UNIT -1

Introduction to 5G technology

Overview of wireless communication systems

What is Wireless Communication?

Wireless communication refers to the transfer of data between two or more points without using cables.

It uses technologies like radio frequency (RF), Bluetooth, Wi-Fi, satellite, and cellular networks.

Basic Components of a Wireless Communication System

Transmitter – Converts information into a signal and sends it

Channel – Medium through which the signal travels (air, space)

Receiver – Receives and converts the signal back into information

Antenna – Radiates or receives electromagnetic waves

Types of Wireless Communication Systems

a) Satellite Communication

Uses satellites orbiting the Earth

Wide coverage

Used in TV broadcasting, GPS, weather, defense

b) Cellular Communication (1G–5G)

Divides service area into cells

Supports mobile phones, mobile internet

Evolved through generations (1G → 5G)

c) Wi-Fi (Wireless LAN)

Short-range wireless networking

Used in homes, offices, hotspots

d) Bluetooth

Very short-range communication

Used in headphones, IoT devices, file transfer

e) Microwave Communication

Point-to-point communication

Used for long-distance telecommunication links

f) Infrared Communication

Line-of-sight communication

Used in TV remotes, short-range devices

Applications of Wireless Communication

- Mobile phones
- Internet and Wi-Fi networks
- Satellite communication
- Smart homes & IoT
- Healthcare (remote monitoring)
- Defense and military
- Vehicle communication (V2X)

Evolution from 1G to 5G

1G – First Generation (1980s)

It was developed in 1980s & completed early 1990s

Technology: It is based on analog system

Standard: AMPS (advanced mobile phone system) was launched by the US & it was the 1G mobile system

Data Rate: speed 2.4 kbps

Features:

- Basic voice communication only
- Poor voice quality
- No data services
- Limited capacity and coverage

2G – Second Generation (1990s)

Technology: Based on Digital

Standards: GSM, CDMA

Data Rate: speed 64–144 kbps

Features:

Services such as:

Digital voice (better clarity)

SMS & MMS services

Enhanced security (encryption)

Basic internet via GPRS/EDGE

3G – Third Generation (2000s)

It was developed between late 1990s & early 2000s

Technology: Packet switching (with circuit switching)

Standards: UMTS, WCDMA, CDMA2000

Data Rate: Transmission speed from 384 kbps to 2 Mbps

Features:

- Mobile internet browsing
- Video calling
- Multimedia streaming
- Faster data transfer

4G – Fourth Generation (2010s)

It was developed in 2010

Technology: All-IP packet switching

Standards: LTE, LTE-A

LTE (Long Term Evolution)

LTE (Long Term Evolution) -Advanced

Data Rate: Transmission speed 10–100 Mbps (up to 1 Gbps)

Features:

- High-speed broadband internet
- HD video streaming
- Improved latency (~50 ms)
- Supports VoLTE
- Better mobility and capacity

5G – Fifth Generation (2020s)

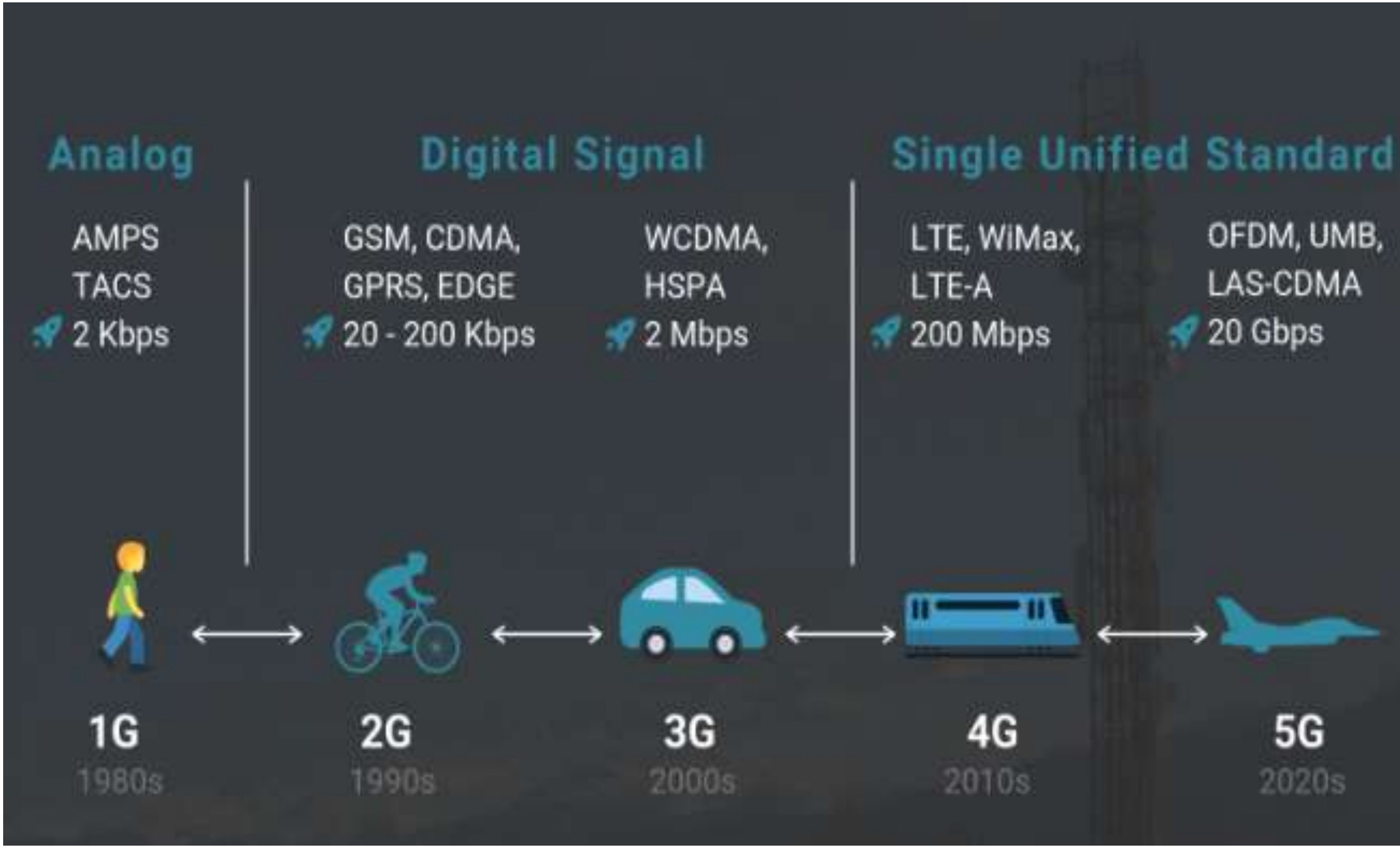
Technology: New Radio (NR), Massive MIMO, mmWave

Data Rate: 1–20 Gbps

Latency: As low as 1 ms

Features:

- Ultra-fast speeds
- Ultra-low latency
- Massive device connectivity (IoT)
- Enhanced mobile broadband (eMBB)
- Ultra-reliable low-latency communication (URLLC)
- Massive machine-type communication (mMTC)
- Network slicing & virtualization


Analog
Digital Signal
Single Unified Standard
AMPS
TACS
2 Kbps
GSM, CDMA,
GPRS, EDGE
20 - 200 Kbps
WCDMA,
HSPA
2 Mbps
LTE, WiMax,
LTE-A
200 Mbps
OFDM, UMB,
LAS-CDMA
20 Gbps
1G
1980s
2G
1990s
3G
2000s
4G
2010s
5G
2020s

Key Features of 5G Networks

1. Enhanced Mobile Broadband (eMBB)

High data rates for HD/4K/8K streaming

Fast downloads & cloud services

2. Ultra-Reliable Low Latency Communication (URLLC)

Latency down to **1 ms**

Supports applications like:

- Autonomous vehicles
- Remote surgery
- Industrial automation

3. Massive Machine Type Communication (mMTC)

Supports **millions of devices/km²**

Ideal for IoT, smart cities, sensors

4. Massive MIMO and Beamforming

Higher capacity and coverage

Efficient use of spectrum

5. Network Slicing

Virtual networks for different applications (e.g., IoT, gaming)

Better customization & flexibility

6. Use of New Spectrum

mmWave (24–100 GHz)

Higher bandwidth → ultra-high speeds

Requirements of 5G Networks

Comparison between 4G and 5G technologies

4G Technology	5G Technology
It stands for Fourth Generation technology	It stands for Fifth Generation technology
The maximum upload rate of 4G technology is 500 Mbps	While the maximum upload rate of 5G technology is 1.25 Gbps
The maximum download rate of 4G technology is 1 Gbps	While the maximum download rate of 5G technology is 2.5 Gbps.
The latency of 4G technology is about 50 ms	While the latency of 5G technology is about 1 ms
4G offers CDMA	While 5G offers OFDM, BDMA

Network Latency

Network latency refers to the time it takes for a data packet to travel from one point to another on a network. It is usually measured in milliseconds (ms) or microseconds (μs).

Formula

Latency ≈ Transmission Delay + Propagation Delay + Processing Delay + Queuing Delay

Transmission Delay : Time to send all bits on the link Packet size, bandwidth

Propagation Delay : Time for signal to travel through medium Distance, propagation speed

Processing Delay : Time to analyze and process the packet Router speed, algorithms

Queuing Delay : Time spent waiting in buffer Congestion, traffic load

Latency in Previous Generations

3G latency: ~100–500 ms

4G latency: ~30–50 ms

Latency in 5G

5G aims to achieve **Ultra-Low Latency**:

Typical 5G latency: 1–10 ms

URLLC target latency: 1 ms or less

Importance of Network Latency in 5G

Network latency is one of the most critical performance parameters in 5G. 5G aims to reduce latency to **as low as 1 millisecond**, enabling extremely fast communication. Low latency is important in 5G because it supports several advanced real-time applications.

1. Real-Time Communication

Low latency ensures:

Smooth video calls

Instant messaging

Lag-free online gaming

2. Autonomous Vehicles

Self-driving cars require **instant data exchange** with surrounding vehicles, sensors, and traffic systems.

Low latency helps cars respond immediately, improving:

Safety

Traffic efficiency

3. Remote Surgery and Healthcare

5G enables **tactile internet** and remote surgery where surgeons operate robots from far away.

Ultra-low latency ensures:

✓Accurate movements

✓No delay in feedback

✓High patient safety

4. Industrial Automation (Industry 4.0)

Factories use robots, sensors, and automated systems that must coordinate in real time.

Low latency in 5G enables:

✓Precision control

✓Predictive maintenance

✓Safe robotic operations

5. Augmented Reality (AR) and Virtual Reality (VR)

AR/VR applications need rapid responses to user actions.

Low latency reduces:

Motion sickness

Visual lag

Improves immersion

6. Smart Cities and IoT

Millions of IoT devices need to share data instantly.

Low latency supports:

Smart traffic lights

Smart power grids

Emergency response systems

5G spectrum bands and frequency ranges

What is the spectrum of 5G?

Spectrum refers to the electromagnetic radio-wave frequencies that wireless communications travel over. With 5G, those frequencies are divided into three frequency bands: low-band, mid-band and high-band frequencies.

Low-Band (Sub-6 GHz)

- **Frequencies:** Around 600-900 MHz (e.g., Bands n71, n28, n5).
- **Pros:** Excellent range, great building penetration, wide coverage.
- **Cons:** Lower speeds (tens to hundreds of Mbps).
- **Use Case:** Broad rural coverage, reliable indoor service.

Mid-Band (1-6 GHz)

- **Frequencies:** 1 GHz to 6 GHz (e.g., Bands n1, n3, n41, n78).
- **Pros:** Best balance of speed (up to 1 Gbps) and coverage, high capacity.
- **Cons:** Less range than low-band.
- **Use Case:** Ideal for dense urban areas and general mobile use.

High-Band (Millimeter Wave / mmWave)

Frequencies: 24-71 GHz (e.g., Bands n258, n260, n261).

Pros: Multi-gigabit speeds (up to 10 Gbps), ultra-low latency.

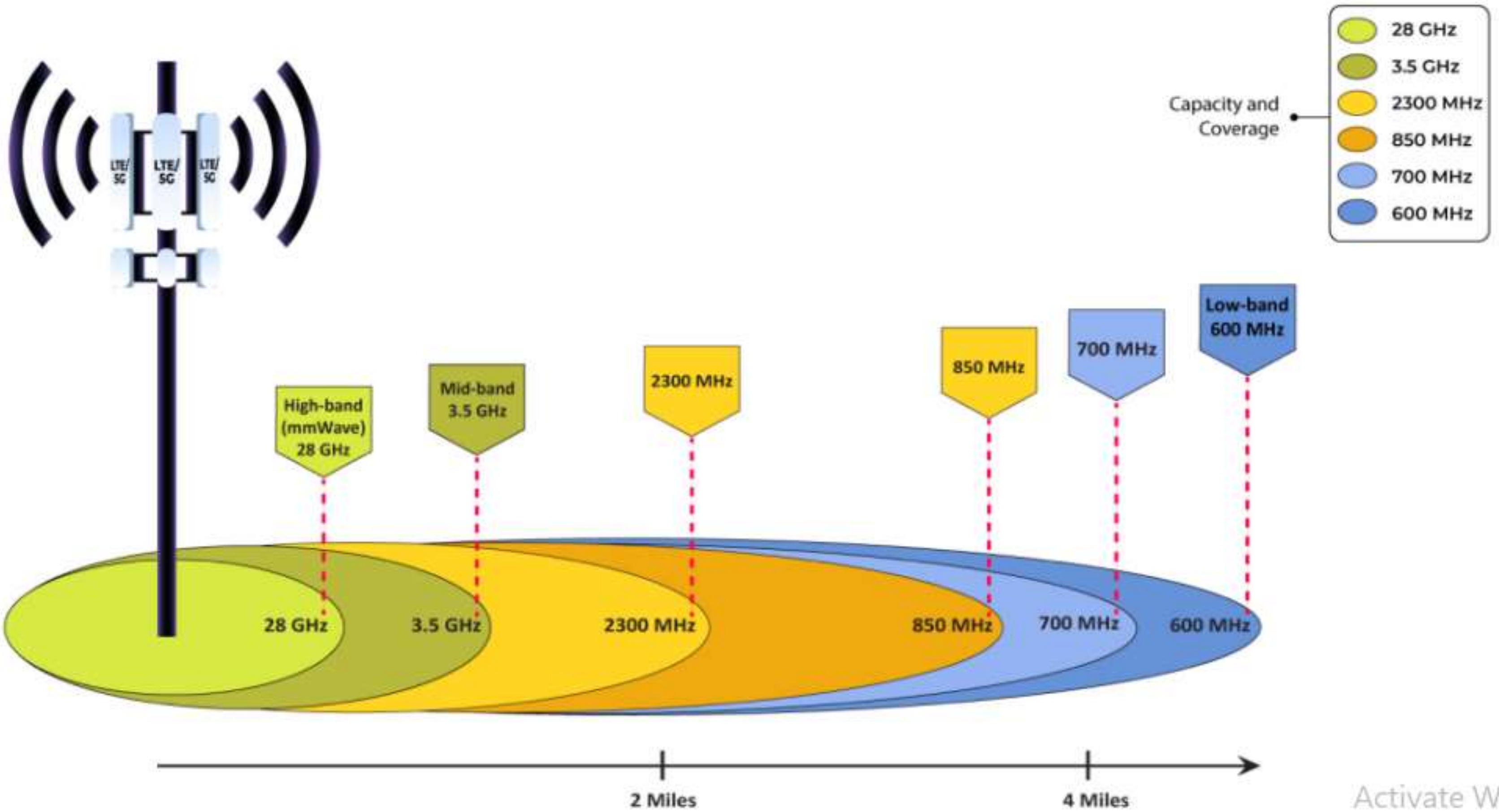
Cons: Very short range, poor building penetration, needs dense small cells.

Use Case: High-traffic venues, fixed wireless access, specialized enterprise needs.

Key Concepts

- **FR1 (Frequency Range 1):** Below 7.125 GHz (Low & Mid-bands).
- **FR2 (Frequency Range 2):** 24-71 GHz (High-band / mmWave).
- **Bandwidth:** Mid-band uses wider channels (up to 100 MHz in FR1), while mmWave uses massive channels (up to 400 MHz) for extreme speeds.
- **Beamforming:** Technology used in mmWave to direct signals, helping to overcome range limitations

Basics of network coverage and capacity in 5G



1. Network Coverage in 5G

- **Lower frequencies (low-band)** provide **wide coverage** and **good indoor penetration**.
- **Higher frequencies (mid-band and mmWave)** provide **shorter coverage** because signals cannot travel far and are easily blocked.
- 5G uses a combination of **macro cells**, **small cells**, and **massive MIMO antennas** to improve coverage.

How 5G improves coverage:

- **Low-band spectrum (<1 GHz)** for long-range coverage
- **Mid-band spectrum (1–6 GHz)** for balanced range and performance
- **Dense small-cell deployment** to fill coverage gaps
- **Massive MIMO** to improve signal strength and quality

2. Network Capacity in 5G

- 5G can handle **massive numbers of devices** (IoT, mobile users, sensors).
- 5G provides **faster data rates** and **higher throughput** due to wider bandwidth.

How 5G increases capacity:

- **High-band (mmWave) spectrum** provides **huge bandwidth** → more data per second
- **Massive MIMO antennas** support **many simultaneous users**
- **Beamforming** directs signals precisely → reduces interference → increases capacity
- **Network slicing** creates virtual networks optimized for different needs
- **Efficient spectrum usage** with technologies like OFDM and carrier aggregation

5G enabled devices and their functionalities

5G is designed to support ultra-fast data speeds, low latency, massive device connectivity, and high reliability. To use 5G networks, devices must be equipped with 5G chipsets/modems and antennas capable of operating in sub-6 GHz and/or mmWave bands.

1. Smartphones

Examples: Samsung Galaxy S-series (S21–S25), iPhone 12–16 series, OnePlus, Xiaomi, Motorola 5G phones

Functionalities

- ➢**High-speed broadband:** Download speeds up to multi-Gbps depending on the band.
- ➢**Ultra-low latency:** Suitable for gaming, VR/AR apps, video calling.
- ➢**5G carrier aggregation:** Combines multiple 5G bands for better throughput.
- ➢**Enhanced voice services (VoNR):** Higher-quality voice over 5G.
- ➢**Edge computing support:** Real-time AI apps, real-time object detection, etc.

2. 5G IoT Devices

These are small sensors or modules used in industrial and commercial applications.

Types & Functionalities

- **5G IoT Sensors:** For smart manufacturing (Industry 4.0), automation, robotics.
- **5G Smart Meters:** Utility monitoring (electricity, water, gas).
- **Healthcare IoT:** Wearables, remote surgeries, patient monitoring systems.
- **Connected cameras:** Higher resolution, real-time surveillance using low latency.
- **Smart home devices:** Smart locks, thermostats with faster connectivity.

3. 5G Routers & CPE (Customer Premises Equipment)

Examples: Airtel Xstream AirFiber, JIO AirFiber, Netgear 5G routers.

Functionalities

- Provide **wireless broadband** using 5G in areas without fiber.
- Connect multiple household devices (smart TVs, laptops, IoT appliances).
- Offer **Gbps-level speeds** for office/home networks.
- Enable **Fixed Wireless Access (FWA)** for rural/remote areas.

4. 5G Laptops & Tablets

Some devices come with built-in 5G modems (eSIM/SIM support).

Functionalities

On-the-go high-speed internet without Wi-Fi.

Enhanced cloud productivity: remote work, video conferencing.

Real-time AR/VR applications for education and design.

5. Autonomous Vehicles & Connected Cars

Many automotive manufacturers use 5G modules for V2X (Vehicle-to-Everything) communication.

Functionalities

V2V: Vehicle-to-vehicle communication for collision avoidance.

V2I: Traffic light communication, road hazard alerts.

Real-time navigation: High-precision maps and route updates.

Automated driving: Low-latency communication with sensors and cloud.

Role of AI and ML in enhancing 5G capabilities

5G networks are highly complex, dynamic, and dense with massive numbers of devices. AI (Artificial Intelligence) and ML (Machine Learning) help optimize, automate, and intelligently manage 5G operations to deliver better performance, reliability, and efficiency.

1. Network Optimization and Self-Organizing Networks (SON)

How AI/ML enhance 5G:

Automatically configure, optimize, and heal the network.

Predict network congestion and take corrective action in advance.

Optimize parameters such as handovers, channel selection, and power levels.

Benefit: Stable connectivity, higher network performance, reduced manual work.

2. Traffic Prediction and Resource Management

Functions:

ML models analyze traffic patterns to predict data demand.

5G dynamically allocates bandwidth and spectrum where needed.

AI-based scheduling reduces network congestion during peak times.

Benefit: Efficient spectrum utilization and improved Quality of Service (QoS).

3. Intelligent Beamforming and Massive MIMO Optimization

5G uses advanced antenna systems (Massive MIMO) and beamforming.

AI/ML help with:

Predicting user location and movement for accurate beam steering.

Reducing interference between beams.

Improving coverage and capacity by optimizing antenna operations.

Benefit: Stronger signals, higher throughput, better coverage.

4. Network Slicing Automation

5G can create multiple virtual networks (“slices”) over the same physical infrastructure.

AI/ML enhance slicing by:

Automating slice creation, scaling, and maintenance.

Predicting slice performance needs (e.g., for IoT, video streaming, autonomous cars).

Benefit: Tailored networks for different applications with high reliability.

5. Improved Quality of Experience (QoE)

AI collects user experience data such as:

Video buffering

Call drops

Latency and throughput

ML algorithms:

Predict user dissatisfaction.

Adjust system parameters to improve user experience.

Benefit: Higher customer satisfaction and service reliability.

Network slicing and its benefits in 5G deployment

What is Network Slicing?

Network slicing is a key 5G feature that allows operators to create multiple **virtual networks** (slices) on a single shared physical infrastructure.

Each slice is customized to meet the specific needs of different applications, industries, or services.

How it works

A single 5G network is divided into multiple **logical slices**.

Each slice has its own:

- Bandwidth
- Latency requirements
- Security level
- QoS (Quality of Service)

Slices operate independently like separate networks but share the same hardware.

Example

5G Network Slicing
Mobile Broadband
Massive IoT
Critical IoT
5G Network
Internet, Entertainment, Communication
Manufacturing, Smart Cities, Retail
Automotive, Medical, Infrastructure

Benefits of Network Slicing in 5G

1. Customization for Different Use Cases

Each slice is designed to meet the performance requirements of a specific application.

Examples:

High-speed video streaming slice → high data rate

2. Efficient Resource Utilization

Network resources (spectrum, bandwidth, compute, storage) are dynamically allocated.

Benefit:

Higher efficiency, less wastage, and optimal performance for each service.

3. Enhanced Quality of Service (QoS)

Each slice has guaranteed performance metrics like:

Speed

Latency

Jitter

Reliability

Benefit:

Consistent and predictable performance for critical applications.

4. Support for Diverse 5G Applications

5G needs to serve three main categories:

eMBB: Enhanced Mobile Broadband

URLLC: Ultra-Reliable Low-Latency Communication

mMTC: Massive Machine-Type Communication

5G architecture and network elements

- 5G is the latest generation of mobile networks, following 1G, 2G, 3G, and 4G. It offers very high-speed internet, with peak speeds of up to 20 Gbps and average speeds of over 100 Mbps
- It uses a technology called OFDM (Orthogonal Frequency-Division Multiplexing) and works over wide frequency channels ranging from 100 to 800 MHz.
- It is designed to support all types of communication not just mobile but also for voice, non-voice, important and regular services, and especially IoT (Internet of Things) devices.

5G Core Network

- The 5G core network is like the control center of the whole 5G system. It connects users safely and reliably to the internet and manages many important tasks like handling mobile connections, keeping track of user information, checking permissions, and applying network rules.

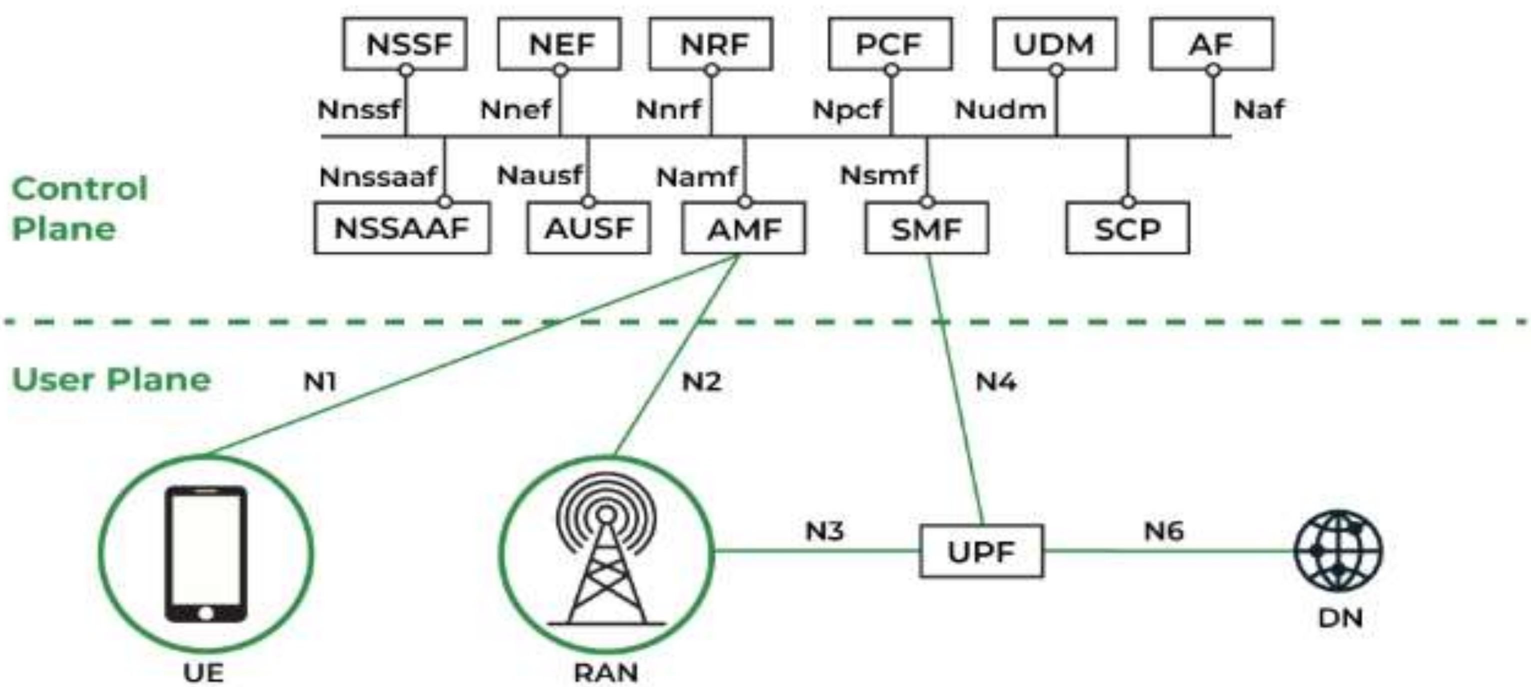
5G Core (5GC) – Service Based Architecture

The core uses cloud technologies, virtualization, and network slicing.

It separates:

Control Plane (CP) → signaling

User Plane (UP) → data forwarding



- Unlike older networks, the 5G core is completely software-based and built to run in the cloud.
- This means it can be set up faster, changed easily, and works with flexible cloud technology

User Equipment (UE):

- The User Equipment, also known as the end-user device, represents the devices used by individuals to connect to the 5G network.
- These devices include smartphones, tablets, laptops, IoT devices, and other wireless devices capable of communicating over 5G.

Radio Access Network (RAN):

- The Radio Access Network is responsible for establishing and maintaining wireless communication between the user equipment and the core network.
- It consists of base stations, antennas, and other equipment deployed in a geographical area to provide wireless coverage. In 5G, the RAN includes two main components:

a. gNB (Next-Generation NodeB):

➢ The gNB, also known as the base station or eNodeB, is responsible for transmitting and receiving wireless signals to and from user equipment.

➢ It supports advanced features like beamforming, massive MIMO (Multiple-Input Multiple-Output), and carrier aggregation to enhance network capacity and coverage.

b. NG-RAN (Next-Generation RAN):

➢ NG-RAN refers to the overall RAN architecture that includes gNBs and other supporting elements. NG-RAN facilitates the coordination and management of multiple gNBs to ensure seamless connectivity and efficient use of network resources.

Core Network (CN):

The Core Network serves as the central part of the 5G architecture, responsible for handling various network functions, service delivery, and management. The 5G Core Network (5GC) consists of several key components:

a. AMF (Access and Mobility Management Function):

AMF manages the mobility of user equipment, including initial network access, authentication, and session mobility between different access points.

b. UPF (User Plane Function):

UPF is responsible for handling the user data traffic, including packet routing, forwarding, and traffic optimization. It ensures efficient and low-latency data transmission between the user equipment and external networks.

c. SMF (Session Management Function):

SMF controls the session management and service delivery aspects of the 5G network. It handles the establishment, modification, and termination of user sessions, as well as service policy enforcement.

d. PCF (Policy Control Function):

PCF manages the policy control and enforcement within the 5G network. It ensures that the network resources are allocated appropriately based on service requirements and user preferences.

e. NRF (NF Repository Function):

NRF serves as a central repository of network function information. It provides a catalog of available network functions and their capabilities, enabling dynamic service orchestration and network slicing.

f. AUSF (Authentication Server Function):

AUSF handles user authentication and security-related functions. It authenticates users, verifies their access rights, and ensures secure communication within the network.

g. UDM (Unified Data Management):

UDM is responsible for managing user-related data and subscriber profiles within the 5G network. It stores user information, access credentials, and service-specific data.

h. NEF (Network Exposure Function):

NEF provides interfaces for third-party applications and services to interact with the 5G network. It enables the exposure of network capabilities and data to external entities, fostering innovation and new service development.