Chapter 2 - Modern Wireless Communication Systems

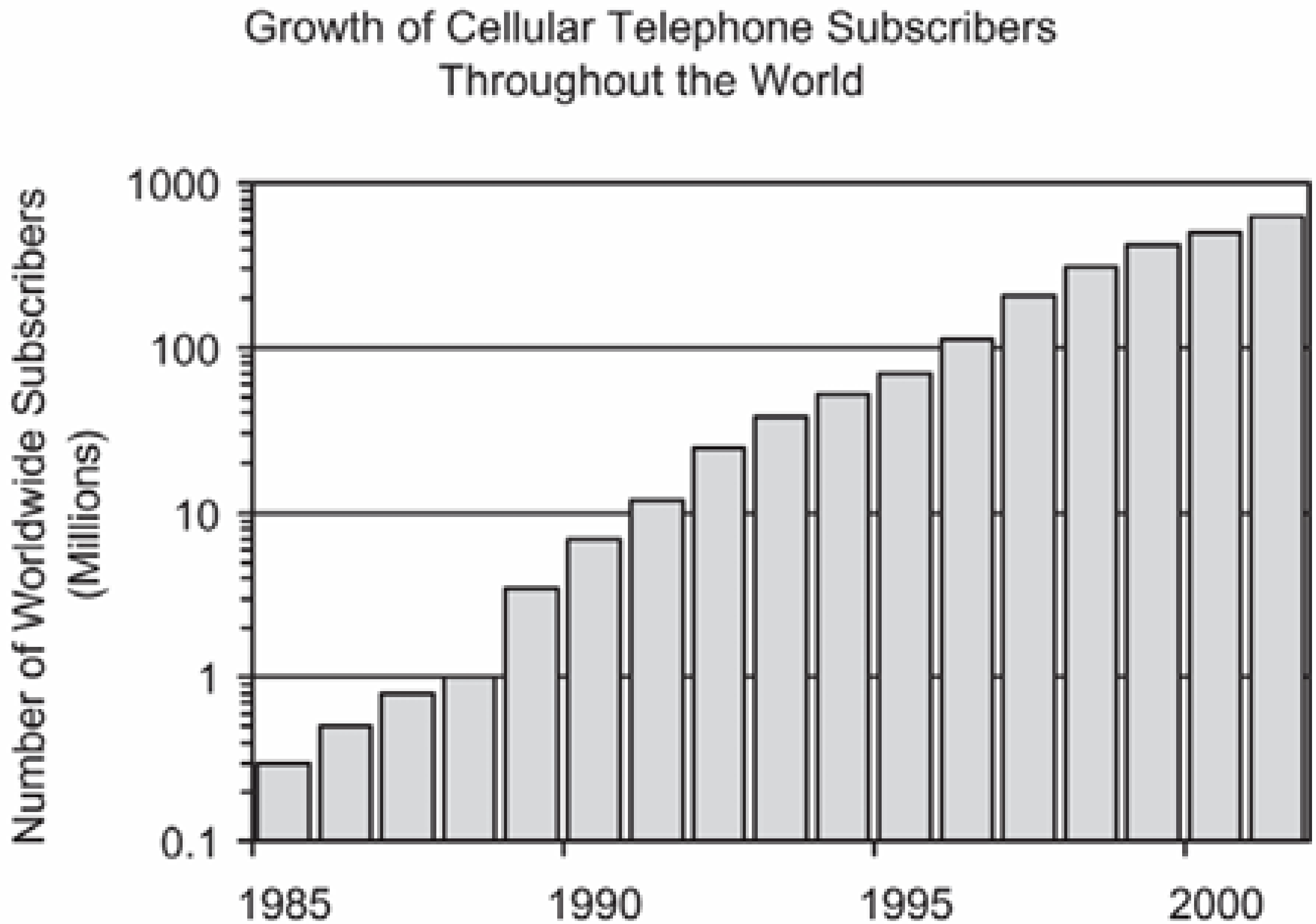
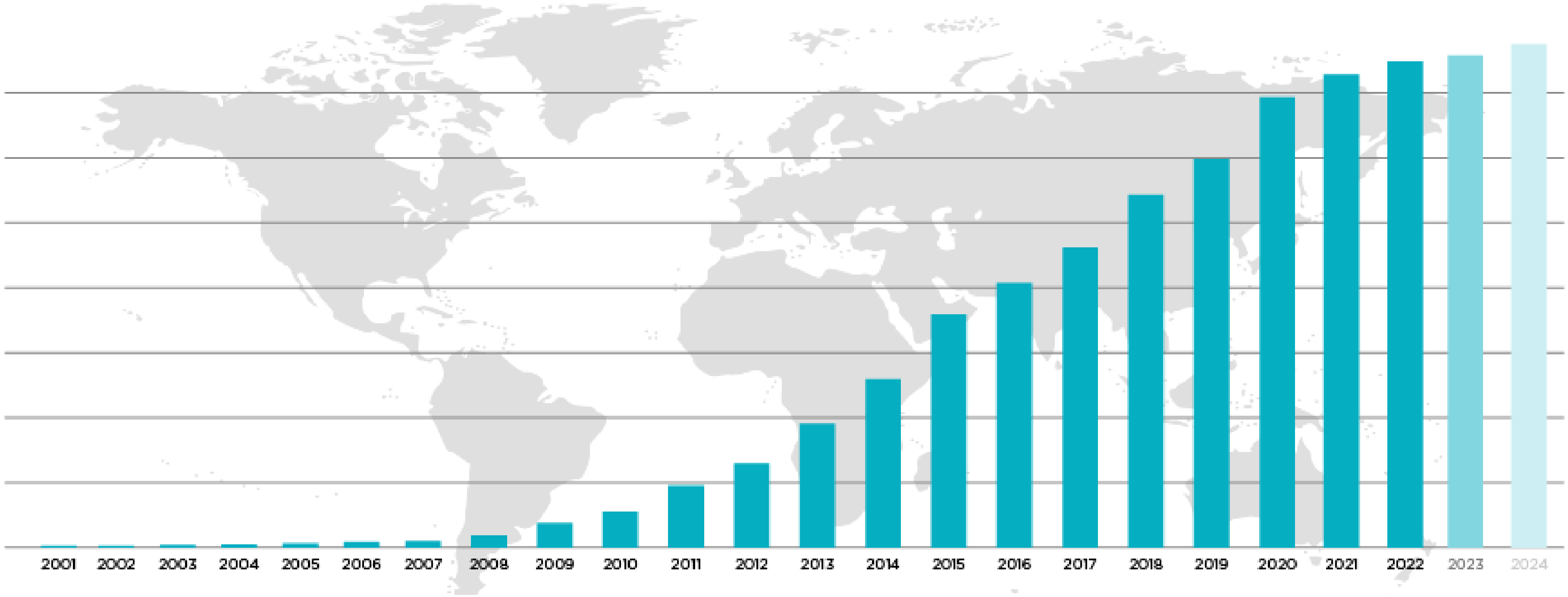


Figure 2.1 Growth of cellular and PCS telephone subscribers throughout the world.

Cell Phone Usage Through Time



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The Shift from 1G to 2G

Feature	1G	2G
Year Introduced	Early 1980s	Early 1990s
Technology	Analog	Digital
Modulation	FM	GMSK (GSM), QPSK (CDMA)
Services	Voice only	Voice, SMS, Limited Data
Security	None	Digital Encryption (A5 in GSM)

Major 2G Standards

Standard	Region	Multiple Access	Key Technology
GSM	Europe/Global	TDMA/FDMA	• GMSK modulation • 200 kHz carriers, 8 slots/frame
IS-136 (D-AMPS)	North America	TDMA	• 30 kHz channels (backward-compatible with AMPS)
IS-95 (cdmaOne)	North America	CDMA	• Spread spectrum/QPSK • 1.25 MHz channels

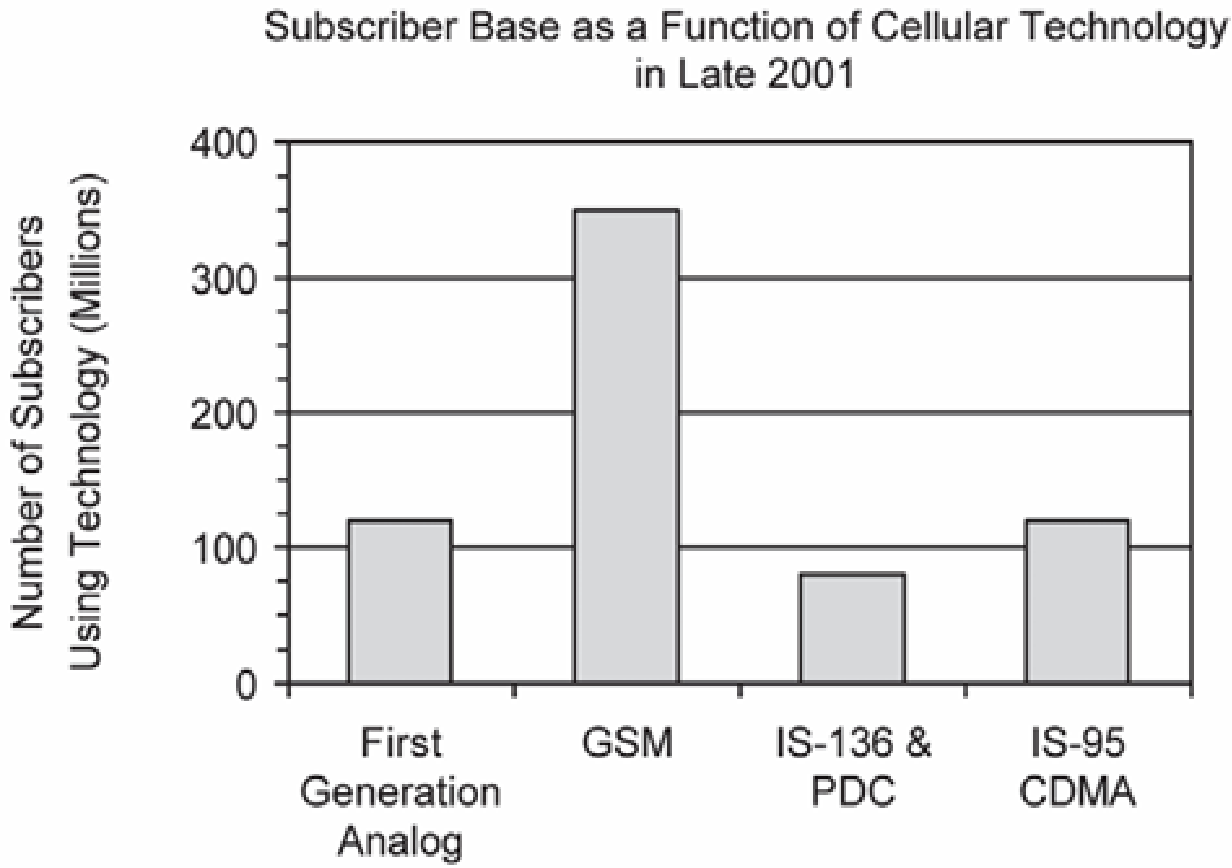
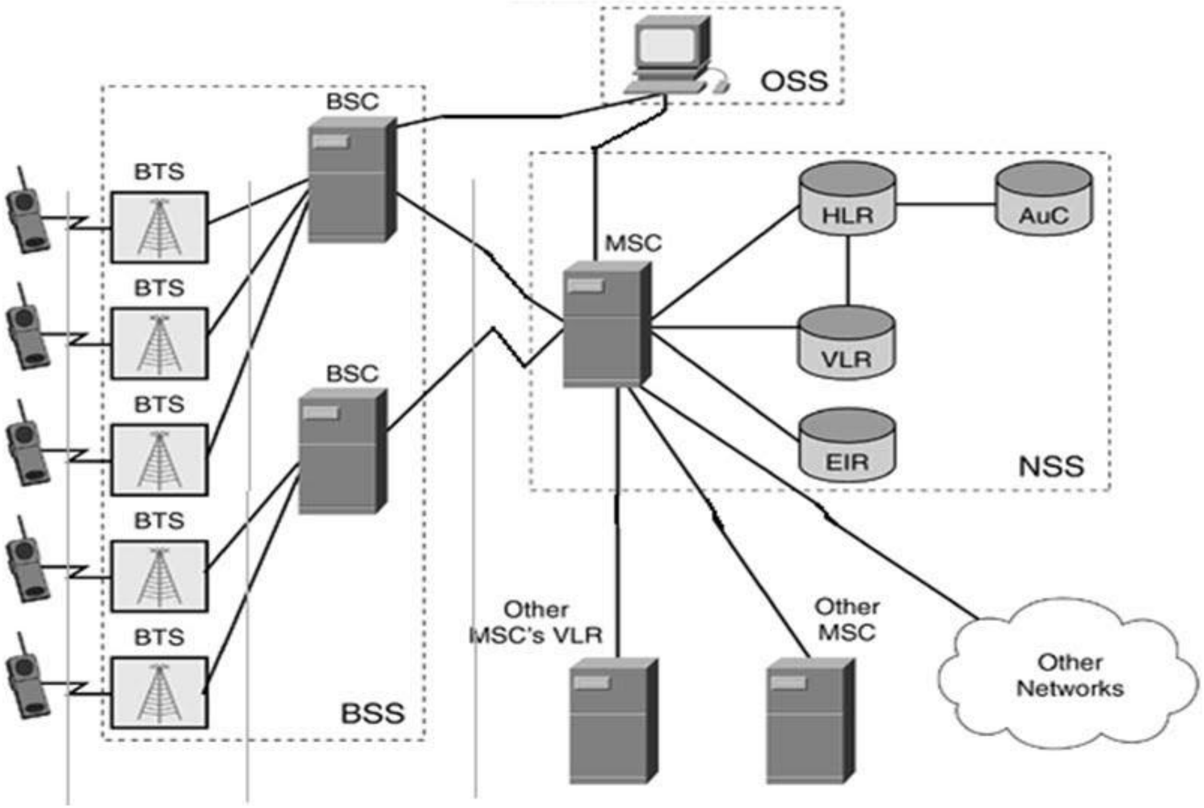


Figure 2.2 Worldwide subscriber base as a function of cellular technology in late 2001.

2G Network Architecture (GSM as Example)

- **Components**:
  - **MS (Mobile Station)**: SIM card enabled.
  - **BTS (Base Transceiver Station)**: Cell tower.
  - **BSC (Base Station Controller)**: Manages handoffs.
  - **MSC (Mobile Switching Center)**: Connects to PSTN.
  - **Home Location Register (HLR)** and **Visitor Location Register (VLR)**
- **Air Interface**:
  - **FDMA**: 900/1800 MHz bands.
  - **TDMA**: 8 users per 200 kHz carrier.

GSM SYSTEM ARCHITECTURE



- **Mobile Station (MS)**
  - Mobile Equipment (ME)
  - Subscriber Identity Module (SIM)
- **Base Station Subsystem (BSS)**
  - Base Transceiver Station (BTS)
  - Base Station Controller (BSC)
- **Network Switching Subsystem(NSS)**
  - Mobile Switching Center (MSC)
  - Home Location Register (HLR)
  - Visitor Location Register (VLR)
  - Authentication Center (AUC)
  - Equipment Identity Register (EIR)

GSM – Global System for Mobile Communication

- Introduced: 1991 (Europe)
- Carrier Bandwidth: 200 kHz
- Modulation: GMSK
- Access Method: TDMA – 8 time slots per carrier

GSM Capacity

Q) A GSM system uses 25 MHz bandwidth. How many simultaneous users can it support?

GSM Capacity

Q) A GSM system uses 25 MHz bandwidth. How many simultaneous users can it support?

Solution:

- Bandwidth per carrier = 200 kHz
- Number of carriers = 25 MHz / 200 kHz = 125
- Time slots per carrier = 8
- Total users supported **= 125 × 8 = 1000 users**

Security in GSM

- Authentication via SIM and secret keys
- Encryption of voice/data using A5 algorithm
- Temporary Mobile Subscriber Identity (TMSI)

IS-95 (cdmaOne) – Code Division Multiple Access

- Introduced: 1993 (Qualcomm)
- Bandwidth: 1.25 MHz
- Multiple Access: CDMA using PN sequences
- Modulation: QPSK
- Soft handoff and better spectral efficiency

CDMA User Capacity

Q) Assume a CDMA system with a processing gain of 20 dB and required Eb/No = 7 dB. What is the maximum number of users (N)?

Formula:

$N = G/(Eb/N0)$

Where $G = W/R$, but in dB form:

$N = 10^{(GdB-(Eb/N0)dB)/10}$

$= 10^{(20-7)/10}$

$= 10^{1.3} \approx 20$ users per cell

CDMA (IS-95) Principles

- **Equation:**

Processing Gain=Chip Rate (1.2288 Mcps)/Data Rate (9.6 kbps)=128

IS-136 (North American TDMA)

- Backward compatible with AMPS
- 3 users per 30 kHz channel (TDMA)
- Uses π/4 DQPSK modulation
- Lower capacity than GSM and CDMA

2G Services and Limitations

- Services:
  - Voice calls
  - Short Messaging Service (SMS)
  - Circuit-switched data (9.6 kbps)
- Limitations:
  - Low data rate
  - Limited multimedia support
  - Circuit-switched architecture

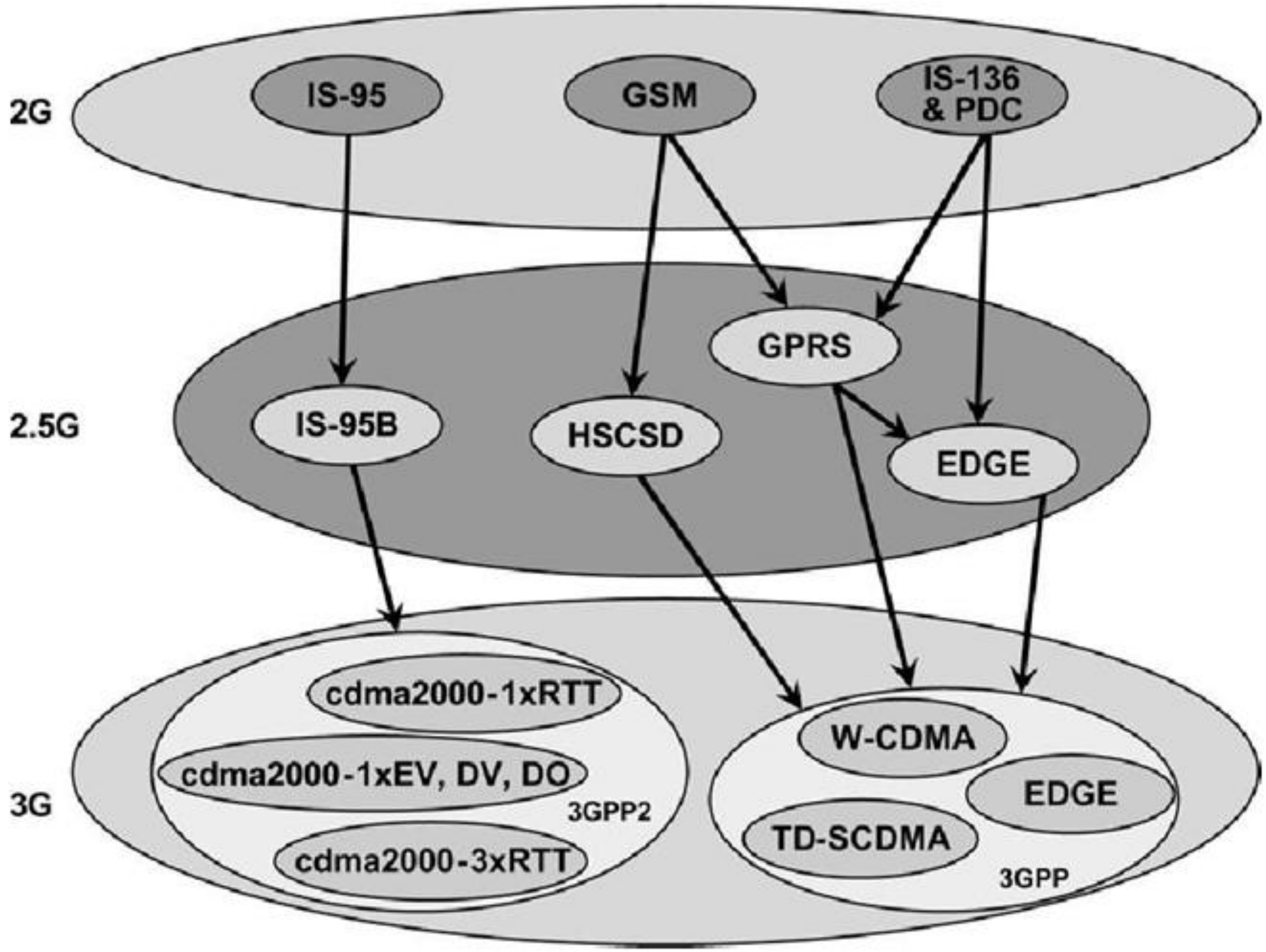


Figure 2.3 Various upgrade paths for 2G technologies.

Evolution to 2.5G Mobile Radio Networks

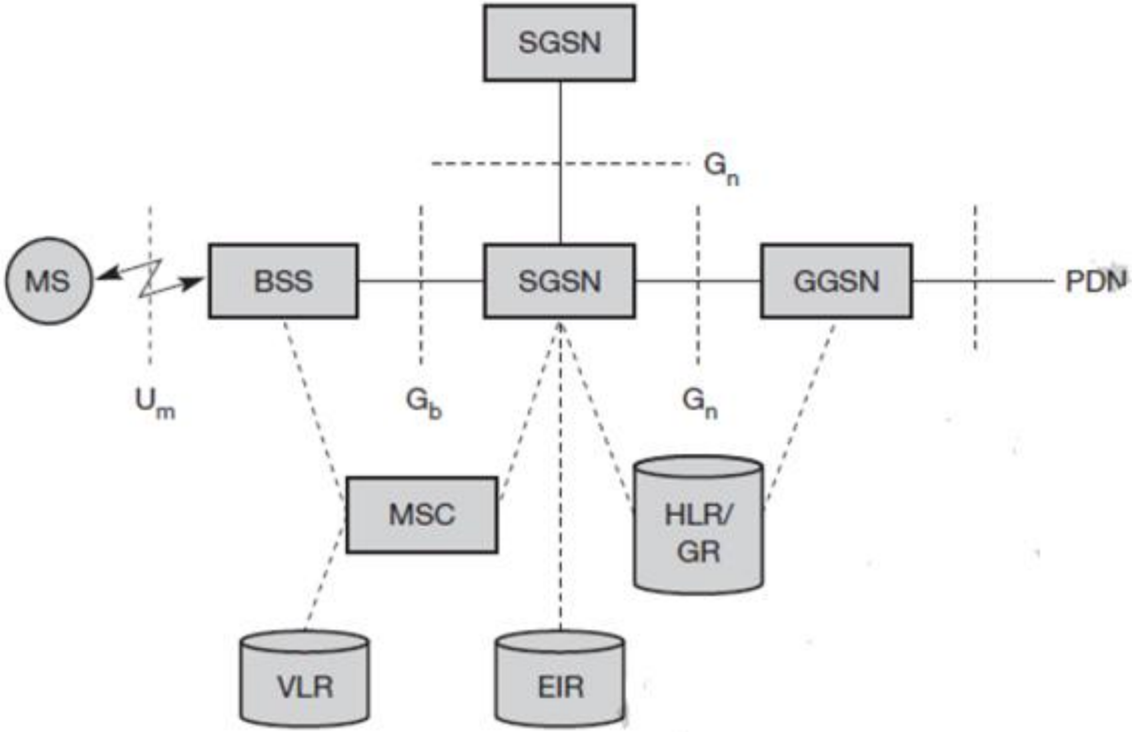
Why 2.5G?

- Need for data services (beyond SMS)
- Email, browsing, multimedia messaging (MMS)

Technology	Enhancement	Data Rate	Description
HSCSD (High Speed Circuit Switched Data)	GSM	~57.6 kbps	Aggregates multiple time slots
GPRS (General Packet Radio Service)	GSM	~171.2 kbps	Packet switching introduced
EDGE (Enhanced Data rates for GSM (or Global) Evolution)	GSM	~384 kbps	Uses 8-PSK modulation for higher data

GPRS Architecture Additions

- New Network Elements:
  - SGSN: Serves mobile packet data
  - GGSN: Gateway to external IP networks
- Packet-switched Core Integration



GPRS Throughput Estimation

Q) How much throughput can a user get if allocated 4 time slots, each giving 21.4 kbps (data rate)?

Solution:

$$\text{Total Throughput} = 4 \times 21.4 = 85.6 \text{ kbps}$$

Evolution for 2.5G TDMA Standards

- HSCSD and GPRS mainly targeted GSM
- IS-136 HS (High-Speed) for North American TDMA:
  - Up to 43.2 kbps
  - Slot aggregation across 3 slots
  - Based on circuit-switching
  - Faced limitations compared to packet-switched GPRS

Introduction to EDGE

EDGE = Enhanced Data rates for GSM Evolution

- Introduced as a **high-speed upgrade** to GPRS
- Backward compatible with GSM
- Known as **EGPRS** (Enhanced GPRS)

Goals:

- Improve spectral efficiency
- Deliver 3G-like data rates over existing 2G infrastructure

EDGE Technical Features

Feature	EDGE
Modulation	**8-PSK** (vs. GMSK in GSM)
Symbol Rate	270.833 ksps (same as GSM)
Bit Rate per Slot	Up to **59.2 kbps**
Max Data Rate	**~384 kbps** with 8 time slots
Coding Schemes	MCS-1 to MCS-9 (modulation + coding)

EDGE Data Rate Calculation

Q) A user is assigned 5 time slots using EDGE with a data rate of 48 kbps per slot. What is the total throughput?

Solution:

- Total Throughput $=5\times48=240$ kbps

IS-95B for 2.5G CDMA

- IS-95B = cdmaOne + Packet Data
- Supported:
  - Up to 14.4 kbps × 8 codes = 115.2 kbps
  - Code multiplexing instead of slot aggregation
- Used pilot, sync, paging, traffic channels more efficiently
- Important Feature:
  - IS-95B allowed simultaneous voice and data transmission

IS-95B Data Rate Calculation

Q) If 6 Walsh codes are used for data, each providing 14.4 kbps, find the user's peak data rate.

– Total Data Rate=$6 \times 14.4 = 86.4$ kbps

2G vs 2.5G – Summary Table

Feature	2G GSM	GPRS/EDGE (2.5G)	IS-95A	IS-95B (2.5G)
Core Switching	Circuit	Packet	Circuit	Circuit + Packet
Data Rate	9.6 kbps	85–171 kbps	14.4 kbps	up to 115 kbps
Access Method	TDMA	TDMA	CDMA	CDMA
Modulation	GMSK	GMSK/8-PSK	QPSK	QPSK

Third Generation (3G) Wireless Networks

Why 3G?

- Increasing demand for mobile internet and multimedia
- 2.5G was data-limited
- Need for global roaming, faster data, and multimedia services
- Multi-megabit Internet access, communications using Voice over Internet Protocol (VoIP), voice-activated calls, unparalleled network capacity, and ubiquitous "always-on" access are just some of the advantages being touted by 3G developers.

3G Network Vision

- Standardized by International Mobile Telephone 2000 (IMT-2000) *(International Telecommunications Union (ITU))*
- Goals:
  - Global mobility
  - High-speed data
  - Video calling, web browsing
- Target data rate:
  - 144 kbps (mobile), 384 kbps (pedestrian), 2 Mbps (indoor)

Key Features of 3G

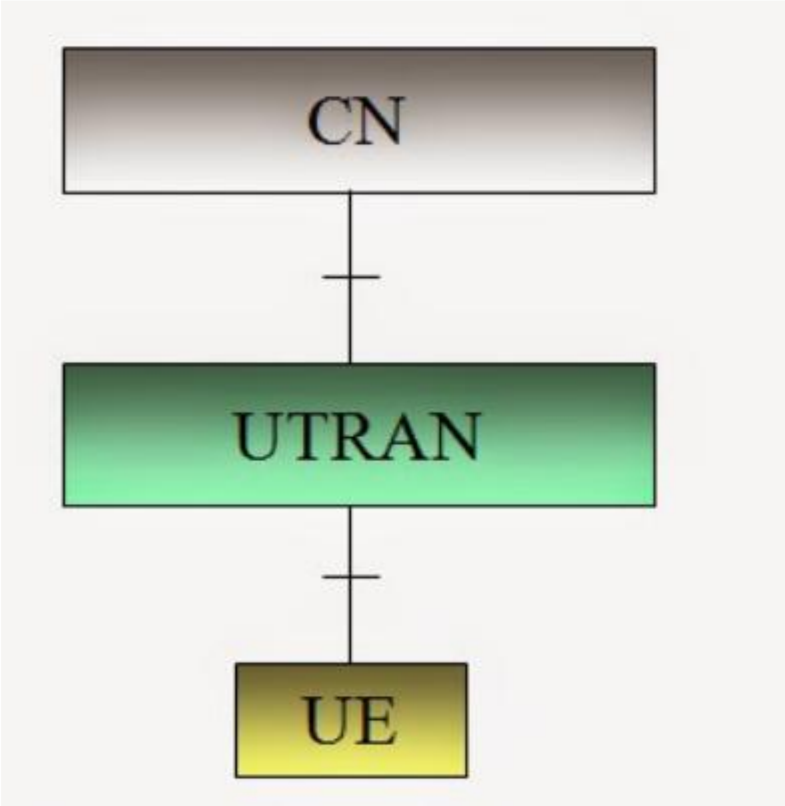
Feature	3G Capability
Technology	W-CDMA, CDMA2000, TD-SCDMA
Data Rates	Up to 2 Mbps
Access Type	CDMA-based (Code Division)
Services	Voice, SMS, MMS, video, web
Mobility Support	Full handoff, seamless IP

IMT-2000 Standards (Overview)

Standard	Access Method	Region	Technology
UMTS (W-CDMA)	CDMA (DS)	Europe, Global	Wideband CDMA (5 MHz channels)
CDMA2000	CDMA (Multi-carrier)	North America	1xRTT (144 kbps), EV-DO (2.4 Mbps)
TD-SCDMA	TDMA/CDMA	China	unique TDD approach

3G System Architecture (UMTS)

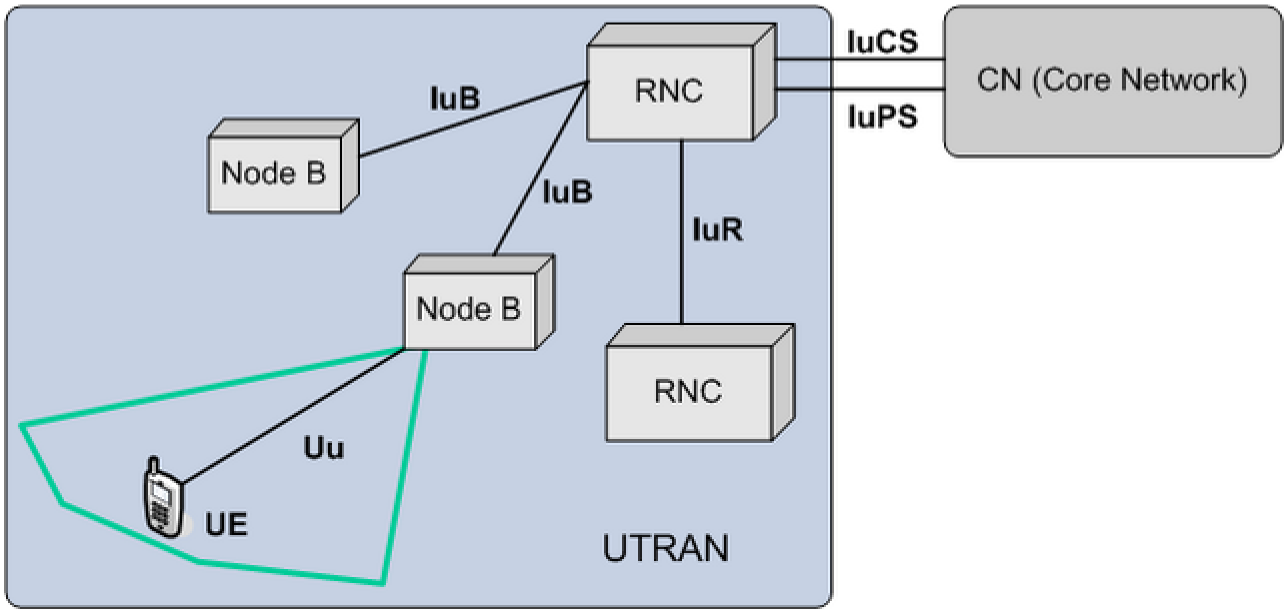
- Core Network (Evolved from GSM/IS-95)
- UMTS Terrestrial Radio Access Network (UTRAN for UMTS)
- UE- User Equipment
- Interfaces: Uu (Radio Interface), Iu (core)



UMTS Architecture

Core Components:

- UE (User Equipment): 3G SIM (USIM).
- Node B: Base station (replaces BTS).
- RNC (Radio Network Controller): Manages handoffs.
- Core Network: Packet-switched (MSC + SGSN/GGSN).



UMTS (Universal Mobile Telecommunications System)

- Based on W-CDMA
- 5 MHz wide channels
- Duplex: FDD and TDD
- Peak data rate: 2 Mbps

UMTS – Air Interface Details

- Chip rate: 3.84 Mcps
- Spreading: Orthogonal Variable Spreading Factor (OVSF)
- Modulation: QPSK
- High spectral efficiency for broadband apps

CDMA2000 Overview

- Evolution of IS-95 CDMA
- Backward compatible
- Family of standards:
  - CDMA2000 1X
  - CDMA2000 1xEV-DO
  - CDMA2000 1xEV-DV

CDMA2000 Technical Features

Version	Max Data Rate	Channel BW
1X	153 kbps	1.25 MHz
1xEV-DO Rev 0	2.4 Mbps DL	1.25 MHz
1xEV-DO Rev A/B	Up to 3.1 Mbps	1.25 MHz

Comparison – UMTS vs CDMA2000

Feature	UMTS (W-CDMA)	CDMA2000
BW	5 MHz	1.25 MHz
Deployment	Europe, Asia	North America
Data Speed	Up to 2 Mbps	Up to 3.1 Mbps
Evolution	LTE	EV-DO → LTE

Numerical Example – Chip Rate

Q: What is the chip duration for a UMTS system with 3.84 Mcps?

Solution:

$$
\begin{aligned}
\text{Chip Duration} &= 1/\text{Chip Rate} \\
&= 1/(3.84\times10^{6}) \\
&\approx 260.4\ \text{ns}
\end{aligned}
$$

Data Rate Calculation – CDMA2000

Q: A user is allocated 1.25 MHz CDMA2000 channel with 1xEV-DO. What is the peak downlink rate?

Solution

- Peak Rate=2.4 Mbps (Rev 0)

TD-SCDMA (Time Division – Synchronous CDMA) – An Overview

- **Developed by:** China Academy of Telecommunications Technology (CATT) with support from Datang and Siemens
- **Standardized by:** 3GPP as part of IMT-2000

Key Features:

- **Access Scheme**: Time Division Duplex (TDD) + CDMA
- **Bandwidth**: 1.6 MHz per carrier
- **Chip Rate**: 1.28 Mcps
- **Asynchronous CDMA replaced by**: **Synchronous transmission**
- **High spectral efficiency** due to flexible uplink/downlink switching

Design Goals

- Reduce dependency on foreign patents
- Optimize for **urban/high-density** environments
- Tailor 3G deployment to China’s traffic pattern: **more downlink than uplink**

TD-SCDMA – Technical Highlights

Modulation & Multiple Access:

- **Modulation**: QPSK, π/4 DQPSK
- **Multiple Access**:
  - **TDMA** (Time Division)
  - **CDMA** (Code Division)
  - **Smart Antennas** (beamforming for interference control)

Frame Structure:

- 10 ms frame → 7 slots for data, 1 pilot, 2 guard
- Dynamic timeslot allocation for uplink/downlink

Applications Enabled by 3G

- Web Browsing
- Video Calls
- Email on Mobile
- Real-time Navigation
- Streaming Audio/Video

Evolution Beyond 3G (Teaser)

- UMTS → HSPA → HSPA+
- CDMA2000 → EV-DO Rev B → LTE
- Both paths led to 4G (LTE) and 5G

Challenges in 3G Deployment

- Expensive spectrum licenses
- Infrastructure overhaul
- Power consumption
- Interference and handover issues

Security in 3G

- **UMTS Security**:
  - **AKA Protocol**: Mutual authentication.
  - **128-bit Encryption** (KASUMI cipher).
- **CDMA2000 Security**:
  - Enhanced long-code masks.
- **Critique**: Vulnerabilities (e.g., false base stations)

Wireless Data Technologies	Channel BW	Duplex	Infrastructure change	Requires New Spectrum	Requires New Handsets
HSCSD	200 KHz	FDD	Requires software upgrade at base station.	No	Yes New HSCSD handsets provide 57.6 Kbps on HSCSD networks, and 9.6 Kbps on GSM networks with dual mode phones. GSM-only phones will not work in HSCSD networks.
GPRS	200 KHz	FDD	Requires new packet overlay including routers and gateways.	No	Yes New GPRS handsets work on GPRS networks at 171.2 Kbps, 9.6 Kbps on GSM networks with dual mode phones. GSM-only phones will not work in GPRS networks.
EDGE	200 KHz	FDD	Requires new transceiver at base station. Also, software upgrades to the base station controller and base station.	No	Yes New handsets work on EDGE networks at 384 Kbps, GPRS networks at 144 Kbps, and GSM networks at 9.6 Kbps with tri-mode phones. GSM and GPRS-only phones will not work in EDGE networks.
W-CDMA	5 MHz	FDD	Requires completely new base stations.	Yes	Yes New W-CDMA handsets will work on W-CDMA at 2 Mbps, EDGE networks at 384 Kbps, GPRS networks at 144 Kbps, GSM networks at 9.6 Kbps. Older handsets will not work in W-CDMA.
IS-95B	1.25 MHz	FDD	Requires new software in base station controller.	No	Yes New handsets will work on IS-95B at 64 Kbps and IS-95A at 14.4 Kbps. CdmaOne phones can work in IS-95B at 14.4 Kbps.
cdma2000 1xRTT	1.25 MHz	FDD	Requires new software in back-bone and new channel cards at base station. Also need to build a new packet service node.	No	Yes New handsets will work on 1xRTT at 144 Kbps, IS-95B at 64 Kbps, IS-95A at 14.4 Kbps. Older handsets can work in 1xRTT but at lower speeds.
cdma2000 IxEV (DO and DV)	1.25 MHz	FDD	Requires software and digital card upgrade on 1xRTT networks.	No	Yes New handsets will work on 1xEV at 2.4 Mbps, 1xRTT at 144 Kbps, IS-95B at 64 Kbps, IS-95A at 14.4 Kbps. Older handsets can work in 1xEV but at lower speeds.
cdma2000 3xRTT	3.75 MHz	FDD	Requires backbone modifica-tions and new channel cards at base station.	Maybe	Yes New handsets will work on 95A at 14.4 Kbps, 95B at 64 Kbps, 1xRTT at 144 Kbps, 3xRTT at 2 Mbps. Older handsets can work in 3X but at lower speeds.

3.5G – High-Speed Enhancements to 3G

Why 3.5G?

- 3G was not enough for:
  - Rich multimedia
  - HD video streaming
  - Mobile apps with high throughput
- Need for **higher data rates** and **lower latency**
- Thus, **3.5G** evolved.

What is 3.5G?

- 3.5G = Enhanced 3G technologies
- **HSPA (HSDPA + HSUPA)** for UMTS
- **EV-DO Rev A/B** for CDMA2000

HSPA – High Speed Packet Access

Feature	HSDPA (Downlink)	HSUPA (Uplink)
Channel BW	5 MHz	5 MHz
Peak Rate	14.4 Mbps	5.76 Mbps
Latency	<100 ms	<150 ms
Tech Used	Adaptive Modulation, HARQ, Fast Scheduling	

HSPA – Technical Details

- Modulation: QPSK, 16-QAM
- HARQ: Hybrid Automatic Repeat Request improves reliability
- Fast scheduling: Node B (base station) allocates resources per user demand

Numerical Example – HSPA Data Rate

Q: Calculate spectral efficiency of HSDPA at 14.4 Mbps over 5 MHz channel.

Spectral Efficiency=14.4 Mbps/5 MHz

=2.88 bps/Hz

CDMA2000 EV-DO Rev A/B

Version	Peak DL Speed	Uplink Speed	Uses
Rev A	3.1 Mbps	1.8 Mbps	VoIP, apps
Rev B	Up to 14.7 Mbps	Higher	Streaming

4G – The Mobile Broadband Revolution

Limitations of 3G/3.5G:

- Limited spectral efficiency
- High latency
- Circuit-switched core
- Can’t handle video + real-time apps

4G = All-IP, High Speed, Low Latency

4G System Goals (ITU-R IMT-Advanced)

- Peak DL/UL Speed: 1 Gbps / 100 Mbps
- Latency: <10 ms
- Spectrum: Scalable from 1.4 MHz to 20 MHz
- IP-Based: All services over IP
- Seamless handoff and roaming

What is LTE (Long Term Evolution)?

- Developed by 3GPP
- Uses OFDMA (DL) and SC-FDMA (UL)
- Flat all-IP architecture
- No backward compatibility with 3G CDMA

LTE – Technical Specifications

Feature	LTE
Modulation	QPSK, 16-QAM, 64-QAM
Peak DL / UL Speed	100 Mbps / 50 Mbps
Bandwidth	Up to 20 MHz
Duplexing	FDD & TDD
Latency	< 10 ms

LTE Data Rate Calculation

Q: What is the data rate for a 10 MHz LTE channel with 64-QAM (6 bits/symbol), 1 OFDM symbol/ms?

Data Rate$=10\times10^{6}$ Hz$\times$(6 bits/symbol)

=60 Mbps (approx, theoretical peak)

Global LTE Adoption

- First LTE launch: TeliaSonera, 2009
- Now globally adopted
- Different spectrum bands across countries
- LTE paved the way for 5G NR

LTE-Advanced (Release 10)

- First true **4G (IMT-Advanced) standard**

Feature	LTE-A
Carrier Aggregation	Yes (up to 100 MHz)
DL Speed	Up to 1 Gbps
MIMO	4x4 and 8x8 Supported
Relay Nodes	Supported

Key Technologies in 4G

- OFDMA: Orthogonal frequency multiplexing
- MIMO: Multiple antennas for higher throughput
- Carrier Aggregation
- Adaptive Modulation & Coding

3G vs 3.5G vs 4G – Comparison Table

Feature	3G (UMTS/ CDMA2000)	3.5G (HSPA/EV-DO)	4G (LTE)
Max Speed (DL)	2 Mbps	14.4–30 Mbps	Up to 1 Gbps
Latency	~150–200 ms	~100 ms	<10 ms
Architecture	Circuit/IP Hybrid	IP-focused	All-IP
Modulation	QPSK	16-QAM	64-QAM, OFDMA

Wireless Local Loop (WLL) and LMDS

What is Wireless Local Loop (WLL)?

WLL is a system that connects subscribers to the public switched telephone network (PSTN) using wireless technology instead of copper wires.

Key Characteristics:

- Fixed wireless access
- Last-mile connectivity
- Rapid deployment in remote areas

Use Case: Ideal for rural or underdeveloped regions where laying cable is impractical

WLL Architecture

- Base Station: Interfaces with PSTN
- Subscriber Unit: Indoor or outdoor fixed transceiver
- Air Interface: FDMA/TDMA/CDMA depending on system
- Coverage: 5–10 km radius typical

WLL Architecture

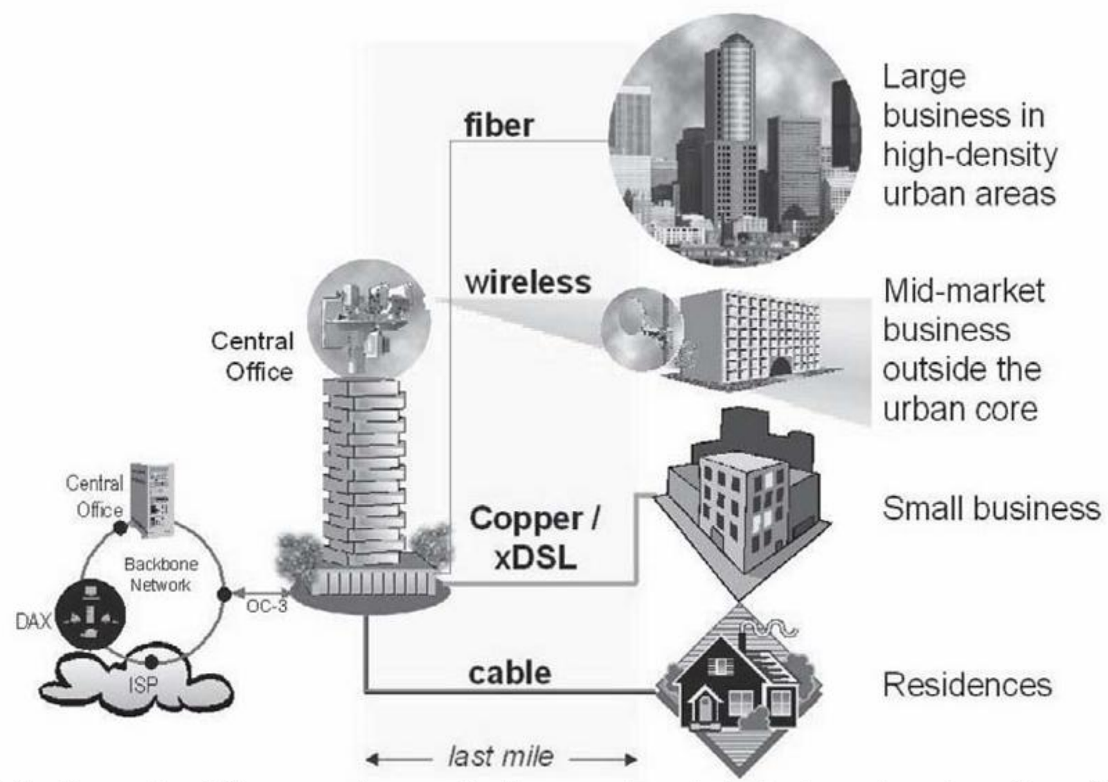


Figure 2.4 Example of the emerging applications and markets for broadband services. (Courtesy of Harris Corporation, ©1999, all rights reserved.)

Local Multipoint Distribution Service (LMDS)

LMDS is a broadband wireless access system that operates in the 28 GHz or higher band, providing high-speed voice, video, and data.

Key Features:

- Point-to-multipoint
- Requires Line-of-Sight (LOS)
- Data rates: 1 Mbps – >100 Mbps
- Range: 1–5 km (high frequency → short range)

LMDS vs WLL

Feature	WLL	LMDS
Frequency Band	< 3 GHz	~28 GHz
Use Case	Telephony (voice, low data)	Broadband (data/video/voice)
Coverage	~10 km	~2–5 km
Line-of-Sight	Not mandatory	Strict LOS required

Applications of WLL and LMDS

- Rapid telecom rollout
- Internet access in urban clusters
- Backup connectivity
- Campus communication networks
- Disaster recovery and emergency services

Wireless Local Area Networks (WLANs)

WLANs provide wireless communication over a local area using radio frequencies (typically 2.4 GHz or 5 GHz).

Standard: IEEE 802.11

Advantages:

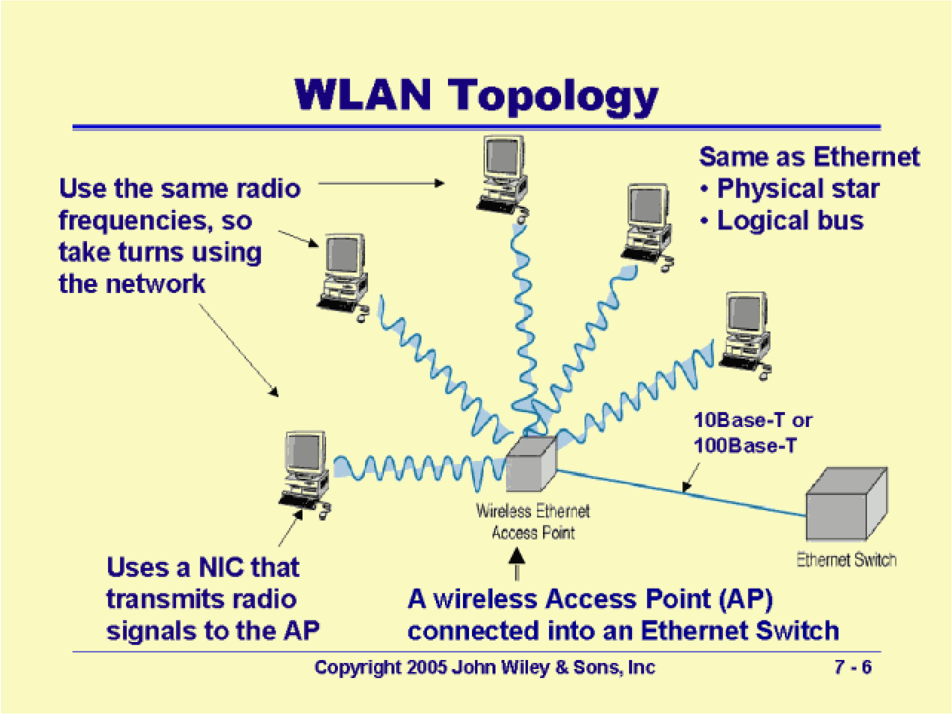
- Mobility
- Easy installation
- Cost-effective for small networks

IEEE 802.11 Standards Summary

Standard	Frequency	Max Speed	Modulation
802.11b	2.4 GHz	11 Mbps	DSSS
802.11a	5 GHz	54 Mbps	OFDM
802.11g	2.4 GHz	54 Mbps	OFDM
802.11n	2.4/5 GHz	600 Mbps	OFDM + MIMO
802.11ac	5 GHz	>1 Gbps	OFDM, MU-MIMO

WLAN Architecture

- Access Point (AP): Acts as a base station
- Stations: Laptops, phones, IoT devices
- Distribution System: Connects APs to wired network



WLAN Modes of Operation

- Infrastructure Mode
  - Devices communicate via AP
- Ad-hoc Mode
  - Peer-to-peer communication without AP

Security Concerns in WLANs

- Threats: Eavesdropping, Rogue APs, DoS attacks
- Encryption: WEP (weak), WPA, WPA2, WPA3 (secure)
- Best Practices:
  - Use strong passwords
  - Enable MAC filtering
  - Disable SSID broadcast when possible

WLAN vs WLL/LMDS – Quick Comparison

Feature	WLAN	WLL	LMDS
Coverage Area	Local (~100m)	~10 km	~2–5 km
User Mobility	High	Low (fixed user)	Low (fixed user)
Purpose	LAN networking	PSTN access	Broadband access

Bluetooth and Personal Area Networks (PANs)

What is a Personal Area Network (PAN)?

- A PAN is a short-range network used for communication between devices within ~10 meters
- Typical Devices: Smartphones, laptops, tablets, smartwatches, earbuds
- Communication Technologies:
  - Bluetooth
  - ZigBee
  - Infrared (IrDA)
  - UWB (Ultra-Wideband)

What is Bluetooth?

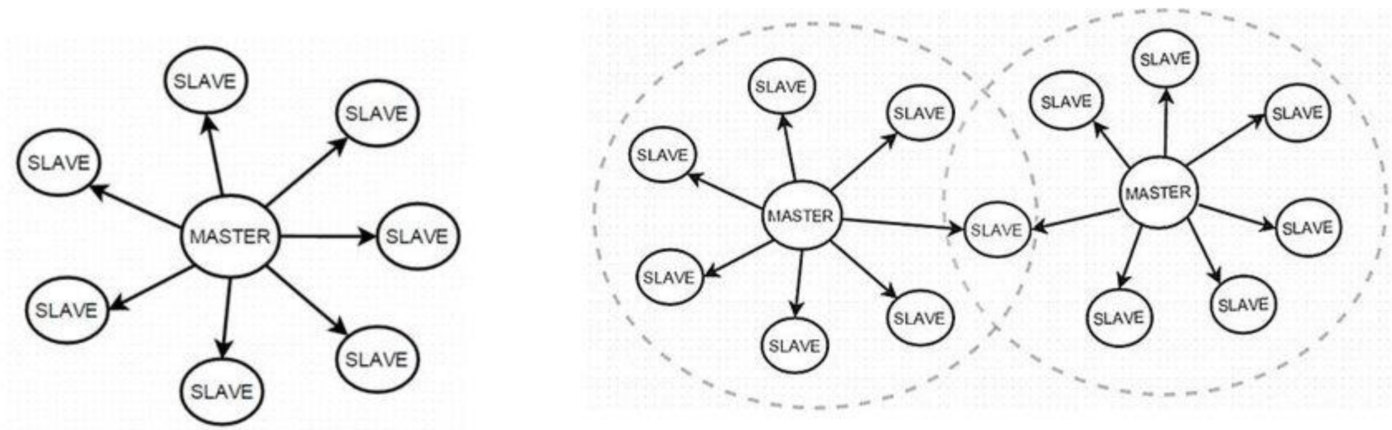
- Wireless standard for PANs
- Operates in 2.4 GHz ISM band
- Based on frequency-hopping spread spectrum (FHSS)
- Developed by Ericsson, standardized as IEEE 802.15.1

Bluetooth – Key Specifications

Feature	Value
Frequency Band	2.4 GHz ISM
Range	10 m (Class 2), up to 100 m (Class 1)
Data Rate	~1 Mbps (Classic), up to 2–3 Mbps (EDR)
Channels	79 channels (1 MHz spacing)
Topology	Master-Slave (Piconet)

Bluetooth Architecture

- Piconet: 1 master + up to 7 active slaves
- Scatternet: Multiple interconnected piconets
- Frequency hopping at 1600 hops/sec for interference resilience



a) Piconet

b) Scatternet with 2 piconets

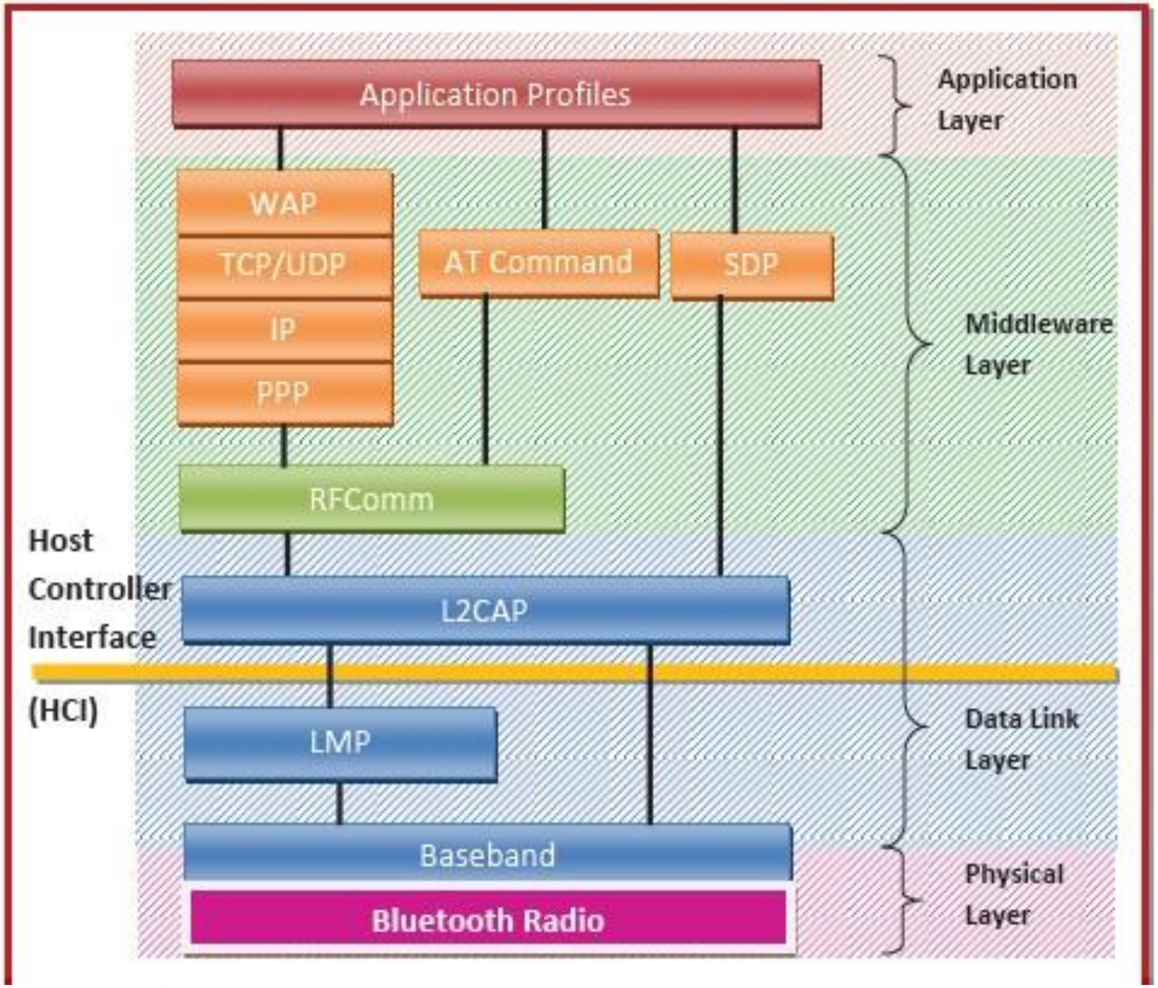
Bluetooth Device Classes

Class	Power (mW)	Range (Approx.)
Class 1	100 mW	~100 meters
Class 2	2.5 mW	~10 meters
Class 3	1 mW	~1 meter

Bluetooth Protocol Stack

- Radio Layer
- Baseband
- Link Manager Protocol (LMP): Used to control and negotiate all aspects of the operation of the Bluetooth connection between two devices.
- Logical Link Control & Adaptation Protocol (L2CAP): Manages the multiplexing and demultiplexing of multiple packet sources
- Host Controller Interface (HCI): provides a command interface to the baseband controller and link manager, and access to hardware status and control registers
- Application Protocols (RFCOMM, SDP, etc.): Provides a reliable, serial-port-like connection for data transfer, often used for legacy applications requiring serial communication.

Bluetooth Protocol Stack



Bluetooth Use Cases

- Wireless headsets & earphones
- File transfer between devices
- Keyboard/mouse connectivity
- Car infotainment systems
- IoT/smart devices

Limitations of Bluetooth

- Lower data rate than Wi-Fi
- Susceptible to interference in crowded 2.4 GHz band
- Not suitable for high-bandwidth or long-range apps
- Connection latency in older versions

PAN vs LAN vs WAN

Network Type	Range	Examples
PAN	~10 m	Bluetooth, ZigBee
WLAN	~100 m	Wi-Fi (802.11)
WAN	~km–1000s	Cellular, Internet

Chapter 2 Completed