3. INTRODUCTION TO PHYSICAL LAYER

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INTRODUCTION TO PHYSICAL LAYER

Move data in the form of electromagnetic signals across a transmission medium

For transmission, data needs to be changed to signals

Objectives:

- Study of analog and digital data
- Periodic analog signals for data communication and related definitions
- Non periodic digital signals for data communication and related definitions
- Transmission impairment and related definitions
- Data rate limit of channel and related definitions
- Performance of data transmission and related definitions

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

CONTENTS

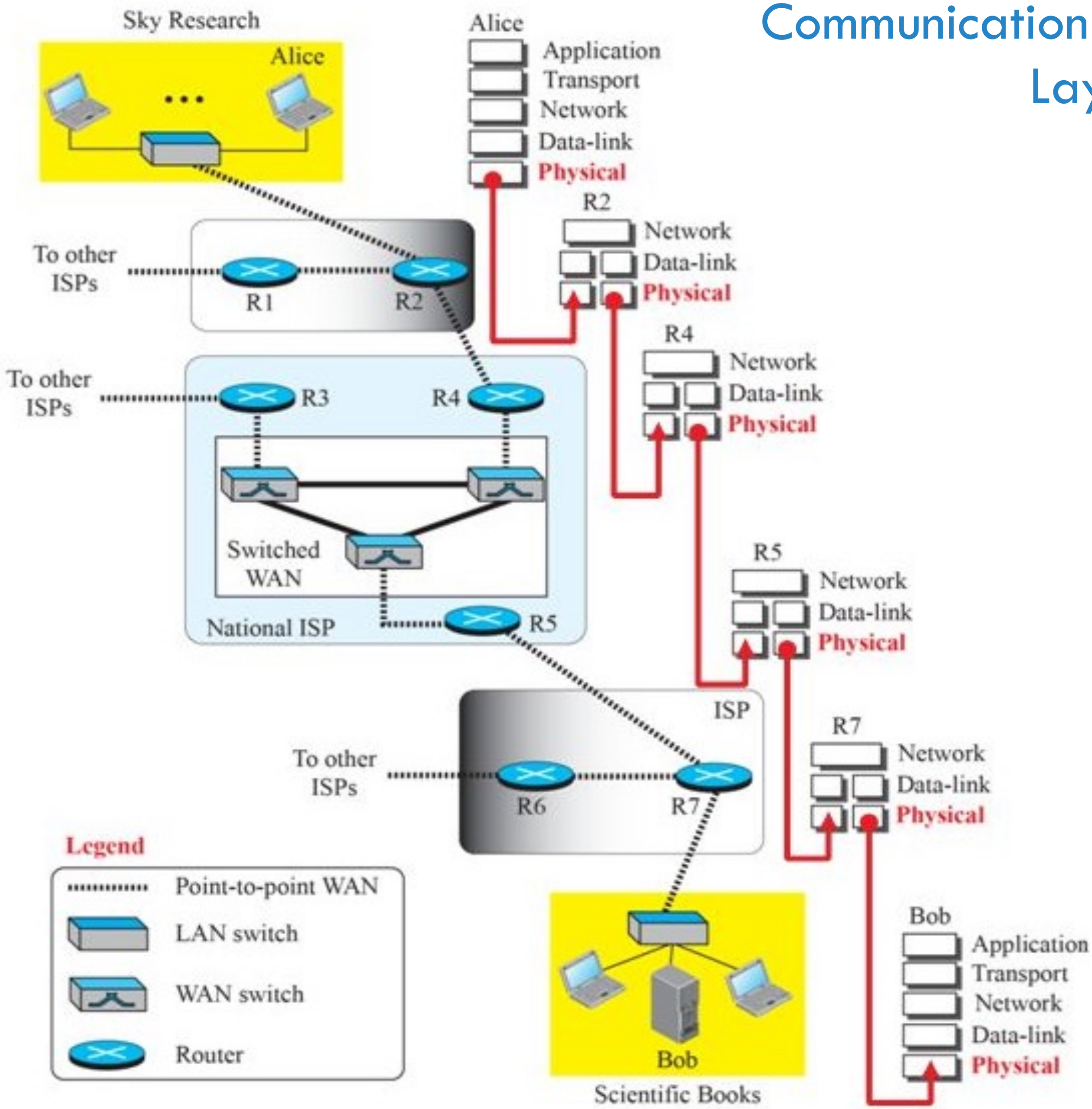
DATA AND SIGNALS

Analog and Digital Data

Analog and Digital Signals

Periodic and Non-periodic

Communication at the Physical Layer



ANALOG AND DIGITAL DATA

Analog data

- Information that is continuous
- Eg. An analog clock, analog voice create by human beings

Digital data

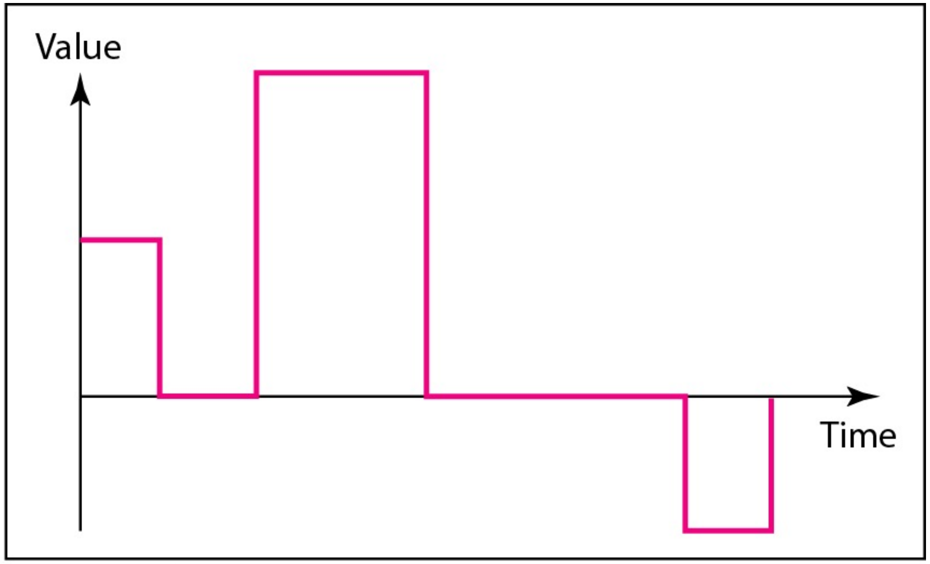
- Information that has discrete states
- Eg. A digital clock, data stored in computer memory in form of 1s and 0s

ANALOG AND DIGITAL SIGNALS

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

a. Analog signal



b. Digital signal

Comparison of Analog and Digital Signals

PERIODIC AND NONPERIODIC

A periodic signal completes a pattern within a measurable time frame, called a period

- Repeats that pattern over subsequent identical periods
- Completion of one full pattern is called a cycle

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

Both analog and digital signals can be periodic or nonperiodic

In data communications, periodic analog signals and nonperiodic digital signals are commonly used

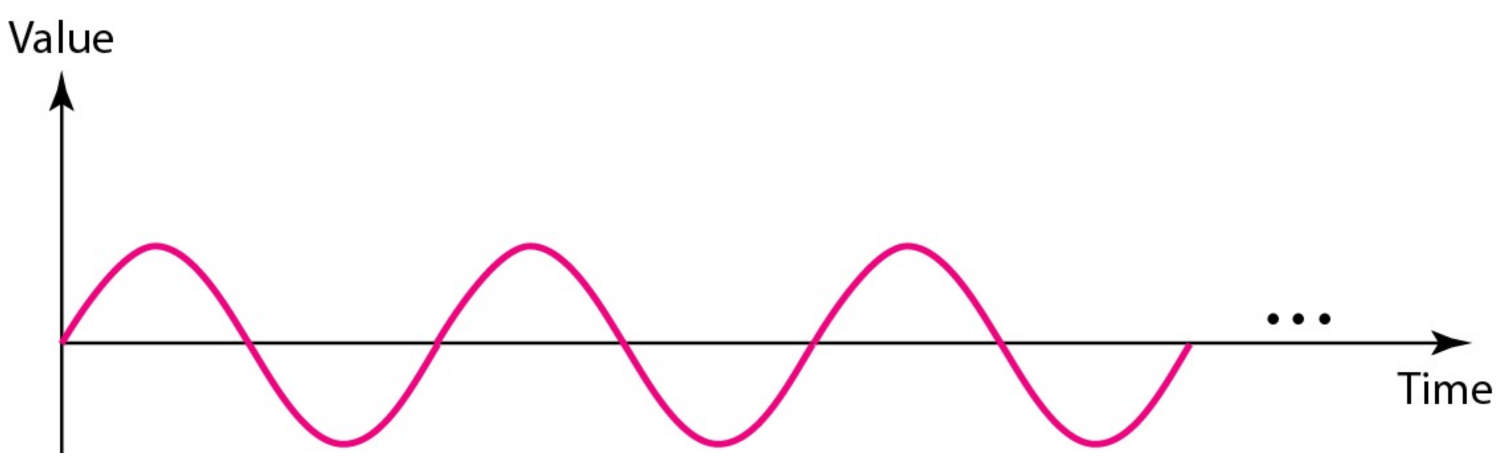
PERIODIC ANALOG SIGNALS
SIMPLE
COMPOSITE

Sine wave
Phase
Wavelength
Time and Frequency Domains
Composite signals
Bandwidth

SINE WAVE

Most fundamental form of a periodic analog signal

Its change over the course of a cycle is smooth and consistent, a continuous, rolling flow

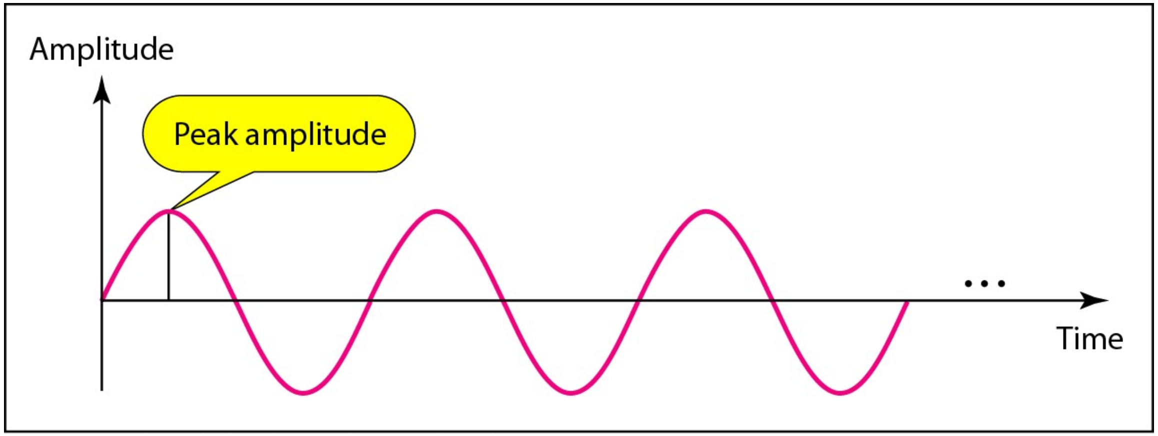


A sine wave

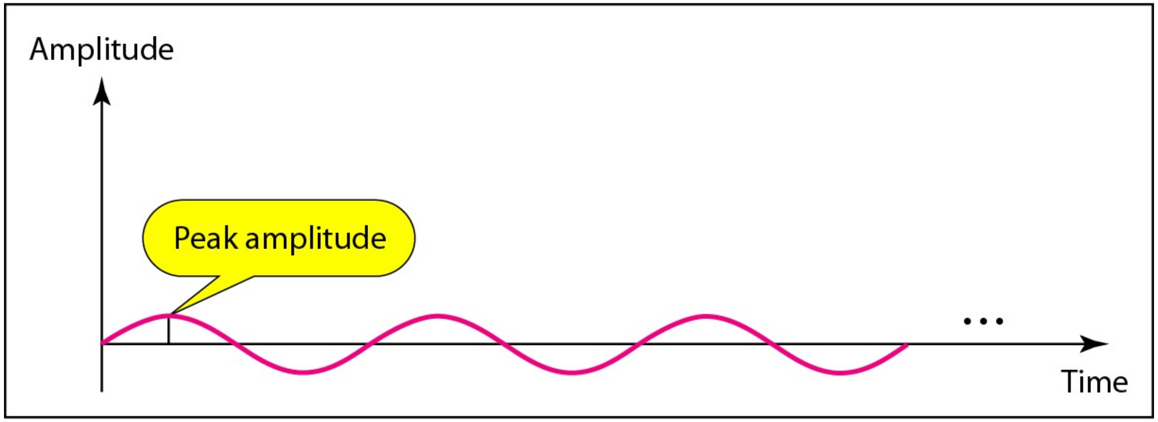
SINE WAVE

Represented by

- **The peak amplitude**
- The frequency and
- The phase



a. A signal with high peak amplitude



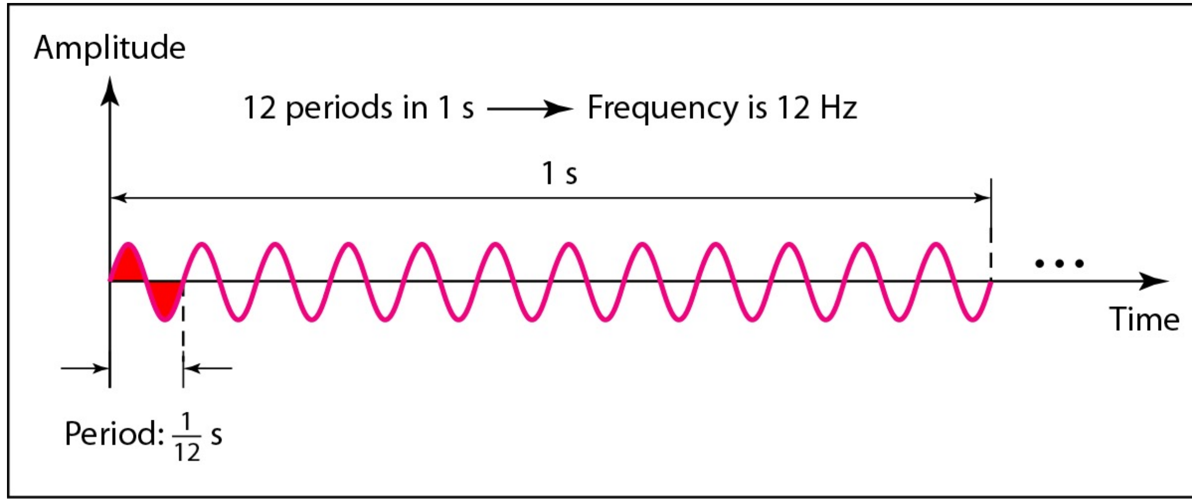
b. A signal with low peak amplitude

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

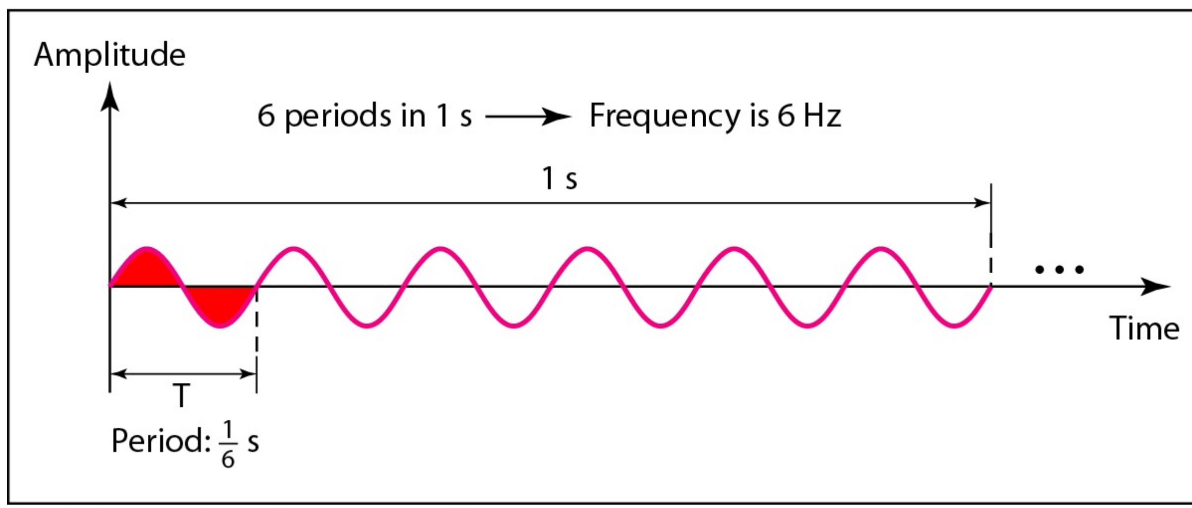
SINE WAVE

Represented by

- The peak amplitude
- **The frequency and**
- The phase



a. A signal with a frequency of 12 Hz



b. A signal with a frequency of 6 Hz

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

SINE WAVE

Represented by

- The peak amplitude
- **The frequency and**
- The phase

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

Period is amount of time, in seconds, a signal takes to complete one cycle

Frequency refers to number of periods per second

Period is inverse of frequency and vice versa

Frequency and period are inverse of each other

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

Units of period and frequency

THE POWER WE USE AT HOME HAS A FREQUENCY OF 60 HZ. THE PERIOD OF THIS SINE WAVE CAN BE DETERMINED AS FOLLOWS:

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

EXPRESS A PERIOD OF 100 MS IN MICROSECONDS.

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

THE PERIOD OF A SIGNAL IS 100 MS. WHAT IS ITS FREQUENCY IN KILOHERTZ?

Solution

First we change 100 ms to seconds, and then we calculate the frequency from the period (1 Hz = 10^{-3} kHz).

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

$$f = \frac{1}{T} = \frac{1}{10^{-1}} \text{ Hz} = 10 \text{ Hz} = 10 \times 10^{-3} \text{ kHz} = 10^{-2} \text{ kHz}$$

SOME EXTREMES OF FREQUENCY

Relationship of a signal to time and that the frequency of a wave is number of cycles it completes in 1s

Measurement of the rate of change

Electromagnetic signals are the oscillating waveforms

- Fluctuate continuously above and below a mean energy level

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 continuously, its frequency is infinite

SINE WAVE

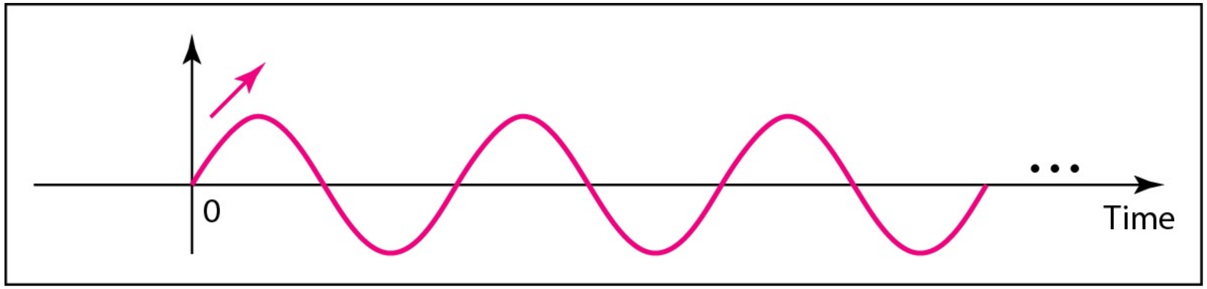
Represented by

- The peak amplitude
- The frequency and
- **The phase or phase shift**

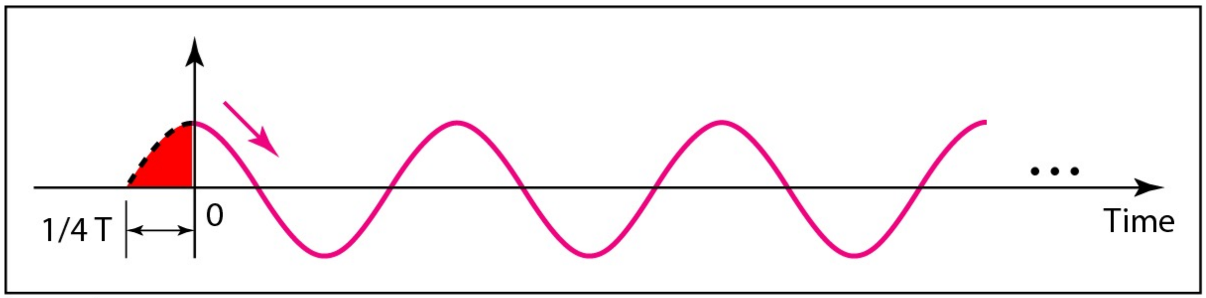
Phase describes the position of the waveform relative to time 0.

Indicates the status of the first cycle

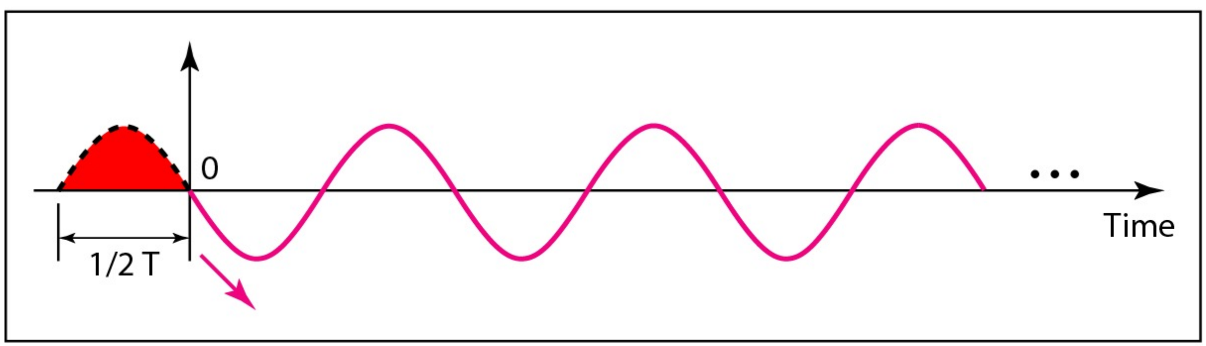
Phase is measured in degrees or radians (360 or 2Π)



a. 0 degrees



b. 90 degrees



c. 180 degrees

Three signals with the same amplitude and frequency, but different phases

A SINE WAVE IS OFFSET 1/6 CYCLE WITH RESPECT TO TIME 0. WHAT IS ITS PHASE IN DEGREES AND RADIANS?

Solution

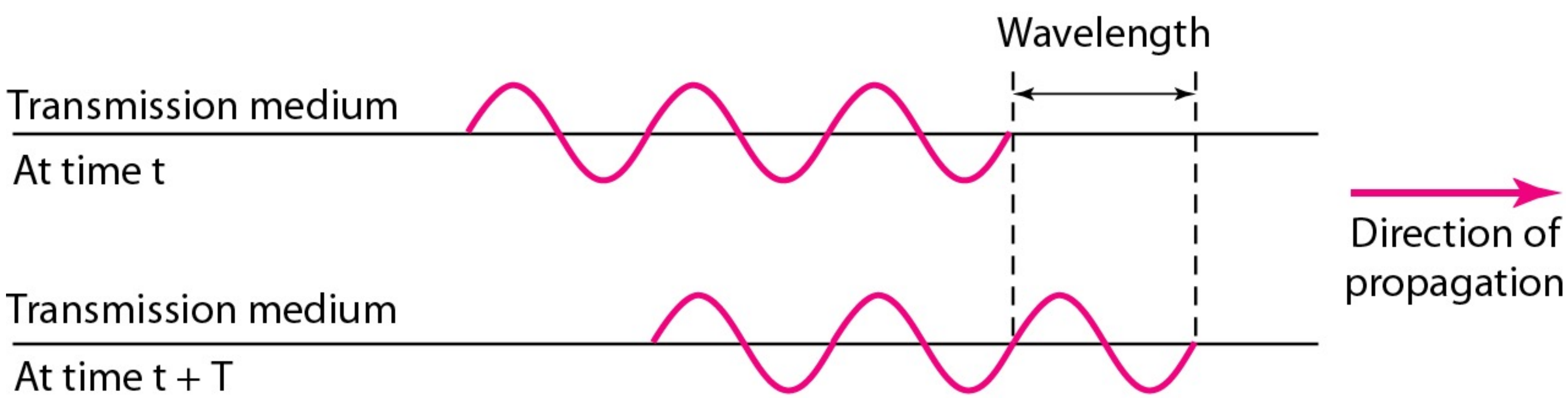
We know that 1 complete cycle is 360°. Therefore, 1/6 cycle is

$$\boxed{\frac{1}{6} \times 360 = 60^\circ = 60 \times \frac{2\pi}{360} \text{ rad} = \frac{\pi}{3} \text{ rad} = 1.046 \text{ rad}}$$

WAVELENGTH

Binds period or the frequency of a simple sine wave to the propagation speed of the medium

Wavelength is the distance a simple signal can travel in one period



Wavelength and Period

WAVELENGTH

Wavelength (λ) is calculated as

Wavelength = (propagation speed) X period

= (propagation speed)/frequency

$$\lambda = c/f$$

Wavelength is used to describe transmission of light in an optical fiber.

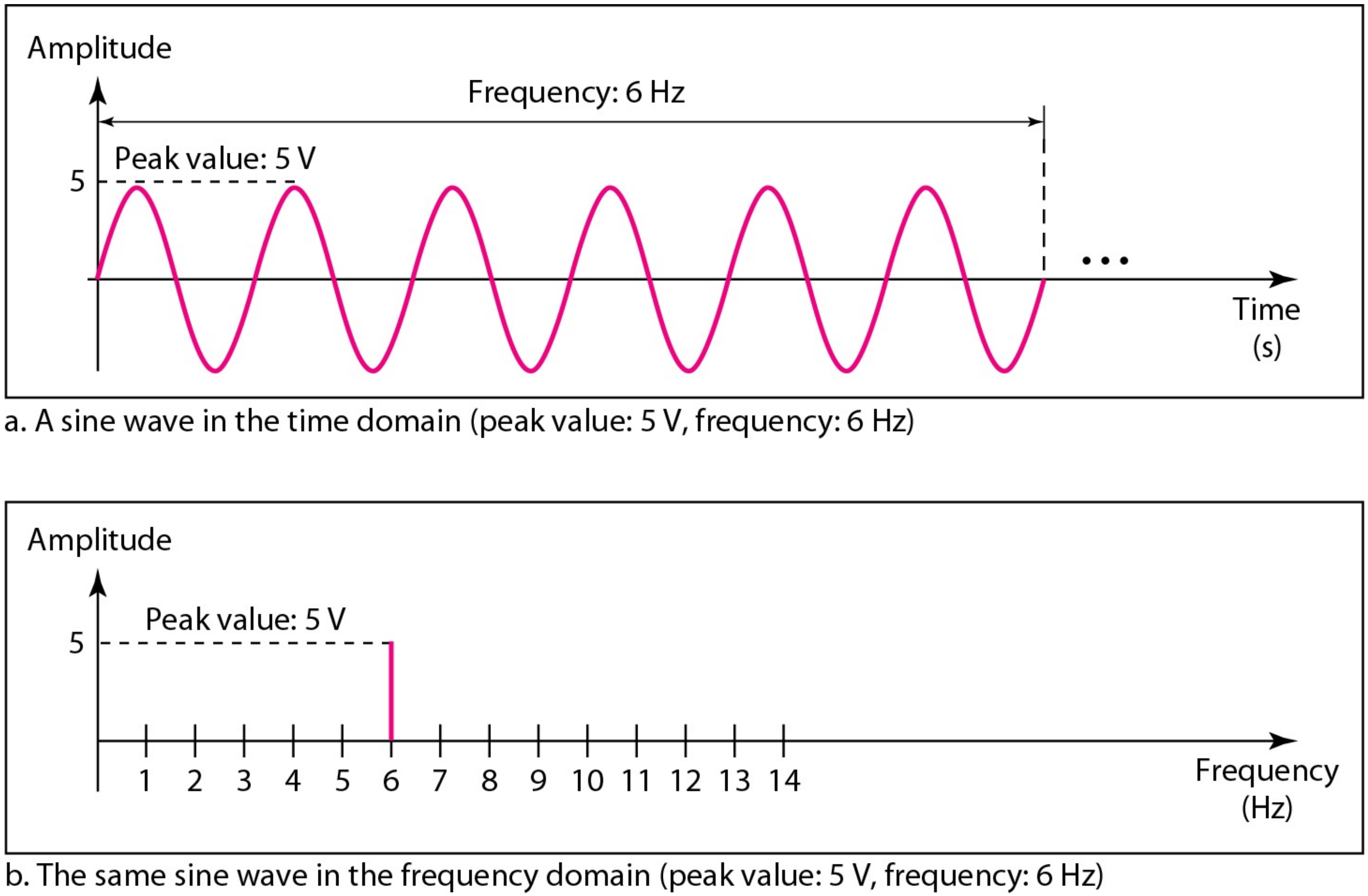
TIME AND FREQUENCY DOMAINS

Time domain plot shows changes in signal amplitude with respect to time

A frequency domain plot is concerned with the peak value and the frequency; changes in amplitude during one period are not shown

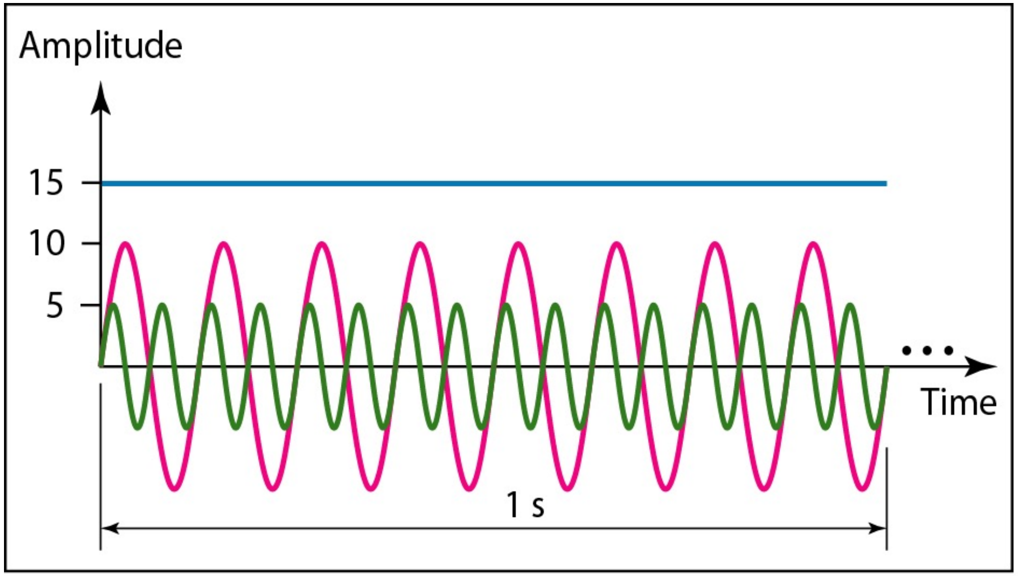
Frequency domain is more compact and useful when dealing with more than one sine wave

A complete sine wave in the time domain can be represented by one single spike in the frequency domain.

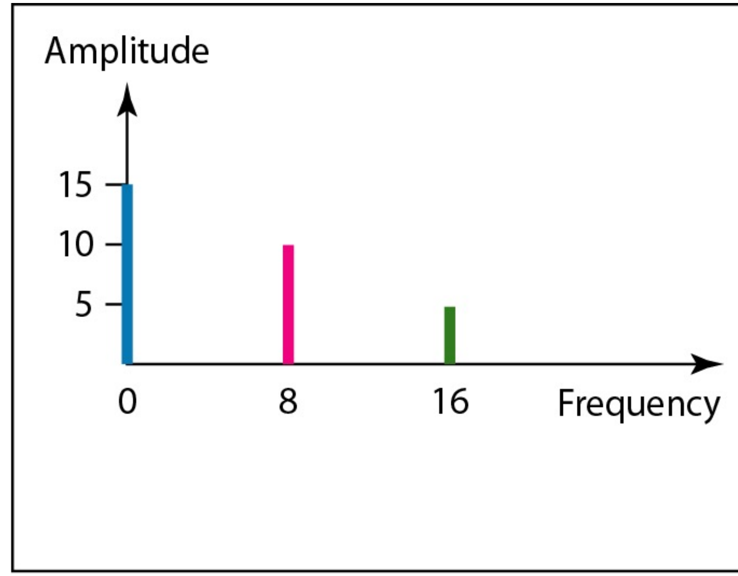


Time and frequency domain of a sine wave

A complete sine wave in the time domain can be represented by one single spike in the frequency domain



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



b. Frequency-domain representation of the same three signals

The time domain and frequency domain of three sine waves

COMPOSITE SIGNALS

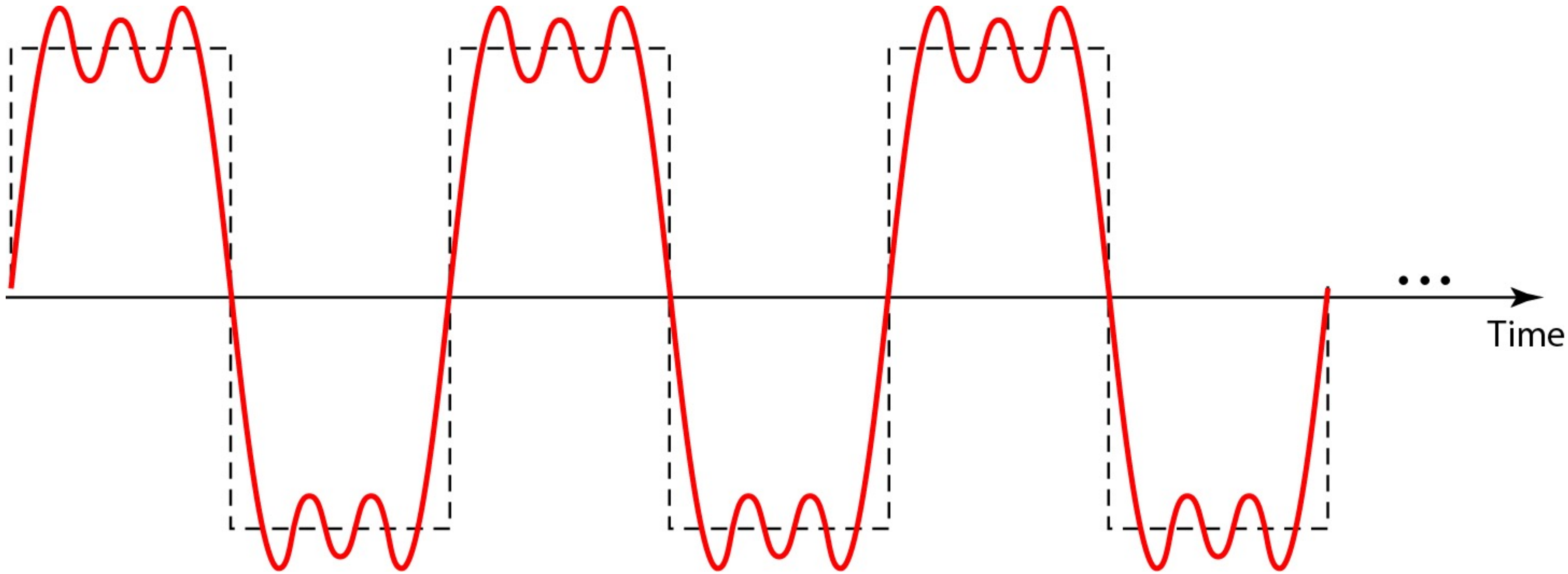
A single-frequency sine wave is not useful in data communications

Composite signals are a combination of simple sine waves with different frequencies, amplitudes, and phases (According to Jean-Bapstite Fourier)

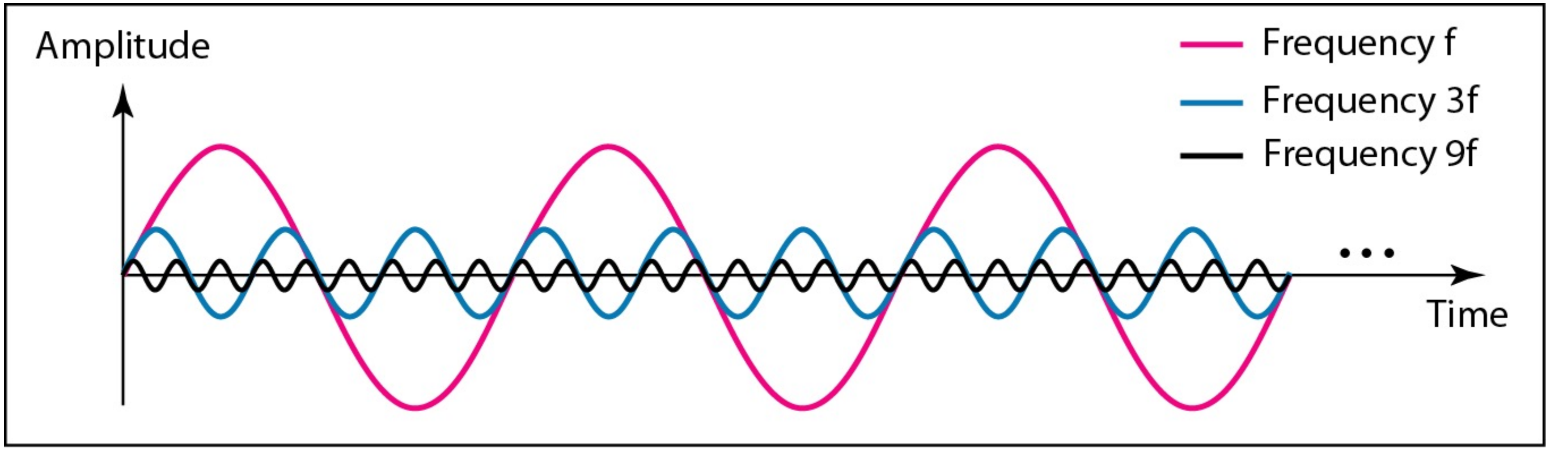
Composite signal can be periodic or nonperiodic

Periodic composite signal can be decomposed into a series of simple sine waves with discrete frequencies

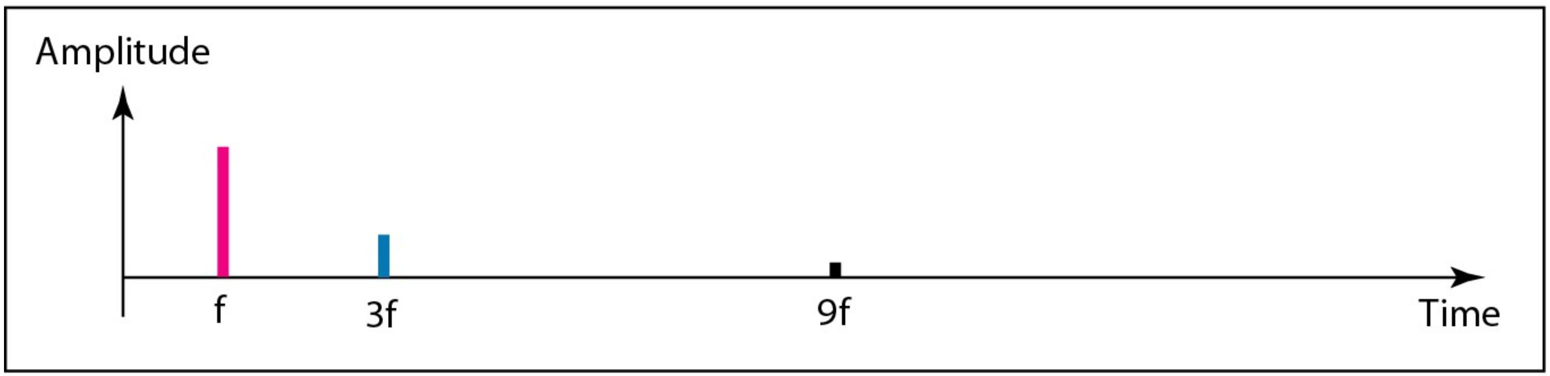
Nonperiodic composite signals can be decomposed into a combination of an infinite number of simple sine waves with continuous frequencies



A composite periodic signal



a. Time-domain decomposition of a composite signal



b. Frequency-domain decomposition of the composite signal

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

COMPOSITE SIGNALS

First harmonic or fundamental frequency

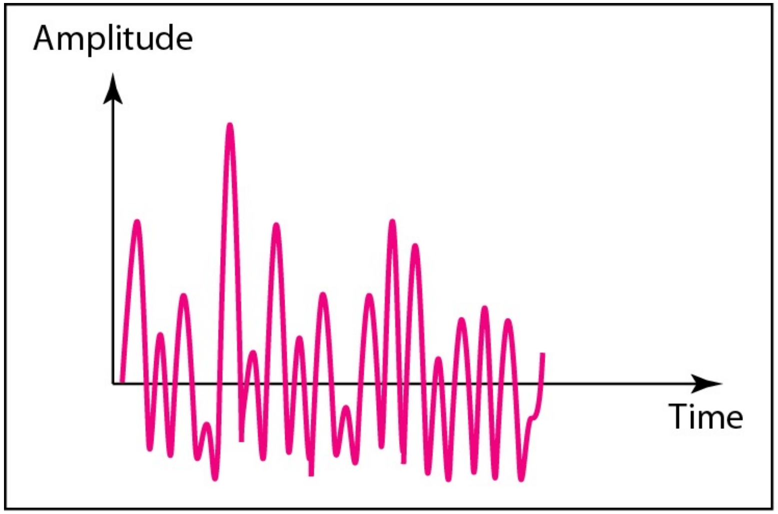
- If decomposed signal has the same frequency as that of composite periodic signal, it is called first harmonic or fundamental frequency
- If the decomposed signal has twice the frequency of composite periodic signal, it is called second harmonic
- Third harmonic
- And so on

Here, first harmonic, third harmonic and ninth harmonic are shown

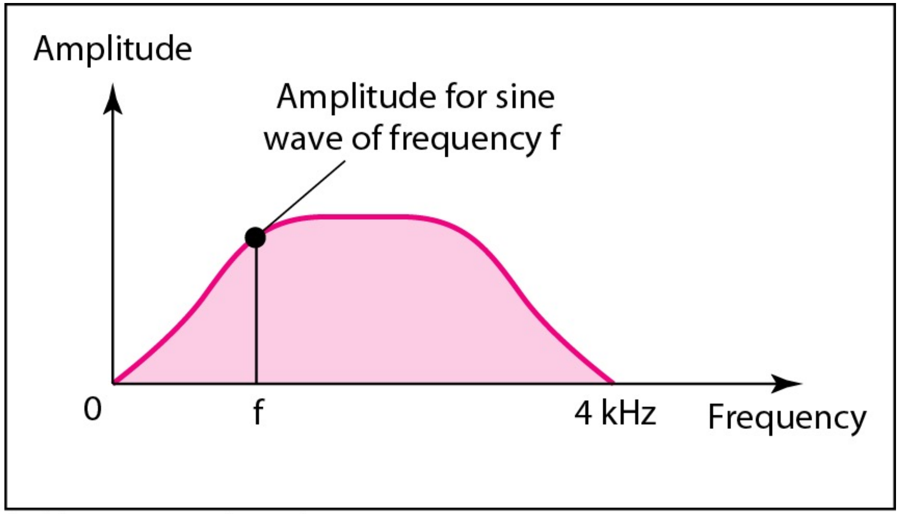
Frequency decomposition of a signal is discrete

Since f is integral, 3f and 9f are also integral

No frequencies exist like 1.2f or 2.6 f



a. Time domain



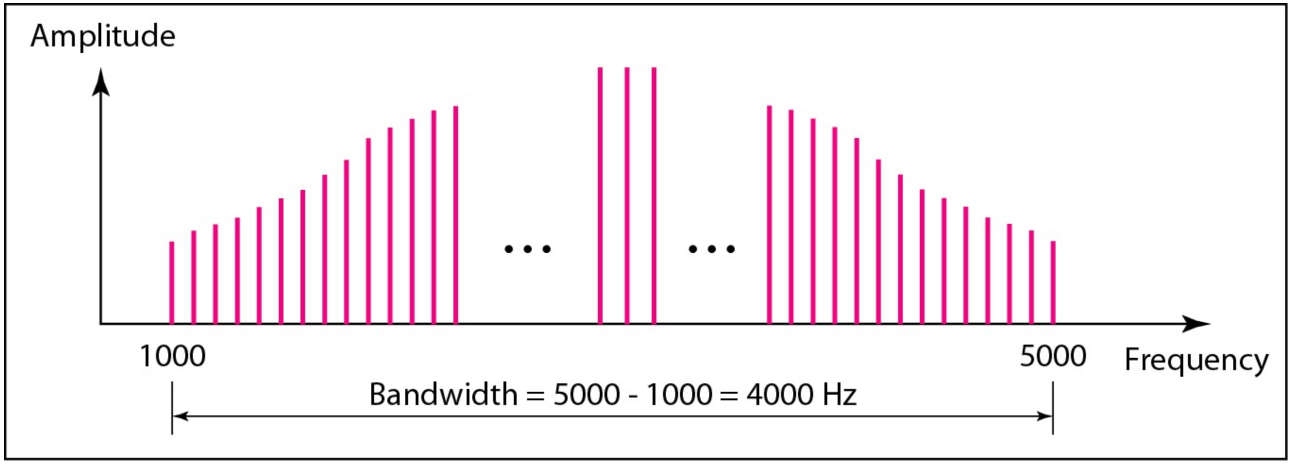
b. Frequency domain

Time and Frequency domains of a nonperiodic signal

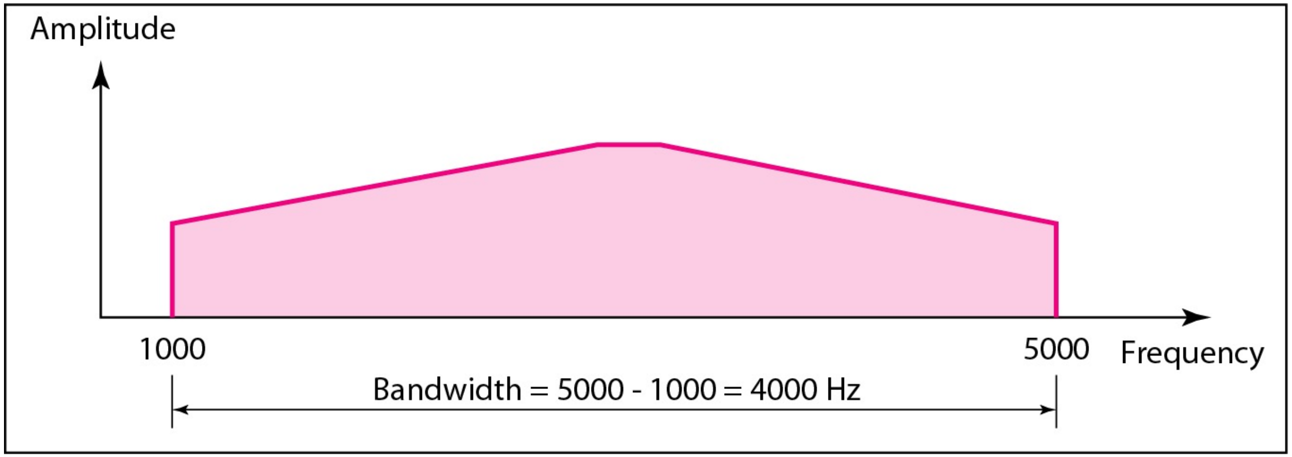
BANDWIDTH

Range of frequencies contained in a composite signal is its bandwidth

Difference between the highest and the lowest frequencies contained in that signal



a. Bandwidth of a periodic signal



b. Bandwidth of a nonperiodic signal

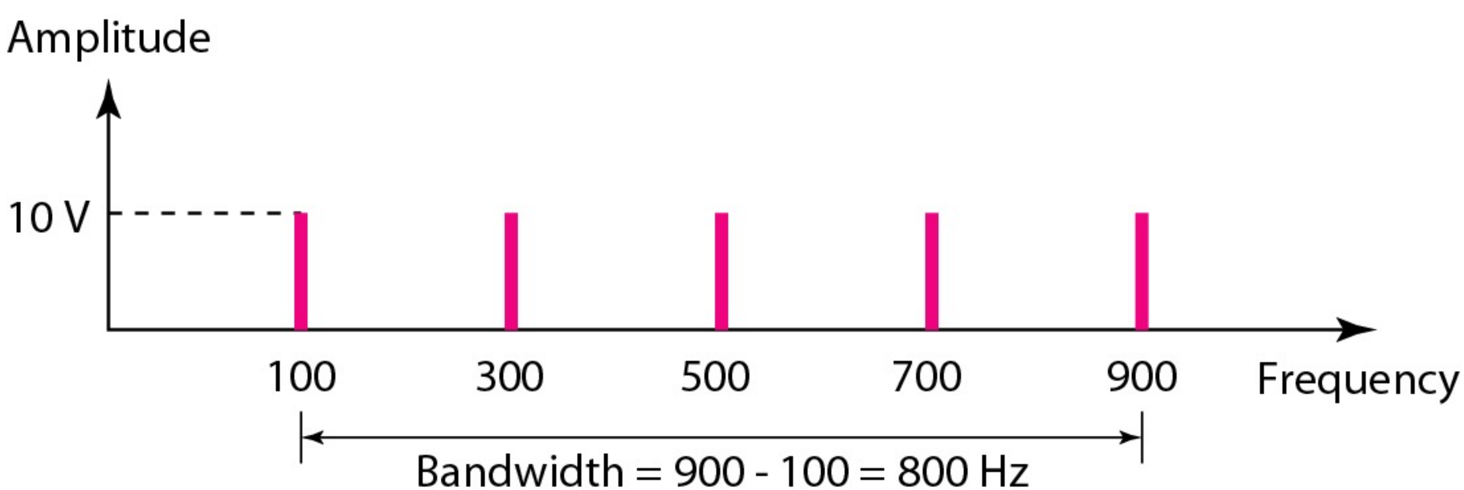
Bandwidth of a nonperiodic signal

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.

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

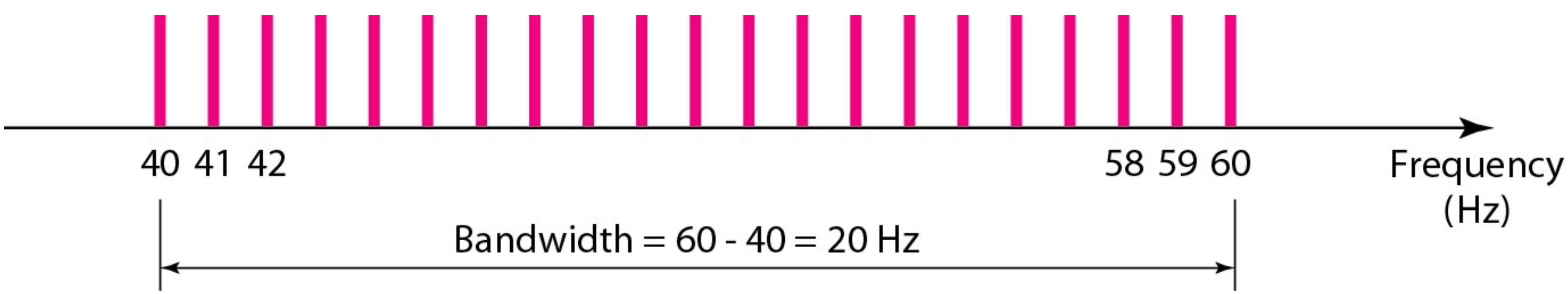


A PERIODIC SIGNAL HAS A BANDWIDTH OF 20 HZ. THE HIGHEST FREQUENCY IS 60 HZ. WHAT IS THE LOWEST FREQUENCY? DRAW THE SPECTRUM IF THE SIGNAL CONTAINS ALL FREQUENCIES OF THE SAME AMPLITUDE.

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

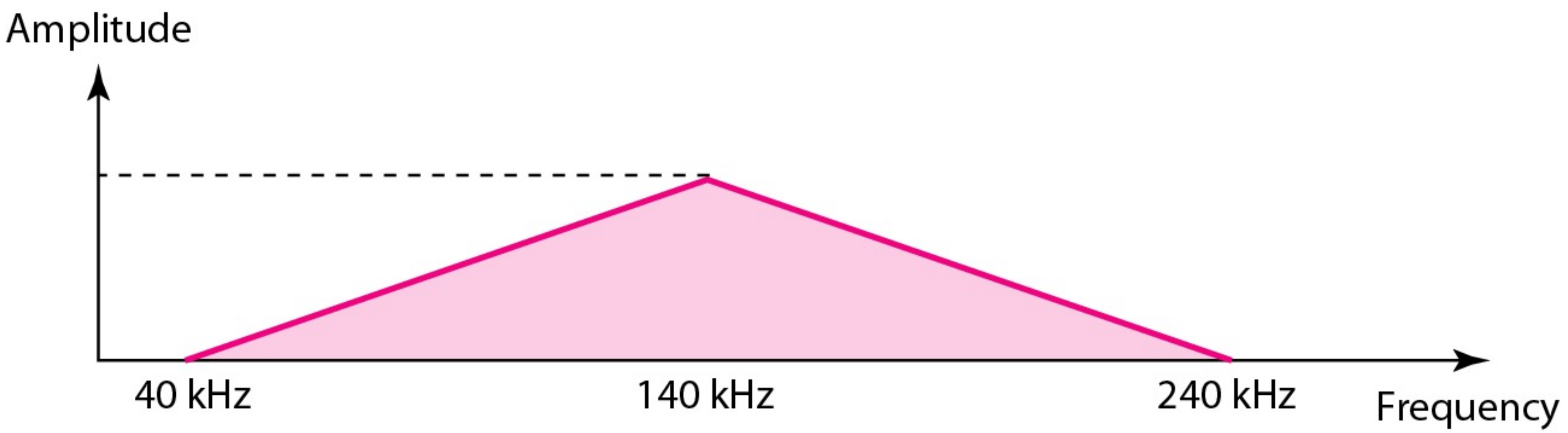
$$\boxed{B = f_h - f_l \quad \Rightarrow \quad 20 = 60 - f_l \quad \Rightarrow \quad f_l = 60 - 20 = 40 \text{ Hz}}$$

The spectrum contains all integer frequencies. We show this by a series of spikes



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.

The lowest frequency must be at 40 kHz and the highest at 240 kHz



An example of a nonperiodic composite signal is the signal propagated by an AM radio station. In the United States, each AM radio station is assigned a 10-kHz bandwidth. The total bandwidth dedicated to AM radio ranges from 530 to 1700 kHz.

Another example of a nonperiodic composite signal is the signal propagated by an FM radio station. In the United States, each FM radio station is assigned a 200-kHz bandwidth. The total bandwidth dedicated to FM radio ranges from 88 to 108 MHz.

Another example of a nonperiodic composite signal is the signal received by an old-fashioned analog black-and-white TV. A TV screen is made up of pixels. If we assume a resolution of 525×700, we have 367,500 pixels per screen. If we scan the screen 30 times per second, this is $367{,}500 \times 30 = 11{,}025{,}000$ pixels per second. The worst-case scenario is alternating black and white pixels. We can send 2 pixels per cycle. Therefore, we need $11{,}025{,}000 / 2 = 5{,}512{,}500$ cycles per second, or Hz. The bandwidth needed is 5.5125 MHz.

DIGITAL SIGNALS

Bit Rate
Bit Length
Digital Signal as a Composite
Analog Signal
Transmission of Digital Signals

DIGITAL SIGNAL

Information can be represented by a digital signal

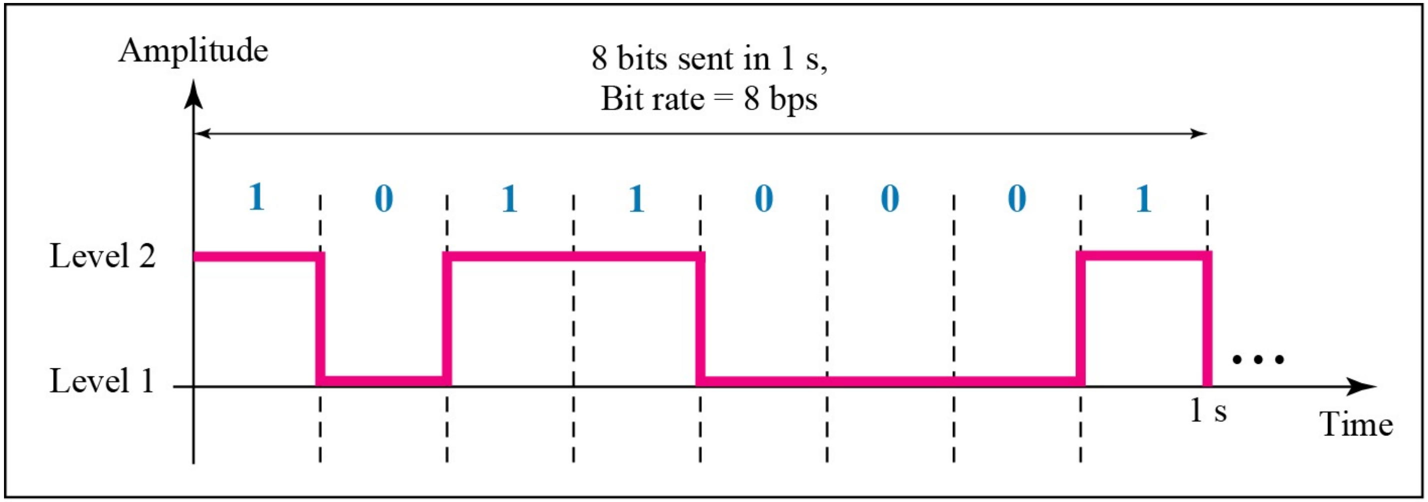
If a signal has L levels, each level needs $\log_2 L$ bits

Example:

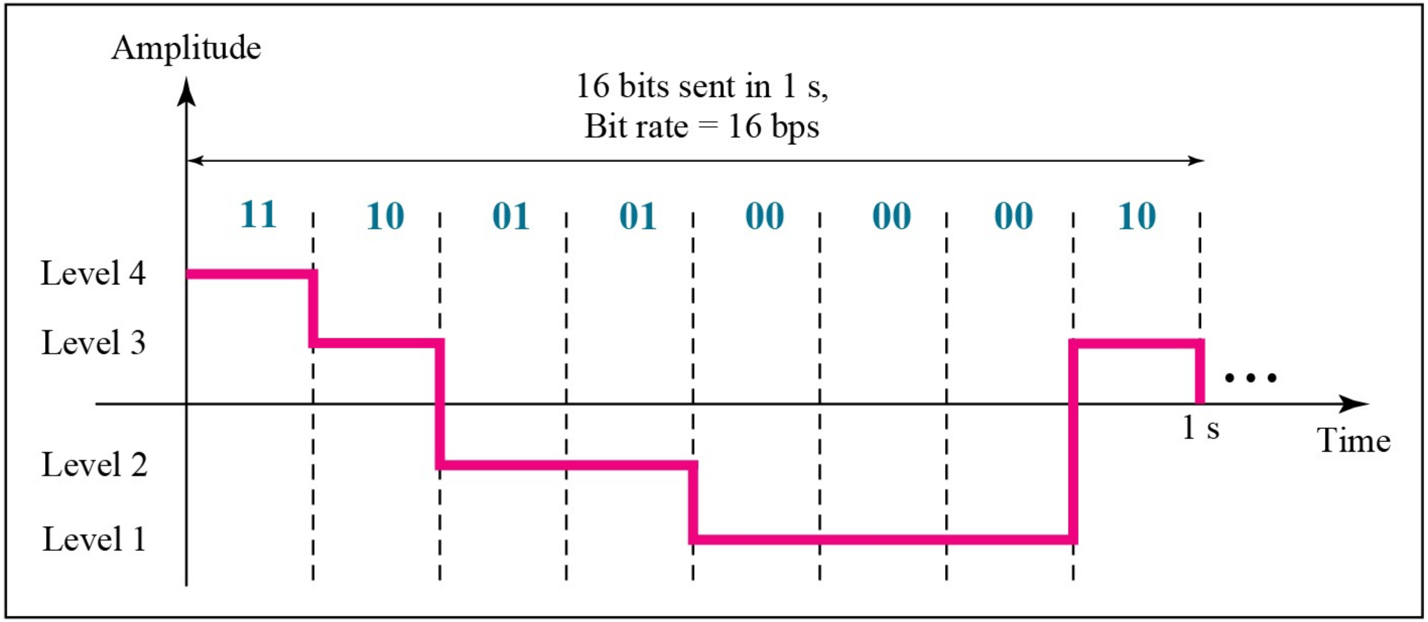
- A digital signal has eight levels. How many bits are needed per level? We calculate the number of bits from the formula

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

- Each signal level is represented by 3 bits



a. A digital signal with two levels



b. A digital signal with four levels

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

A DIGITAL SIGNAL HAS NINE LEVELS. HOW MANY BITS ARE NEEDED PER LEVEL?

Each signal level is represented by 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

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 sec. 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 (ASCII), the bit rate is 100 X 24 X 80 X 8 = 1.536 Mbps

A digitized voice channel, is made by digitizing a 4-kHz bandwidth analog voice signal. We need to sample the signal at twice the highest frequency (two samples per hertz). We assume that each sample requires 8 bits. What is the required bit rate?

The bit rate can be calculated as

$$\boxed{2 \times 4000 \times 8 = 64{,}000 \text{ bps} = 64 \text{ kbps}}$$

What is the bit rate for high-definition TV (HDTV)?

HDTV uses digital signals to broadcast high quality video signals. The HDTV screen is normally a ratio of 16 : 9. There are 1920 by 1080 pixels per screen, and the screen is renewed 30 times per second. Twenty-four bits represents one color pixel

$$\boxed{1920 \times 1080 \times 30 \times 24 = 1{,}492{,}992{,}000 \text{ or } 1.5 \text{ Gbps}}$$

The TV stations reduce this rate to 20 to 40 Mbps through compression

BIT LENGTH

Similar to wavelength for analog signals

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

Bit length = propagation speed X bit duration

DIGITAL SIGNAL AS A COMPOSITE ANALOG SIGNAL

A digital signal is a composite analog signal

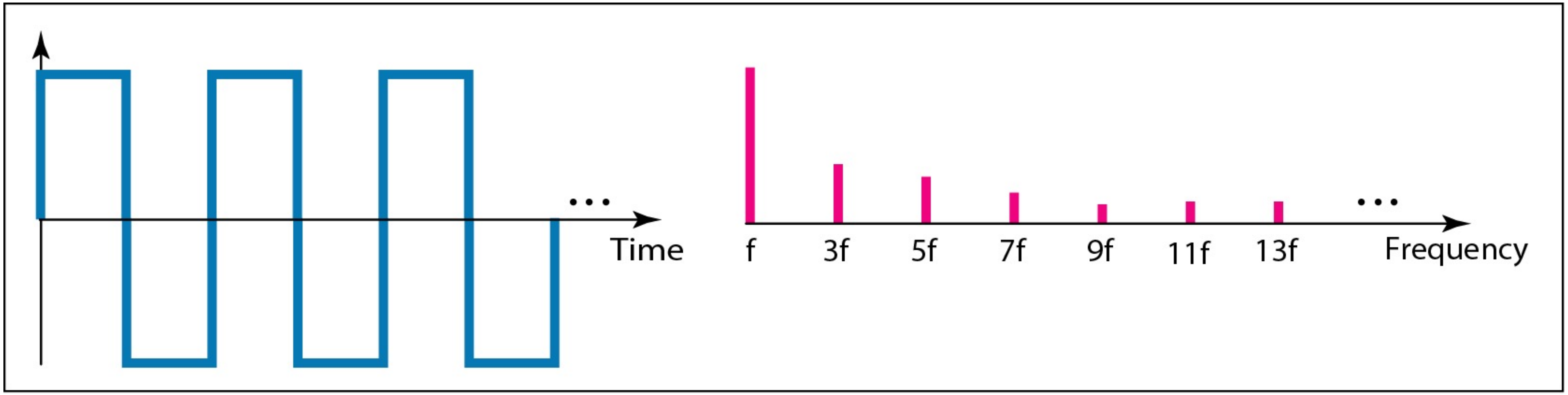
Infinite bandwidth

Periodic digital signal

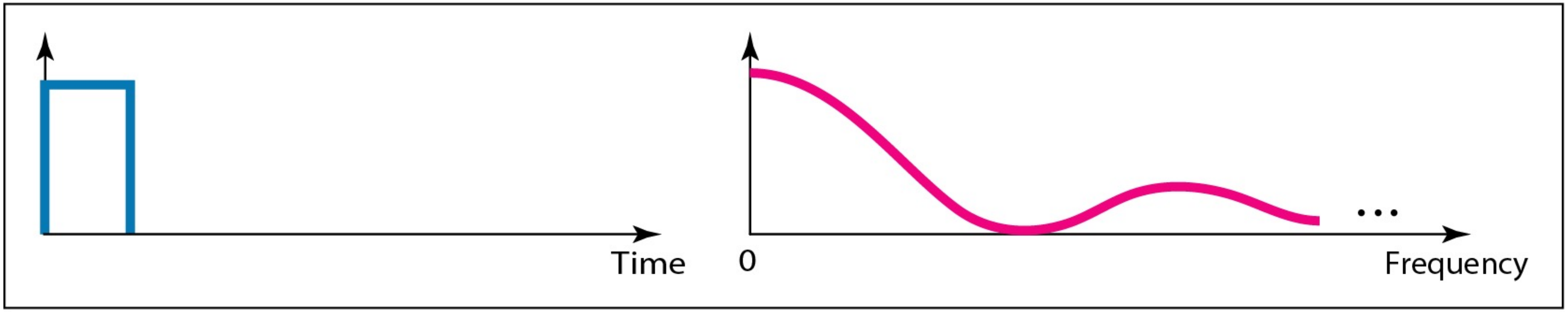
- Rare in data communication
- Frequency domain representation has infinite bandwidth and discrete frequencies

Nonperiodic digital signal

- Decomposed signal still has an infinite bandwidth
- Frequencies are continuous



a. Time and frequency domains of periodic digital signal



b. Time and frequency domains of nonperiodic digital signal

The time and frequency domains of periodic and nonperiodic digital signals

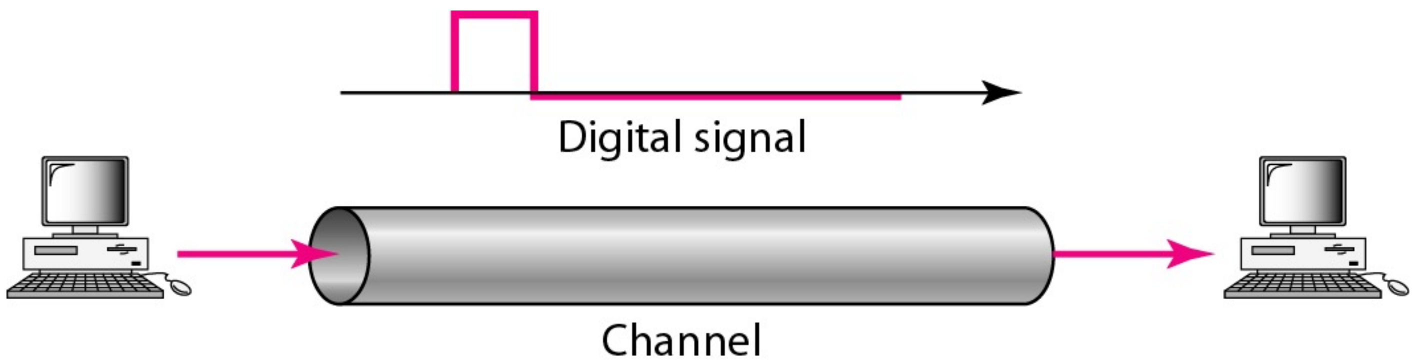
TRANSMISSION OF DIGITAL SIGNALS

Digital signal is a composite analog signal with frequencies between zero and infinity

Transmission of digital signal is possible by 2 approaches

- Baseband transmission
- Broadband transmission (using modulation)

TRANSMISSION OF DIGITAL SIGNALS: BASEBAND TRANSMISSION

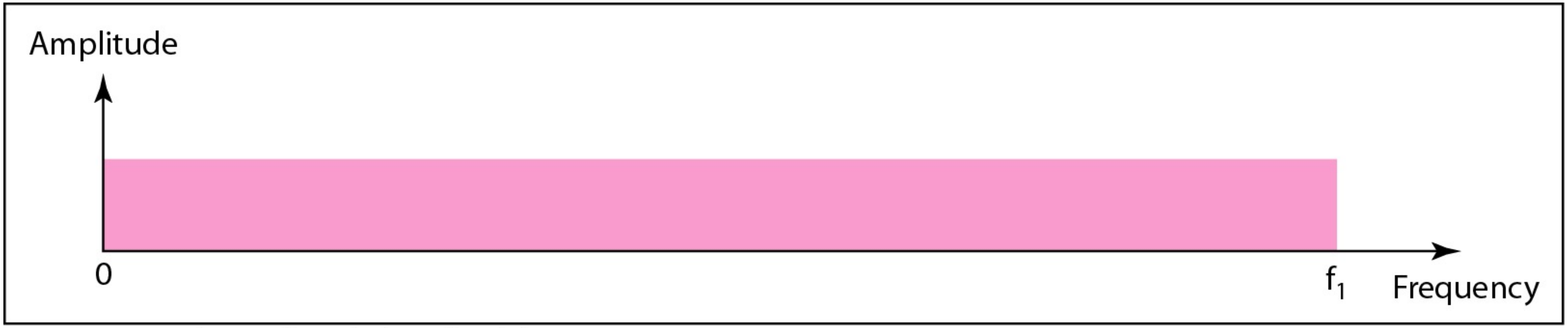


Baseband Transmission

Sending a digital signal over a channel without changing the digital signal to an analog signal

Requires a **low-pass channel** with a bandwidth that **starts from zero**

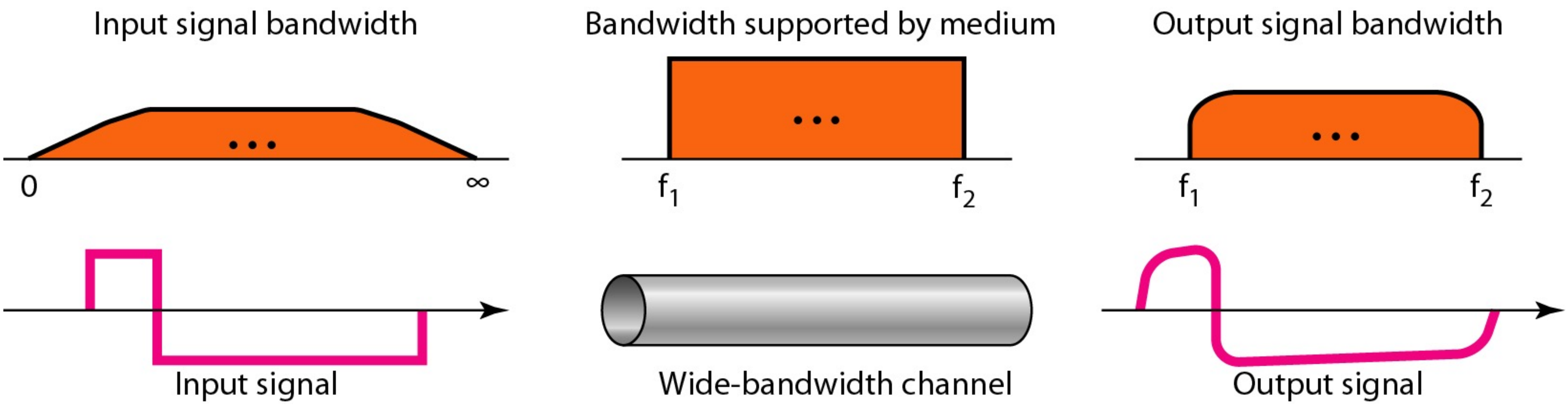
Means a dedicated medium with a bandwidth constituting only one channel



a. Low-pass channel, wide bandwidth

b. Low-pass channel, narrow bandwidth

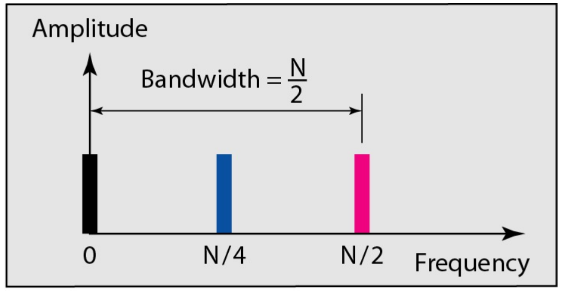
Bandwidths of Low pass channels

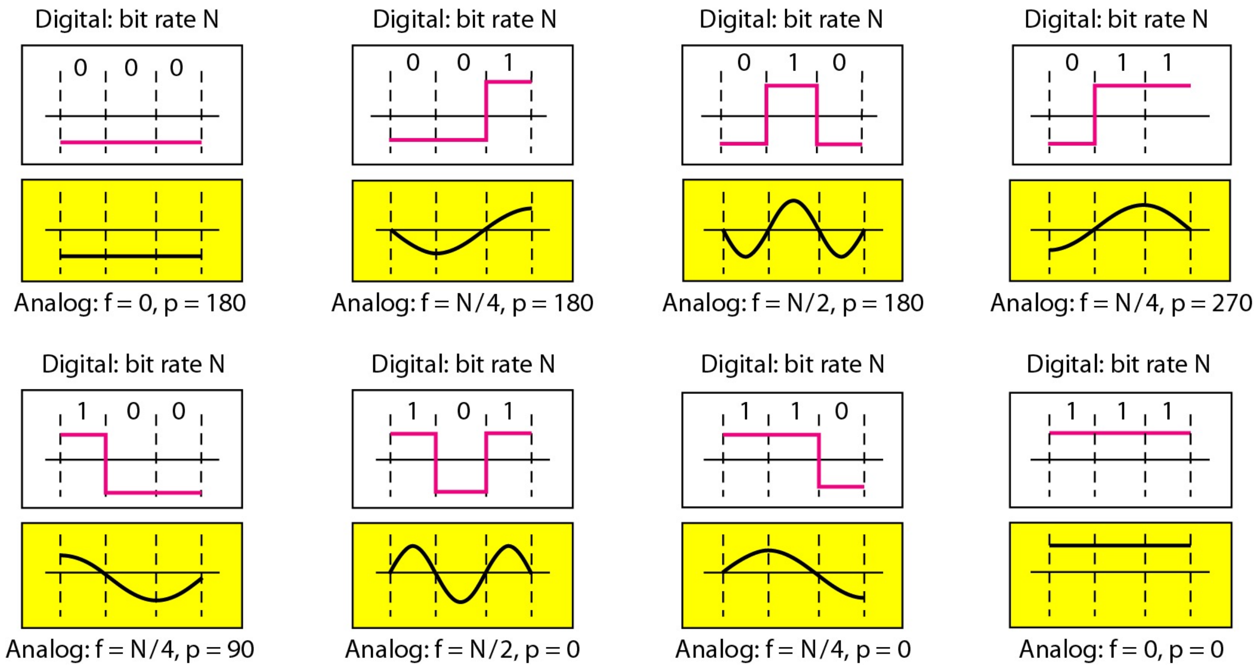


Baseband transmission using a dedicated medium

An example of a dedicated channel where the entire bandwidth of the medium is used as one single channel is a LAN. Almost every wired LAN today uses a dedicated channel for two stations communicating with each other. In a bus topology LAN with multipoint connections, only two stations can communicate with each other at each moment in time (timesharing); the other stations need to refrain from sending data. In a star topology LAN, the entire channel between each station and the hub is used for communication between these two entities.

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



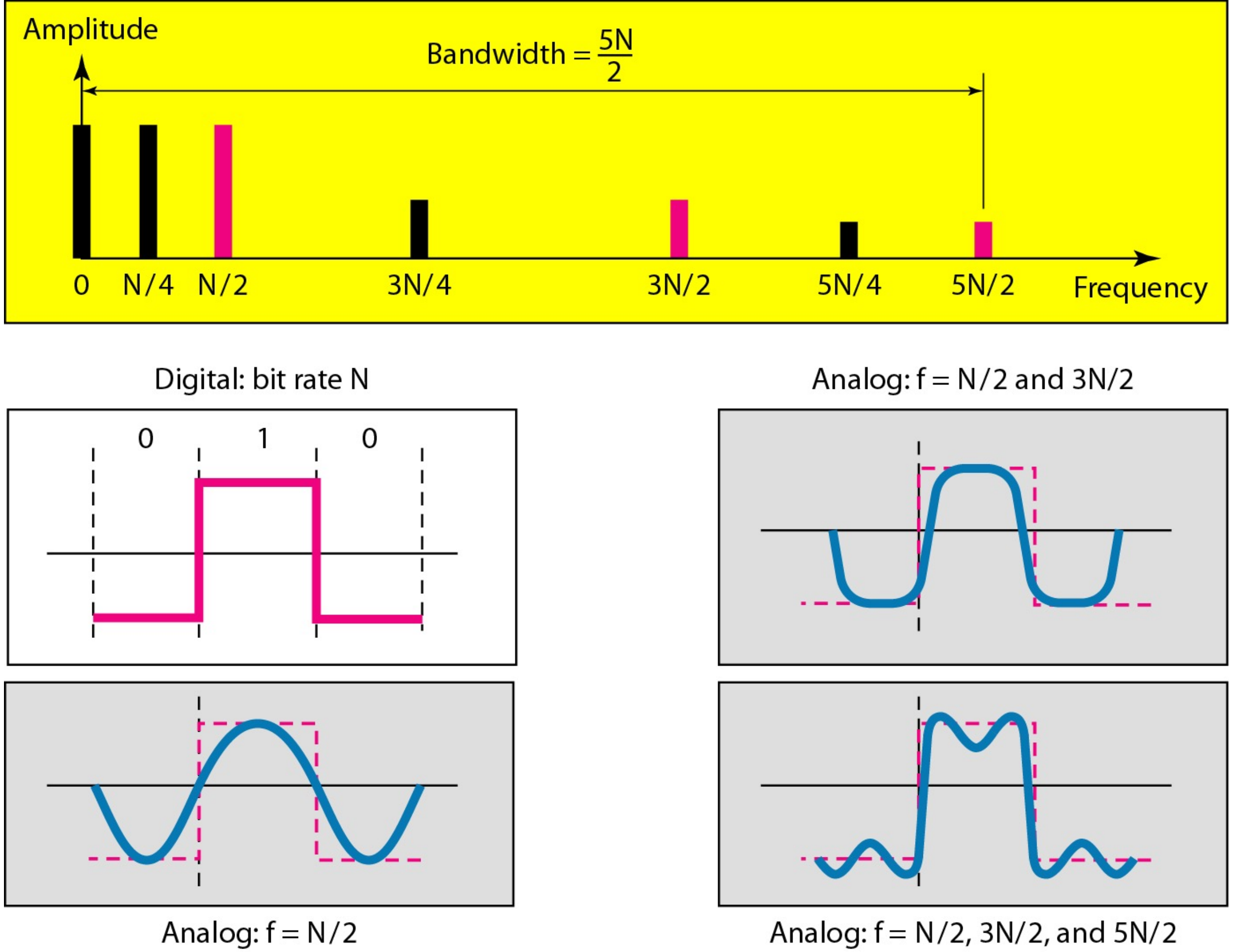


Rough approximation of a digital signal using first harmonic for worst case

Assumption: We have a digital signal of bit rate N

Conclusions:

- Analog representation for the 3-bit pattern is shown
- Phases involved are 90, 180, 270, 0
- Highest frequency is N/2 and lowest frequency is 0
- Bandwidth = N/2 (First harmonic)



Simulating the digital signal with first three harmonics

Better approximation:

- Add more harmonics and increase bandwidth to 3N/2, 5N/2, 7N/2 and so on
- Required bandwidth is proportional to bit rate
    - Want to send bits faster, need more bandwidth

Bit Rate	*Harmonic 1*	*Harmonics 1, 3*	*Harmonics 1, 3, 5*
$n = 1$ kbps	$B = 500$ Hz	$B = 1.5$ kHz	$B = 2.5$ kHz
$n = 10$ kbps	$B = 5$ kHz	$B = 15$ kHz	$B = 25$ kHz
$n = 100$ kbps	$B = 50$ kHz	$B = 150$ kHz	$B = 250$ kHz

Bandwidth requirements

WHAT IS THE REQUIRED BANDWIDTH OF A LOW-PASS CHANNEL IF WE NEED TO SEND 1 MBPS BY USING BASEBAND TRANSMISSION?

The answer depends on the accuracy desired.

a. The minimum bandwidth, is B = bit rate /2, or 500 kHz.

b. A better solution is to use the first and the third harmonics with $B = 3 \times 500$ kHz = 1.5 MHz.

c. Still a better solution is to use the first, third, and fifth harmonics with $B = 5 \times 500$ kHz = 2.5 MHz.

WE HAVE A LOW-PASS CHANNEL WITH BANDWIDTH 100 KHZ. WHAT IS THE MAXIMUM BIT RATE OF THIS CHANNEL?

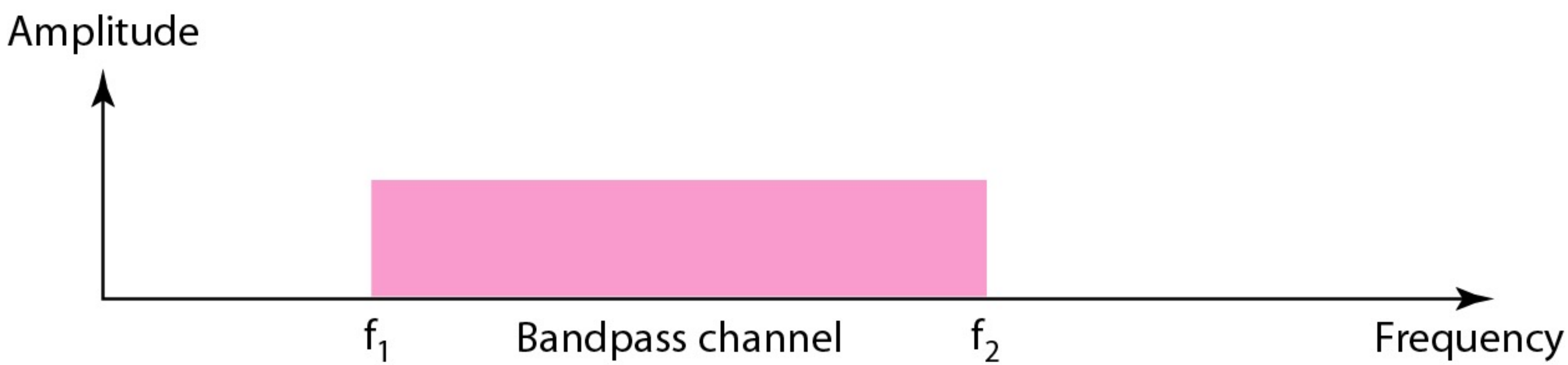
The maximum bit rate can be achieved if we use the first harmonic.
The bit rate is 2 times the available bandwidth, or 200 kbps

BROADBAND TRANSMISSION (USING MODULATION)

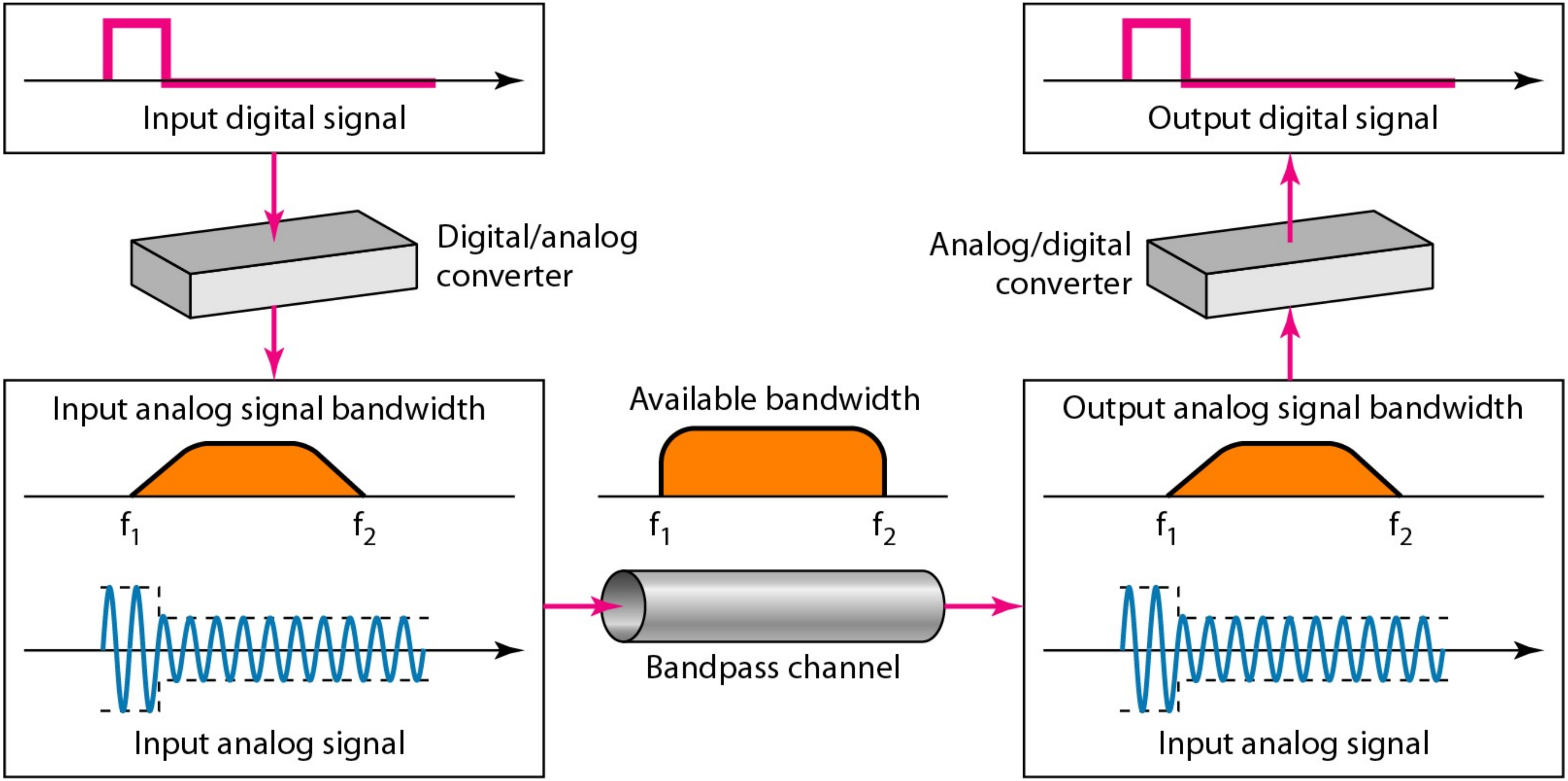
Changing a digital signal into analog signal for transmission

Modulation allows us to use a bandpass channel

- A channel with bandwidth that does not start from 0
- More available than a low-pass channel



Bandwidth of a Bandpass channel



Modulation of a digital signal for transmission on a bandpass channel

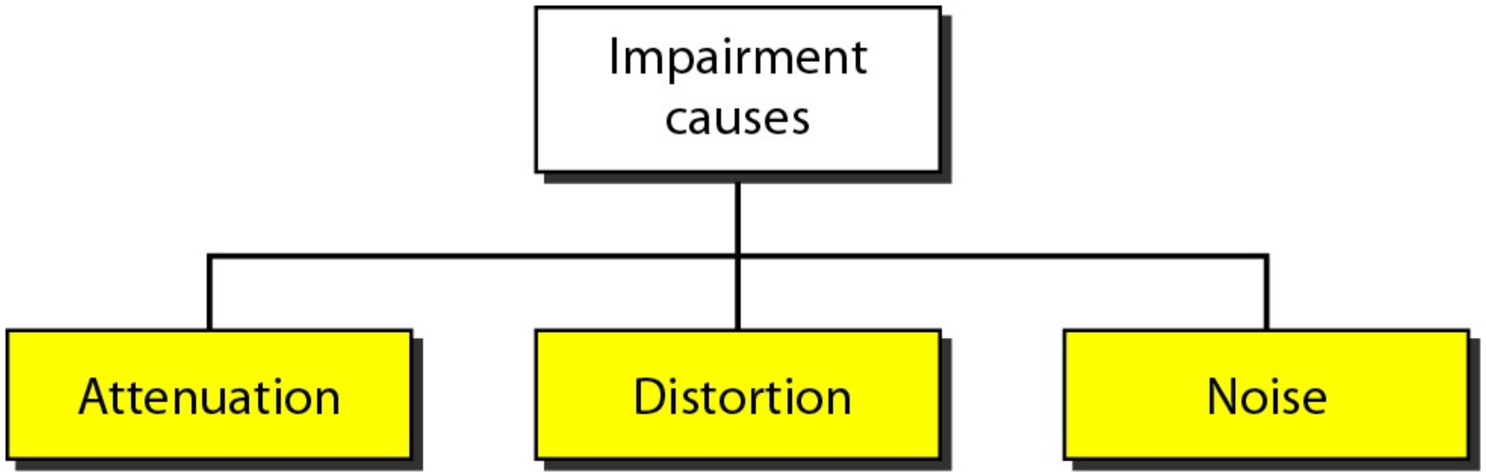
If the available channel is a bandpass channel, we cannot send the digital signal directly to the channel; we need to convert the digital signal to an analog signal before transmission.

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

A second example is the digital cellular telephone. For better reception, digital cellular phones convert the analog voice signal to a digital signal. Although the bandwidth allocated to a company providing digital cellular phone service is very wide, we still cannot send the digital signal without conversion. The reason is that we only have a bandpass channel available between caller and callee. We need to convert the digitized voice to a composite analog signal before sending.

TRANSMISSION IMPAIRMENT

Attenuation
Distortion
Noise

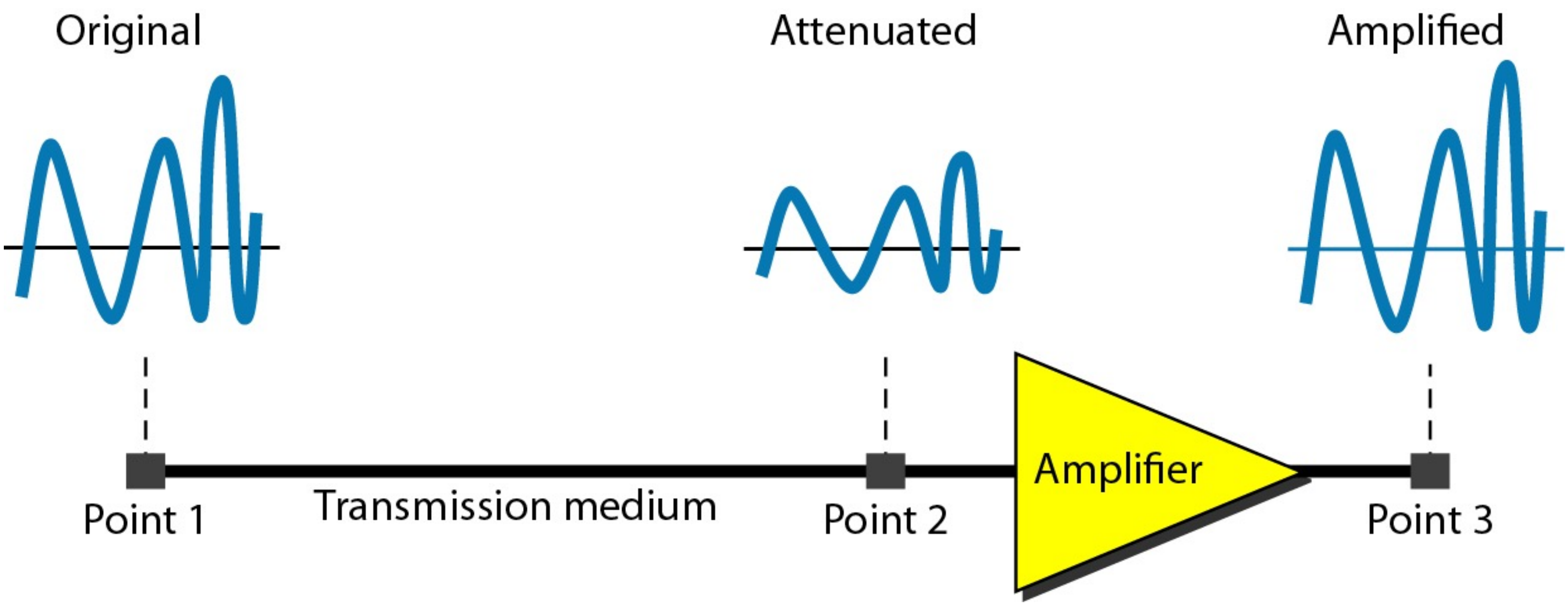


Causes of Impairment

- Signals travel through transmission media, which are not perfect
- Imperfection causes signal impairment
  - Signal at the beginning of the medium is not the same as the signal at the ned of medium

Attenuation

- Loss of energy
- Signal loses some energy in overcoming the resistance of medium
- Hence, amplifiers are used to amplify the signal



Attenuation

Measurement of Attenuation

- Measured in decibels

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

P_1 - input signal

P_2 - output signal

- Some books define decibels in terms of voltage instead of power. In such a case,

$$dB = 20\log_{10}(V_2/V_1)$$

V_1 - input voltage

V_2 - output voltage

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

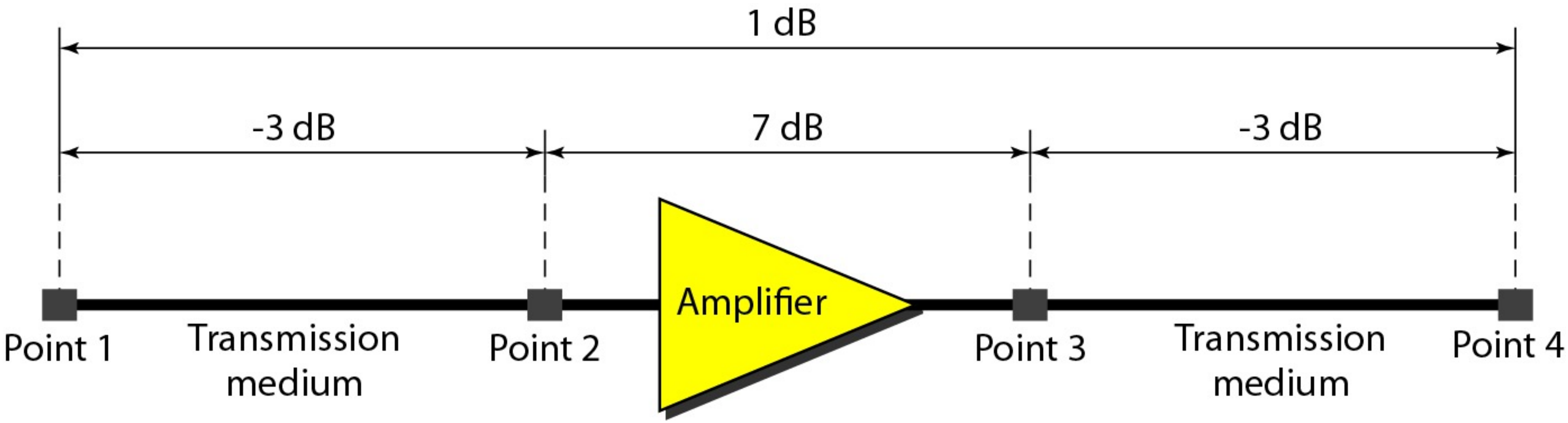
$$10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{0.5P_1}{P_1} = 10 \log_{10} 0.5 = 10(-0.3) = -3 \text{ dB}$$

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

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 Figure, a signal travels from point 1 to point 4. In this case, the decibel value can be calculated as

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

This implies that the signal has gained in power.

Sometimes the decibel is used to measure signal power in milliwatts. In this case, it is referred to as dB_m and is calculated as $dB_m = 10 \log10 P_m$, where P_m is the power in milliwatts. Calculate the power of a signal with $dB_m = -30$.

$$\mathrm{dB_m} = 10\log_{10} P_m = -30$$
$$\log_{10} P_m = -3 \qquad P_m = 10^{-3}\ \mathrm{mW}$$

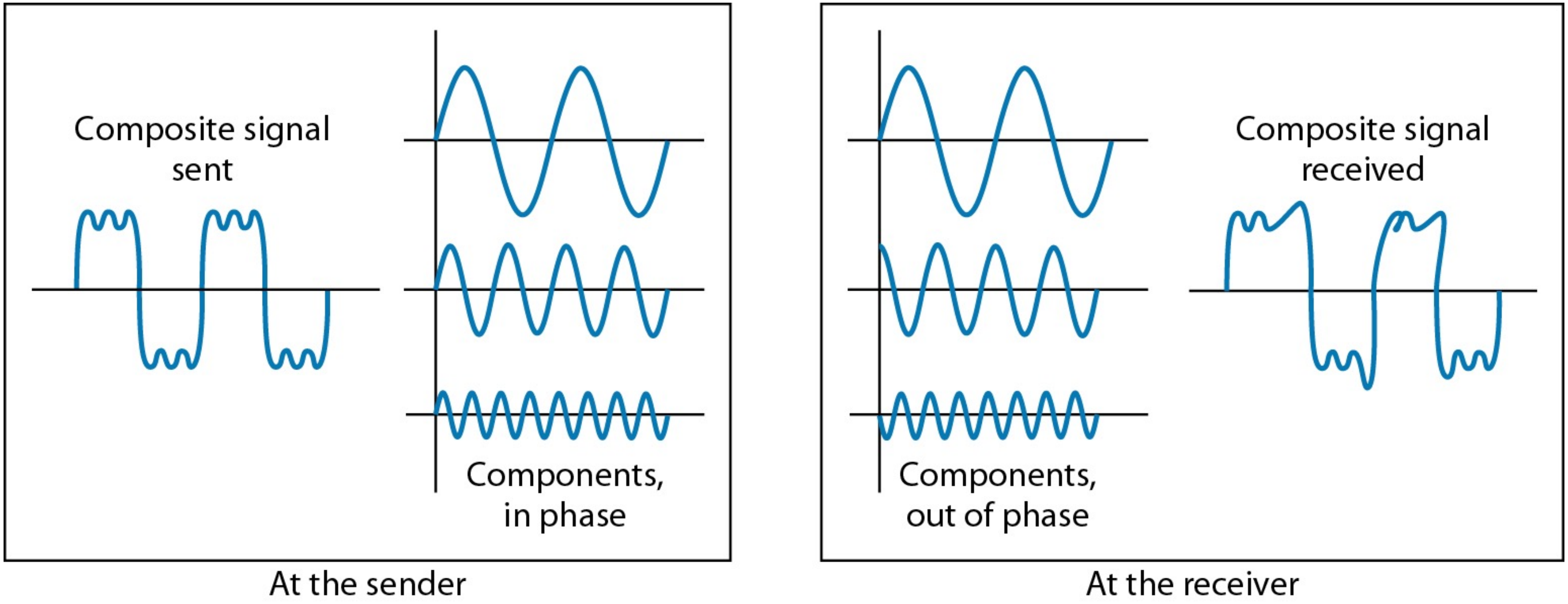
The loss in a cable is usually defined in decibels per kilometer (dB/km). If the signal at the beginning of a cable with −0.3 dB/km has a power of 2 mW, what is the power of the signal at 5 km?

The loss in the cable in decibels is $5 \times (-0.3) = -1.5$ dB. We can calculate the power as

$$\mathrm{dB} = 10\log_{10}\frac{P_2}{P_1} = -1.5$$
$$\frac{P_2}{P_1} = 10^{-0.15} = 0.71$$
$$P_2 = 0.71 P_1 = 0.7 \times 2 = 1.4\ \mathrm{mW}$$

Distortion

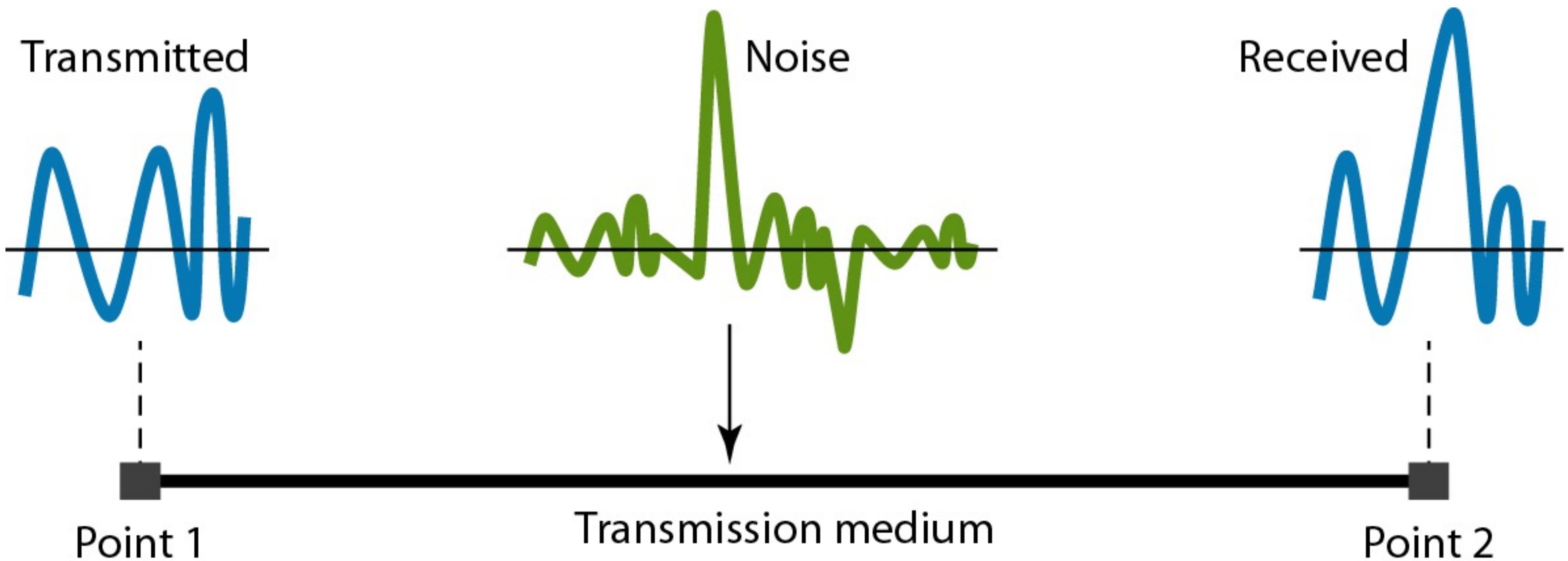
- Signal changes its form or shape
- Distortion can occur in a composite signal made of different frequencies
    - Each signal component has its own propagation speed through a medium and its own delay in arriving at final destination
- Differences in delay may create a difference in phase if the delay is not exactly the same as period duration



Distortion

Noise

- Thermal Noise - random noise of electrons in the wire creates an extra signal
- Induced Noise - from motors and appliances, devices act are transmitter antenna and medium as receiving antenna
- Crosstalk Noise - same as above but between two wires
- Impulse - Spikes that result from power lines, lightning, etc.

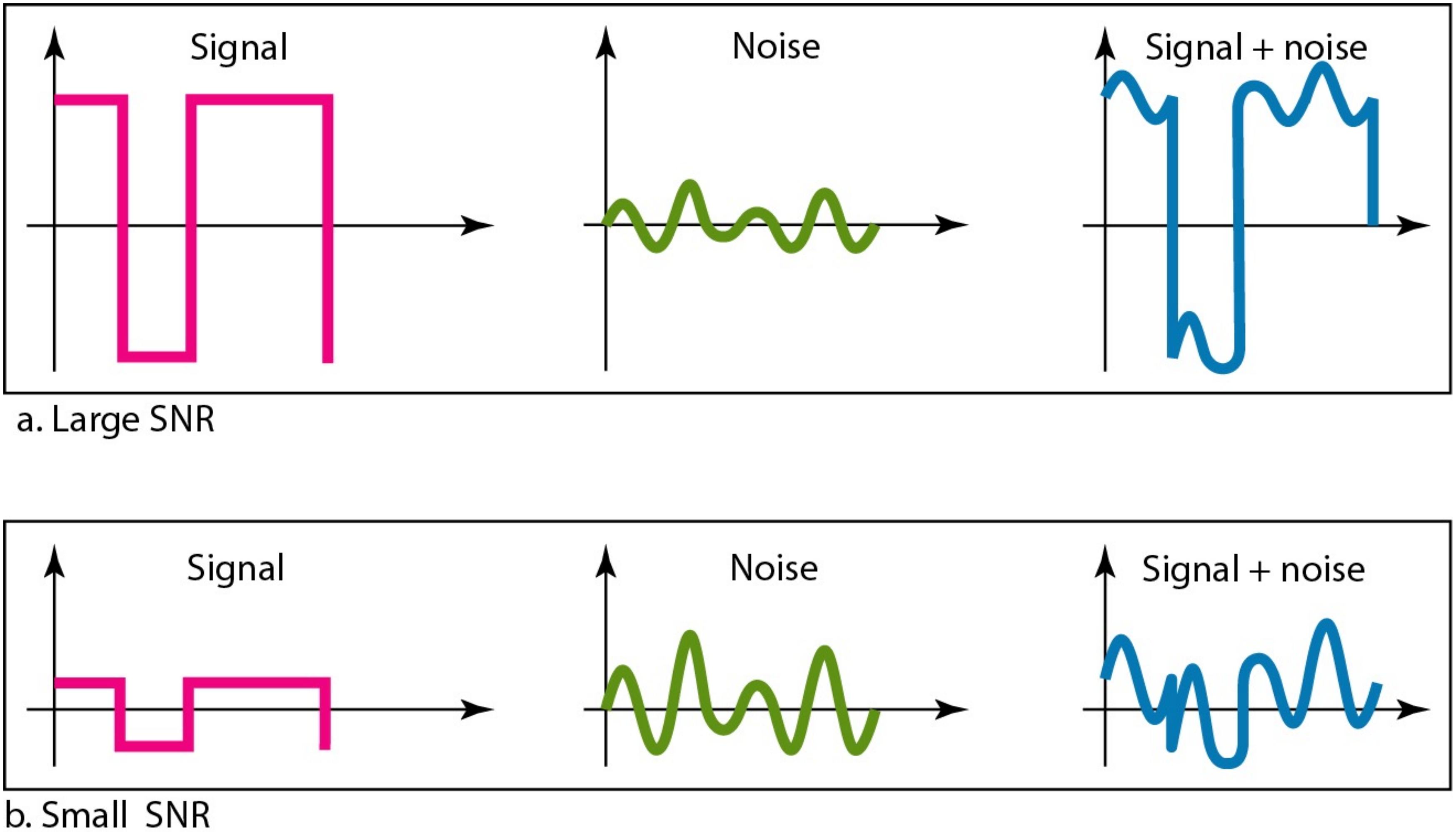


Noise

Noise Measurement

- Measured using Signal-to-Noise Ratio (SNR)
- SNR is the theoretical bit rate limit
- It is usually given in dB and referred to as $SNR_{dB.}$
- SNR = (average signal power)/(average noise power)
- SNR is ratio of what is wanted (signal) and what is not wanted (noise)

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



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

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} ?

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

$$SNR_{dB} = 10 \log_{10} 10{,}000 = 10 \log_{10} 10^4 = 40$$

The values of SNR and SNRdB for a noiseless channel are unachievable as -

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

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

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

DATA RATE LIMITS

Noiseless Channel: Nyquist Bit Rate
Noisy Channel: Shannon Capacity
Using Both Limits

DATA RATE LIMITS

Data rate depends on 3 factors

- The bandwidth available
- The level of the signals we use
- The quality of the channel (the level of noise)

Two theoretical formulas were developed to calculate data rate

- By Nyquist for a noiseless channel
- By Shannon for a noisy channel

NOISELESS CHANNEL: NYQUIST BIT RATE

Nyquist bit rate defines the theoretical maximum bit rate

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

The bit rate of a system increases with an increase in the number of signal levels we use to denote a symbol.

A symbol can consist of a single bit or “n” bits.

The number of signal levels = 2^n.

As the number of levels goes up, the spacing between level decreases, increasing the probability of an error occurring in the presence of transmission impairments

- Increasing the signal levels impose burden on receiver to distinguish between different levels

Increasing the levels of a signal increases the probability of an error occurring, in other words it reduces the reliability of the system. Why??

NOISELESS CHANNEL: NYQUIST BIT RATE

Nyquist gives the upper bound for the bit rate of a transmission system by calculating the bit rate directly from the number of bits in a symbol (or signal levels) and the bandwidth of the system (assuming 2 symbols/per cycle and first harmonic)

Nyquist theorem states that for a noiseless channel:

$$C = 2\ B \log_2 2^n$$

C= capacity in bps

B = bandwidth in Hz

Does the Nyquist theorem bit rate agree with the intuitive bit rate described in baseband transmission?

They match when we have only two levels. In baseband transmission, the bit rate is 2 times the bandwidth if we use only the first harmonic in the worst case. However, the Nyquist formula is more general; it can be applied to baseband transmission and modulation. Also, it can be applied when we have two or more levels of signals.

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

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

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

$$265{,}000 = 2 \times 20{,}000 \times \log_2 L$$

$$\log_2 L = 6.625 \qquad L = 2^{6.625} = 98.7 \text{ levels}$$

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, the bit rate is 280 kbps. If we have 64 levels, the bit rate is 240 kbps

NOISY CHANNEL: SHANNON CAPACITY

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:

$$\text{Capacity} = \text{bandwidth} \times \log_2(1+\text{SNR})$$

There is no indication of the signal level

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.

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 implies 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

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

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

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

For practical purposes, when the SNR is very high, we can assume that SNR + 1 is almost the same as SNR. In these cases, the theoretical channel capacity can be simplified to

$$C = B \times \frac{SNR_{dB}}{3}$$

We can calculate the theoretical capacity of the previous example as

$$C = 2 \text{ MHz} \times \frac{36}{3} = 24 \text{ Mbps}$$

USING BOTH LIMITS

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?

We use the Shannon formula to find the upper limit

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

For better performance we choose something lower, 4 Mbps, for example. Then we use the Nyquist formula to find the number of signal levels

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

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?

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

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

PERFORMANCE

- Bandwidth
- Throughput
- Latency
- Bandwidth Delay Product
- Jitter

BANDWIDTH

Bandwidth is used in two contexts

- Bandwidth in Hertz
  - refers to the range of frequencies in a composite signal or the range of frequencies that a channel can pass
- Bandwidth in Bits per Second
  - refers to the speed of bit transmission in a channel or link;
  - often referred to as Capacity

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.

If the telephone company improves the quality of the line and increases the bandwidth to 8 kHz, we can send 112,000 bps by using the same technology as mentioned in Example 3.42.

THROUGHPUT

Measure of how fast we can actually send data through a network

Bandwidth Vs Throughput

- Bandwidth is a potential measurement of a link
- Throughput is an actual measurement of how fast we can send data
  - Link with a bandwidth of 1Mbps, but devices connected may handle only 200 kbps
  - Hence, we can't send more than 200 kbps through this link

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?

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

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

Made of four components

- Propagation time
- Transmission time
- Queuing time
- Processing delay

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

Propagation Time

- Measures the time required for a bit to travel from the source to the destination
- Calculated by dividing the distance by propagation speed

Propagation Delay = Distance/Propagation speed

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.

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

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

Transmission Time

- There is a time between the first bit leaving the sender and the last bit arriving at the receiver
- Transmission time depends on size of the message and the bandwidth of the channel

Transmission time = (Message Size) / Bandwidth

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 × 108 m/s.

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

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

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.

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.

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

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

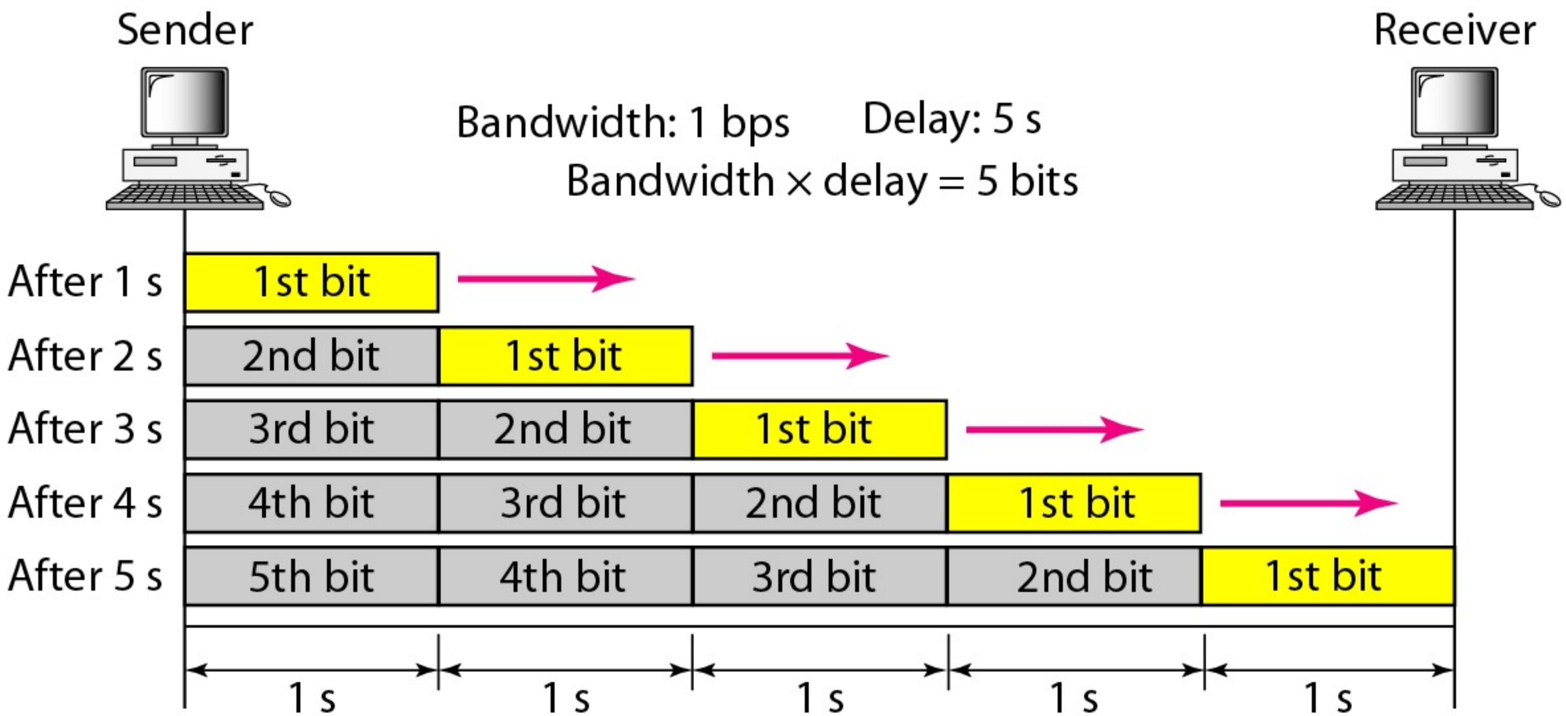
Note that in this case, because the message is very long and the bandwidth is not very high, the dominant factor is the transmission time, not the propagation time. The propagation time can be ignored.

Queuing Time

- Time needed for each intermediate or end device to hold the message before it can be processed
- Not a fixed factor; it changes with the load imposed on the network
- When there is heavy traffic on the network, queuing time increases
- Routers queue the packets

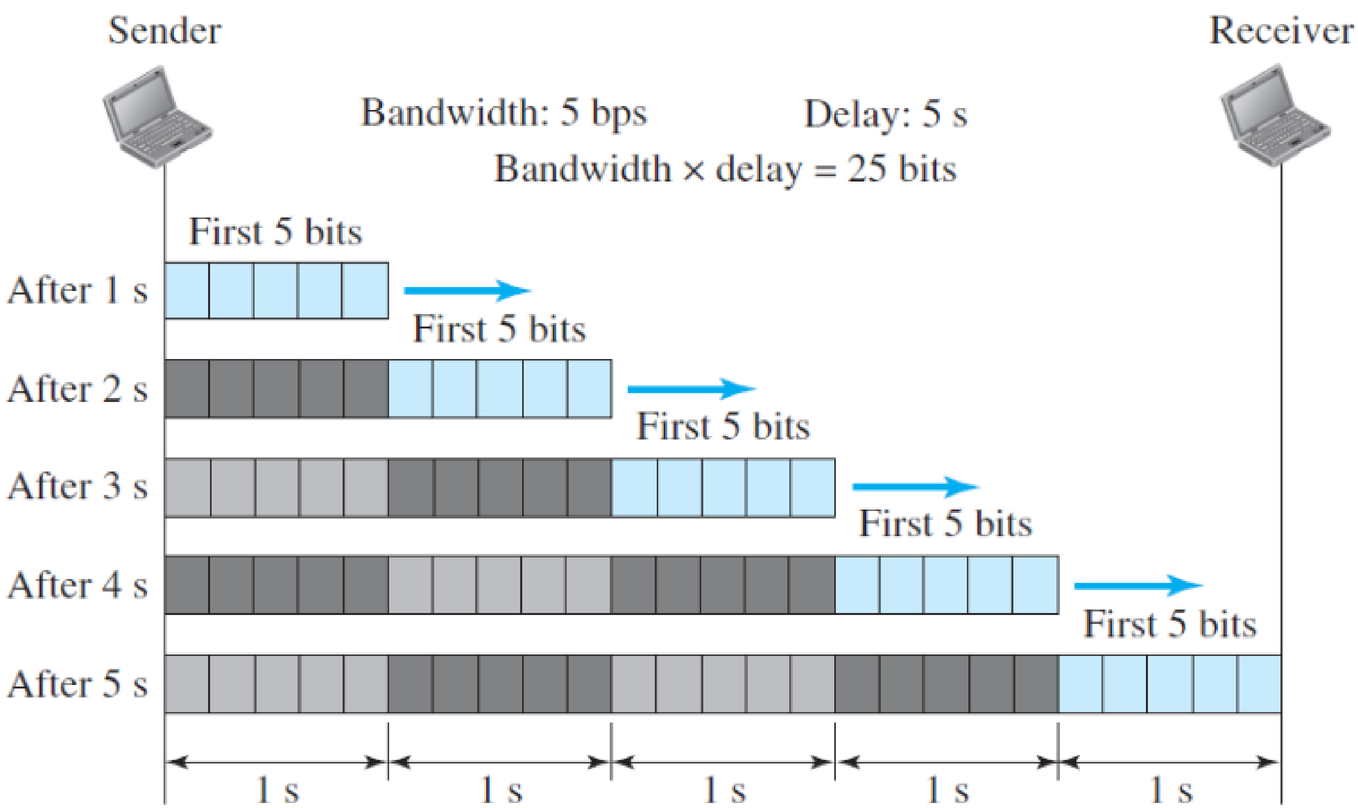
BANDWIDTH DELAY PRODUCT

Bandwidth and delay are two performance metrics of a link

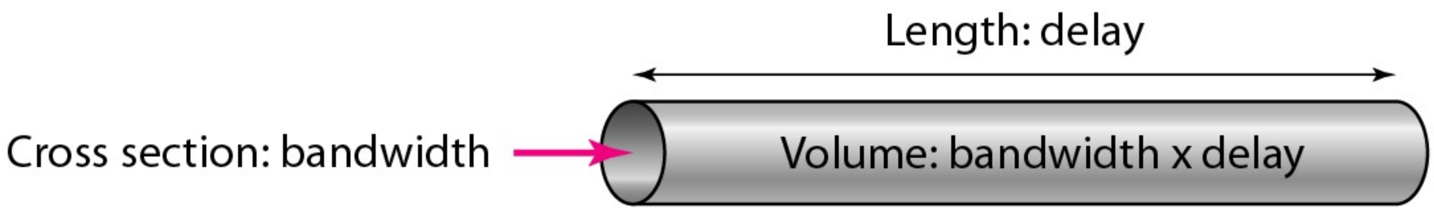


Filling the link with bits for Case 1

We can think about the link between two points as a pipe. The cross section of the pipe represents the bandwidth, and the length of the pipe represents the delay. We can say the volume of the pipe defines the bandwidth-delay product



Filling the link with bits for Case 2



Concept of Bandwidth Delay Product

The bandwidth-delay product defines the number of bits that can fill the link

Jitter

- Jitter is a problem if different packets of data encounter different delays and the application using the data at the receiver site is time-sensitive

THANK YOU!!!

Any Questions!!!