Mobile/Cellular Networks

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Overview

- Mobile phone subscriptions worldwide reached almost 7 billion at the end of 2014 ➔ 96% penetration rate [ITU ICT Facts and Figures, 2014]
  - More than fixed Internet hosts and telephone lines combined
  - In the UK, more than 83 million mobile phone users ➔ 1.3 mobile phones per person!
- Originally intended for mobile voice communication
- But increasingly data oriented to keep up with the demand for mobile Internet use from smartphones, tablets and USB mobile broadband dongles
  - Note that texting (SMS) is also a form of data communication
- Use on the move and everywhere ➔ need blanket wide area coverage, even across country borders
  - Blanket coverage especially crucial to support emergency calls

Overview (Contd.)

- Also known as:
  - Mobile (broadband) networks
  - Mobile cellular networks
  - Public land mobile network (PLMN)

- We will study:
  - Cellular concept
  - Historical evolution of cellular technologies
  - Take a closer look at 2G/3G/4G cellular systems based on 3GPP standards

Cellular Concept
Motivation: Efficient Use of Scarce Spectrum

- Design approach for early mobile radio systems: a single, high-powered transmitter with an antenna mounted on a tall tower to cover a large service area (e.g., city)
- Similar to over-the-air radio and television broadcasting
- Works well from a coverage perspective
- But system capacity (e.g., number of simultaneous mobile users or voice calls supported) limited by available spectrum, which is scarce and tightly regulated
- E.g., Bell mobile system in New York City in the 1970s could only support a max. of 12 simultaneous calls over a thousand square miles area

Cellular Concept

- Replace a high power transmitter with many lower power transmitters, each covering only small portion of the service area called a *cell*
- Channel allocation and *frequency reuse*:
  - Each transmitter (base station) is allocated a portion of the available spectrum, specifically a subset of channels from the total number of channels available
  - Neighbouring base stations assigned different sets of channels to minimize mutual interference
  - Base stations that are further away can reuse the same set of channels, exploiting signal power falloff with distance

Cellular System Capacity

- Let S be the total number of channels available
- Each cell allocated a subset of k $(k < S)$ channels
- If S channels evenly distributed among N neighbouring cells, collectively called a **cluster**:

  $S = k \times N$

- **Frequency reuse factor**: N
- If a cluster is replicated M times in the system then system capacity, C, can be measured as:

  $C = M \times k \times N = M \times S$

- The parameters M and N allow the system designer control over the system capacity even if available spectrum is fixed and limited
- Increase M to increase C, by:
  - Reducing cell size (e.g., macrocells ➔ microcells)

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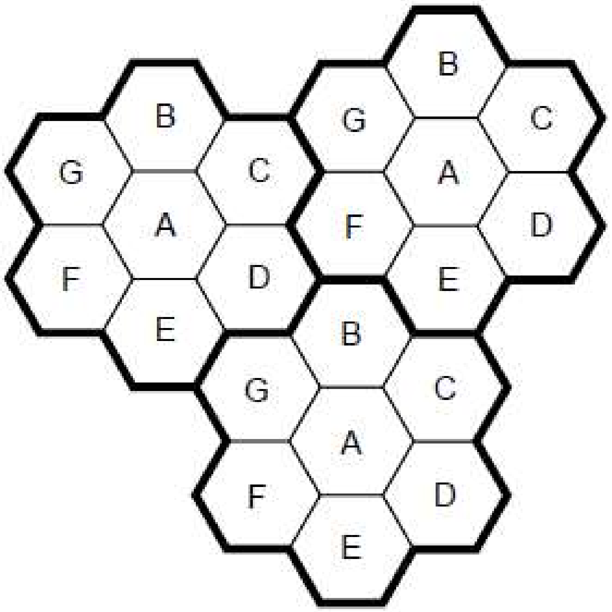
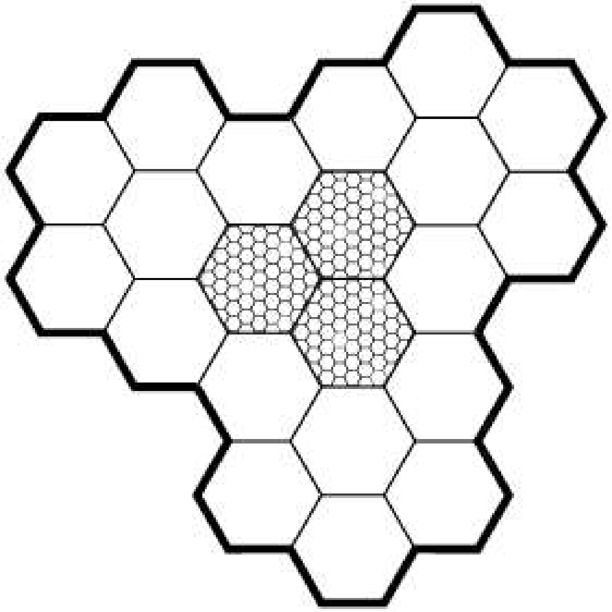
Illustrating the Impact of Cellular Frequency Reuse and Cell Size on System Capacity

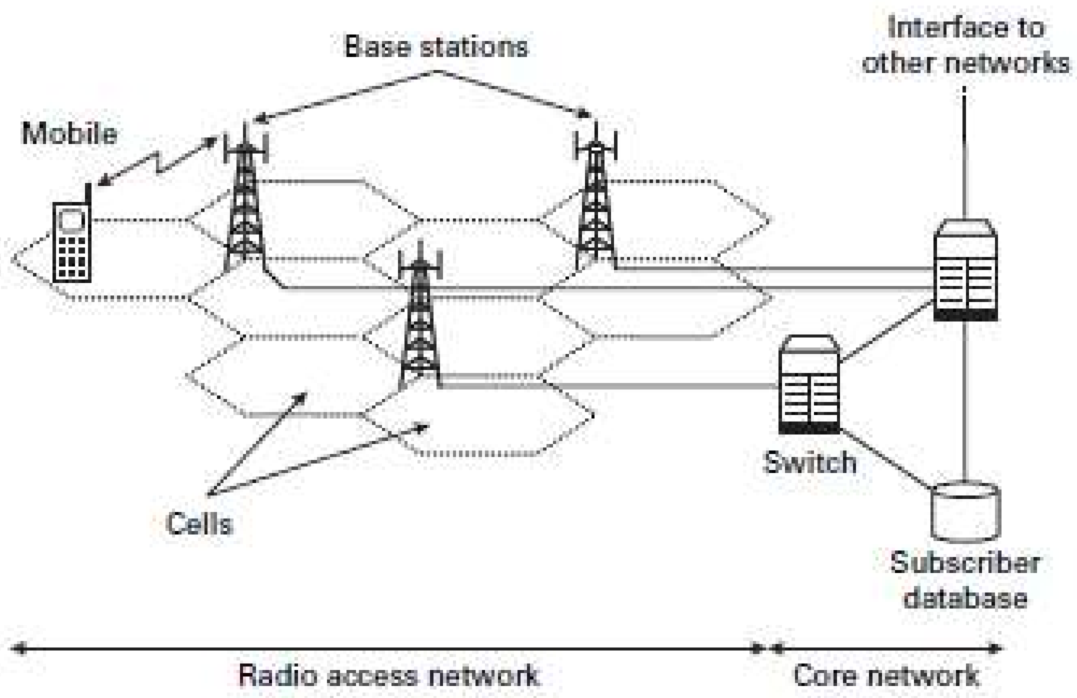


Cellular frequency reuse pattern: cell cluster outlined in **bold** is replicated over the coverage area



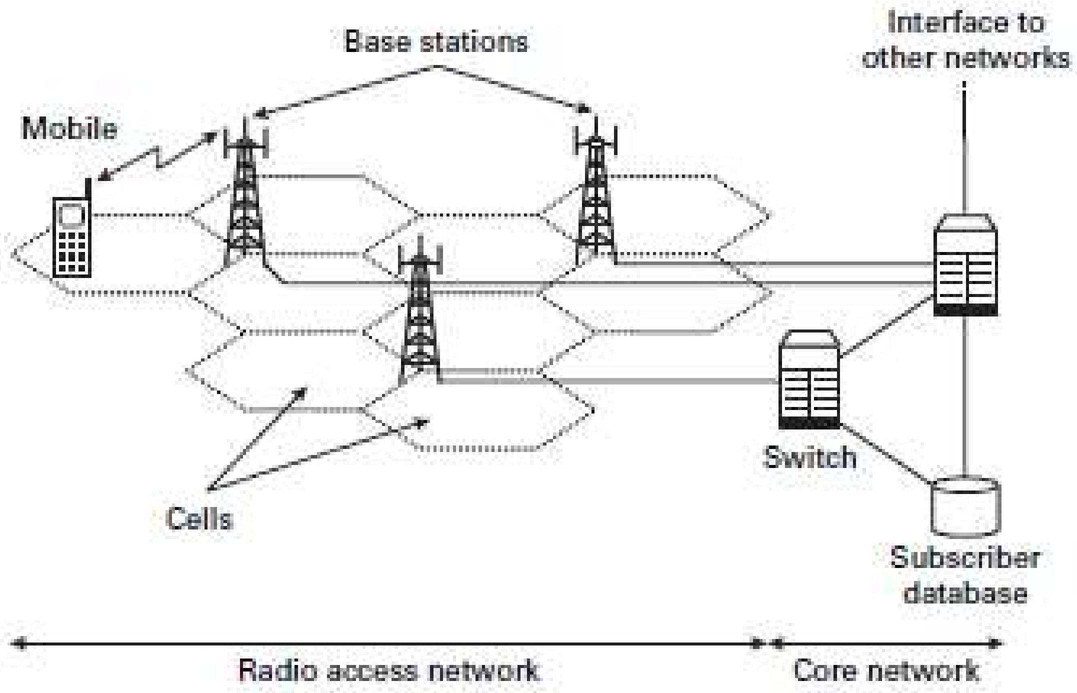
Smaller cells for increased system capacity

A Simplified Cellular Network Architecture & Terminology



- **Mobile phone** also known as: **mobile**, **cell phone**, **user equipment (UE)** from UMTS (a third-generation cellular technology standard) onwards
- **Air interface** or **radio interface**
  - **Downlink (DL)** or **forward link**: from base station to mobile
  - **Uplink (UL)** or **reverse link**: from mobile to base station

A Simplified Cellular Network Architecture & Terminology



- **Base station**
  - Typically located at corner of a cell and area around it divided into multiple sectors, each served by a different sector antenna
- Cells of different sizes and overlapping cells:
  - **Macrocells** (coverage up to few kms)
  - **Microcells** (up to few hundreds of metres)
  - **Picocells** (up to few tens of metres)
  - **Femtocells** (cover a few metres across such as a home)

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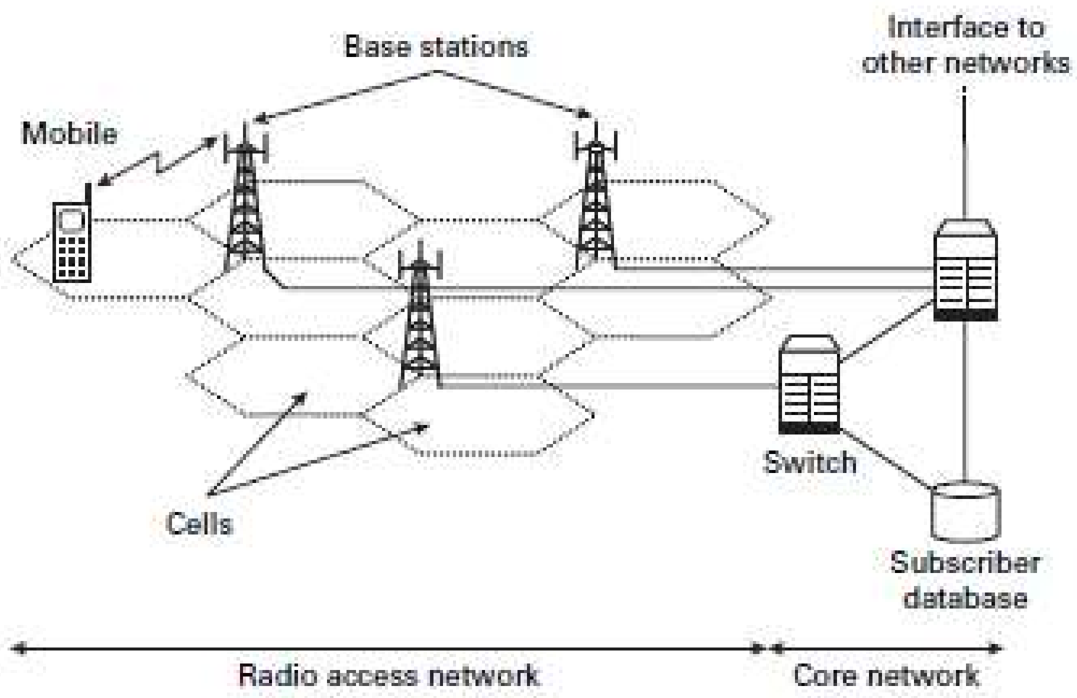
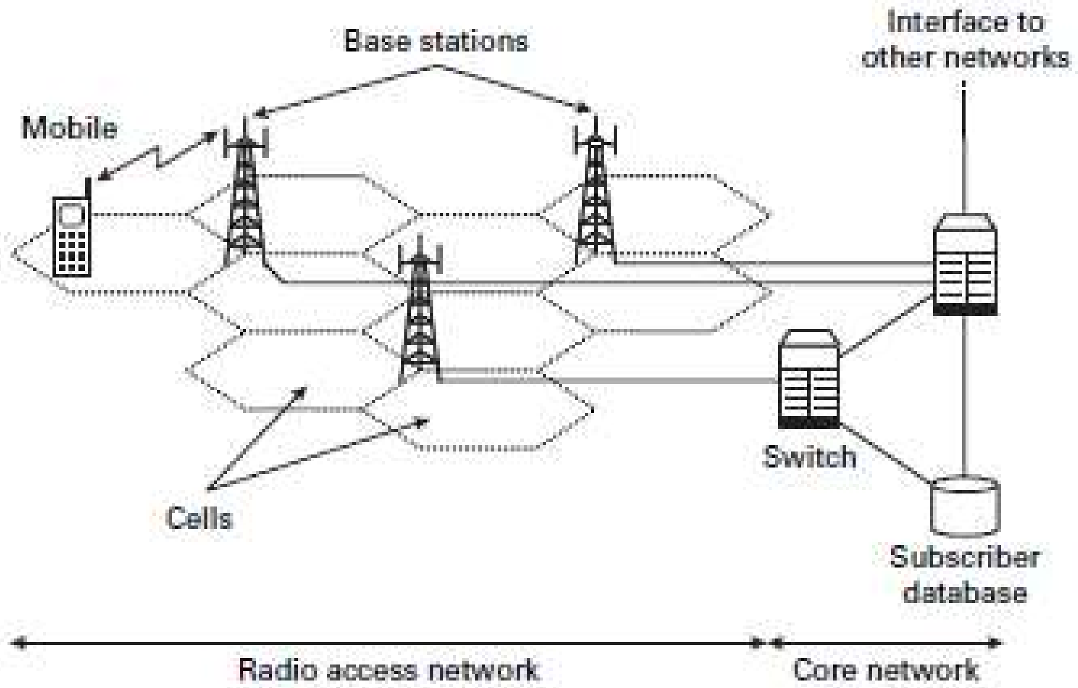
A Simplified Cellular Network Architecture & Terminology



- **Radio Access Network (RAN):** the access part of the cellular network that consists of base stations and controllers, and provides connectivity between mobiles and core network
- **Core Network:** interconnects RANs and also connects them to external networks, including telephone network and Internet

A Simplified Cellular Network Architecture & Terminology



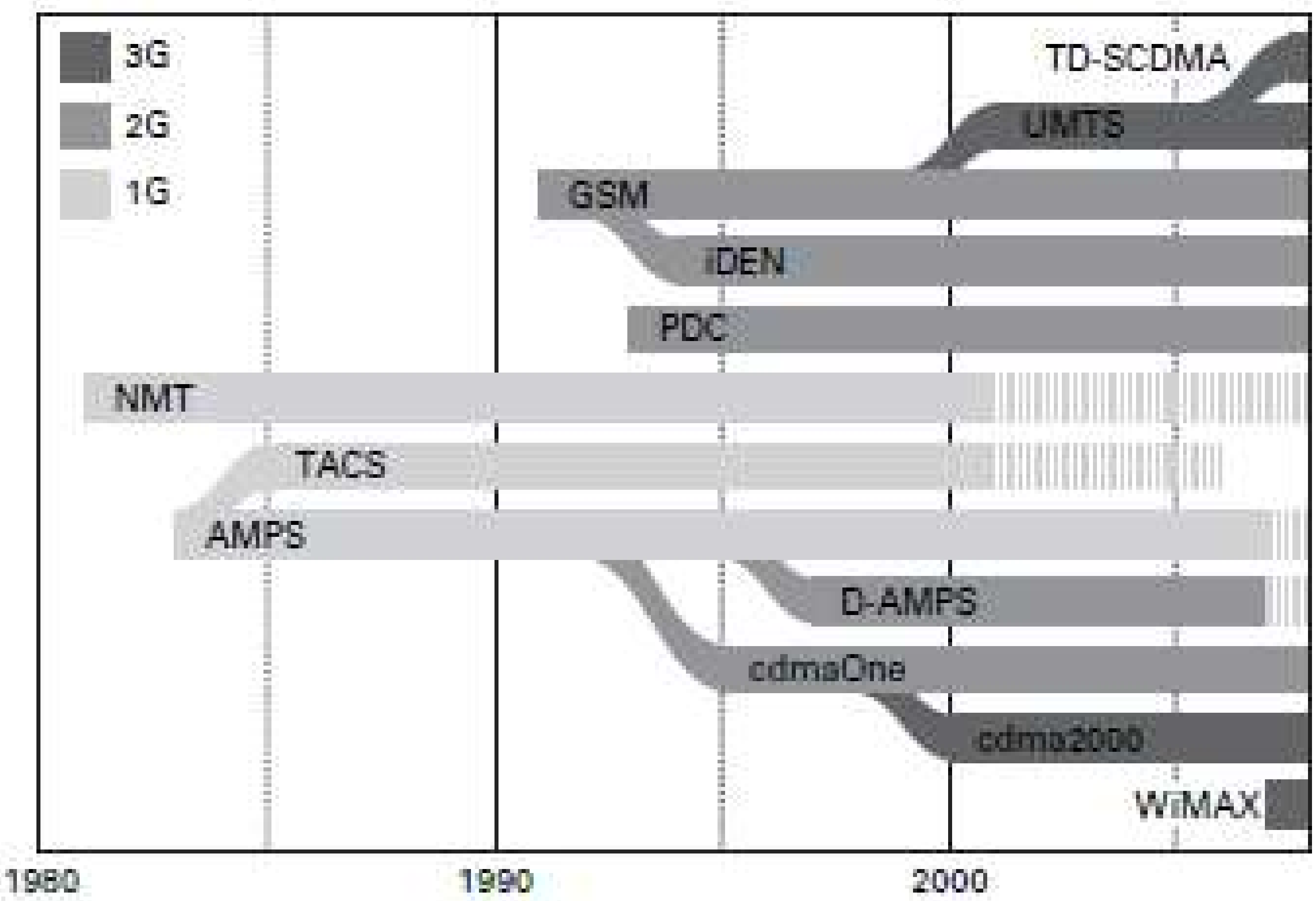
- **Handover/Handoff**: the process of switching connectivity for a mobile from one cell to another (e.g., while moving); can be hard vs. soft
- **Home network:** the cellular network of a mobile's operator
- **Visited network:** a cellular network different from that of a mobile's operator
- **Roaming:** when a mobile connects via a visited network

Evolution of Cellular Network Technologies/Standards

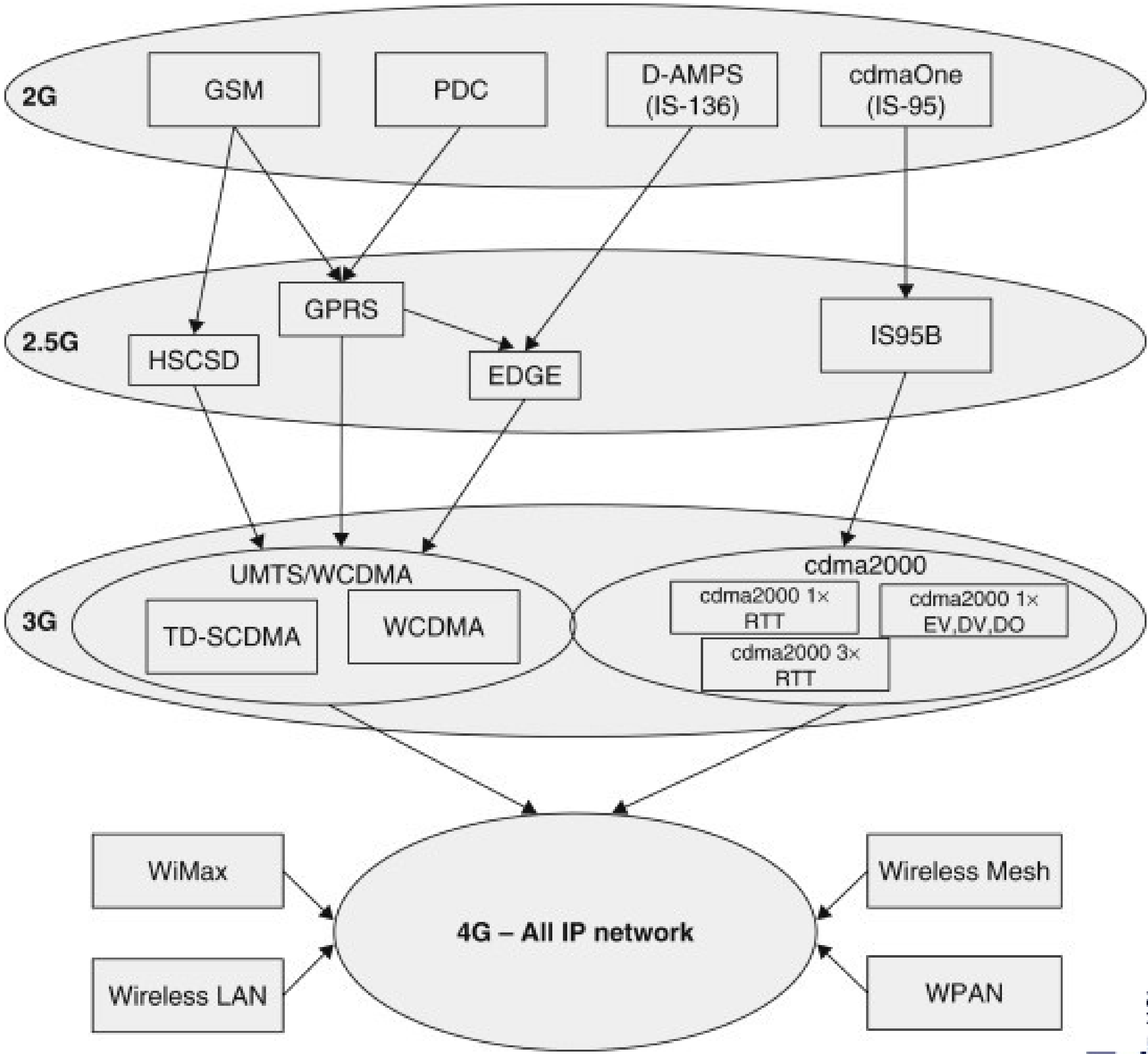
- As different generations: first generation – 1G, second generation – 2G, ..
  - 1G: analogue, voice only, based on FDMA
  - 2G: digital, initially designed for voice but later extended to support data (2.5G)
  - 3G: digital voice and data with greater emphasis on data and higher data rates
  - 4G: same as 3G but focus on even higher data rates + all IP core

1G (e.g., AMPS) → **2G** (e.g., GSM, cdmaOne) → **2.5G** (e.g., GPRS, EDGE) → **3G** (e.g., UMTS, cdma2000) → **3.5G** (e.g., HSDPA) → **4G** (LTE, LTE-Advanced)

Another View of the Technology Evolution



Yet Another View of the Evolution



Frequency vs. Time Division Duplex

- Modes to ensure uplink and downlink transmissions do not interfere with each other
- Frequency Division Duplex (FDD)
  - Each base station and mobile pair assigned a pair of frequencies for simultaneous uplink and downlink transmissions
  - More common as it is easier to implement
  - Do not require accurate time synchronization
  - Less prone to interference due to frequency separation
- Time Division Duplex (TDD)
  - Both base station and mobile transmit using the same frequency but at different times ➔ more efficient
  - Also more flexible: if more traffic in downlink than uplink then more time for downlink

Second Generation (2G) Cellular Wireless Technologies

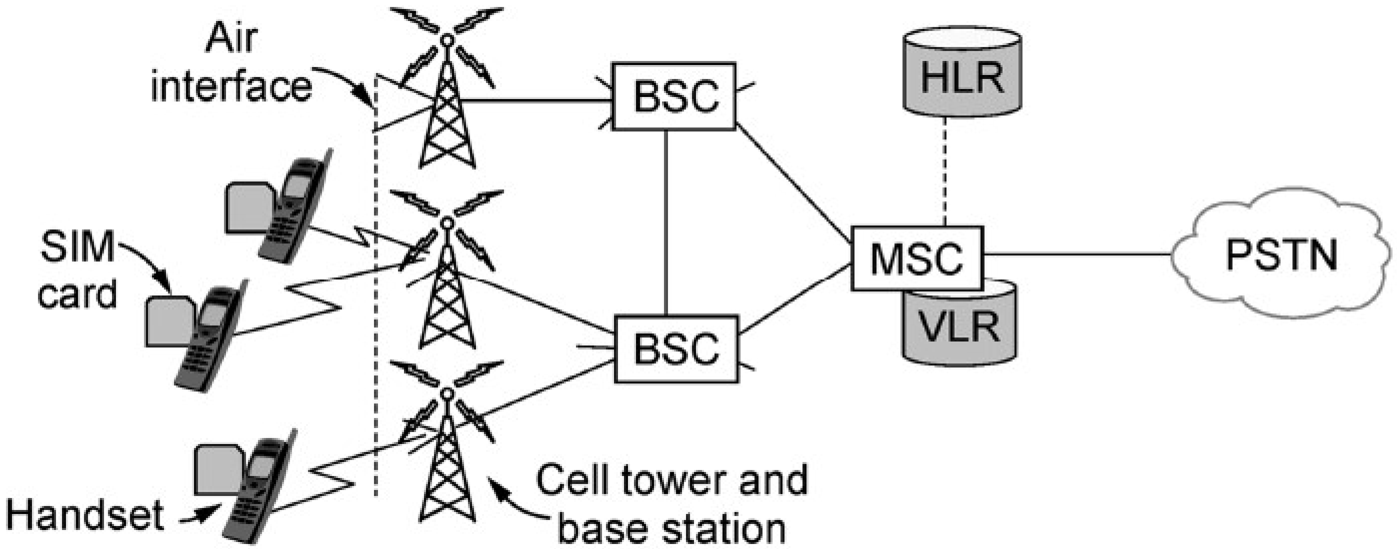
- Major difference from 1G: from analogue to digital
  - Allows compression and encryption ➔ Increased capacity and security
  - Enables inherently digital services (text messaging, email, web access, etc.)
- Sometimes referred to under the name "Personal Communications Services (PCS)"
- Three prominent standards:
  - Digital AMPS (D-AMPS) standardized initially as IS-54 and then as IS-136
    - Originated in US
    - Uses a combination of TDMA and FDMA: TDMA within each full-duplex frequency channel
    - Coexists with AMPS
  - Global System for Mobile Communications (GSM)
    - Originated in Europe, first installed in 1991
    - The dominant 2G technology/standard
    - Like D-AMPS, uses a mix of TDMA and FDMA
  - cdmaOne (IS-95 standard)
    - Based on CDMA

GSM Overview

- Retain several key ideas from 1G systems: cellular design, frequency use and mobility support via handoffs
- But a digital system
- Combined FDM/TDM: 200 KHz bands with each band supporting 8 TDM calls
- Besides voice, provides basic data services (e.g., SMS)
- Mobile now split into two parts:
  1. Handset
  2. SIM (Subscriber Identity Module) card
     - *Removable* chip with subscriber and account info
     - Needed to activate handset
     - Contains security keys

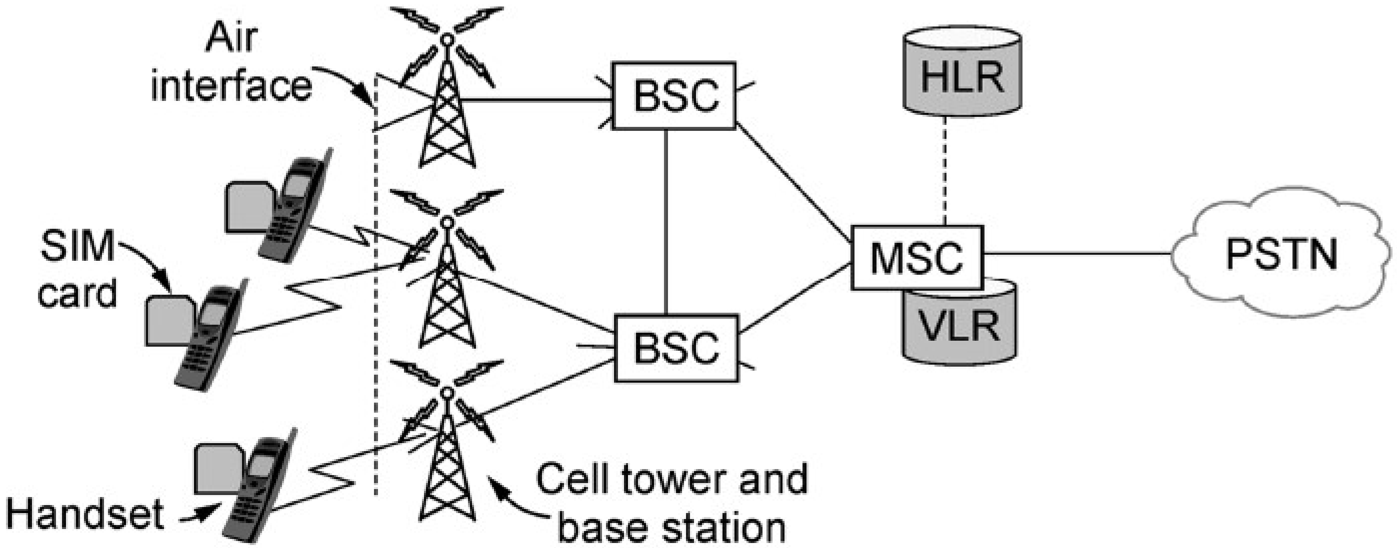
GSM Architecture

- Elements of GSM architecture:
  - Mobile subscribers
  - BTS (base transceiver station)
  - BSC (base station controller)
  - BSS (base station system): BSC + BTSs
  - MSC (mobile switching centre)



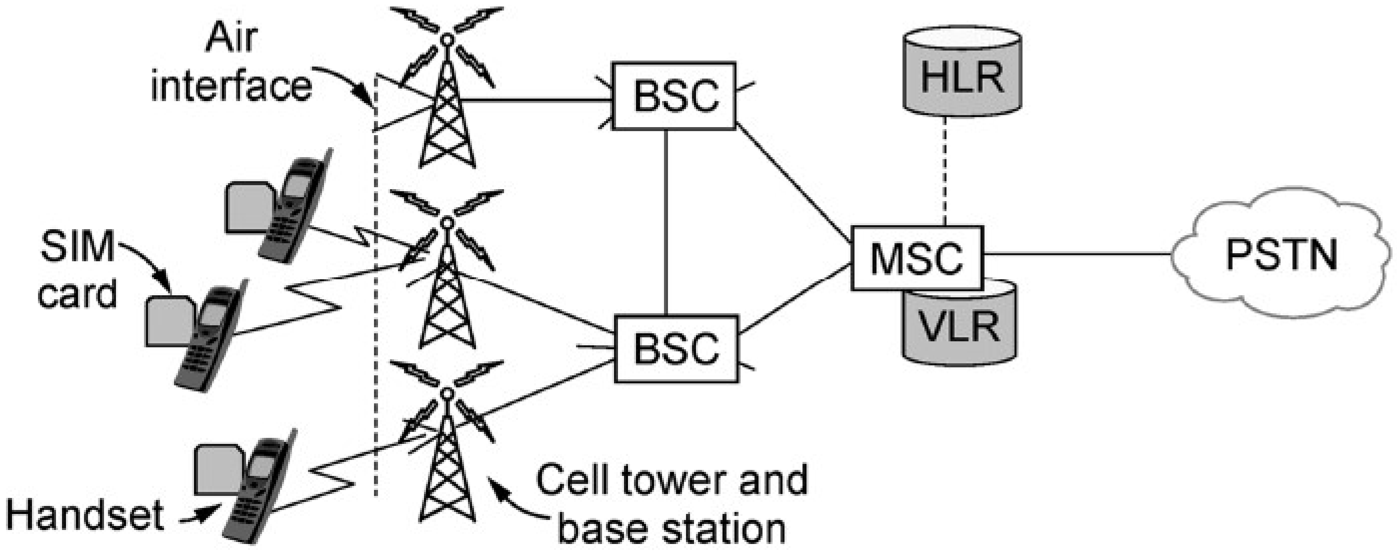
GSM Architecture (contd.)

- Base Station Controller (BSC)
  - Serves several tens of BTSs
  - Manages radio resources of cells (e.g., allocates BTS radio channels to mobile subscribers)
  - Performs paging (finding the cell where the mobile user is currently present)
  - Controls handoffs among BTSs within the same BSS



GSM Architecture (contd.)

- Mobile Switching Centre (MSC)
  - Plays the key role in user authorization, accounting, call establishment/teardown and handoffs
    - ➢ Facilitates handoffs across different BSCs
  - Manages subscriber database and up-to-date location of mobiles via Home Location Register (HLR) and Visitor Location Register (VLR)
  - Gateway MSC connects to the larger public telephone network (PSTN)
  - One MSC for every 5 BSCs and ~200K subscribers

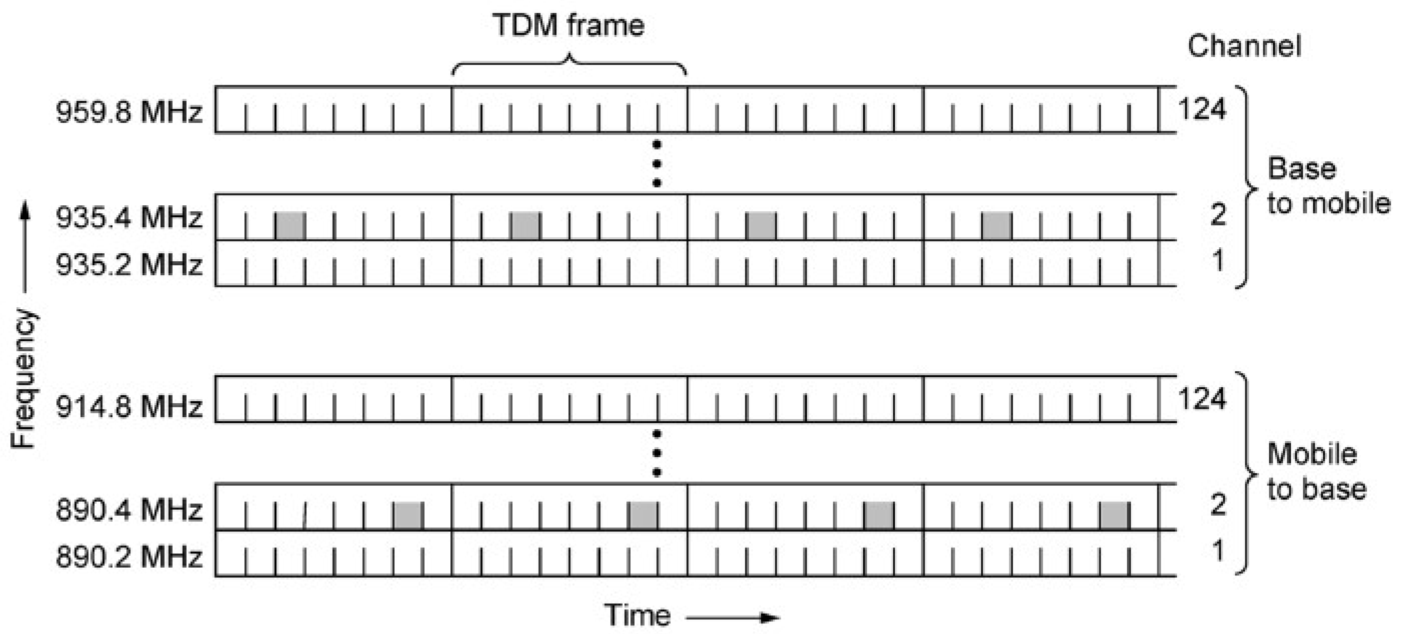


GSM Channels

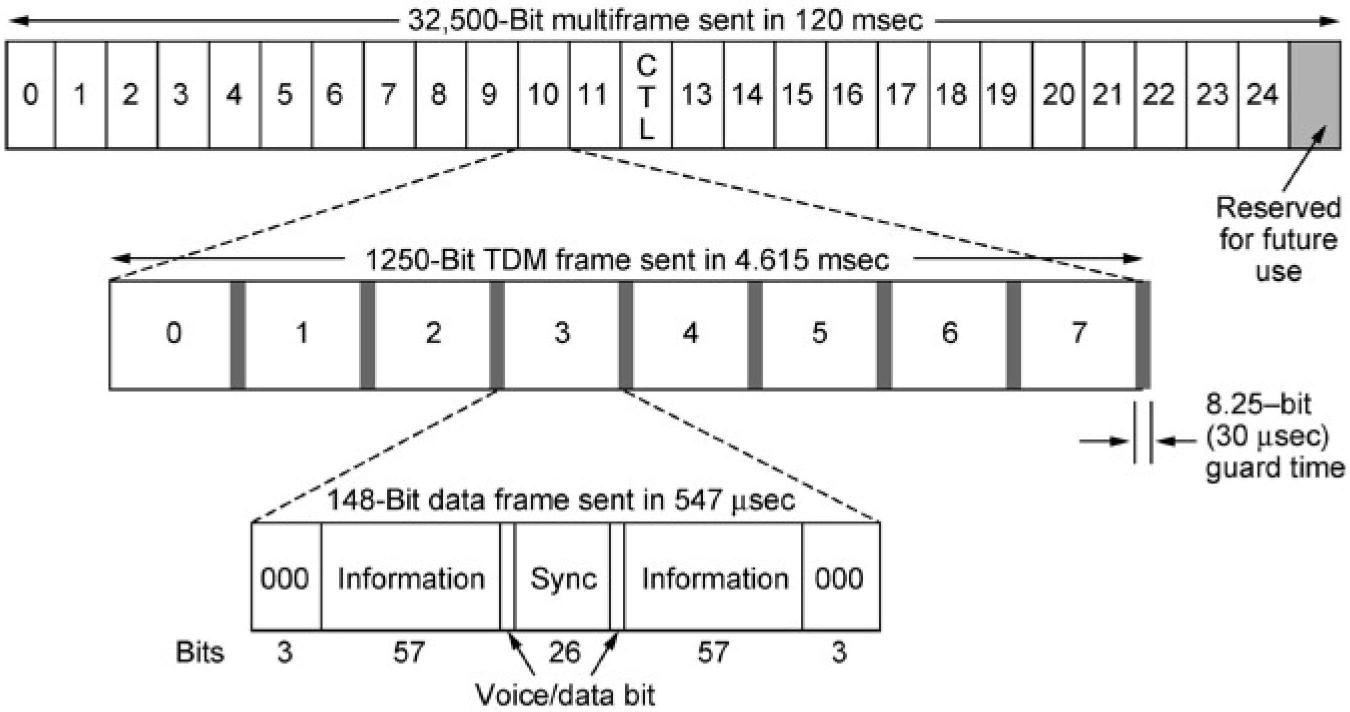
- Works over several frequency bands (e.g., 900MHz, 1800MHz, 1900MHz) depending on country and operator
- FDD like AMPS
- GSM frequency allocation in UK
(http://maps.mobileworldlive.com/network.php?cid=39&cname=United%20Kingdom)
  - In two bands: 900MHz and 1800MHz
    - 900MHz band – downlink: 925-960MHz; uplink: 880-915MHz
    - 1800MHz band – downlink: 1805-1880MHz; uplink: 1710-1785MHz
  - O2/Telefonica: 900MHz and 1800MHz
  - Vodafone: 900MHz and 1800MHz
  - Everything Everywhere (Orange): 1800MHz
  - Everything Everywhere (T-Mobile): 1800MHz
  - PMN, another GSM licensee : 1800MHz
- More spectrum compared to AMPS, used in the form of wider channels to support larger number of users (200KHz vs. 30KHz)

GSM Air Interface

- Each full-duplex channel divided into 8 time slots to accommodate 8 active base-mobile connections (the TDMA part)
  - GSM radios half-duplex, so different slots used for downlink and uplink part of the connection



GSM Framing Structure



- 1250 bits over 4.615ms across 8 users ➔ gross data rate of ~270.8Kbps
- After discounting overhead: 24.7Kbps per user before error correction and 13Kbps after error correction
- GSM encodes speech at 13kbps and 12.2 kbps

GSM Framing Structure (contd.)

- There is also a 51 slot multiframe with some slots used for control channels, e.g.,
  - *Broadcast control channel* over downlink with continuous broadcast of base station identity and channel status; also used by mobiles to monitor signal strength from base station
  - *Dedicated control channel* to keep VLR up-to-date via location updating, registration and call setup
  - *Common control channel* divided further into *three logical subchannels*
    - *Paging channel*: used by base stations to announce incoming calls to mobiles
    - *Random access channel*: for mobile to request a slot on dedicated control channel
    - *Access grant channel*: used to inform mobile of assigned slot in response to request on random access channel
- Handoff procedure different from AMPS
  - *Mobile Assisted HandOff (MAHO)*: each mobile uses idle slots to measure signal quality to nearby base stations and informs BSC to help it in making handoff decision

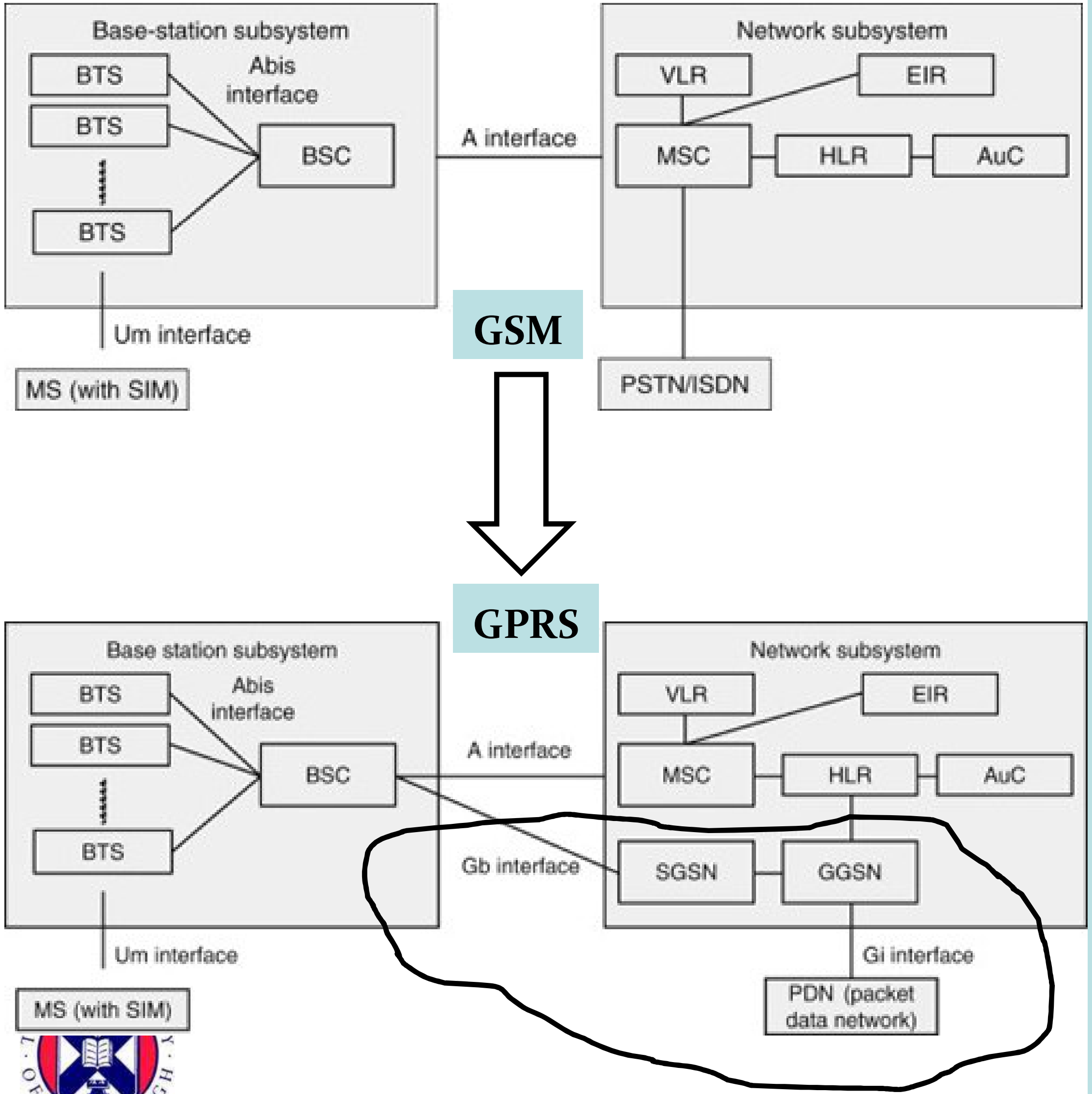
GSM Evolution ➔ HSCSD, GPRS and EDGE

- Examples of 2.5G cellular wireless technologies
- Aimed at improving data rates from ~10Kbps with GSM to better support data services (e.g., e-mail, web browsing)
- High-Speed Circuit-Switched Data (HSCSD) is the first step in this direction towards higher data rates with GSM
- New features with HSCSD:
  - 14.4 Kbps data rate per time slot by reducing error correction overhead
  - Higher data rates up to 57.6 Kbps by using multiple 14.4 Kbps time slots

General Packet Radio Service (GPRS)

- Unlike HSCSD, GPRS takes a packet-oriented approach to data transmission
- In GPRS, data transmissions are supported on-demand without prior connection establishment and reservation of channels
- Like with HSCSD, a data transfer operation can use multiple time slots in a 8-slot TDM frame
  - Number of time slots available for data transmission limited by slots reserved for voice communication as GPRS needs to coexist with voice services
- Introduced 4 bit-rates (ranging from 9.05Kbps to 21.4 Kbps per time slot), all with GMSK modulation but using 4 different coding rates
- Maximum data rate supported is 171.2Kbps but expected data rate is typically around 115Kbps

GPRS Architecture



- Two new components:
  1. Serving GPRS support node (SGSN)
  2. Gateway GPRS support node (GGSN)
- SGSN and GGSN are packet-switched counterparts of MSC and GMSC
  - GGSN does NAT, and enables communication between GPRS mobile and external PDN (e.g., Internet) via SGSN over GPRS Tunnelling Protocol (GTP)
  - Also does authentication and accounting
- Mobile stations need GPRS terminal functionality, and BTSs need a software upgrade
- Packet control unit (PCU) device in the BSC to separate/multiplex circuit-switched and packet-switched traffic

Enhanced Data rates for Global Evolution (EDGE)

- GPRS enhancement to support data rates up to 384Kbps
- Via introduction of a new modulation scheme 8-PSK that allows 3 data bits per symbol over the air interface as opposed to 1 bit per symbol with GMSK
- Features 9 different modulation and coding schemes (MCSs) in all, each supporting different bit-rates per time slot
  - Higher bit-rates via 8-PSK modulation whereas lower bit-rates MCSs use GMSK modulation
  - Can automatically switch between them to optimise higher data rate or reliability based on measured channel quality (SNR)

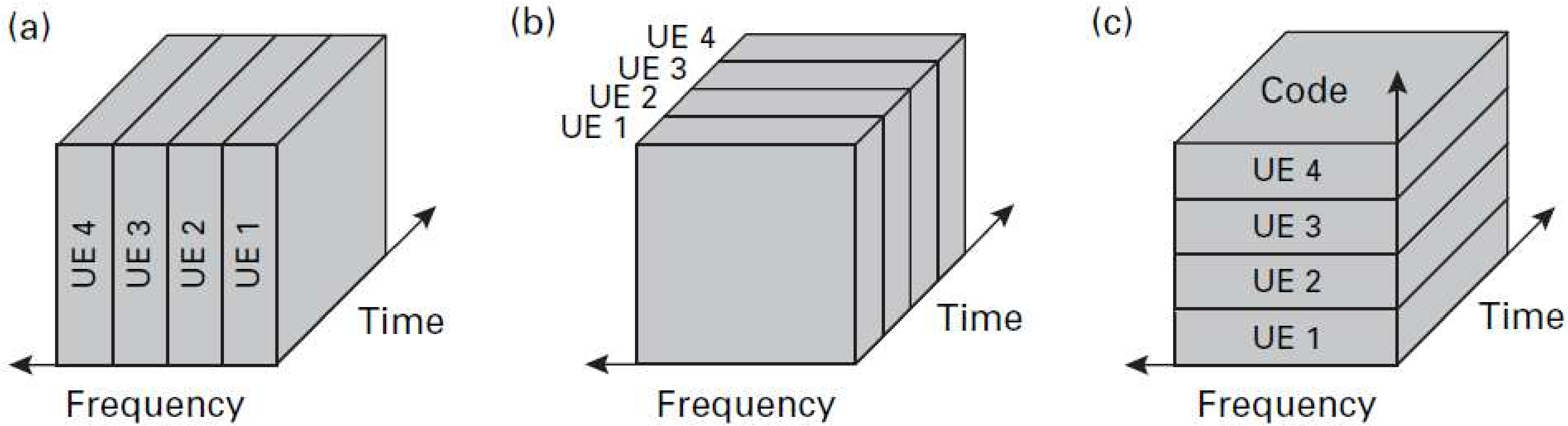
3G Cellular Wireless Technologies
Overview

- Still digital like 2G but higher data rates through changes to the air interface, aimed at supporting advanced data-oriented services (e.g., Internet access)
  - To support growing mobile data traffic which was anticipated to exceed voice traffic; in fact, it did in 2010
  - Cater to "converged" mobile devices, e.g., likes of iPhones
- In 1997, ITU set out blueprint under the name "International Mobile Telecommunications 2000 (IMT-2000)"
  - For standardization of single worldwide third generation cellular technology by 2000
  - For use by a single type of device in contrast to 2G case (GSM vs. CDMA)

3G Cellular Wireless Technologies *Overview (Contd.)*

- IMT-2000 requirements
  - Provide ubiquitous and always-on access
  - Support diverse services with QoS guarantees: voice, messaging, multimedia, Internet access, …
  - Target data rates: >= 2Mbps for stationary/indoor users, >= 384Kbps for walking users; >144Kbps in a moving vehicle
- Several proposals selected of which two are of primary interest, both based on CDMA:
  - **Universal Mobile Telecommunications System (UMTS) aka Wideband CDMA (WCDMA)**
    - From EU (Ericsson et al.), successor to GSM
    - Uses 5MHz channels
  - **CDMA2000**
    - From US (Qualcomm), successor to cdmaOne
    - Uses 1.25MHz channels

Recall: Code Division Multiple Access (CDMA)



(a) FDMA, (b) TDMA, (c) CDMA.

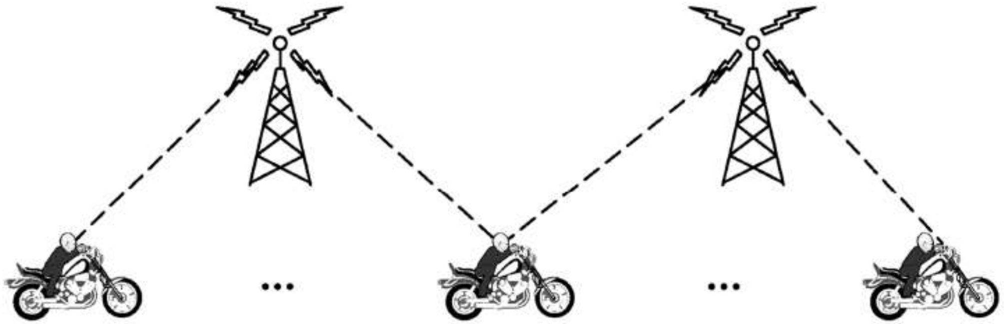
- Allows multiple users to operate on the same frequency at the same time by separating their transmissions with orthogonal codes

CDMA Advantages

1. Improves capacity
   - Allows using all frequencies in all cells
     - Obviates the need for frequency planning required in AMPS and GSM systems
   - Cell capacity limited by interference ➔ no interference when mobile not transmitting or receiving
     - Silence periods during voice calls can be exploited to increase number of simultaneous calls
     - Also exploits the times with fewer *active* users (or low interference periods)
   - Short chip duration allows receiver to do multipath diversity processing via rake receiver to counter fading, thereby obviate the need for higher received signal power (and consequent possibility of higher interference)

CDMA Advantages (contd.)

2. Facilitates soft handoffs for seamless movement between cells
   - By allowing association with both old and new base stations during the transition period
   - Naturally possible because all frequencies are used in every cell

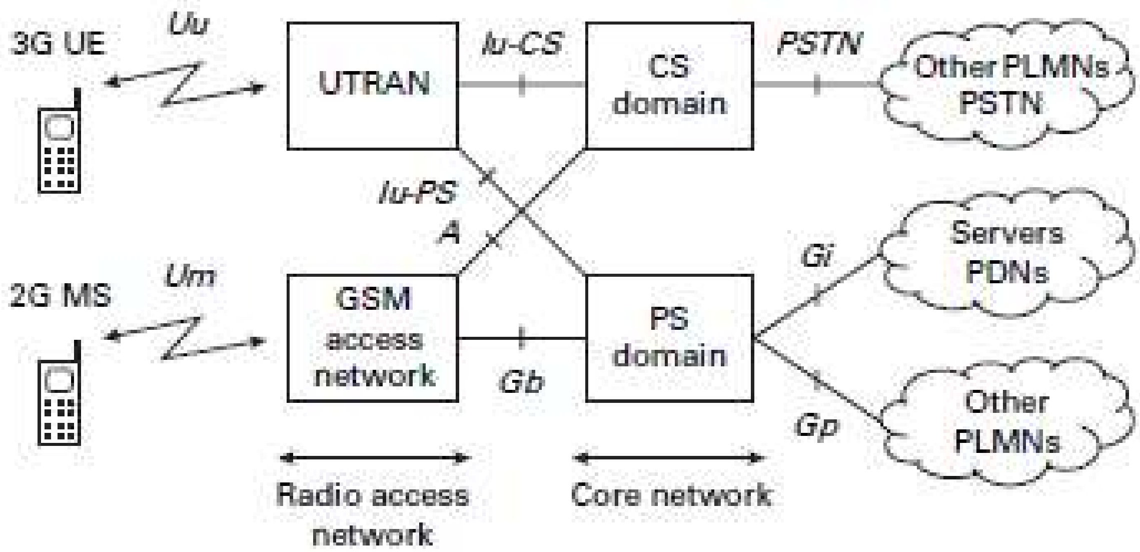


Soft handoff (a) before, (b) during, and (c) after.

CDMA in Practice

- Our earlier discussion on CDMA implicitly assumed that when there is more than one transmitter, they all are time synchronized besides using orthogonal codes (chip sequences)
- An unrealistic assumption in uplink direction, so need codes that are orthogonal with each other *at all time offsets*
- Also need sufficient number of codes to use same set of carrier frequencies in all cells
- The above two requirements approximated by long pseudorandom sequences (scrambling codes in UMTS parlance)
- Use of scrambling codes not enough if received signal powers from different mobiles not same , otherwise interference between signals from different mobiles
  - A signal from nearby mobile can drown out the signal from a distant one (near-far problem)
  - Need transmit power control to counter this effect
- Radio network planning more complex as cells can cause interference to each other and thus cannot be planned independently

High Level Architecture of UMTS Network



UTRAN: UMTS Terrestrial Radio Access Network

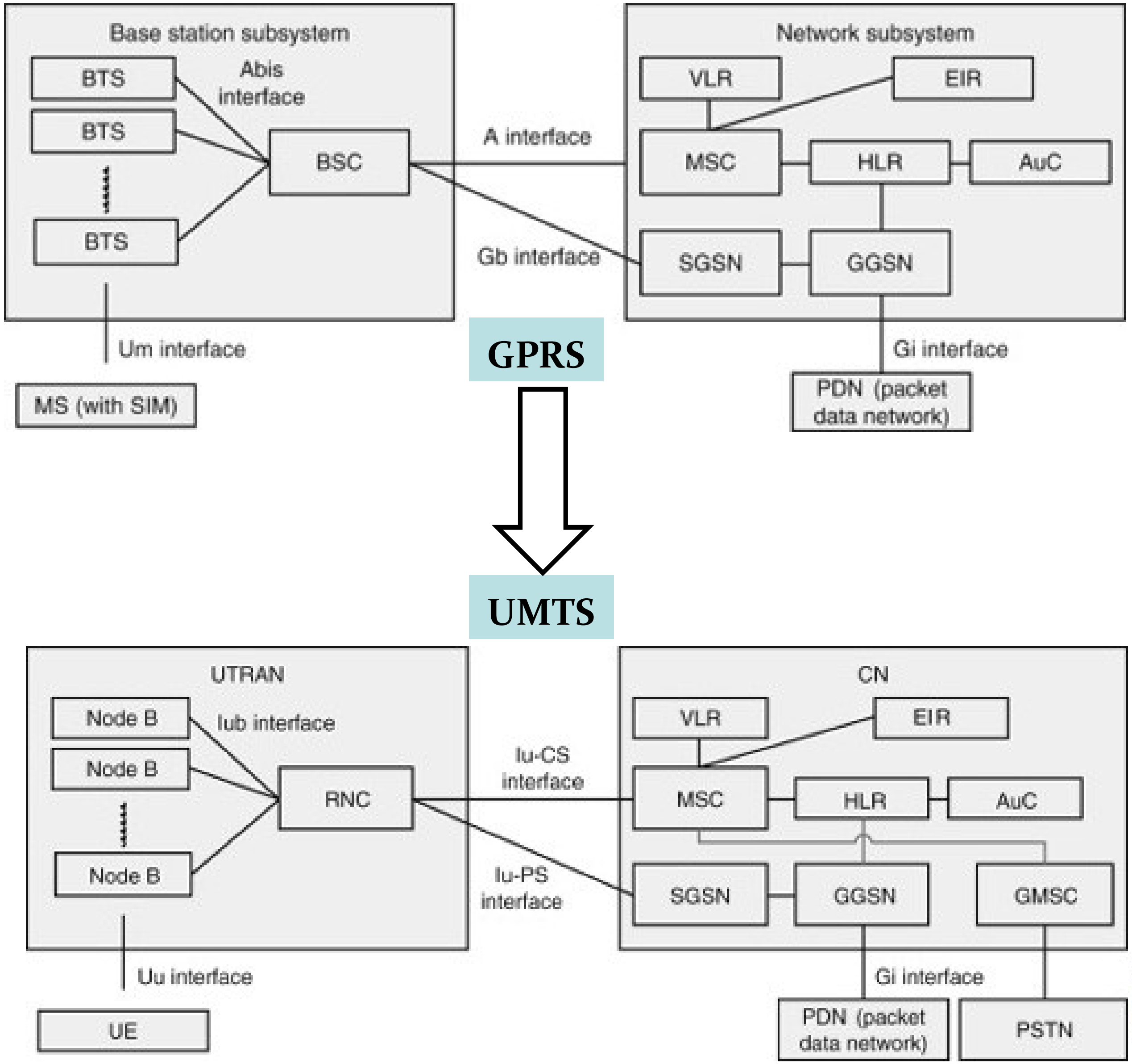
PLMN: Public Land Mobile Network

PSTN: Public Switched Telephone Network

PDN: Packet Data Network

- Like in GPRS and EDGE networks, two domains in core network: circuit switched (CS) and packet switched (PS)
- UTRAN is the UMTS radio access network but the system designed to maintain backward compatibility with GSM via GSM radio access network (and GSM-enabled user devices)
- Interfaces between different system components have their own protocol stacks
- Multiplexing mechanism over the air interface: CDMA within TDMA slots, which are available in multiple frequencies ➔ combined use of FDM, TDM and CDM approaches

UMTS vs. GPRS/GSM Architectural Differences



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GSM → UMTS Terminology Changes

GSM

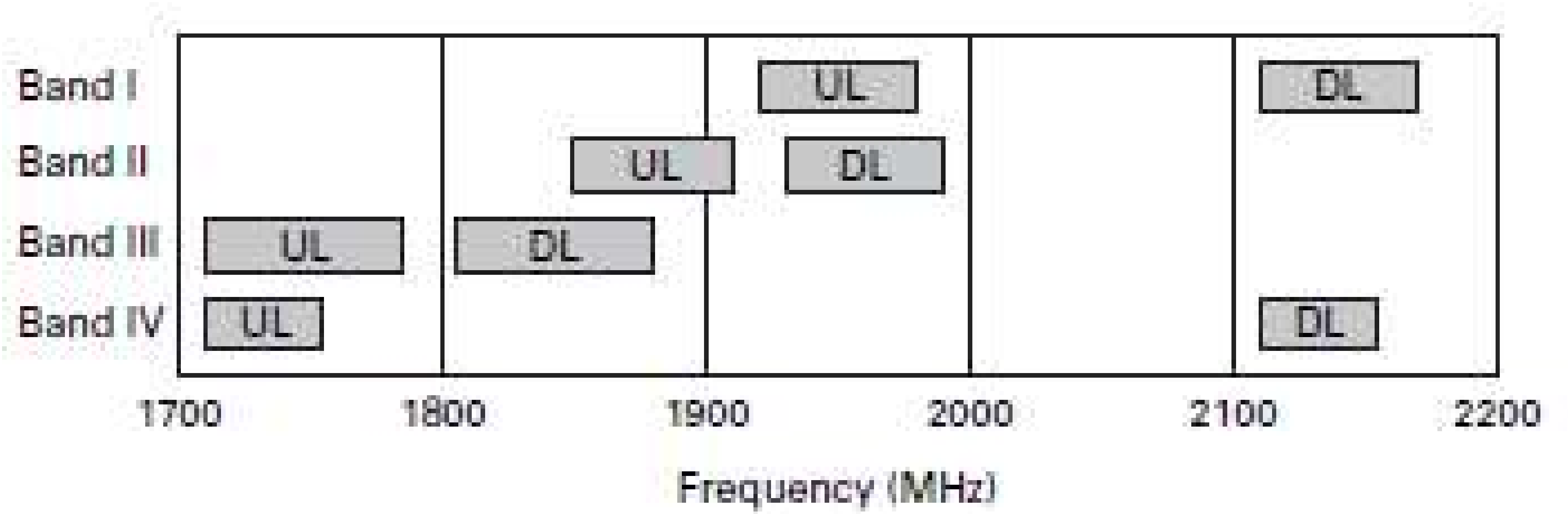
1. Mobile Station (MS)
2. Base Transceiver Station (BTS)
3. Base Station Controller (BSC)
4. Base Station Subsystem (BSS)

UMTS

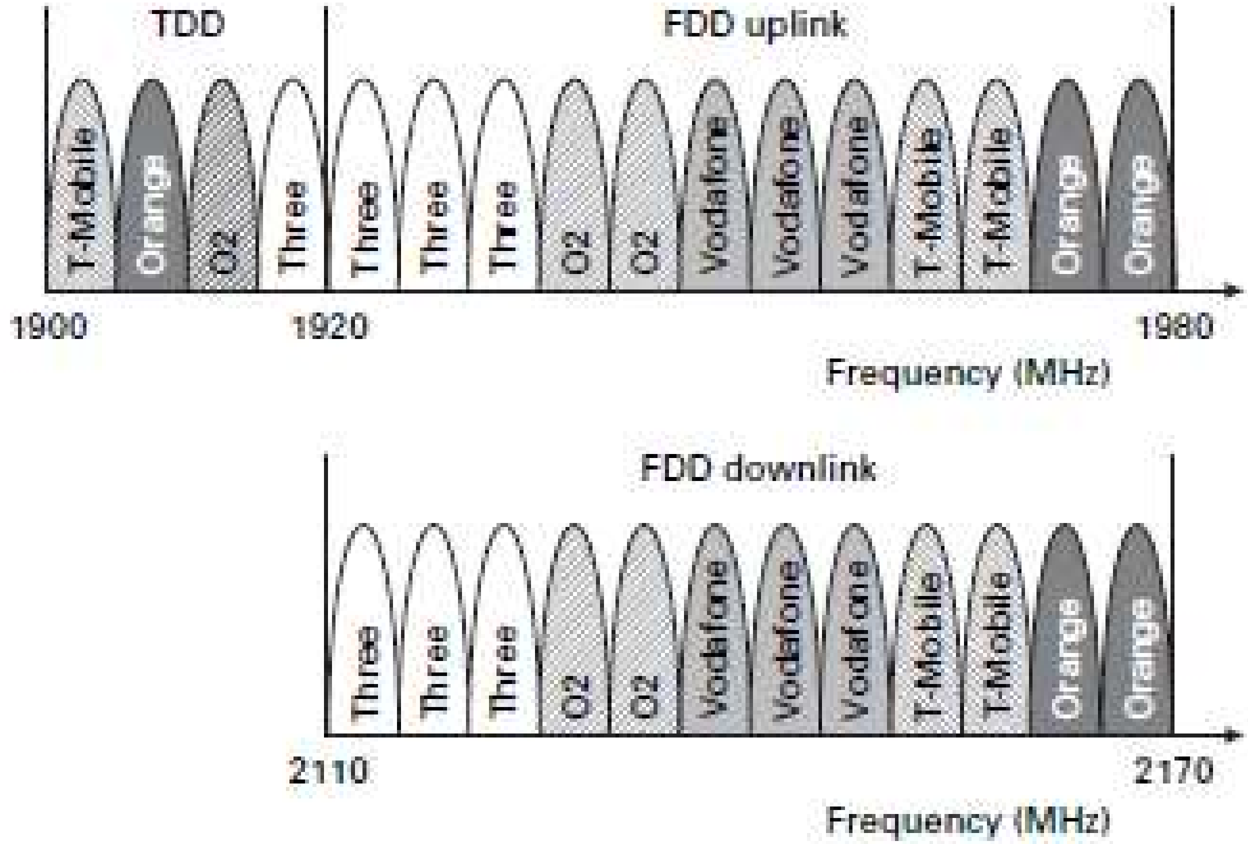
1. User Equipment (UE)
2. Node B
3. Radio Network Controller (RNC)
4. UMTS Terrestrial Radio Access Network (UTRAN)

UMTS Worldwide Frequency Allocations

- UMTS has two modes of operation: FDD and TDD
- FDD variant is more common, except in China
- Key FDD bands: mostly, Band I: 1920-1980MHz (uplink) and 2110-2170MHz (downlink) with 12 full duplex channels, each 5MHz wide



UMTS Frequency Allocation in the UK



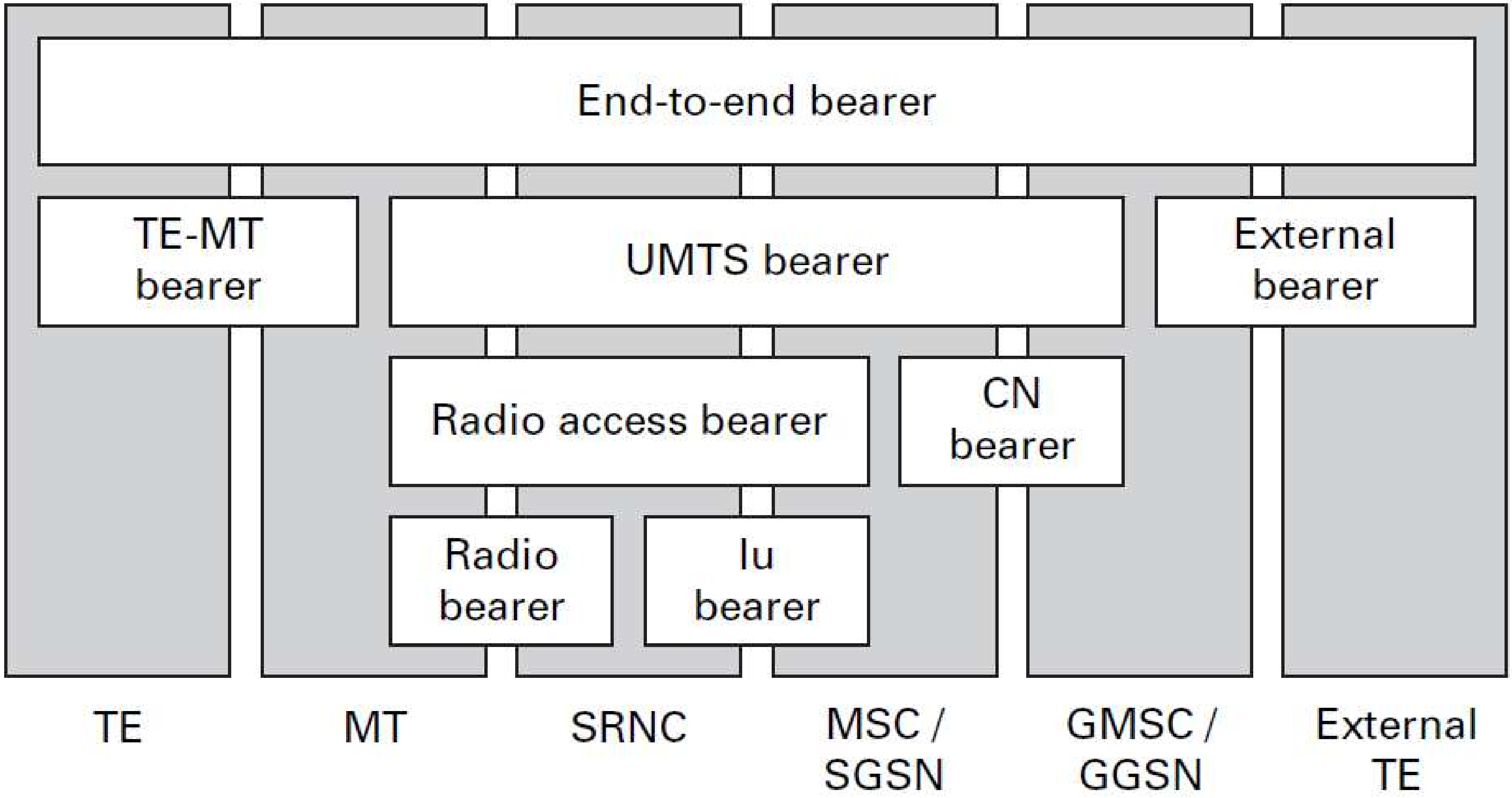
- Given UMTS based on CDMA, different full duplex channels used:
  - For cells of different sizes: macrocells, microcells, picocells
  - Or, to increase capacity of any of these type of cells

Important New Concepts of UMTS

- The Radio Access Bearer (RAB)
- The Access Stratum and Non-Access Stratum
- Common protocols for circuit-switched (CS) and packet-switched (PS) modes
  - a single lower layer protocol, **RLC/MAC**, instead of separate protocols used in GSM/GPRS for different types of data

UMTS Data Streams: Bearers

- A *bearer* is a data stream that spans some part of the system and has a specific quality of service (QoS)
- Most important bearers in UMTS shown below

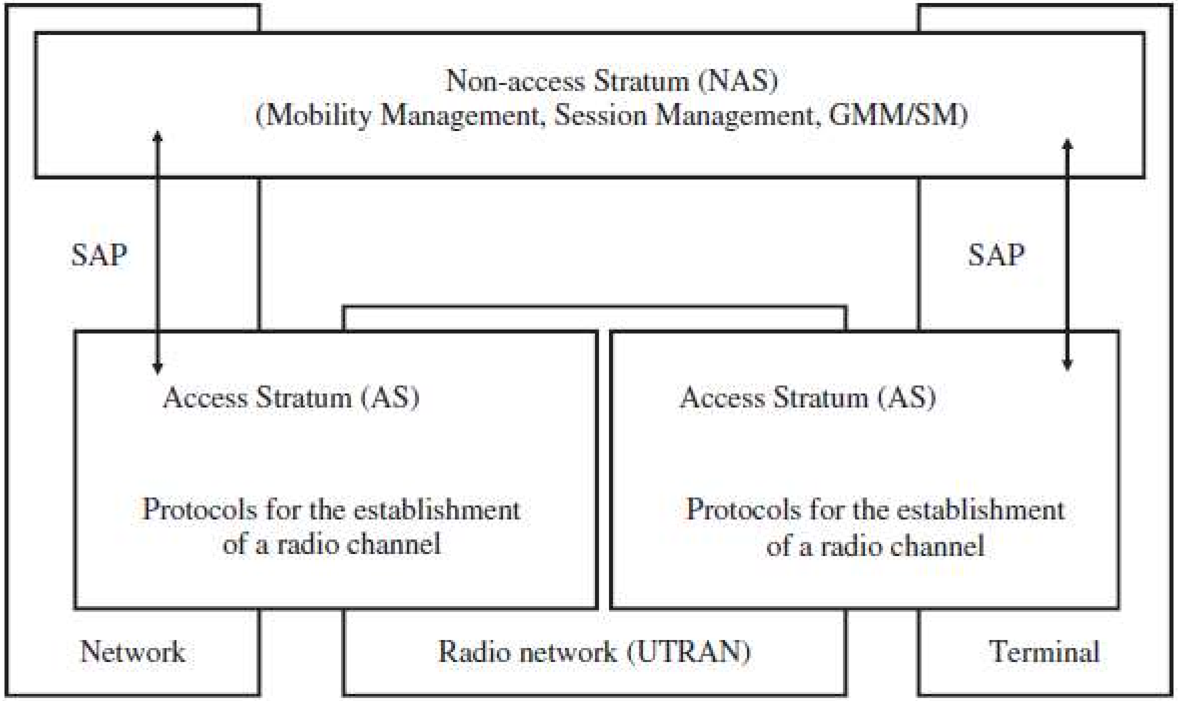


The Radio Access Bearer (RAB)

- RAB is a description of the transmission channel between the network and a user
  - Divided into radio bearer on the air interface and the Iu bearer in the radio network (UTRAN)
  - Needs to be established before data can be exchanged between a user and the network
  - This channel used for both signalling and user data
  - RAB established by a request of MSC/SGSN, which indicates only a description of required channel properties as listed below:
    - service class (conversational, streaming, interactive or background);
    - maximum speed;
    - guaranteed speed;
    - delay;
    - error probability.
  - UTRAN maps these properties to a physical connection
    - RAB properties also influence the settings of parameters like coding scheme, logical and physical transmission channel selected

The Access Stratum and Non-Access Stratum

- UMTS aims to separate core network functionalities from those of the access network as much as possible, to allow each of them to evolve independently
- Access Stratum (AS) covers all functionalities that are associated with the radio network ('the access') and the control of active connections between a user and the radio network, e.g., handover control



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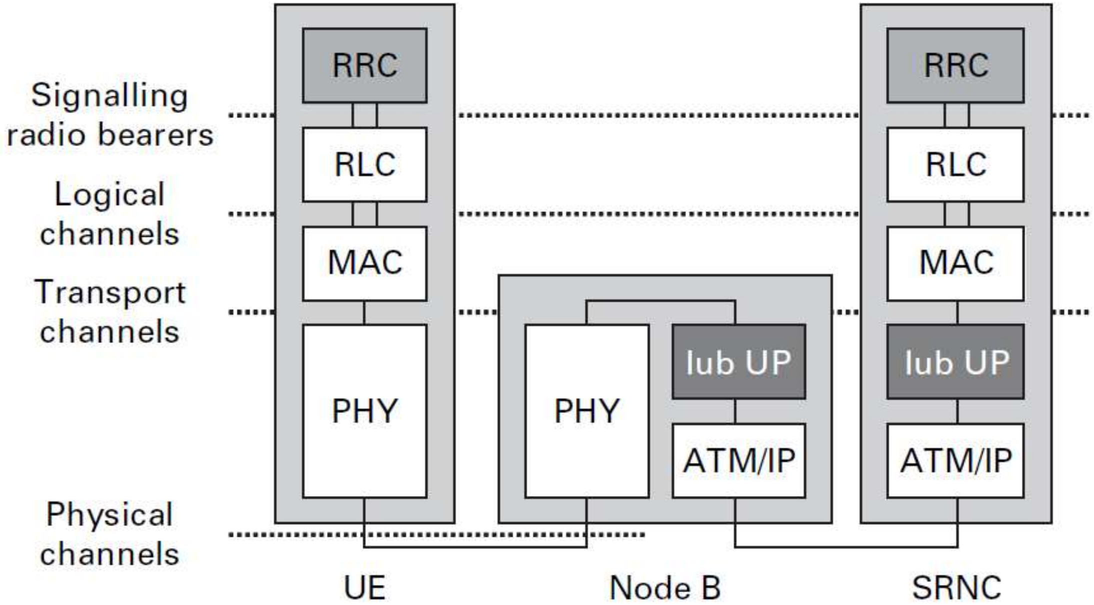
Non-Access Stratum

- The NAS contains all functionalities and protocols that are used directly between the mobile device (UE) and the core network
  - no direct influence on the properties of the established RAB and its maintenance
  - NAS protocols transparent to the access network
  - NAS functionalities are those controlled via MSC and SGSN (e.g., mobility and session management)
- Some NAS protocols (e.g., call control, session management) need to request bearer establishment, modification or termination which is enabled by three different service access points (SAPs):
  - notification SAP (Nt, e.g., for paging);
  - dedicated control SAP (DC, e.g., for RAB setup);
  - general control SAP (GC, e.g., for modification of broadcast messages, optional).

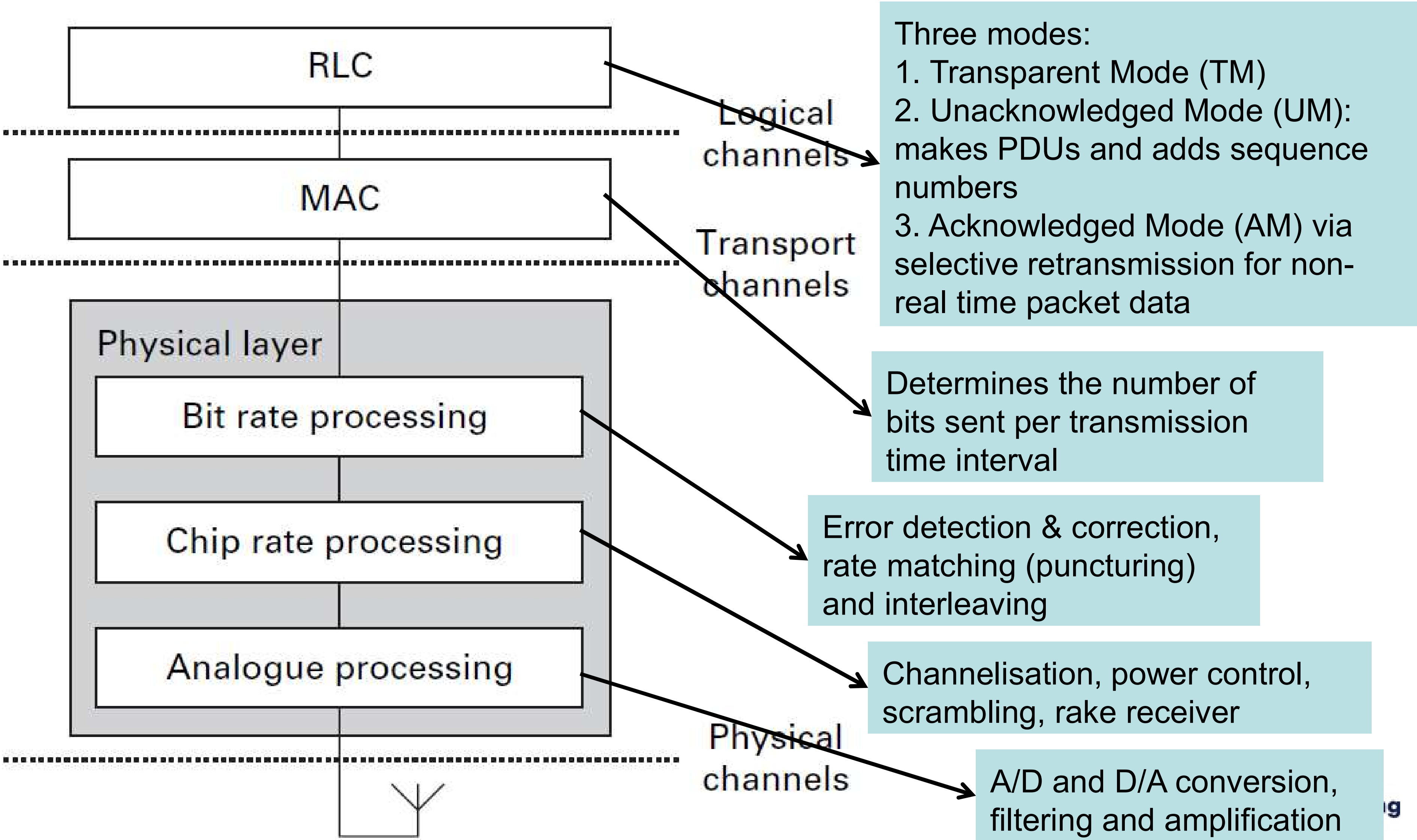
UMTS Data Streams: Channels

- With respect to the air interface, data flows between different protocols are called *channels*
  1. *Logical channels* between RLC and MAC protocols
  2. *Transport channels* between the MAC and PHY
  3. *Physical channels* below the air interface's physical layer
     - ➢ Each physical channel is roughly a CDMA code allocated for a specific purpose
- Example below illustrates channels and bearers



UMTS Air Interface

- Enables a maximum downlink/uplink data rate of 2Mbps



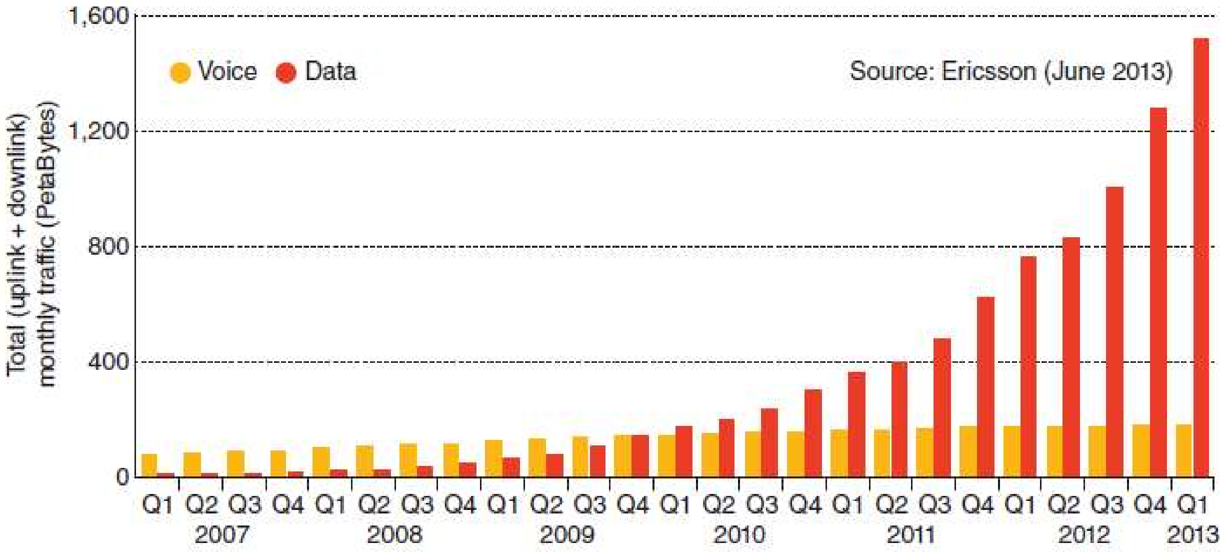
UMTS Evolution → HSDPA, HSUPA, HSPA+

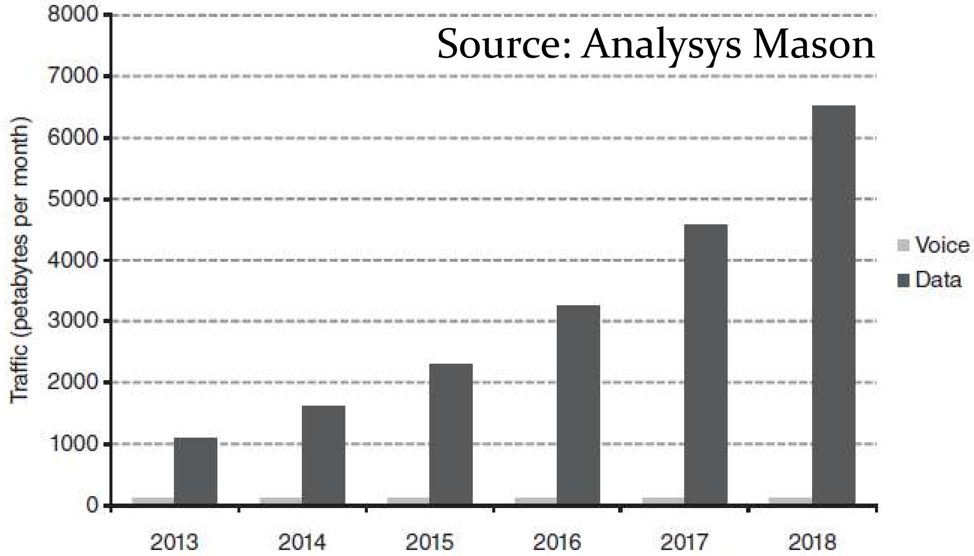
- Examples of 3.5G cellular wireless technologies
- High-Speed Downlink Packet Access (HSDPA)
  - Increases the downlink data rate up to 14Mbps
  - Uses a combination of Hybrid ARQ with soft combining, fast scheduling (at the Node B), and adaptive modulation and coding (also at Node B)
- High-Speed Uplink Packet Access (HSUPA)
  - Increases uplink data rate up to 5.7Mbps
  - Uses a combination of Hybrid ARQ with soft combining, and fast scheduling (at the Node B)
- High-Speed Packet Access Evolution (HSPA+)
  - Enables significant increase in max downlink and uplink speeds to 84Mbps and 11Mbps, respectively
  - Via the use of 2x2 MIMO, higher bit-rate modulation schemes in both uplink and downlink directions, etc.

Motivations for 4G

- Increase system capacity to meet growing demand for mobile data (see next slide for historical/forecasted mobile voice/data traffic growth)
- Reduced capital and operational expenditure for mobile operators by maintaining only one (packet-switched) core network instead of two with 2G/3G (circuit-switched for voice and packet-switched for data)
- Reduce end-to-end delay (from ~100ms with 3G networks for data applications)
- Improving system performance without the need to support legacy devices; in other words, a lower complexity solution approach

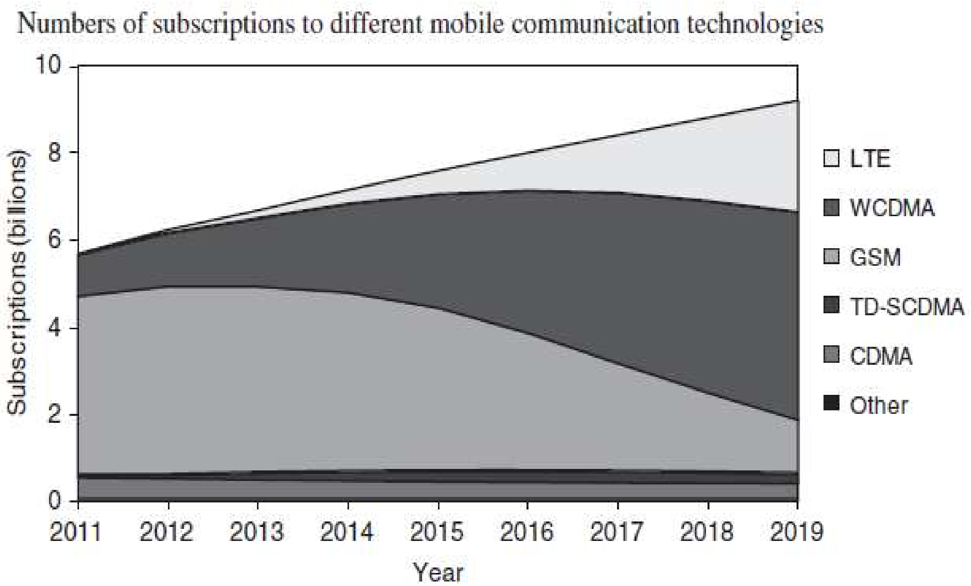
Mobile Data Traffic Growth

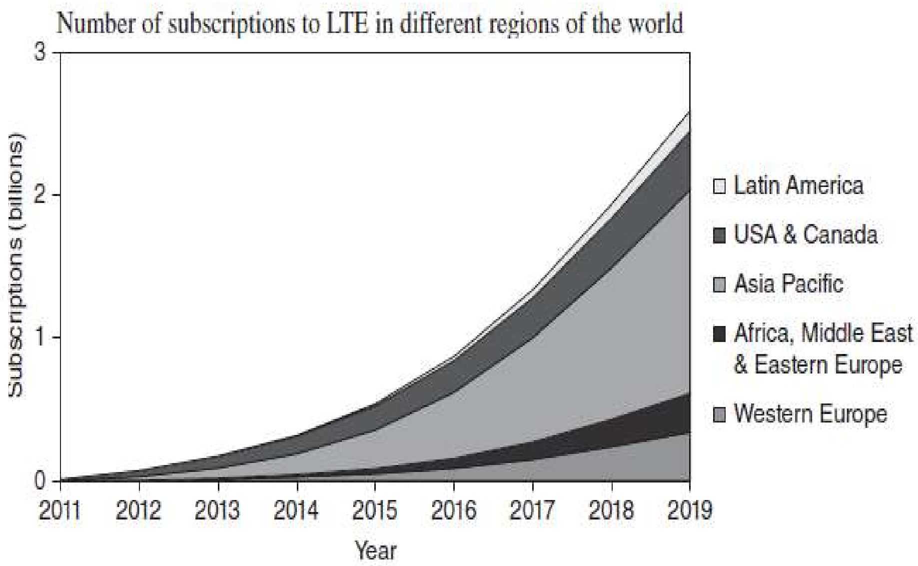




LTE Growth in #Subscriptions

- Historical data up to 2013, forecast thereafter





Source: Ericsson

3GPP Requirements for Long-Term Evolution (LTE) / Air Interface

- Peak data rates
  - 100Mbps in downlink
  - 50 Mbps in uplink
- Spectral efficiency (cell capacity per unit bandwidth) relative to WCDMA (Release 6)
  - 3-4 times greater in downlink
  - 2-3 times greater in uplink
- Latency
  - Less than 5ms latency between mobile and fixed network
  - Less than 100ms to switch from standby to active state
- Coverage
  - Optimized for cell sizes up to 5Km, degraded performance up to 30Km and support cell sizes up to 100Km
- Mobility
  - Optimized for mobile speeds up to 15Km/h, work with high performance up to 120Km/h and support speeds up to 350Km/h

3GPP Requirements for System Architecture Evolution / Core Network

- Route packets using IP
- Provide always-on connectivity
- 10ms user-plane latency for non-roaming mobile, 50ms in a roaming scenario
- Support inter-system handovers both with older 3GPP and non-3GPP systems

3GPP Specifications for LTE

3GPP specification releases for UMTS and LTE

Release	Date frozen	New features
R99	March 2000	WCDMA air interface
R4	March 2001	TD-SCDMA air interface
R5	June 2002	HSDPA, IP multimedia subsystem
R6	March 2005	HSUPA
R7	December 2007	Enhancements to HSPA
R8	December 2008	LTE, SAE
R9	December 2009	Enhancements to LTE and SAE
R10	June 2011	LTE-Advanced
R11	June 2013	Enhancements to LTE-Advanced
R12	September 2014	Enhancements to LTE-Advanced

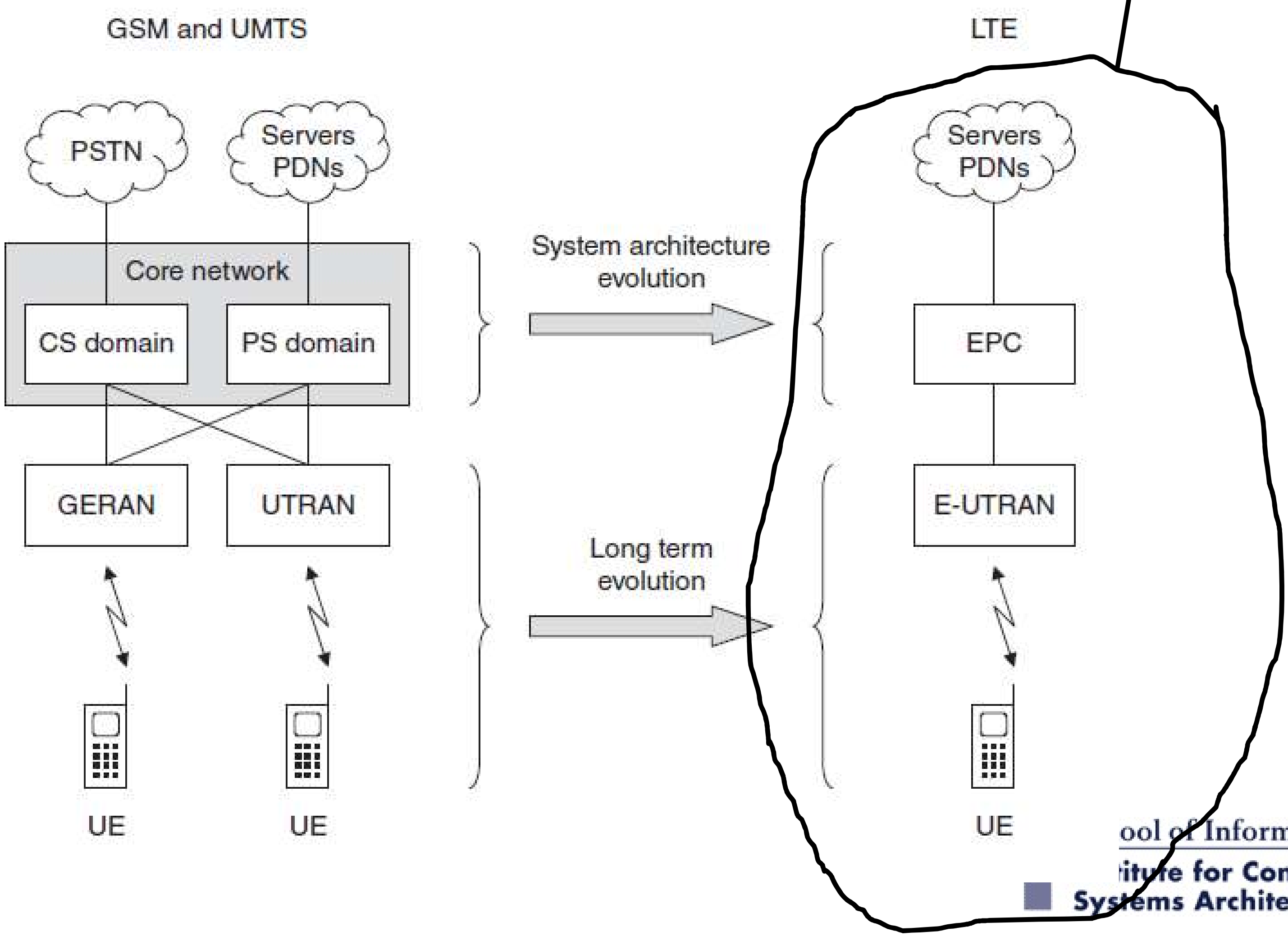
3GPP specification series used by UMTS and LTE

Series	Scope
21	High-level requirements
22	Stage 1 service specifications
23	Stage 2 service and architecture specifications
24	Non-access stratum protocols
25	WCDMA and TD-SCDMA air interfaces and radio access network
26	Codecs
27	Data terminal equipment
28	Tandem free operation of speech codecs
29	Core network protocols
30	Programme management
31	UICC and USIM
32	Operations, administration, maintenance, provisioning and charging
33	Security
34	UE test specifications
35	Security algorithms
36	LTE air interface and radio access network
37	Multiple radio access technologies

Architectural differences between GSM/UMTS and LTE

- LTE acronym used in practice to refer to EPS, the whole system

Evolved packet system (EPS)



LTE FDD (Paired) Frequency Bands

Band number	Operating frequencies (MHz) Downlink	Uplink	Spectrum availability
1	1920–1980	2110–2170	EMEA, Brazil, Japan, India
2	1850–1910	1930–1990	Americas
3	1710–1785	1805–1880	EMEA, Asia–Pacific
4	1710–1755	2110–2155	USA
5	824–849	869–894	Americas, Australia
6	830–840	875–885	Japan
7	2500–2570	2620–2690	EMEA, China, S. America, Canada
8	880–915	925–960	EMEA, Asia–Pacific, S. America
9	1749.9–1784.9	1844.9–1879.9	Japan
10	1710–1770	2110–2170	Americas
11	1427.9–1447.9	1475.9–1495.9	Japan
12	698–716	728–746	USA
13	777–787	746–756	USA
14	788–798	758–768	USA
17	704–716	734–746	USA
18	815–830	860–875	Japan
19	830–845	875–890	Japan
20	832–862	791–821	EMEA
21	1447.9–1462.9	1495.9–1510.9	Japan
22	3410–3500	3510–3600	EMEA, S. America, Asia–Pacific
[23]	2000–2020	2180–2200	USA
[24]	1626.5–1660.5	1525–1559	USA
[25]	1850–1915	1930–1995	Americas

EMEA, Europe, Middle East, and Africa.

LTE TDD (Unpaired) Frequency Bands

Band number	Operating frequencies (MHz)	Spectrum availability
33	1900–1920	Africa, China
34	2010–2025	Africa, China
35	1850–1910	N. America
36	1930–1990	N. America
37	1910–1930	N. America
38	2570–2620	Africa, Europe, S. America
39	1880–1920	China
40	2300–2400	Asia, China, Europe
41	2496–2690	Africa, Americas, Asia, Europe
[42]	3400–3600	EMEA, Americas, Asia–Pacific
[43]	3600–3800	EMEA, S. America, Asia–Pacific

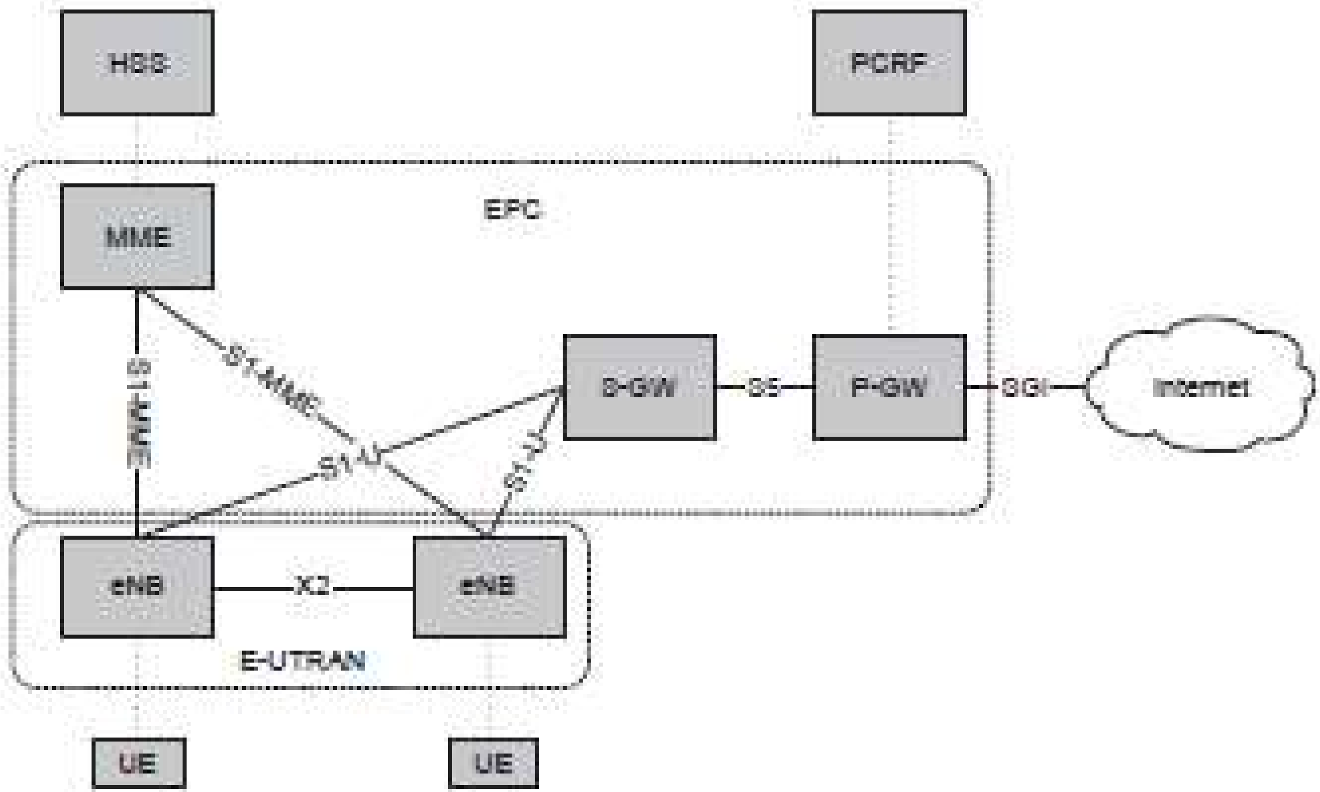
4G Spectrum Allocation in the UK

- Result of Ofcom's 4G spectrum auction from March 2013

Licensee	Frequencies assigned
Everything Everywhere Limited	796 to 801 MHz and 837 to 842 MHz
	2535 to 2570 MHz and 2655 to 2690 MHz
Hutchison 3G UK Limited	791 to 796 MHz and 832 to 837 MHz
Niche Spectrum Ventures Limited	2520 to 2535 MHz and 2640 to 2655 MHz
	2595 to 2620 MHz
Telefónica UK Limited	811 to 821 MHz and 852 to 862 MHz
Vodafone Limited	801 to 811 MHz and 842 to 852 MHz
	2500 to 2520 MHz and 2620 to 2640 MHz
	2570 to 2595 MHz

LTE System Architecture

- Two main components:
  1. **Evolved Universal Terrestrial Radio Access Network (E-UTRAN)**
  2. **Evolved Packet Core (EPC)**



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Two Main Interfaces in LTE

- S1 and X2 interfaces
- **X2 interface for communication among eNBs** to transfer user/control plane info
  - E.g., handover info, measurement and interference coordination reports, load measurements, eNB configuration setups, forwarding of user data
- **S1 interface used to connect eNBs to the EPC (MME/S-GW)**
  - S1-U interface for transferring user data between eNB and S-GW
  - S1-MME interface between eNB and MME for transferring control plane info
    - ➢ E.g., mobility support, paging, data service management, location services and network management

EPC Functions

- Mobile core network providing the following functions:
  - **Mobility management**: signaling support between UE and network using NAS protocols
  - **Session management**: establishment and management of data bearers
  - **Security management**: data encryption and authentication services for the users
  - **Policy control and charging**: operator prescribed access and control of services
    - E.g., QoS management, metering, service control based on user classification, policy control enforcement, charging and billing of services

EPC Entities

- Mainly three:
  1. **Mobility Management Entity (MME)**
     - ➢ Control entity of the EPC
     - ➢ Main functionalities provided: NAS signaling and security, P-GW and S-GW selection, roaming support, user authentication, bearer management, and idle-state mobility handling
  2. **Serving Gateway (S-GW)**
     - ➢ Manages user data plane between eNBs and P-GW
     - ➢ Also serves as a mobility anchor when UEs move between different eNBs
  3. **Packet Data Network Gateway (P-GW)**
     - ➢ Provides data connectivity to external packet data networks
     - ➢ Functions: packet filtering and routing, IP address allocation, charging and policy enforcement via PCRF, lawful interception

HSS and PCRF

- Also generally considered part of the EPC
- **Home Subscriber Server (HSS)** maintains a database of subscriber related info
  - User profile and state info: roaming restrictions, QoS, access-point info, security info, location info, access/service authorization
  - Stores info about P-GWs that a user can connect to
- **Policy Control and Charging Rules Functions (PCRF)** has two main functions: policy control and flow-based charging

Voice Calls in LTE

- Voice calls in earlier standards supported via the circuit-switched part of the core network
- Since LTE is fully packet-switched, voice calls supported via:
  - **Circuit switched fallback (CSFB)**: voice calls made over legacy 2G/3G via their circuit-switched domain
  - **IP multimedia subsystem (IMS)**: external network that includes signalling functions needed to set up, manage and tear down a voice over IP call

Key Features of Core Networks of UMTS and LTE

Feature	UMTS	LTE
IP version support	IPv4 and IPv6	IPv4 and IPv6
USIM version support	Release 99 USIM onwards	Release 99 USIM onwards
Transport mechanisms	Circuit & packet switching	Packet switching
CS domain components	MSC server, MGW	n/a
PS domain components	SGSN, GGSN	MME, S-GW, P-GW
IP connectivity	After registration	During registration
Voice and SMS applications	Included	External

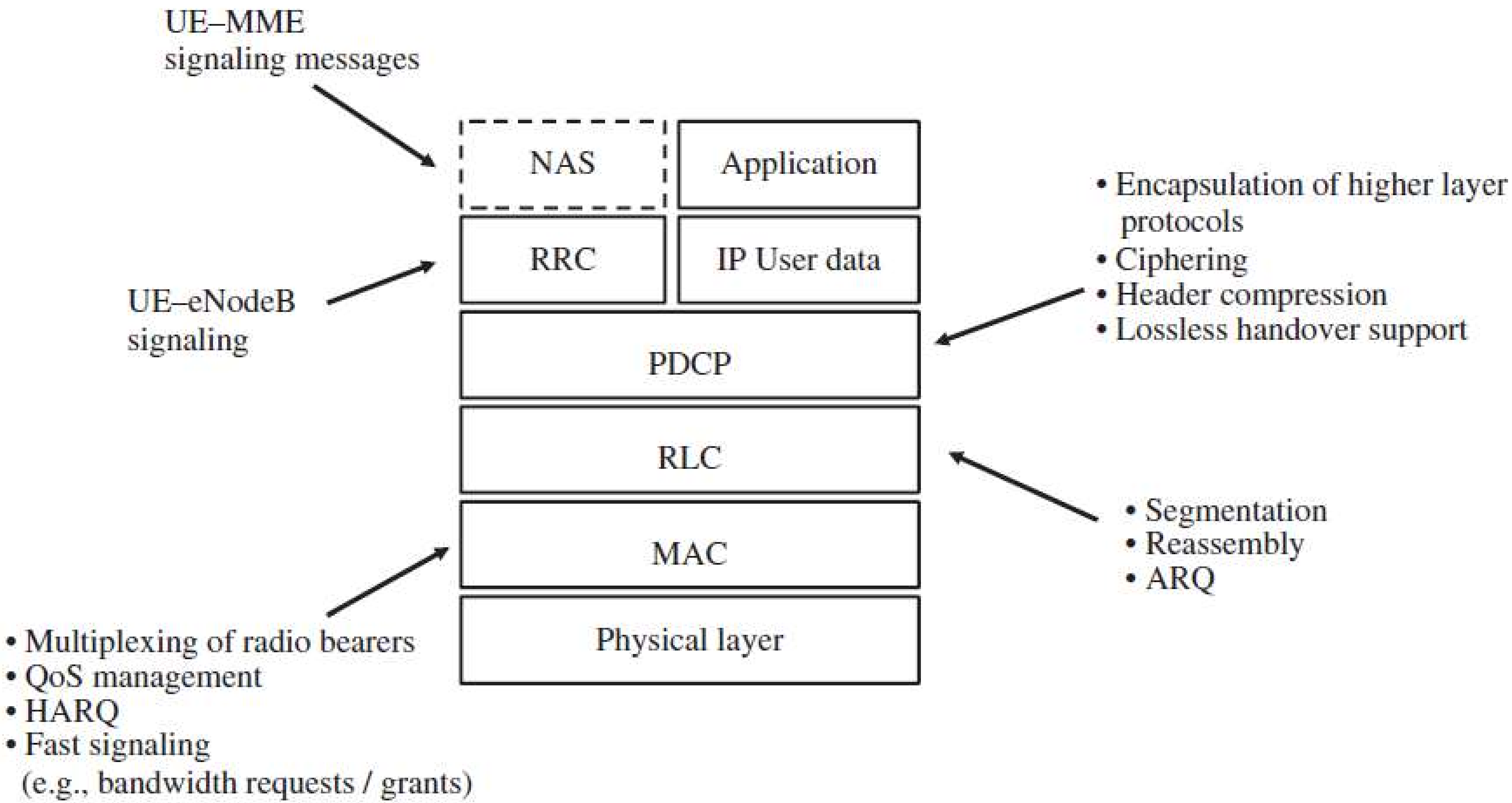
E-UTRAN

- Consists of only eNodeBs (eNBs) or base stations
- Broadly speaking, responsible for management of radio access and provides user- and control-plane support to the UEs
  - User plane: group of protocols used to support user data transmission throughout the network
  - Control plane: group of protocols for controlling user data transmission and managing connection between UE and networks
    - Example connection management functions: handover, service establishment, resource control
- Functions supported:
  - Radio resource management, measurements, access-stratum security, IP header compression and encryption of user data stream, MME selection, U-plane data routing to S-GW, scheduling and transmission of paging messages, broadcast info, public warning system messages

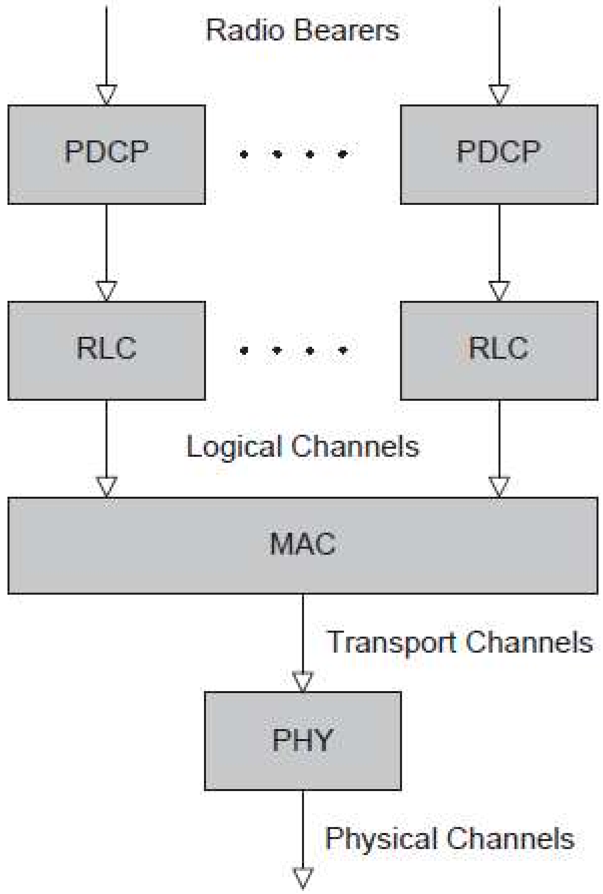
Key Features of Radio Access Networks of UMTS and LTE

Feature	UMTS	LTE
Radio access network components	Node B, RNC	eNB
RRC protocol states	CELL_DCH, CELL_FACH, CELL_PCH, URA_PCH, RRC_IDLE	RRC_CONNECTED, RRC_IDLE
Handovers	Soft and hard	Hard
Neighbour lists	Always required	Not required

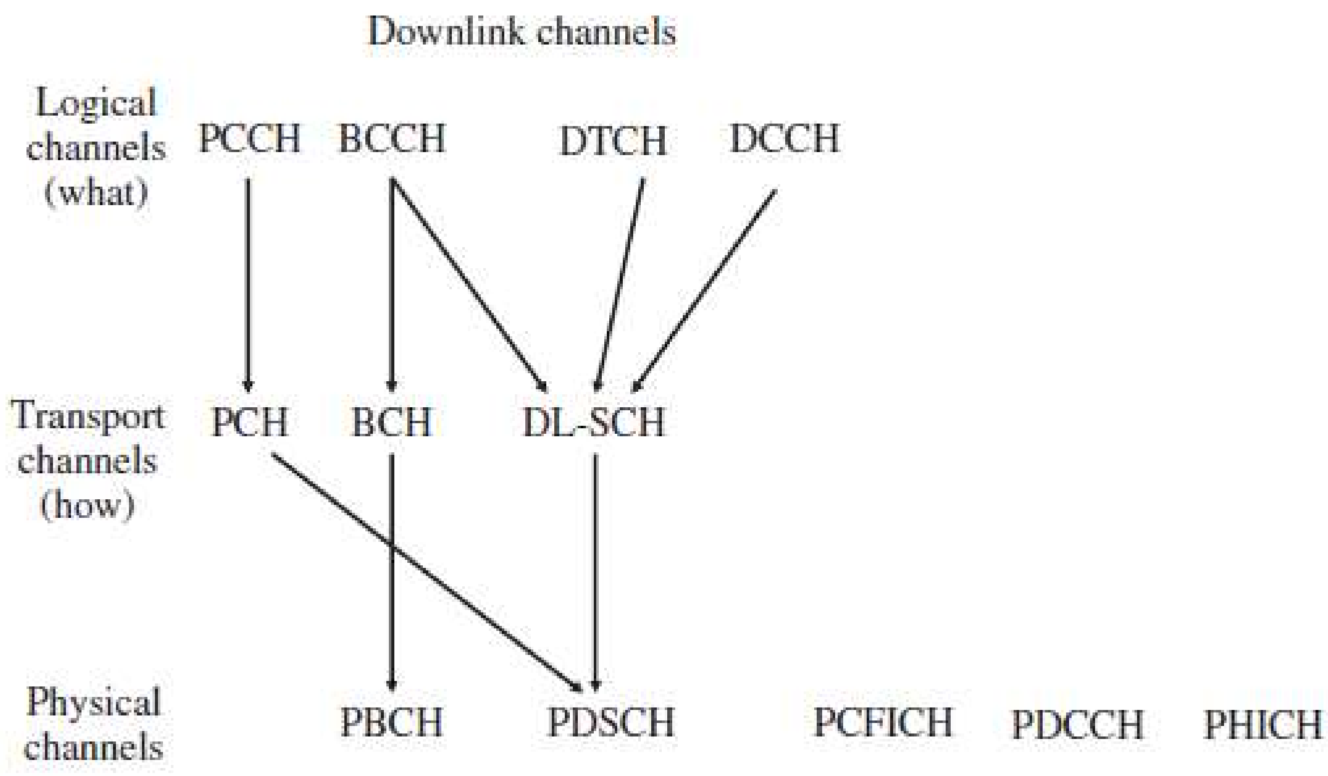
Air Interface Protocol Stack



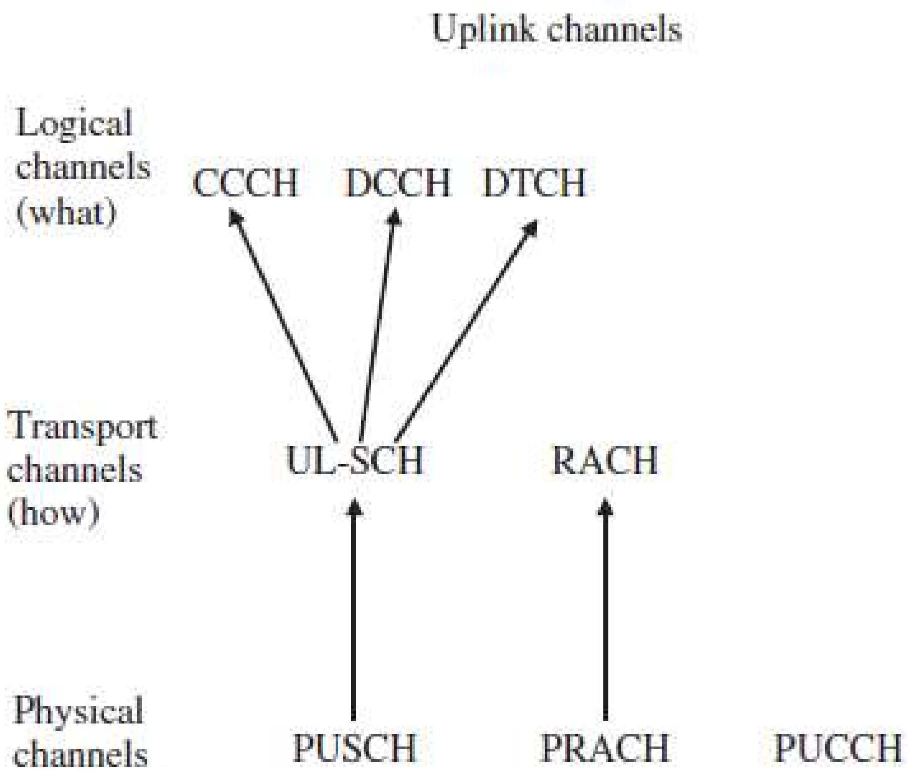
User-Plane Data Flow Chart



LTE Downlink Channels



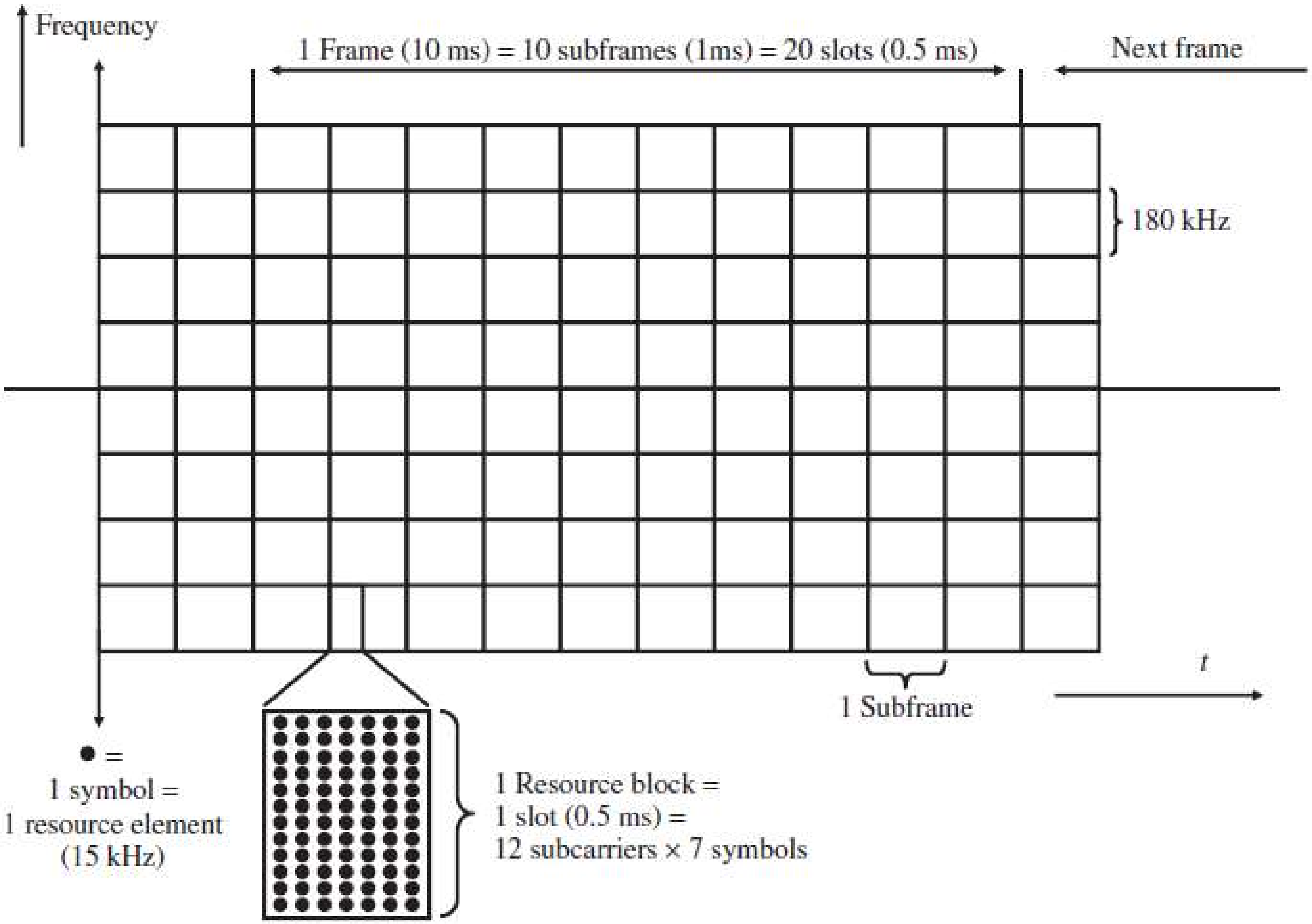
LTE Uplink Channels



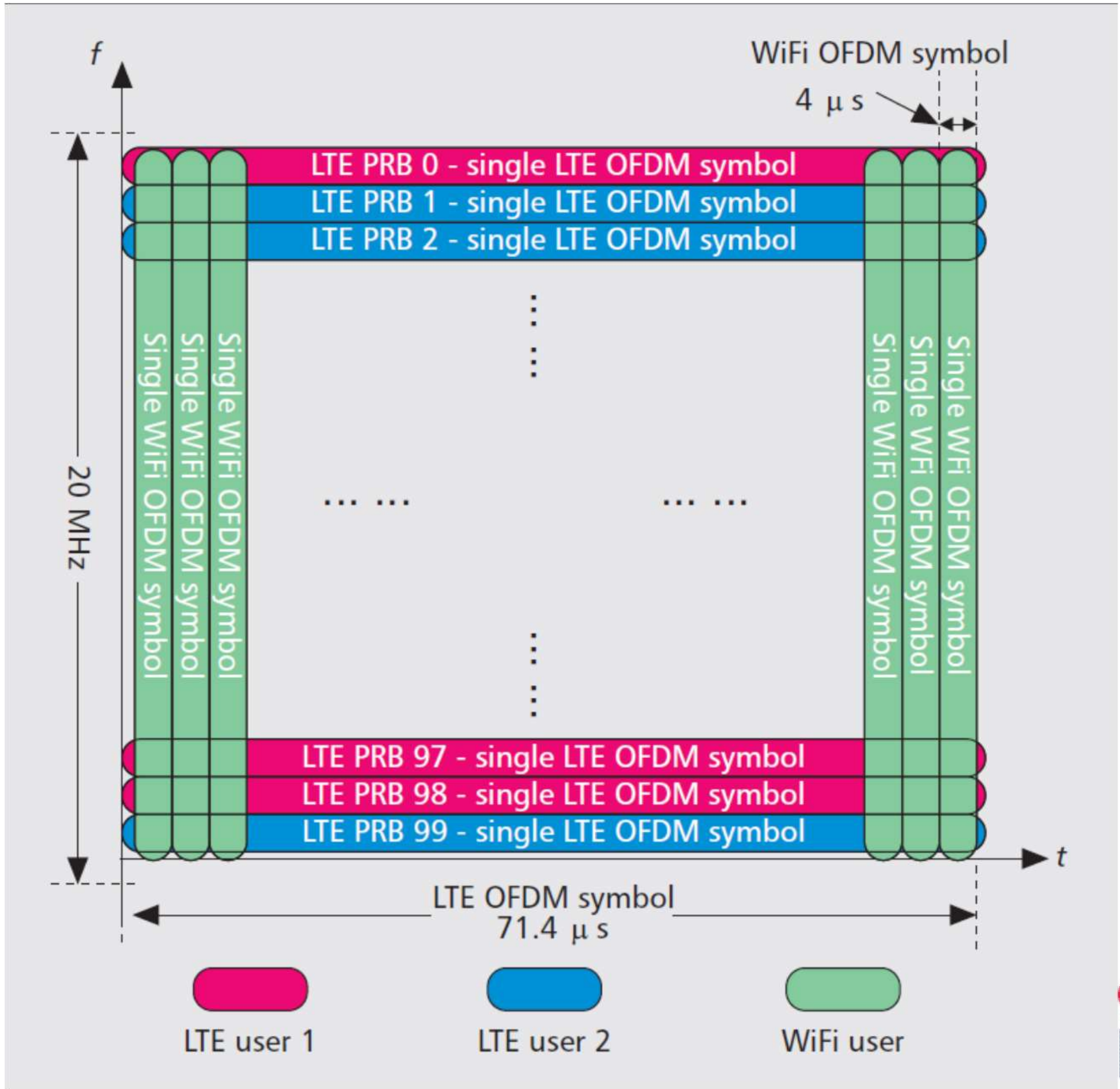
LTE Radio Transmission Scheme

- **Orthogonal Frequency Division Multiple Access (OFDMA) for the downlink**: OFDM based multiple access scheme that allocates different users to different subsets of subcarriers
- A variant of OFDMA called **single carrier FDMA (SC-FDMA) in the uplink direction** to suit lower cost and battery operated mobile transmitters with non-linear amplifiers

LTE Resource Grid



Comparing LTE and Wi-Fi



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Key Features of Air Interfaces of WCDMA (in UMTS) and LTE

Feature	WCDMA	LTE
Multiple access scheme	WCDMA	OFDMA and SC-FDMA
Frequency re-use	100%	Flexible
Use of MIMO antennas	From Release 7	Yes
Bandwidth	5 MHz	1.4, 3, 5, 10, 15 or 20 MHz
Frame duration	10 ms	10 ms
Transmission time interval	2 or 10 ms	1 ms
Modes of operation	FDD and TDD	FDD and TDD
Uplink timing advance	Not required	Required
Transport channels	Dedicated and shared	Shared
Uplink power control	Fast	Slow

UE Categories

- Used to refer to UEs with different hardware capabilities

UE category	Maximum number of bits in a subframe: Downlink	Maximum number of bits in a subframe: Uplink	Maximum number of downlink MIMO layers
1	10296	5160	1
2	51024	25456	2
3	102048	51024	2
4	150752	51024	2
5	299552	75376	4

- Besides UE category, feature group indicators also used to indicate other different UE capabilities
  - E.g., support for inter-frequency handover, periodic measurements for self-optimized networks, inter-RAT measurements, intra-subframe frequency hopping in the uplink, simultaneous transmission of uplink control info, semi-persistent scheduling

ITU 4G Requirements and LTE-Advanced

- IMT-Advanced (2008): ITU published requirements for 4G communication systems
  - Peak data rates of at least 600Mbps (DL) / 270Mbps (UL) in a bandwidth of 40MHz
- Not met by 3GPP LTE (300Mbps DL/75Mbps UL)
- This led to "LTE-Advanced" with ambitious requirements:
  - 1000Mbps (DL)/500Mbps (UL)
    - Actual LTE-A standard exceeded these requirements: 3000Mbps (DL) / 1500Mbps (UL) using 100MHz bandwidth
  - Spectral efficiency 4.5-7 times greater than Rel. 6 WCDMA in DL and 3.5-6 times in UL
  - Backward compatibility with LTE
- LTE/LTE-Advanced have emerged as the de facto 4G mobile communication systems standard