Wireless Communication Networks & Systems

Spring 2025

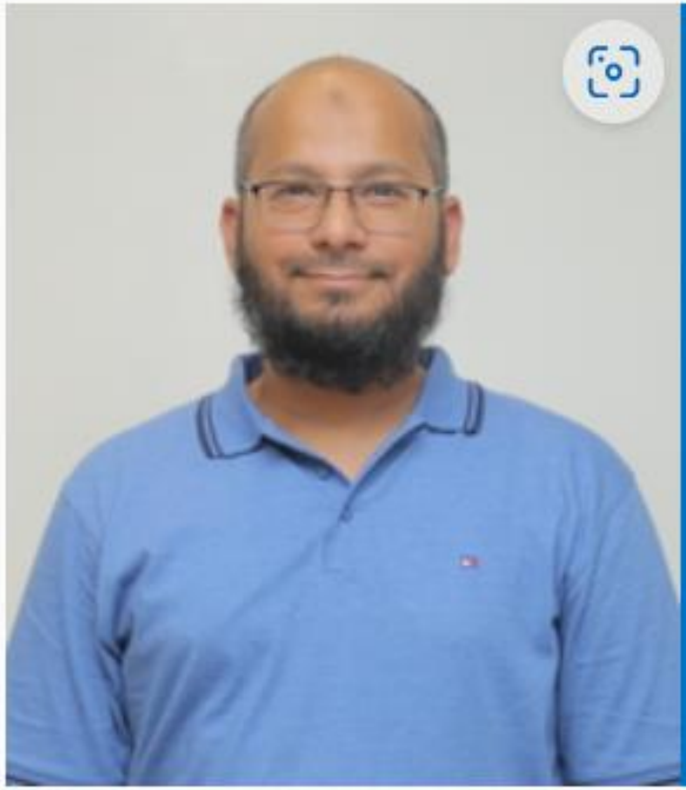
Week # 01

Lecture Highlights:

- Instructor Introduction
- Course Introduction
- Course Learning Outcomes (CLO)
- CLO mapping to Program Learning Outcome (PLO)
- Reading Material
- Course Grade Rubric & Assessments
- Beginning WCNS Module-I

Instructor Introduction:

Tariq Mumtaz, Ph.D.



ASSISTANT PROFESSOR, ELECTRICAL AND COMPUTER ENGINEERING

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Course Introduction:

- What is Network
- What is communication Network
- What is a Wireless Network
- Significance of Wireless Networks in the Digital world & IR 4.0
- Why EE/CE/CS should know about Wireless Network

A Network

A Network:

A **network** is a system of interconnected entities to share resources. In different contexts, it can refer to various types of connections:

- **Social Network**: A structure of individuals or organizations connected by social relationships, such as friends, colleagues, or business partners. It often involves the exchange of information, ideas, or resources.

- **Business Network**: A group of individuals or organizations that collaborate, share resources, or provide mutual support within an industry or community.

Communication Network

Communication Network:

The communication networks use traditional and modern technologies to facilitate voice, video, and data communication over long distances. Some examples of Networks are:

- **Computer Network**: A group of computers, servers, and other devices connected through communication channels to share data, resources, and services. Examples include local area networks (LANs), wide area networks (WANs), and the internet.

- **Telecommunication Network**: A system of transmitters, receivers, and communication channels (such as telephone lines) that enables the transmission of data or voice between different locations.

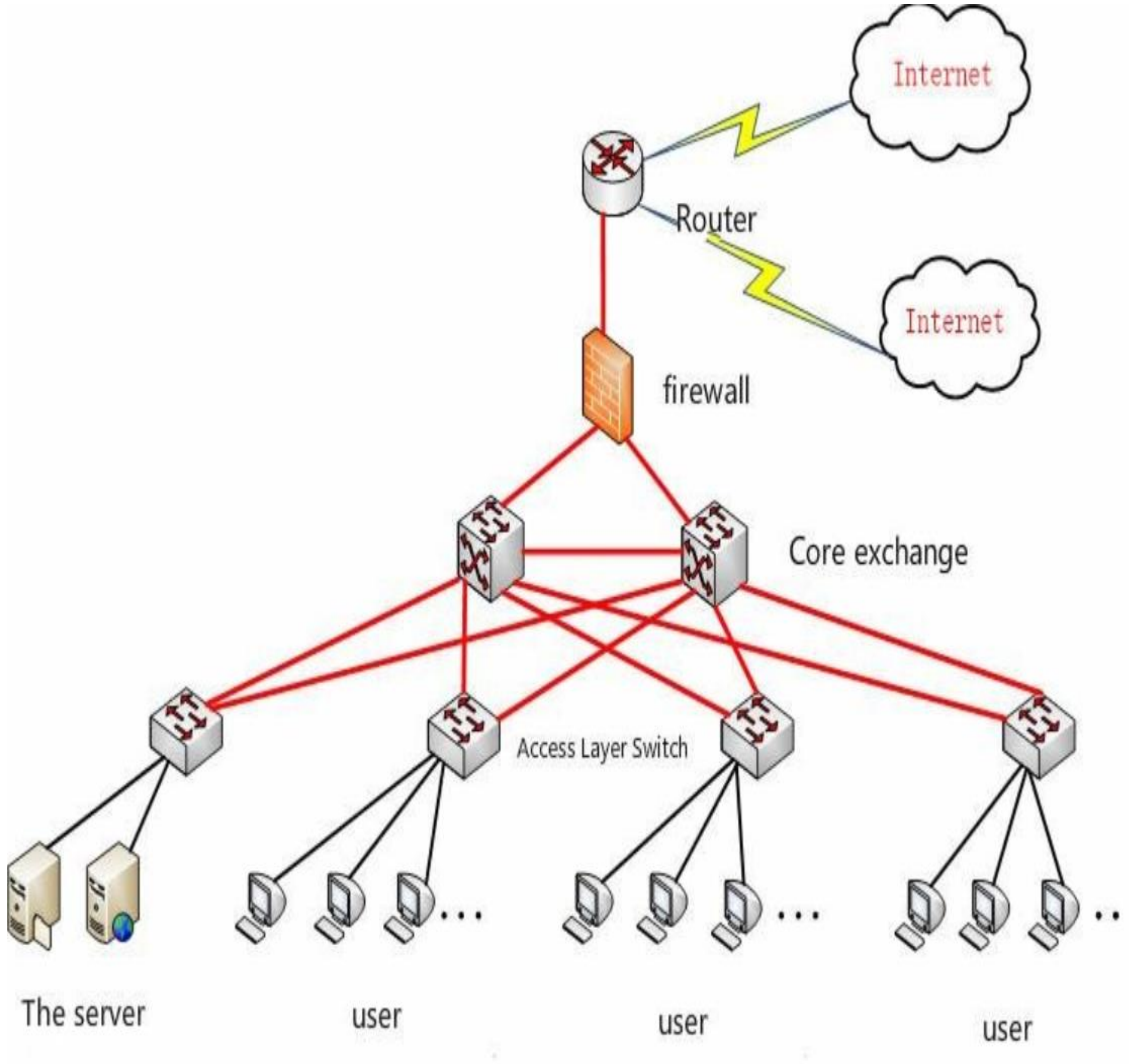
Wired Communication Network

Wired Communication Network:

Wired Networks need a physical medium for information transfer. Example are:

- **Landline Telephone system** has copper, DSL (Digital subscriber line), and fiber-optic cables to provide internet services and telephone connectivity.

- **Local Area Network (Campus Network)** has copper, coaxial, or Ethernet cables to provide computer/ device connectivity within specific premises.

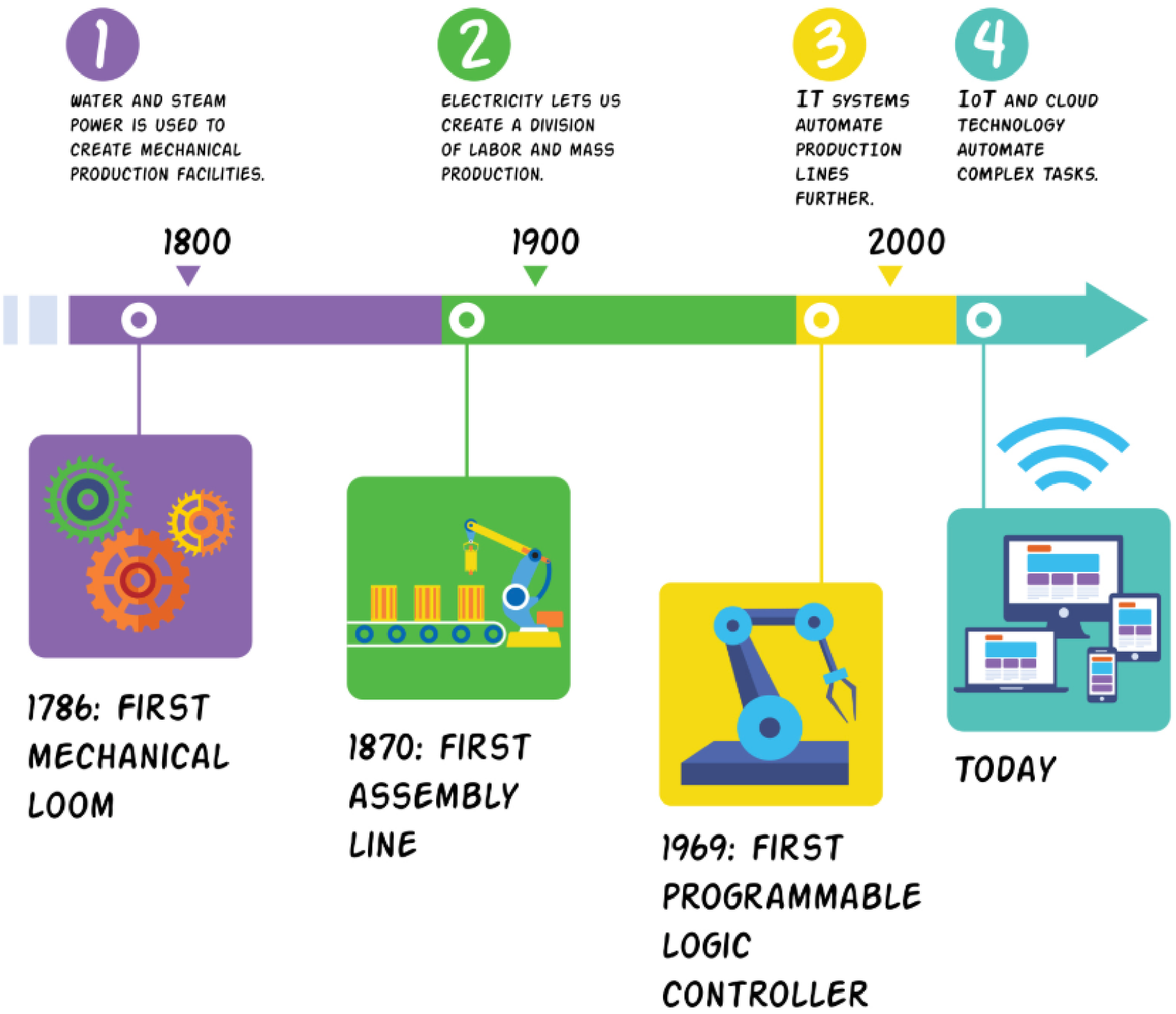


Wireless Communication Network

Wireless Communication Network:

- A **wireless network** is a type of network where devices communicate and exchange data without the use of physical cables or wires.
- It relies on radio waves, infrared signals, or other wireless technologies to transmit data over the air.
- The salient features of wireless networks are scalability, mobility and flexibility.

Industrial Revolution 4.0 (IR 4.0) :



- Wireless networks play a crucial role in **Industry 4.0** (IR 4.0) by enabling the seamless communication and connectivity required for the integration of advanced digital technologies in manufacturing and industrial environments.

- These networks allow devices, machines, and systems to communicate in real time, improving operational efficiency, automation, and data exchange

Industrial Revolution 4.0 (IR 4.0) :

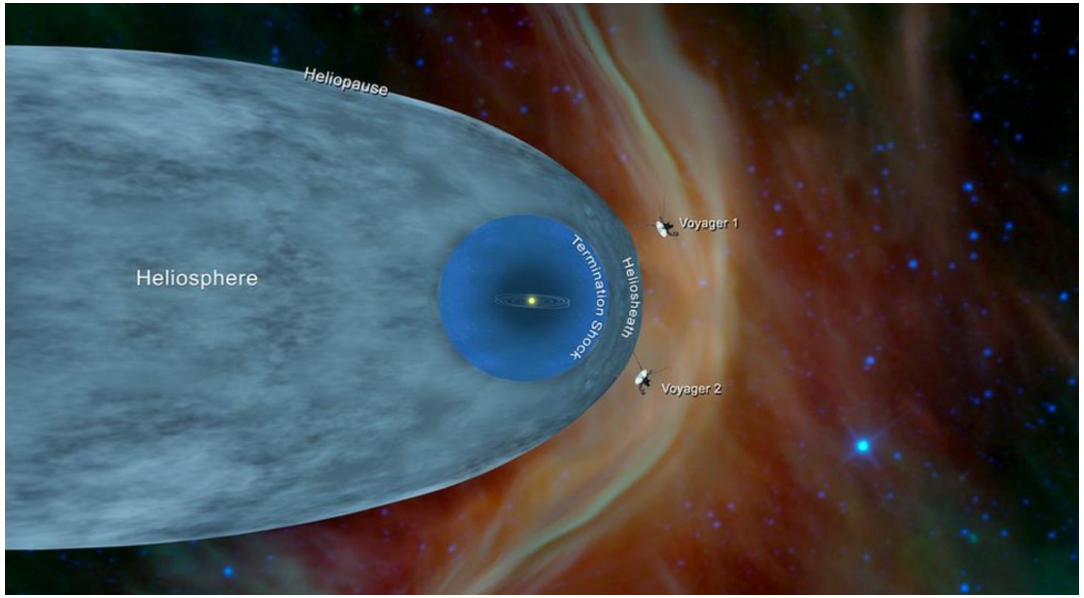
- A **Cyber-Physical System (CPS)** refers to the integration of **cyber (computational)** elements, such as software, algorithms, and data, with **physical processes** and systems.
- CPS is a fundamental concept in **Industry 4.0**, where it enables the automation, optimization, and real-time monitoring of industrial systems.

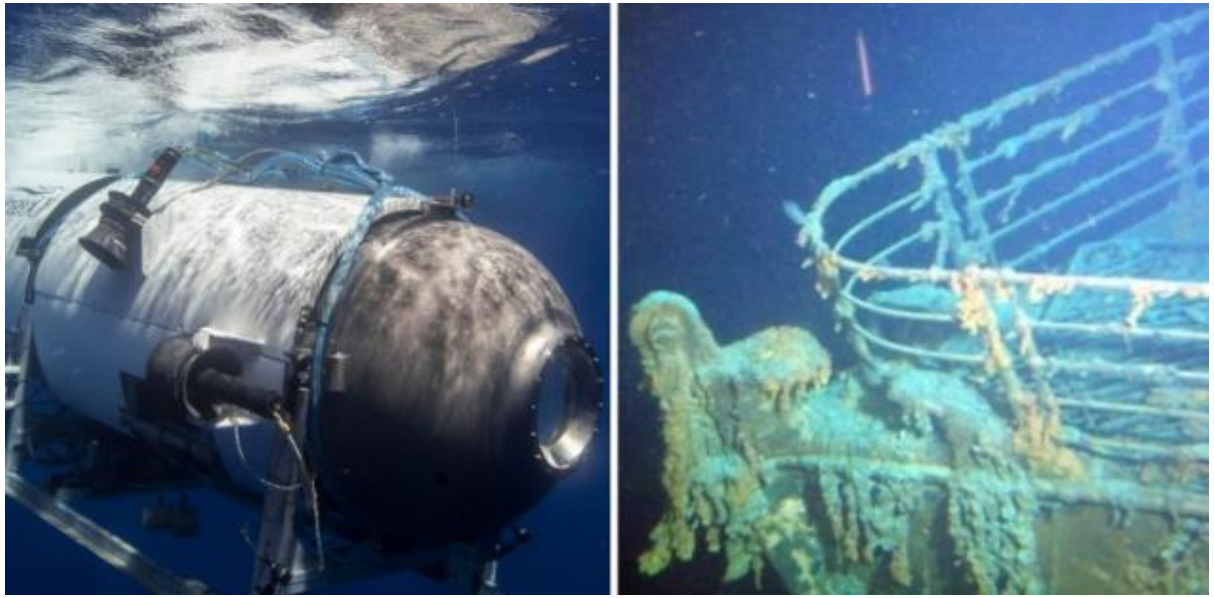
Components of Cyber-Physical Systems:

- **Sensors**: Devices that collect data from the physical environment (e.g., temperature, pressure, motion).
- **Actuators**: Devices that take actions based on commands or feedback, such as adjusting a valve, moving a robotic arm, or changing the speed of a motor.
- **Computational Units**: Software, algorithms, and computing resources that process the data and generate commands to control the physical components.
- **Wireless Networks**: Wireless networks that transmit data between sensors, actuators, and computational units. These networks ensure timely data exchange and synchronization.

Wireless Networks: Class Activity

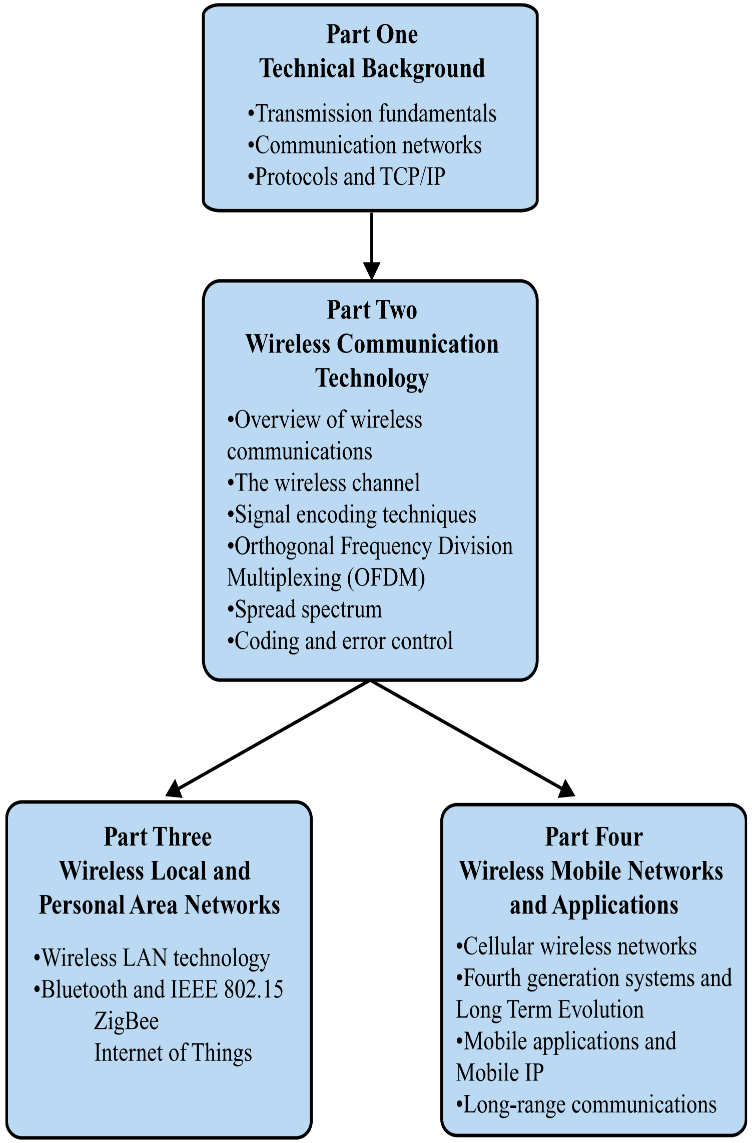
- Communication within our Planet
- Communication Under Water
- Communication for Space – Solar Systems and Beyond…





What we will cover in the WCNS course:

- <u>Part One – Technical Background</u>
  - Process of data communications, protocols, TCP/IP, and data networks.
- <u>Part Two – Wireless Communication Technology</u>
  - Overview of Wireless Communications
  - The process of sending a wireless signal and combating the effects of the wireless channel.
- <u>Part Three – Wireless Local Area Networks</u>
  - Details on IEEE project 802, WiFi, Bluetooth, the Internet of Things, and ZigBee.
- <u>Part Four – Wireless Mobile Networks</u>
  - Mobile cellular systems principles, 4G/5G/6G
  - Long-range communications using satellite (if time permits)

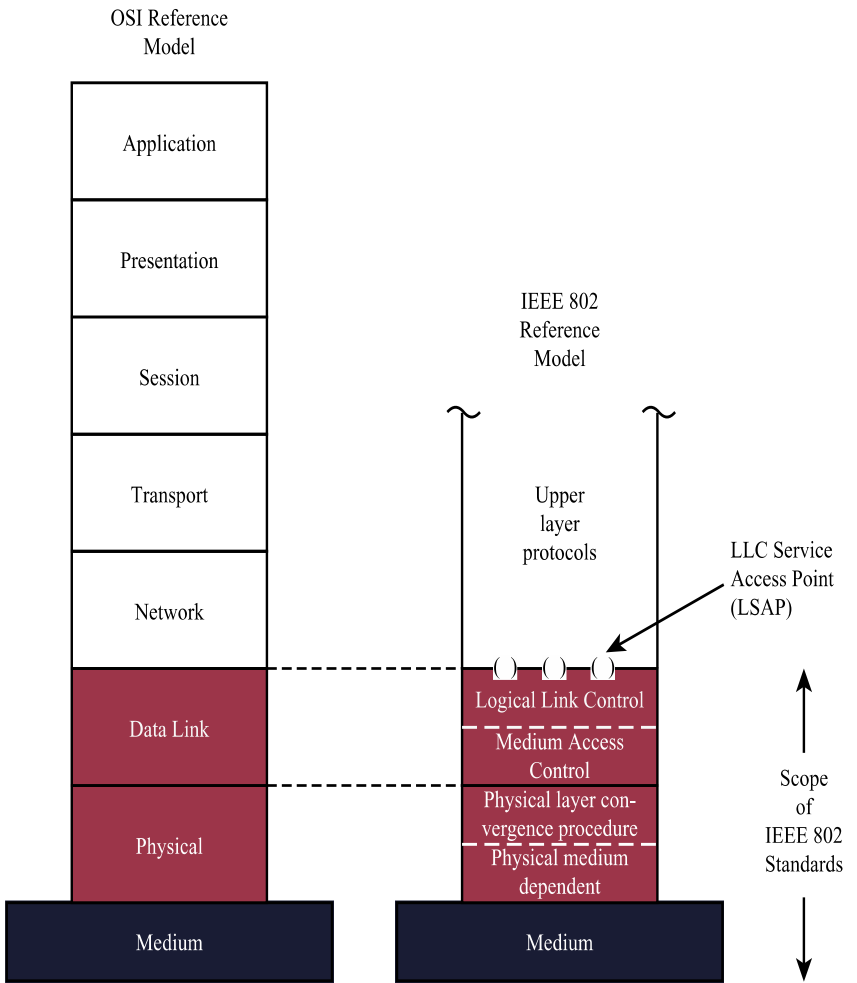


What we will cover in the WCNS course:

How do we learn about many Wireless Networks around us?

System Level Approach

- Architecture
- Protocols
- Devices/Tools (Recitations)



Course Learning Outcomes (CLOs):

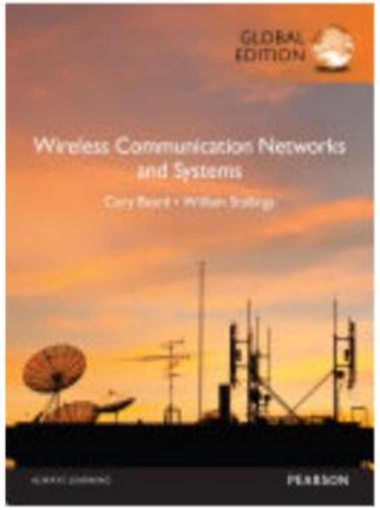
CLO # 01	Demonstrate an in-depth understanding of wireless network system’s architecture, protocols, and Services.	**Cog. 3**
CLO # 02	Explore advanced technologies and features in wireless networks related to coverage, capacity, interference management, and mobility.	**Cog. 3**
CLO # 03	Examine the evolution of Wi-Fi networks, highlighting architectural differences across its various standards.	**Cog. 4**
CLO # 04	Analyze key cellular concepts used in cellular networks and the architectural advancements in 5G and beyond.	**Cog. 4**

Program Learning Outcomes (PLOs):

Program Learning Outcomes (PLOs) mapped to Course Learning Outcomes (CLOs)					
	CLOs of the course are designed to cater following PLOs:				
	Distribution of CLO weightage for each PLO				
	CLO 1	CLO 2	CLO 3	CLO 4	
PLO 2	50%	50%			
PLO 4			50%	50%	

PLO 2: Problem Analysis
PLO 4: Investigation

Course Reading Material:



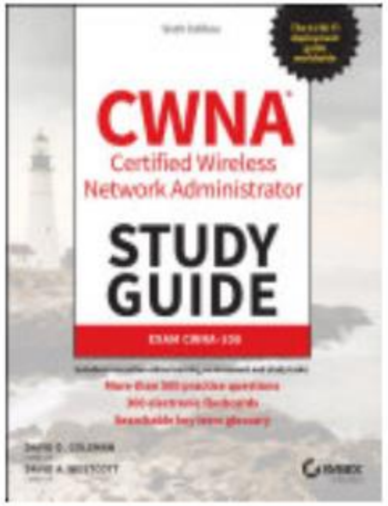
Wireless Communication Networks and Systems, Global Edition

ISBN: 9781292108728

Authors: Cory Beard, William Stallings

Publisher: Pearson Higher Ed

Publication Date: 2016-01-05



CWNA Certified Wireless Network Administrator Study Guide

ISBN: 9781119736332

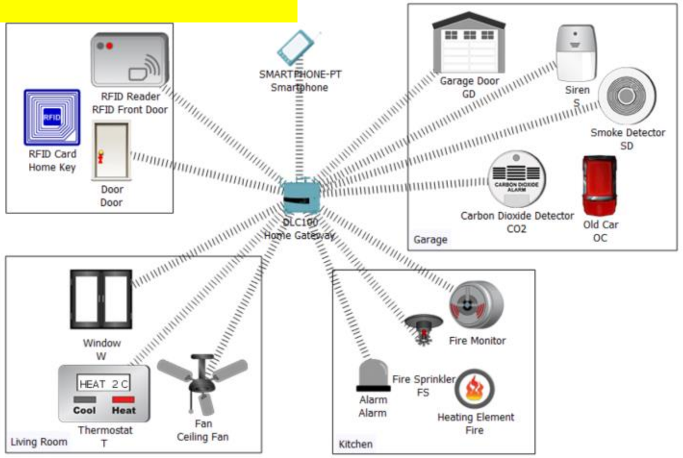
Authors: David A. Westcott, David D. Coleman

Publisher: John Wiley & Sons

Publication Date: 2021-02-17

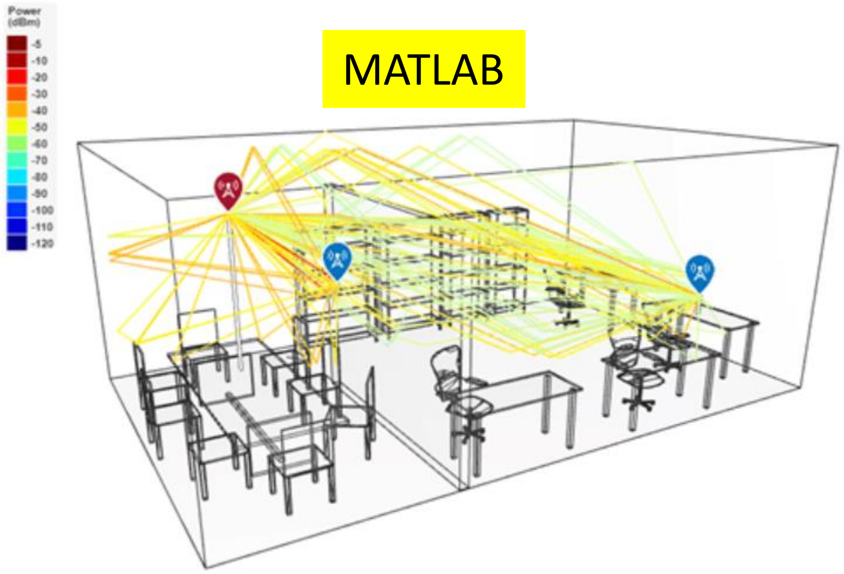
Recitation Sessions Objective:

Packet Tracer



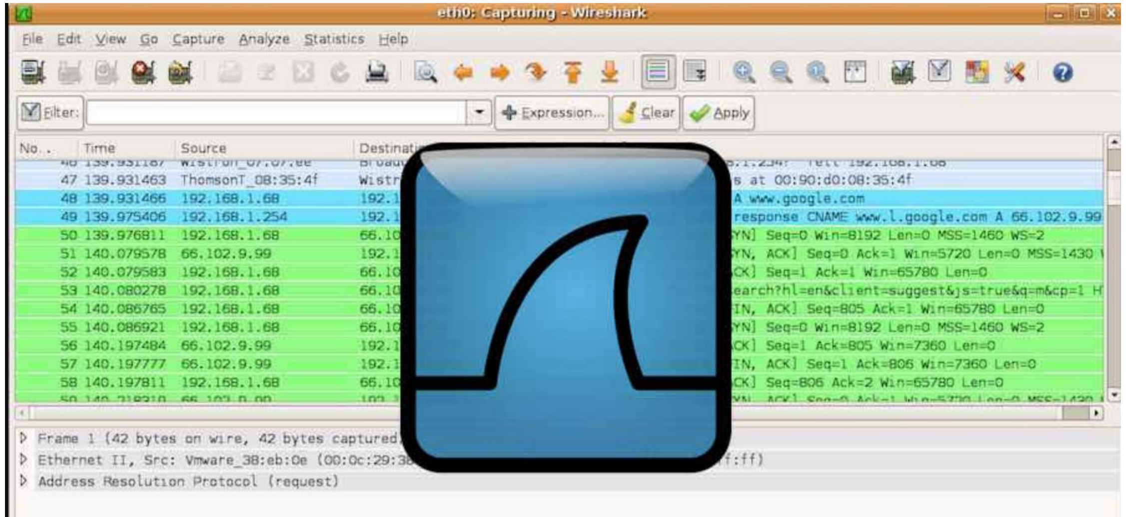
HU WiFi Network

MATLAB



Software-defined Radio (SDR)

Wireshark



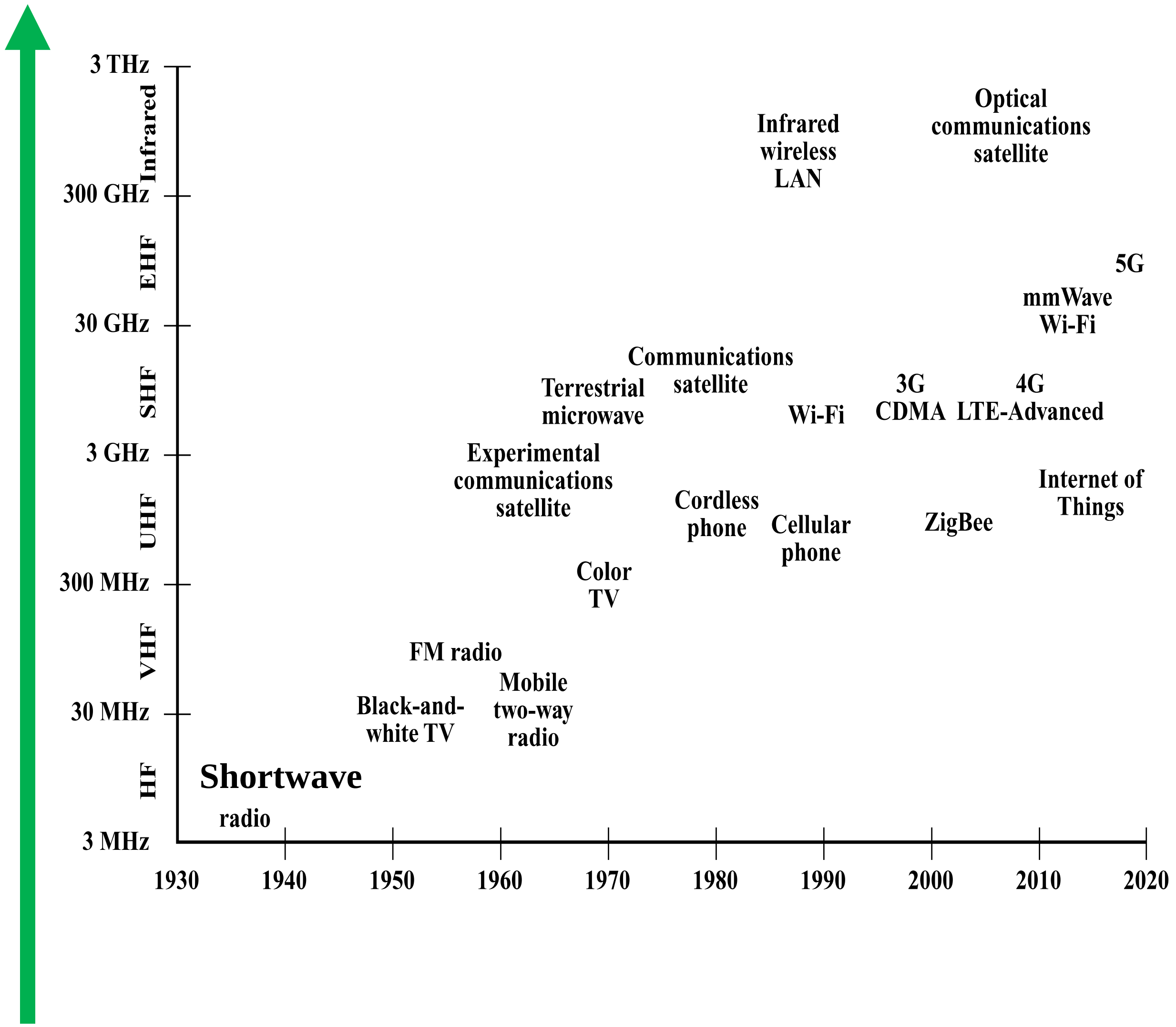
Course Grade Rubric & Assessments:

Homework:	20%	Inclusive Recitation session
Quiz:	20%	Inclusive Class participation
Midterm Exam:	20%	
Final Exam:	20%	
Research:	20%	Four milestones (5% each)

End of session # 01

Key Milestone of Wireless Networks:

- Guglielmo Marconi invented the wireless telegraph in 1896, Sent telegraphic signals across the Atlantic Ocean
- Communications satellites launched in the 1960s
- Advances in wireless technology
  - Radio, television, mobile telephone, mobile data, communication satellites
- More recently
  - Wireless networking, cellular technology, mobile apps, Internet of Things



Current Trends of Wireless Networks

- 5G and Wi-Fi 7 now being deployed
- The Internet of Things (IoT)
  - Healthcare, disaster recovery, energy savings, security and surveillance, environmental awareness, education, manufacturing, and many others
- Digital world
  - Home sensors collaborate with home appliances, HVAC systems, lighting systems, electric vehicle charging stations, and utility companies. Data mining and decision support with data analytics AI/ML

Wireless Network
Short Vs Long Range

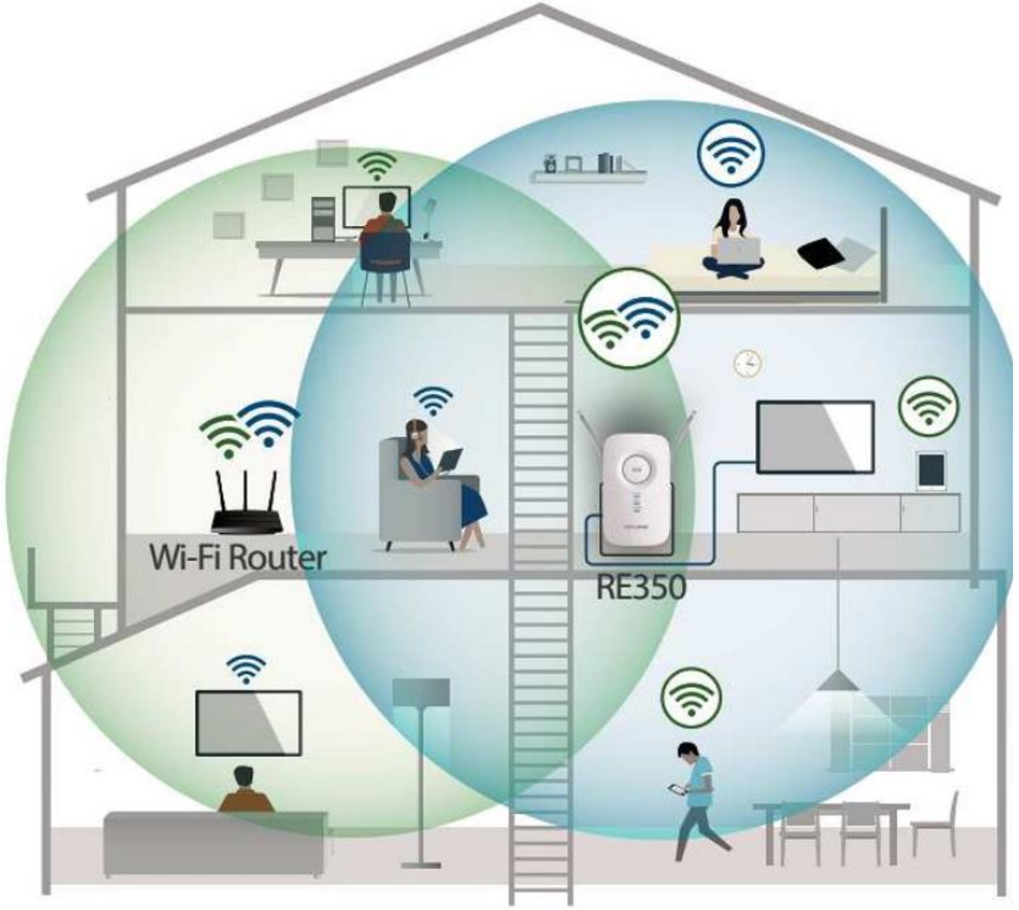
Short Range Wireless Networks:

These networks typically cover small areas, often within a building or nearby vicinity. Its range is typically up to 100 meters or less. Some important examples are:

- **Wi-Fi (802.11 standards):** Most commonly used for home and office internet connections. The range usually within 50 meters indoors and up to 100 meters outdoors.
- **Bluetooth:** Typically used for connecting devices like headphones, speakers, and peripherals, with a range up to 100 meters (depending on the Bluetooth class).
- **Zigbee:** A low-power wireless standard used for short-range applications like smart home devices, with a range of about 10-100 meters.

Applications:

- Home and office networks (Wi-Fi)
- Personal area networks (Bluetooth)
- Smart home devices (Zigbee)



Local Area Networks- LAN

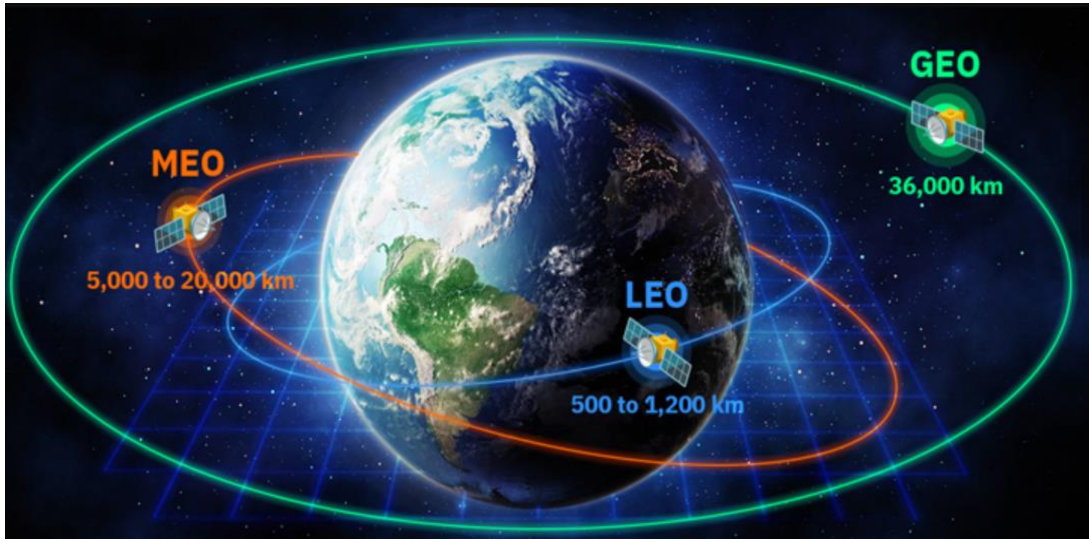
Long Range Wireless Networks:

These networks cover larger areas and can span between cities, regions, or even countries. Its typical range is several kilometers (a few miles) to thousands of kilometers. Some examples are:

- **Cellular networks (4G, 5G):** Cellular networks offer extensive coverage over long distances, including rural or distant areas
- **LoRaWAN (Long Range Wide Area Network):** A low-power, wide-area network used for IoT devices over distances of 2-5 km in urban areas and up to 15 km in rural areas.
- **Satellite Networks:** Provide global coverage for internet and communication, typically in remote or rural areas.

Applications:

- Mobile networks (cellular networks, 4G/5G)
- IoT and smart city infrastructure (LoRaWAN, Sigfox)
- Global communication (satellite networks)



Wide Area Networks- WAN

What we will cover in the WCNS course:

The Key types of wireless networks will be covered in this WCNS:

LAN:

•**Wi-Fi**: A common wireless networking technology used for local area networks (LANs), allowing devices to connect to the internet

•**Bluetooth**: A short-range wireless technology used to connect devices like headphones, keyboards, and smartphones.

WAN:

•**Cellular Networks**: Used by mobile phones and other devices to connect to the internet and make calls

•**Satellite Networks**: Provide wireless communication over long distances, such as in remote areas.

WCNS linked with other Courses:

WCNS connection with other ECE courses:

Signals & Systems

- What is Signal and its types (Analog, Digital and A2D)
- Signal representation in the time and frequency domain
- Signal design parameters - <u>Frequency and bandwidth</u>

Data Communication and Networking

- Network Architecture, Protocols, devices – TCP/IP Network Model
- Signal Transmission – Baseband and Broadband
- Signal Impairment during transmission (Attenuation, Noise, Interference)
- Quality of Service (QoS)
- Error control, Flow and Congestion control
- Security

WCNS linked with other Courses::

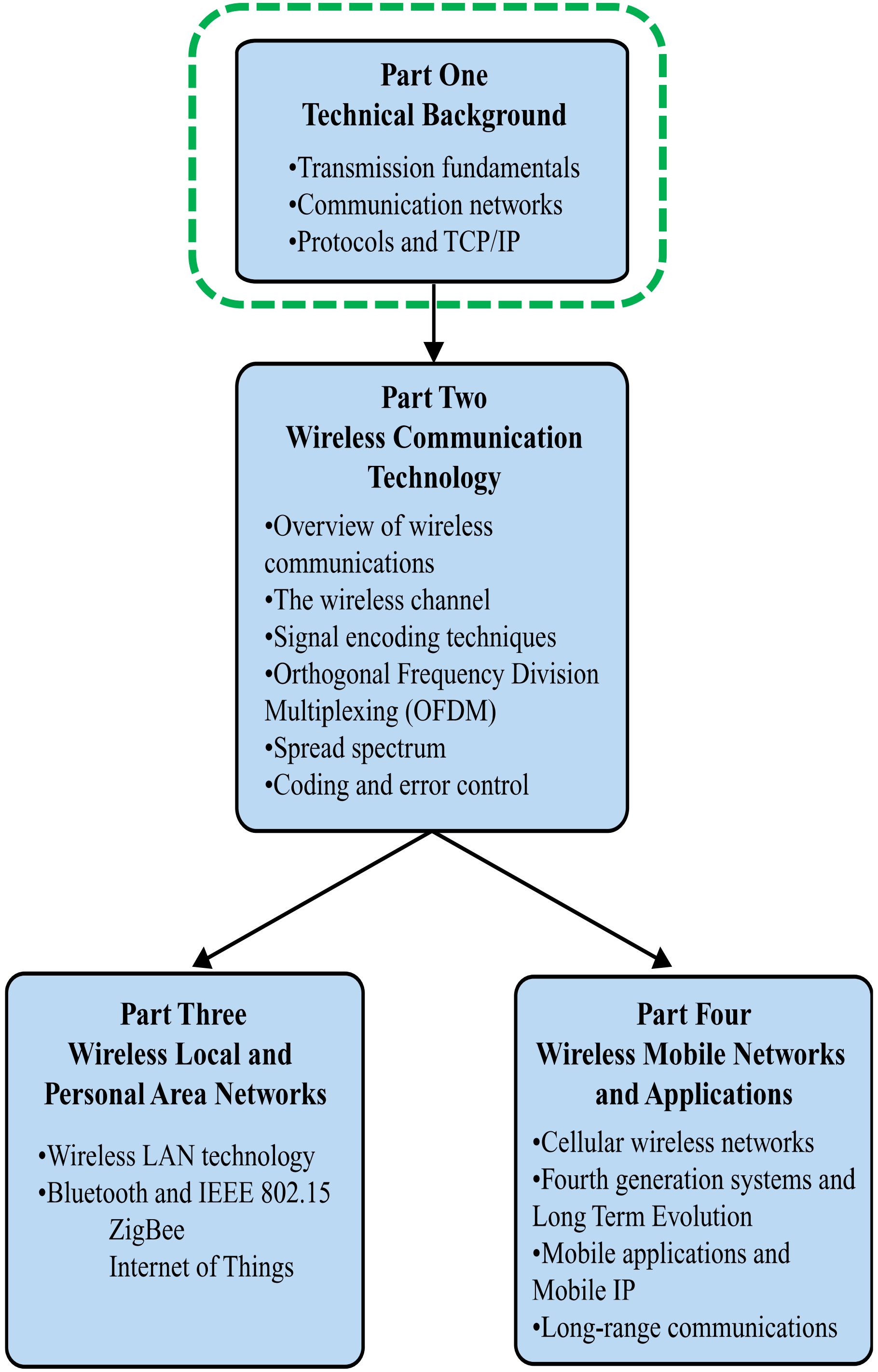
WCNS connection with other ECE courses:

MCI Lab:

- Lab 9: I^2C Communication
- Lab 10: Bluetooth Communication

  Wireless communication is swiftly replacing the wired connection when it comes to electronics and communication. Designed to replace cable connections HC-05 uses serial communication to communicate with the electronics. Usually, it is used to connect small devices like mobile phones using a short-range wireless connection to exchange files. It uses the 2.45GHz frequency band. The transfer rate of the data can vary up to 1Mbps and is in range of 10 meters. The HC-05 module can be operated within 4-6V of power supply. It supports baud rate of 9600, 19200, 38400, 57600, etc.

WCNS Module- I



Textbook Reference

<u>Module 01- Technical Background of Wireless Networks</u>

- Chapter 02 – The Signals and Transmission Fundamentals
- Chapter 03 – Communication Networks, QoS & Admission Control
- Chapter 04 – TCP/IP Network Model

The Signals and Transmission Fundamentals

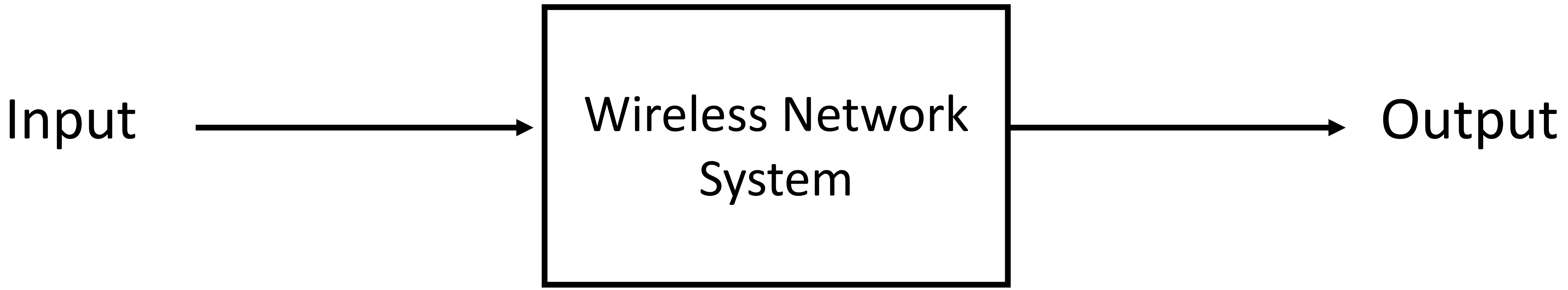
LEARNING OBJECTIVES

After studying this chapter, you should be able to:

- Distinguish between digital and analog information sources.
- Explain the various ways in which audio, data, image, and video can be represented by electromagnetic signals.
- Discuss the characteristics of analog and digital waveforms.
- Explain the roles of frequencies and frequency components in a signal.
- Identify the factors that affect channel capacity.
- Compare and contrast various forms of wireless transmission.

Wireless Networks Systems

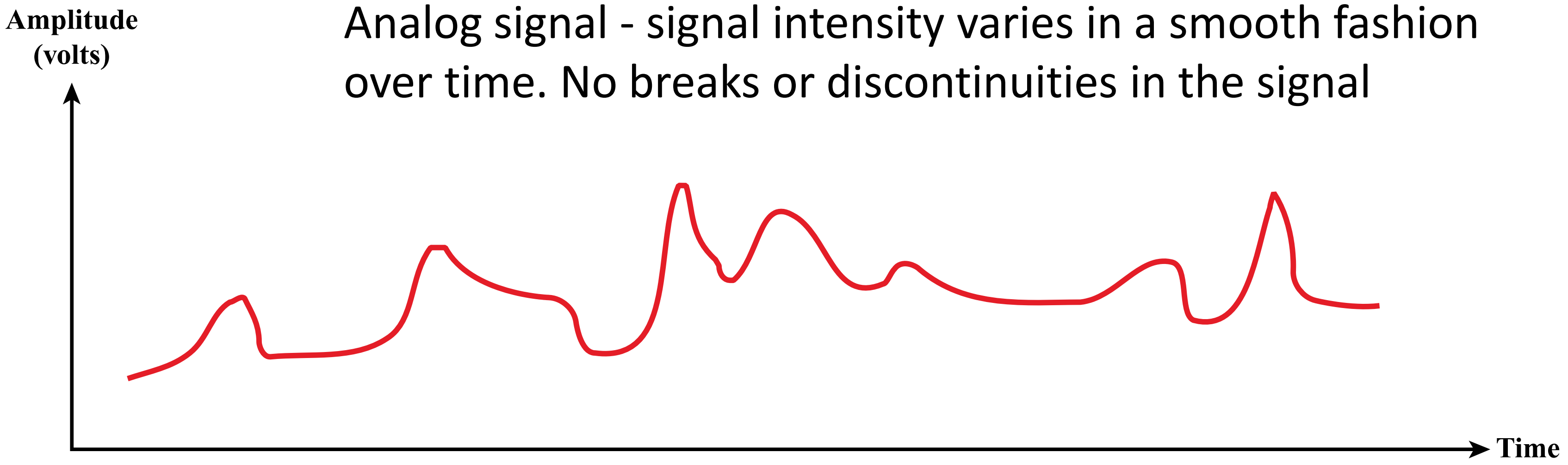
- Input
- Output
- System's Main building Blocks



Input/Output of the Wireless Networks: The Signal

Time domain representation of Signals

Analog signal - signal intensity varies in a smooth fashion over time. No breaks or discontinuities in the signal



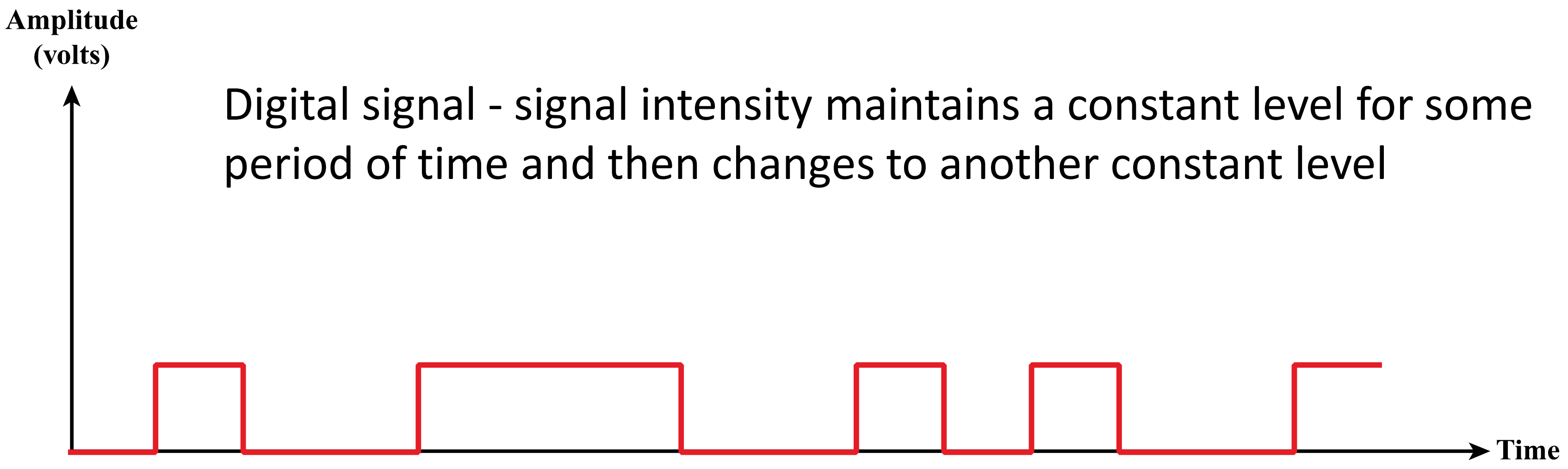
(a) Analog

Examples:

Analog
- Video
- Audio

Digital
- Text
- Integers

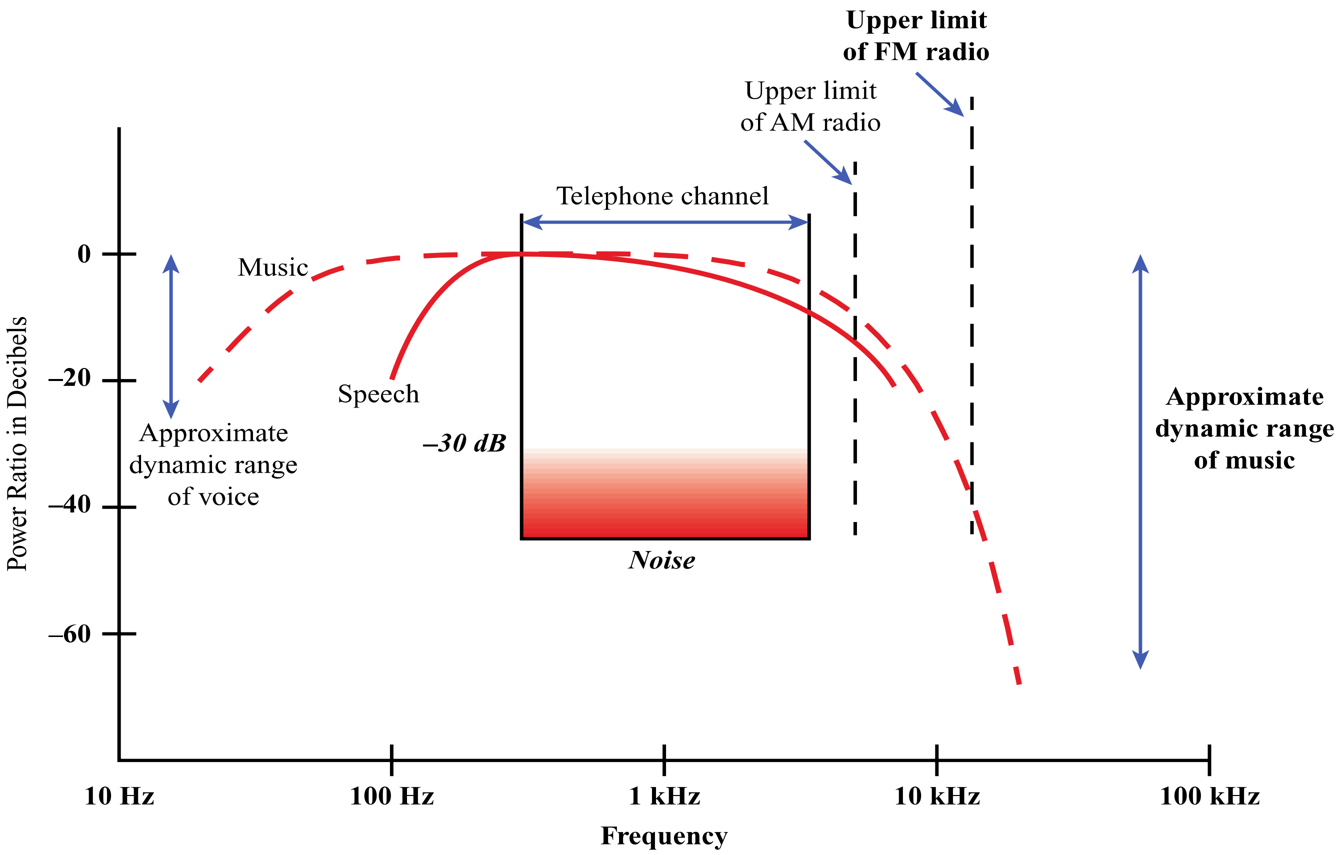
Digital signal - signal intensity maintains a constant level for some period of time and then changes to another constant level



(b) Digital

Frequency domain representation of Signals

Spectrum of Speech and Music

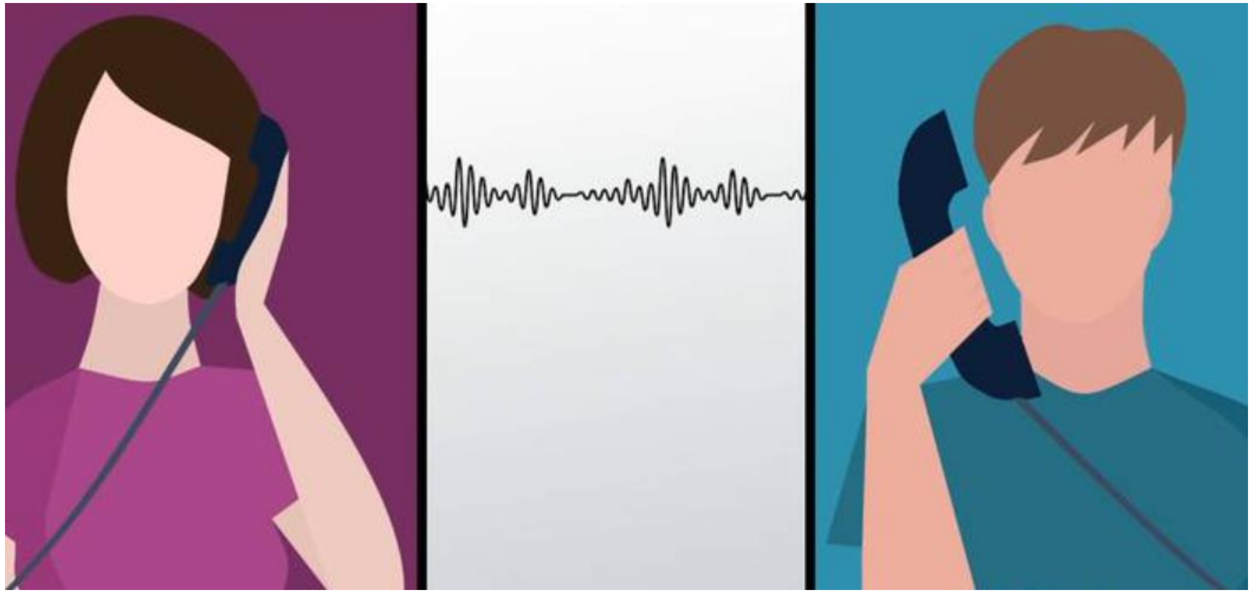


- Spectrum - range of frequencies that a signal contains
- Absolute bandwidth - width of the spectrum of a signal
- Effective bandwidth (or just bandwidth) – a narrow band of frequencies that most of the signal's energy is contained in

Analog Signals

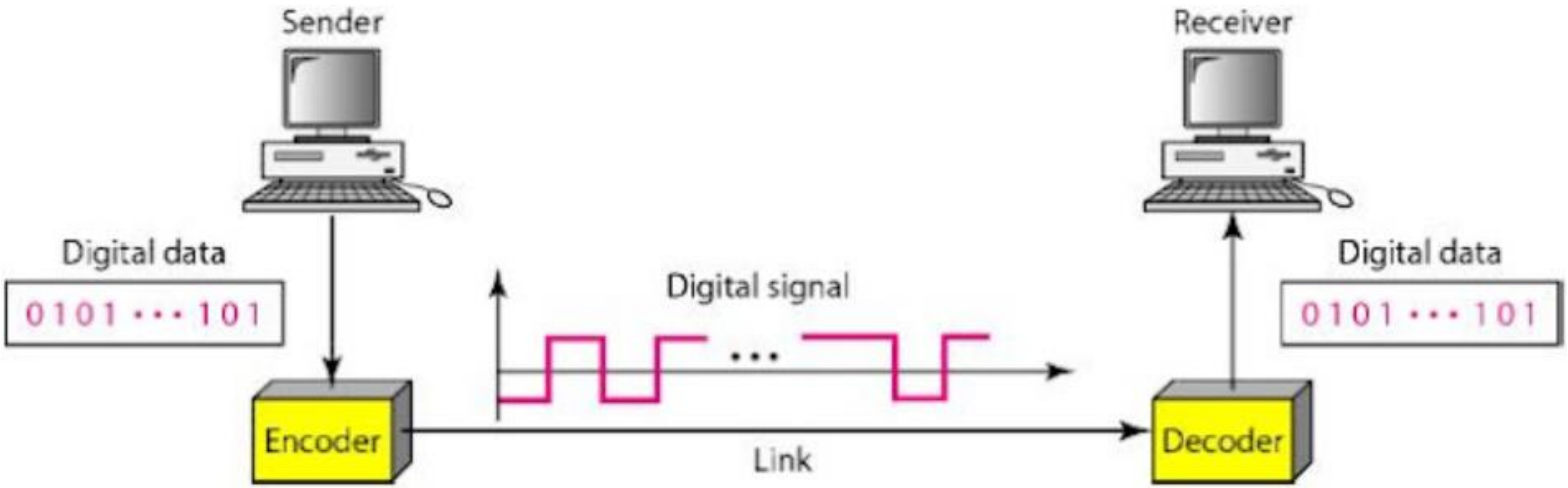
- A continuously varying electromagnetic wave that may be propagated over a variety of media, depending on frequency

- Examples of media:
  - Copper wire media (twisted pair and coaxial cable)
  - Fiber optic cable
  - Atmosphere or space propagation

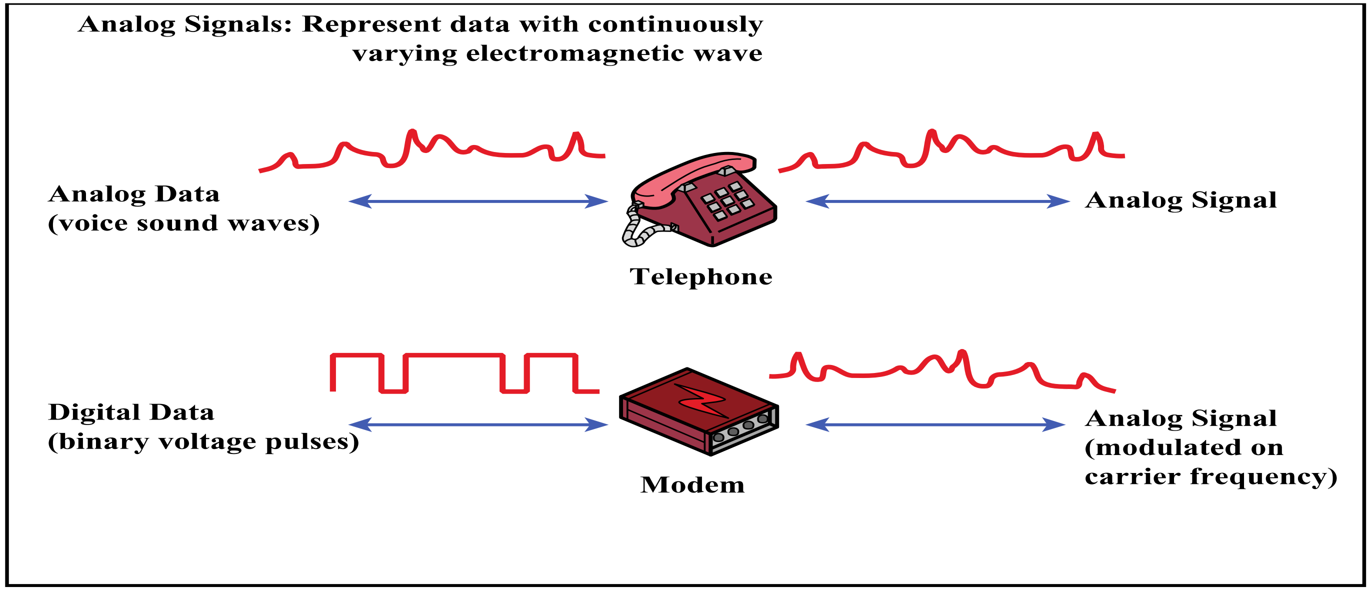


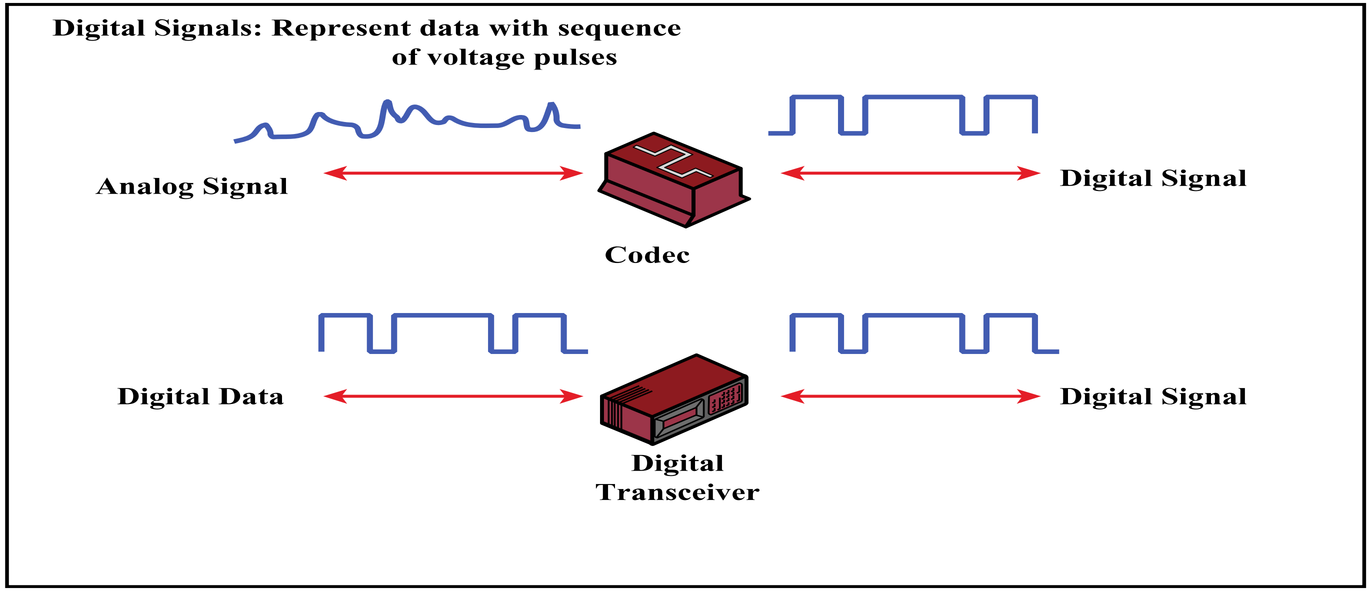
Digital Signals

- A sequence of voltage pulses that may be transmitted over a copper wire medium
- Less susceptible to noise interference but suffer more from attenuation

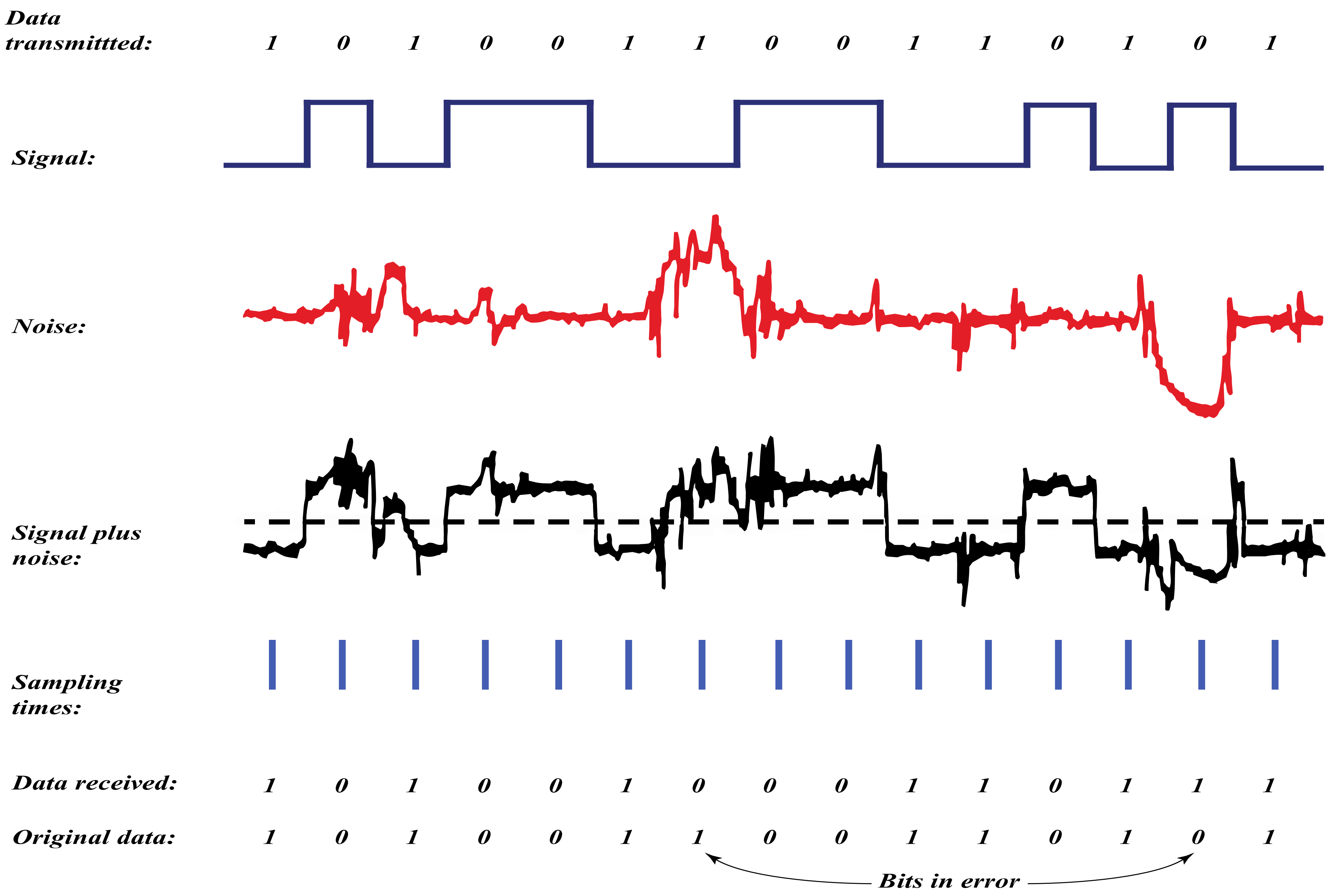


Combination of Data and Signal Combinations





Effect of Noise on Digital Signal



Key factors associated with channel

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

Channel Capacity and its Limits

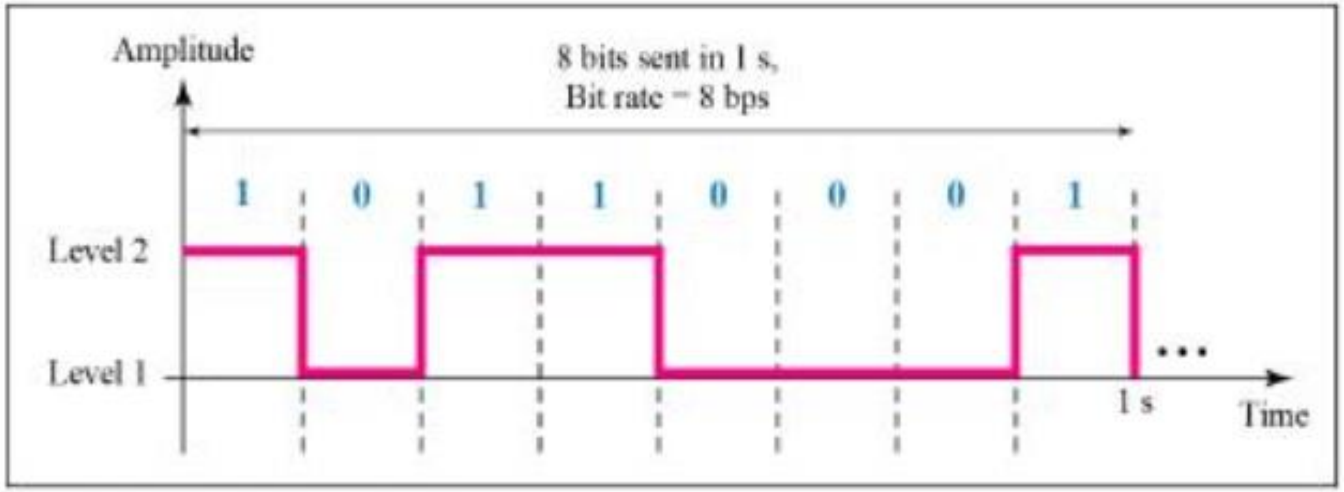
- Channel Capacity – the maximum rate at which data can be transmitted over a given communication path, or channel, under given conditions
- Main channel impairments are: Attenuation, Noise, and Interference.
- Impairments, such as noise, limit the data rate that can be achieved. For digital data, to what extent do impairments limit data rate?

Channel Capacity under Noise Free Transmission conditions

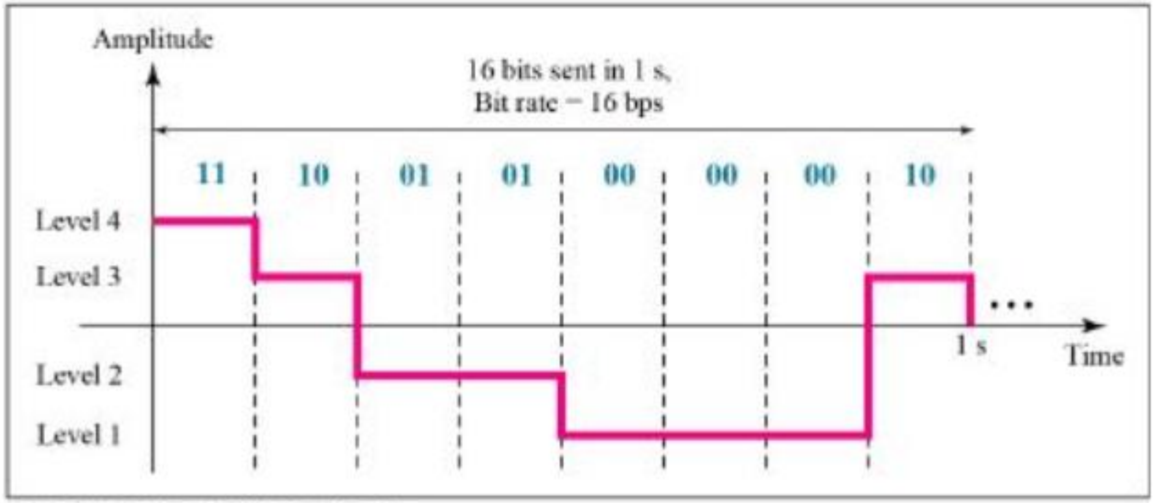
<u>Nyquist Bandwidth Formula:</u> $$C = 2B\log_2 M$$

Here,

- C: Channel capacity (Bits/sec)
- B: Channel Bandwidth (Hertz)
- M: The number of discrete signal elements or voltage levels



a. A digital signal with two levels



b. A digital signal with four levels

Channel Capacity under Noisy Transmission conditions

Shannon Capacity Formula: $$C = B\log_2(1+\text{SNR})$$

Represents the theoretical maximum that can be achieved.

Here,

- C: Channel capacity (Bits/sec)
- B: Channel Bandwidth (Hertz)
- SNR: Signal to Noise ration (in decimal)

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
- SNR sets upper bound on achievable data rate

Example of Shannon Formulations

Example 2.1 Let us consider an example that relates the Nyquist and Shannon formulations. Suppose that the spectrum of a channel is between 3 MHz and 4 MHz and $SNR_{dB} = 24$ dB. Then

$$B = 4\,\text{MHz} - 3\,\text{MHz} = 1\,\text{MHz}$$

$$SNR_{dB} = 24\text{ dB} = 10\log_{10}(SNR)$$

$$SNR = 251$$

Using Shannon's formula,

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

This is a theoretical limit and, as we have said, is unlikely to be reached. But assume we can achieve the limit. Based on Nyquist's formula, how many signaling levels are required? We have

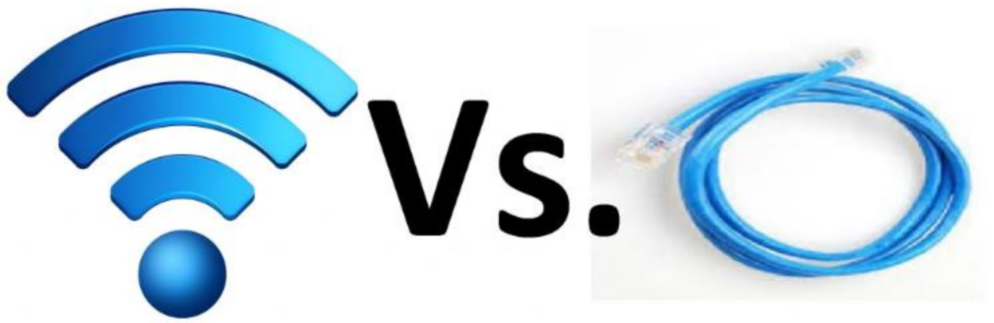
$$C = 2B\log_2 M$$

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

$$4 = \log_2 M$$

$$M = 16$$

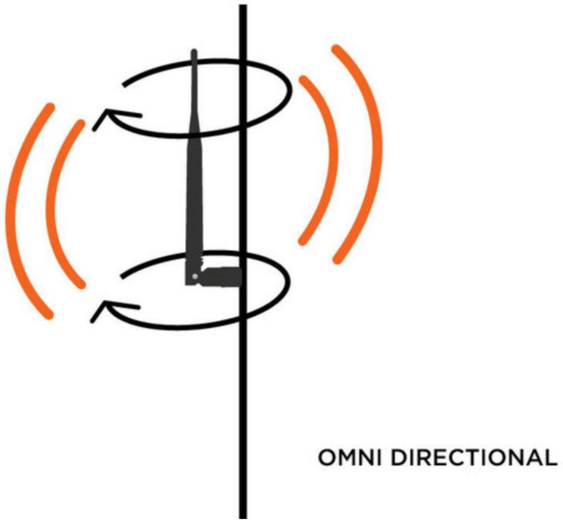
Classifications of Transmission Media

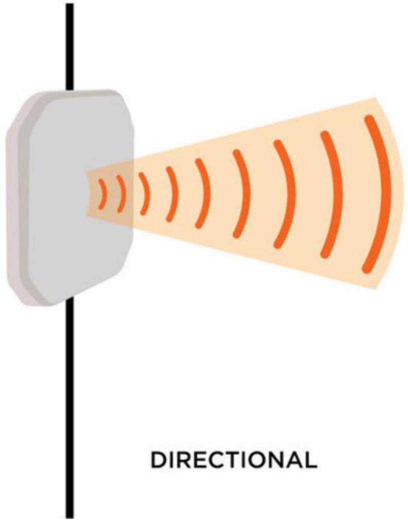


- Transmission Medium
  - Physical path between transmitter and receiver
- Guided Media
  - Waves are guided along a solid medium
  - E.g., copper twisted pair, copper coaxial cable, optical fiber
- Unguided Media
  - Provides means of transmission but does not guide electromagnetic signals
  - Usually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

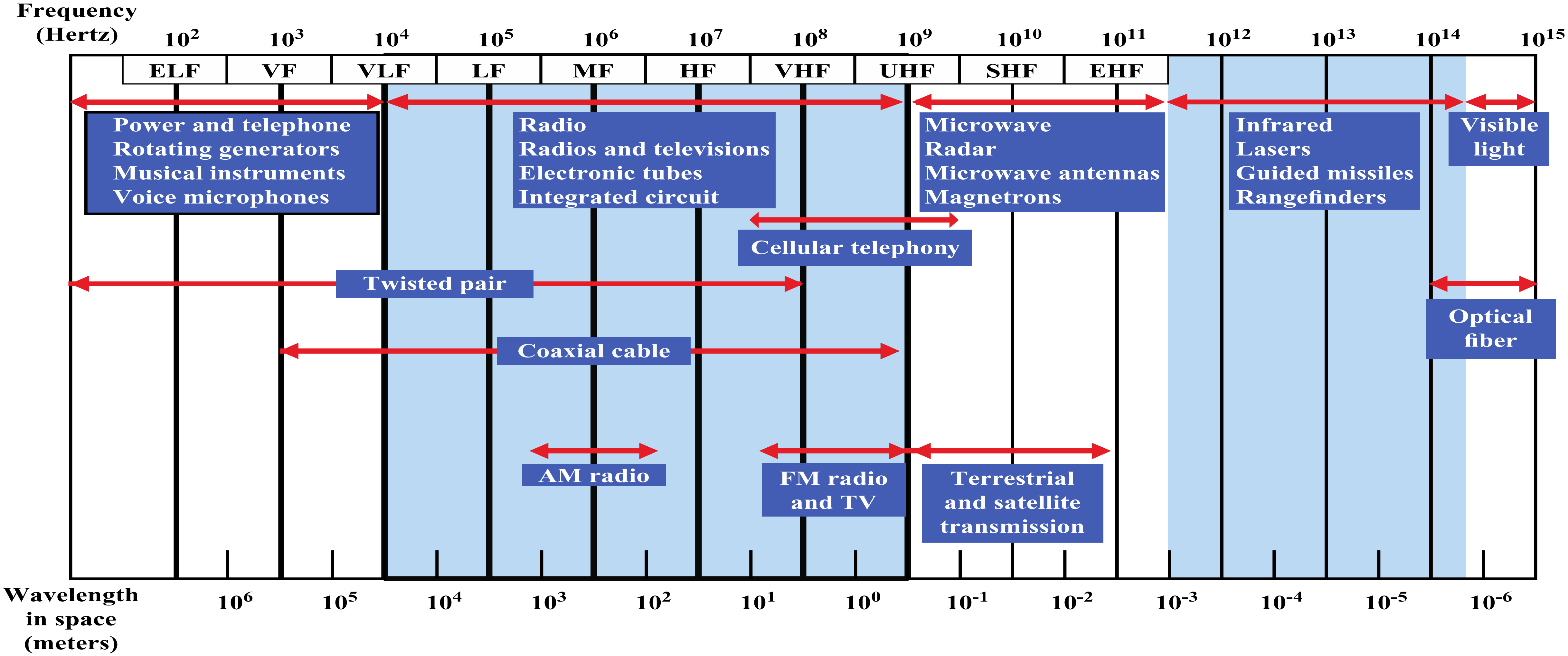
Unguided Media

- Transmission and reception are achieved by means of an antenna
- Configurations for wireless transmission
  - Directional
  - Omnidirectional





Electromagnetic Spectrum

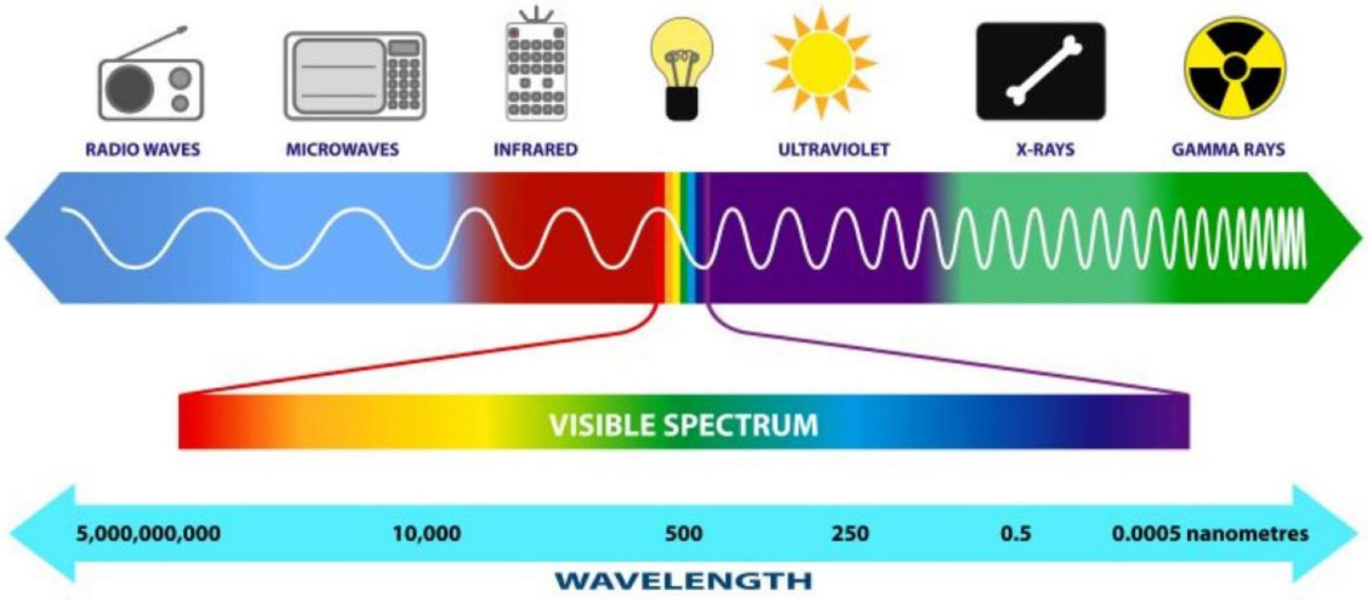


ELF = Extremely low frequency
VF = Voice frequency
VLF = Very low frequency
LF = Low frequency

MF = Medium frequency
HF = High frequency
VHF = Very high frequency

UHF = Ultrahigh frequency
SHF = Superhigh frequency
EHF = Extremely high frequency

General Frequency Ranges



- <u>Radio frequency range</u>
  - 30 MHz to 1 GHz
  - Suitable for omnidirectional applications
  - Used in cellular communications
- <u>Microwave frequency range</u>
  - 1 GHz to 40 GHz
  - Directional beams possible
  - Suitable for point-to-point transmission
  - Used for satellite communications
- <u>Infrared frequency range</u>
  - Roughly, $3x10^{11}$ to $2x10^{14}$ Hz
  - Useful in local point-to-point multipoint applications within confined areas

Terrestrial Microwave

Terrestrial microwave is a type of wireless communication that uses microwave radio frequencies to transmit data over long distances on the Earth's surface.

- Description of common microwave antenna
  - Parabolic "dish", rigid 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

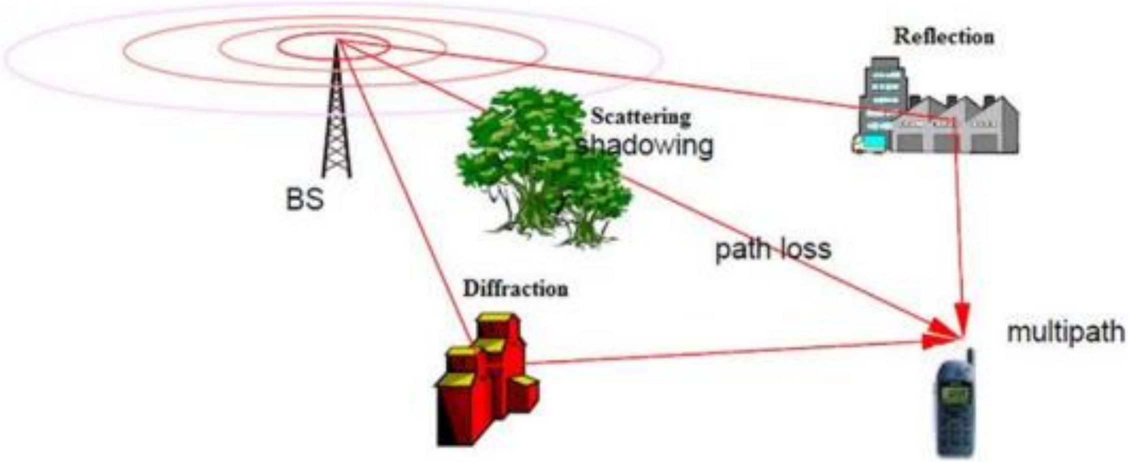
Satellite Microwave

Satellite microwave refers to a communication system that uses microwave radio frequencies to transmit data between Earth and satellites orbiting in space.

- Description of communication satellite
  - This system enables long-range communication by relaying signals through satellites that act as intermediaries between ground stations.
  - Operating in the microwave frequency range, typically between 1 GHz and 30 GHz
  - A single orbiting satellite will operate on a number of frequency bands, called transponder channels, or simply transponders.
- Applications
  - Long-distance transmission- Communication @ K2
  - Private business networks
  - Internet Provider (Starlink) – Case study

Broadcast Radio

- The principal difference between broadcast radio and microwave is that the former is omnidirectional and the latter is directional.
- The broadcast radio does not require dish-shaped antennas, and the antennas need not be rigidly mounted to a precise alignment
- Radio is a general term used to encompass frequencies in the range of 3 kHz to 300 GHz.
- A prime source of impairment for broadcast radio waves is multipath interference. Reflection from land, water, and natural or human-made objects can create multiple paths between antennas.
- It is a one-to-many communication, for example AM and FM radio (FM101)



InfraRed

- Infrared communication refers to the transmission of data using infrared (IR) radiation, a type of electromagnetic radiation with wavelengths longer than visible light but shorter than microwaves.
- Infrared communication is typically line-of-sight and it is widely used due to its simplicity, low power consumption, and security, as IR signals cannot penetrate walls or other obstacles.
- This technology is commonly used for short-range communication between devices, such as remote controls, wireless data transfer between smartphones, and device pairing.

Wireless Signal strength loss – Attenuation

With any transmission system, the main source of signal strength loss is attenuation.

For microwave (and radio frequencies), the loss can be expressed as:

$$L = 10 \log \left(\frac{4 \pi d}{\lambda} \right)^2 \text{dB}$$

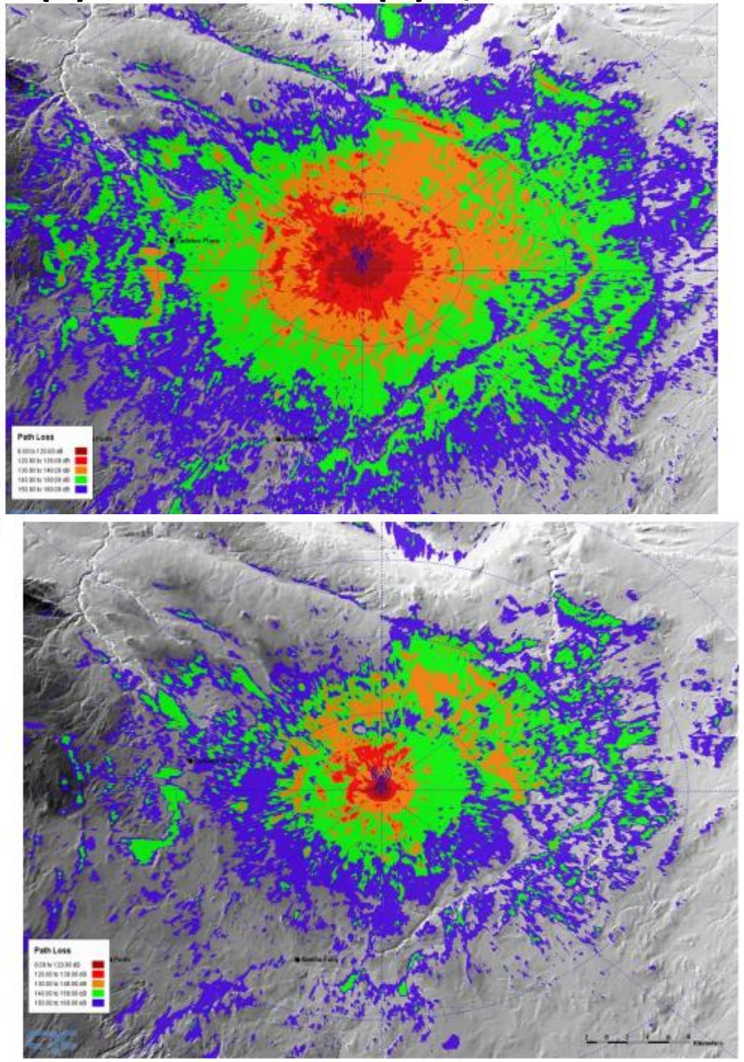
where d is the distance and l is the wavelength

Analysis:

I. The signal loss varies as the square of the distance.

II. As frequency increases, wavelength decreases, and loss increases.

Coverage plots for site @ Rural terrain at (a) 700 MHz and (b) 2,500 MHz



Wireless Networks Systems - Constraints

The main challenges or constraints of WCN are:

- Frequency Spectrum and allocated Bandwidth
- Power
- Channel Impairments

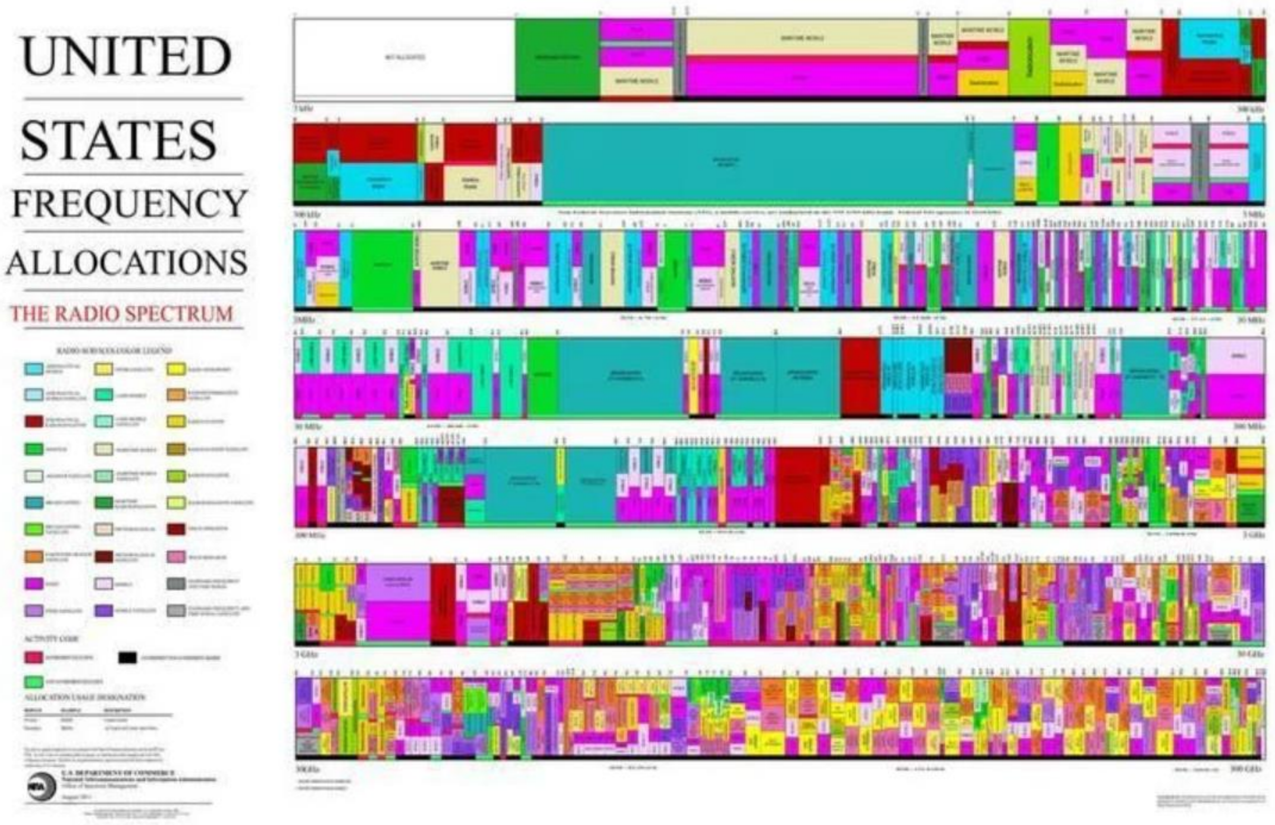
With the growing popularity of microwave and Radio, transmission areas overlap and interference is always a danger. Thus the assignment of frequency bands is strictly regulated.

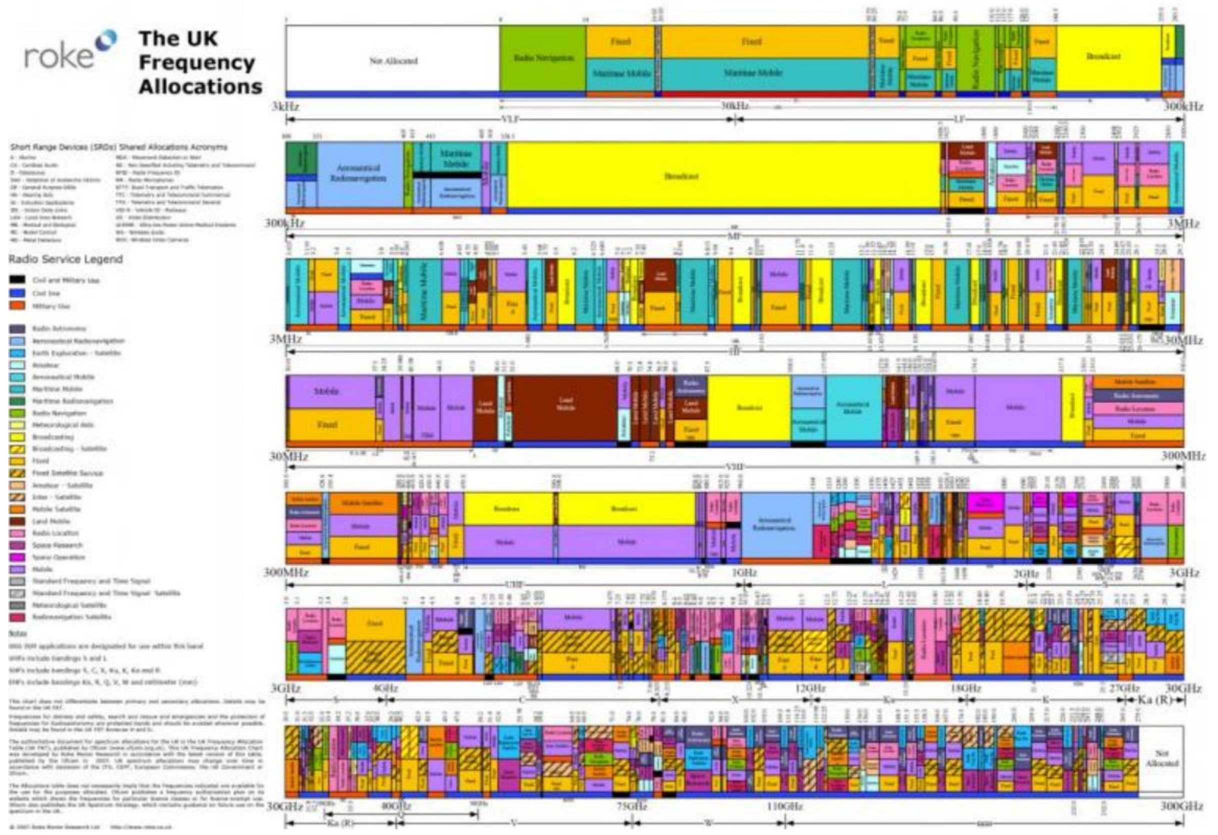
Pakistan Frequency Allocation Board (FAB) or Pakistan Telecommunication Authority (PTA) https://www.pta.gov.pk

USA Federal Communications Commission (USA)

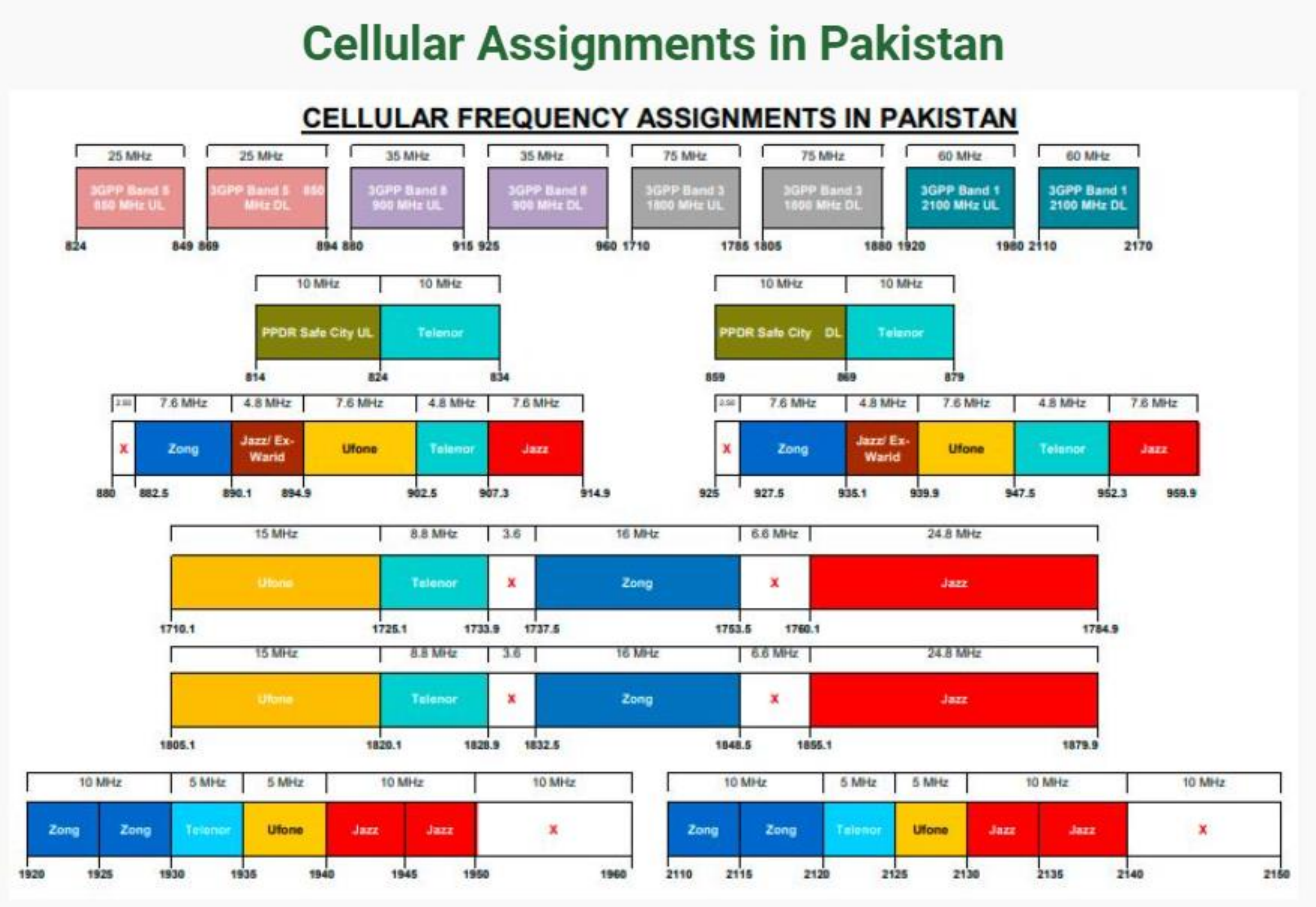
Federal Communications Commission - Wikipedia

Frequency Allocation Boards





Frequency Allocation Boards



The Challenges associated with wireless!

Wireless is convenient, flexible, and scalable in comparison with wired networks. However, certain limitations and technical difficulties inhibit wireless technologies

Limited Spectrum: The frequency spectrum available for wireless communication is finite and increasingly congested, especially in urban areas where many devices are connected simultaneously. This could lead to congestion, long delays and slower data rates. Different countries have different laws and regulations regarding spectrum allocation. Managing international standards and ensuring compliance with regulatory requirements is one of the biggest challenges of Wireless Networks.

Signal Interference: Wireless signals are susceptible to interference from various sources, for instance, physical obstacles, and weather conditions. The interference could lead to reduced signal quality, slower data rates, or connection dropouts/packet drops.

The Challenges associated with wireless!

Path Loss or Propagation Loss: Wireless signals lose strength (power/energy of the signal) as they travel through the air, especially over long distances or through obstacles like buildings, trees, or mountains - this phenomenon is known as path loss.

Multipath Effects: Wireless signals often bounce off buildings, trees, and other surfaces, creating multiple paths for the signal to reach the receiver. This can result in multipath fading, where signals from different paths interfere with each other, leading to signal degradation.

Weather Conditions: Factors like rain, fog, and snow can attenuate wireless signals, especially at higher frequencies (e.g., millimeter-wave bands). Atmospheric conditions such as temperature and humidity can also affect signal strength and quality.

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The Challenges associated with wireless!

Network Coverage: Maintaining seamless coverage in different types of clutters like dense urban, urban, suburban, and rural areas is the biggest challenge of Wireless. The diverse wireless network technologies use different frequency spectra while signal power/energy is inversely related to frequency.

Seamless Handover: For mobile users moving across different coverage areas (e.g., from one cell tower to another in case of cellular or one Access point to another in WiFi), maintaining a stable connection is difficult to attain. Ensuring that user sessions are handed over smoothly without dropped calls or interrupted data transmission is a challenge of Wireless Networks.

Capacity and QoS Issues: Wireless networks can experience congestion when too many users are connected to the same base station or Access point. Ensuring a high level of QoS for critical applications (like Autonomous cars) while ensuring fairness with other applications (like web browsers) is a big challenge, especially in environments with many simultaneous users (like Arenas, Airport).

CP # 01

Review Questions

2.1 Differentiate between an analog and a digital electromagnetic signal.
2.2 What are three important characteristics of a periodic signal?
2.3 How many radians are there in a complete circle of 360 degrees?
2.4 What is the relationship between the frequency and period of a periodic signal?
2.5 What is the relationship between a signal's spectrum and its bandwidth?
2.6 What is fundamental frequency?
2.7 Define the absolute bandwidth of a signal.
2.8 What key factors affect channel capacity?
2.9 Differentiate between infrared and microwave transmission.
2.10 What are some major advantages and disadvantages of microwave transmission?
2.11 What is direct broadcast satellite?
2.12 Why must a satellite have distinct uplink and downlink frequencies?
2.13 Indicate some significant differences between broadcast radio and microwave.
2.14 Why is multiplexing so cost-effective?
2.15 How is interference avoided by using frequency division multiplexing?
2.16 How is efficiency improved by the byte-interleaving technique in TDM systems?

CP # 01

2.9 Using Shannon's formula, find the channel capacity of a teleprinter channel with a 450-Hz bandwidth and a signal-to-noise ratio of 5 dB.

2.10 A signal element in a digital system encodes an 8-bit word.

a. If the digital system is required to operate at 4800 bps, what is the minimum required bandwidth of the channel?

b. Repeat part (a) for a system that is required to operate at 19200 bps.

2.11 Study the works of Shannon and Nyquist on channel capacity. Each places an upper limit on the bit rate of a channel based on two different approaches. How are the two related?

2.12 Given the narrow (usable) audio bandwidth of a telephone transmission facility, a nominal SNR of 56 dB (400,000), and a distortion level of <0.2%,

a. What is the theoretical maximum channel capacity (kbps) of traditional telephone lines?

b. What is the actual maximum channel capacity?

2.13 Given a channel with an intended capacity of 14 Mbps, the signal-to-noise ratio is 127. What should the bandwidth of the channel be to achieve this capacity?

2.14 Show that doubling the transmission frequency or doubling the distance between transmitting antenna and receiving antenna attenuates the power received by 6 dB.

2.15 Fill in the missing elements in the following table of approximate power ratios for various dB levels.

Decibels	1	2	3	4	5	6	7	8	9	10
Losses			0.5							0.1
Gains			2							10

Thanks!