PART II

Physical Layer

Chapters

Chapter 3

Signals

Note:

To be transmitted, data (analog or digital) must be transformed to electromagnetic signals.

Analog and Digital

Analog and Digital Data

Analog and Digital Signals

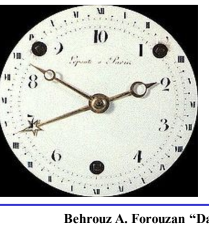
Periodic and Aperiodic Signals

ANALOG and DIGITAL

Data

Analog data: refers to information that is continuous as analog clock and human voice. This can be converted to analog signal or sampled and converted to digital signal

digital data: refers to information that has discrete states as digital clock and data stored in computer memory in forms of 1s and 0s . This can be converted to digital signal or modulated into an analog signal.



Note

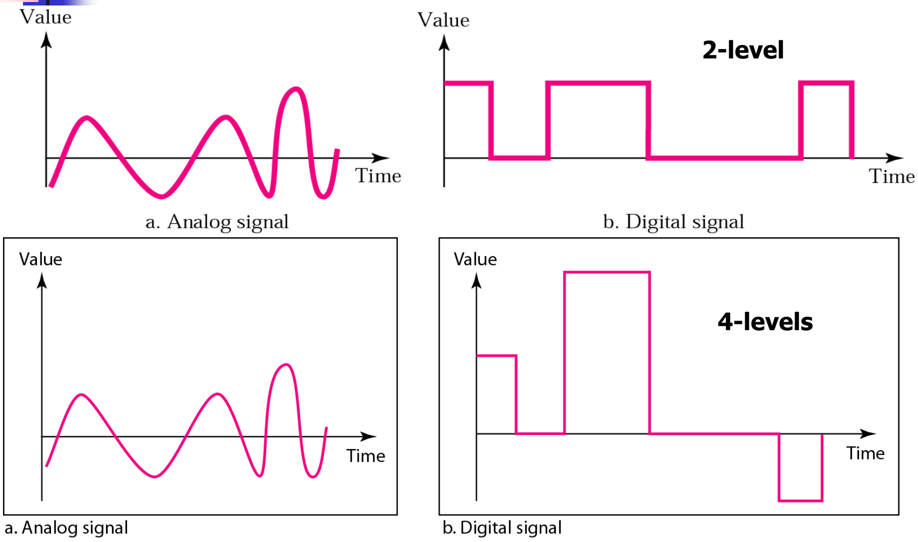
Data can be analog or digital.
Analog data are continuous and take continuous values.
Digital data have discrete states and take discrete values.

Note

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.**

Comparison of analog and digital signals



Periodic and aperiodic signals

Both digital and analog can be periodic or aperiodic (non periodic) signals

Periodic signal : It consists of repeating pattern within a measurable time called a period. The competition of full pattern called cycle.

Aperiodic : changes without exhibiting a pattern or cycle repeats over time.

In data communications, we commonly use periodic analog signals(need less B-W) and nonperiodic digital signals (they can represent many variation).

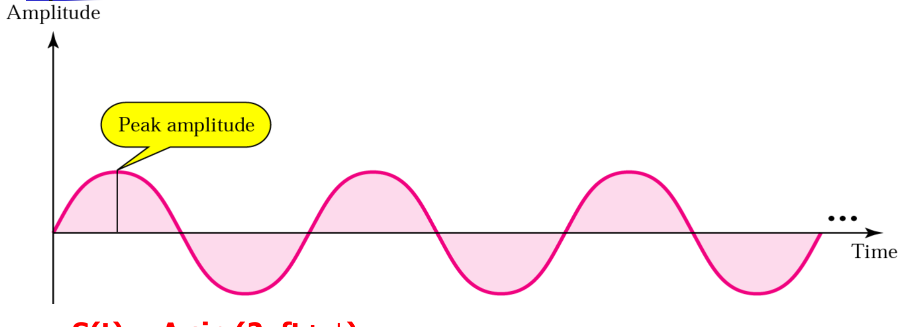
3-2 PERIODIC ANALOG SIGNALS

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.

Sin wave



S(t)= A sin (2πft+ ϕ)

S: is the instantaneous amplitude

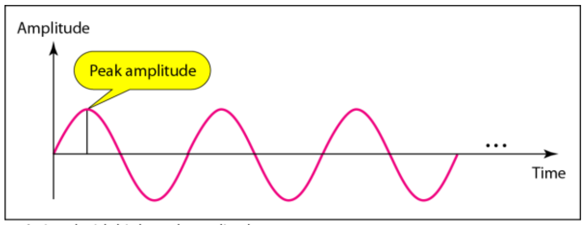
A: peak amplitude(absolute value of its highest intensity)

F: frequency

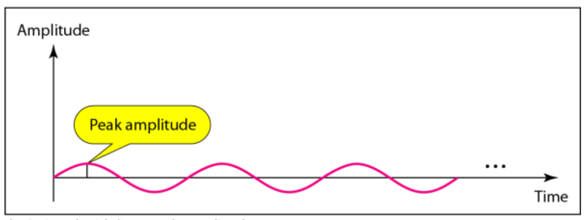
ϕ : Phase shift

Peak Amplitude

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

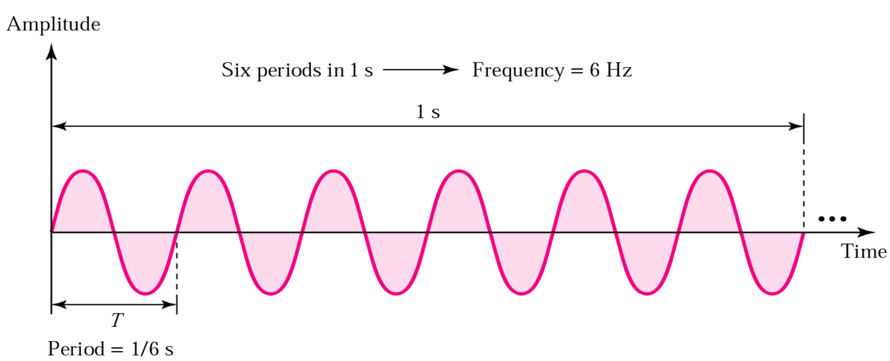


a. A signal with high peak amplitude



b. A signal with low peak amplitude

Period and frequency



Period: **amount of time in sec. a signal can complete one cycle (amount of time signal takes for one repetition)**

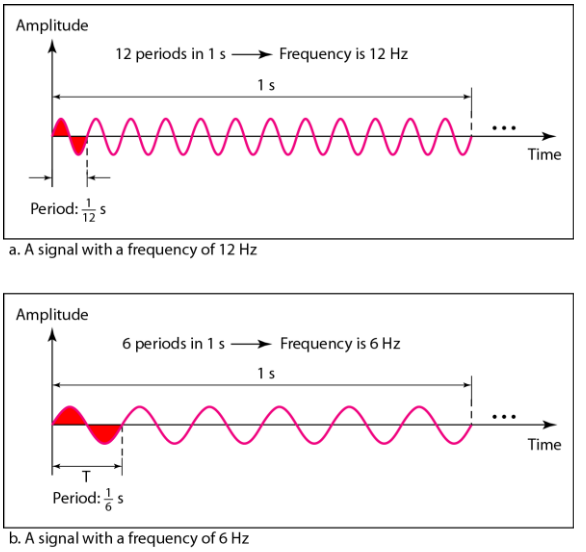
Frequency: no of cycles (period s) per sec.

Note:

Frequency and period are the inverse of each other.

$$f = \frac{1}{T} \quad \text{and} \quad T = \frac{1}{f}$$

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



$F_a = 2\ F_b$

$T_a = 1/2\ T_b$

Units of periods and frequencies

Unit	*Equivalent*	*Unit*	*Equivalent*
Seconds (s)	1 s	Hertz (Hz)	1 Hz
Milliseconds (ms)	10^{-3} s	Kilohertz (kHz)	10^{3} Hz
Microseconds (μs)	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

Example

The power we use at home has a frequency of 60 Hz. The period of this sine wave can be determined as follows:

$$T = \frac{1}{f} = \frac{1}{60} = 0.0166 \text{ s} = 0.0166 \times 10^{3} \text{ ms} = 16.6 \text{ ms}$$

Note: our eyes are not sensitive enough to distinguish these rapid changes in amplitude

Example

Express a period of 100 ms in microseconds, and express the corresponding frequency in kilohertz.

Solution

From previous table we find the equivalent of 1 ms. We make the following substitutions:

$100\text{ ms} = 100 \times 10^{-3}\text{ s} = 100 \times 10^{-3} \times 10^{6}\ \mu\text{s} = 10^{5}\ \mu\text{s}$

Now we use the inverse relationship to find the frequency, changing hertz to kilohertz

$100\text{ ms} = 100 \times 10^{-3}\text{ s} = 10^{-1}\text{ s}$

$f = 1/10^{-1}\text{ Hz} = 10 \times 10^{-3}\text{ KHz} = 10^{-2}\text{ KHz}$

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.

Note

Two Extremes

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

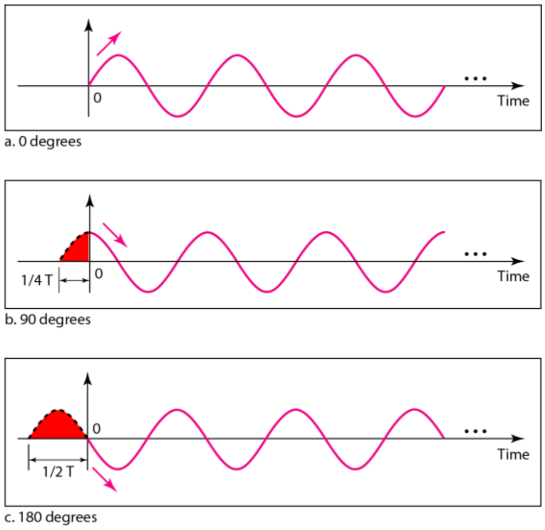
Phase shift

- ***Phase describes the position of the waveform relative to time zero.***
- ***Phase is measured in degrees or radians***

$1^{O} = 2\pi/360$ rad & 1 rad $= 360/2\pi$ ^{o}

- ***A phase shift of 360 :shift of a complete period***
- ***A phase shift of 180: one half of a period(1/2 cycle) .***
- ***A phase shift of 90: one quarter of period (1/4) cycle.***

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



starts at 0 with Zero amplitude. The amplitude increasing.

Starts at time Zero with a peak amplitude. The amplitude is decreasing

starts at time Zero with a zero amplitude. The amplitude is decreasing

Example

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

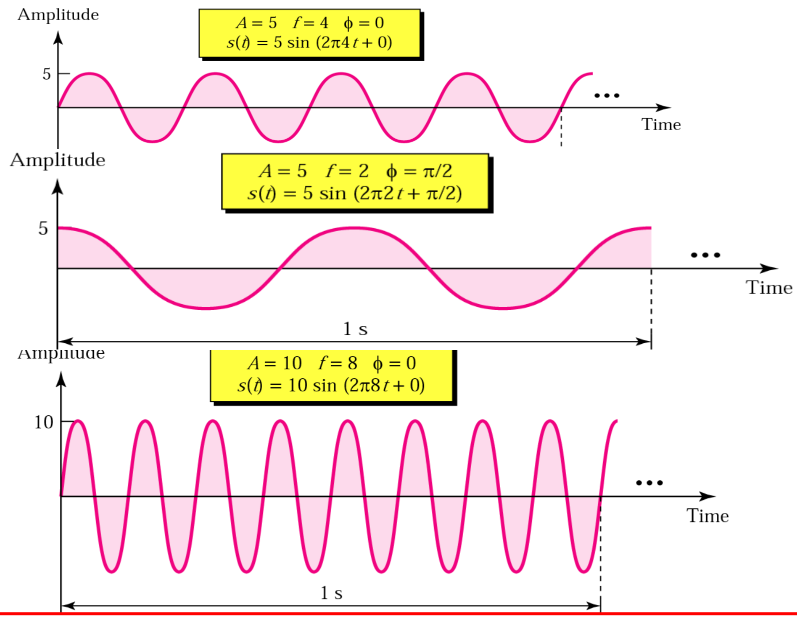
Solution

We know that one complete cycle is 360 degrees.

Therefore, 1/6 cycle is

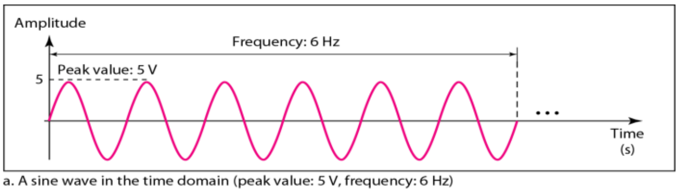
(1/6) 360 = 60 degrees = 60 x 2π /360 rad = 1.046 rad

Sine wave examples

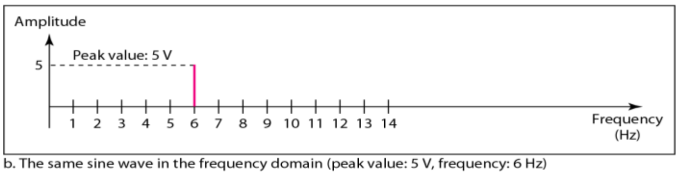


The time-domain and frequency-domain plots of a sine wave

Time domain plot: shows changes in signal amplitude with respect to time
Frequency domain plot: is concerned only with *peak value* of amplitude and the *frequency*



a. A sine wave in the time domain (peak value: 5 V, frequency: 6 Hz)



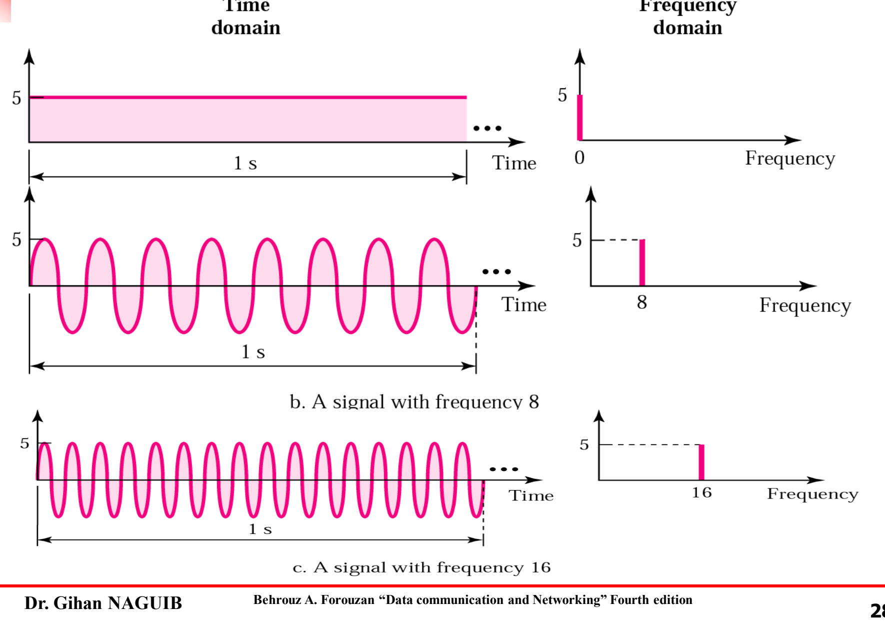
b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

Note

An analog signal is best represented in the frequency domain. WHY?

- *A complete sine wave in the time domain can be represented by one single spike in the frequency domain.*
- *we show two characteristics of a signal (amplitude and frequency) with only one spike*
- *Frequency domain is more compact and useful when we are dealing with more than on sine wave (composite signal)*

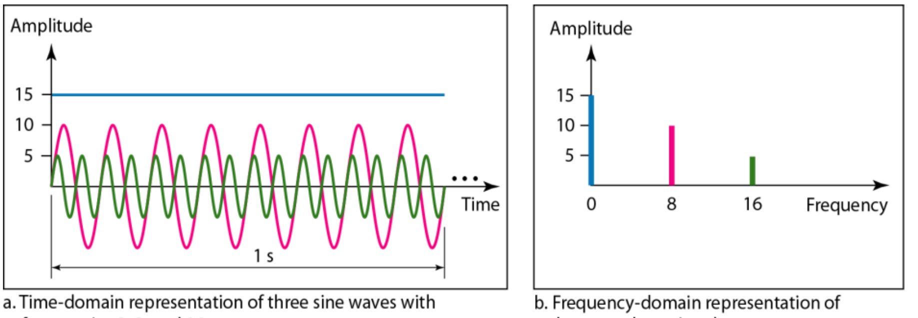
Time and frequency domains



Example

The frequency domain is more compact and useful when we are dealing with more than one sine wave. For example, the following Figure shows three sine waves, each with different amplitude and frequency. All can be represented by three spikes in the frequency domain.

The time domain and frequency domain of composite signal



a. Time-domain representation of three sine waves with frequencies 0, 8, and 16

b. Frequency-domain representation of the same three signals

Note:

- ***A single-frequency sine wave (simple sine wave) is not useful in data communications; we need to change one or more of its characteristics to make it useful.***
- ***When we change one or more characteristics of a single-frequency signal, it becomes a composite signal made of many frequencies***

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

Note:

According to Fourier analysis, any composite signal can be represented as a combination of simple sine waves with different frequencies, phases, and amplitudes.

Fourier analysis

For periodic composite signal:

$S(t)= A_0 + A_1\sin(2\prod f_1 t+ \phi_1)+ A_2\sin(2\prod f_2 t+ \phi_2)+ A_3\sin(2\prod f_3 t+ \phi_3)+\ldots$

- A_0: Average value (DC component)
- f_1: Fundamental frequency or first harmonic. (the same frequency of the composite signal)
- f_2= 2 x f : second harmonic
- f_3= 3 x f : Third harmonic, … etc

A_0: Dc component

A1: The amplitude of the sin wave of frequency f_1(is the same as the peak amplitude of the composite signal)

A2: The amplitude of the sin wave of frequency f_2

A3: the amplitude of the sin wave of f_3

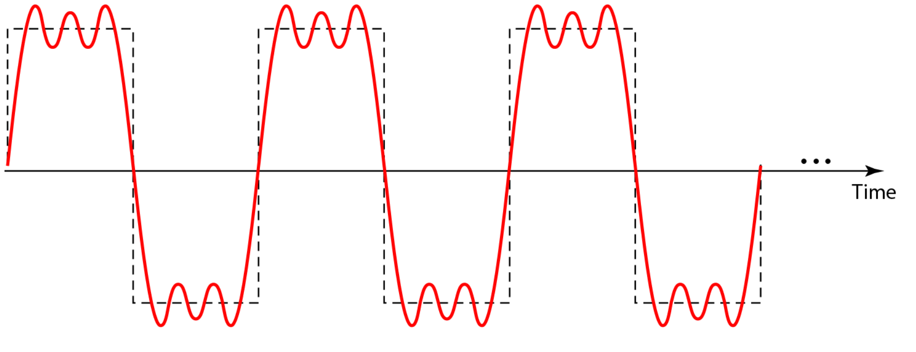
Note

If the composite signal is periodic, the decomposition gives a series of signals with discrete frequencies
if the composite signal is nonperiodic, the decomposition gives a combination of sine waves with continuous frequencies: frequencies that have real values .

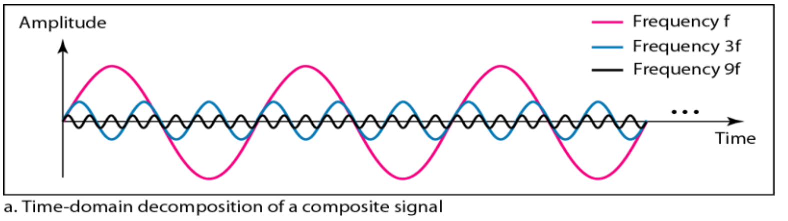
Example

The Figure shows a periodic composite signal with frequency f. This type of signal is not typical of those found in data communications.. The analysis of this signal can give us a good understanding of how to decompose signals.

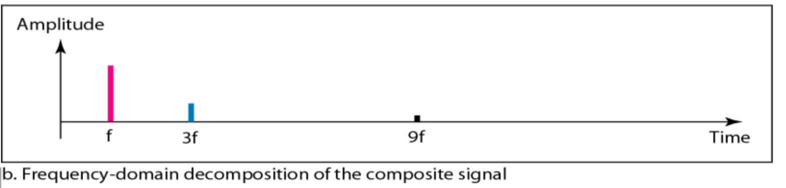
A composite periodic signal



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



a. Time-domain decomposition of a composite signal



b. Frequency-domain decomposition of the composite signal

Note

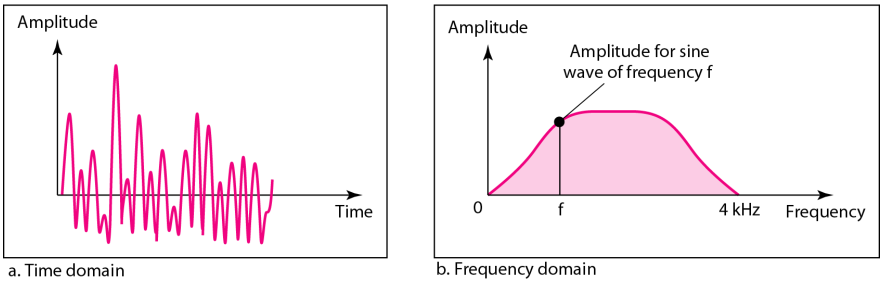
the frequencies decomposition of the signal is discrete and integral ; it has f, 3f and 9f.

Example

The following Figure shows a nonperiodic composite signal. It can be the signal created by a microphone or a telephone set when a word or two is pronounced. In this case, the composite signal cannot be periodic, because that implies that we are repeating the same word or words with exactly the same tone.

The number of frequencies in a human voice is infinite, the range is limited between o and 4KHZ.

The time and frequency domains of a __nonperiodic__ signal



Note

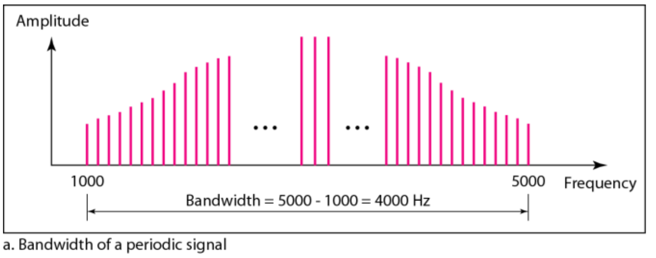
The frequency decomposition of the signal yields a continuous curve .There are an infinite number of frequencies between 0 and 4000HZ (real values)

The bandwidth

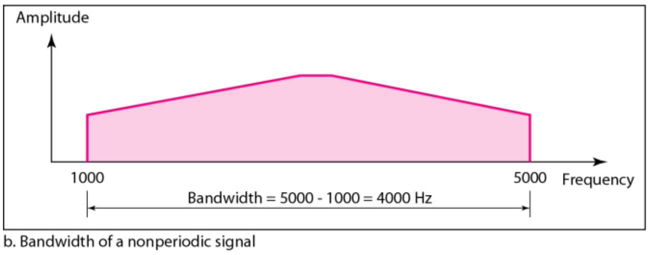
The bandwidth

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

The bandwidth of periodic and nonperiodic composite signals



a. Bandwidth of a periodic signal



b. Bandwidth of a nonperiodic signal

Note:

The term bandwidth refer to

➢ ***a property of a medium*: *It is the difference between the highest and the lowest frequencies that the medium can satisfactorily pass OR***

➢ ***The width of a signal spectrum***

signal spectrum*: *all frequencies contained in the signal .

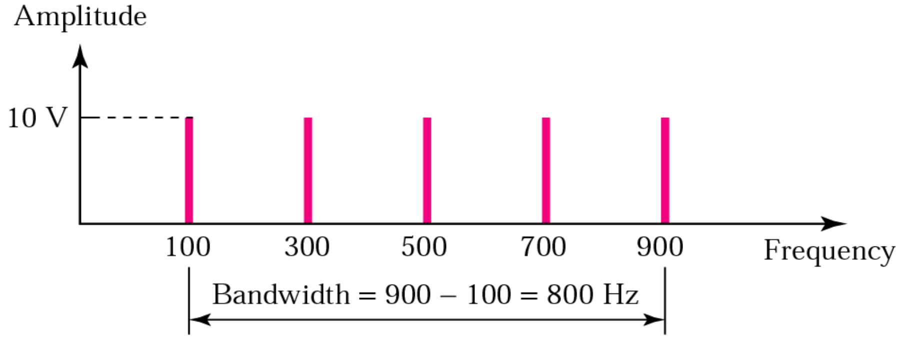
Example

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 10 V.

Solution

$B = f_h - f_l = 900 - 100 = 800$ Hz
The spectrum has only five spikes, at 100, 300, 500, 700, and 900

Example



Example

A periodic 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 frequencies of the same amplitude.

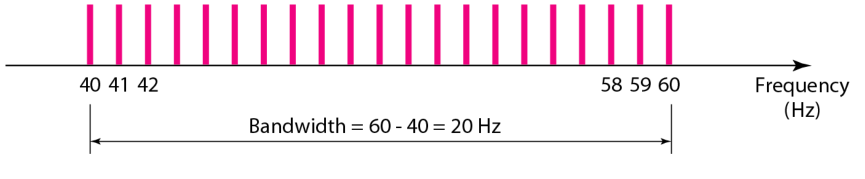
Solution

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

$$B = f_h - f_l \quad \Rightarrow \quad 20 = 60 - f_l \quad \Rightarrow \quad f_l = 60 - 20 = 40 \text{ Hz}$$

The spectrum contains all integer frequencies. We show this by a series of spikes (see the following Figure).

The bandwidth for the Example



Example

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?

Solution

The answer is definitely no. Although the signal can have the same bandwidth (1000 Hz), the range does not overlap. The medium can only pass the frequencies between 3000 and 4000 Hz; the signal is totally lost.

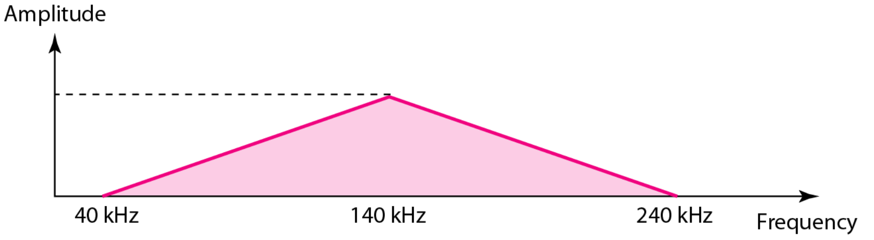
Example

A nonperiodic composite signal has a bandwidth of 200 kHz, with a middle frequency of 140 kHz and peak amplitude of 20 V. The two extreme frequencies have an amplitude of 0. Draw the frequency domain of the signal.

Solution

The lowest frequency must be at 40 kHz and the highest at 240 kHz. The following Figure shows the frequency domain and the bandwidth.

The bandwidth for the Example

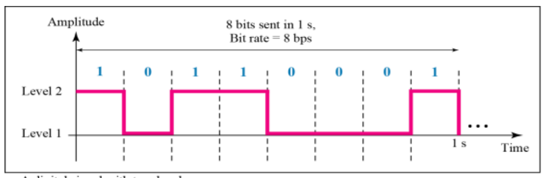


Examples 3.13, 3.14 and 3.15 (page 71) are excluded

DIGITAL SIGNALS

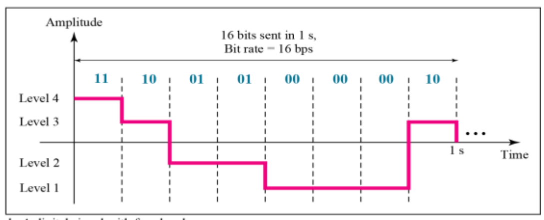
In addition to being represented by an analog signal, information can also be represented by a digital signal. For example, a 1 can be encoded as a positive voltage and a 0 as zero voltage. A digital signal can have more than two levels. In this case, we can send more than 1 bit for each level.

Two digital signals: one with two signal levels and the other with four signal levels



a. A digital signal with two levels

Send 1-bit per level



b. A digital signal with four levels

Send 2-bit per level

If a signal has L level, no of bits/level= $\log_2 L$ bits

Example

A digital signal has eight levels. How many bits are needed per level? We calculate the number of bits from the formula

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

Each signal level is represented by 3 bits.

Example

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

We calculate the number of bits by using the formula:

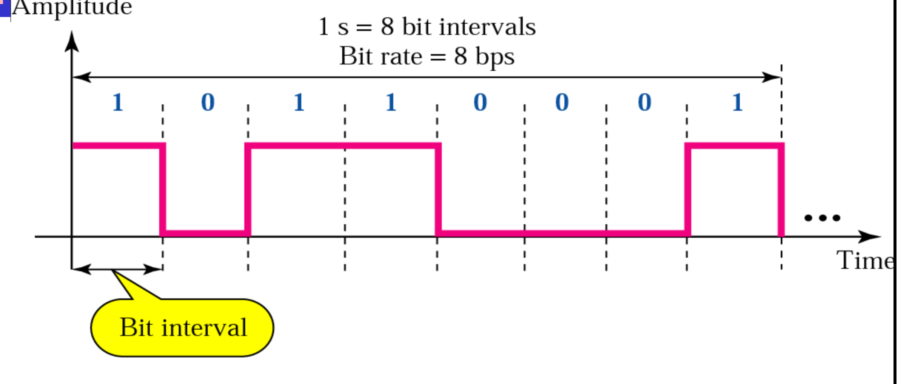
Log2 L= number of bits in each level

Log2 (9) = **3.17 bits.**

However, this answer is not realistic. The number of bits sent per level needs to be an integer as well as a power of 2.

For this example, 4 bits can represent one level.

Bit rate and bit interval



Most digital signals are nonperiodic, frequency and period are not appropriate. Another terms instead of frequency is bit rate and instead of period : bit interval (bit duration)

Bit rate: number of bits per second bps

Bit interval=1/bit rate

Example

A digital signal has a bit rate of 2000 bps. What is the duration of each bit (bit interval)

Solution

The bit interval is the inverse of the bit rate.

Bit interval = 1/ 2000 s = 0.000500 s
= 0.000500 x 10^6 µs = 500 µs

Example

Assume we need to download text documents at the rate of 100 pages per minute. 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:

$$\frac{100 \times 24 \times 80 \times 8}{60} = 25.6 \text{Kbps}$$

Digital Signal as a composite Analog Signal

Note

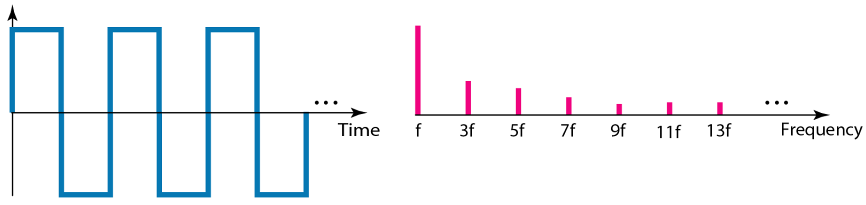
A digital signal is a composite analog signal with an infinite bandwidth.

Digital Signal as a composite Analog Signal

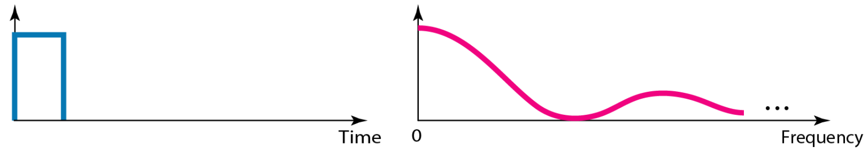
Fourier analysis can be used to decompose a digital signal

- ***If the digital signal is periodic (rare in data communications), the decomposed signal has a frequency domain representation with an infinite Bandwidth and discrete frequencies***
- ***If it is nonperiodic, the decomposed signal still has infinite B-W, but the frequencies are continuous.***

The time and frequency domains of periodic and nonperiodi c digital signals



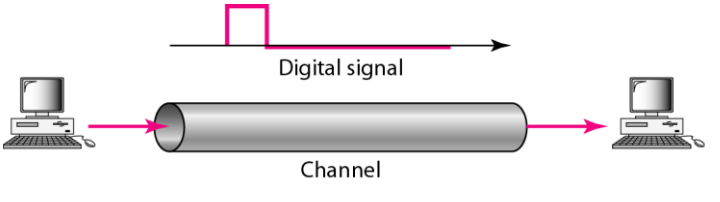
a. Time and frequency domains of periodic digital signal



b. Time and frequency domains of nonperiodic digital signal

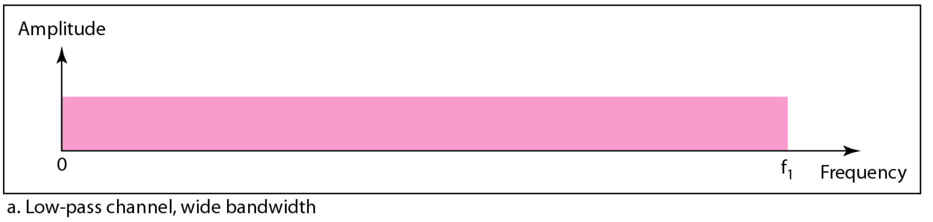
Transmission of Digital Signals

***Baseband transmission:* means sending a digital signal over a channel without changing the digital signal to an analog signal**

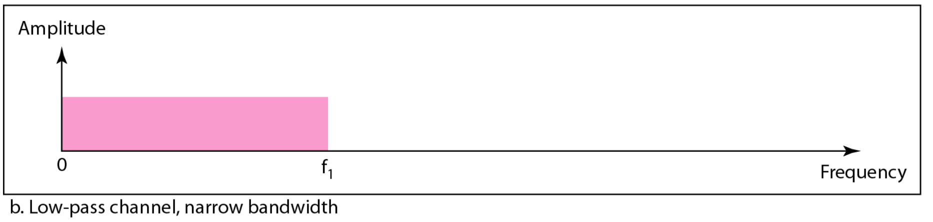


Base band transmission required a low-pass channel (channel with a B-W that starts from zero

Bandwidths of two low-pass channels



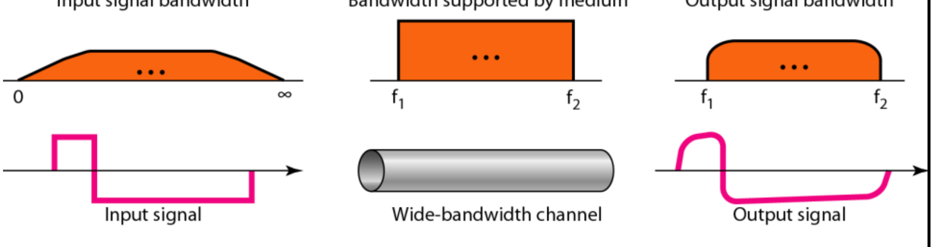
a. Low-pass channel, wide bandwidth



b. Low-pass channel, narrow bandwidth

Low-pass channel with wide B-W

Baseband transmission using a dedicated medium



•f_1 is close to zero, f_2 is very high

Note

Although the output signal is not exact the original signal , the data can still be deduced from the received signal.

Note

Baseband transmission of a digital signal that preserves the shape of the digital signal is possible only if we have a low-pass channel with an infinite or very wide bandwidth.

Note:

- ***A digital signal is a composite signal with an infinite bandwidth.***
- ***If a medium has a wide bandwidth, we can send a digital signal through it***

•Can we send data through a band-limited medium?

Yes (we send data by using band-limited telephone line to the Internet every day)

What is the minimum required bandwidth in HZ?

Note:

The bit rate and the bandwidth are proportional to each other. **if we need to send bits faster, we need more bandwidth**

Note:

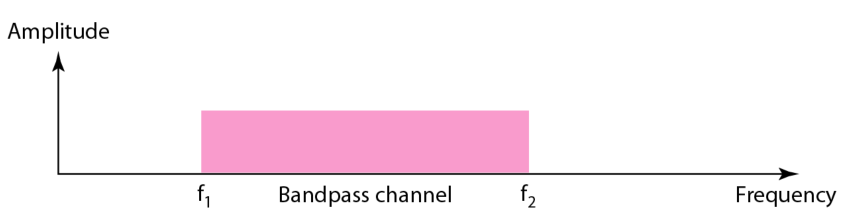
The analog bandwidth of a medium is expressed in hertz; the digital bandwidth, in bits per second.

Note:

Analog transmission can use a band-pass channel.

Bandwidth of a band-pass channel

Broadband Transmission or modulation means changing the digital signal to an analog signal for transmission. Modulation allows use a band-pass channel (a channel with a B-W that doesn't start from Zero. This type of channel is more available than a low-pass channel.



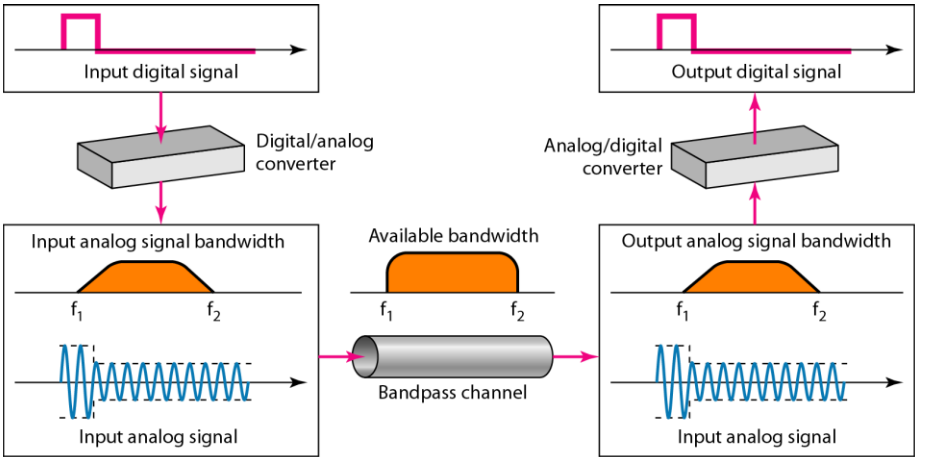
Note

A low-pass channel can be considered a band-pass channel with the lower frequency zero

Note

If the available channel is a bandpass channel, we cannot send the digital signal directly to the channel; we need to convert the digital signal to an analog signal before transmission.

Modulation of a digital signal for transmission on a bandpass channel



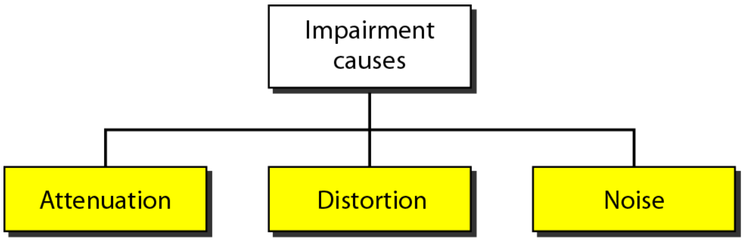
Example of broadband transmission

An example of broadband transmission using modulation is the sending of computer data through a telephone subscriber line, the line connecting a resident to the central telephone office. These lines are designed to carry voice with a limited bandwidth. The channel is considered a bandpass channel. We convert the digital signal from the computer to an analog signal, and send the analog signal. We can install two converters to change the digital signal to analog and vice versa at the receiving end. The converter, in this case, is called a modem

TRANSMISSION IMPAIRMENT

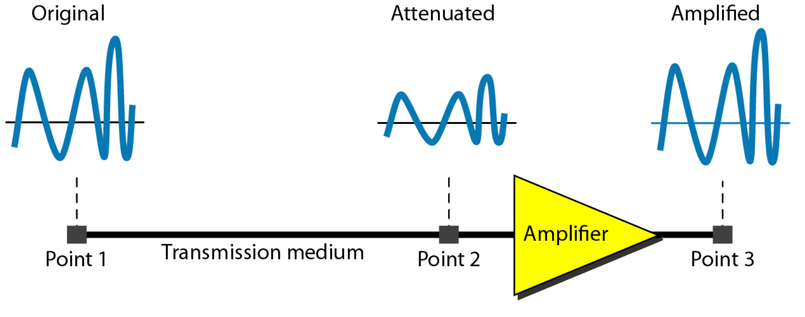
Signals travel through transmission media, which are not perfect. The imperfection causes signal impairment. This means that the signal at the beginning of the medium is not the same as the signal at the end of the medium. What is sent is not what is received. Three causes of impairment are attenuation, distortion, and noise.

Causes of impairment



Attenuation (means loss of energy)

when Signal travels through a medium, it losses some of its energy in overcoming the resistance of the medium. To compensate for this loss, amplifiers are used to amplify the signal.



Decibel: Measure the relative power (attenuation)

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

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.

Example

A signal travels through an amplifier, and its power is increased 10 times. This means that $P_2 = 10P_1$. In this case, the amplification (gain of power) can be calculated as

$$10\log_{10}\frac{P_2}{P_1} = 10\log_{10}\frac{10P_1}{P_1}$$

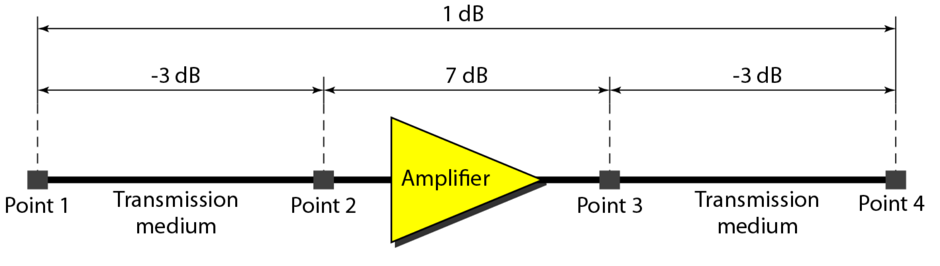
$$= 10\log_{10}10 = 10(1) = 10\text{ dB}$$

One reason that engineers use the decibel to measure the changes in the strength of a signal is that decibel numbers can be added (or subtracted) when we are measuring several points (cascading) instead of just two. In the following Figure a signal travels from point 1 to point 4.

Note

- **The decibel is negative if a signal is attenuated**
- **The decibel is positive if a signal is amplified**

Example



In this case, the decibel value can be calculated as

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

Example

The loss in a cable is usually defined in decibels per kilometer (dB/km). If the signal at the beginning of a cable with −0.3 dB/km has a power of 2 mW, what is the power of the signal at 5 km?

Solution

The loss in the cable in decibels is 5 × (−0.3) = −1.5 dB. We can calculate the power as

$$\text{dB} = 10 \log_{10} \frac{P_2}{P_1} = -1.5$$

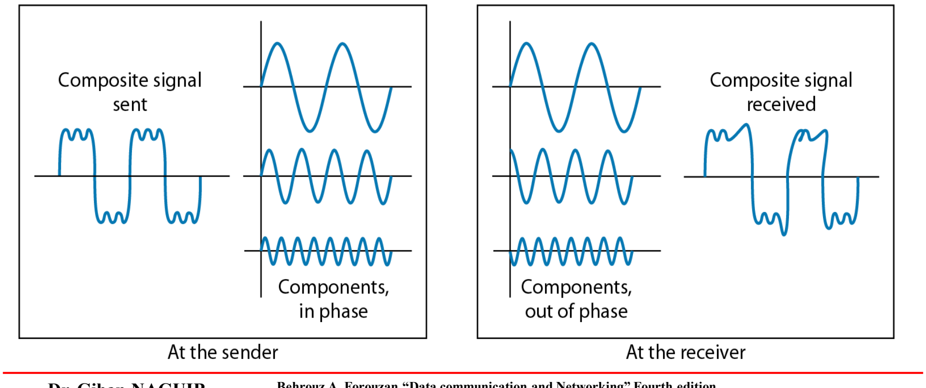
$$\frac{P_2}{P_1} = 10^{-0.15} = 0.71$$

$$P_2 = 0.71 P_1 = 0.7 \times 2 = 1.4 \text{ mW}$$

Distortion

Distortion : **means that signal changes its form or shape.**

➢ **Each signal component has its own propagation speed through the medium and therefore ,its own delay in arriving final destination**



Noise

Several types of noise:

- **Thermal noise**
- **Induced noise**
- **Crosstalk noise**
- **Impulse noise**

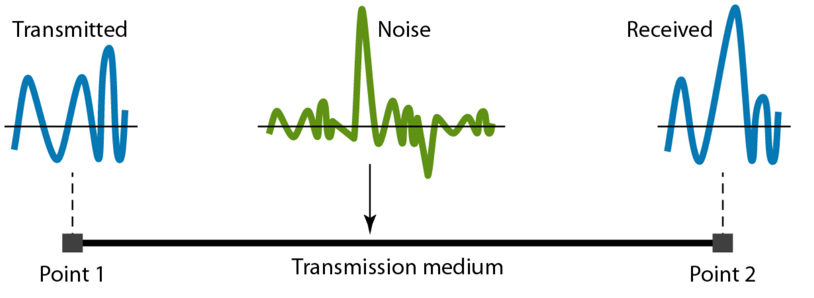
Noise

- **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.
- **Crosstalk noise:**
  Is the effect of one wire on the other

Noises

Impulse Noise:

is a spike (a signal with high energy in a very short time) that comes from power lines, lighting and so on.



Signal-to-Noise Ratio SNR

SNR: ratio between signal power to the noise power

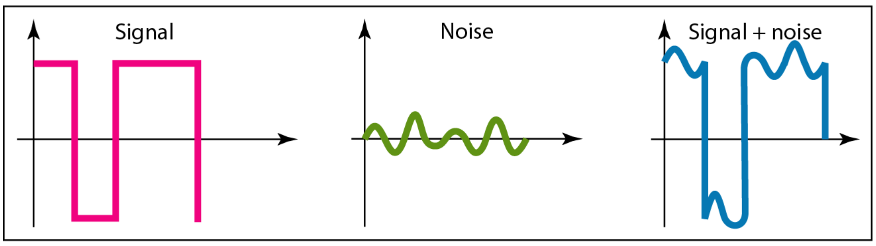
$$SNR = \frac{\text{average signal power}}{\text{average noise power}}$$

- **A high SNR :means the signal is less corrupted by noise**
- **A low SNR :means the signal is more corrupted by noise.**

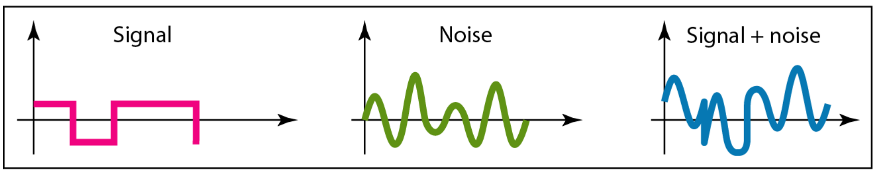
SNR can be described in db units SNR_{db}

$$SNR_{db} = 10 \log_{10} SNR$$

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



a. Large SNR



b. Small 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

Solution

The values of SNR can be calculated as follows:

$$SNR = \frac{10 \times 10^{-3}\ W}{1 \times 10^{-6}\ W} = 10{,}000$$

$$SNR_{db} = 10 \log_{10} 10{,}000 = 40$$

Example

The values of SNR and SNR_{dB} for a noiseless channel are

$$SNR = \frac{\text{signal power}}{0} = \infty$$

$$SNR_{dB} = 10 \log_{10} \infty = \infty$$

We can never achieve this ratio in real life; it is an ideal.

DATA RATE LIMITS

Avery 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

Bit Rate = 2 x bandwidth x $\log_2 L$

L: No of signal levels used to represent data

Note

$$\log_2 Y = \frac{\log_{10} Y}{\log_{10} 2}$$

Examples

***Ex1**: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*

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

***Ex2**: 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*

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

Note

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

Example

We need to send 265 kbps over a noiseless channel with a bandwidth of 20 kHz. How many signal levels do we need?

Solution

We can use the Nyquist formula as shown:

$$265{,}000 = 2 \times 20{,}000 \times \log_2 L$$
$$\log_2 L = 6.625 \qquad L = 2^{6.625} = 98.7 \text{ levels}$$

Since this result is not a power of 2, we need to either increase the number of levels or reduce the bit rate. If we have 128 levels(7-bits/level), the bit rate is 280 kbps. If we have 64 levels(6-bit/level), the bit rate is 240 kbps.

Noisy Channel: Shannon Capacity

Shannon Capacity

Capacity= bandwidth x $\log_2$ (1+SNR)

Capacity: capacity of the channel in bps (max data rate)

Note

- **In the shannon formula there is no indication of the signal level**
- **We cannot achieve a data rate higher than the capacity of the channel. In other word the formula defines a characteristic of the channel , not the method of transmission**

Example

Consider an extremely noisy channel in which the value of the signal-to-noise ratio is almost zero. In other words, the noise is so strong that the signal is faint. For this channel the capacity C is calculated as

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

This means that the capacity of this channel is zero regardless of the bandwidth. In other words, we cannot receive any data through this channel.

Example

We can calculate the theoretical highest bit rate of a regular telephone line. A telephone line normally has a bandwidth of 3000HZ. 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.

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?

Solution

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

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

Assume bit rate =4Mbps (less than C), then we use the Nyquist formula to find the number of signal levels.

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

Note

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

Note

In networking, we use the term bandwidth in two contexts.

- **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.**

Example

The bandwidth of a subscriber line is 4 kHz for voice or data. The bandwidth of this line for data transmission
can be up to 56,000 bps using a sophisticated modem to change the digital signal to analog.

PERFORMANCE

One important issue in networking is the performance of the network—how good is it?

- **Bandwidth**
- **Throughput**
- **Latency (Delay)**

Throughput (bps)

- Is a measure of how fast we can actually send data through a network
- The bandwidth is potential measurement of a link; the throughput is an actual measurement of how fast we can send data
- Throughput less than B-W

Example: a highway designed to transmit 1000 cars per minute, if there is congestion on the road, this figure may be reduced to 100 cars per minute . The B-W 1000 and throughput =100

Example: if we have a link with B-W 1Mbps, but the devices connected to the end of the link may handle only 200Kbps.

B-W=1Mbps &Throughput= 200Kbps

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

$$\text{Throughput} = \frac{12{,}000 \times 10{,}000}{60} = 2 \text{ Mbps}$$

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

Latency (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 (Delay) = propagation time + transmission time +queuing time + processing time

1. propagation time

time required for a bit to travel from the source to the destination

$$\text{Propagation time} = \frac{\text{Distance}}{\text{Propagation speed}}$$

Propagation speed depend on the medium and on the frequency of the signal

Ex: light propagate by $3x10^8$ m/s in vacuum. It is lower in air ; it is much lower in cable

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 × 10⁸ m/s in cable.

Solution

We can calculate the propagation time as

$$\text{Propagation time} = \frac{12{,}000 \times 1000}{2.4 \times 10^8} = 50 \text{ ms}$$

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.

2. Transmission time

- **The time required for transmission of a message .**
- **It depends on the size of the message and the bandwidth of the channel**

$$\text{Transmission time} = \frac{\text{Message size}}{\text{Bandwidth (bps)}}$$

Example

What are the propagation time and the transmission time for a 2.5-kbyte message (an e-mail) 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 shown on the next slide:

Example (continued)

$$\text{Propagation time} = \frac{12{,}000 \times 1000}{2.4 \times 10^8} = 50 \text{ ms}$$

$$\text{Transmission time} = \frac{2500 \times 8}{10^9} = 0.020 \text{ ms}$$

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.

Example

What are the propagation time and the transmission time for a 5-Mbyte message (an image) if the bandwidth of the network is 1 Mbps? 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 times as shown on the next slide.

Example (continued)

$$\text{Propagation time} = \frac{12{,}000 \times 1000}{2.4 \times 10^8} = 50 \text{ ms}$$

$$\text{Transmission time} = \frac{5{,}000{,}000 \times 8}{10^6} = 40 \text{ s}$$

Note that in this case, because the message is very long and the bandwidth is not very high, the dominant factor is the transmission time, not the propagation time. The propagation time can be ignored.

Queuing time : the time needed for each end device to hold the message before it can be processed.

•It changes with the load imposed on the network, if there is heavy traffic on the network , the queuing time increases