Department of Communications Engineering, College of Engineering, University of Diyala

Digital Communication I

This Course covers the following topics:

1. Introduction: Basic Elements of Digital Communication Systems, Communication Channels.
2. Pulse Modulation Techniques: PAM, PWM, PPM. PCM, DPCM, DM, Adaptive Delta Modulation (ADM), Noise in pulse modulations.
3. Multiplexing Techniques: TDM, FDM, applications.
4. Optimum Receivers for the AWGN Channel: Receiver for Signals Corrupted by AWGN, Performance of Memoryless Modulation, Trade off of power, bandwidth, data rate, and error probability.
5. Digital Modulation Techniques: ASK, PSK, FSK, QPSK, DPSK, DEPSK, MSK, M-ary-FSK, M-ary-PSK, QAM, M-ary-QAM.
6. Orthogonal Frequency Division Multiplexing (OFDM)

Textbooks:

1. Abbas Kattoush, "**Digital communications",** Dar Al-Manahej for Pub. & Distributing, Amman, 2005.
2. Ziemer, Rodger E., **"Principles of communication : systems, modulation, and noise",** John Wiley & Sons, 2015.
3. John Proakis & Masoud Salehi, **"Digital Communications",** McGraw-Hill Education, 2005.
4. John G. Proakis, Masoud Salehi, Gerhard Bauch, **"Contemporary Communication Systems Using MATLAB",** Cengage Learning, 2013.
5. Sanjay Sharma, **"Principles of Communication",** S.K. Kataria & Sons, 2011.

Lecture # 1

Introduction

Introduction: Basic Elements of Digital Communication Systems, Communication Channels, Review of Sampling Theory

Introduction:

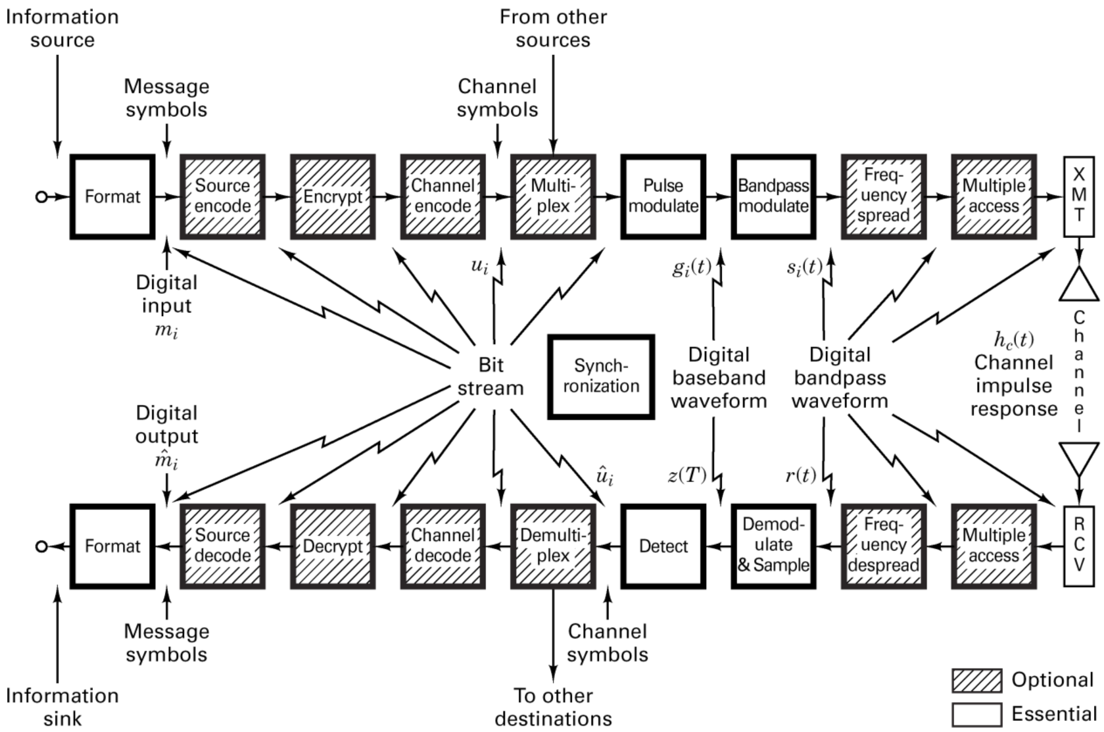
Because of the rapid development of communication system, many application and services have been appeared, such as video streaming, online gaming, and social media applications and so on. These new applications became more popular through the time. However, the new applications and services require more data rates with high quality of service. Therefore, communication systems need to be developed more and more. In the following list, you will see history of data and communication systems development across the years.

1. Before 3000 B.C. Egyptians develop a picture language called hieroglyphics.
2. A.D. 800 Arabs adopt our present number system from India.
3. 1440 Johannes Gutenberg invents movable metal type.
4. 1752 Benjamin Franklin's kite shows that lightning is electricity.
5. 1827 Georg Simon Ohm formulates his law (I = E/R).
6. 1834 Carl F. Gauss and Ernst H. Weber build the electromagnetic telegraph.
7. 1838 William F. Cooke and Sir Charles Wheatstone build the telegraph.
8. 1844 Samuel F. B. Morse demonstrates the Baltimore, MD, and Washington, DC, telegraph line.
9. 1850 Gustav Robert Kirchhoff first publishes his circuit laws.
10. 1858 The first transatlantic cable is laid and fails after 26 days.
11. 1864 James C. Maxwell predicts electromagnetic radiation.
12. 1871 The Society of Telegraph Engineers is organized in London.
13. 1876 Alexander Graham Bell develops and patents the telephone.
14. 1883 Thomas A. Edison discovers a flow of electrons in a vacuum, called the "Edison effect," the foundation of the electron tube.
15. 1884 The American Institute of Electrical Engineers (AIEE) is formed.
16. 1887 Heinrich Hertz verifies Maxwell's theory.
17. 1889 The Institute of Electrical Engineers (IEE) forms from the Society of Telegraph Engineers in London.
18. 1894 Oliver Lodge demonstrates wireless communication over a distance of 150 yards.
19. 1900 Guglielmo Marconi transmits the first transatlantic wireless signal.
20. 1905 Reginald Fessenden transmits speech and music by radio.
21. 1906 Lee deForest invents the vacuum-tube triode amplifier.
22. 1907 The Society of Wireless Telegraph Engineers is formed in the United States.
23. 1909 The Wireless Institute is established in the United States.
24. 1912 The Institute of Radio Engineers (IRE) is formed in the United States from the Society of Wireless Telegraph Engineers and the Wireless Institute.
25. 1915 Bell System completes a U.S. transcontinental telephone line.
26. 1918 Edwin H. Armstrong invents the superheterodyne receiver circuit.
27. 1920 KDKA, Pittsburgh, PA, begins the first scheduled radio broadcasts.

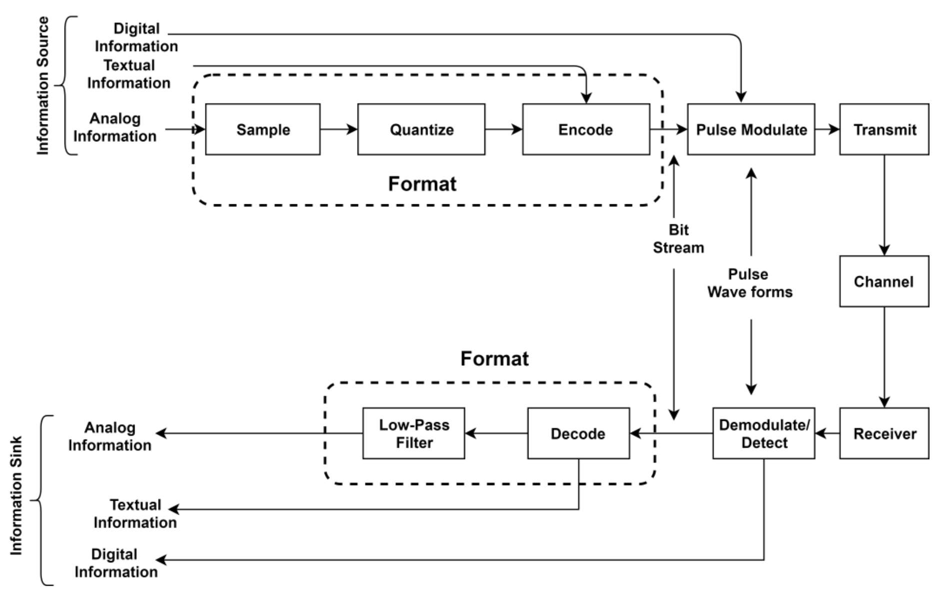
28. 1920 J. R. Carson applies sampling to communications.
29. 1923 Vladimir K. Zworkykin devises the “iconoscope” television pickup tube.
30. 1926 J. L. Baird (England) and C. F. Jenkins (United States) demonstrate television.
31. 1927 The Federal Radio Commission is created in the United States.
32. 1927 Harold Black develops the negative-feedback amplifier at Bell Laboratories.
33. 1928 Philo T. Farnsworth demonstrates the first all-electronic television system.
34. 1931 Teletypewriter service is initiated.
35. 1933 Edwin H. Armstrong invents FM.
36. 1934 The Federal Communication Commission (FCC) is created from the Federal Radio Commission in the United States.
37. 1935 Robert A. Watson-Watt develops the first practical radar.
38. 1936 The British Broadcasting Corporation (BBC) begins the first television broadcasts.
39. 1937 Alex Reeves conceives pulse code modulation (PCM).
40. 1941 John V. Atanasoff invents the digital computer at Iowa State College.
41. 1941 The FCC authorizes television broadcasting in the United States.
42. 1945 The ENIAC electronic digital computer is developed at the University of Pennsylvania by John W. Mauchly.
43. 1947 Walter H. Brattain, John Bardeen, and William Shockley devise the transistor at Bell Laboratories.
44. 1947 Steve O. Rice develops a statistical representation for noise at Bell Laboratories.
45. 1948 Claude E. Shannon publishes his work on information theory.
46. 1950 Time-division multiplexing is applied to telephony.
47. 1950s Microwave telephone and communication links are developed.
48. 1953 NTSC color television is introduced in the United States.
49. 1953 The first transatlantic telephone cable (36 voice channels) is laid.
50. 1957 The first Earth satellite, *Sputnik I*, is launched by USSR.
51. 1958 A. L. Schawlow and C. H. Townes publish the principles of the laser.
52. 1958 Jack Kilby of Texas Instruments builds the first germanium integrated circuit (IC).
53. 1958 Robert Noyce of Fairchild produces the first silicon IC.
54. 1961 Stereo FM broadcasts begin in the United States.
55. 1962 The first active satellite, *Telstar I*, relays television signals between the United States and Europe.
56. 1963 Bell System introduces the touch-tone phone.
57. 1963 The Institute of Electrical and Electronic Engineers (IEEE) is formed by merger of the IRE and AIEE.
58. 1963–66 Error-correction codes and adaptive equalization for high-speed error-free digital communications are developed.
59. 1964 The electronic telephone switching system (No. 1 ESS) is placed into service.
60. 1965 The first commercial communications satellite, *Early Bird*, is placed into service.
61. 1968 Cable television systems are developed.
62. 1971 Intel Corporation develops the first single-chip microprocessor, the 4004.
63. 1972 Motorola demonstrates the cellular telephone to the FCC.
64. 1976 Personal computers are developed.
65. 1979 64-kb random access memory ushers in the era of very large-scale integrated (VLSI) circuits.
66. 1980 Bell System FT3 fiber-optic communication is developed.
67. 1980 Compact disk is developed by Philips and Sony.
68. 1981 IBM PC is introduced.
69. 1982 AT&T agrees to divest its 22 Bell System telephone companies.
70. 1984 Macintosh computer is introduced by Apple.
71. 1985 FAX machines become popular.
72. 1989 Global positioning system (GPS) using satellites is developed.
73. 1995 The Internet and the World Wide Web become popular.
74. 2000s Era of digital signal processing with microprocessors, digital oscilloscopes, digitally tuned receivers, megaflop personal computers, spread spectrum systems, digital satellite systems, digital television (DTV), and personal communications systems (PCS).
75. 2010s Introduction of fourth-generation cellular radio. Technological convergence of communications-related devices---e.g., cell phones, television, personal digital assistants, etc.

Elements of Digital Communication Systems:

The following block diagram explains the sophisticated communication system. However, it is shown that the first block (**Format**), sixth and seventh blocks (**Pulse Modulate**) and (**Bandpass Modulate**) are the *Essential building blocks of digital communication system*, while other blocks are optional.



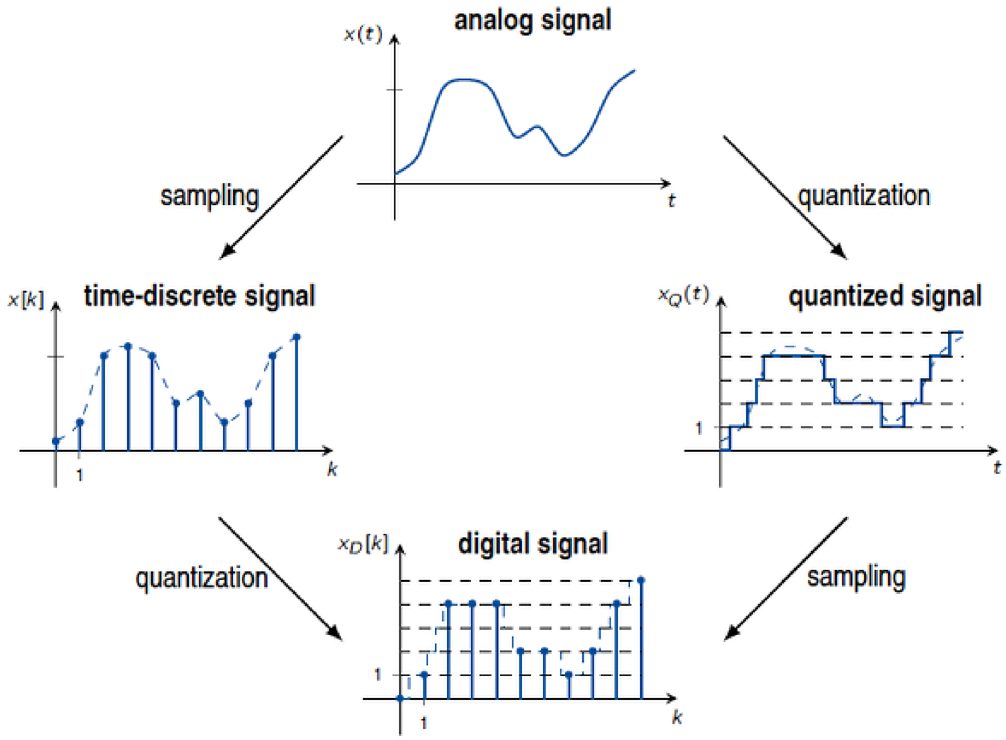
In this course we are interested in the essential blocks, thus, the first block which is **Format** can be seen in more details in the following figure;



Information Source: The sources of information maybe analog or digital, the analog signal must be sampled (according to the sampling theorem), quantized, and encoded, then it will be passed to the pulse modulator. While the digital data signal is either textual or digital audio or digital image, or digital video. These data are directly passed to the pulse modulator, while the textual information will be fed to the encoder to convert them to the appropriate binary data before feeding it to the pulse modulator.

Sample: Sampling is the first step to convert analog signals into digital one. The amplitudes of the samples now bear the information of the original continuous time signal. Hence, sampling converts the continuous-time signals, $x(t)$, to discrete-time signal $x[n]$.

Quantize: The input signal to the quantizer is discrete-time but continuous-amplitude, the quantizer will make limitation to the unlimited amplitudes of the signal such that the output signal has limited amplitudes as shown in the Figure below. *That is, quantization converts the discrete-time signal to digital signal, which is discrete in time and amplitude*.

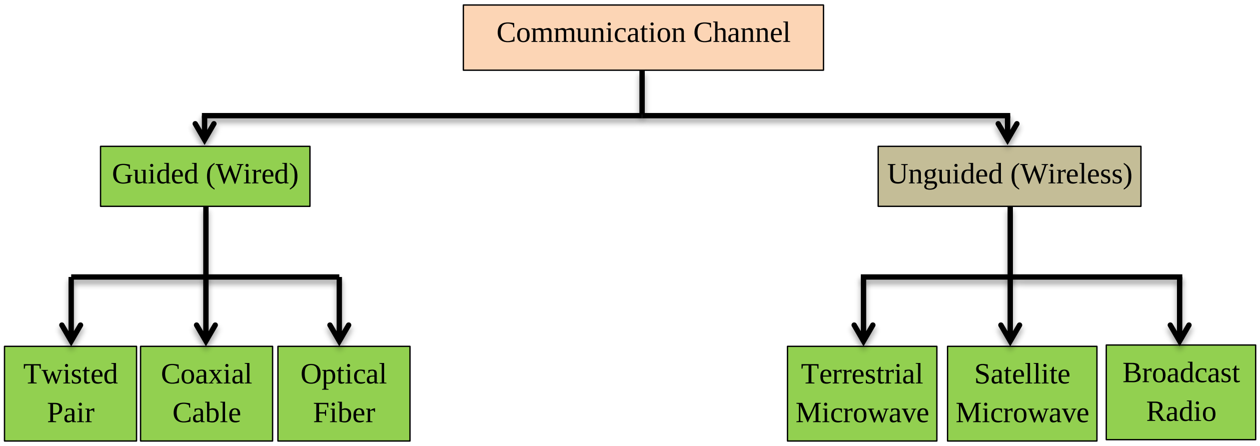


Encoder: the process of efficiently converting the output of whether analog or digital source into a sequence of binary digits is known as source encoding.

Pulse Modulate: Up to this step, the signal has been converted to a stream of binary digits, thus, it must be converted to pulses. Hence, line coding, i.e. representing the binary digits by pulses, will be employed as well as pulse shaping.

Transmit: This is the last step where the signal will be RF converted. In other words, the signal will be converted from baseband to passband using radio frequency (RF) carrier. As you studied this type of modulation, there are two main categories of RF modulation, Linear modulation and Angle modulation.

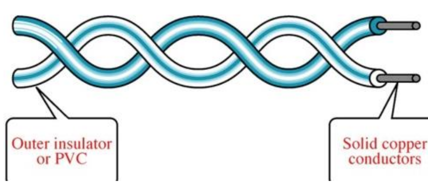
Channel: Transmission medium is called the channel. In other words, the media by which data travel from the transmitter to the receiver. Communication channels can be classified into two categories: Guided and Unguided.

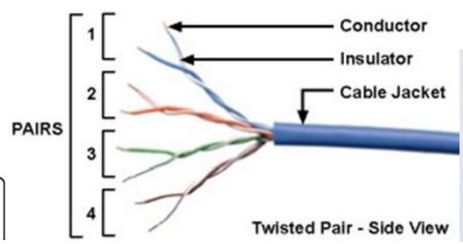


It is possible to pass the data through water, this type of channel called Underwater Acoustic Channel. Furthermore, the channel can be portable such as magnetic tapes and magnetic disks etc.

1. Twisted-Pair Cable:

- One of the wires carries signal, the other is used only as a ground reference.
- Number of twists per unit length determines the quality of the cable.





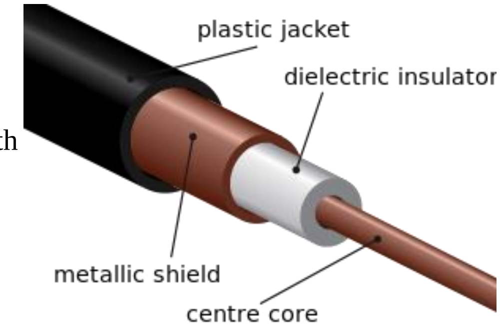
There are two types of Twisted Pair-Cables:

1. Shielded twisted-pair cable (STP)
2. Unshielded twisted-pair cable (UTP)

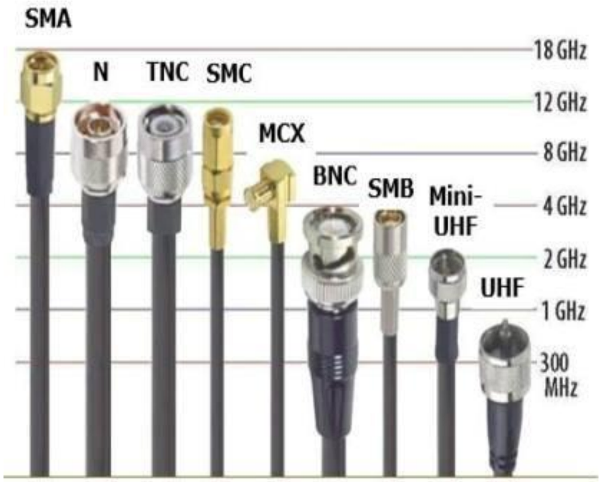
Categories of Twisted-Pair Cables:

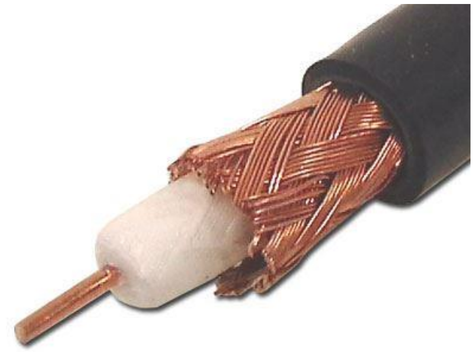
1. Category 1- 0.1 Mbps
2. Category 2- 2 Mbps
3. Category 3- 10 Mbps
4. Category 4- 20 Mbps
5. Category 5- 100 Mbps
6. Category 6- 200 Mbps
7. Category 7- 600 Mbps

2. Coaxial cable:



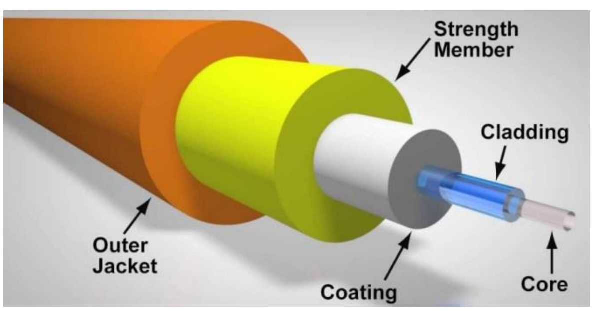
- Used for both analog and digital signals
- Effectively used at higher data rate and higher bandwidth
- For analog signals need amplifiers every few km
- For digital signals requires repeater every 1km

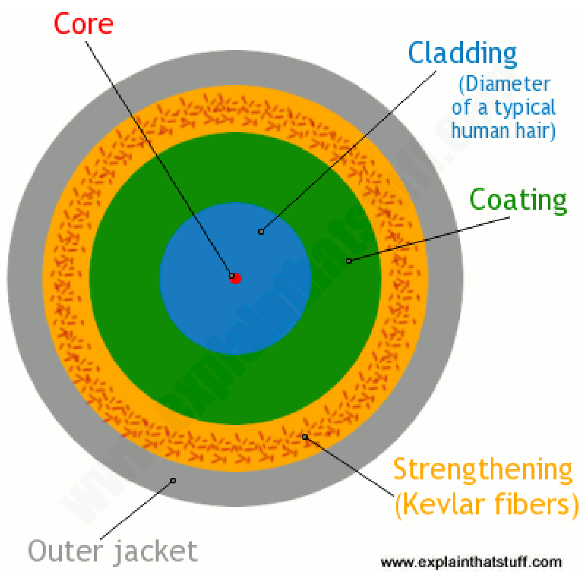




3. Optical Fiber:

A fiber-optic cable, also known as an optical fiber cable, is an assembly similar to an electrical cable, but containing one or more optical fibers that are used to carry light. The optical fiber elements are typically individually coated with plastic layers and contained in a protective tube suitable for the environment where the cable will be deployed. Different types of cable are used for different applications, for example long distance telecommunication, or providing a high-speed data connection between different parts of a building.



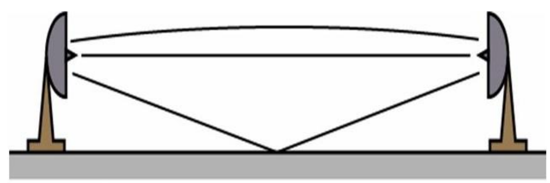


Differences between the three guided channels:

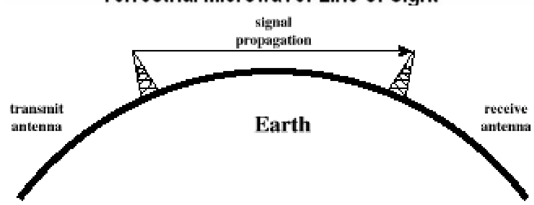
Coaxial Cable	Twisted-Pair Cable	Fiber-Optic Cable
Transmissions of ***signals are an electrical form*** over the inner conductor of the cable.	Transmissions of ***signals are an electrical form*** over the metallic conducting wires.	Transmissions of ***signals are an optical form*** over a glass of fiber.
Higher noise immunity than twisted-pair cable	**Low** noise immunity	**Highest** noise immunity
Moderate cost	Cheapest	Expensive
Moderately high bandwidth	Low bandwidth	Very high bandwidth
Low attenuation	Very high attenuation	Very low attenuation
Easy to install	Easy to install	Difficult to install
Get distributed by external magnetic field	Get distributed by external magnetic field	Not affected by the external magnetic field

4. Terrestrial Microwave:

- Requires fewer repeaters
- Use a parabolic dish to focus a narrow beam.
- 1-40 GHz frequencies

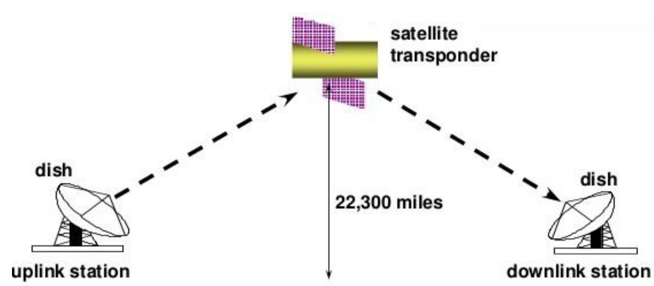


Terrestrial Microwave: Line of Sight

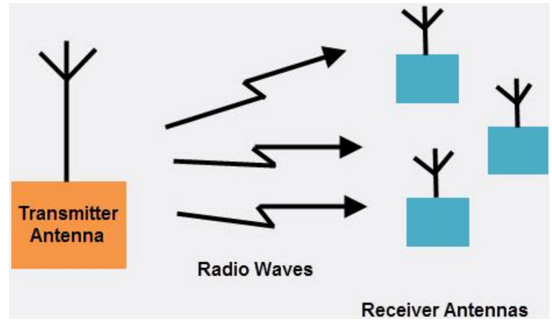


5. Satellite Communication:

- Receives on one frequency, and transmits on another frequency. For example: uplink 5.925-6.425 GHz & downlink 3.7-4.2 GHz
- Height 35,784km
- Spaced at least 3-4° apart



6. Broadcast Radio:



- Radio frequency range is 3kHz to 300GHz
- Use broadcast radio of 30MHz - 1GHz, for:
  - FM radio
  - UHF and VHF television
- Is a unidirectional
- Suffers from multipath interference
  - Reflections from land, water, other objects
- Are used for multicasts communications, such as radio and television, and paging system.

TRANSMISSION IMPAIREMENT

When signals transmit from one transmission medium to other, the signal that is received may differ from the signal that is transmitted, due to various transmission impairments.

- **Consequences:**
- For analog signals: degradation of signal quality
- For digital signals: **bit errors**

The most significant impairments include:

1. ***Attenuation*** (*Attenuation refers to* ***lose of energy by a signal during time***)
2. ***Distortion*** (*Distortion means* ***signal changes its form or shape***)
3. ***Noise*** (*Additional* ***unknown signals maybe added to the signal****, corrupt the signal*)

Sampling Theory:

- Signals are two types: continuous-time and discrete-time.
- Processing of discrete time signals is preferable to processing continuous-time signals because of the development of digital systems. Therefore, dealing with discrete-time signals becomes:
  - Inexpensive,
  - Light weight,
  - Programmable, and
  - Easily reproducible
- Therefore, we should be able to convert a continuous-time signal into discrete-time signal.
- Therefore, **sampling theorem may be viewed as a *bridge between continuous-time signals and discrete-time signals***.
- A continuous time signal is first converted to discrete time signal by sampling process.

A continuous-time signal may be completely represented in its samples and recovered back if the sampling frequency is $f_s \geq 2f_m$. Here f_s is the sampling frequency and f_m is the maximum frequency present in the signal.

Given a Continuous-time signal $x(t)$ then its sampled or the discrete-time version $x_\delta(t) = x(nT_s) = x[n]$ is:

$$x_\delta(t) = \sum_{n=-\infty}^{n=\infty} x(nT_s)\delta(t - nT_s)$$

$\boldsymbol{T_s = \frac{1}{F_s}}$ is the sampling interval and $\boldsymbol{F_s}$ is called ***Nyquist frequency*** *if it is the minimum sampling frequency*. It is known that $\delta(t - nT_s)$ is zero everywhere except at $t = nT_s$, then

$$x_\delta(t) = \sum_{n=-\infty}^{n=\infty} x(t)\delta(t - nT_s) = x(t) \sum_{n=-\infty}^{n=\infty} \delta(t - nT_s)$$

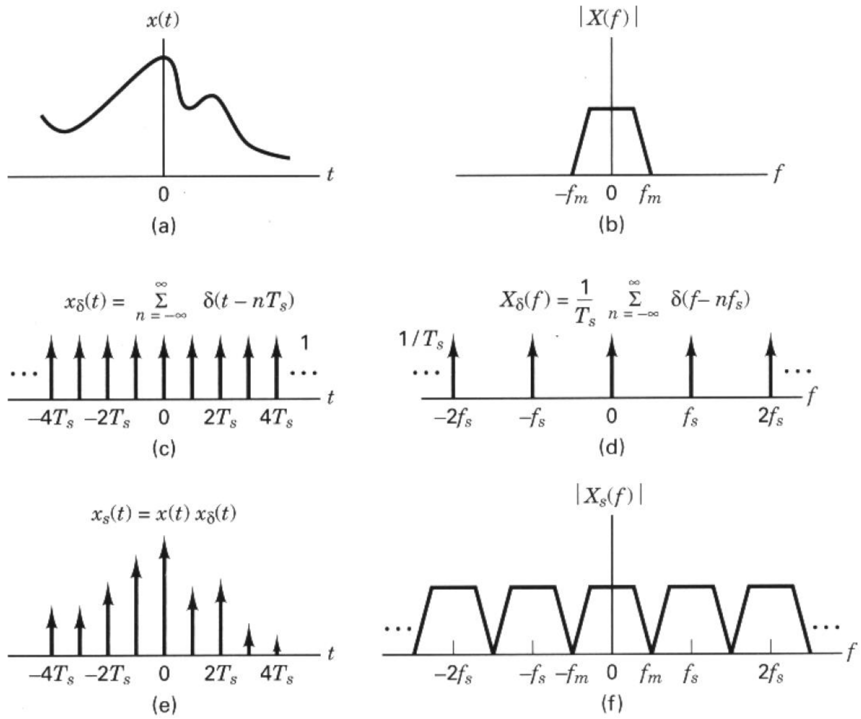
$$X_\delta(f) = X(f) * \left[F_s \sum_{n=-\infty}^{n=\infty} \delta(f - nF_s)\right]$$

But

$$X(f) * \delta(f - nF_s) = X(f - nF_s)$$

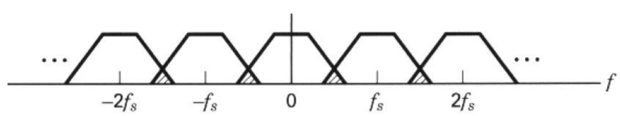
Then

$$\boxed{X_\delta(f) = F_s \sum_{n=-\infty}^{n=\infty} X(f - nF_s)}$$

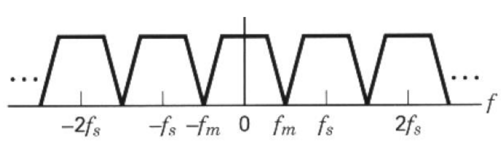


1. If $F_s < 2f_m$, the separate terms overlap, $x(t)$ cannot be recovered from $x_\delta(t)$. This is called aliasing frequency

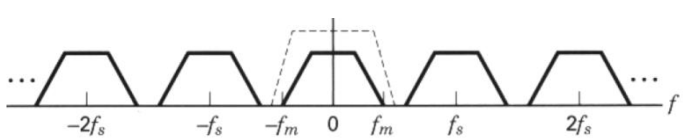
$$\boxed{f_a = F_s - f_m}$$



2. If $F_s = 2f_m$, the separate terms touch each other, $x(t)$ can be recovered from $x_\delta(t)$ using a sharp LPF.



3. If $F_s > 2f_m$, the separate terms touch each other, $x(t)$ can be recovered from $x_\delta(t)$ using LPF.



Reconstructing the Signal: reconstructing filter is simply a LPF which is also known as ***interpolation filter***. Interpolation or reconstructing filter has a bandwidth of $B\ Hz$:

$$\boxed{F_m \leq B \leq F_s - F_m}$$

- The process of reconstructing the signal from the discrete-time version is called ***interpolation***.
- Assuming ideal LPF:

$$H(f) = C\,\mathrm{rct}\left(\frac{f}{2B}\right) e^{-j2\pi f t_o}$$

In which $\boldsymbol{C}$ is constant and $F_m \le B \le F_s - F_m$, then

$$Y(f) = F_s C\, X(f) e^{-j2\pi f t_o}$$

In the time-domain, the last expression becomes (which is the reconstructed signal):

$$y(t) = F_s C\, x(t - t_0)$$

$$y(t) = \sum_{n=-\infty}^{n=\infty} x(nT_s) h(t - nT_s)$$

$$y(t) = 2BC \sum_{n=-\infty}^{n=\infty} x(nT_s)\, \mathrm{sinc}[2B(t - t_0 - nT_s)]$$

Since: $\boldsymbol{f_m = \frac{F_s}{2}}$, $\boldsymbol{C = T_s}$, assuming $\boldsymbol{t_0 = 0}$ for simplicity, then

$$y(t) = \sum_{n=-\infty}^{n=\infty} x(nT_s)\, \mathrm{sinc}[F_s(t - nT_s)]$$

BandPass Signal Sampling:

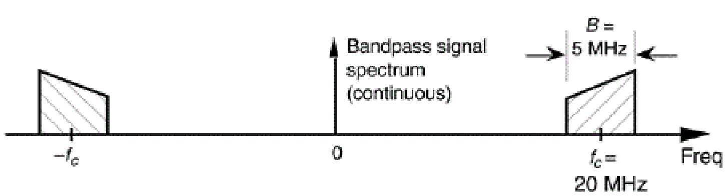
If a signal has spectrum $B\ Hz$ and upper frequency $F_H\ Hz$, then a rate $F_s\ Hz$ at which the signal can be sampled is

$$\boxed{\frac{2F_H}{K} \le F_s \le \frac{2(F_H - B)}{K - 1}}$$

Where

$$K \le \left\lfloor \frac{F_H}{B} \right\rfloor$$

Example: For the signal shown in the following figure, Calculate the sampling frequency.



Solution: the Bandwidth of the signal is $B = 5MHz$.

From the figure, the Highest frequency $F_H = F_c + \frac{B}{2} = 20M + \frac{5M}{2} = 22.5MHz$.

$$K \leq \left\lfloor \frac{F_H}{B} \right\rfloor = \left\lfloor \frac{22.5M}{5M} \right\rfloor = 4$$

$$\frac{2F_H}{K} \leq F_s \leq \frac{2(F_H - B)}{K - 1}$$

$$\frac{2(22.5M)}{4} \leq F_s \leq \frac{2(22.5M - 5M)}{3}$$

$$11.25MHz \leq F_s \leq 11.666MHz$$

Example 1: A continuous time signal $x(t) = 8\cos(200\pi t)$. Determine, (1) Minimum sampling rate (Nyquist rate to avoid aliasing), (2) If sampling frequency $f_s = 400Hz$, what is the discrete-time signal $x(n)$ or $x(nT_s)$ obtained after sampling? (3) If sampling frequency $f_s = 150Hz$, what is the discrete-time signal $x(n)$ or $x(nT_s)$ obtained after sampling? (4) What is the frequency $0 < f < f_s/2$ that yields samples identical to those obtained in part (3)?

Solution: $x(t) = 8\cos(200\pi t) \rightarrow f = 100Hz.$

(1) $f_s = 2f = 2 \times 100 = 200Hz.$
(2) $f_s = 400Hz \rightarrow x(nT_s) = x\left(\frac{n}{f_s}\right) = 8\cos\left(2\pi n\frac{100}{400}\right) = 8\cos\left(\frac{\pi n}{2}\right)$, so $\rightarrow x(n) = x(nT_s) = 8\cos\left(\frac{\pi n}{2}\right)$
(3) $f_s = 150Hz \rightarrow x(nT_s) = x\left(\frac{n}{f_s}\right) = 8\cos\left(2\pi n\frac{100}{150}\right) = 8\cos\left(\frac{4\pi n}{3}\right) = 8\cos\left(\frac{6\pi n}{3} - \frac{2\pi n}{3}\right)$

$$x(nT_s) = x(n) = 8\cos\left[\left(2\pi - \frac{2\pi}{3}\right)n\right] = 8\cos\left(\frac{2\pi n}{3}\right)$$

(4) $f_s = 150Hz \rightarrow x(nT_s) = x\left(\frac{n}{f_s}\right) = 8\cos(2\pi f t) = 8\cos\left(2\pi f\frac{fn}{150}\right)$,
From Part **(3)** $\frac{2\pi n}{3} = \frac{2\pi f n}{150} \rightarrow f = \frac{150}{3} = 50Hz \rightarrow x_4(t) = 8\cos(100\pi t)$

Example 2: An analog signal expressed as $x(t) = 3\cos(50\pi t) + 10\sin(300\pi t) - \cos(100\pi t)$. Calculate the Nyquist rate for this signal.

Solution: $x(t) = 3\cos(50\pi t) + 10\sin(300\pi t) - \cos(100\pi t)$

$x(t) = 3\cos(\omega_1 t) + 10\sin(\omega_2 t) - \cos(\omega_3 t)$

$\omega_1 = 50\pi \rightarrow f_1 = 25Hz$

$\omega_2 = 300\pi \rightarrow f_2 = 150Hz$

$\omega_3 = 100\pi \rightarrow f_3 = 50Hz$

Largest frequency is $f_2 = 150Hz$

Then $f_s = 2f_2 = 2 \times 150 = 300Hz$

Example 3: Find the Nyquist rate and the Nyquist interval for the signal $x(t) = \frac{1}{2\pi}\cos(4000\pi t)\cos(100\pi t)$.

Solution: Since $2\cos(A)\cos(B) = \cos(A+B) + \cos(A-B)$

$$\therefore\ x(t) = \frac{1}{2\pi}\cdot\frac{2}{2}\cos(4000\pi t)\cos(1000\pi t) = \frac{1}{4\pi}[2\cos(4000\pi t)\cos(1000\pi t)]$$

$$= \frac{1}{4\pi}[\cos(4000\pi t + 1000\pi t) + \cos(4000\pi t - 1000\pi t)]$$

$$= \frac{1}{4\pi}[\cos(5000\pi t) + \cos(3000\pi t)]$$

$$\omega_1 = 2\pi f_1 = 5000\pi\ \rightarrow f_1 = 2500Hz$$

$$\omega_2 = 2\pi f_2 = 3000\pi\ \rightarrow f_2 = 1500Hz$$

Largest frequency is $f_1 = 2500Hz$, Then $f_s = 2f_1 = 2\times 2500 = 5000Hz$ (is the Nyquist Rate)

$T_s = \frac{1}{f_s} = \frac{1}{5000} = 0.2\times 10^{-3}\ sec$ (is the Nyquist Period).

Example 4: Determine the Nyquist rate for a continuous-time signal $x(t) = 6\cos(50\pi t) + 20\sin(300\pi t) - 10\cos(100\pi t)$.

Solution : In a general form, any continuous-time signal may be expressed as

$$x(t) = A_1\cos\omega_1 t + A_2\cos\omega_2 t + A_3\cos\omega_3 t$$

And the given signal is

$$x(t) = 6\cos 50\pi t + 2\sin 300\pi t - 10\cos 100\pi t$$

$$f_1 = \frac{\omega_1}{2\pi} = \frac{50\pi}{2\pi} = 25\text{ Hz}$$

$$f_2 = \frac{\omega_2}{2\pi} = \frac{300\pi}{2\pi} = 150\text{ Hz}$$

$$f_3 = \frac{\omega_3}{2\pi} = \frac{100\pi}{2\pi} = 50\text{ Hz}$$

Thus, the highest frequency component of the given message signal will be

$$f_{max} = 150\text{ Hz}$$

Therefore, Nyquist rate $= 2f_{max} = 2\times 150 = 300$ Hz **Ans.**