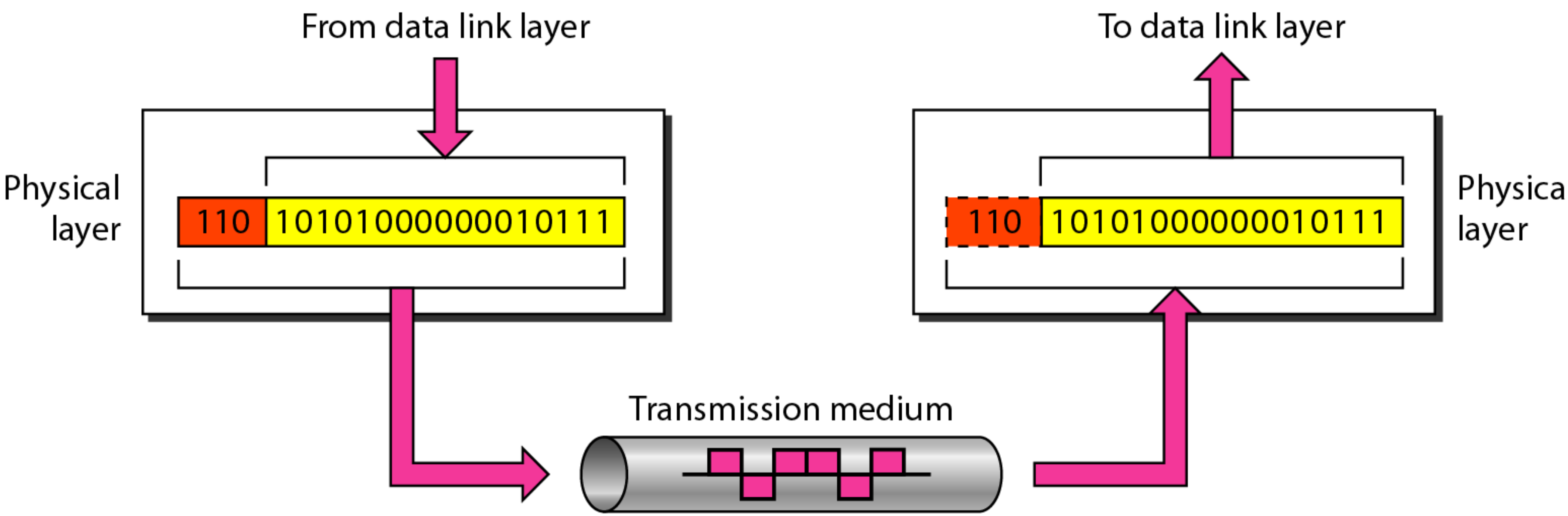
Chapter 6: Physical Layer

Data Transmission

Instructor: HOU, Fen

2025

Physical layer

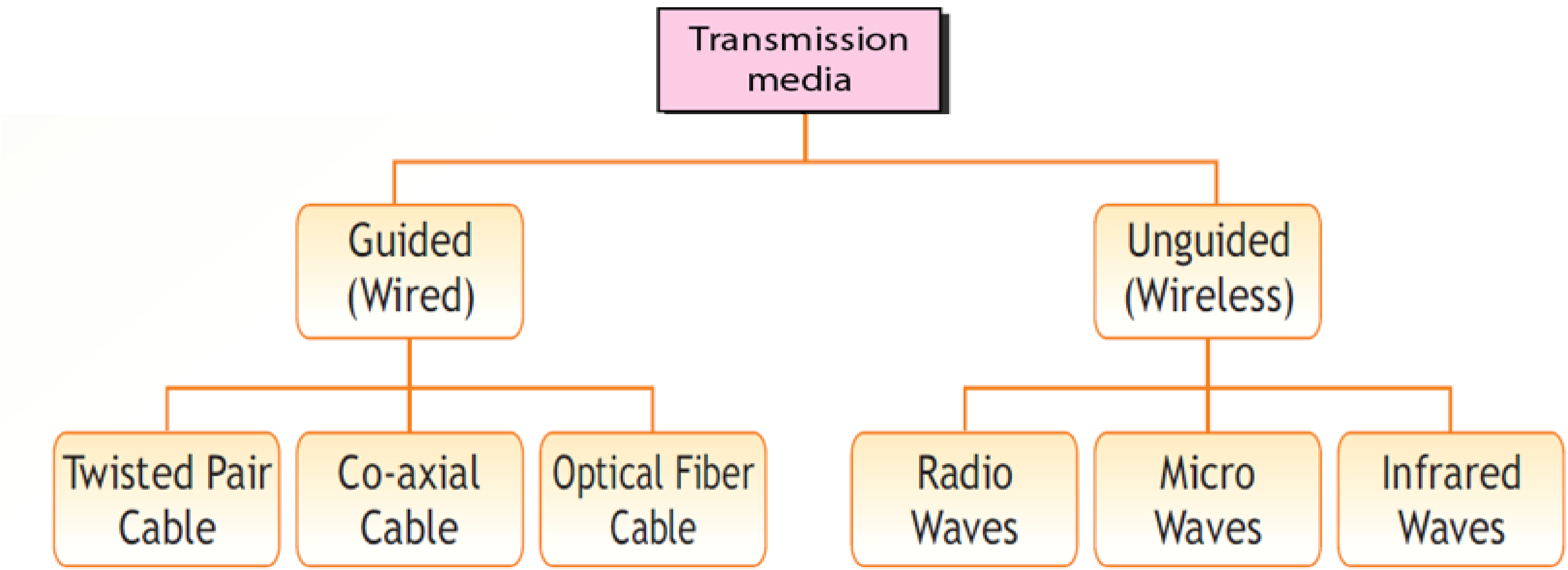


To be transmitted,
data must be transformed to electromagnetic signals.

- The transmission medium is a path through which a signal of a particular frequency travels.

Classes of Transmission Medium

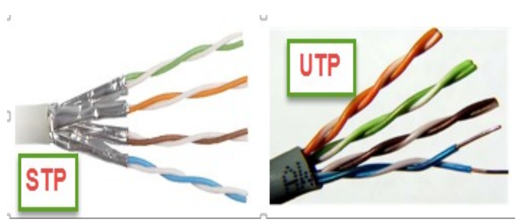
Guided media: Provide a physical path (wired)
Unguided media: employ an antenna for transmission (wireless)

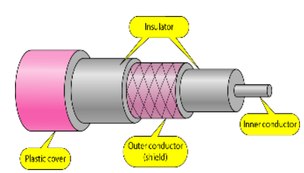


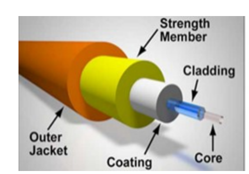
双绞线 同轴电缆 光纤

STP：shielded twisted pair

UTP：unshielded twisted pair

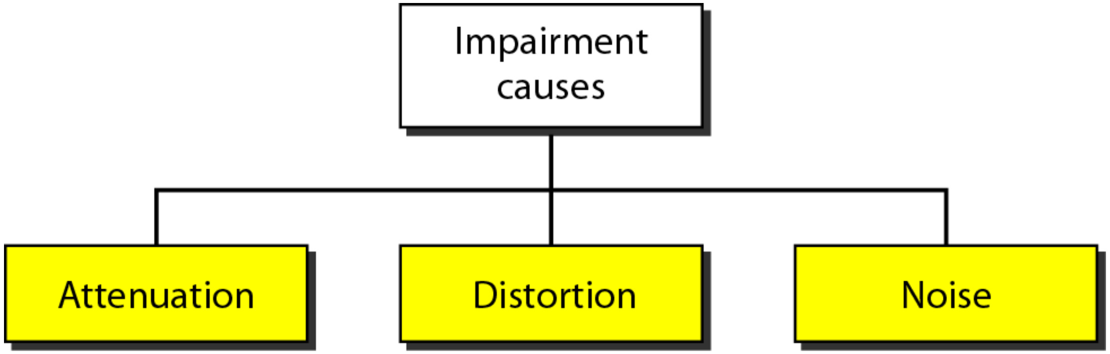




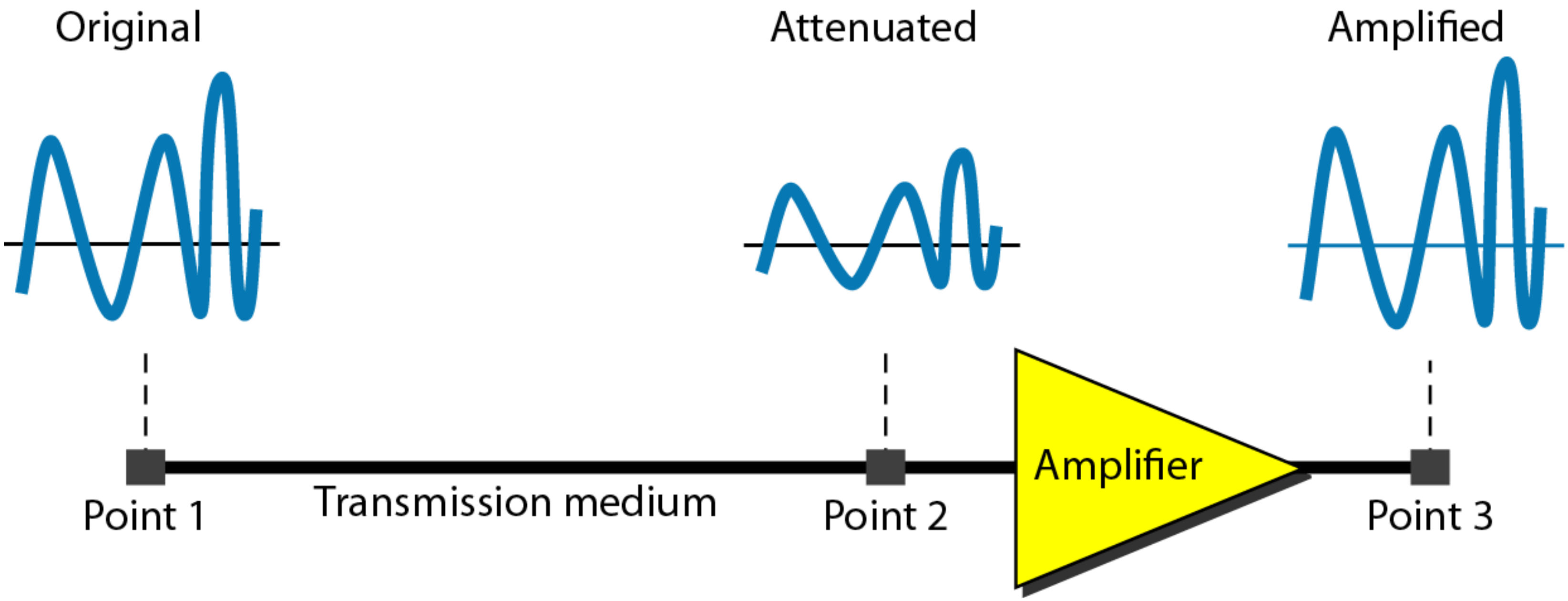


TRANSMISSION IMPAIRMENT 传输损耗

- 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 (衰減), distortion(变形), and noise (噪聲）.



Attenuation



Decibels 分贝

- dB is a relative measure of loss (or gain)
- dB value is calculated by taking the log of the ratio of ending power P2 with respect to a reference/beginning power P1, and the result is multiplied by 10 to obtain the value in dB
  - $dB = 10 \times \log_{10} (P2 / P1)$
    - P1 = sending/beginning power level in watts
    - P2 = receiving/ending power level in watts
- dB value is calculated with respect to a standard or specified reference value.

Example

Suppose a signal travels through a transmission medium and its power is reduced to one-half. Calculate the loss of power (i.e., signal attenuation).

This means that P_2 is $(1/2)P_1$.

In this case, the attenuation (loss of power) can be calculated as

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

A loss of 3 dB (–3 dB) is equivalent to losing one-half of the power/signal strength. (1/2 rule)

Example

A signal travels through an amplifier, and its power is increased by 10 times. Please calculate the amplification (gain of power in dB)?

This means that $P_2 = 10P_1$.

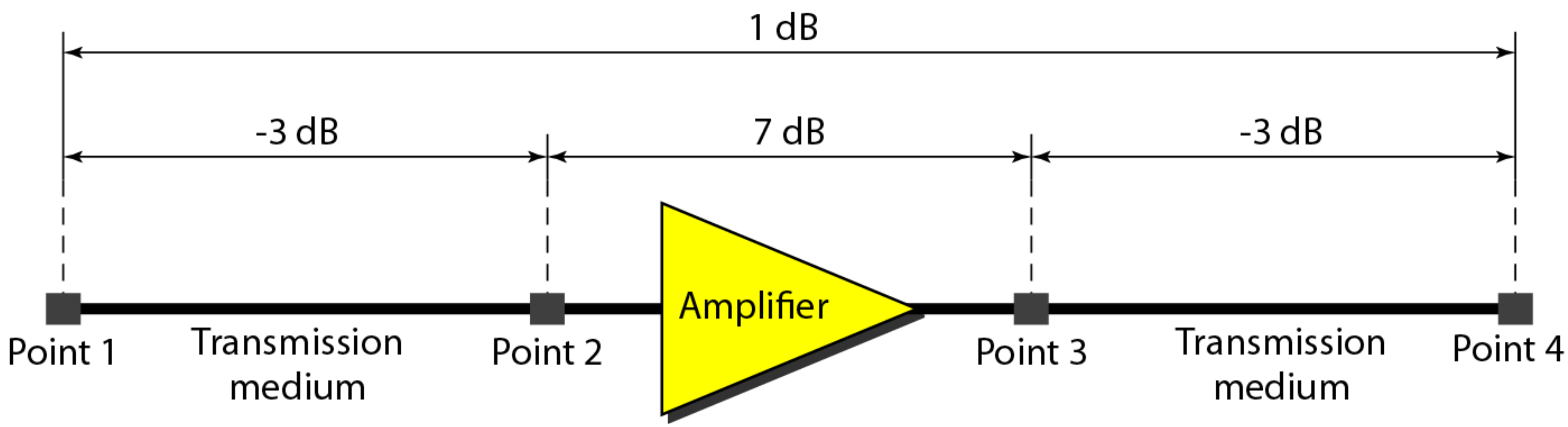
$$\boxed{10 \log_{10} \frac{P_2}{P_1} = 10 \log_{10} \frac{10P_1}{P_1}}$$

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

Example

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 instead of just two.

A signal travels from point 1 to point 4.

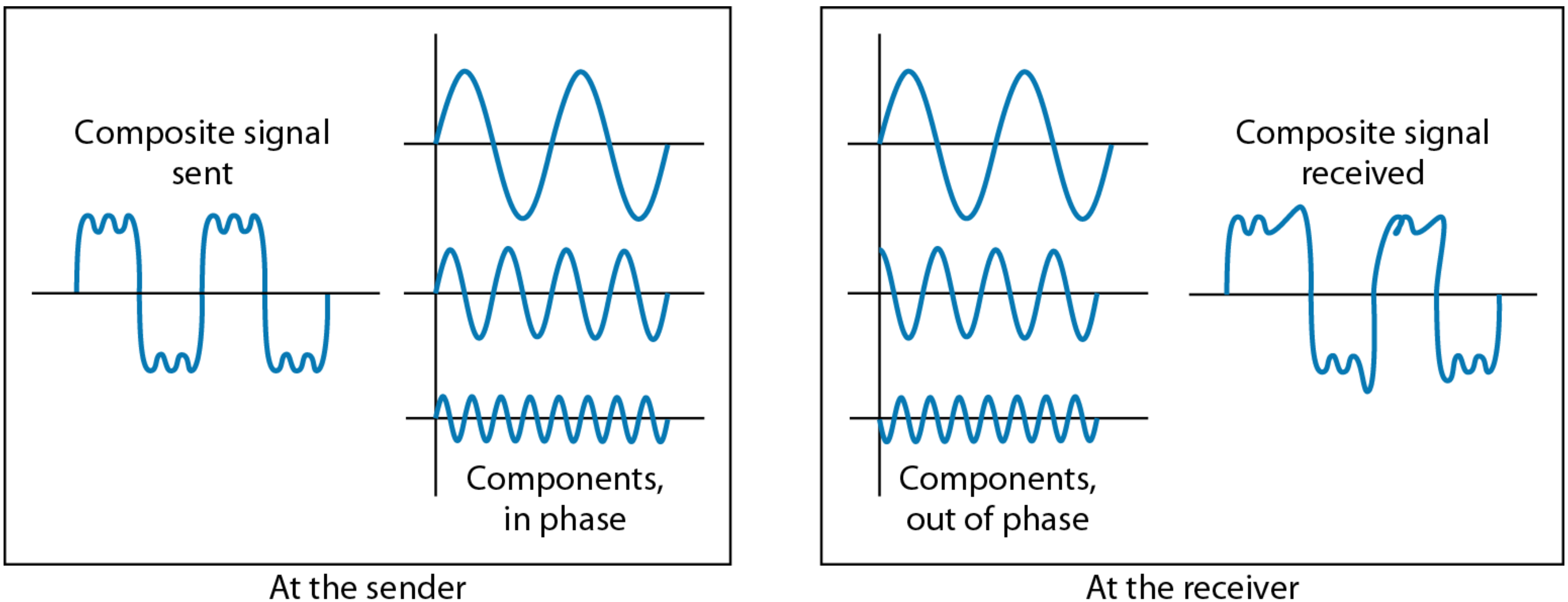


In this case, the decibel value can be calculated as

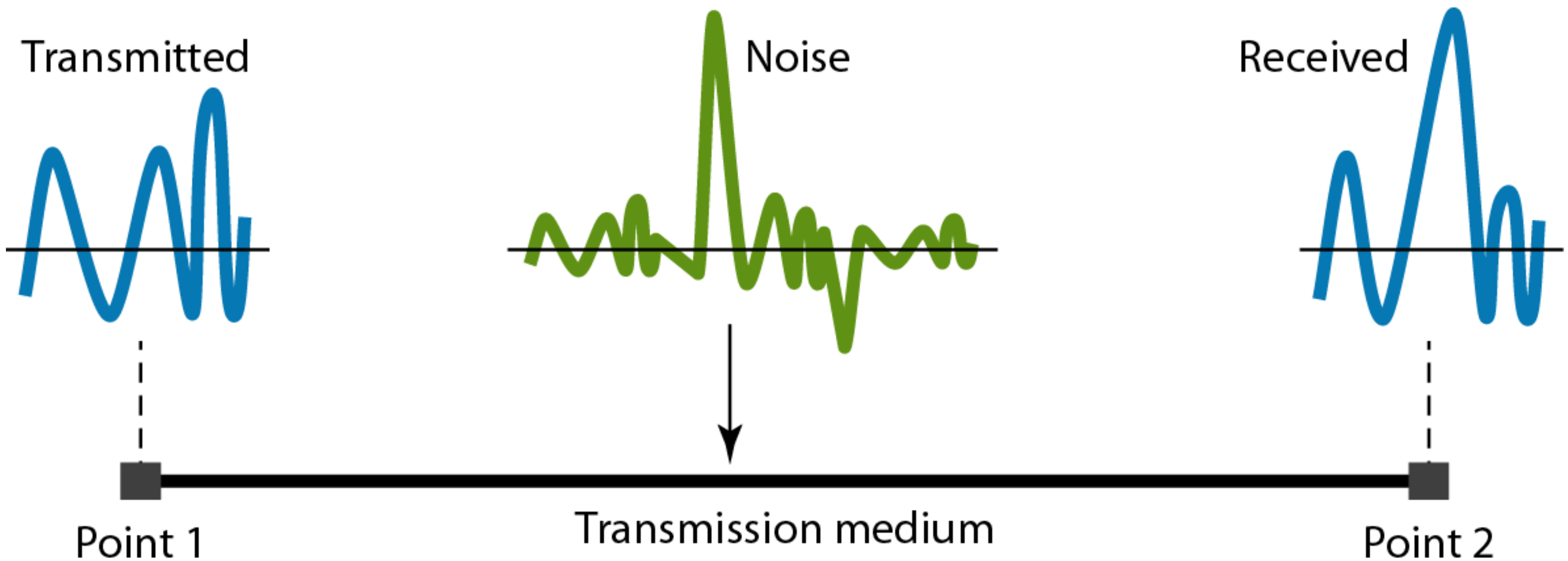
$$\boxed{dB = -3 + 7 - 3 = +1}$$

Losses and gains are additive

Distortion: the alteration of the original shape or other characteristics. For instance, phase distortion, amplitude distortion, etc.



Noise


Transmitted
Noise
Received
Point 1
Transmission medium
Point 2

Data Rate and Bandwidth

- The transmission medium is a path through which a signal of a particular frequency travels.
- We use the term bandwidth to indicate the feature of transmission media. It is defined as the range of frequencies which a transmission medium can carry.
- Any transmission medium has a limited band of frequencies

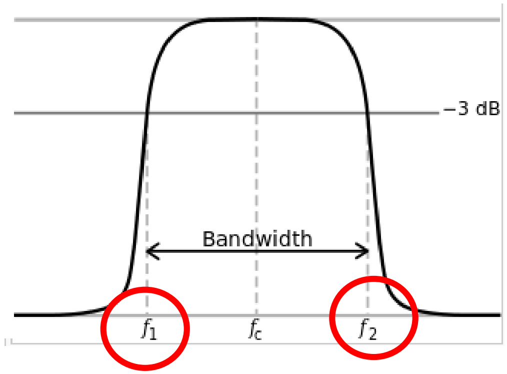


Fig. Magnitude transfer function of a bandpass transmission media with lower 3dB cutoff frequency f1 and upper 3dB cutoff frequency f2

Data Rate and Bandwidth

- Any transmission medium has a limited band of frequencies
- This limits the data rate that can be carried

	Frequency Range	**Typical Attenuation**	**Typical Delay**	**Repeater Spacing**
Twisted pair (with loading)	0 to 3.5 kHz	0.2 dB/km @ 1 kHz	50 µs/km	2 km
Twisted pairs (multi-pair cables)	0 to 1 MHz	0.7 dB/km @ 1 kHz	5 µs/km	2 km
Coaxial cable	0 to 500 MHz	7 dB/km @ 10 MHz	4 µs/km	1 to 9 km
Optical fiber	186 to 370 THz	0.2 to 0.5 dB/km	5 µs/km	40 km

ANALOG AND DIGITAL Data

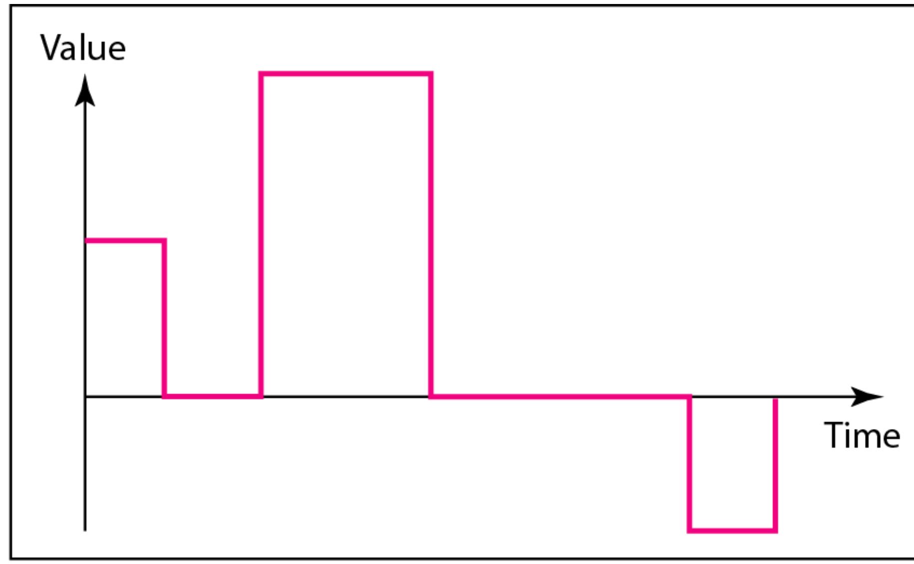
Data can be analog or digital

- Analog data refers to information that is continuous
- Analog data take on continuous values
- Analog signals can have an infinite number of values in a range

- Digital data refers to information that has discrete states
- Digital data take on discrete values
- Digital signals can have only a limited number of values

Comparison of analog and digital signals

a. Analog signal



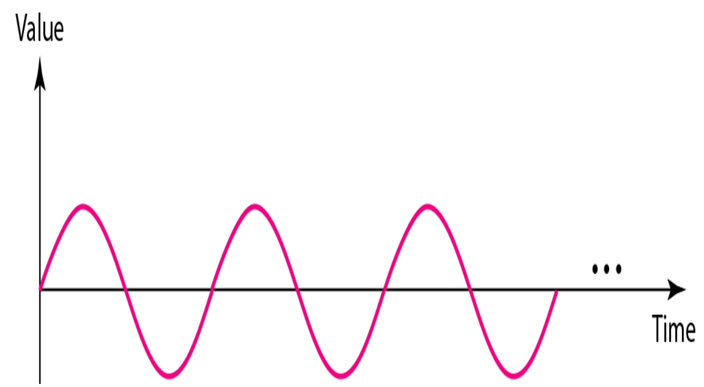
b. Digital signal

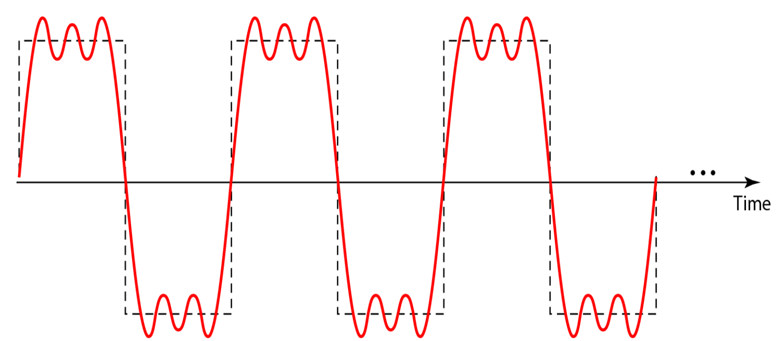
In data communications, we commonly use periodic analog signals and nonperiodic digital signals.

3-2 PERIODIC ANALOG SIGNALS

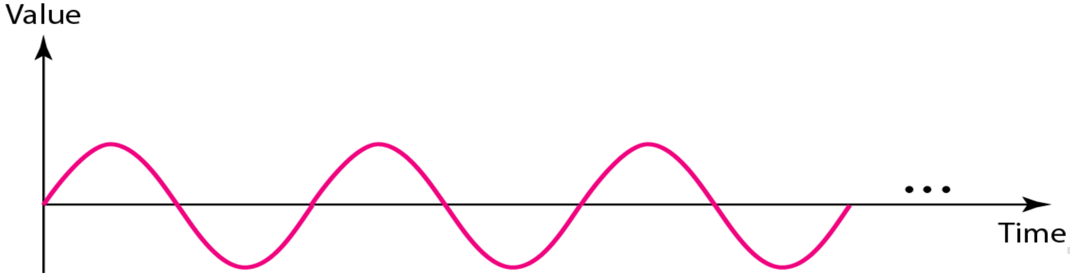
Periodic analog signals can be classified as simple or composite.

- 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.





A simple periodic signal: a single sine wave



The power we use at home has a frequency of 60 Hz. What is the period of this sine wave ?

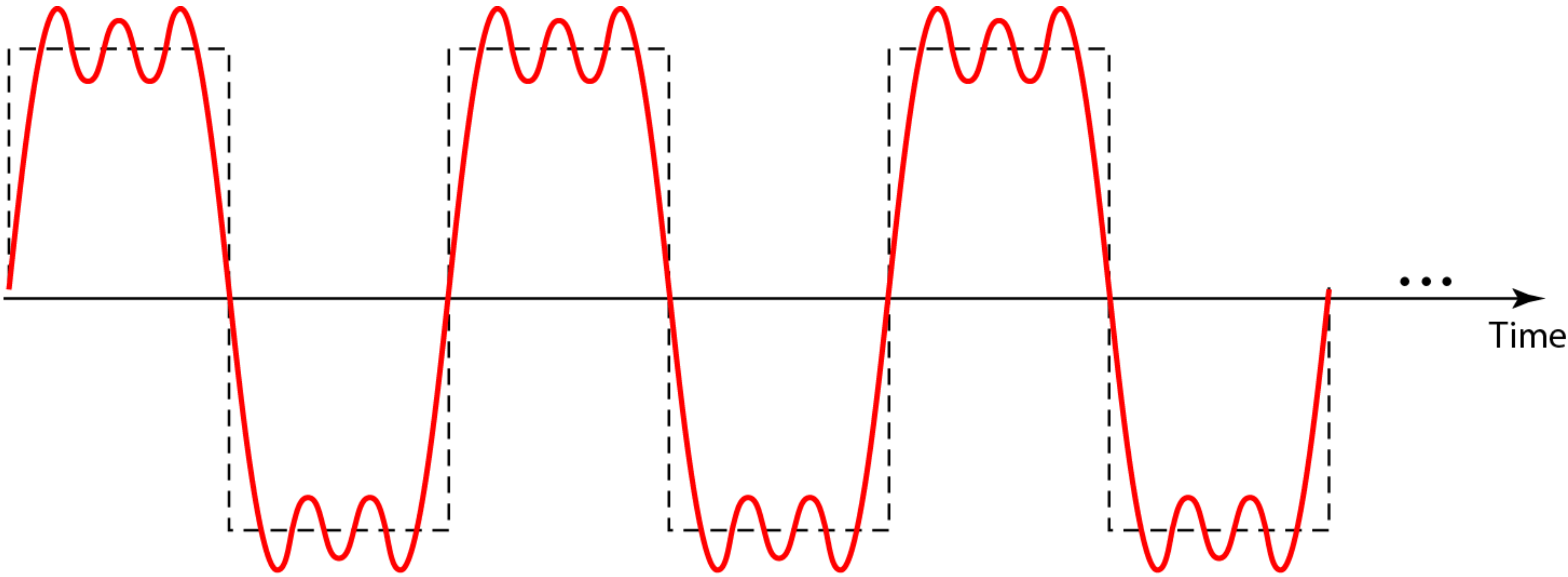
$$T = \frac{1}{f} = \frac{1}{60} = 0.0166 \text{ s} = 0.0166 \times 10^3 \text{ ms} = 16.6 \text{ ms}$$

The period of a signal is 100 ms. What is its frequency in kilohertz?

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

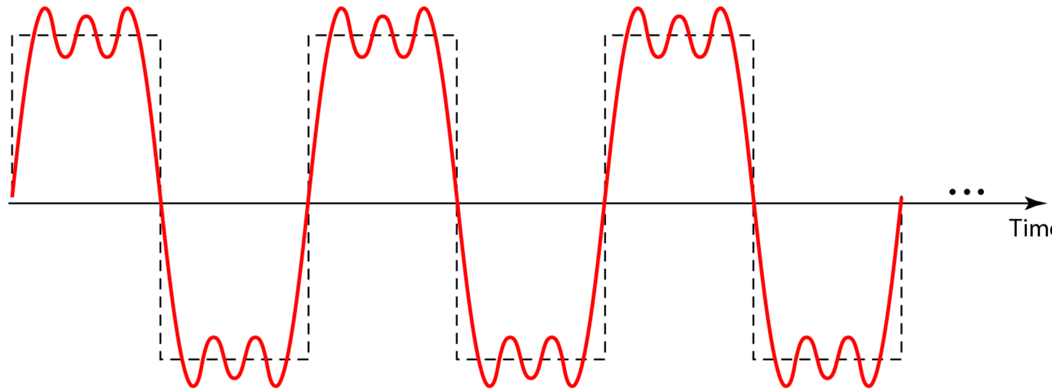
$$f = \frac{1}{T} = \frac{1}{10^{-1}} \text{ Hz} = 10 \text{ Hz} = 10 \times 10^{-3} \text{ kHz} = 10^{-2} \text{ kHz}$$

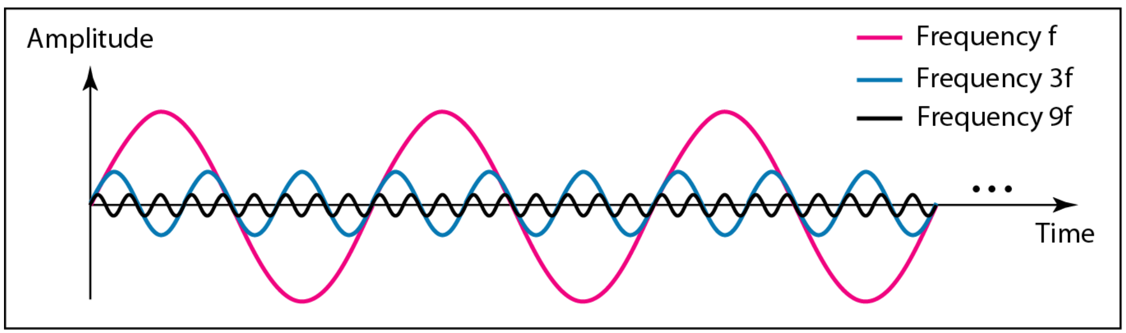
A composite periodic signal



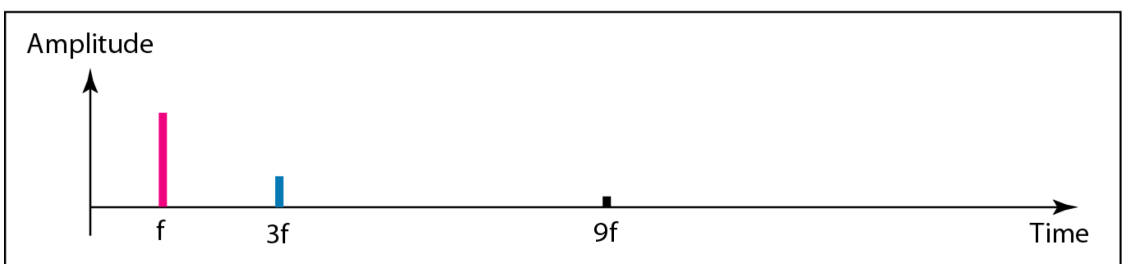
Any composite periodic signal is a combination of multiple simple sine waves with different parameters such as frequency, amplitude and phase.

A composite periodic signal





a. Time-domain decomposition of a composite signal

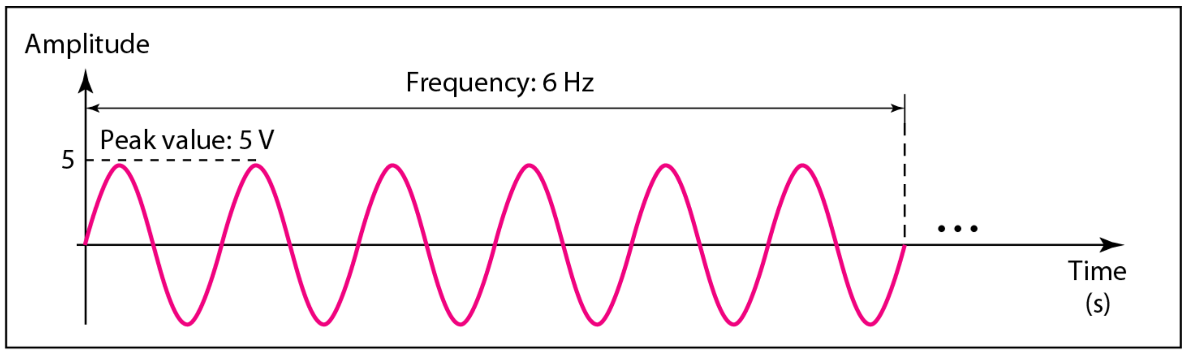


b. Frequency-domain decomposition of the composite signal

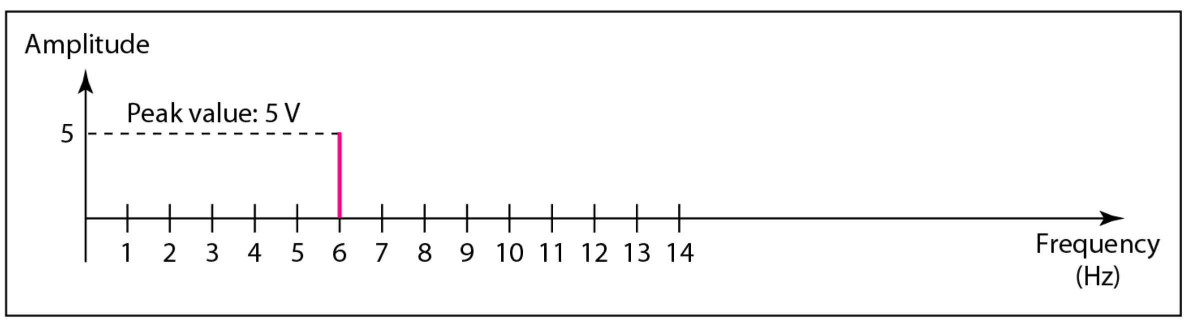
Decomposition of the composite periodic signal in the time and frequency domains

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

Time-domain and frequency-domain plots of a sine wave

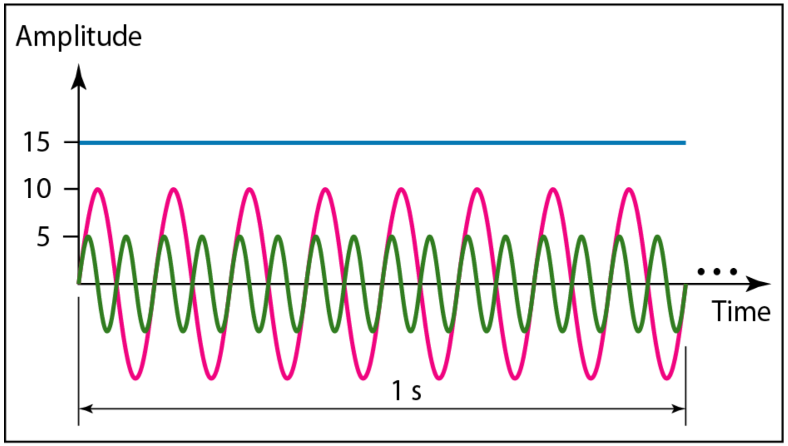


a. A sine wave in the time domain (peak value: 5 V, frequency: 6 Hz)

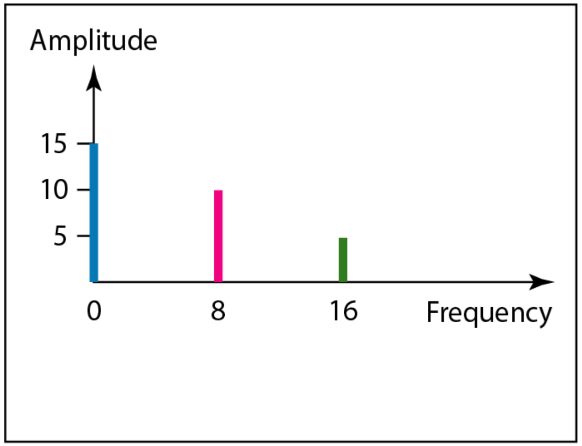


b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

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

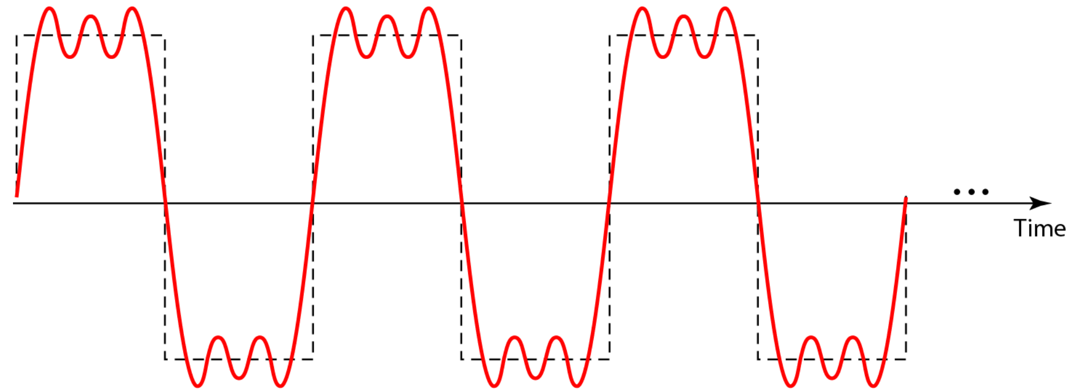
- The frequency domain is more compact and useful when we are dealing with more than one sine wave.

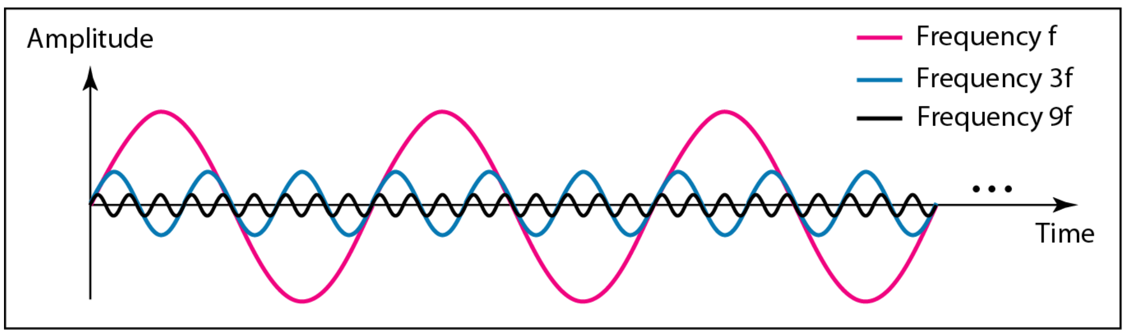
- A single-frequency sine wave is not useful in data communication
  - We need to send a composite signal, a signal made of many simple sine waves.

Frequency Domain

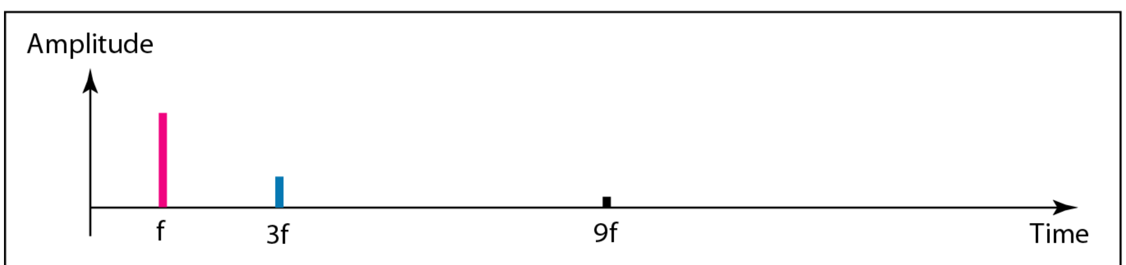
- If the composite signal is periodic, the decomposition gives a series of signals with discrete frequencies;
- If the composite signal is nonperiodic, the decomposition gives a combination of sine waves with continuous frequencies.

A composite periodic signal





a. Time-domain decomposition of a composite signal

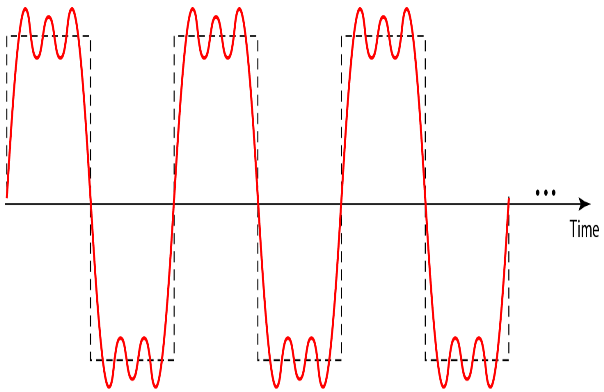


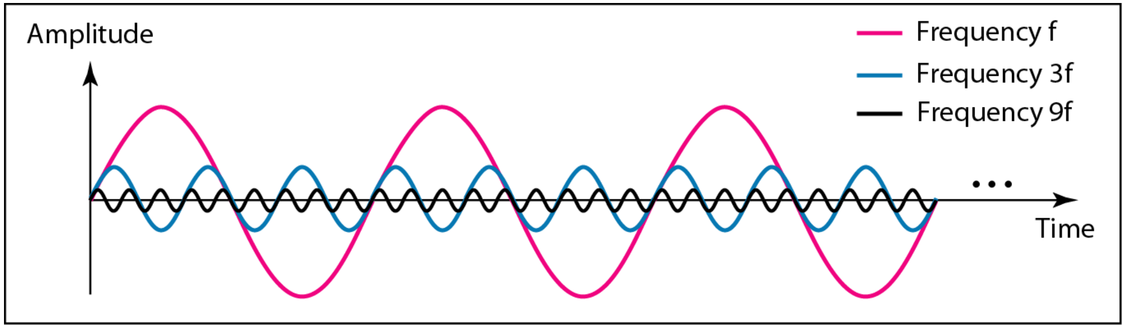
b. Frequency-domain decomposition of the composite signal

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

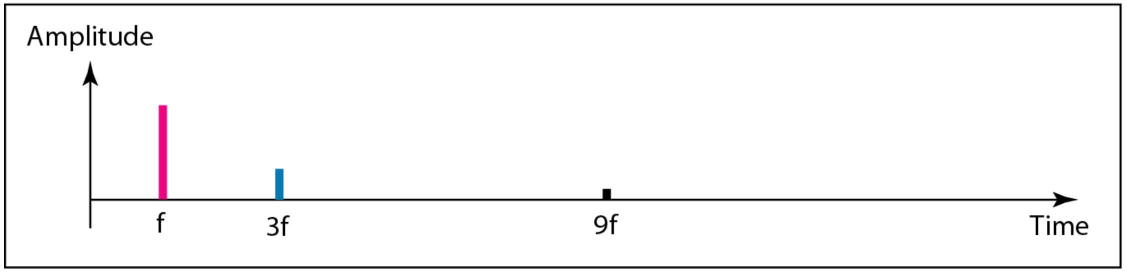
Bandwidth of a composite signal

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



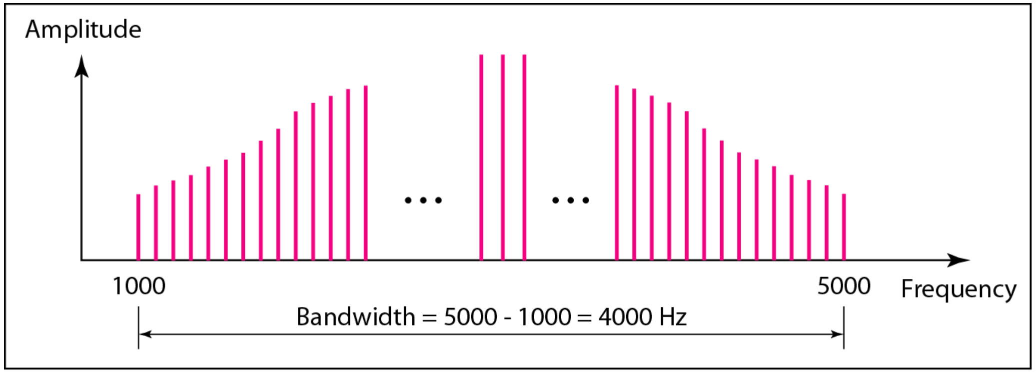


a. Time-domain decomposition of a composite signal

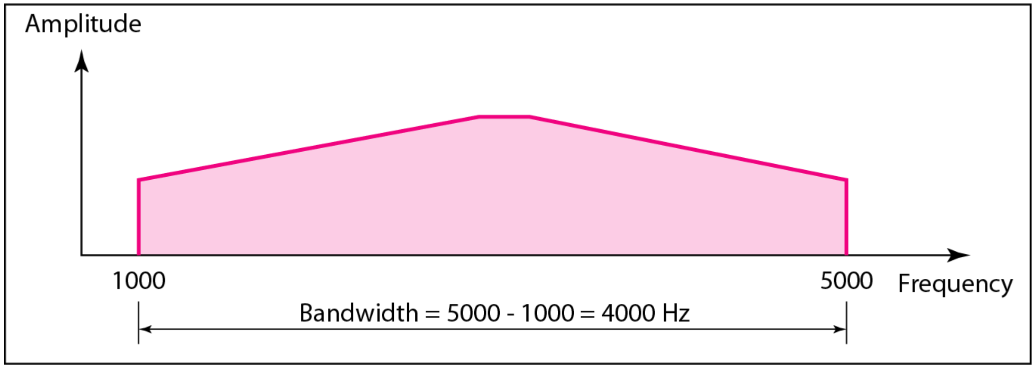


b. Frequency-domain decomposition of the composite signal

Example



a. Bandwidth of a periodic signal



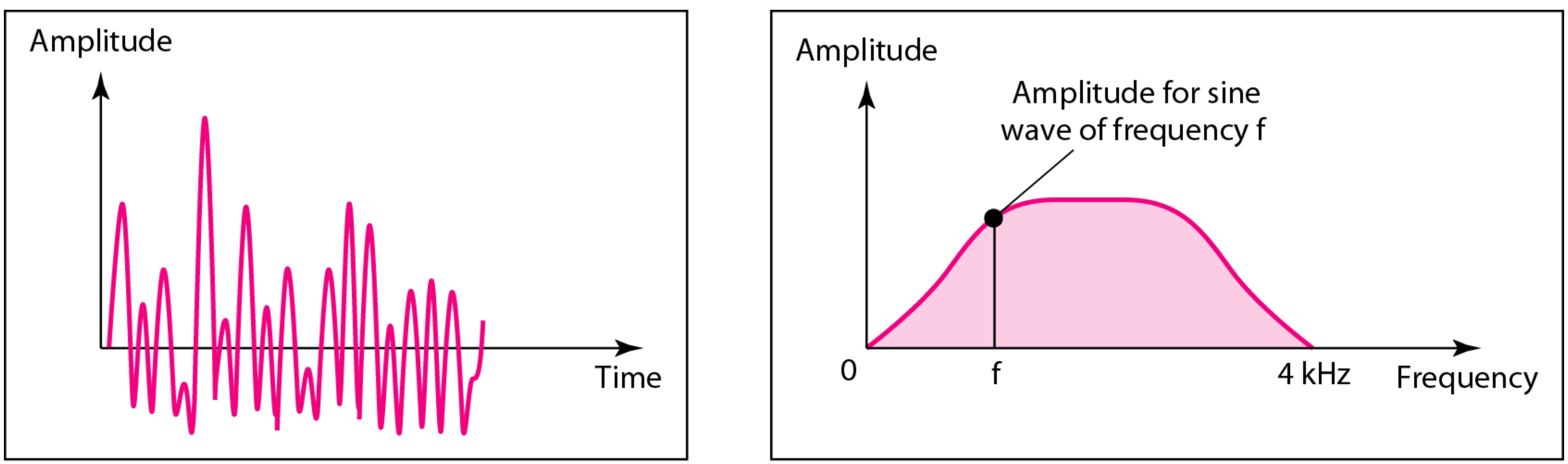
b. Bandwidth of a nonperiodic signal

Frequency Domain

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

Time and frequency domains of a nonperiodic signal

- A nonperiodic composite signal
  - For example, it can be a signal created by a microphone or a telephone set when a word or two is pronounced.

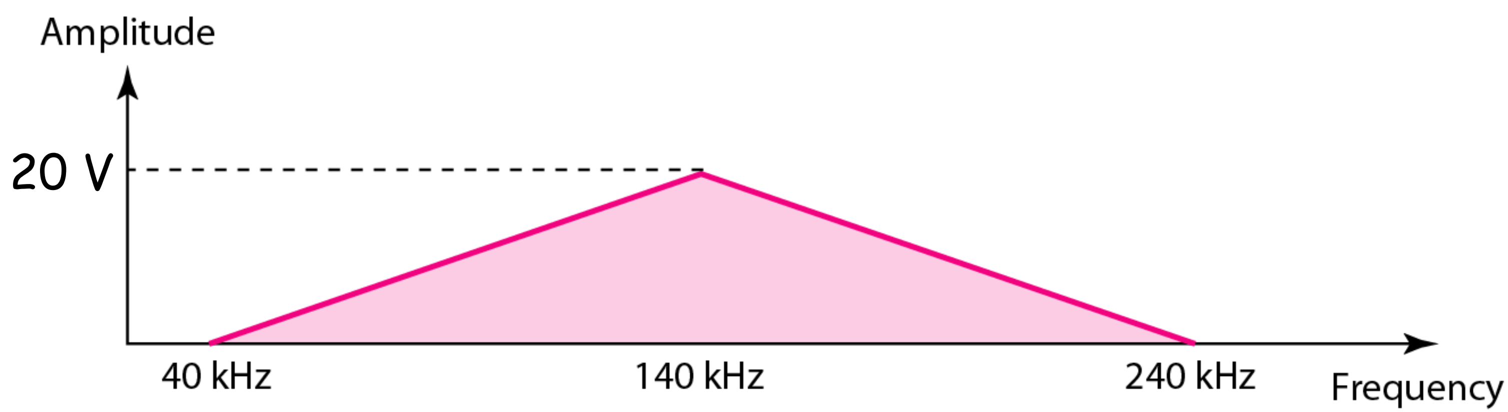


a. Time domain

b. Frequency domain

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 lowest frequency must be at 40 kHz and the highest at 240 kHz. The two extreme frequencies have an amplitude of 0. The frequency domain of the signal is shown as follows.



Example

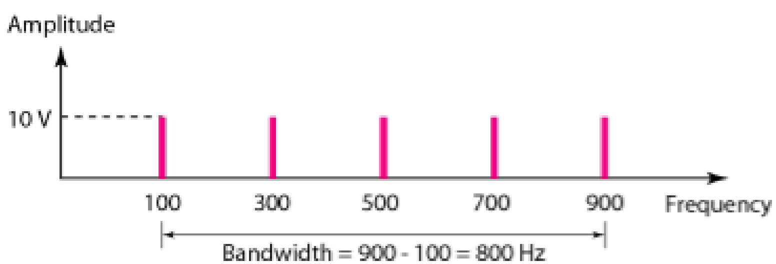
If a periodic signal is decomposed into five sine waves with frequencies of 100, 300, 500, 700, and 900 Hz, what is its bandwidth? Draw the spectrum by a series of spikes, assuming all components have a maximum amplitude of 10 V.

Solution

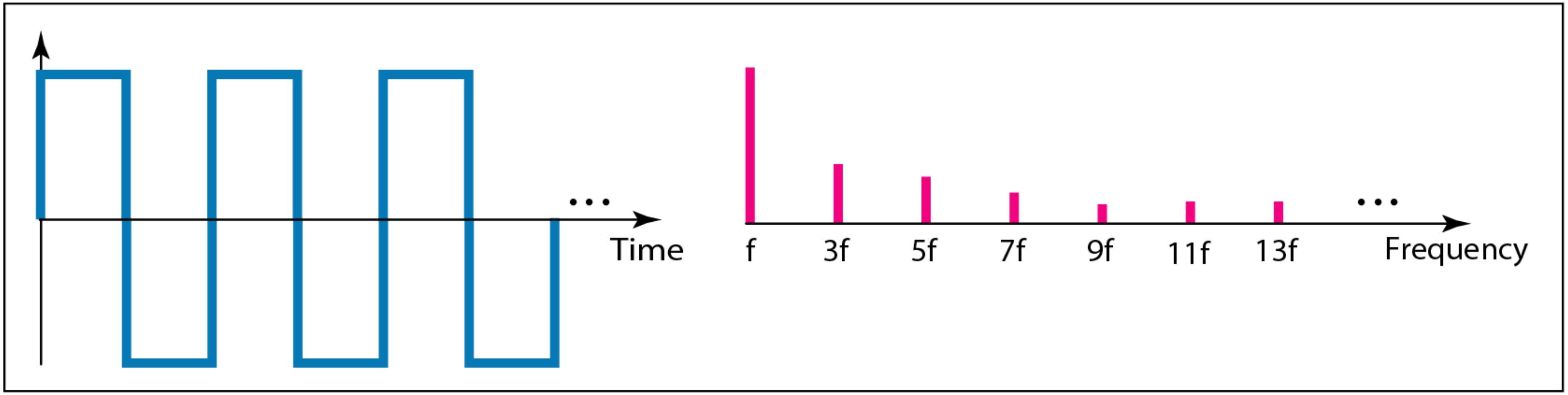
Let f_h be the highest frequency, f_l the lowest frequency, and B the bandwidth. Then

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

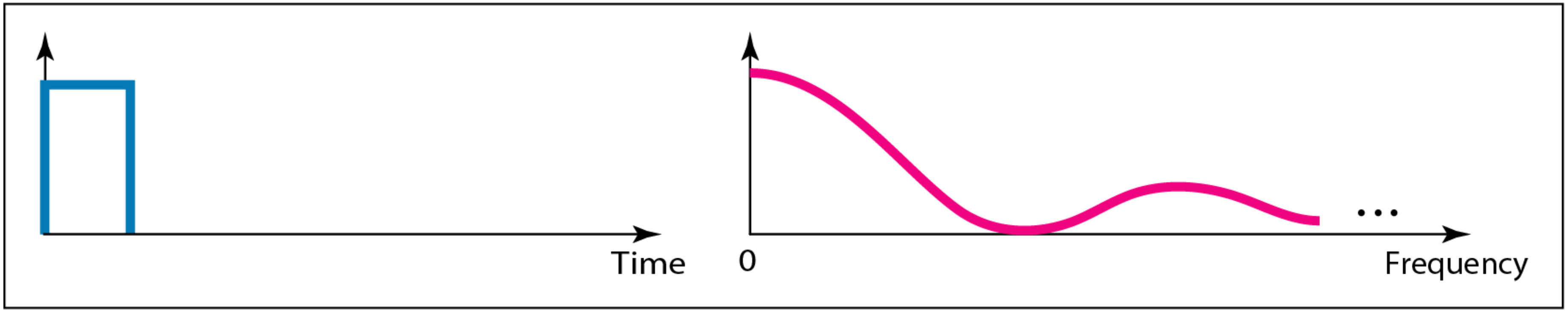
Draw the frequency domain of the signal: only five spikes, at 100, 300, 500, 700, and 900 Hz.



The time and frequency domains of periodic and nonperiodic digital signals



a. Time and frequency domains of periodic digital signal

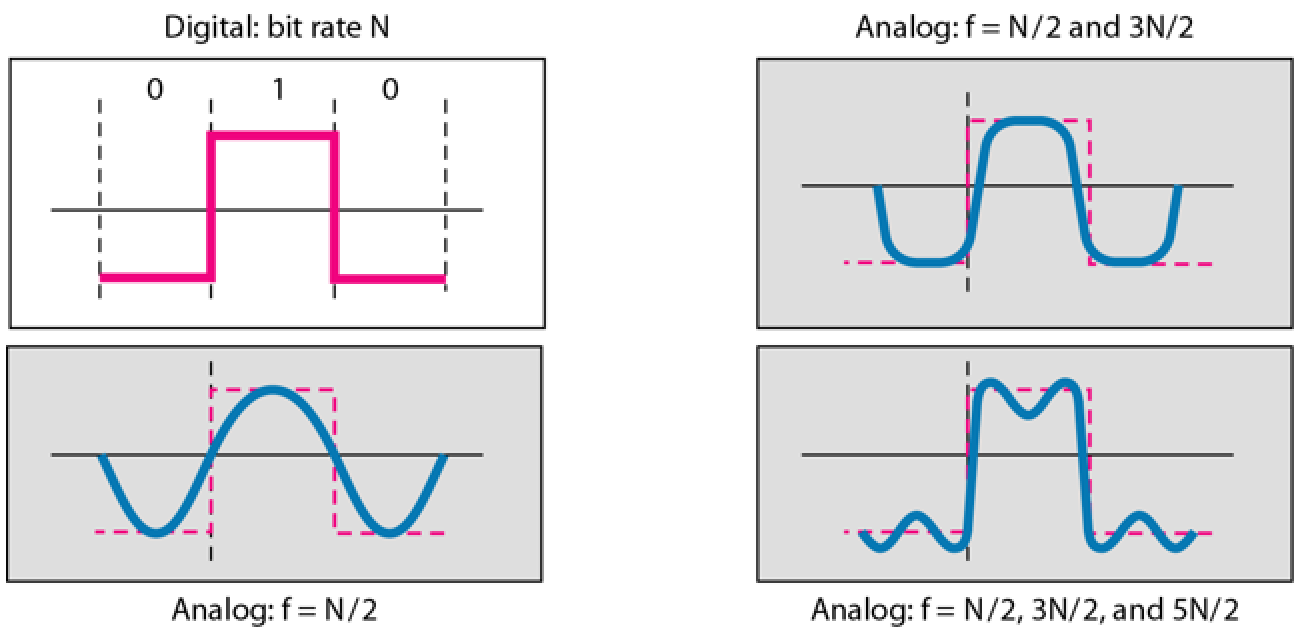


b. Time and frequency domains of nonperiodic digital signal

Data Rate and Bandwidth

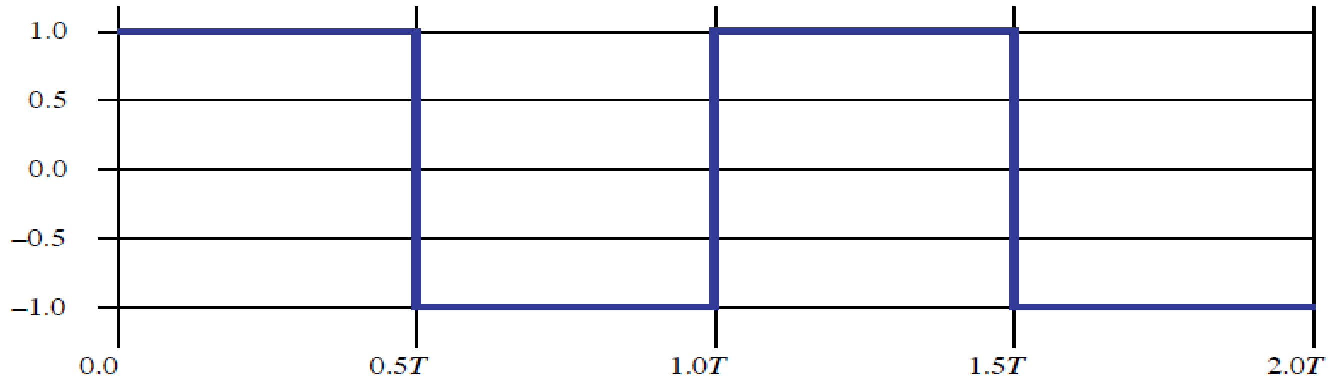
- A square wave has infinite components and hence bandwidth
- But most energy is in first few components

Simulating a digital signal with first three harmonics 谐波



Bit rate of N bps corresponds to a digital signal with frequency N/2 Hz. That is The frequency f = bit rate /2=N/2.

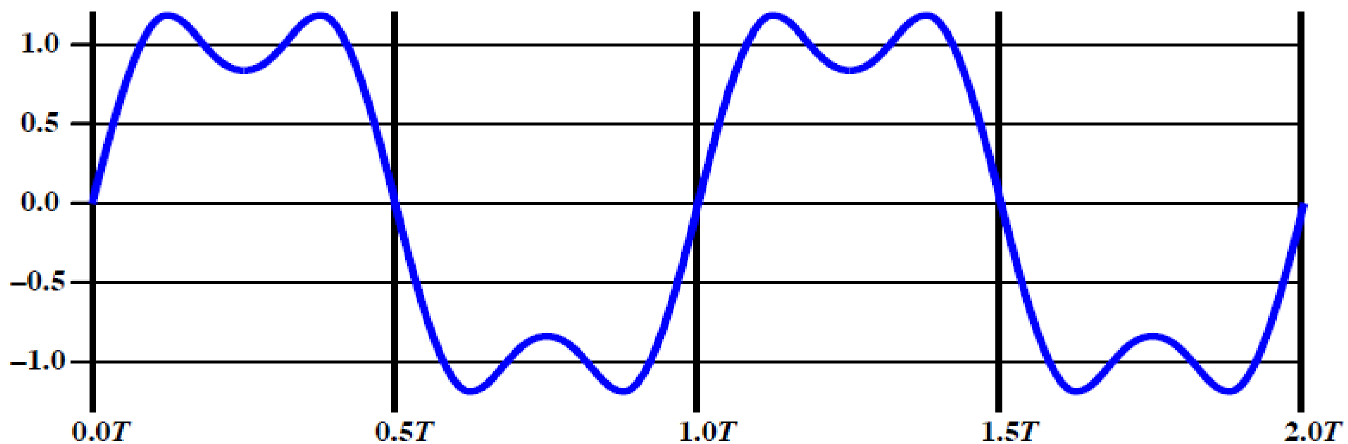
Simulating a digital signal with finite harmonics.



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

Figure 3.7 Frequency Components of Square Wave ($T = 1/f$)

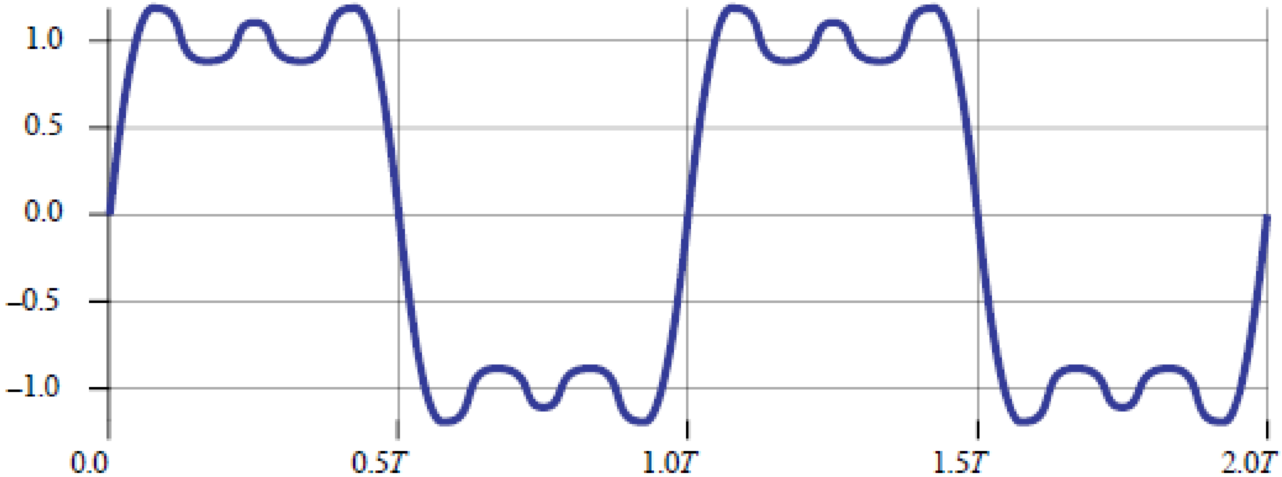
Bit time = T / 2



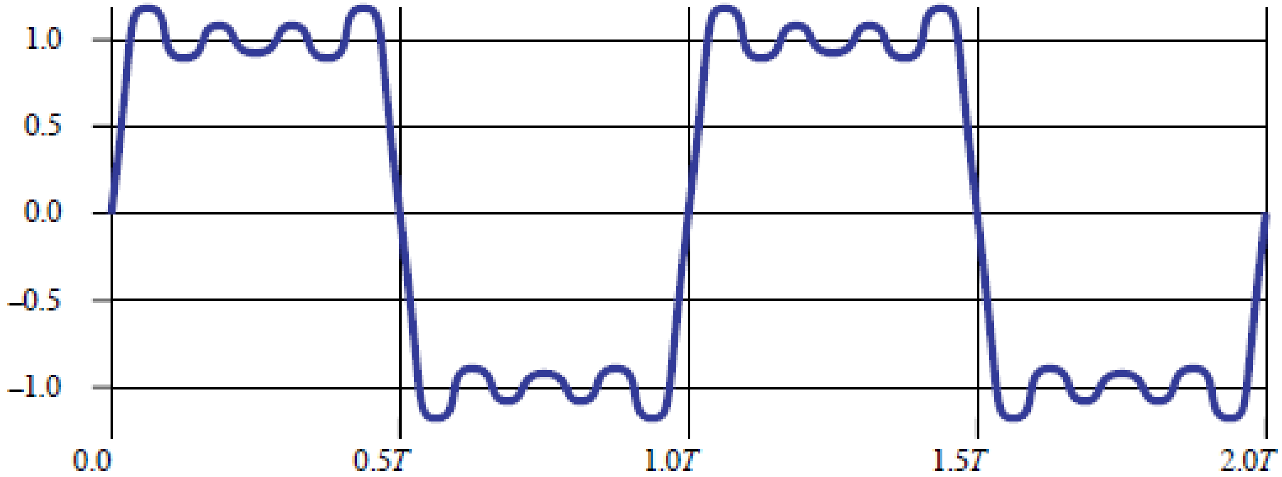
(c) $(4/\pi)\,[\sin(2\pi ft) + (1/3)\sin(2\pi(3f)t)]$

Figure 3.4 Addition of Frequency Components ($T = 1/f$)

Data Rate and Bandwidth



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



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

Data Rate and Bandwidth

- A square wave has infinite components and hence bandwidth
- But most energy is in first few components
- Limited bandwidth increases distortion
- Have a direct relationship between data rate & bandwidth

Example

We use the basic quality signal (use 1^{st} harmonic to represent the digital signal). What is the required bandwidth of a low-pass channel if we need to send 10 Mbps by using baseband transmission?

Solution

Bit rate 10Mbps corresponds to a digital signal with frequency 5MHz (since f = bit rate /2).

Answer: The bit rate of 10kbps means that the frequency of the digital signal is f= 5MHz (since f = bit rate /2). We use 1st harmonic to represent the digital signal, therefore, the frequency band of the analogy signal are f Hz = 5MHz. That is, the highest frequency is 5MHz。 Therefore, we need a channel with the bandwidth of 5MHz to carry the analogy signal.

Example

We use the basic quality signal (use 1st and 3rd harmonics to represent the digital signal). What is the required bandwidth of a low-pass channel if we need to send 10 Mbps by using baseband transmission?

Solution

Data rate 10Mbps corresponds to a digital signal with frequency 5MHz (since f = bit rate /2).

Answer: The bit rate of 10Mbps means that the frequency of the digital signal is f= 5MHz (since f = bit rate /2). We use 1st and 3rd harmonics to represent the digital signal, therefore, the frequency band of the analogy signal are f Hz and 3f Hz. That is, the highest frequency is 3f=15MHz. Therefore, we need a channel with the bandwidth of 15MHz to carry the analogy signal.

Data Rate vs. Bandwidth

- Same data rate
  - Large Bandwidth → provide better signal quality
  - Better signal quality requirement→ large bandwidth requirement for channel

Example

We use the middle quality signal (use 1st and 3rd harmonics to represent the digital signal). What is the required bandwidth of a low-pass channel to achieve the bit rate of 1kbps, 10kbps, and 100kbps respectively.

Solution

Bit rate 1kbps corresponds to a digital signal with frequency 500Hz (since f = bit rate /2).

Answer: a. The bit rate of 1kbps means that the frequency of the digital signal is f= 500Hz (since f = bit rate /2). We use 1st and 3rd harmonics to represent the digital signal, therefore, the frequency band of the analogy signal are f Hz and 3f Hz. That is, the highest frequency is 3f=1.5 KHz. Therefore, we need a channel with the bandwidth of 1.5KHz to carry the analogy signal.

b. The bit rate of 10kbps means that the frequency of the digital signal is f= 5KHz (since f = bit rate /2). We use 1st and 3rd harmonics to represent the digital signal, therefore, the frequency/bandwidth band of the analogy signal are f Hz and 3f Hz. That is, the highest frequency is 3f=15 KHz. Therefore, we need a channel with the bandwidth of 15KHz to carry the analogy signal.

c. The bit rate of 100kbps means that the frequency of the digital signal is f= 50 KHz (since f = bit rate /2). We use 1st and 3rd harmonics to represent the digital signal, therefore, the frequency/bandwidth band of the analogy signal are fHz and 3fHz. That is, the highest frequency is 3f=150 KHz. Therefore, we need a channel with the bandwidth of 150KHz to carry the analogy signal.

Data Rate vs. Bandwidth

- Same signal quality
  - High data rate ↑→ large bandwidth requirement

Bandwidth requirements

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

In baseband transmission, the required bandwidth is proportional to the bit rate;
if we need to send bits faster, we need more bandwidth.

Data Rate vs. Bandwidth

- Same data rate
  - Large Bandwidth ↑ → better signal quality
- Same signal quality
  - High data rate ↑→ large bandwidth requirement
- Same bandwidth
  - Higher signal quality ↑→ lower data rate