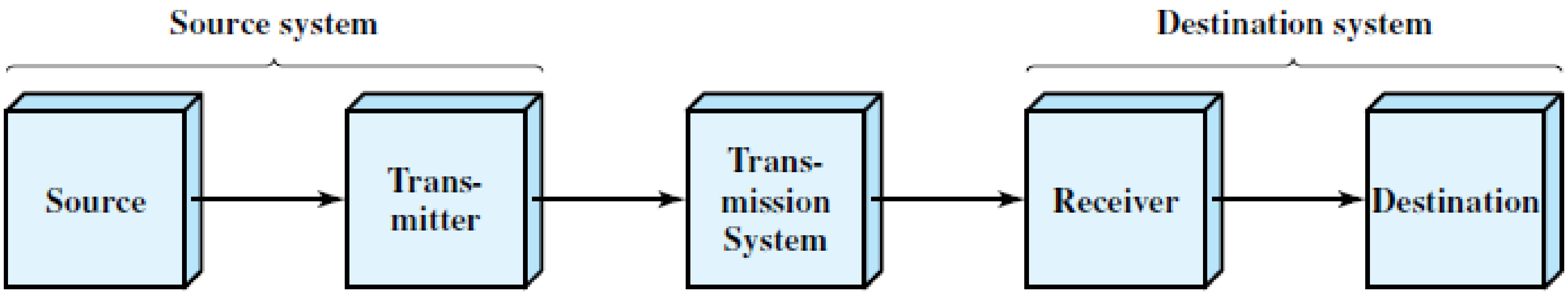
Principles of Data Communications (ICT 2156)

Concepts and Terminology



(a) General block diagram

Communication mode : simplex, half-duplex, full-duplex

Analog and Digital Data

- An entity that conveys some meaning based on some mutually agreed up conventions between a sender and a receiver.

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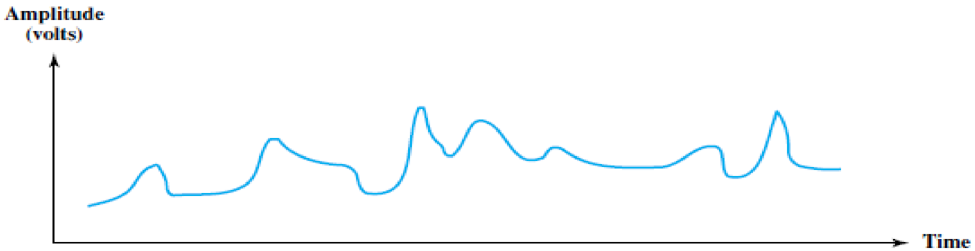
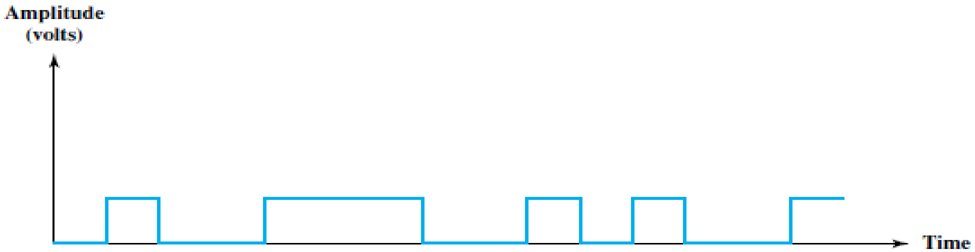
- **Analog data** have continuous values over a time.
- **Digital data** takes discrete value.

Analog and Digital Signals

- Signal : is a electric, electromagnetic or optical representation of data which can be sent over a communication media.



(a) Analog



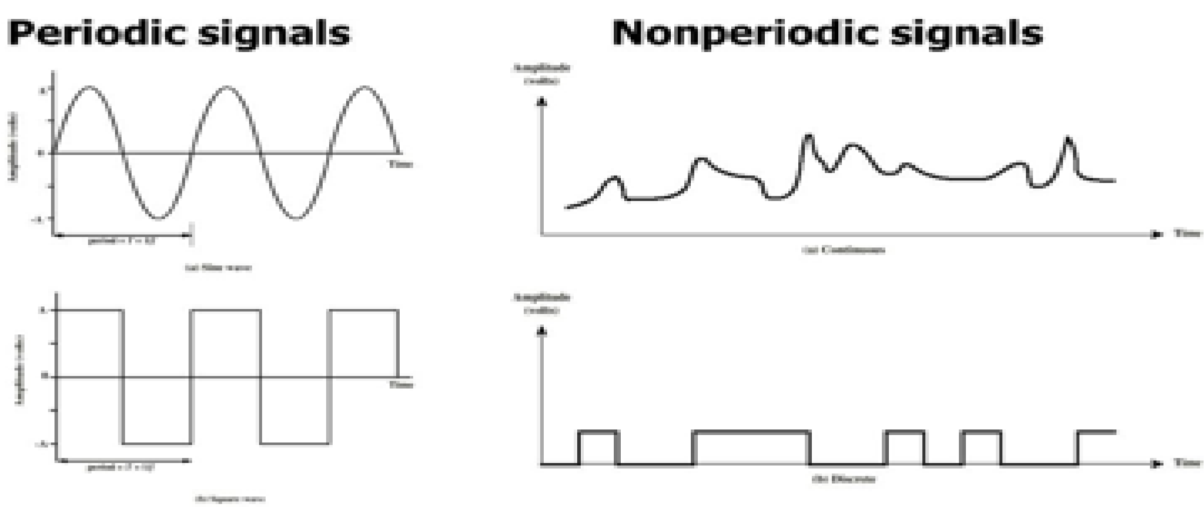
(b) Digital

- Analog signal : signal intensity varies in a smooth fashion over time.

- Digital signal : signal intensity maintains a constant level for some period of time and then abruptly changes to another constant level.

Periodic and Nonperiodic Signals

- 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 that repeats over time.
- Both analog and digital signals can be periodic or nonperiodic.



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.

PERIODIC ANALOG SIGNALS

Sine Wave

- fundamental form of a periodic analog signal.
- Characterized by three parameters: ***peak amplitude***, ***frequency***, and ***phase***.

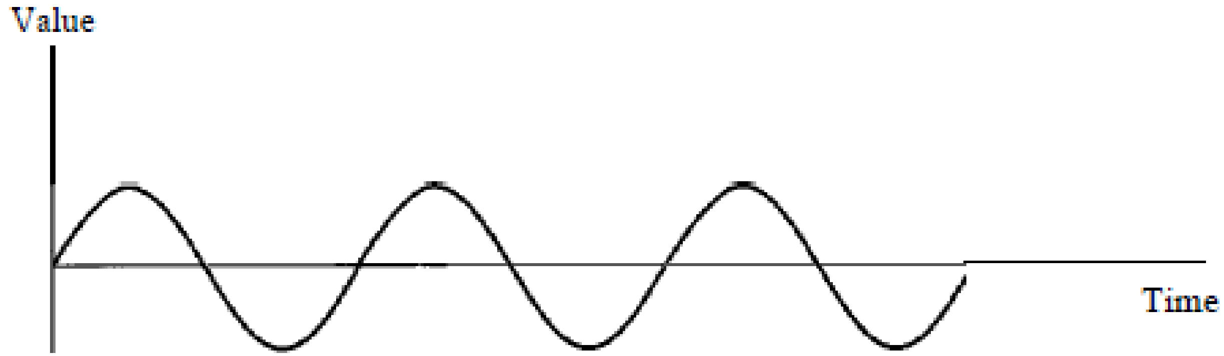


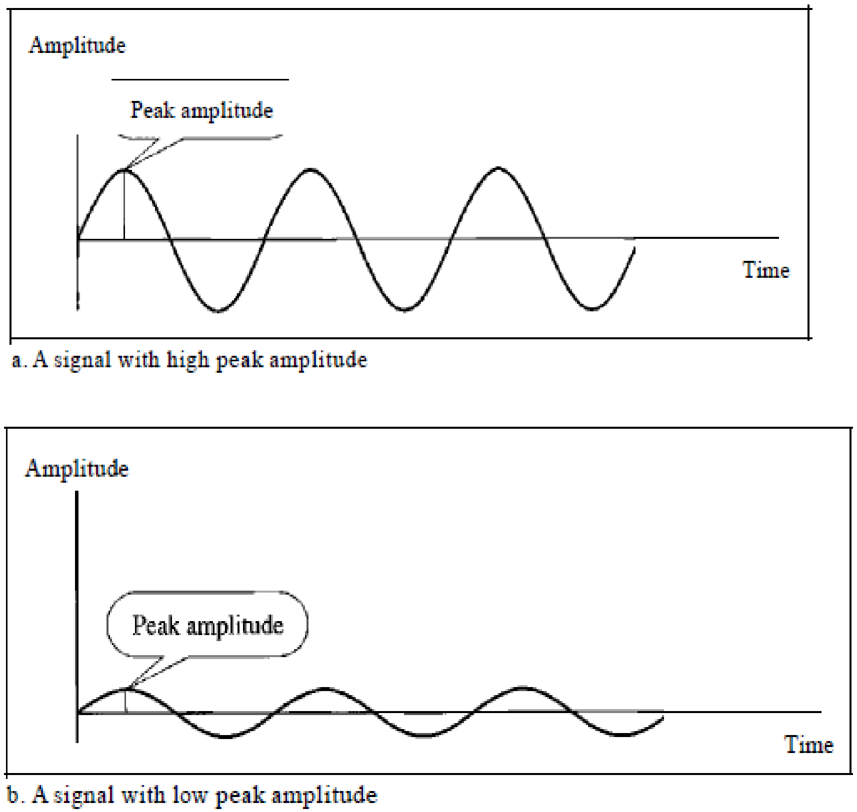
Figure : *A sine wave*

- The general sine wave can be written

$$s(t) = A \sin(2\pi f t + \phi)$$

Sine Wave : *Peak Amplitude*

- The peak amplitude of a signal is the absolute value of its highest intensity, proportional to the energy it carries.



signals with the same phase and frequency, but different amplitudes

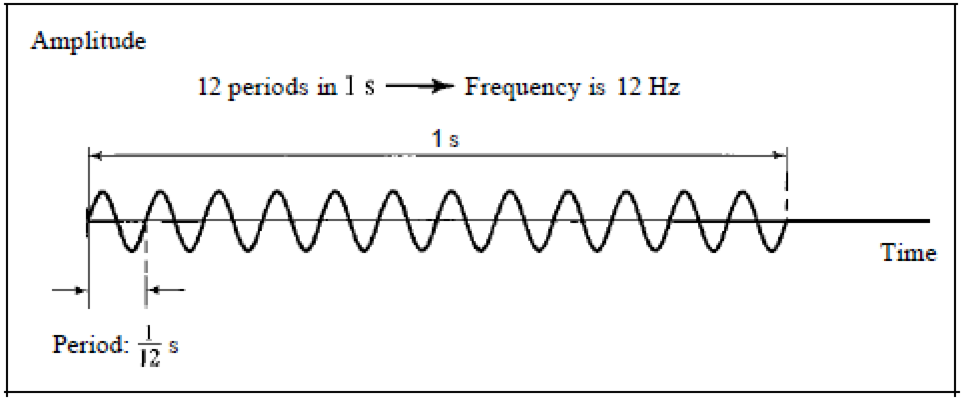
Sine Wave : *Period and Frequency*

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

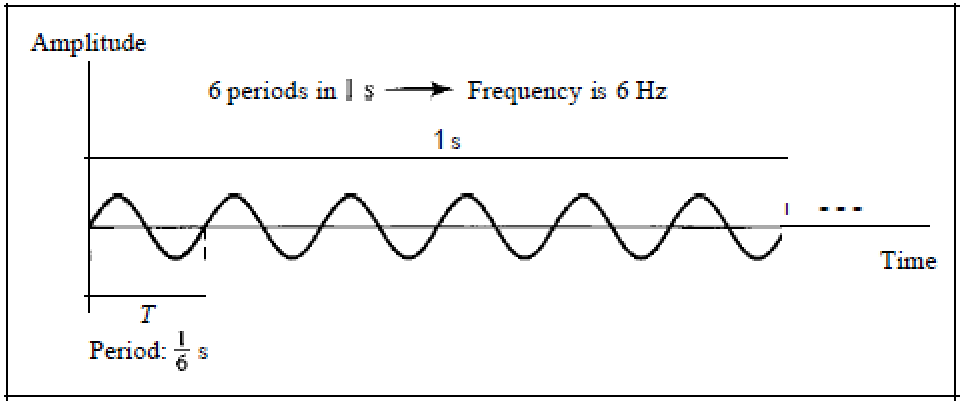
- Frequency refers to the number of periods in 1 s.

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

Sine Wave : *Period and Frequency*



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 : *Period and Frequency*

- Period is formally expressed in seconds.
- Frequency is formally expressed in Hertz (Hz), which is cycle per second.

Table 3.1 *Units of period and frequency*

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

Sine Wave : *Period and Frequency*

- The power we use at home has a frequency of 60 Hz.
- The period of this sine wave is:

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

- Period of the power for our lights at home is 0.0116 s, or 16.6 ms.

- Our eyes are not sensitive enough to distinguish these rapid changes in amplitude.

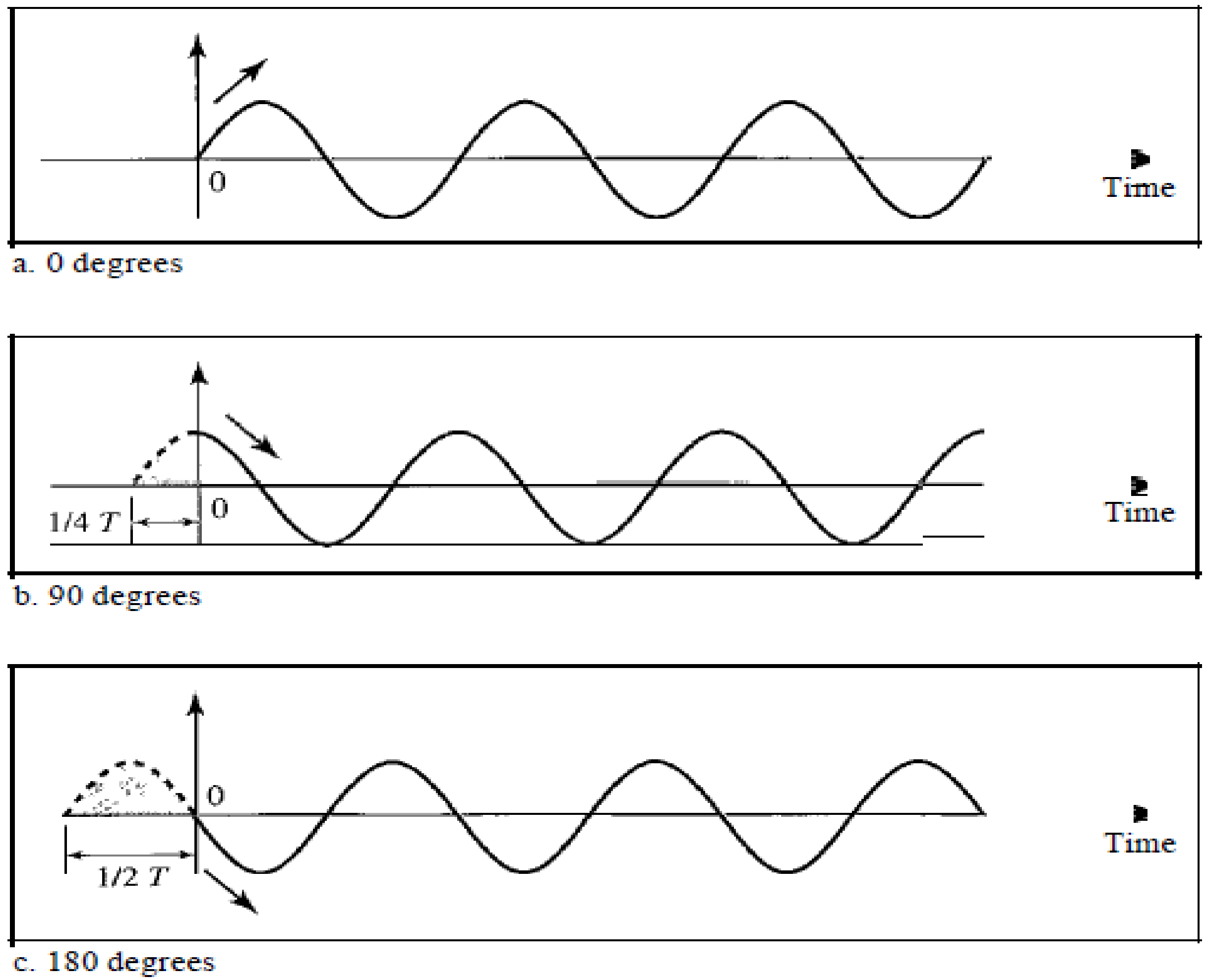
Sine Wave : *Period and Frequency*

- 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.

Sine Wave : Phase

- phase describes the position of the waveform relative to time O.
- It indicates the status of the first cycle.
- Phase is measured in degrees or radians.
- A phase shift of 360° corresponds to a shift of a complete period;
- a phase shift of 180° corresponds to a shift of one-half of a period;
- and a phase shift of 90° corresponds to a shift of one-quarter of a period.

Sine Wave : Phase



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

Sine Wave : Phase

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

2. A sine wave with a phase of 90° is shifted to the left by 1/4 cycle.

3. A sine wave with a phase of 180° is shifted to the left by 1/2 cycle

Sine Wave : Phase

A sine wave is offset 1/6 cycle with respect to time 0. What is its phase in degrees and radians?

Sine Wave : Phase

A sine wave is offset 1/6 cycle with respect to time 0. What is its phase in degrees and radians?

Solution

1 complete cycle is 360°. Therefore, *1/6* cycle is

$$1/6 * 360 = 60$$

wavelength

- Distance occupied in space by a single period.

- Wavelength = propagation speed / frequency.

Example : wavelength of redlight (frequency = $4*10^{14}$ Hz) is

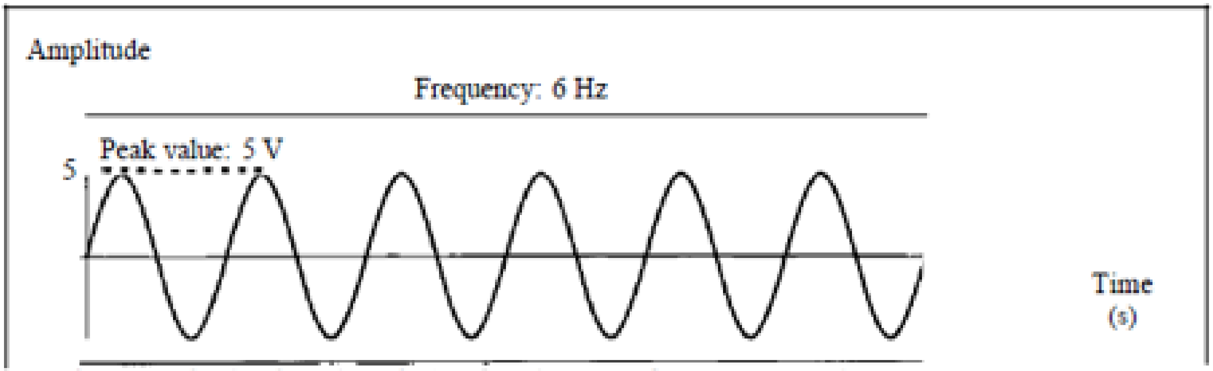
$c/f = 3*10^{8}$m/s $/4*10^{14}$

= 0.75 micro meter

Time and Frequency Domains

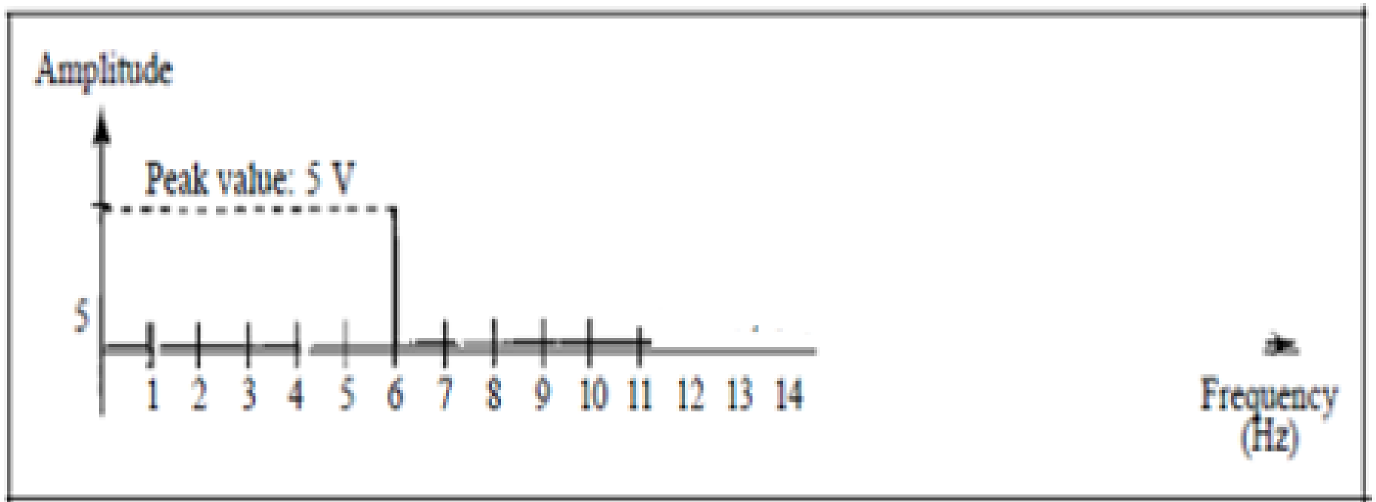
- The time-domain plot shows changes in signal amplitude with respect to time.

- It is an amplitude-versus-time plot.



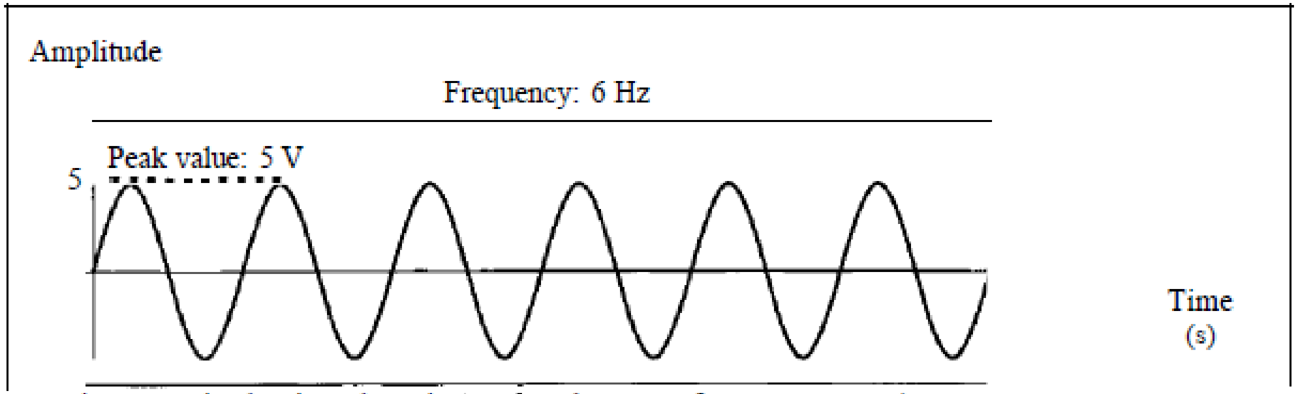
a. A sine wave in the time domain (peak value: 5 V, frequency: 6 Hz)

Time and Frequency Domains

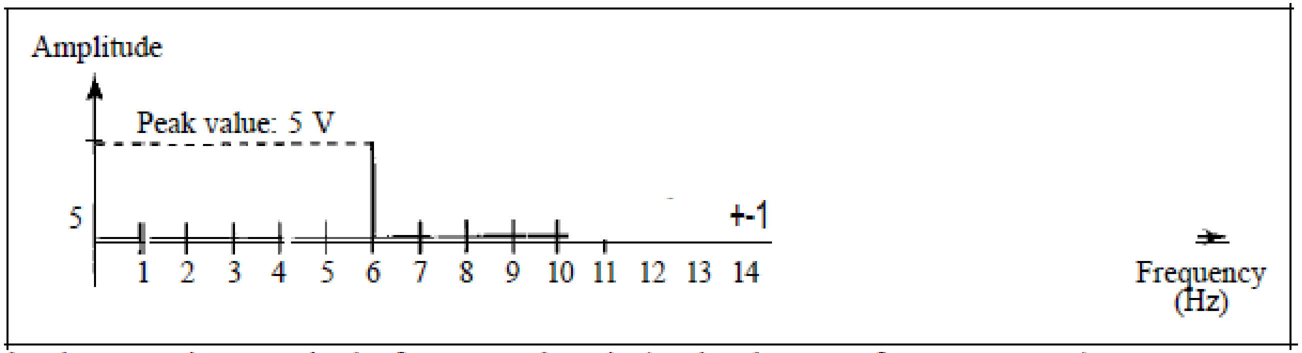


b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

Time and Frequency Domains



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

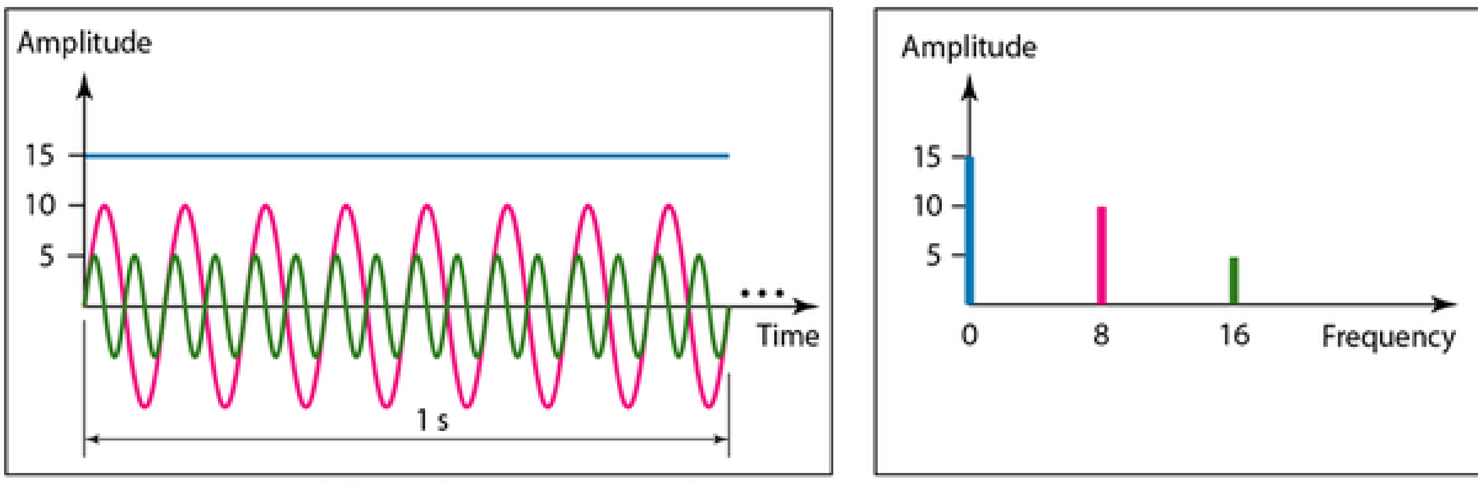


b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

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

Time and Frequency Domains

- Figure shows 3 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 three sine waves

Composite Signals

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

- We need to send a composite signal to communicate data.

- A composite signal is made of many simple sine waves.

Composite Signals

- In the early 1900s, the French mathematician Jean-Baptiste Fourier showed that any composite signal is actually a combination of simple sine waves with different frequencies, amplitudes, and phases.

Composite Signals

- A composite signal can be periodic or nonperiodic.

- A periodic composite signal can be decomposed into a series of simple sine waves with discrete frequencies that have integer values (1, 2, 3, and so on).

- A nonperiodic composite signal can be decomposed into a combination of an infinite number of simple sine waves with continuous frequencies, frequencies that have real values.

Composite Signals

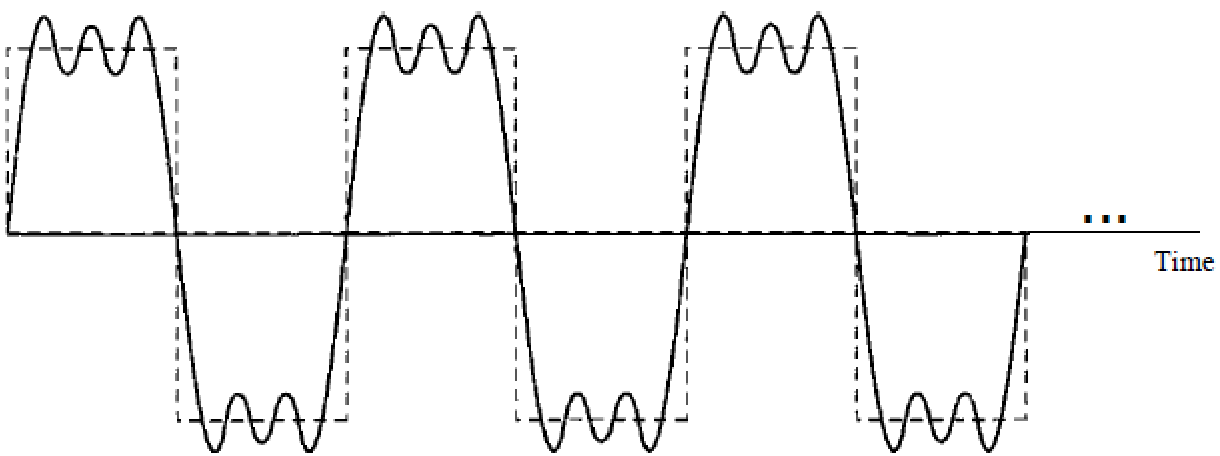
- If the composite signal is periodic, the decomposition gives a series of signals with discrete frequencies;

- if the composite signal is nonperiodic, the decomposition gives a combination of sine waves with continuous frequencies.

Composite Signals

- Figure shows a periodic composite signal with frequency *f.*

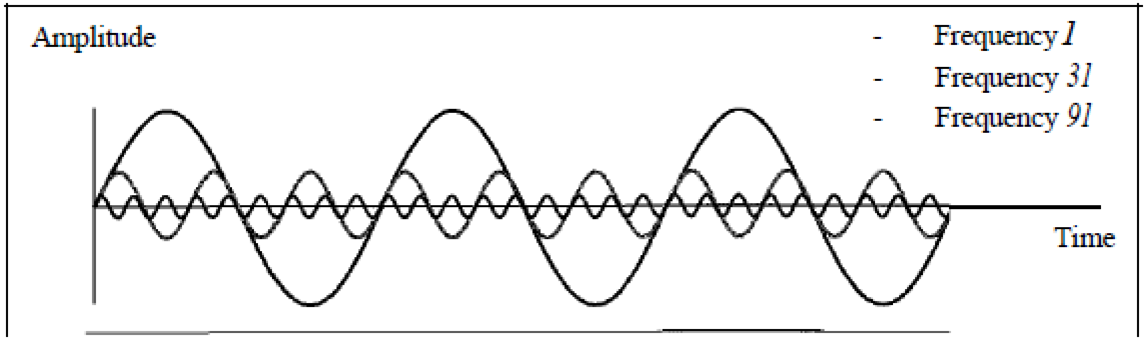
- This type of signal is not typical of those found in data communications.



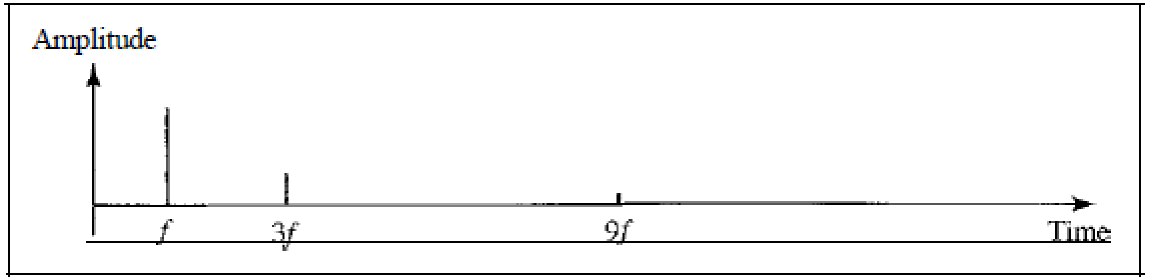
A composite periodic signal

Composite Signals

- It is difficult to manually decompose signal into a series of simple sine waves.
- There are tools, both hardware and software, that can help us do the job.



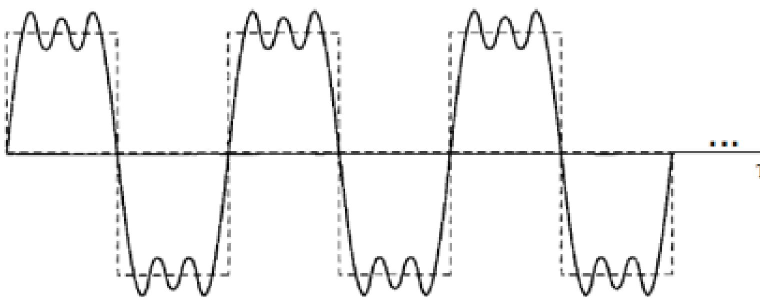
a. Time-domain decomposition of a composite signal

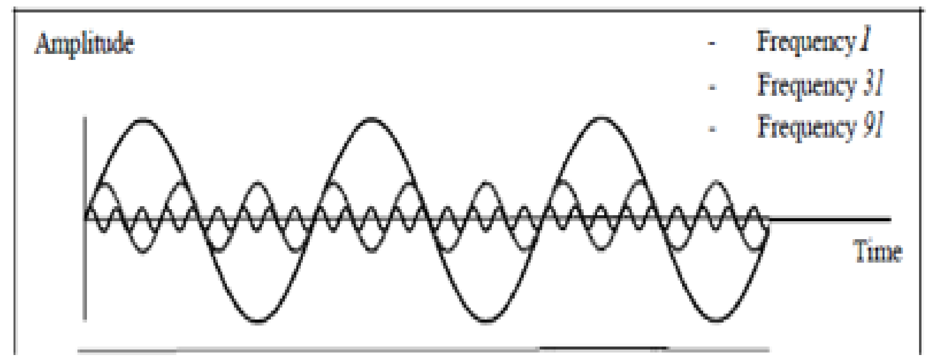


b. Frequency-domain decomposition of the composite signal

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

Composite Signals





a. Time-domain decomposition of a composite signal

- The amplitude of the sine wave with frequency *f* is almost the same as the peak amplitude of the composite signal.

- The amplitude of the sine wave with frequency *3f* is one-third of that of the first, and the amplitude of the sine wave with frequency *9f* is one-ninth of the first.

Composite Signals

- The frequency of the sine wave with frequency *f* is the same as the frequency of the composite signal; it is called the **fundamental frequency, or first harmonic**.

- The sine wave with frequency 3f has a frequency of 3 times the fundamental frequency; it is called the third harmonic.

- The third sine wave with frequency *9fhas* a frequency of 9 times the fundamental frequency; it is called the ninth harmonic.

Periodic analog signal

$$s(t + T) = s(t) \qquad -\infty < t < +\infty$$

where T is the period of the signal.

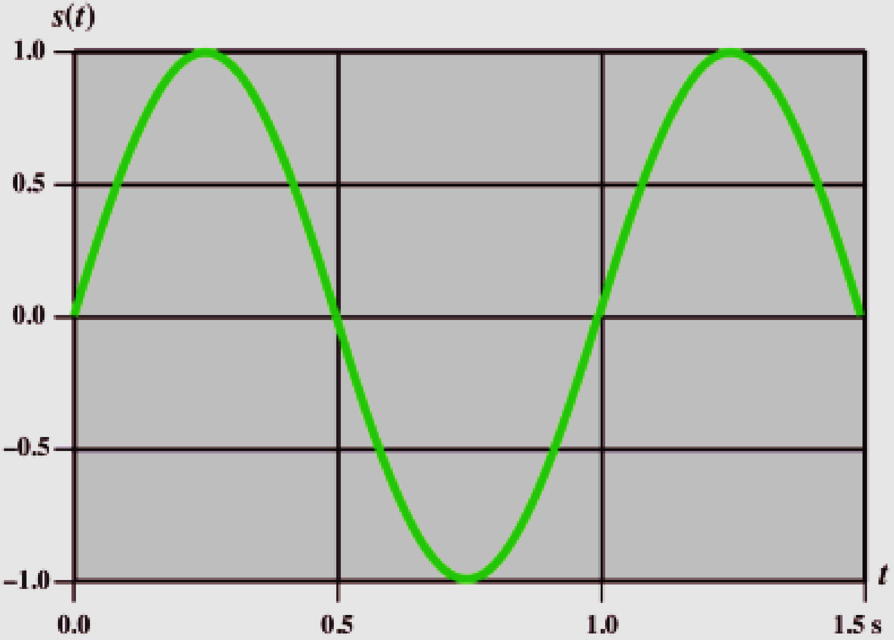
Periodic analog signal

Periodic analog signal characterized by 3 parameters.

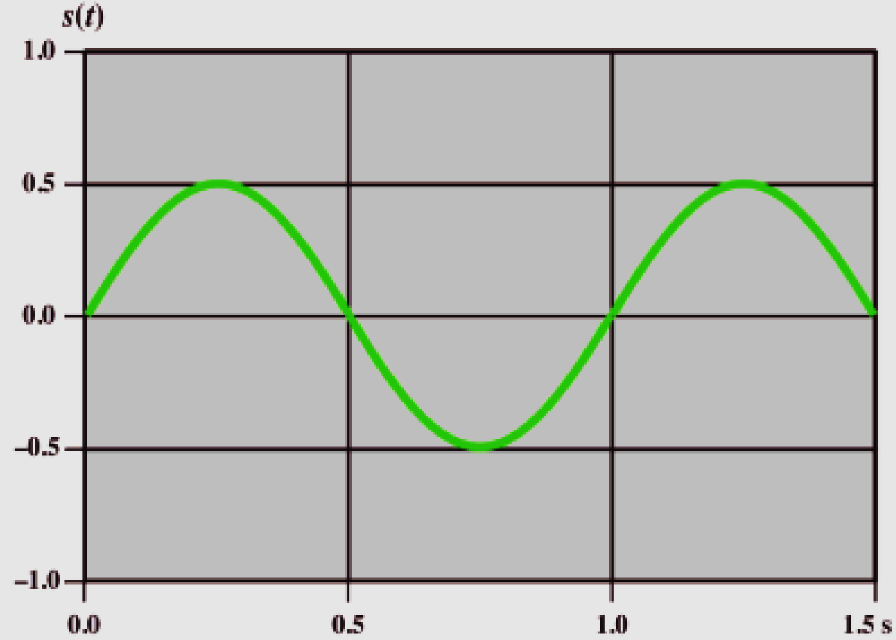
Representation of sine wave

$$s(t) = A \sin(2\pi f t + \varphi)$$

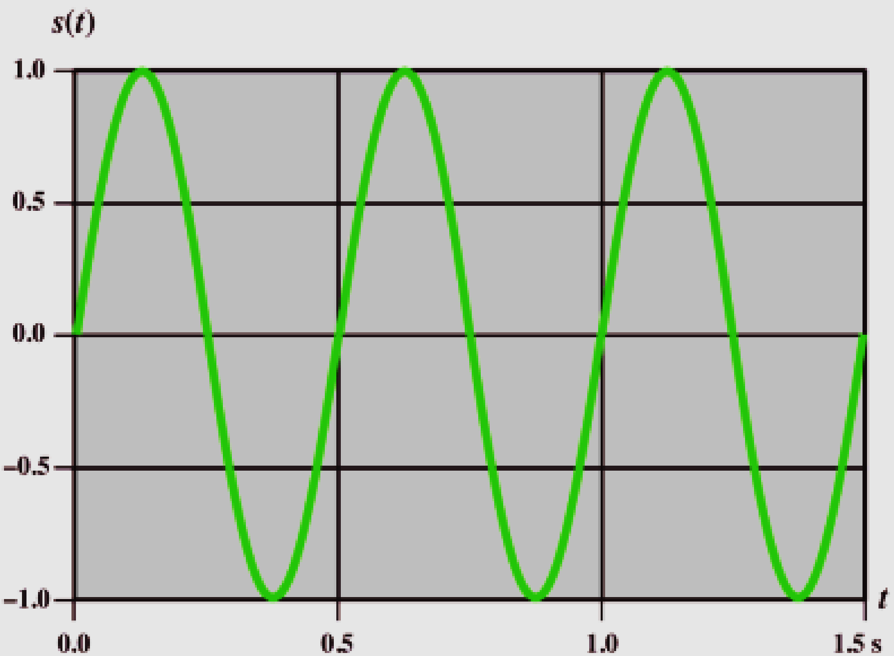
Where A is peak amplitude.



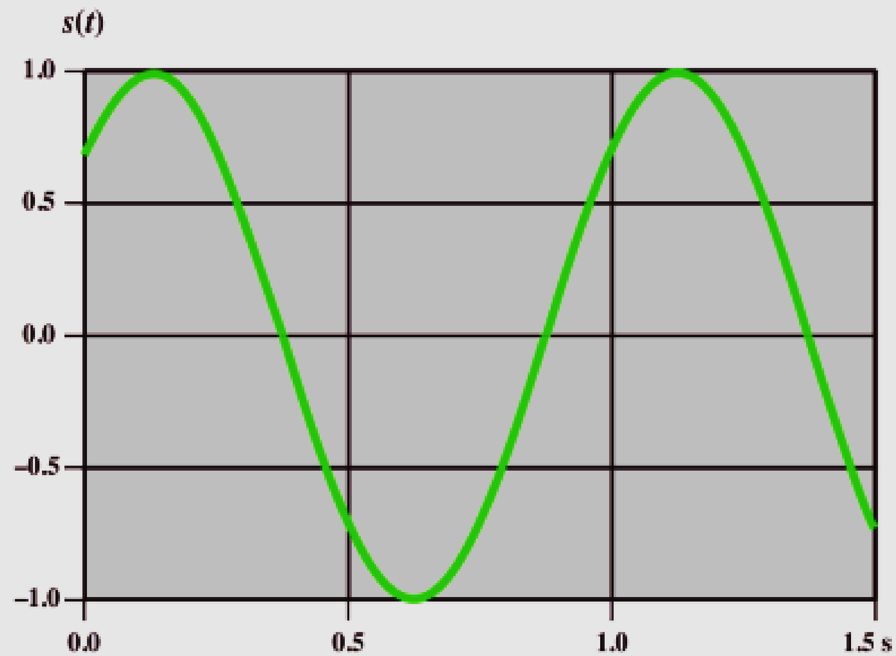
(a) $A = 1, f = 1, \phi = 0$



(b) $A = 0.5, f = 1, \phi = 0$



(c) $A = 1, f = 2, \phi = 0$



(d) $A = 1, f = 1, \phi = \pi/4$

UNITS of Parameter

Amplitude : volts, milli (10^{-3}) volt, KV(10^{3})

Frequency : Hz, KHz(10^{3}), MHz(10^{6}), GHz(10^{9}), THz(10^{12})

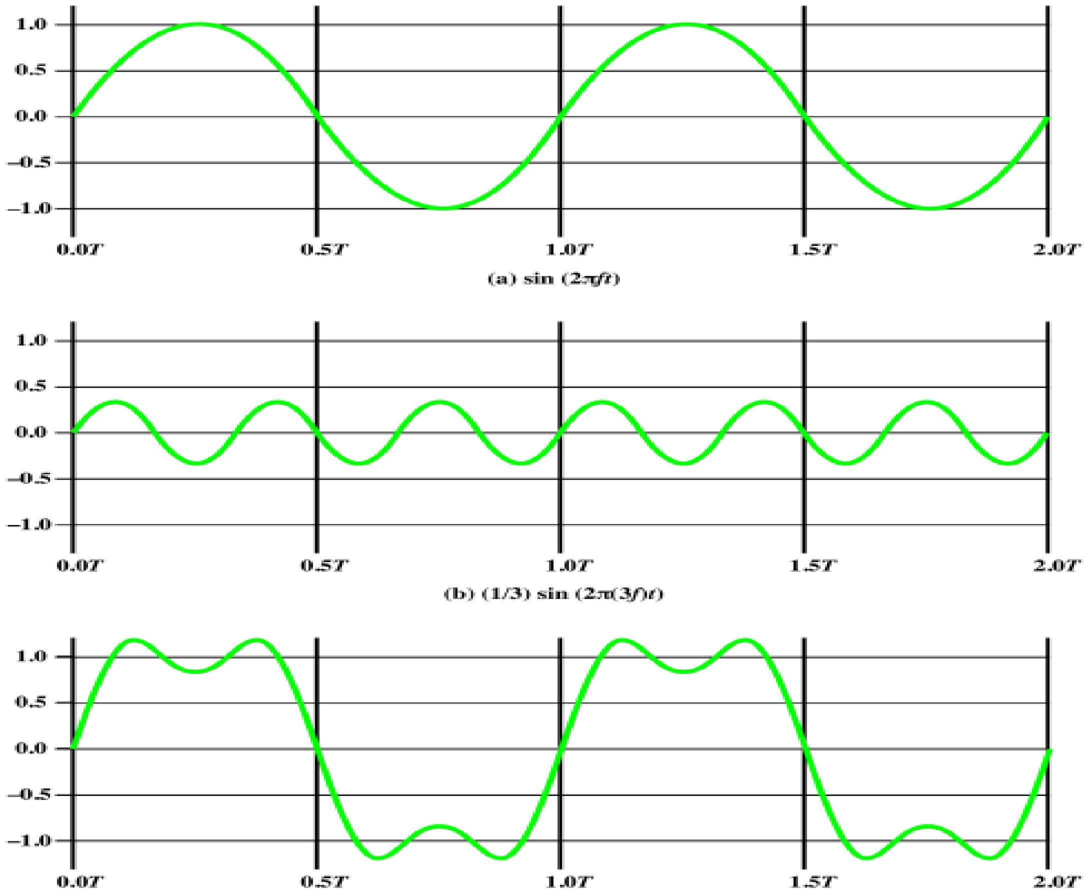
Time : second, milli second(10^{-3}), micro second(10^{-6}), ns(10^{-9}), ps(10^{-12})

Phase : degree , radian

Composite signals can be expressed as a combination of simple sine waves with different amplitude, frequency and phase.

$$s(t) = A_1 \sin(2\pi f_1 t + \varphi_1) + A_2 \sin(2\pi f_2 t + \varphi_2) + A_3 \sin(2\pi f_3 t + \varphi_3) + \ldots\ldots$$

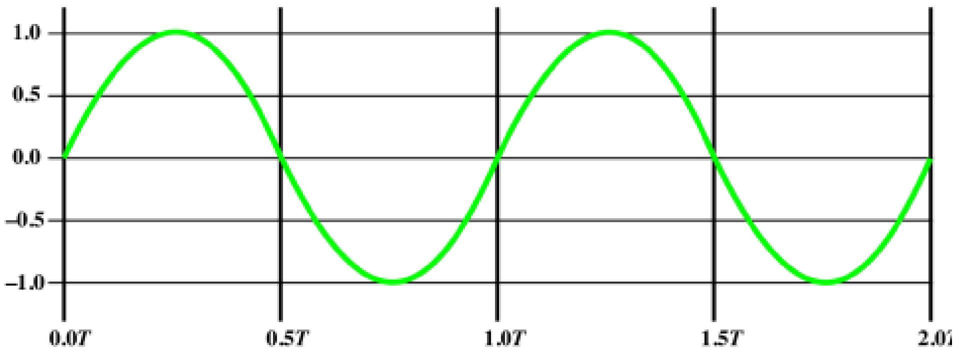
$$s(t) = A_1 \sin(2\pi f_1 t + \varphi_1) + A_2 \sin(2\pi f_2 t + \varphi_2) + \ldots\ldots$$



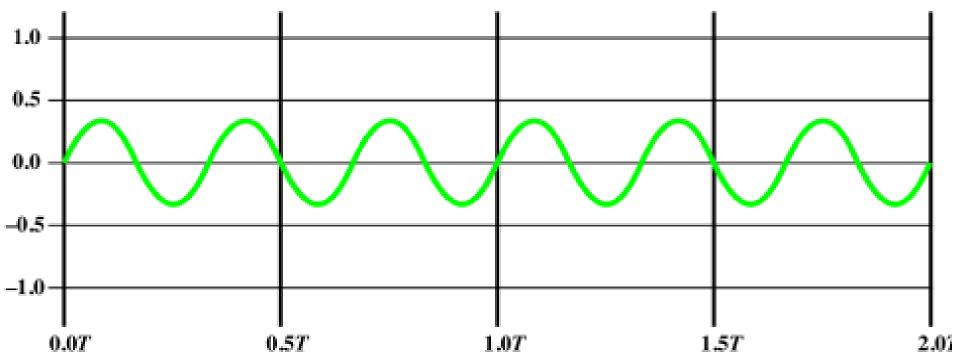
(a) sin (2πft)

(b) (1/3) sin (2π(3f)t)

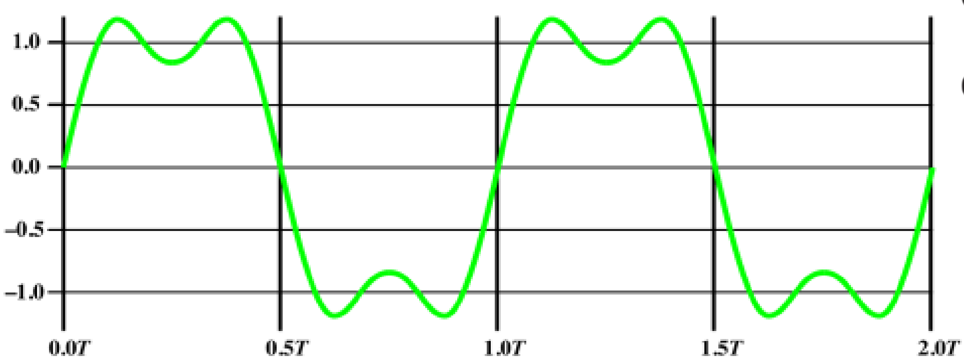
(c) (4/π) [sin (2πft) + (1/3) sin (2π(3f)t)]



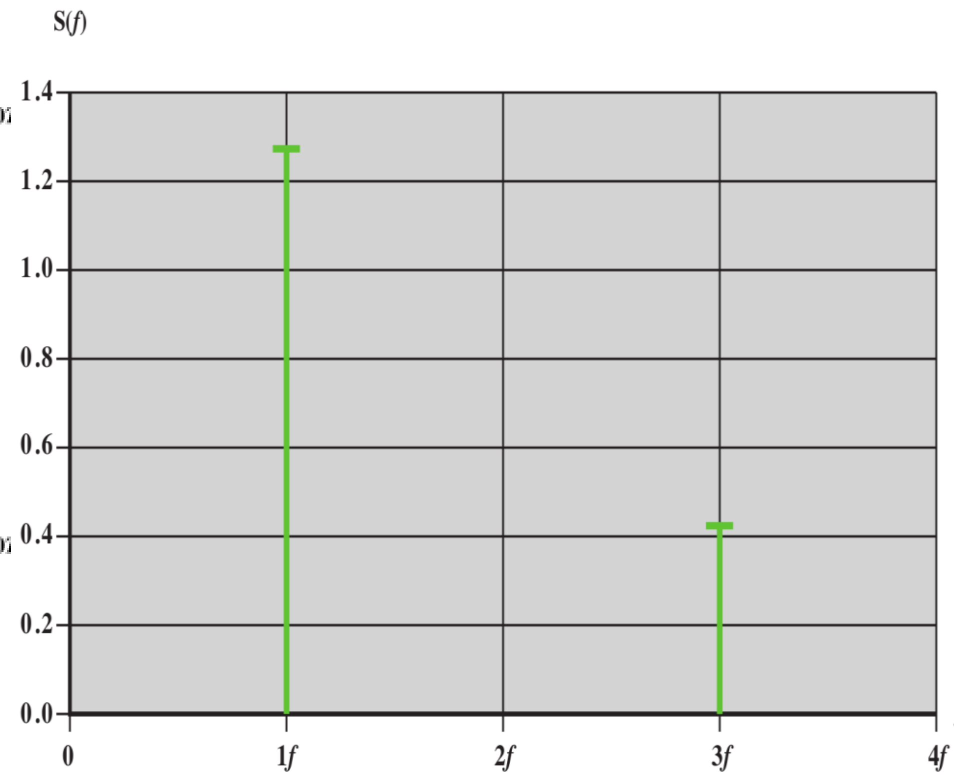
(a) sin (2πft)



(b) (1/3) sin (2π(3f)t)



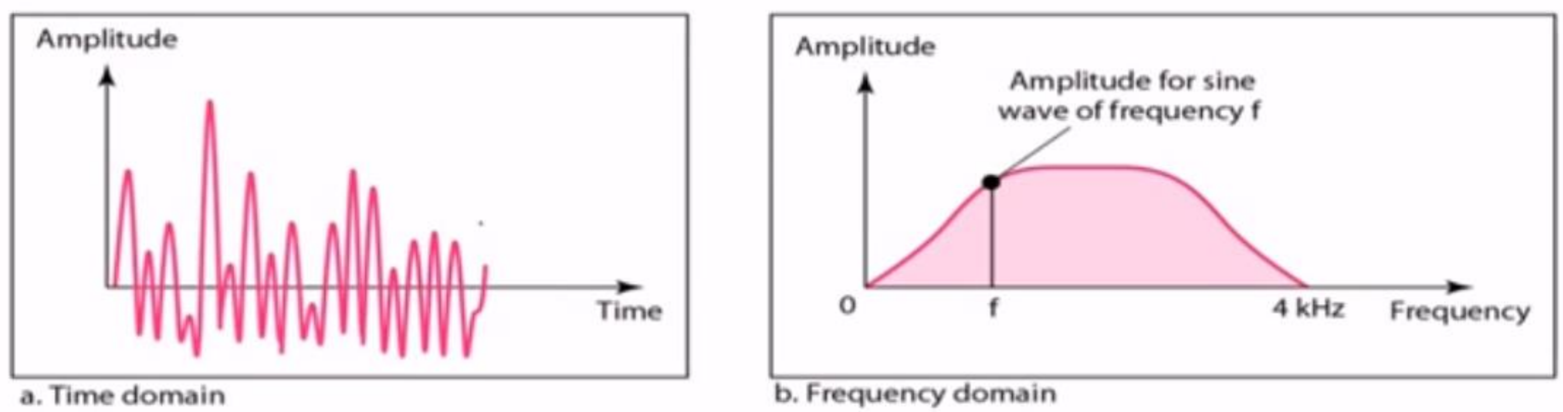
(c) (4/π) [sin (2πft) + (1/3) sin (2π(3f)t)]



(a) s(t) = (4/π) [sin (2πft) + (1/3) sin (2π(3f)t)]

Composite Signals

- Figure shows a nonperiodic composite signal.
- signal created by a microphone or a telephone.



- There are an infinite number of simple sine frequencies.
- Although the number of frequencies in a human voice is infinite, range is limited.
- Range of frequencies between 0 and 4 kHz.

Frequency Domain Concepts

- The **spectrum** of a signal is the range of frequencies that it contains.
- The **absolute bandwidth** of a signal is the width of the spectrum.
- Many signals have an infinite bandwidth.
- Most of the energy in the signal is contained in a relatively narrow band of frequencies.
- This band is referred to as the **effective bandwidth**, or just **bandwidth**.

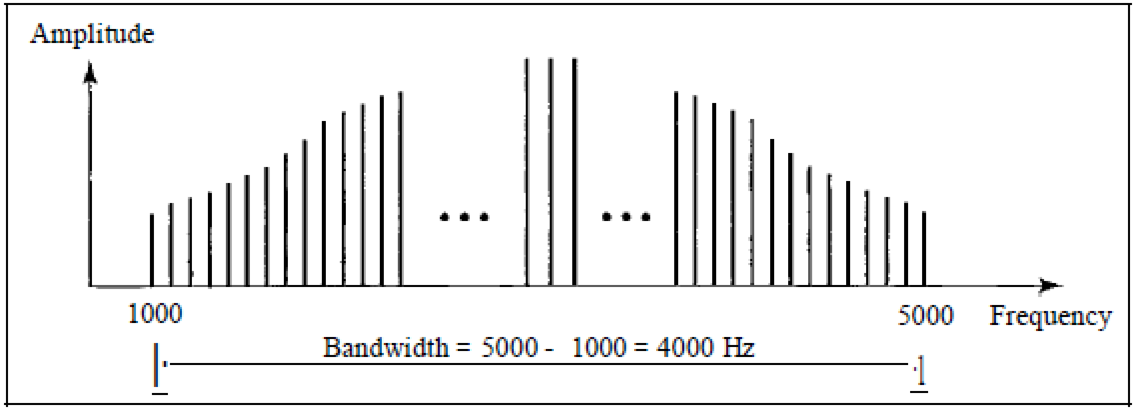
Bandwidth

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

- If a composite signal contains frequencies between 1000 and 5000, its bandwidth is 5000 - 1000, or 4000.

Bandwidth

- The figure depicts periodic composite signals.
- The bandwidth of the periodic signal contains all integer frequencies between 1000 and 5000 (1000, 100 I, 1002, ...).

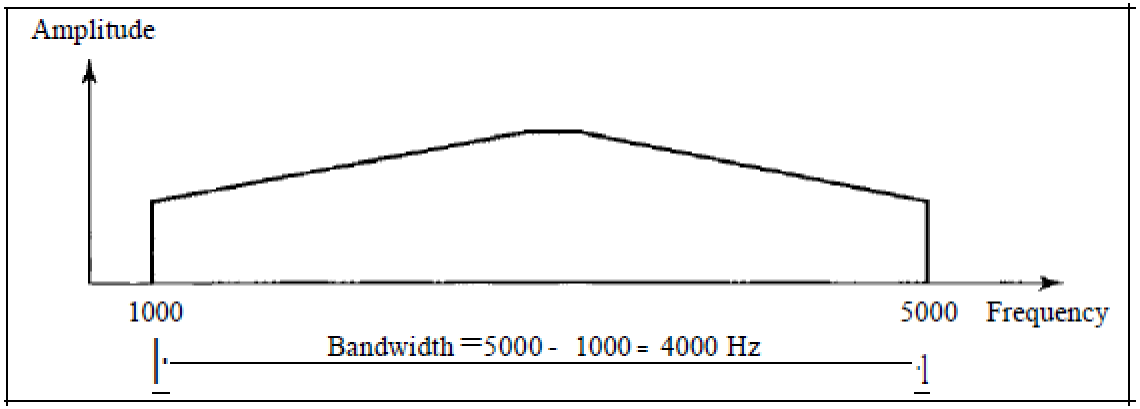


a. Bandwidth of a periodic signal

Figure 3.12 *The bandwidth of periodic composite signals*

Bandwidth

- Below nonperiodic composite signals.
- The bandwidth of the nonperiodic signals has the same range, but the frequencies are continuous.



b. Bandwidth of a nonperiodic signal

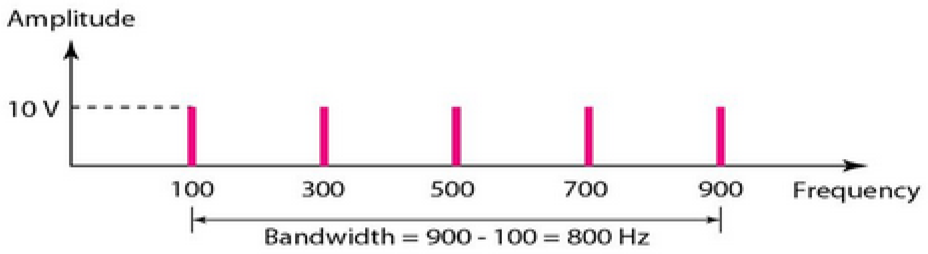
The bandwidth of nonperiodic composite signals

Bandwidth

- 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

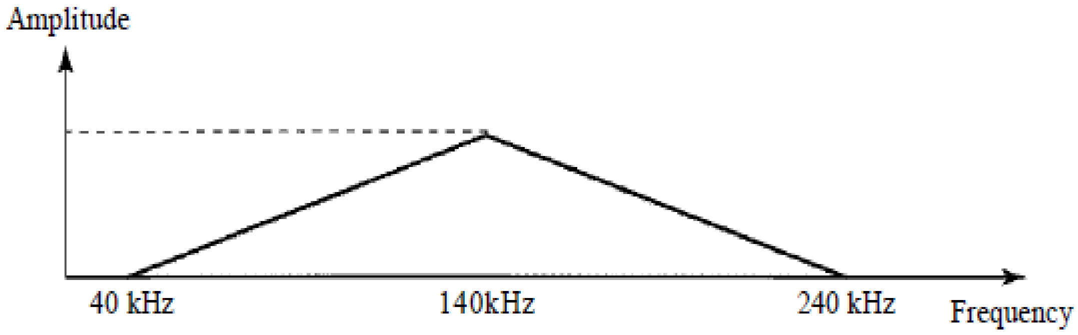
- Then $B = f_h - i_t = 900 - 100 = 800$ Hz

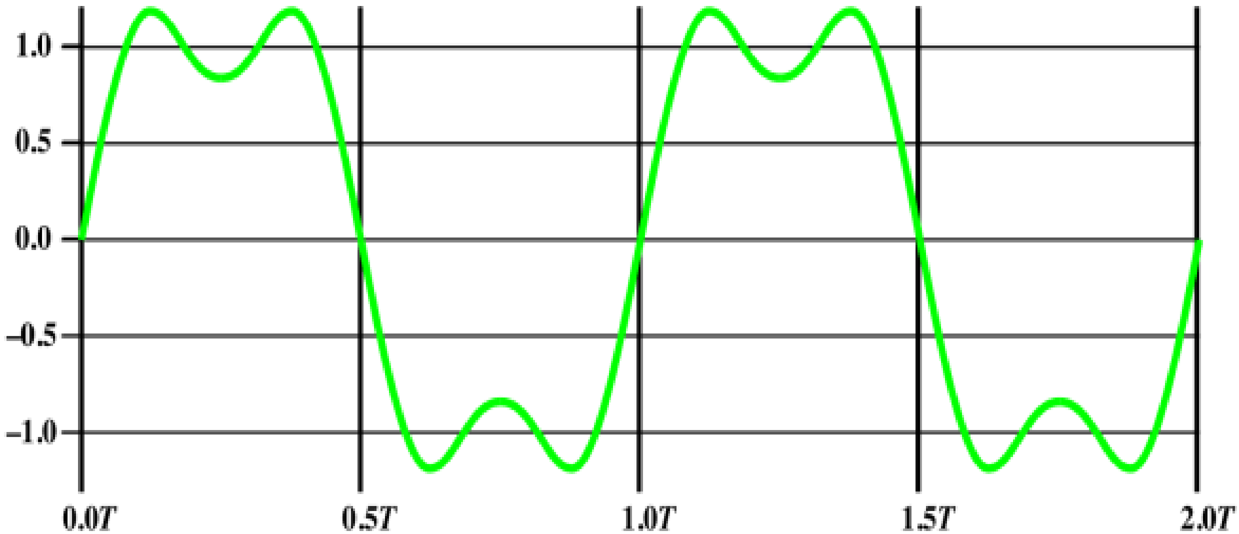


Bandwidth

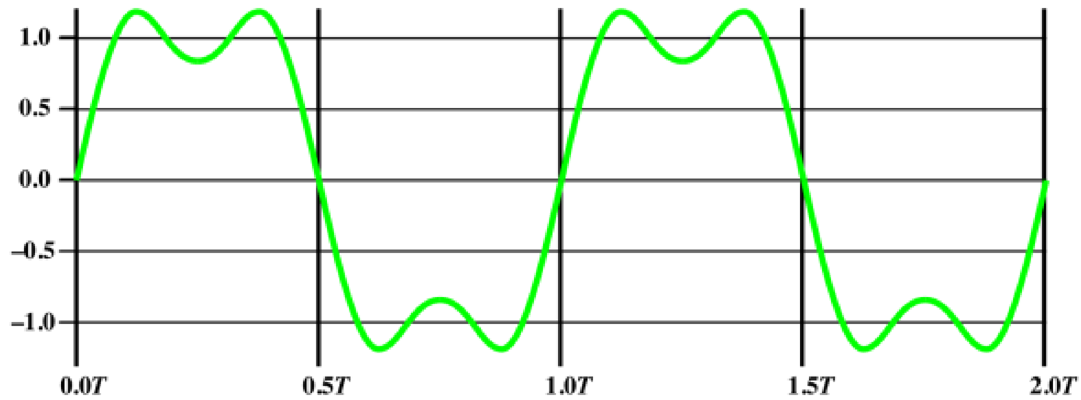
- A nonperiodic composite signal has a bandwidth of 200 kHz, with a middle frequency of140 kHz and peak amplitude of 20 V.
- The two extreme frequencies have an amplitude of 0.
- Draw the frequency domain of the signal..

Solution

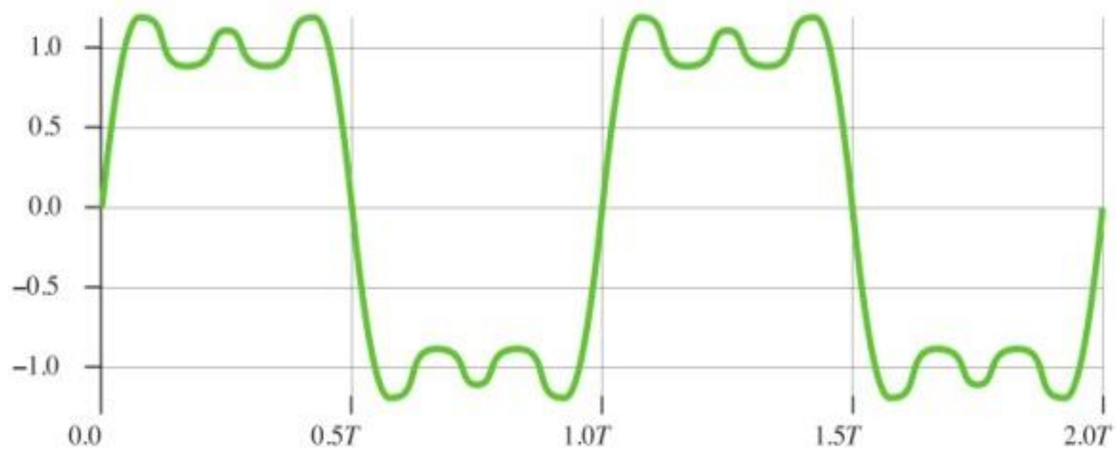




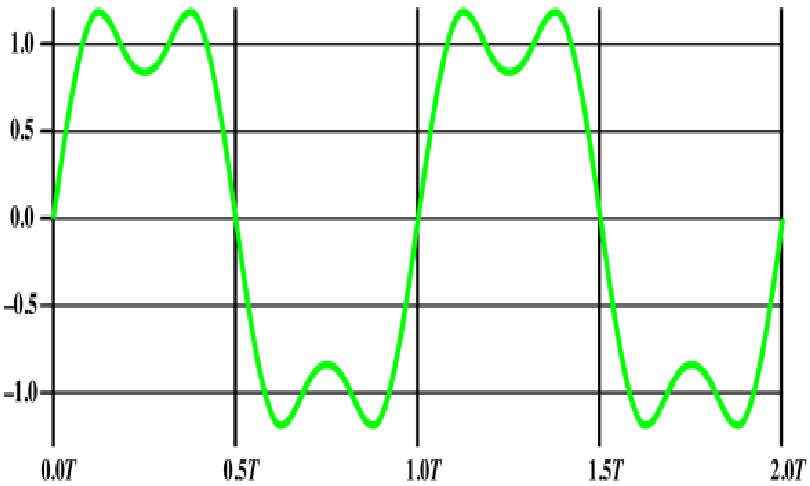
(c) $(4/\pi)\,[\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t)]$



(c) $(4/\pi)$ [$\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t)$]



(a) $(4/\pi)$ [$\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t) + (1/5)\sin(2\pi(5f)t)$]



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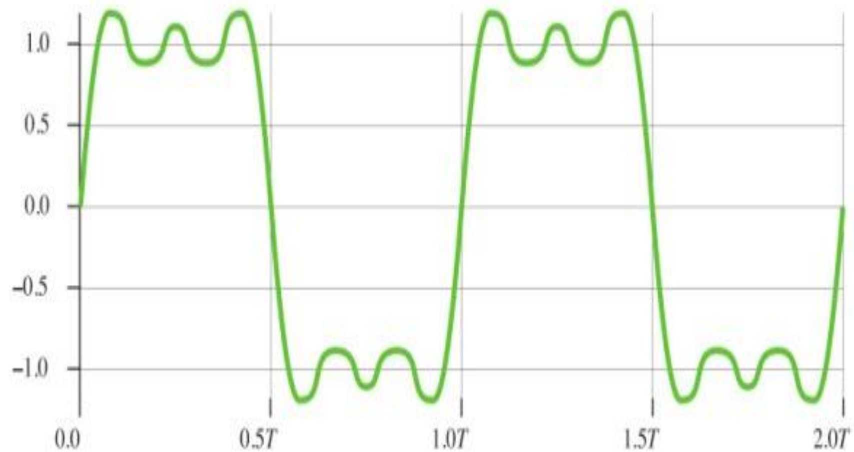

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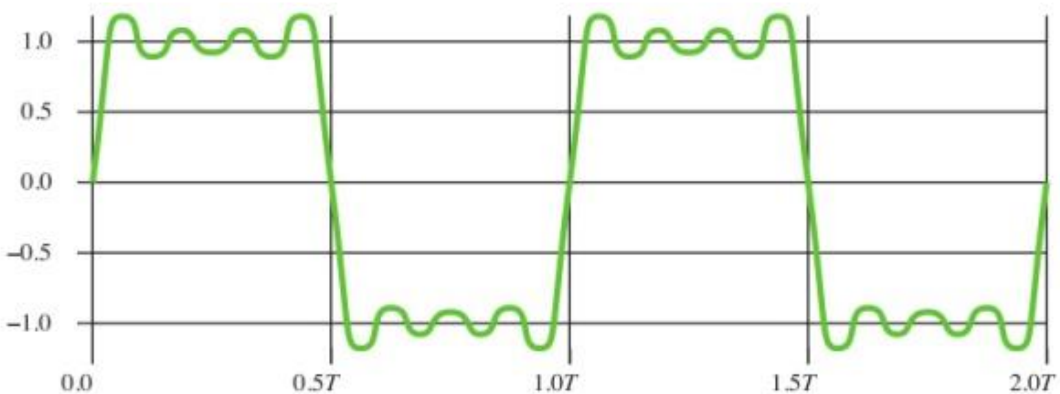
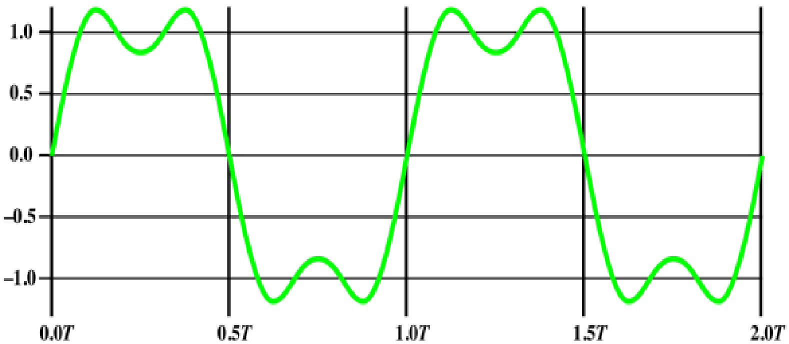
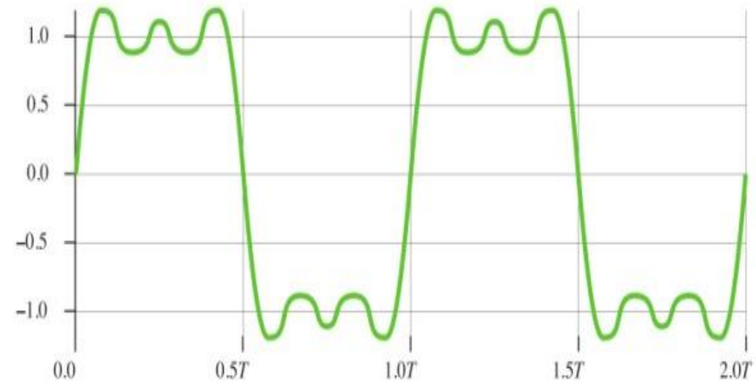


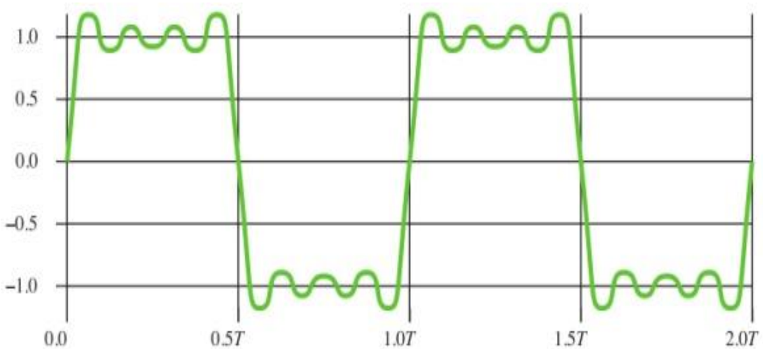
(b) $(4/\pi)\ [\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t) + (1/5)\sin(2\pi(5f)t) + (1/7)\sin(2\pi(7f)t)]$



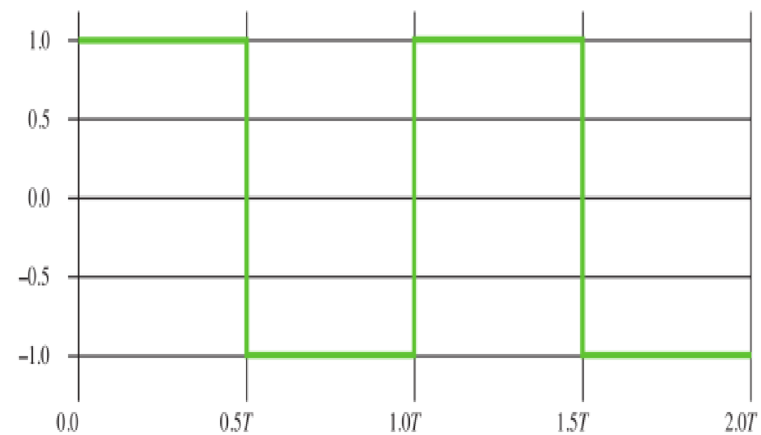
(c) $(4/\pi)$ [sin $(2\pi ft)$ + (1/3) sin $(2\pi(3f)t)$]



(a) $(4/\pi)$ [sin $(2\pi ft)$ + (1/3) sin $(2\pi(3f)t)$ + (1/5) sin $(2\pi(5f)t)$]



(b) $(4/\pi)$ [sin $(2\pi ft)$ + (1/3) sin $(2\pi(3f)t)$ + (1/5) sin $(2\pi(5f)t)$ + (1/7) sin $(2\pi(7f)t)$]



(c) $(4/\pi)\sum(1/k)$ sin $(2\pi(kf)t)$, for k odd

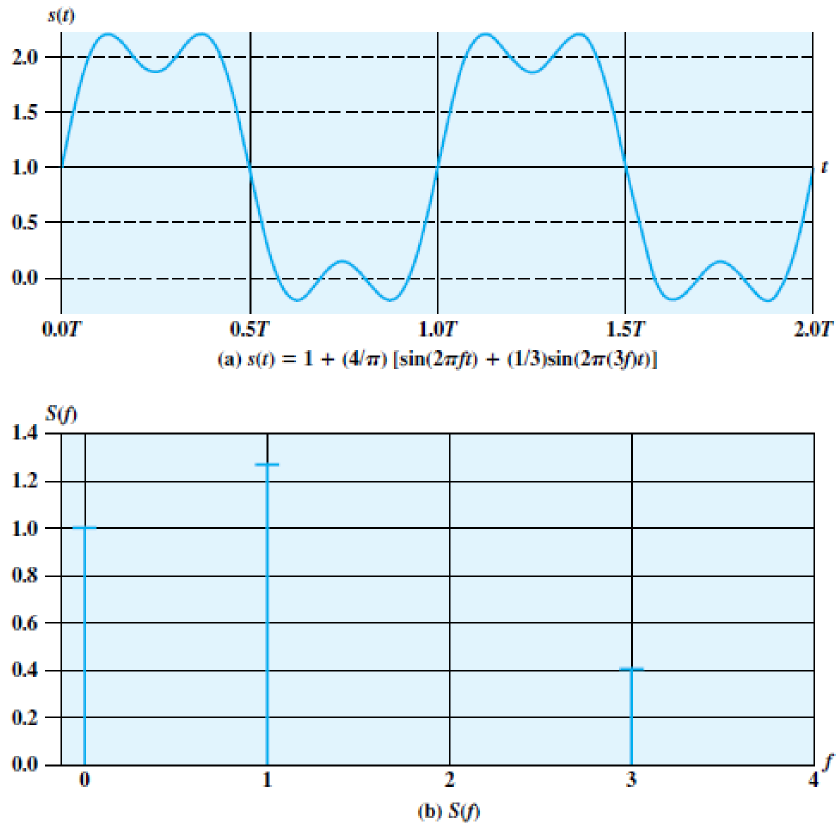
- The frequency components of the square wave with amplitudes A and can be expressed as follows:

$$s(t) = A \times \frac{4}{\pi} \times \sum_{k \text{ odd}, k=1}^{\infty} \frac{\sin(2\pi k f t)}{k}$$

If a signal includes a component of zero frequency, that component is a direct current (dc) or constant component.

With no dc component, a signal has an average amplitude of zero, as seen in the time domain.

With a dc component, it has a frequency term at f=0 and a nonzero average amplitude.

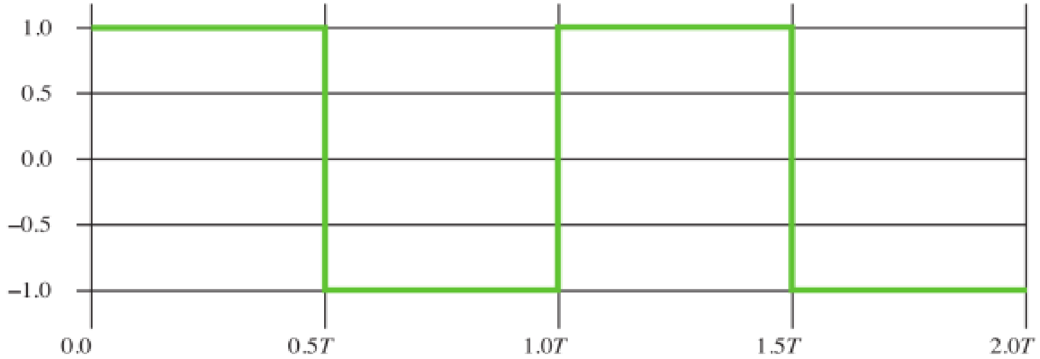


Signal with dc Component

Digital signal

Based on Fourier analysis, a digital signal is a composite analog signal.

A digital signal can be considered as a signal with an infinite number of frequencies.

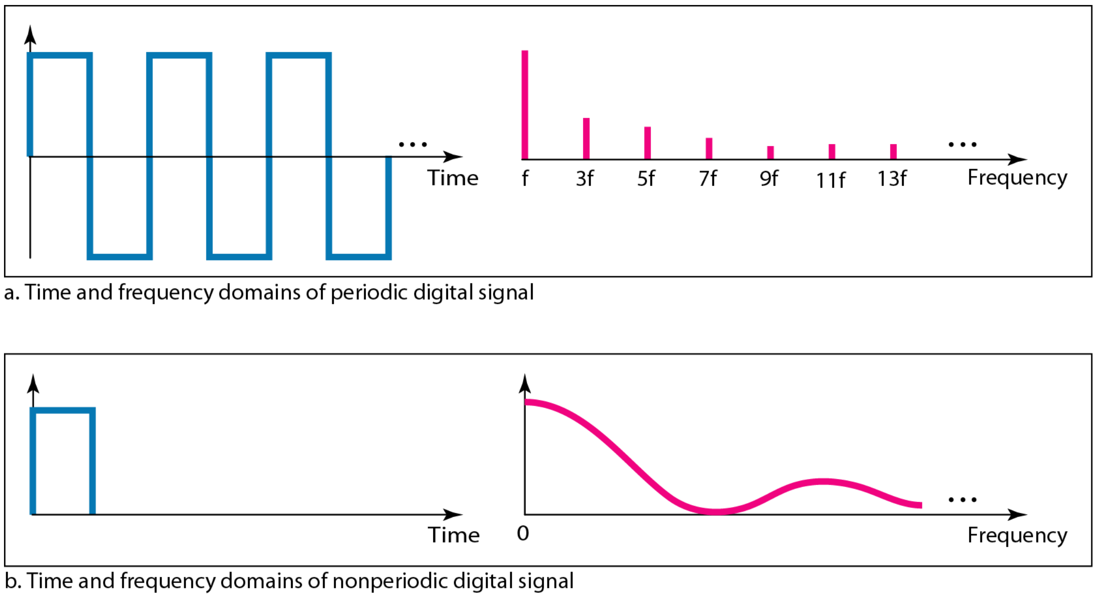


(c) $(4/\pi)\sum(1/k)\sin(2\pi(kf)t)$, for k odd

DIGITAL SIGNALS

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.

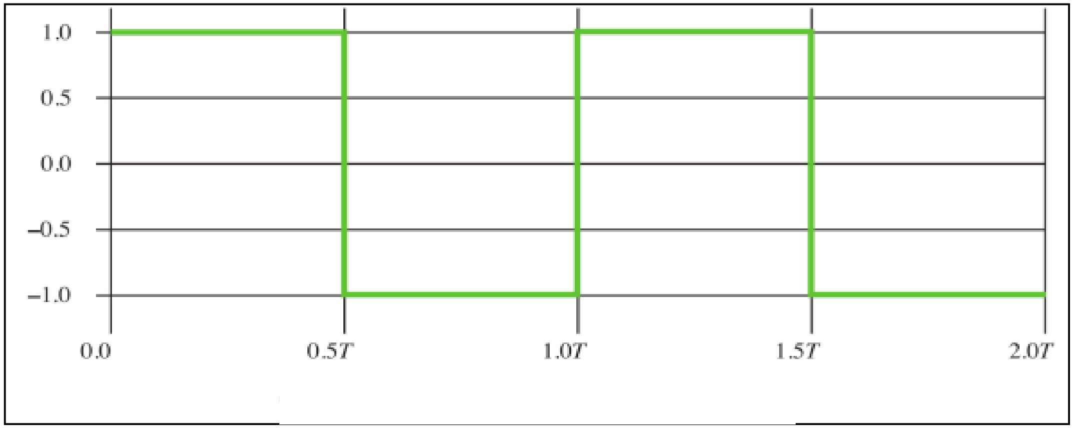
- If the digital signal is nonperiodic, the decomposed signal still has an infinite bandwidth, but the frequencies are continuous.

Digital signal

- Most digital signals are nonperiodic
- period and frequency are not appropriate characteristics.

Bit interval

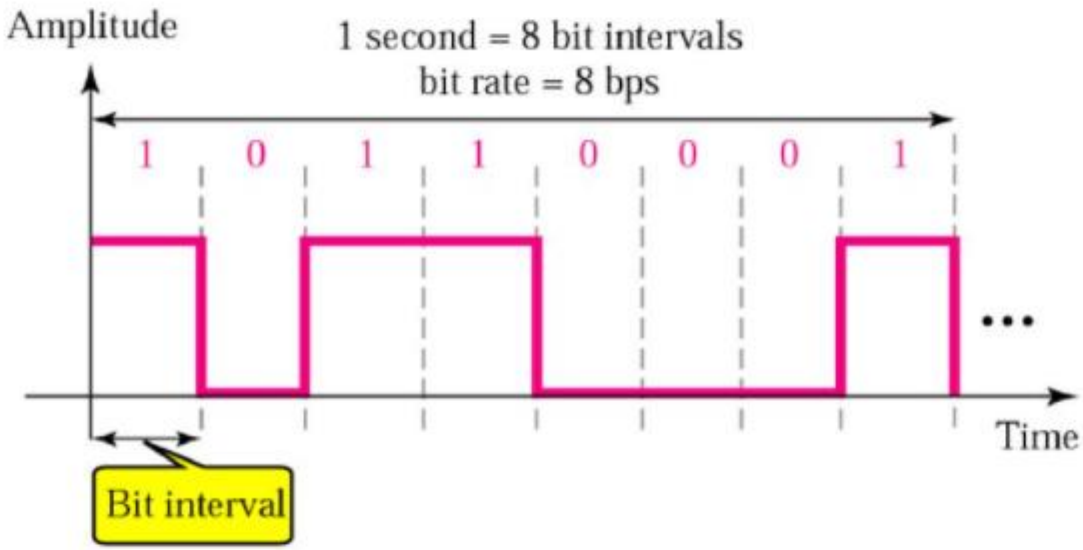
- Time required to send a single bit.



Digital signal

Bit Rate

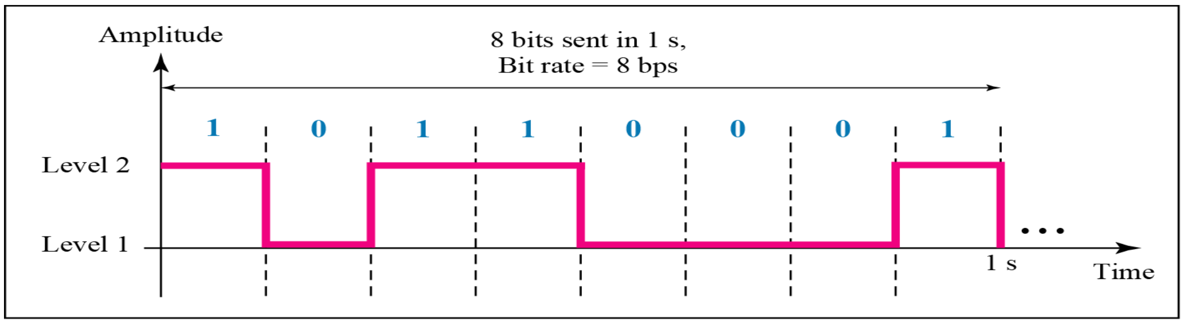
- Number of bits sent in 1 second, expressed in bits per second (bps).
- Number of bit intervals per second.



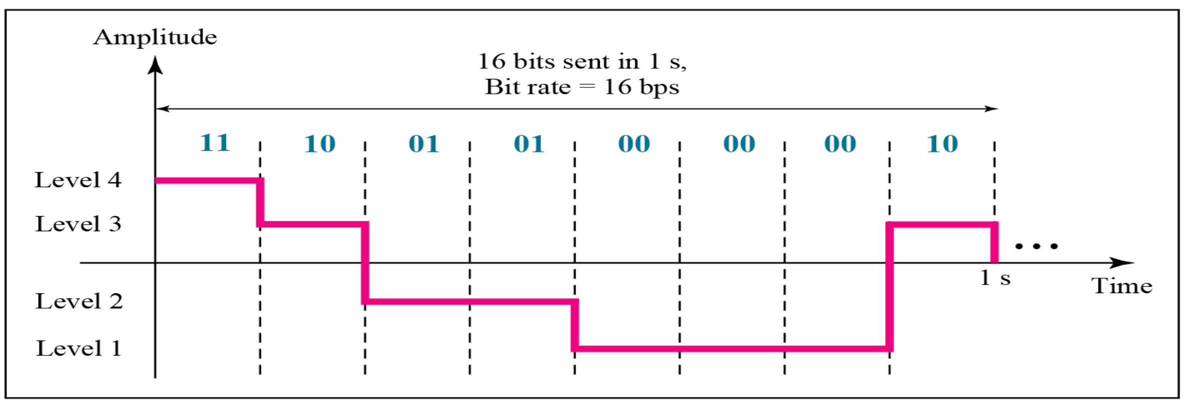
Digital signal

A digital signal can have more than two levels.

In this case, we can send more than 1 bit for each level.



a. A digital signal with two levels



b. A digital signal with four levels

DIGITAL SIGNALS

- We send 1 bit per level in part a and 2 bits per level in part b of the figure.

- In general, if a signal has *L* levels, each level needs $\log_2 L$ bits.

DIGITAL SIGNALS

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

DIGITAL SIGNALS

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

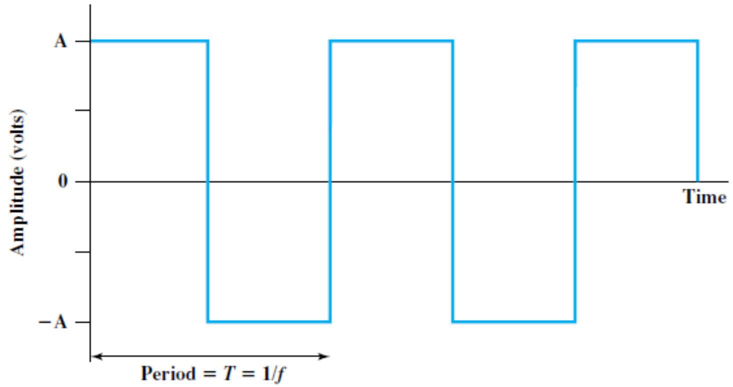
Number of bits per level $= \log_2 8 = 3$

Each signal level is represented by 3 bits.

Relationship between Data Rate and Bandwidth

consider the square wave.

let positive pulse represent binary 0 negative pulse represent binary 1.



(b) Square wave

Then the waveform represents the binary stream 0101. . . .

The duration of each pulse is $T/2 = 1/(2f)$

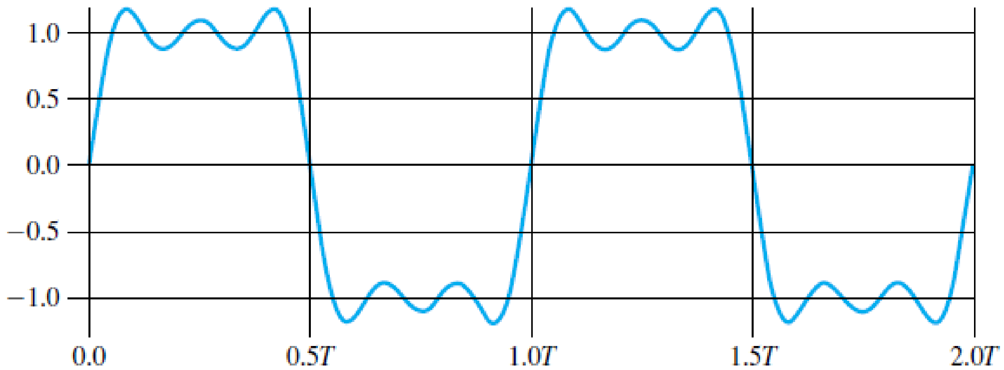
thus the data rate is $2f$ bits per second (bps).

Relationship between Data Rate and Bandwidth

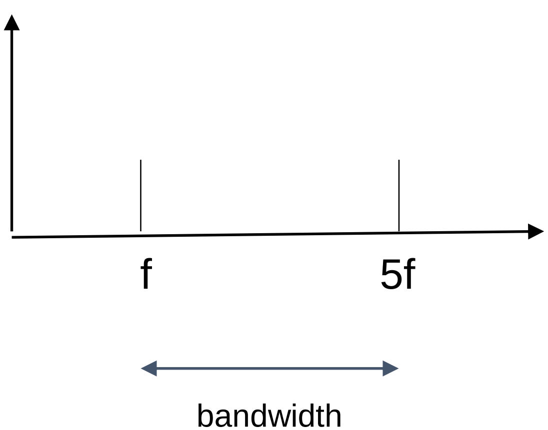
- Waveform has an infinite number of frequency components and hence an infinite bandwidth.
- What happens if we limit the bandwidth to just the first three frequency components?
- Suppose a digital transmission system is capable of transmitting signals with a bandwidth of 4 MHz.
- What data rate can be achieved? We look at 3 cases.

Relationship between Data Rate and Bandwidth

Case I.



(a) $(4/\pi)\,[\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t) + (1/5)\sin(2\pi(5f)t)]$



5f – f = 4MHz

f = 1 MHz

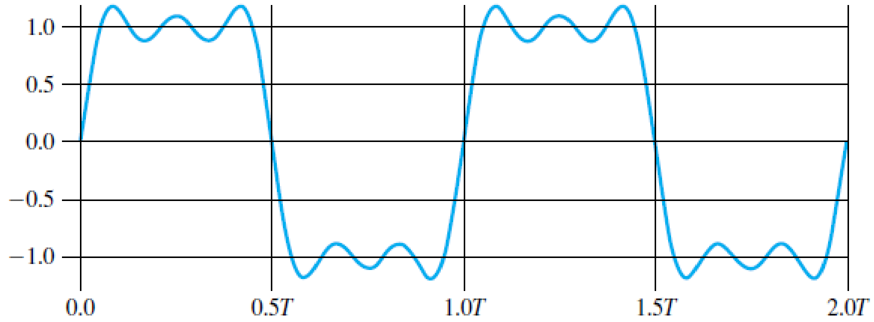
T = 1/f = 1/1MHz = $1\,\mu s.$

In $1\,\mu s.$ we can send 2bits

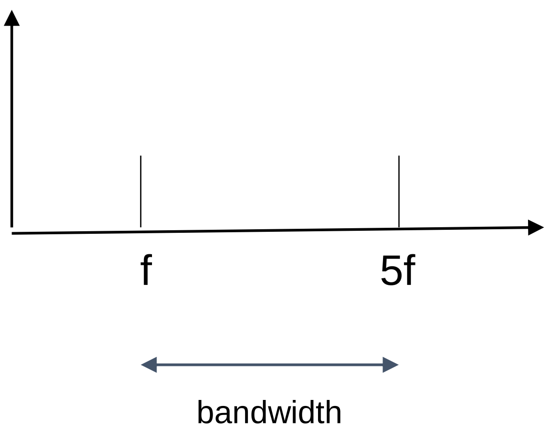
So in 1 second we can send 2Mbps

Relationship between Data Rate and Bandwidth

Case 2



(a) $(4/\pi)\,[\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t) + (1/5)\sin(2\pi(5f)t)]$



5f – f = 8MHz

f = 2 MHz

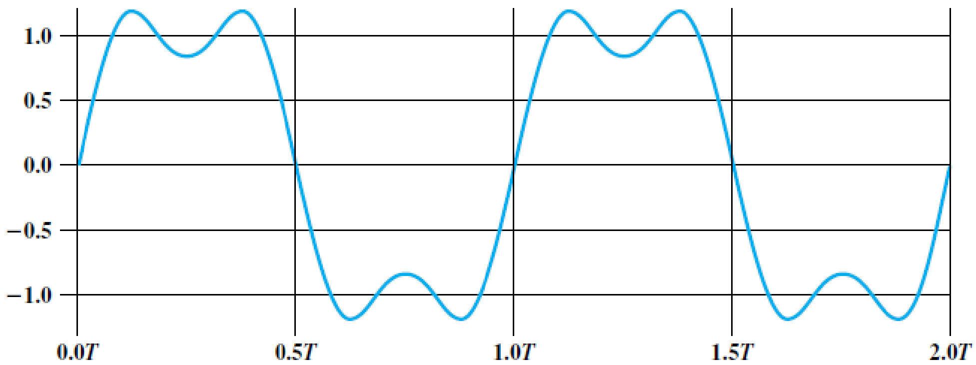
T = 1/f = 1/2MHz = $0.5\ \mu s.$

In $0.5\ \mu s.$ we can send 2bits

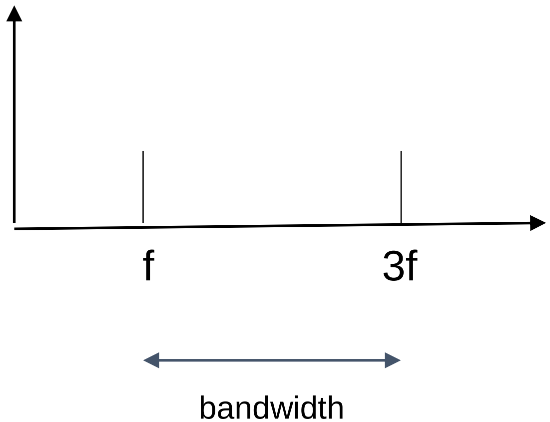
So in 1 second we can send 4Mbps

Relationship between Data Rate and Bandwidth

Case 3



(c) $(4/\pi)\,[\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t)]$



3f – f = 4MHz

f = 2 MHz

T = 1/f = 1/2MHz = 0.5 μs.

In 0.5 μs. we can second 2bits

So in 1 second we can send 4Mbps