upper limit; the Nyquist formula tells us how many signal levels we need.

Bandwidth

the term Bandwidth can be used in two different contexts with two different measuring values: bandwidth in hertz and bandwidth in bits per second

-The first, bandwidth in hertz, refers to the range of frequencies in a composite signal or the range of frequencies that a channel can pass.

-The second, bandwidth in bits per second, refers to the speed of bit transmission in a channel or link.

Throughput

The throughput is a measure of how fast we can actually send data through a network.

For example, we may have a link with a bandwidth of 1 Mbps, but the devices connected to the end of the link may handle only 200 kbps. This means that we cannot send more than 200 kbps through this link.

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

Throughput = (12,000 × 10,000) / 60 = 2 Mbps

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

Latency (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.

Latency = propagation time + transmission time + queuing time + processing delay

Propagation Time

Propagation time measures the time required for a bit to travel from the source to the destination.

Propagation time = Distance / (Propagation Speed)

The propagation speed of electromagnetic signals depends on the medium and on the frequency of the signal.

Transmission Time

The transmission time of a message depends on the size of the message and the bandwidth of the channel (In data communications we don’t send just 1 bit, we send a message).

Transmission time = (Message size) / Bandwidth

Example

What are the propagation time and the transmission time for a 2.5-KB (kilobyte) message (an email) 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 × 108 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. The transmission time can be ignored.

Queuing Time

the time needed for each intermediate or end device to hold the message before it can be processed. The queuing time is not a fixed factor; it changes with the load imposed on the network.

Bandwidth-Delay Product

The bandwidth-delay product defines the number of bits that can fill the link. (Bandwidth and delay are two performance metrics of a link)

Jitter

Another performance issue that is related to delay is jitter, for example). If the delay for the first packet is 20 ms, for the second is 45 ms, and for the third is 40 ms, then the real-time application that uses the packets endures jitter.