EEEN3008J: Advance wireless communications

Transmission fundamentals

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Electromagnetic Signal

- Function of time
- Can also be expressed as a function of frequency
  - Signal consists of components of different frequencies

Time-Domain concepts

- Analog signal - signal intensity varies in a smooth fashion over time
  - No breaks or discontinuities in the signal
- Digital signal - signal intensity maintains a constant level for some period of time and then changes to another constant level
- Periodic signal - analog or digital signal pattern that repeats over time

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

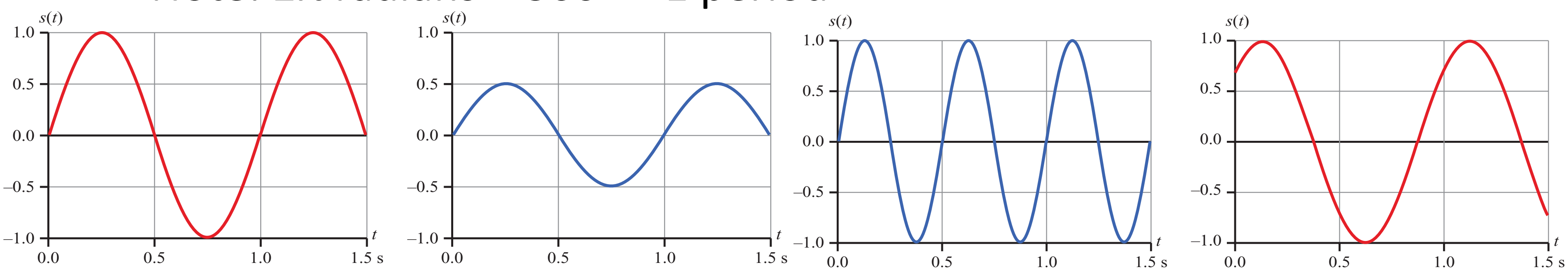
➢ where *T* is the period of the signal

Time-Domain Concepts

- Aperiodic signal - analog or digital signal pattern that doesn't repeat over time
- Peak amplitude (A) - maximum value or strength of the signal over time; typically measured in volts
- Frequency (f)
  - Rate, in cycles per second, or Hertz (Hz) at which the signal repeats
- Period (T) - amount of time it takes for one repetition of the signal
  - $T = 1/f$
- Phase (ϕ) - measure of the relative position in time within a single period of a signal
- Wavelength (λ) - distance occupied by a single cycle of the signal
  - Or, the distance between two points of corresponding phase of two consecutive cycles

Sine Wave Parameters

- General sine wave
  - $s(t) = A \sin(2\pi ft + \phi)$
- Figure below shows the effect of varying each of the three parameters
  - (a) $A = 1$, $f = 1$ Hz, $\phi = 0$; thus $T = 1$ s
  - (b) Reduced peak amplitude; A=0.5
  - (c) Increased frequency; $f = 2$, thus $T = ½$
  - (d) Phase shift; $\phi = \pi/4$ radians (45 degrees)
- Note: 2π radians = 360° = 1 period



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

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

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

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

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

Problem 1

- Decompose the signal $(1 + 0.1 \cos 5t)\cos 100t$ into a linear combination of sinusoidal function, and find the amplitude, frequency, and phase of each component.

Solution:

$(1 + 0.1 \cos 5t) \cos 100t = \cos 100t + 0.1 \cos 5t \cos 100t$. From the trigonometric identity $\cos a \cos b = (1/2)(\cos(a + b) + \cos(a - b))$, this equation can be rewritten as the linear combination of three sinusoids: $\cos 100t + 0.05 \cos 105t + 0.05 \cos 95t$

Problem 2

- Consider two periodic functions $f_1(t)$ and $f_2(t)$, with periods T_1 and T_2, respectively. Is it always the case that the function $f(t) = f_1(t) + f_2(t)$ is periodic? If so, demonstrate this fact. If not, under what conditions is $f(t)$ periodic?

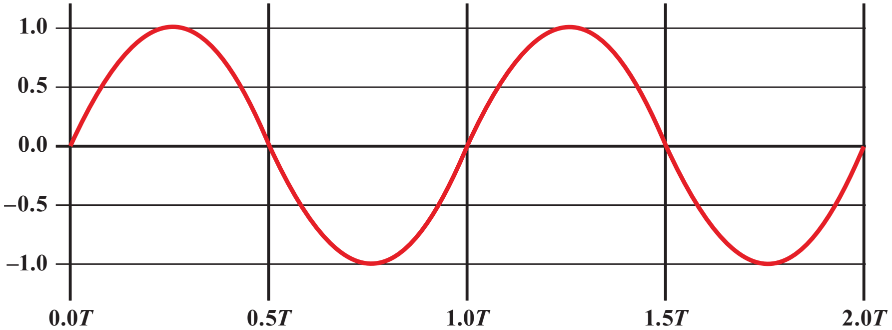
Solution:
If $f_1(t)$ is periodic with period X, then $f_1(t) = f_1(t + X) = f_1(t + nX)$ where n is an integer
and X is the smallest value such that $f_1(t) = f_1(t + X)$. Similarly, $f_2(t) = f_2(t + Y) = f_2(t +$
$mY)$. We have $f(t) = f_1(t) + f_2(t)$. If $f(t)$ is periodic with period Z, then $f(t) = f(t + Z)$.
Therefore $f_1(t) + f_2(t) = f_1(t + Z) + f_2(t + Z)$. This last equation is satisfied if $f_1(t) = f_1(t$
$+ Z)$ and $f_2(t) = f_2(t + Z)$. This leads to the condition $Z = nX = mY$ for some integers
n and m. We can rewrite this last as $(n/m) = (Y/X)$. We can therefore conclude that if the ratio (Y/X) is a rational number, then $f(t)$ is periodic.

Time vs. Distance

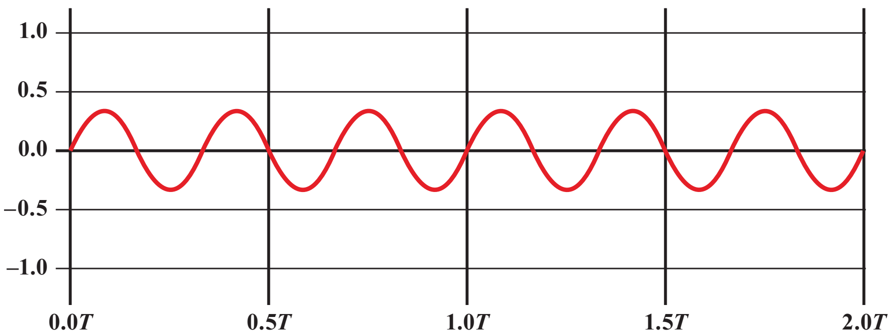
- When the horizontal axis is *time*, as in the Figure, graphs display the value of a signal at a given point in *space* as a function of *time*
- With the horizontal axis in *space*, graphs display the value of a signal at a given point in *time* as a function of *distance*
  - At a particular instant of time, the intensity of the signal varies as a function of distance from the source

Frequency-Domain Concepts

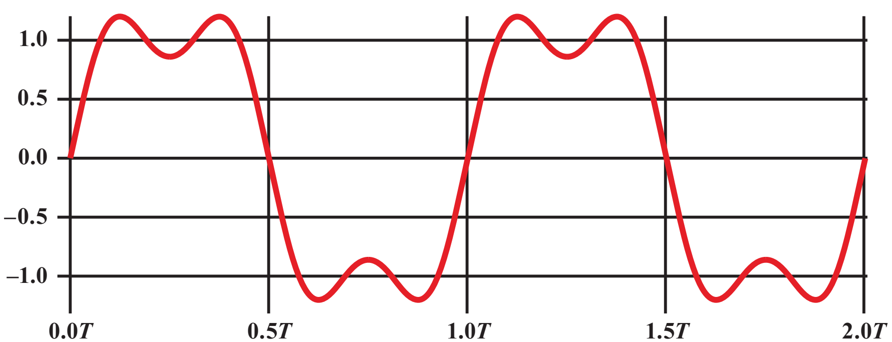
- Fundamental frequency - when all frequency components of a signal are integer multiples of one frequency, it’s referred to as the fundamental frequency
- Spectrum - range of frequencies that a signal contains
- Absolute bandwidth - width of the spectrum of a signal
- Effective bandwidth (or just bandwidth) - narrow band of frequencies that most of the signal’s energy is contained in
- Any electromagnetic signal can be shown to consist of a collection of periodic analog signals (sine waves) at different amplitudes, frequencies, and phases



(a) sin $(2\phi f t)$

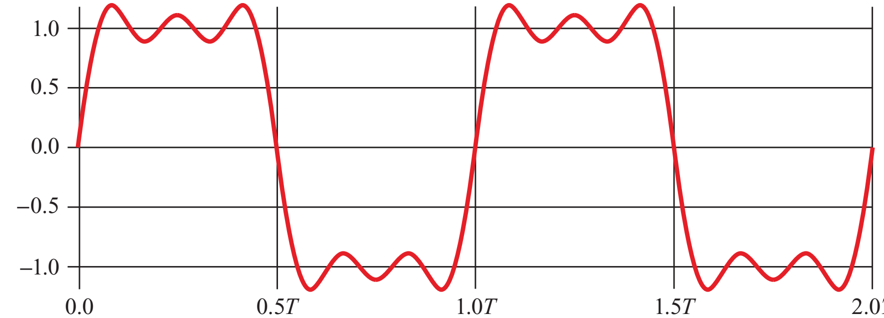


(b) (1/3) sin $(2\phi(3f)t)$

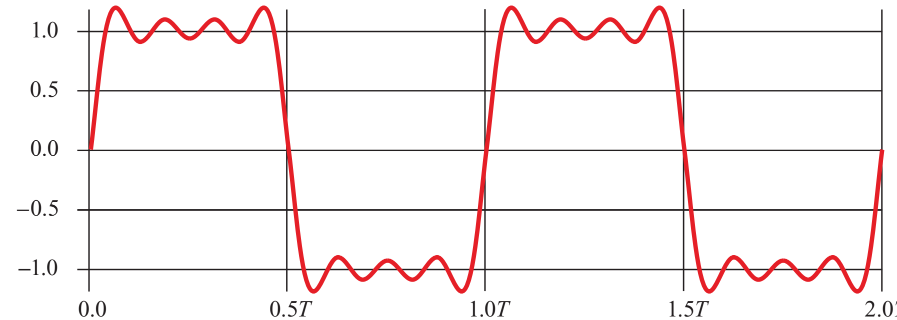


(c) $(4/\phi)$ [sin $(2\phi f t)$ + (1/3) sin $(2\phi(3f)t)$]

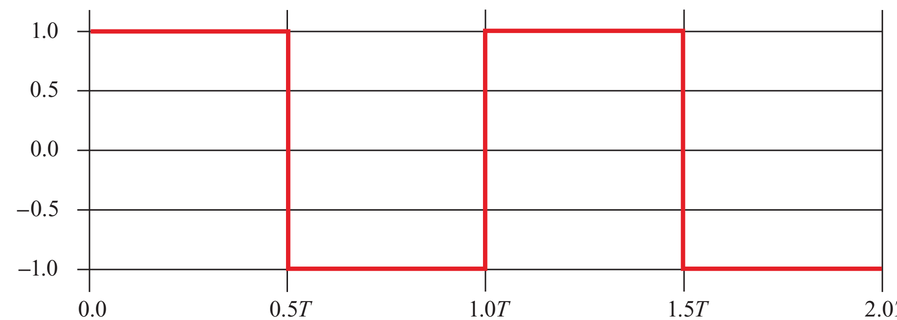
Addition of frequency Components(T = 1/*f*)



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



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

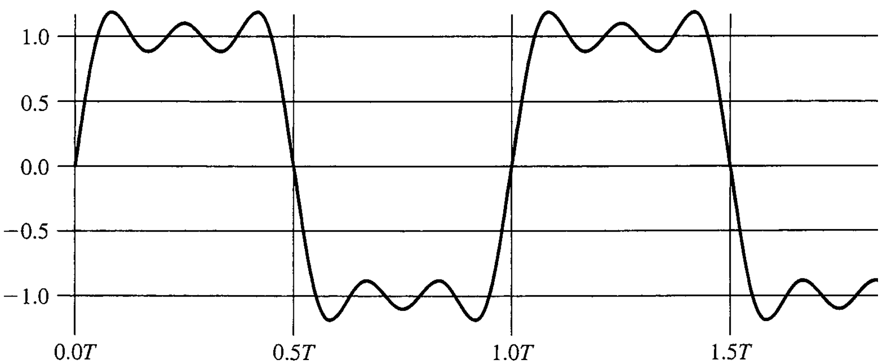


(c) $(4/\phi)$ $\Sigma(1/k)$ sin $(2\phi(kf)t)$, for k odd

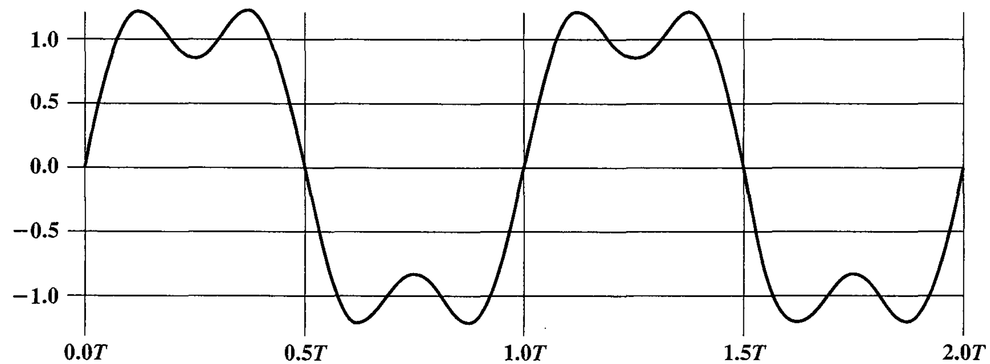
Frequency Components of Square Wave

Problem 3

a) Given a approximated square wave with three sinusoidal signals below (left), calculate the bandwidth and and the data rate of this square wave if the fundamental frequency f = 2 MHz.



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



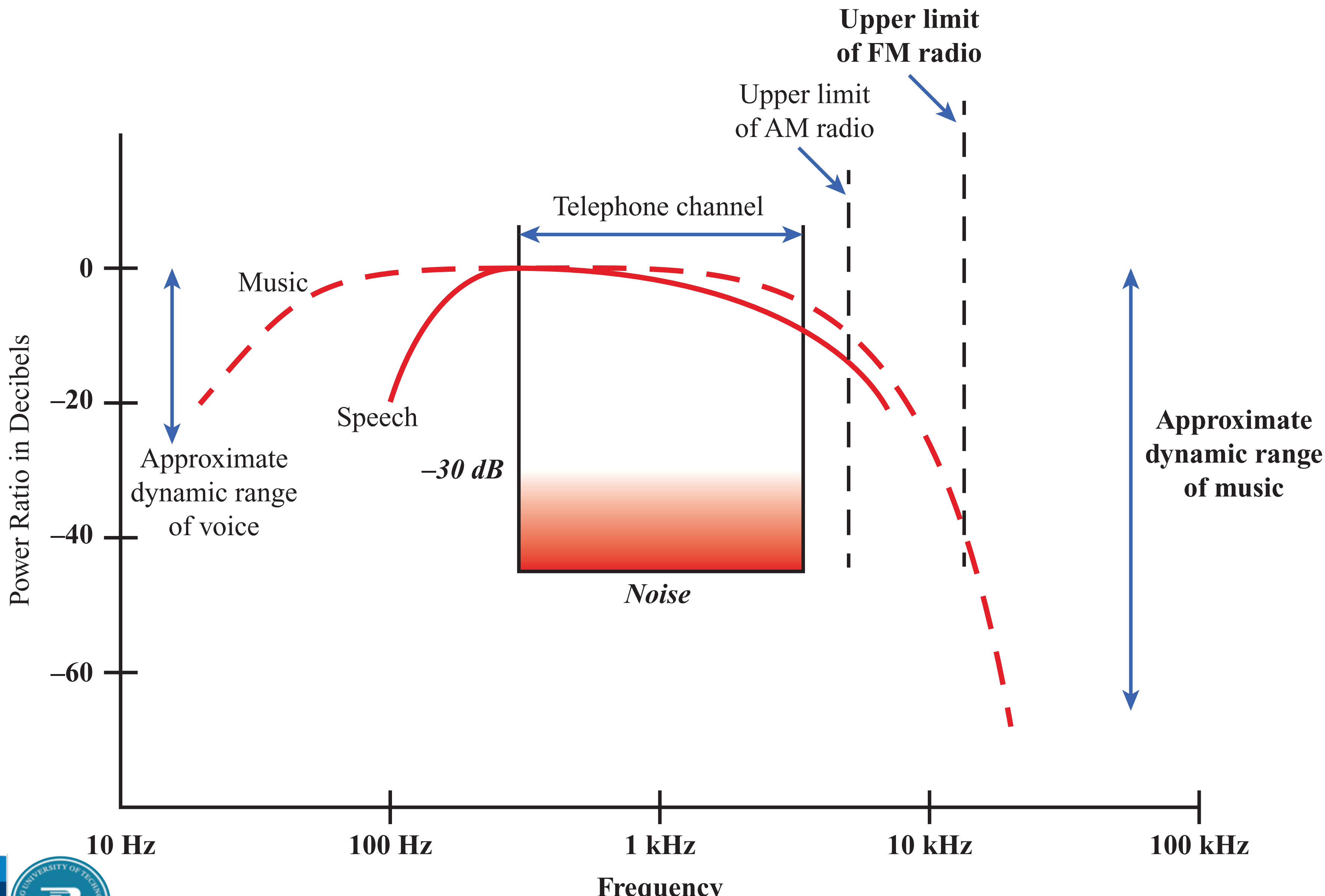
:) $(4/\pi)\,[\sin(2\pi f t) + (1/3)\sin(2\pi(3f)t)]$

b) Repeat the same with the square wave approximated with two sinusoids on the right.

Relationship between Data Rate and Bandwidth

- The greater the bandwidth, the higher the information-carrying capacity
- Conclusions
  - Any digital waveform will have infinite bandwidth
  - BUT the transmission system will limit the bandwidth that can be transmitted
  - AND, for any given medium, the greater the bandwidth transmitted, the greater the cost
  - HOWEVER, limiting the bandwidth creates distortions

Acoustic Spectrum of Speech and Music



Data Communication Terms

- Data - entities that convey meaning, or information
- Signals - electric or electromagnetic representations of data
- Transmission - communication of data by the propagation and processing of signals

Examples of analogue and digital data

- Analog
  - Video
  - Audio
- Digital
  - Text
  - Integers

Analog Signals

- A continuously varying electromagnetic wave that may be propagated over a variety of media, depending on frequency
- Examples of media:
  - Copper wire media (twisted pair and coaxial cable)
  - Fiber optic cable
  - Atmosphere or space propagation
- Analog signals can propagate analog and digital data

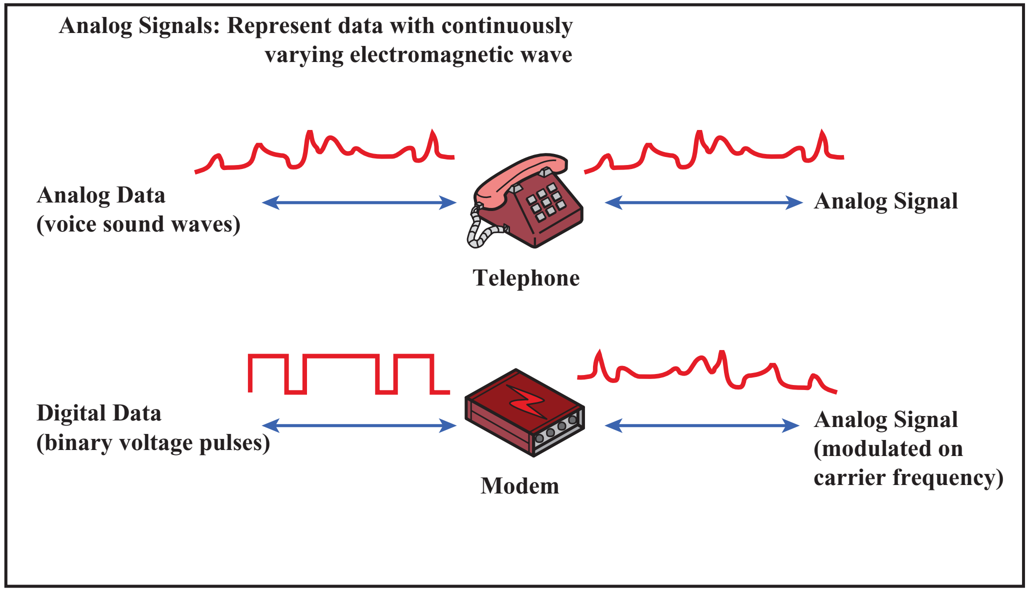
Digital Signals

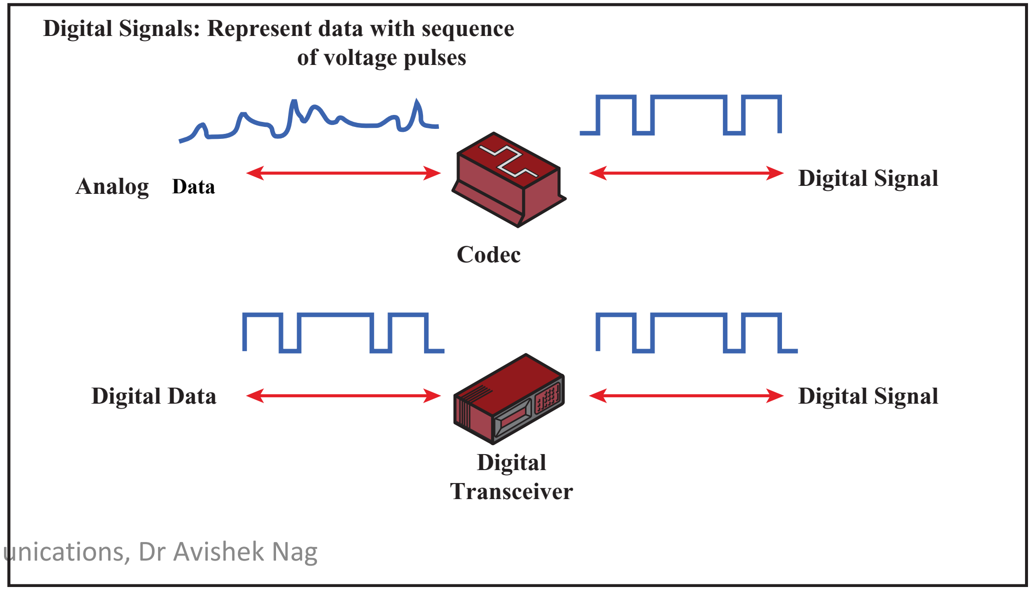
- A sequence of voltage pulses that may be transmitted over a copper wire medium
- Generally cheaper than analog signaling
- Less susceptible to noise interference
- Suffer more from attenuation
- Digital signals can propagate analog and digital data

Reasons for Choosing Data and Signal Combinations

- Digital data, digital signal
  - Equipment for encoding is less expensive than digital-to-analog equipment
- Analog data, digital signal
  - Conversion permits use of modern digital transmission and switching equipment
- Digital data, analog signal
  - Some transmission media will only propagate analog signals
  - Examples include optical fiber and satellite
- Analog data, analog signal
  - Analog data easily converted to analog signal

Analog and Digital Signaling of Analog and Digital Data





Analog Transmission

- Transmit analog signals without regard to content
- Attenuation limits length of transmission link
- Cascaded amplifiers boost signal's energy for longer distances but cause distortion
  - Analog data can tolerate distortion
  - Introduces errors in digital data

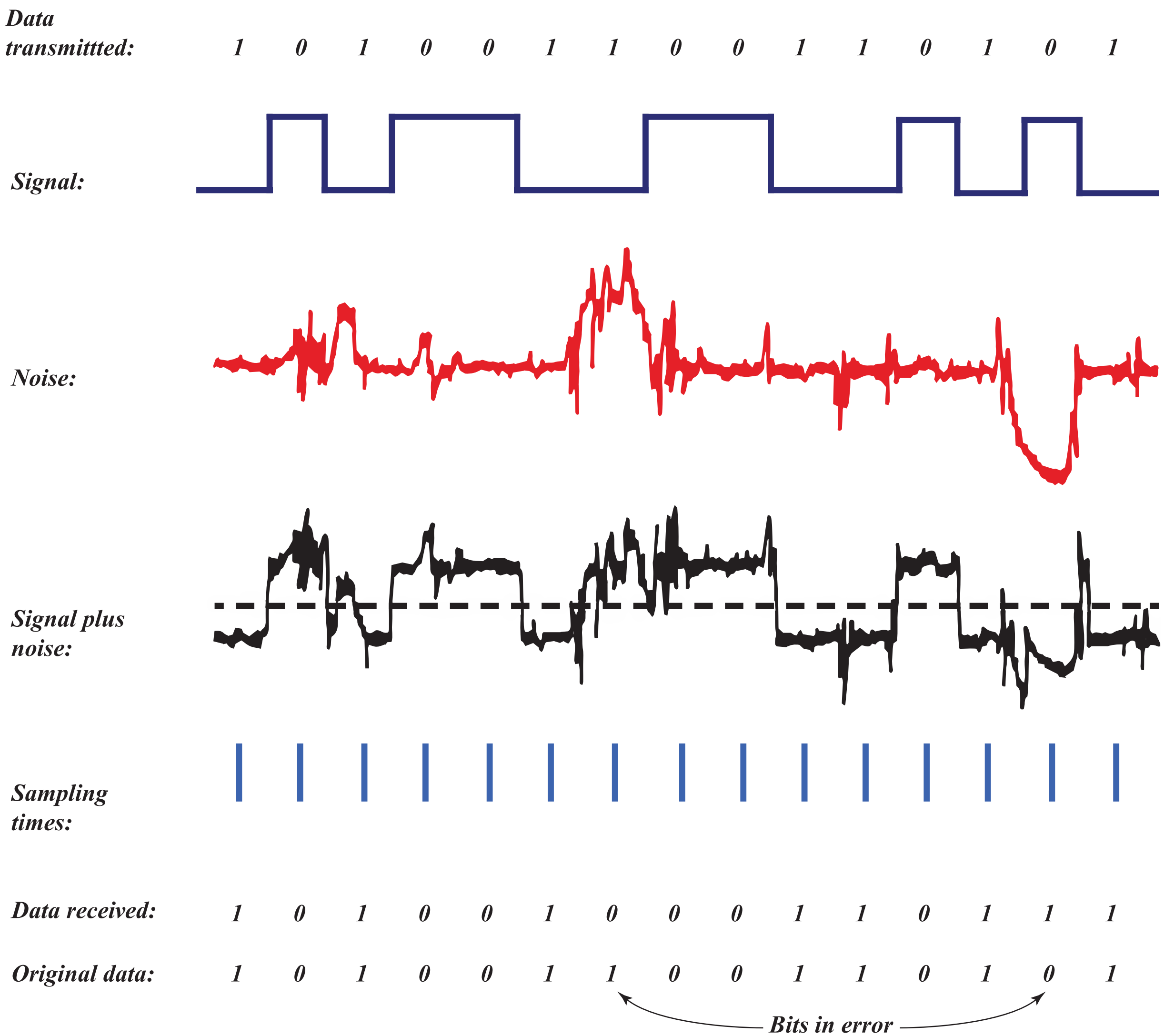
Digital Transmission

- Concerned with the content of the signal
- Attenuation endangers integrity of data
- Digital Signal
  - Repeaters achieve greater distance
  - Repeaters recover the signal and retransmit
- Analog signal carrying digital data
  - Retransmission device recovers the digital data from analog signal
  - Generates new, clean analog signal

About Channel Capacity

- Impairments, such as noise, limit data rate that can be achieved
- Channel Capacity – the maximum rate at which data can be transmitted over a given communication path, or channel, under given conditions

Effect of Noise on Digital Signal



Concepts Related to Channel Capacity

- Data rate - rate at which data can be communicated (bps)
- Bandwidth - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
- Noise - average level of noise over the communications path
- Error rate - rate at which errors occur
  - Error = transmit 1 and receive 0; transmit 0 and receive 1

Nyquist Bandwidth

- For binary signals (two voltage levels)
  - $C = 2B$
- With multilevel signaling
  - $C = 2B \log_2 M$
    - ➢ M = number of discrete signal or voltage levels

Signal-to-Noise Ratio

- Ratio of the power in a signal to the power contained in the noise that's present at a particular point in the transmission
- Typically measured at a receiver
- Signal-to-noise ratio (SNR, or S/N)

$$(SNR)_{\mathrm{dB}} = 10\log_{10}\frac{\text{signal power}}{\text{noise power}}$$

- A high SNR means a high-quality signal, low number of required intermediate repeaters
- SNR sets upper bound on achievable data rate

Shannon Capacity Formula

- Equation:

$$C = B\log_2\left(1+\mathrm{SNR}\right)$$

- Represents theoretical maximum that can be achieved
- In practice, only much lower rates achieved
  - Formula assumes white noise (thermal noise)
  - Impulse noise is not accounted for
  - Attenuation distortion or delay distortion not accounted for

Example of Nyquist and Shannon Formulations

Spectrum of a channel between 3 MHz and 4 MHz ; $\mathrm{SNR}_{\mathrm{dB}}$ = 24 dB

$$B = 4\ \mathrm{MHz} - 3\ \mathrm{MHz} = 1\ \mathrm{MHz}$$

$$\mathrm{SNR}_{\mathrm{dB}} = 24\ \mathrm{dB} = 10\log_{10}(\mathrm{SNR})$$

$$\mathrm{SNR} = 251$$

Using Shannon's formula

$$C = 10^6 \times \log_2(1+251) \approx 10^6 \times 8 = 8\mathrm{Mbps}$$

- How many signaling levels are required?

$$C = 2B\log_2 M$$

$$8\times 10^6 = 2\times(10^6)\times\log_2 M$$

$$4 = \log_2 M$$

$$M = 16$$

Problem 4

- A digital signaling system is required to operate at 9600 bps.

  a) If a signal element encodes a 4-bit word, what is the minimum required bandwidth of the channel?

  b) Repeat part (a) for the case of 8-bit words.

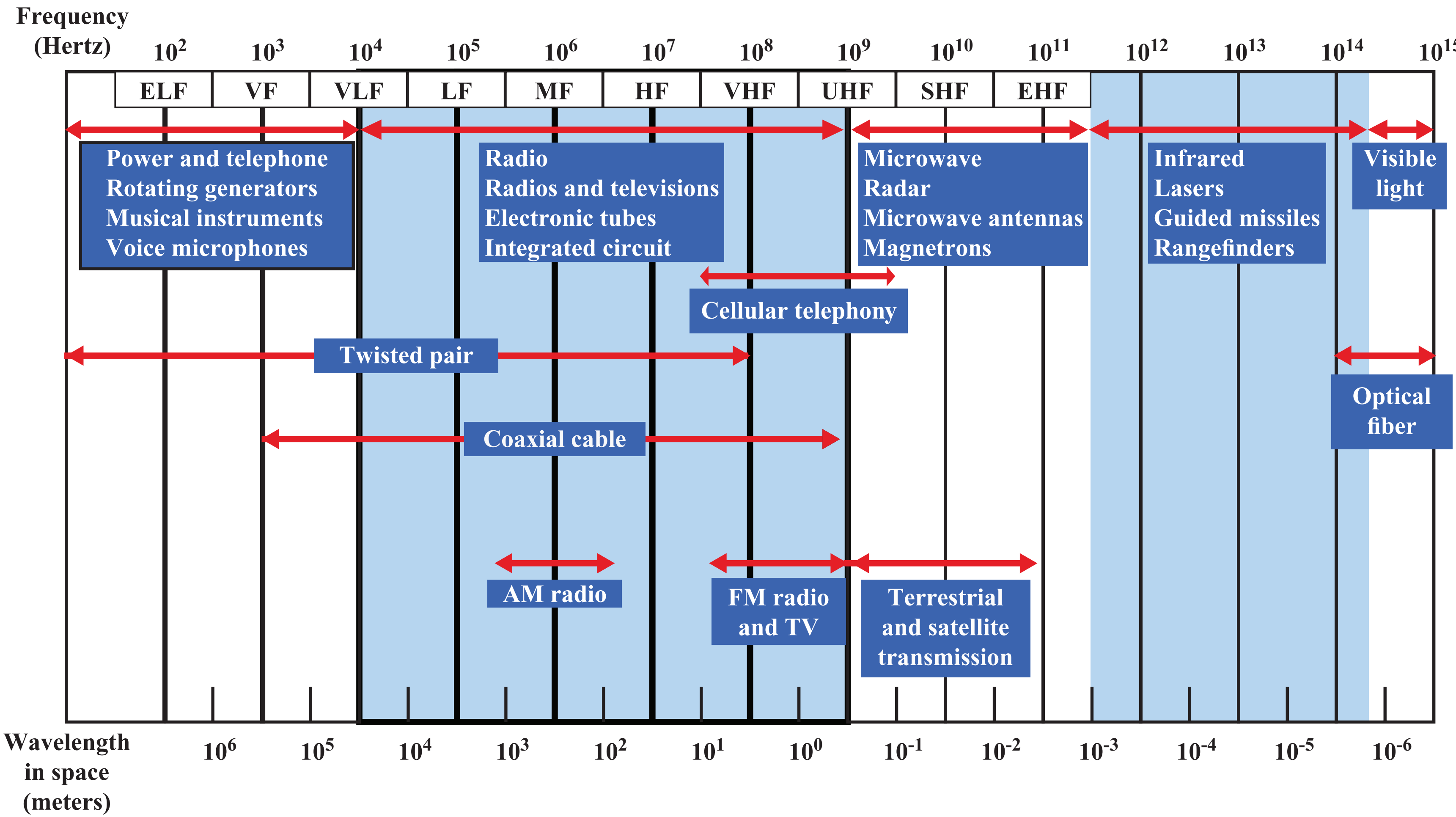
Solution:

Using Nyquist's equation: $C = 2B \log_2 M$ We have $C = 9600$ bps
1. $\log_2 M = 4$, because a signal element encodes a 4-bit word Therefore, $C = 9600 = 2B \cdot 4$, and
2. $B = 1200$ Hz
3. $9600 = 2B \cdot 8$, and $B = 600$ Hz

Classifications of Transmission Media

- Transmission Medium
  - Physical path between transmitter and receiver
- Guided Media
  - Waves are guided along a solid medium
  - E.g., copper twisted pair, copper coaxial cable, optical fiber
- Unguided Media
  - Provides means of transmission but does not guide electromagnetic signals
  - Usually referred to as wireless transmission
  - E.g., atmosphere, outer space
  - Transmission and reception are achieved by means of an antenna
  - Configurations for wireless transmission
    - Directional
    - Omnidirectional

Electromagnetic spectrum of Telecommunications



ELF = Extremely low frequency
VF = Voice frequency
VLF = Very low frequency
LF = Low frequency
MF = Medium frequency
HF = High frequency
VHF = Very high frequency
UHF = Ultrahigh frequency
SHF = Superhigh frequency
EHF = Extremely high frequency

General Frequency Ranges

- Microwave frequency range
  - 1 GHz to 40 GHz
  - Directional beams possible
  - Suitable for point-to-point transmission
  - Used for satellite communications
- Radio frequency range
  - 30 MHz to 1 GHz
  - Suitable for omnidirectional applications
- Infrared frequency range
  - Roughly, 3×10^{11} to 2×10^{14} Hz
  - Useful in local point-to-point multipoint applications within confined areas

Terrestrial Microwave

- Description of common microwave antenna
  - Parabolic "dish", 3 m in diameter
  - Fixed rigidly and focuses a narrow beam
  - Achieves line-of-sight transmission to receiving antenna
  - Located at substantial heights above ground level
- Applications
  - Long haul telecommunications service
  - Short point-to-point links between buildings

Satellite Microwave

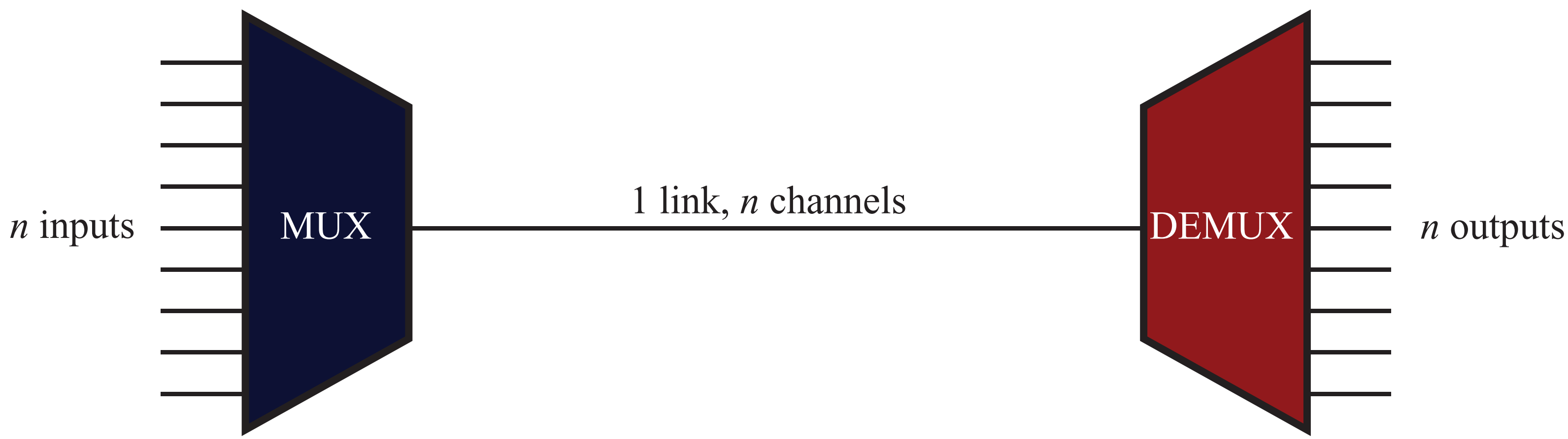
- Description of communication satellite
  - Microwave relay station
  - Used to link two or more ground-based microwave transmitter/receivers
  - Receives transmissions on one frequency band (uplink), amplifies or repeats the signal, and transmits it on another frequency (downlink)
- Applications
  - Television distribution
  - Long-distance telephone transmission
  - Private business networks

Broadcast Radio

- Description of broadcast radio antennas
  - Omnidirectional
  - Antennas not required to be dish-shaped
  - Antennas need not be rigidly mounted to a precise alignment
- Applications
  - Broadcast radio
    - VHF and part of the UHF band; 30 MHZ to 1GHz
    - Covers FM radio and UHF and VHF television

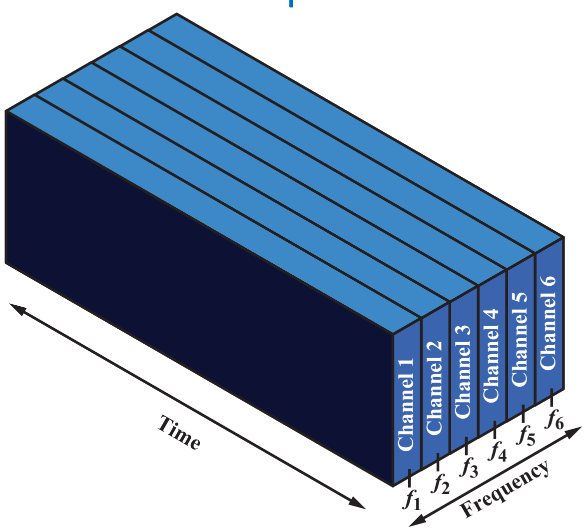
Multiplexing

- Capacity of transmission medium usually exceeds capacity required for transmission of a single signal
- Multiplexing - carrying multiple signals on a single medium
  - More efficient use of transmission medium
- Cost per kbps of transmission facility declines with an increase in the data rate

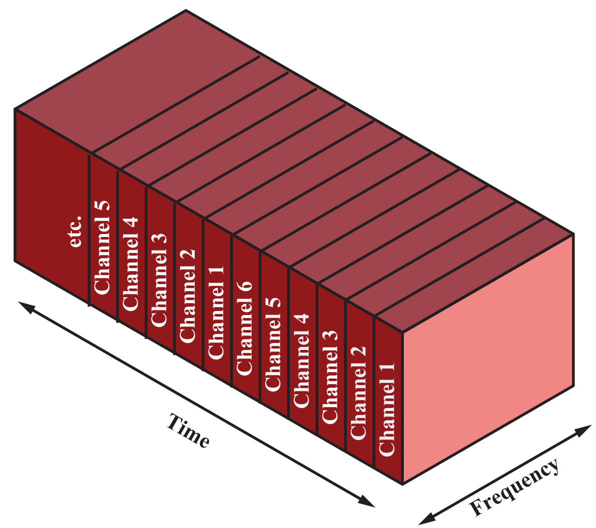


Multiplexing Techniques

- Frequency-division multiplexing (FDM)
  - Takes advantage of the fact that the useful bandwidth of the medium exceeds the required bandwidth of a given signal
- Time-division multiplexing (TDM)
  - Takes advantage of the fact that the achievable bit rate of the medium exceeds the required data rate of a digital signal



(a) Frequency division multiplexing



(b) Time division multiplexing