An introduction to Mobile Communications Systems (MCS)

Lecture 11

Content

- MCS: Generations
- MCS: Basic Concepts
- MCS: GSM
- MCS: GPRS
- MCS: LTE
- MCS: 5G

MCS: Generations

MCS: Generations

- ‘Prehistory’ 1946 St Louis (Missouri) –manual, uni-cellular, expensive [JS]
- 1G: (around 1979-1985)
  - analog wireless networks,
  - different standards in different countries
- 2G (1992 GSM):
  - mostly digital (GSM the most representative)
    - Designed and launched in Europe, but spread worldwide
  - but also analog in US (AMPS)!
- 2.5 G: GPRS (2001):
  - a data service (Packet Switching, or PS) implemented OVER the existing Circuit Switching (CS) networks
  - Typically over GSM, but not only (in US, it works with other networks)

Generations: 3G

- 2001 Japan IMT-2000 [JS]
- Based on CDMA (initially a military technique)
- Intended to be universal, but ending as different types of CDMA in different parts of the Globe:
  - WCDMA in Europe (UMTS), TDD-CDMA in China, CDMA 2000, etc
- Big hype followed by big crash:
  - 3G came with un-realistic marketing promises
  - Many companies, even without any telecom experience, invested in 3G licenses huge amounts of money and failed !
- 3G was eventually implemented on the market, running in parallel with 2G and 2.5 G (GPRS)
  - UMTS has better performance, but poorer coverage (smaller cells) than GSM/GPRS
  - => used more in dense populated areas, i.e. urban areas

Generations: 4G

- Initially considered to be a collection of different radio access technologies (RATs), with an all IP based core network
- After 3G, people avoided to link 4G to a single radio access technology
- Eventually it was based on LTE
- Officially the 4G RAT is LTE advanced
- It is commercially available in Europe, US, Asia, etc

Generations: 5G. Challenges

- The capacity is expected to grow 1000 times between 2010 and 2020 !
- 10- to 100- fold increase in data rates
- E2E (end-to-end) delays of 5 ms, even 1 ms for some applications:
  - Augmented reality and vehicle-to-vehicle (V2V) and vehicle to infrastructure (V2I) communications
  - 1 ms is today the transmission time interval (TTI) (scheduling cycle) in LTE !!!
- Other challenges: massive number of connection, cost, quality of experience (QoE)

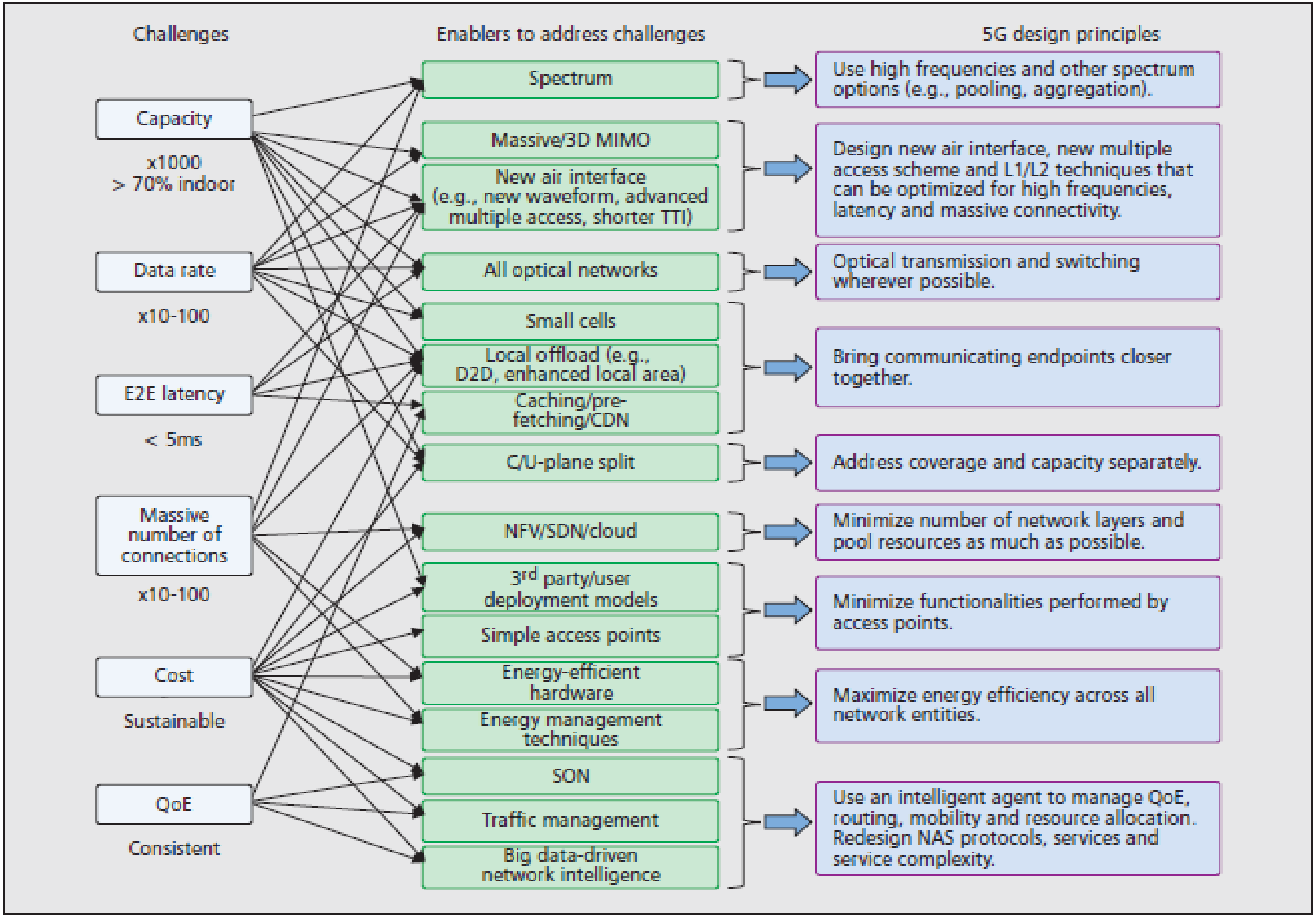


Figure 1. 5G challenges, potential enablers, and design principles.

Fig 1 from [AISKB14]

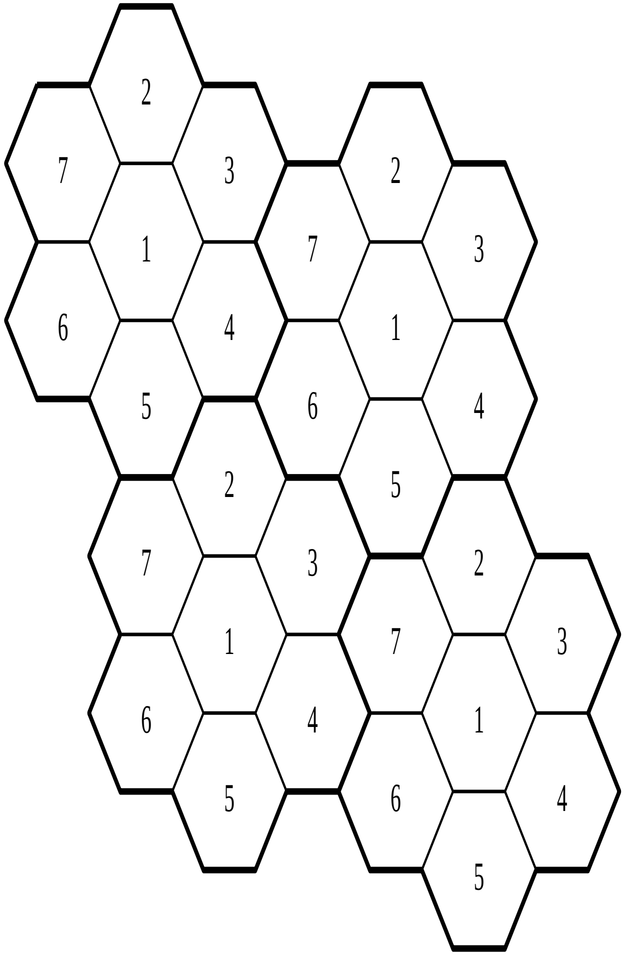
5G: NFV, SDN, CDN

- NFV – Network Function Virtualization
  - Means to implement network functions in software that runs on standard hardware equipments (servers, storage elements, switches)
  - Dedicated hardware equipment (e.g. SGSN, GGSN, firewalls, etc) will be replaced with this general purpose hardware equipment
  - NFV will reduce the cost, time to market, but rises performance challenges
- SDN - Software Defined Networks:
  - Idea is to separate data and control plane
  - Network management is simplified and new services can be introduced easily
- CDN – Content Delivery Networks [Wikipedia]
  - Delivers information (webpages) to users based on their geographical location
  - CDN server behave like a caching system: requested information is copied from the original server to servers that are geographically closer to the requiring users

MCS: Basic Concepts

Cellular concept [PP]

- **A cell is a geographical area served by a base station (BS). BS allocates radio resources to users situated inside the cell.**
- Each frequency channel is used in many different cells, say cells numbered 1 use channel 1, those numbered 2 use channel 2 and so on.
- The same frequencies can thus be re-used to cover an infinite area.
- **This is the essence of the cellular concept:- a limited amount radio spectrum to be accessed by many users.**
- Cells can have different shapes and dimensions



Frequency reuse pattern

- Usualy, a cell contains several frequencies, one of them being used for broadcasting information to all MS in the cell. This is the ‘beacon’ frequency.
- Frequency reuse pattern:
  - In one pattern, all cells use different frequencies
  - The same beacon frequency is re-used for 2 cells with the same position (same nr) in 2 adjacent patterns
  - A mobile can receive 2 beacons at the same frequency from 2 different patterns, they are distinguished by the ‘color code’ BSIC (BS Identity Code)
- BSIC = BCC (BS Color Code 3 bits) + NCC (Network Color Code – to distinguish between PLMNs)

Carrier to Interference Ratio (C/I)

- A mobile will experience interference from surrounding cells.
- Most of this is in other frequency channels - removed by filtering.
- Co-channel interference cannot be distinguished from the desired signal from that cell’s base station.
- Thus, as we move away from our base station and its signal becomes weaker, we experience a net increase in the level of co-channel interference.
- Spacing between cells selected so that the co-channel interference at the edge of the cell is just below the level where it will start to degrade signal quality.
- This has a similar effect to the signal degradation due to noise

Cell types

- Size:
  - Macro-cells (radius<35Km): traffic not so dense
  - Mini-cell (Alcatel: radius 1Km)
  - Micro-cells (radius <300m): urban
  - Pico-cells: indoor
  - Femto-cells: your cell at home !
- Hierarchical structure:
  - Umbrella cell (macro-cell) covers a group of
  - Overlaid cells (micro-cells)
  - For fast moving users in an urban environment
- Power of the transceiver:
  - Normal cell: the same power
  - Concentric cell: *inner* zone (less power) / *outer* zone (maximum power)
- Shape:
  - Omnidirectional
  - Sectored
  - Unidirectional

Channel assignment issues

- GSM – Assign frequencies to cells or clusters of cells (FDM)
  - Uses TDMA to assign timeslots on a particular radio channel to a user
- GPRS – Packet data, can assign resources on a per timeslot basis
- EDGE – Extension of GPRS giving approximately 3 times the throughput
- CDMA – Assign codes to cells
- UMTS and EDGE – variable data rates – dynamic allocation of resources

Cells. Advantages

- Main advantage of cells: cover a large area (i.e., a country) with a limited amount of spectrum
- Can serve more users
  - If we want to increase the number of users served by a mobile network, we add more cells
    - Problem: what happens if one country is covered by only one cell ? (e.g. in GSM)
    - The number of users that can be served simultaneously is: 124 GSM carriers / 3 GSM operators in the country *8 time slots on each frequency * 1 user per time slot ≈ 320 users
  - In urban area, where users have higher density, cells are smaller
  - Femtocells: your cell at home
    - Discussion: pros and cons femtocells vs Wi-Fi

Cells. Drawbacks: handover

- Radio resources are allocated to users on a cell basis, by the base station (BS) serving that cell
- When the user moves to another cell, it will disconnect from the current BS and connect to the new BS
- This process is called *handover* (or handoff)
- The process is quite complex and it takes time
- Handover can fail (e.g., no radio resources in the new cell)
  - In that case the user call (session) will be dropped !
  - This is considered to be very annoying for that user

Types of handover

- Horizontal vs vertical handover
  - Horizontal handover means that the user is moving to another cell that uses the same radio access technology (RAT) and belongs to the same operator
  - Vertical handover (VHO): the new cell uses another RAT and/or belongs to another network operator
- Hard vs soft HO
  - Hard HO: when the user first disconnects from the current BS, and then it connects to the new BS
  - Soft HO: first the user connects to the new BS, then it disconnects from the current BS
    - Not all technologies support it: GSM does not support soft HO, CDMA does !

Traffic vs. signalling

- Traffic = information interchanged from user to user, after setting up a call [Alc]
- Signalling = information interchanged, in some cases without the user's knowledge, between the mobile equipment and the network elements (machines). Signals are not *payload* and don't bring revenue
- Signalling classification:
  - *During a call* (e.g. call release, handover) vs. *Out of call* (for managing mobiles, to set up a call)
  - *Inband* (control info carried within the traffic CH) vs. *Outband* (signalling on separate channels)
  - For *Mobility Management (MM), Radio Resource management (RR), Call Control (CC)*
- Signalling in cellular networks is much higher than in other types of networks, mainly due to mobility (MM and RR) !

Spectrum efficiency

- Is the ratio of information transferred to the amount of spectrum utilization.
- The purpose is to increase the number of subscribers using the same radio bandwidth on the same area at the same time
- Techniques used to increase spectrum efficiency:
  - Power conrol
  - Handover
  - Frequency hopping
  - Discontinuous transmission (DTX)

Spectrum efficiency. Techniques

- Power control: if the power is too high, there are interferences, if it is too low, the transmission quality decreases
- Handover: based on the measurements made by MS, the network decides which is the best cell and the best radio resources to be used by MS
- Frequency hopping: different carriers can be used on the same channel. Instead of having one channel affected by errors for a long time, all channels will have short periods of bad radio conditions
- DTX:
  - used to minimize interference during calls (and to reduce the power consumption).
  - No signal transmitted during the silence periods, only a ‘confort noise’
  - DTX mandatory in UL and optional in DL

MCS: GSM

Global System for Mobile Communications

GSM evolution

- GSM=Global System for Mobile Communications
- GSM Evolution:
  - 1979 the 900MHz band reserved
  - 1982 *Groupe Spécial Mobile* under CEPT (Post &Telecom European Conference)
  - 1988-89 GSM taken over by ETSI (European Telecommunication Standard Institute)
  - 1990-91
    - 'Phase 1' recommendations
    - DCS1800
  - 1992 first commercial GSM networks
  - 1995 'Phase 2' recommendtions issued
  - 1998 3GPP (3rd Generation Partnership Project)

GSM 900, 1800, 1900

- GSM 900: 2 x 25 MHz frequency bands:
  - 890-915 MHz UL, 935-960 MHz DL
  - 124 carriers, 200 kHz each
  - Extended version: 2x35MHz 880-915MHz UL, 925-960MHz DL, 174 carriers, 200kHz each
- GSM 1800 (Digital Cellular System -DCS)
  - At the request of the UK
  - 2x75MHz frequency bands:
  - 1710-1785 MHz UL, 1805-1880 MHz DL
  - 374 carriers (200kHz/carrier)
- GSM 1900 (Personal Communication System or PCS1900)
  - North and South American version of DCS 1800
- GSM 850
  - same frequency range like AMPS, D-AMPS, IS-95 (American standards)
  - 824-890MHz UL, 869-894MHz DL, 124x200kHz carriers

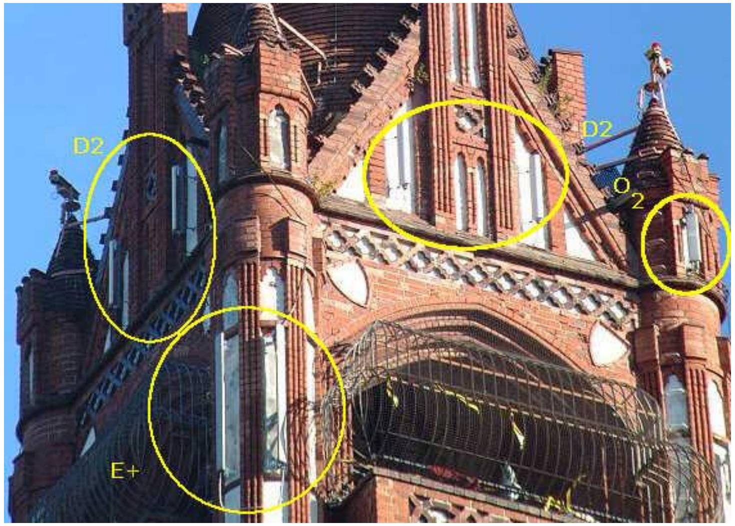
Architecture of the GSM system [JS]

- GSM is a PLMN (Public Land Mobile Network)
  - several providers setup mobile networks following the GSM standard within each country
  - components
    - MS (mobile station)
    - BS (base station)
    - MSC (mobile switching center)
    - LR (location register)
  - subsystems
    - RSS (radio subsystem): covers all radio aspects
    - NSS (network and switching subsystem): call forwarding, handover, switching
    - OSS (operation subsystem): management of the network

Ingredients 1: Mobile Phones [JS]

The visible but smallest part of the network!

Ingredients 2: Antennas [JS]



Still visible – cause many discussions…

Ingredients 3: Infrastructure 1[JS]

Base Stations

Cabling

Microwave links

Ingredients 3: Infrastructure 2[JS]

Switching units

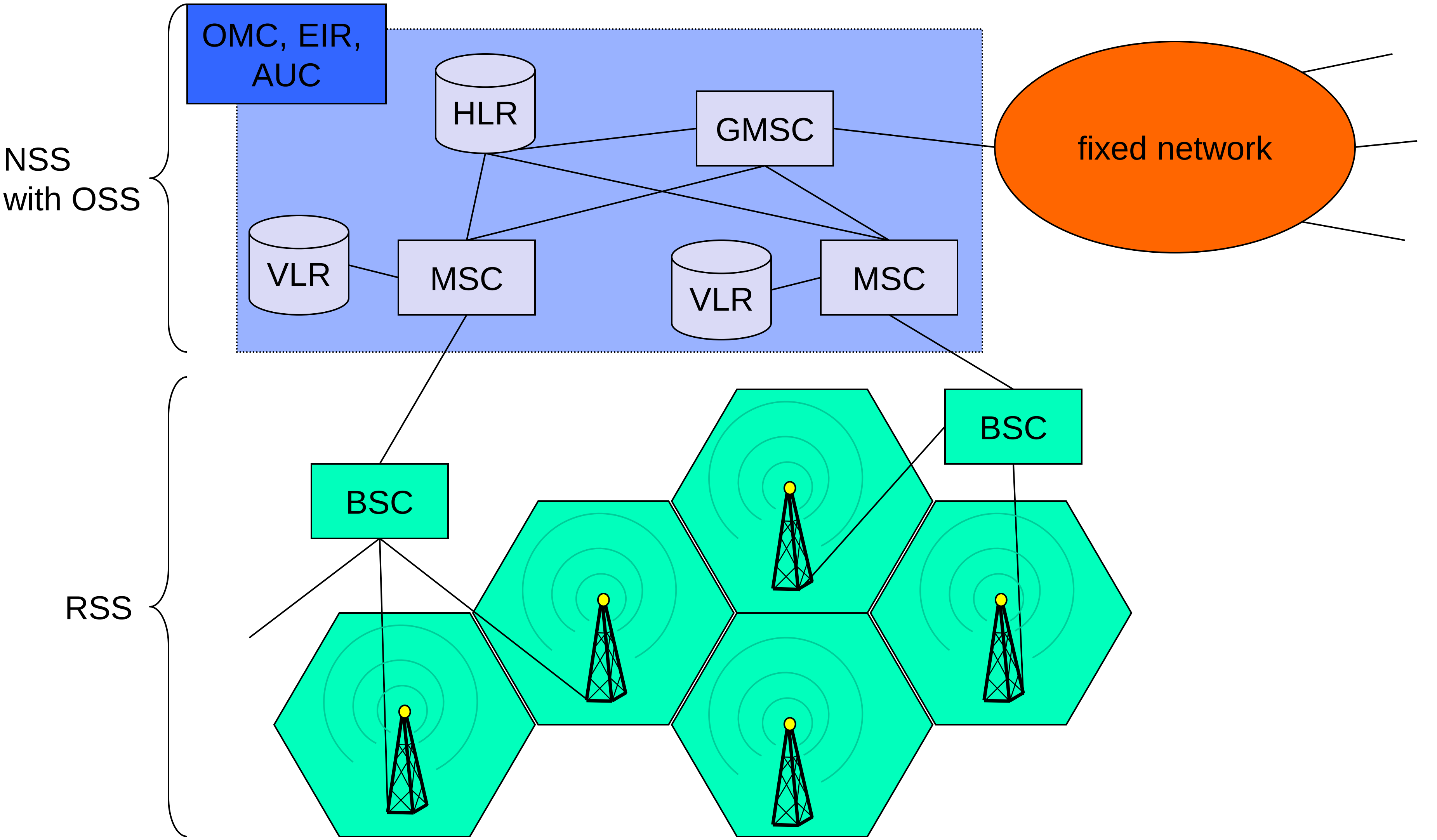
Management

Data bases

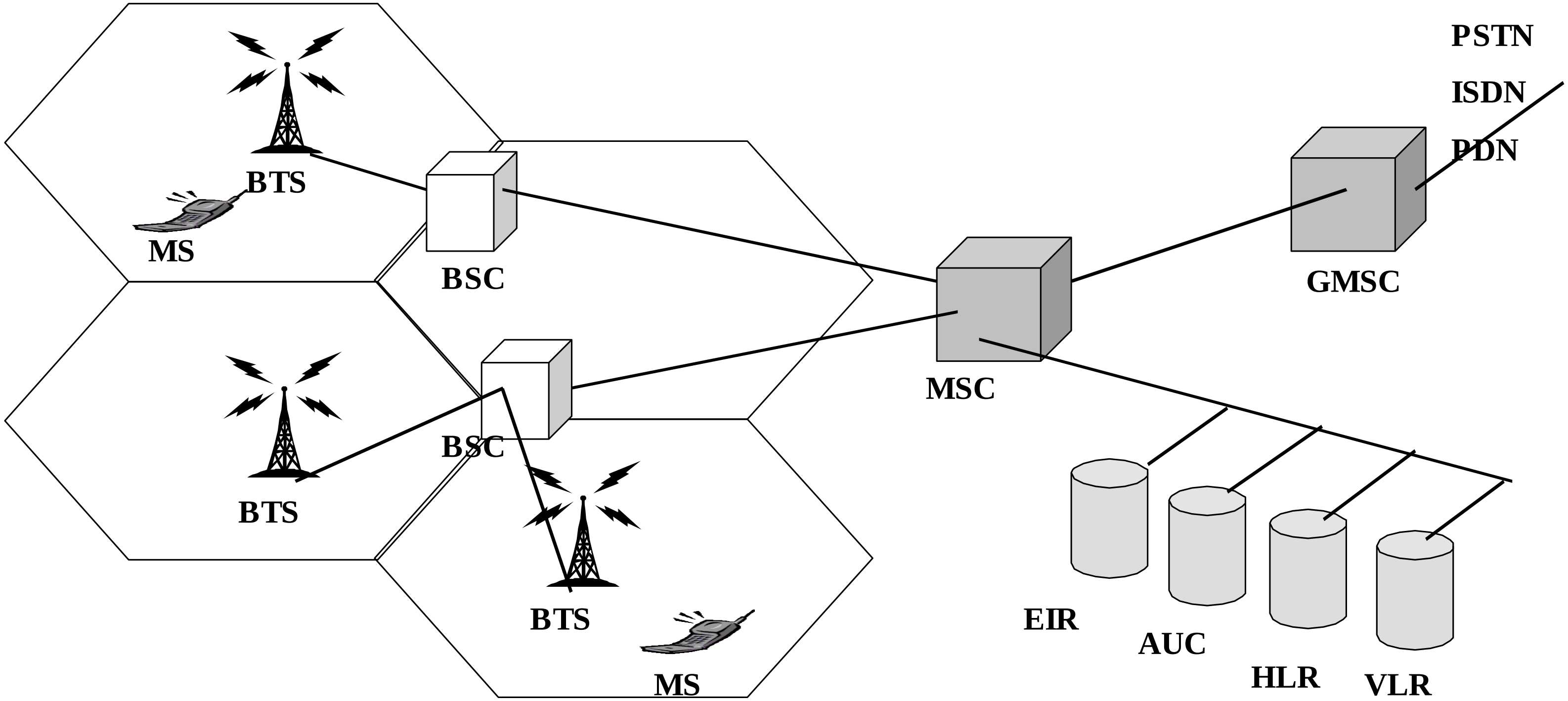
Not „visible“, but comprise the major part of the network (also from an investment point of view…)

Monitoring

GSM: overview[JS]



GSM architecture



BTS = Base Transceiver Station
BSC = Base Station Controller
BSS = Base Station Subsystem (BTS+BSC)
MSC= Mobile Switching Center
GMSC = Gateway MSC
MS = Mobile Station

HLR = Home Location Register
VLR = Visitor Location Register
EIR = Equipment Identity Register
AUC = Authentication Center
PSTN = Public Switched Telephone Network
ISDN = Integrated Services Digital Network
PDN = Packet Data Network

GSM architecture. Elements

- Radio subsystem (RSS) (mobile station + base station subsystem)
  - Used for radio access
  - If the network deals with both CS and PS traffic, their path is common in RSS
- Core network or Network Sub System (*NSS*):
  - Separate CS and PS paths, if both are available
- Operation Sub System (*OSS*) – resources used by the operator to manage the network.
  - Often called OMC (Operation and Management Center)

GSM architecture. Radio subsystem

- *MS* (Mobile Station) (or UE – user equipment)
  - used by a subscriber to call another subscriber
  - Consists of SIM (Subscriber Identity Module) and MT (Mobile Terminal)
  - SIM stores administrative and security data, location data
  - Only emergency calls can be done without SIM
  - MT: radio transmission, speech encoding/decoding, cyphering, Human machine interface, SMS, etc
- *BSS* (Base Station Subsystem), consisting of
  - *BTS* (Base Transceiver Station): sender and receiver, antenna, deals with physical channels, consists of high power elements
  - *BSC* (Base Station Controller): controlling several BTSs, manages radio resources, logical channel management, handover management
  - BSS = BSC + sum(BTS) + interconnection

GSM architecture. Core network

- MSC:
  - Main component of the public land mobile network (PLMN) of GSM
  - switch exchange with specific GSM functions regarding mobility, handover, etc
  - Covers a geographical area and manages several BSCs
- Databases:
  - HLR (home location register – permanent and semi-permanent data of all subscribers, including the current VLR)
  - VLR (located on MSC) – contains copy of HLR data for the users in the area of the MSC + location information (location area – group of cells)
- Network nodes involved in authentication process: AuC – authentication center

Data services in GSM II [JS]

- GPRS (General Packet Radio Service)
  - packet switching
  - using free slots only if data packets ready to send (e.g., 50 kbit/s using 4 slots temporarily)
  - standardization 1998, introduction 2001
  - advantage: one step towards UMTS, more flexible
  - disadvantage: more investment needed (new hardware)
- GPRS network elements
  - GSN (GPRS Support Nodes): GGSN and SGSN
  - GGSN (Gateway GSN)
    - interworking unit between GPRS and PDN (Packet Data Network)
  - SGSN (Serving GSN)
    - supports the MS (location, billing, security)
  - GR (GPRS Register)
    - user addresses: in HLR

MCS: GPRS

General Packet Radio Service

GPRS - motivation

- Data transmission in GSM: CSD (fixed 9.6 kbps data rate), SMS (max 256 characters/message), HSCSD High Speed Circuit Switched Data
- Drawbacks of using circuit switching for data transfer:
  - Long connection establishment duration (due to negociations for resource reservations) compared to data transfer duration
  - Network resources are reserved for the entire duration of the connection, even if there is no data to be transferred: not suited for *bursty* traffic, as it is most of the data traffic (e.g. WWW)
  - Billing is time-based, not based on the volume of data transfered
- Packet switching (PS) is much more efficient for data traffic
- GPRS: truly PS service for data transfer, implemented **over** the existing GSM networks
- Requirements: minimum costs, different services than those offered in GSM
- Applications: e-mail, FTP, WWW, multimedia, etc.

GPRS - Motivation

- General Packet Radio Service (GPRS) – mainly IP
  - Connectionless data transfer - always on-line
  - New set of interfaces - new packet switched network
  - Instantaneous bit rates can range from 8 kbps to 115 kbps
- **Dynamic allocation of resources:**
  - **a MS can use several channels, and several MS can be multiplexed on the same channel**
- Problem is not only with the air interface
- Channel path through the entire system should be different for packet data and voice
- Entire new architecture required to overlay existing GSM system
- EGPRS: uses a different modulation techniques in order to ensure higher data rates (approx 3 times higher than in GPRS)

General architecture of GPRS network

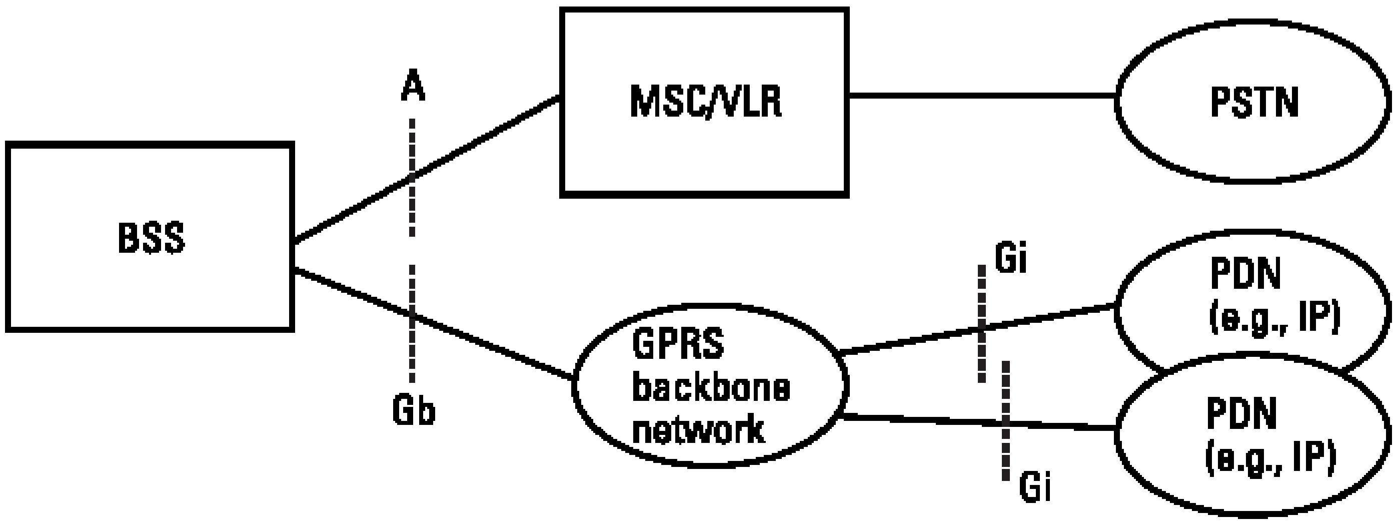
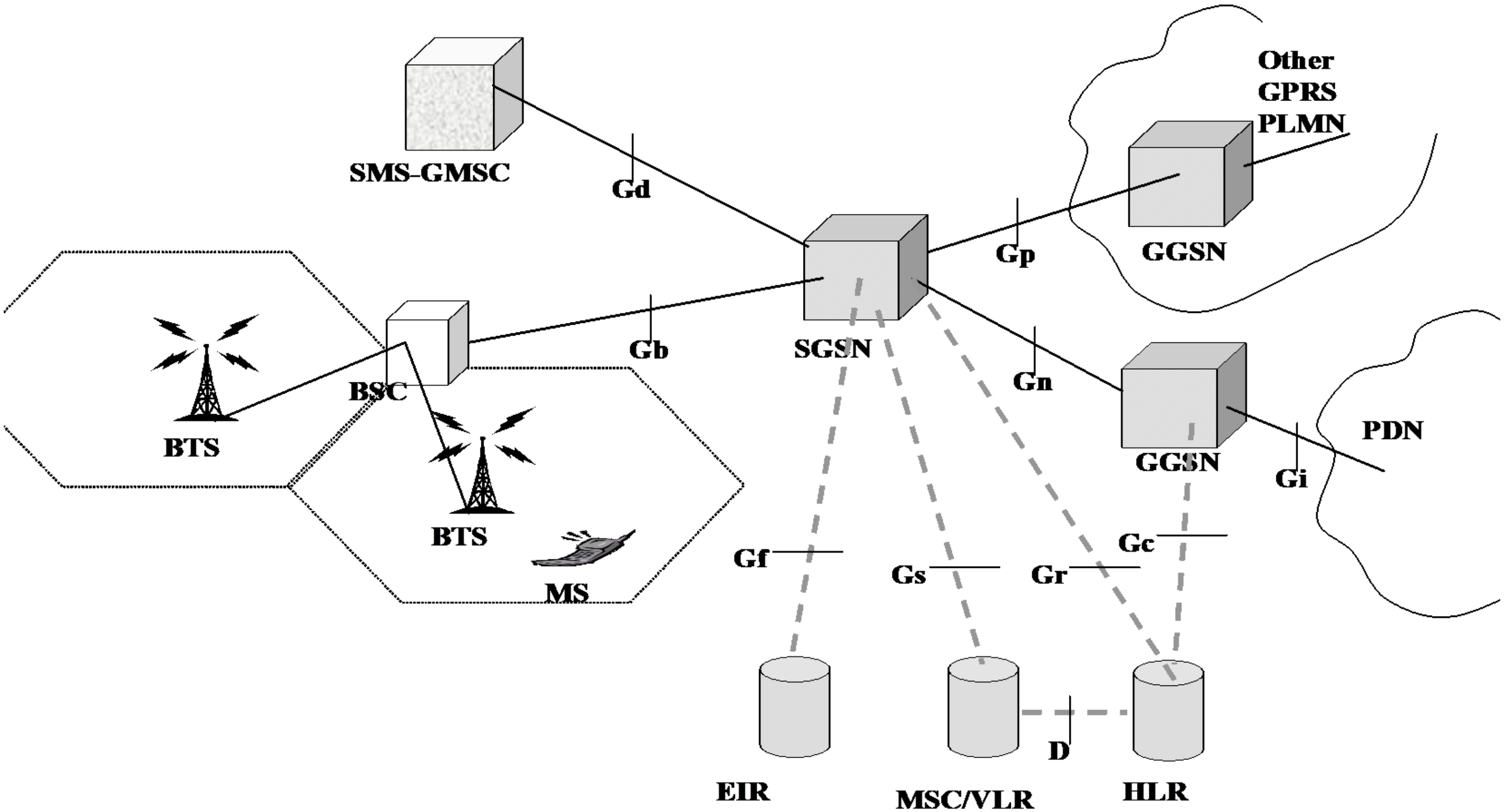


Fig. 1.1 ‘General architecture of the GPRS network’ from [SSP03]

PS traffic routed through the GPRS backbone network (GSS – GPRS SubSystem) towards the external Packet Data Networks (PDNs)

GPRS system architecture



SGSN = Serving GPRS Support Node
GGSN = Gateway GPRS Support Node
SMS-GMSC = SMS-Gateway MSC
PDN = Packet Data Network
PLMN = Public Land Mobile Network

Fig 1.2. from [Tod06]. Based on [CG97] and [BVE99]

Legend

- MS - Mobile Station
- (MN - Mobile Node: UMTS designation for MS)
- BTS - Base Transceiver Station
- BSC - Base Station Controller
- PCU - Packet Control Unit
- SGSN - Serving GPRS Support Node
- GGSN - Gateway GPRS Support Node
- PCU is part of the BSS
- BSC must communicate with an SGSN and an MSC
- Packet switched traffic and circuit switched traffic have different core networks

Overview of resource allocation in GPRS

- In GPRS, resources are allocated at different levels:
  - GPRS attach:
    - a logical link established between MS and SGSN
  - Session, or PDP context activation:
    - A route is established between MS, SGSN, GGSN and an external server outside GPRS network
  - Micro-connection (TBF establishment):
    - Between MS and BSS, in one direction and one cell
    - Radio channels are allocated to a user (a MS)
  - Radio block:
    - different users that share a PDCH are scheduled on a time basis
    - Level: MAC
    - Period: radio block period (20ms)

Main transactions. Resource allocation in GPRS

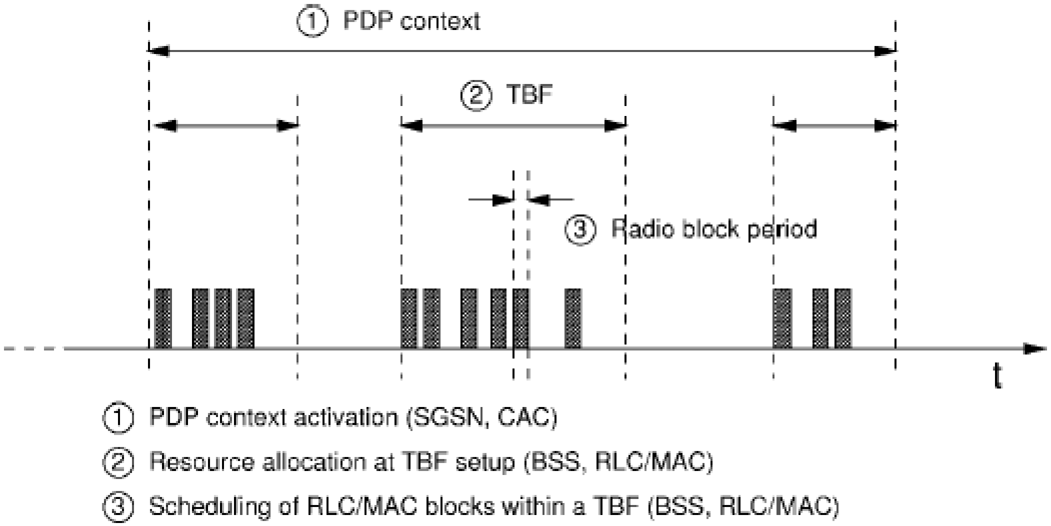


Fig. 2. ‘Three-stage QoS management’ from [SM01]

GPRS QoS specification

- Release'97:
- Characterised by:
  - The service precedence
  - Delay
  - reliability
  - Peak and mean throughput
- Problems:
  - Only 1 QoS profile per PDP context
  - BSS not involved in QoS negotiation
  - Too manny QoS classes

- Release'99:
- Same like UMTS QoS
- Characterised by traffic classes:
  - Conversational (voice, telent)
  - Streaming
  - Interactive (WWW)
  - Background (e-mail, FTP)
- Solves the problems of Rel'97 QoS specifsication

MCS: LTE

Long Term Evolution

An introduction to LTE

- LTE = Long Term Evolution of 3G
- Defined by 3rd Generation Partnership Project (3GPP) in order to meet the increasing performance requirements for mobile broadband [LLMP+09], [EFKM+06], [ADFJ+09]
- Aimed to ensure 3G competitiveness in 10 year perspective and beyond and to replace GSM systems
- Major step toward International Mobile Telephony (IMT)-Advanced
- Initial deployment at end of 2009

Targets

- Higher data rates than current HSDPA and HSUPA (High Speed Downlink /Uplink Packet Access – enhancements of UMTS)
  - 3-4 times higher average throughput
  - 3 times higher cell-edge throughput
  - Peak rates of 300Mbps in DL and 75Mbps in UL
  - One way radio network delay less than 5ms
- Improved spectrum efficiency: 3 times better than current standards
- Spectrum flexibility, i.e. the possibility to work in different spectrum allocations
  - with different bandwidths and
  - Both paired and unpaired bands
  - Smooth migration into other frequency bands (including 2G GSM frequencies)
- Flat network architecture
  - Fewer nodes => reduced latency on both radio and core network sides
  - All IP core network
- Reduced cost for operators and users:
  - Smooth evolution from other 3GPP systems (TD-SCDMA, WCDMA/HSPA, cdma2000)
    - (TD-SCDMA: Time Division Synchronous Code Division Multiple Access (also known as UMTS-TDD) is the CDMA version used in China)

Solutions: OFDM

- Radio technology: Orthogonal Frequency Division Multiplexing (OFDM) for DL
- A modified version of OFDM, called Single-Carrier Frequency-Division Multiple Access (SC-FDMA) in UL
- OFDM uses a large number of parallel, narrow band carriers
- Allows for both time-domain and frequency-domain scheduling => more robust to narrowband interference than (W)-CDMA
  - In CDMA the narrowband interference signal is spread over a large spectrum
  - In OFDMA a user can receive non-interfered frequencies due to frequency-domain scheduling.
  - This is called channel-dependent scheduling and is supported in both time-domain and frequency-domain scheduling.
- Can be easily adapted to different spectrum bandwidths (spectrum flexibility):
  - LTE bandwidth: from 1.4 MHz to 20MHz
  - The larger the bandwidth, the higher the data rates can be
  - All terminals support the widest bandwidth
  - The system information occupies only the most narrow bandwidth

OFDMA principles

- OFDMA uses narrow orthogonal sub-carriers: in LTE sub-carrier spacing is 15 kHZ
- Orthogonality: at the sample moment of a subcarrier, the other sub-carriers have a zero value (see Fig 1)
- Direct and Inverse Fast Fourier Transforms are needed in order to process the signals

OFDM: principles

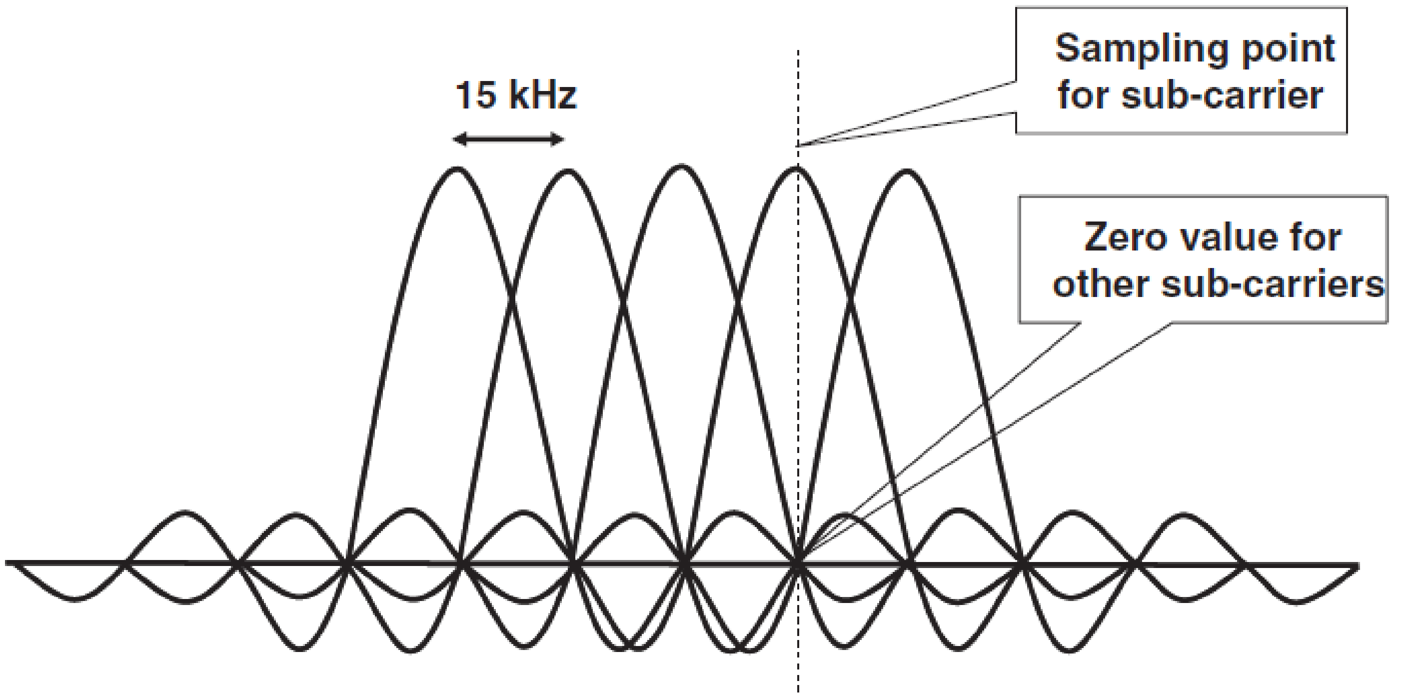


Figure 16.4. Adjacent sub-carrier with OFDMA

Fig 1. OFDMA principles (is Figure 16.4 from [HT07], p 467)

OFDMA and SC-FDMA

- DL: OFDMA allows for relatively simple receivers => reduced User Equipment (UE) costs
- UL: the idea is to move the most part of the processing power at the receiver, in order to keep simple the UE and to avoid high power consumption in UE.
  - OFDMA has a high peak-to-average power ratio => not suited for UL
  - Single carrier transmission, called SC-FDMA is used for UL
    - It has smaller peak-to-average power ratio => terminals can be less complex and use less power
    - SC-FDMA employs a discrete Fourier transform (DFT) spread-OFDM [LLMP+09], hence it maintains the orthogonality
    - SC-FDMA imposes restrictions for UL scheduling, i.e. one UE must transmit on adjacent sub-carriers

OFDMA and spectrum flexibility

- Spectrum flexibility – duplex scheme:
  - LTE can use for UL/DL
    - Frequency Division Duplex (FDD) for paired spectrum (left in Fig2) (one frequency band for DL, another one for UL)
    - Time Division Duplex (TDD) for unpaired spectrum (right side of Fig 2): same frequency band for UL and DL
      - Guard periods needed between UL and DL
    - Combined FDD/TDD (middle of Fig 2) – for reduced UE complexity

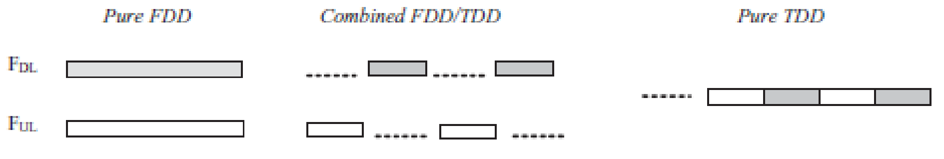


Figure 3.35 Possible TDD/FDD modes and interactions.

Fig 2. FDD/TDD modes (Fig 3.35 from [LL08], page 119).

Solutions: frame structure

- For FDD, one frequency band used for DL and another one for UL
- The frame structure is shown next, in Fig3:
  - 1 ms sub-frame duration, 1 frame = 2 slots, 0.5 ms each slot
  - 10 ms frame duration = 10 sub-frames

Fig 3. Frame structure for type 1 frames (Fig 16.1 from [DPSB07], page 317.)

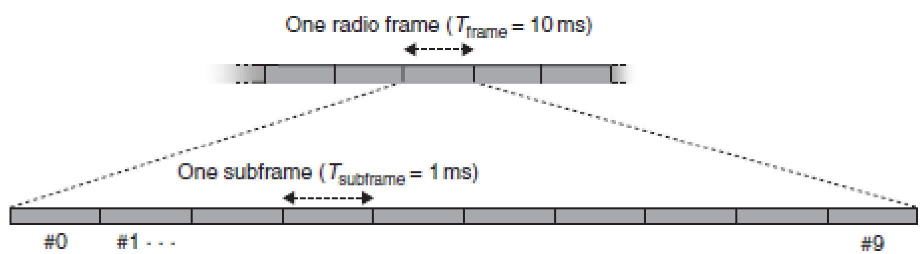


Figure 16.1 *LTE time-domain structure.*

For TDD there is another frame structure, called type 2 frame structure, not presented here.

Solutions: architecture

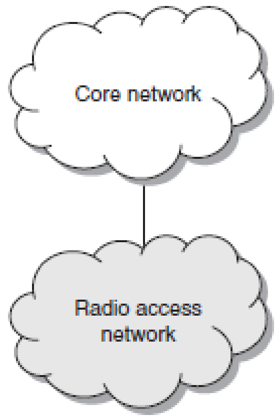


Figure 18.1 *Radio access network and core network.*

Fig 4. Radio access and core network (Figure 18.1 from [DPSB07], p 371)

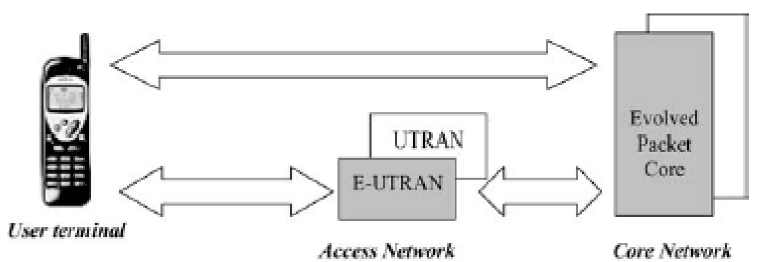


Figure 1.13 Towards 'Evolved UMTS' networks.

Fig 5 LTE architecture (Figure 1.13 from [LL08], p 23)

- A mobile network has two parts (fig 4):
  - Radio access network
  - Core network
- LTE architecture consists of:
  - User terminal (or User Equipment UE)
  - Radio access network called E-UTRAN (Evolved UTRAN)
    - UTRAN: UMTS Terrestrial Radio Access Network
  - Core network called Evolved Packet Core (EPC)
  - In Fig 5 UTRAN and E-UTRAN co-exist, using the same EPC.
  - EPC + E-UTRAN = EPS (Evolved Packet System)
  - Terminology
    - LTE – refers to radio-part only, i.e. LTE = E-UTRAN
    - EPC is denoted SAE (System Architecture Evolution)
    - However, LTE term is very often used to denote both radio and core network parts, i.e. LTE = LTE +SAE ! (same way as EDGE is used to denote E-GPRS !)

Solutions: architecture

- First mobile networks were designed only for voice =>
  - Circuit Switching (CS) resource allocation
  - core network based on legacy protocols from fixed telephony.
- Data services need
  - Packet Switching (PS) allocation of radio resources
  - and a separate core network, IP based
- CS and PS resource allocation and different core networks coexisted in 2G and 3G networks.
- The trend is to give priority to data =>
  - LTE uses only packet switching for radio resource allocation
  - and an IP based core network
    - => voice will be transmitted as voice over IP (VoIP) over radio !
- The architecture evolution is shown on the next slide.

Architecture evolution

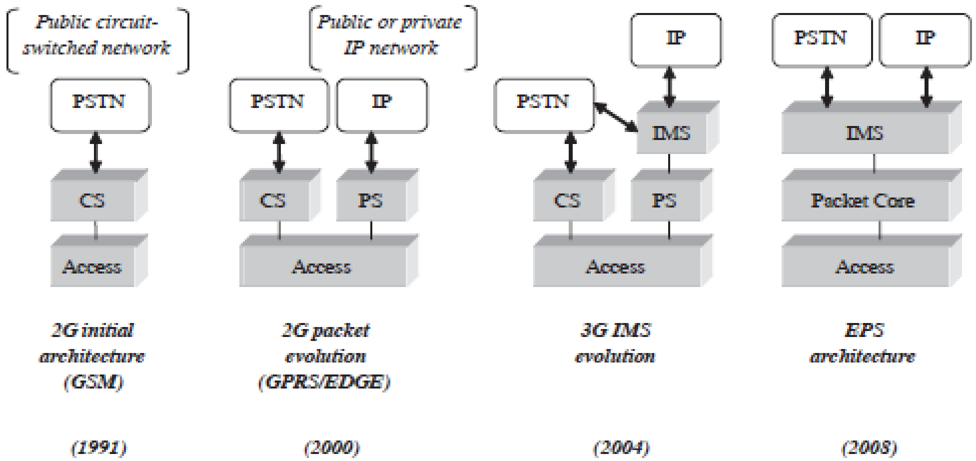


Figure 2.4 Evolution of network architecture (from circuit to packet).

Fig 6. Mobile network architecture evolution (figure 2.4 from [LL08], p 34).

PSTN= Packet Switched Telephone Network (i.e, public telephony)

IMS= IP Multimedia Subsystem ("3GPP multimedia framework, designed for delivering IP multimedia services to end users" [LL08], p 327).

EPS – Evolved Packet System, i.e., LTE.

Note that in LTE the CS part has been removed !

LTE architecture

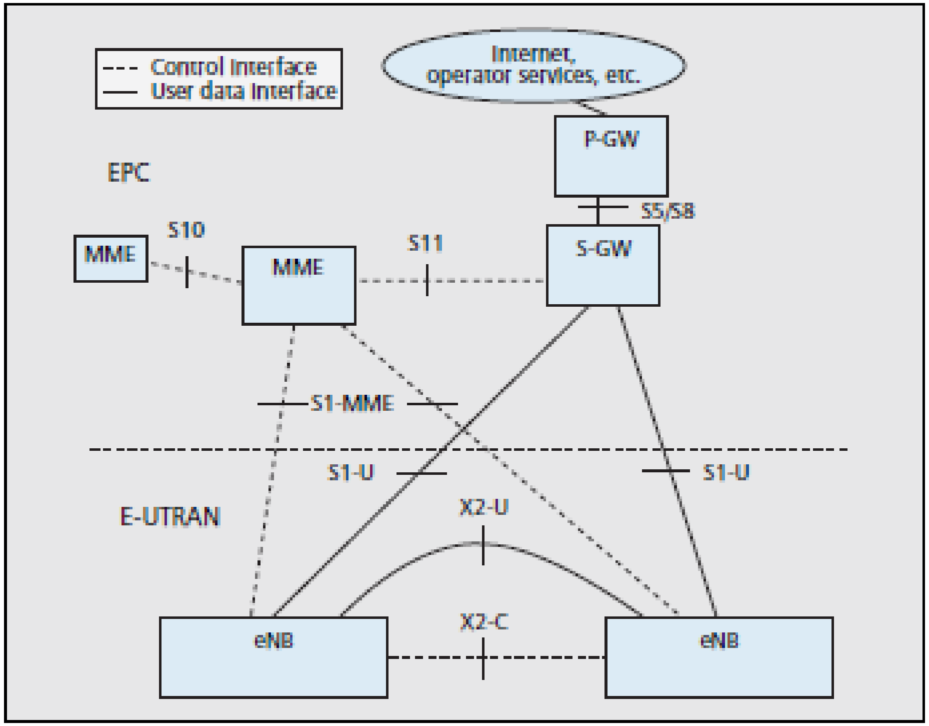


Figure 1. *Overview of the EPC/LTE architecture.*

Fig 7 LTE architecture (Figure 1 from [LLMP+09], p 53)

LTE architecture: EPC

- HSS – Home Subscriber Server (not shown in Fig7) – a database with users, similar to the HLR in 2G and 3G:
  - S6 interface connects HSS to EPC
- EPC:
  - In the control plane:
    - MME – Mobility Management Entity
  - In the user plane:
    - S-GW =Serving Gateway
    - P-GW = Packet data network Gateway
      - SGi interface (not shown in Fig 7) connects EPC to internet
    - S-GW and P-GW can be in the same physical node
    - Or MME and S-GW can be in the same physical node (see Fig 8).
- E-UTRAN:
  - eNB – enhanced node B (denoted also eNodeB)
    - Interface X2 connects different eNBs (e.g. used during handover):
      - X2-U for user plane and X2-C for control plane
    - Interface S1: connects eNB to EPC
      - It has an user plane part: S1-U
      - And a control plane part: S1-C or S1-MME.

LTE architecture from [LL08]

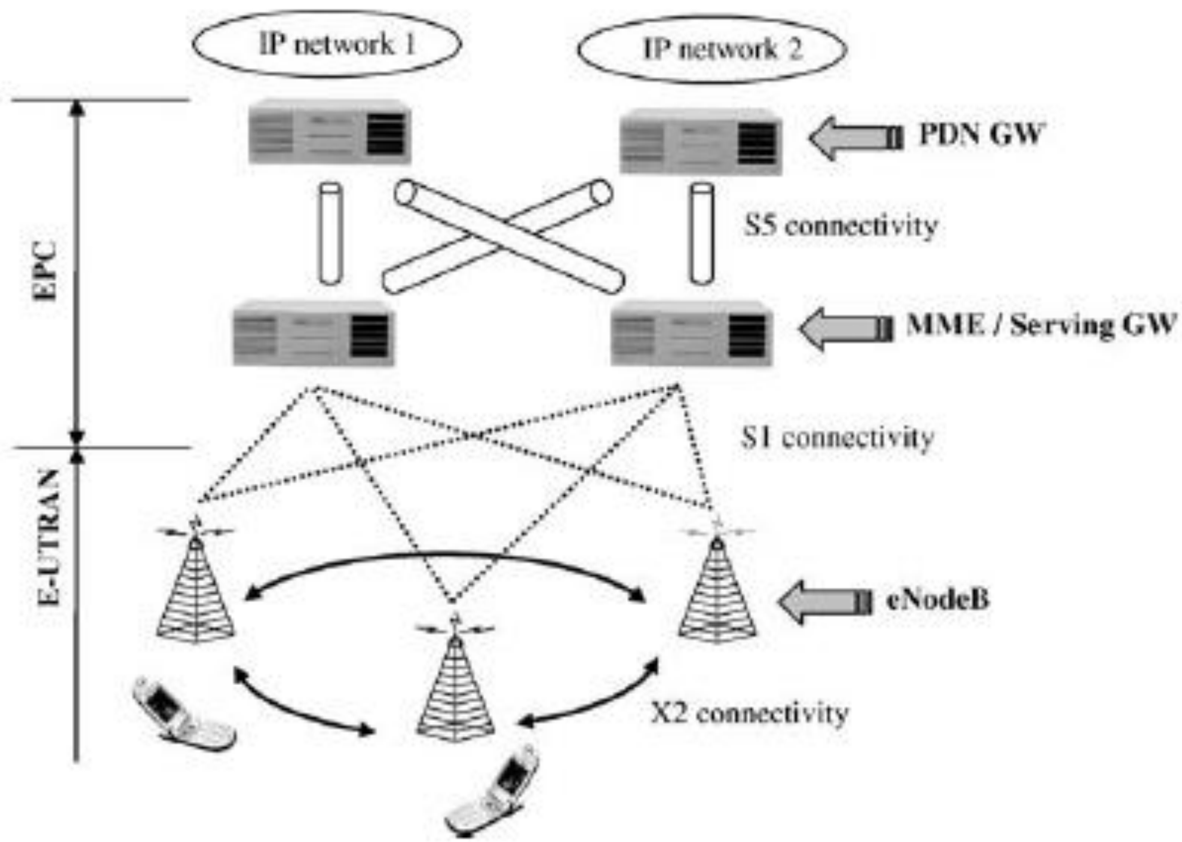


Figure 4.1 EPS architecture – user and control plane connectivity.

Fig 8 EPS architecture as presented in [LL08], p172, Figure 4.1.

Comparison LTE RAN – UMTS RAN architectures

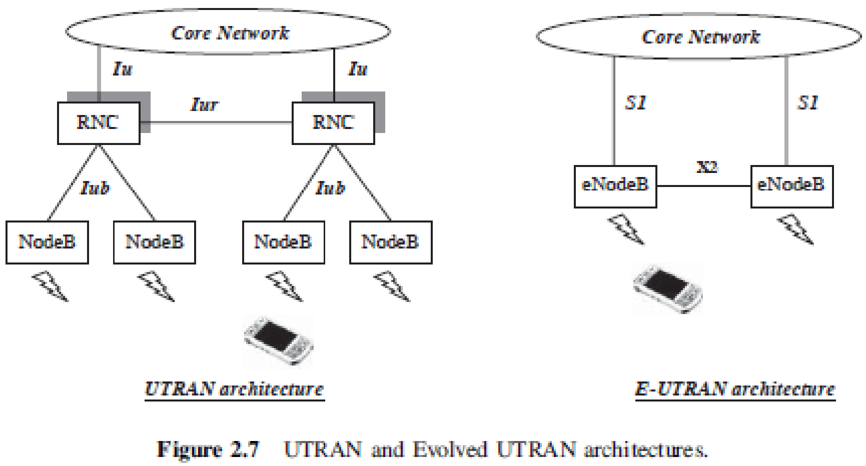


Fig 9. Comparison between radio access architecture for UMTS and LTE (fig 2.7 from [LL08], p38)

From fig 9 it can be observed that eNodeB functions in LTE comprise both NodeB and RNC functionality in UMTS.

This enables reduced latency on the radio side, simpler protocols, reduced costs for operators (less interfaces to be installed and tested)

Protocol stacks. User plane radio

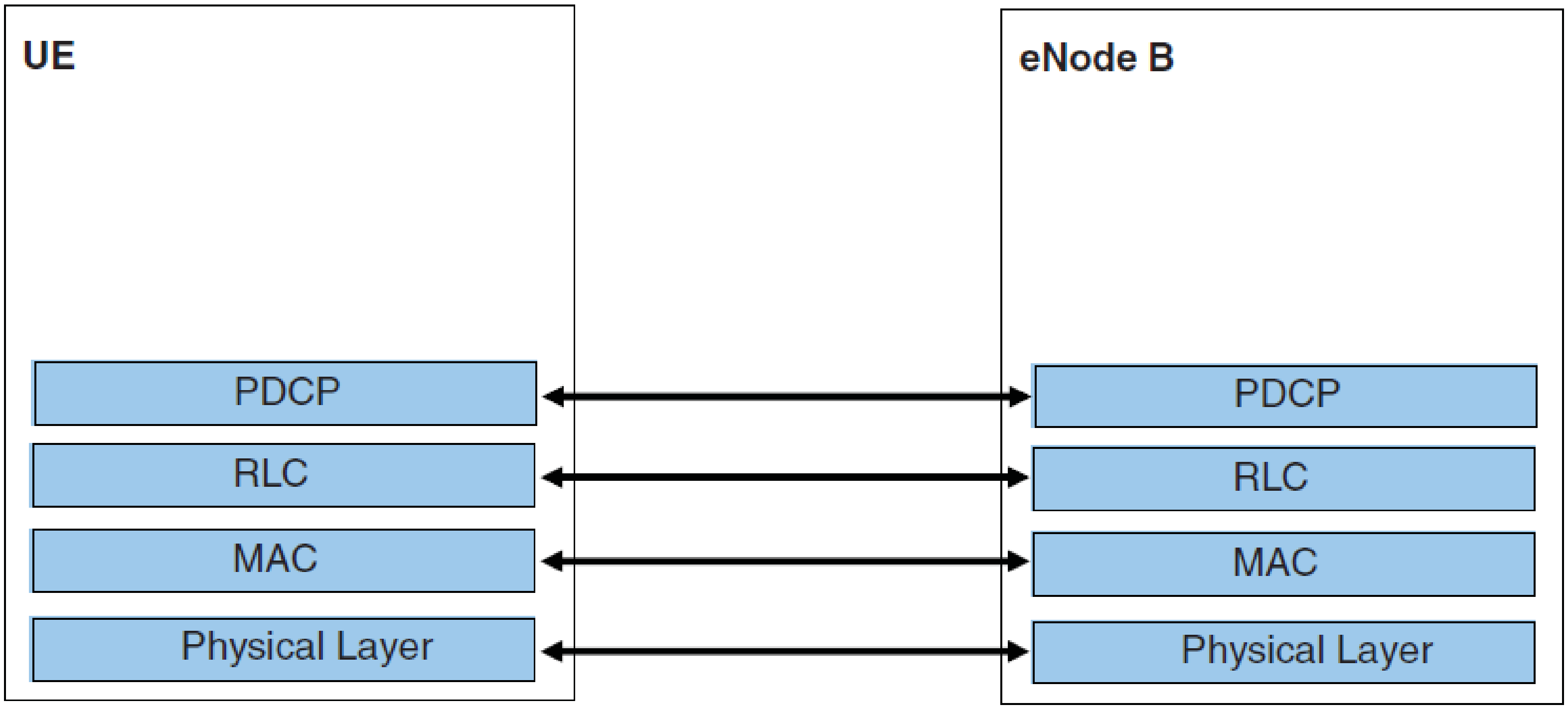


Figure 16.14. LTE user-plane protocol stack distribution

Fig 10. LTE user-plane protocol stack (Figure 16.14 from [HT07], pp 475).

User plane protocols: functions

- Packet Data Convergence Protocol (PDCP):
  - IP header compression
  - Ciphering
  - Supports mobility for inter-eNBs handover
- Radio Link Control (RLC):
  - Can work in Acknowledge Mode (AM) or Unacknowledged Mode (UM).
  - ARQ functionality (selective-repeat ARQ) in AM
  - Supports data segmentation and concatenation in order to reduce protocol overhead
  - Reordering. Used when MAC HARQ fails, and some RLC blocks need retransmission (AM).
- Medium Access Control (MAC):
  - Hybrid ARQ (HARQ):
    - Multiple stop-and-wait protocols: compared to simple stop-and-wait, it allows continuous transmission
    - Single bit feedback ACK/NACK with a fixed timing relation to the corresponding transmission attempt [LLMP+09]
    - It is simple, ensures low-delay, 10^{-4} - 10^{-3} packet loss. If the application requires lower packet loss, then RLC ARQ is used, otherwise RLC can work in unacknowledged mode (UM).
    - Being terminated in the same nodes like RLC, it can send a local NACK to the RLC ARQ in order to signal that an RLC block cannot be send at MAC level and has to be retransmitted => reduces the retransmission time. Such a case can occur if radio conditions are too bad for the chosen modulation and coding scheme ([LLMP+09], p55)
  - Scheduling: will be discussed
  - Random access: when the time alignment between UEs and eNB has to be established or re-established, a random access (RA) procedure takes place
- Physical layer
  - Coding, modulation, antenna and resource mapping

Protocol stack: control plane

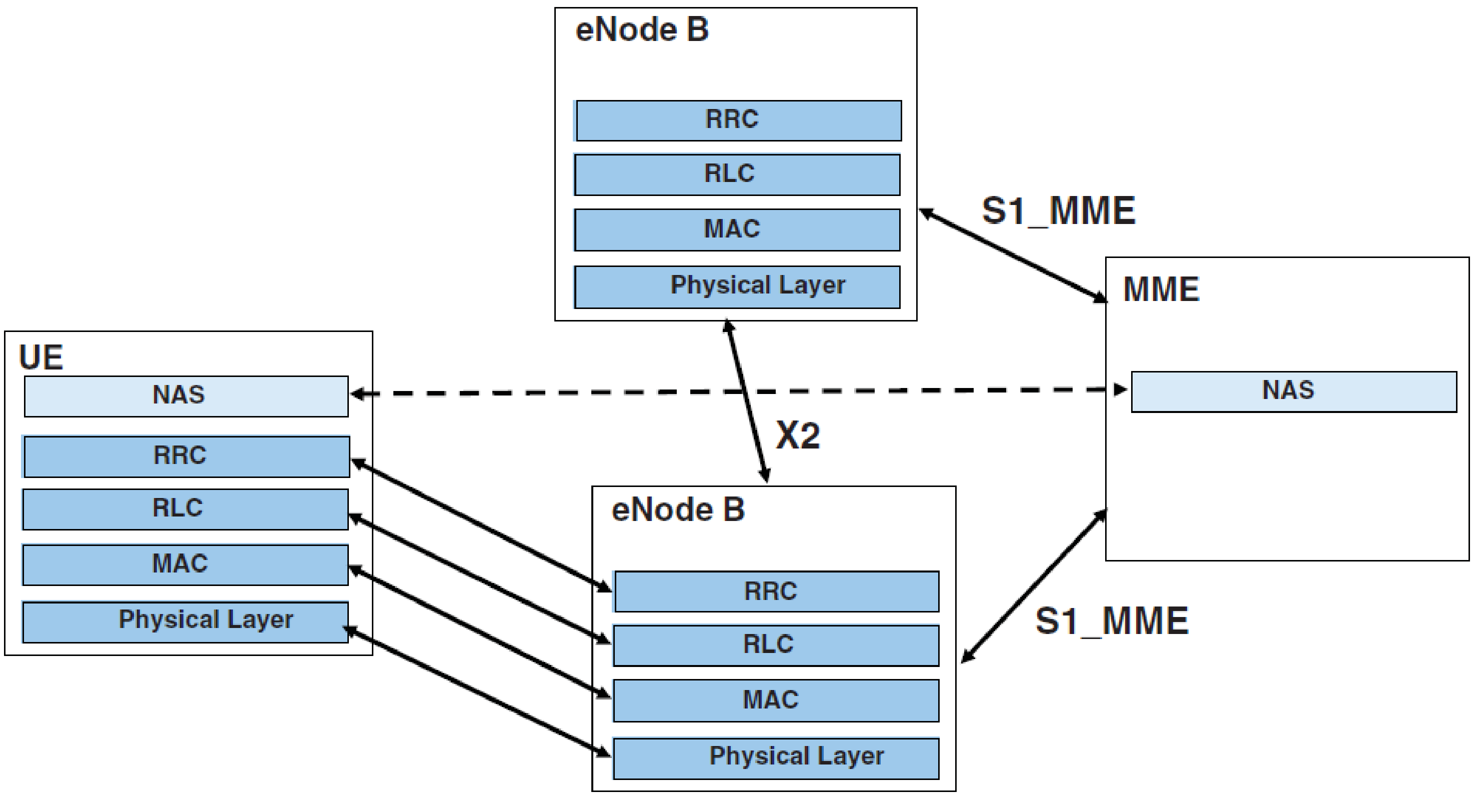


Figure 16.16. LTE control-plane protocol stack

Fig 11. LTE control-plane protocols (Figure 6.16 from [HT07], p 447).

Protocol stack: control plane

- Both NAS and RRC are used for signalling
- NAS: Non Access Stratum:
  - Functions and services independent of radio access technology, i.e. signalling at the core network level.
  - For signalling needed by procedures like network attachment and Data session setup, similar to GMM (GPRS Mobility Management) and SM (Session Management) procedures from GPRS.
- RRC: Radio Resource Control.
  - Used for signalling at radio level.
  - It supports:
    - Radio bearer management
    - Radio mobility
    - User paging

Another view of LTE protocols in user plane, for DL

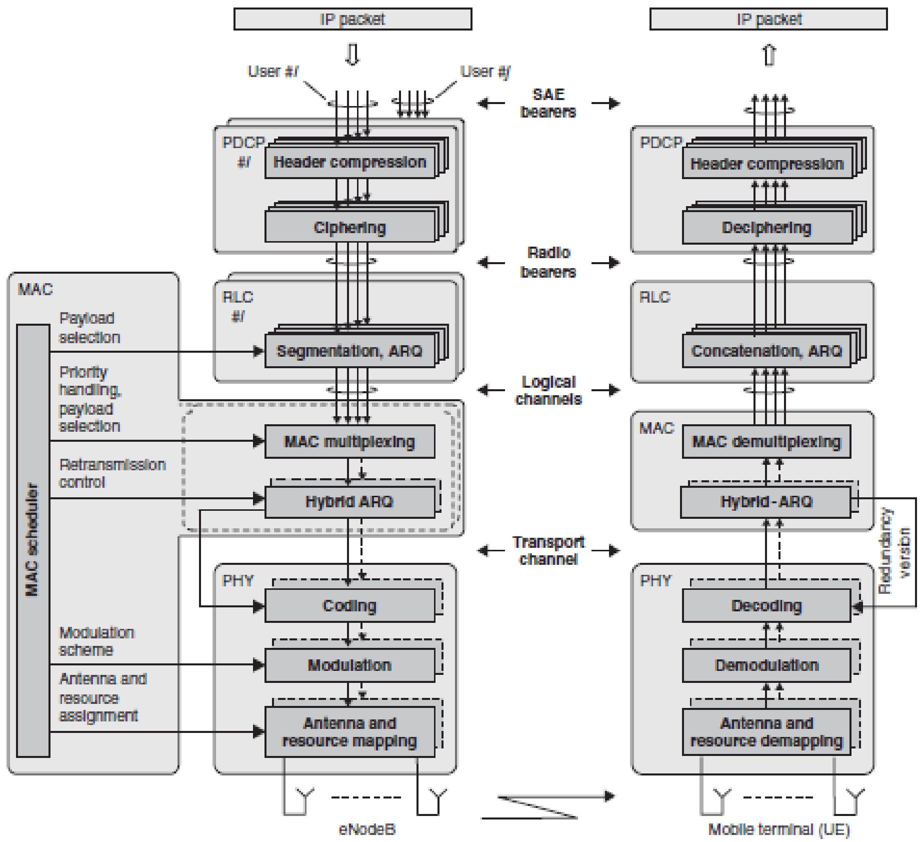


Figure 15.1 *LTE protocol architecture (downlink).*

Priority handling concerns users' differentiation in the scheduler according to their subscription or according to application type (i.e. VoIP receives higher priority in scheduling than background traffic).

Fig 14 emphasizes the importance of scheduler in LTE.

Fig 14. LTE protocols: architecture and functions (Fig 15.1 from [DPSB07], p 300)

Scheduling in LTE: general issues

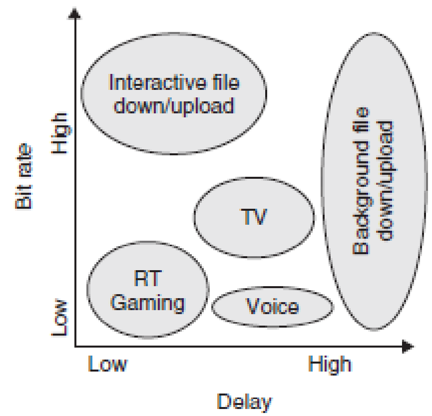


Figure 2.2 *The bit rate – delay service space that is important to cover when designing a new cellular system.*

Fig 10. Delay and bit rate requirements for different traffic types (aplications) (Figure 2.2 from [DPSB07], p22)

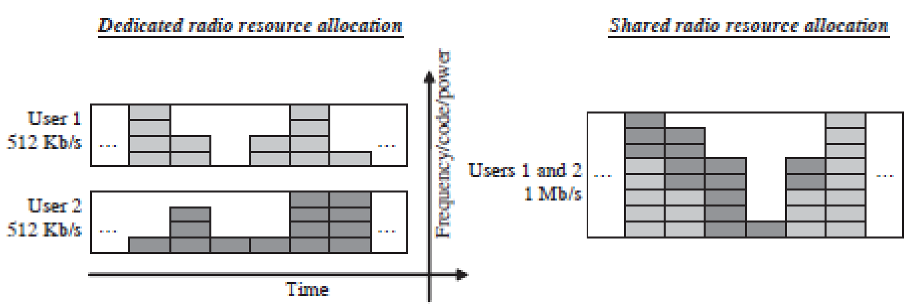


Figure 2.5 Dedicated versus shared resource allocation.

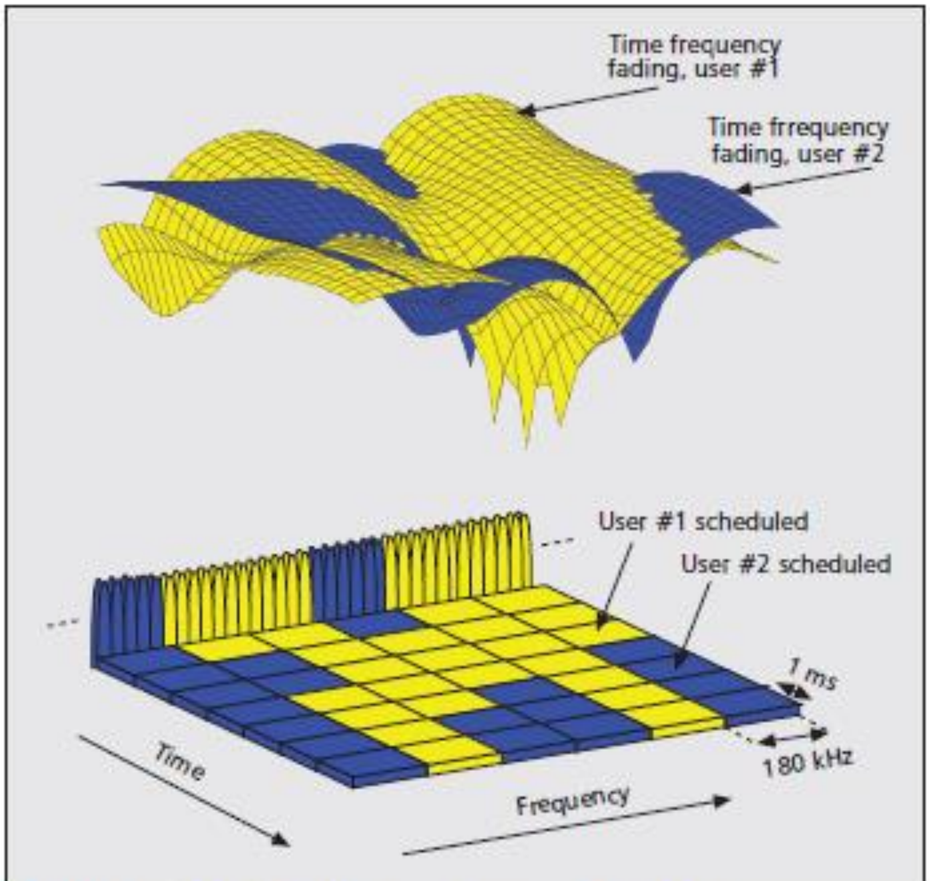
Fig 11. Advantage of shared radio channels for bursty traffic (Figure 2.5 from [LL08], p 35)

Fig 10 shows the requirements of different applications concerning delay and bit rate. Note that the requirements concerning reliability are not shown here. Reliability is achieved by coding, link adaptation and retransmissions (ARQ and HARQ).

Delay and bit rate are achieved by scheduling.

Fig 11 illustrates the advantages of shared radio channel for data traffic, which is bursty in nature.

Time-frequency allocation



■ **Figure 3.** *Channel-quality variations in frequency and time.*

Fig 12. Channel-dependent scheduling in DL, in time and frequency domains (Figure 3 from [ADFJ+09])

LTE scheduling

- The scheduler controls both UL and DL transmissions, in both time and frequency domain.
- The scheduling is performed with a granularity of one Physical Resource Block (PRB), also called Resource Block (RB),
  - i.e. a user can receive an integer number of PRBs, but not fractions of PRB
- The dimensions of a PRB are:
  - 1ms in time domain
  - 180 kHz in frequency domain (see Fig 12)
- The scheduling is performed every Transmission Time Interval (TTI), 1 TTI = 1ms
- The scheduler determines in each TTI:
  - Which users are allowed to transmit /receive
  - On what frequencies
  - What data rate to use
- Channel dependent scheduling means that each user receives radio resources (i.e. PRBs) on frequencies and at TTIs where its radio link is better (less affected by fading)
  - Rapid channel variations due to fading are then exploited, not suppressed [ADFJ+09]
  - More efficient use of radio resources is then obtained
- In order to perform channel dependent scheduling, the scheduler needs to "know" the channel quality.
  - In DL this is obtained through Channel Quality Indicators (CQIs) from UEs, i.e. "feedback reports from user terminals" [LCKX+09].
    - "A CQI is an estimate of the downlink channel at the individual users obtained using reference signals from the base station" (eNB) [LCKX+09]
  - In UL this is based on channel sounding, i.e. each user sends Sounding Reference Signals (SRS).
    - SRS are processed at eNB to extract near-instantaneous frequency selective Channel State Information (CSI) [CMRA+08]
- In DL the PRBs allocated to a user don't have to be contiguous on frequency domain, while in UL they must be contiguous due to SC-FDMA limitations.

Another view of frequency domain scheduling

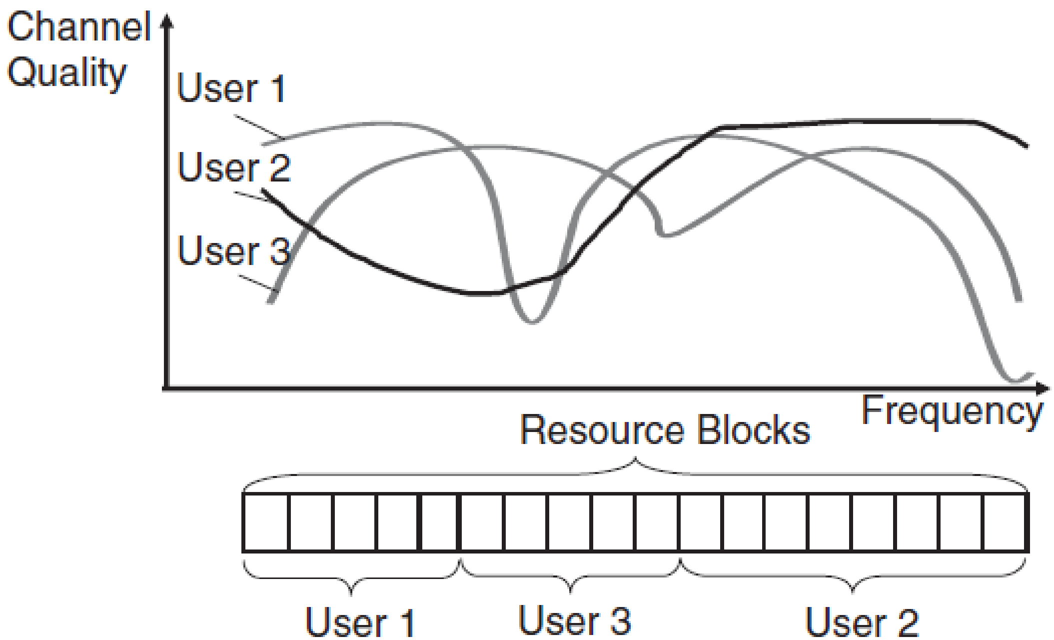


Figure 16.1. Frequency domain scheduling

Fig 13 Frequency domain scheduling (Figure 16.1 from [HT07], p 465)

Fig 13 presents a simplified view of channel dependent scheduling, only for frequency domain, i.e. the time domain is not represented in the figure.

It can be seen that each user is scheduled when its channel quality is better than the channel quality of the other users.

Other techniques used in LTE for performance improving

- Multiple Input Multiple Output (MIMO)
  - Both eNB and UE have at least 2 antennas
  - Normally if one antenna receives a bad signal, for the other antenna the signal will be better
  - These signals are combined in order to obtain a good signal at the receiver
  - In very good radio conditions it is possible, at least for DL, that eNB sends two different data stream to the 2 UE's antennas, doubling the transfer rate
- Inter-cell interference coordination (ICIC):
  - In LTE the interference between users in a cell is small, because of orthogonality between users
  - However, interference from other cells (inter cell interference) limits the performance, mostly for users situated at the cell edge.
  - ICIC means that scheduling in neighbor cells is coordinated such that users situated at cell edge in neighbor cells use different (complementary) parts of the spectrum [ADFJ+09]

MCS: 5G

5th Generation

Use cases, services, traffic types

- The new use cases that will be supported by 5G are:
  1. enhanced Mobile Broadband (eMBB):
     - Traffic generated by smartphones (the types of traffic considered before 5G)
  2. Ultra-Reliable Low Latency Communications (URLLC):
     - Emerging critical applications: enhanced reality, autonomous driving, tele-medicine
  3. massive Machine Type Communications (mMTC):
     - IoT, sensor networks
- The new use cases are associated to new services and new traffic types

5G radio access roadmap

- Contains two directions (tracks):
- 1. Evolution of LTE:
  - Enhancements of LTE in order to support as many 5G use cases as possible
- 2. New Radio (NR):
  - No backward compatibility constraints with LTE
  - => fundamental changes:
    - Short transmission time intervals (TTI), flexible subcarrier spacing, mm-Wave frequencies, new numerologies, network slicing

EN-DC

- The transition from LTE to full NR systems will be supported by non-standalone (NSA) versions of NR, working in conjunction with LTE in dual connectivity (DC) mode
- Both LTE and NSA-NR will be connected to LTE evolved packet core (EPC)
- The tide interaction between LTE and NR is called **EN-DC**: E-UTRA-NR Dual Connectivity

EN-DC

- In EN-DC the LTE is the master technology:
  - LTE controls the radio connection of user equipment (UEs)
  - and the control plane connection to the EPC
- NR provides enhanced capacity to UEs using new air interfaces, new spectra, etc
- After the completion of NSA NR, next phase will be SA NR (stand alone new radio), when the 5G NR network will work without the help of LTE

New Radio technologies

- New numerology:
  - flexible TTI: shorter than 1 ms for URLLC traffic, and longer for mMTC traffic, flexible subcarrier spacing, shorter codes for URLLC packets
- New spectra:
  - mm-Waves: between 6 GHz and 52.6 GHz
  - Different propagation characteristics: much higher path loss compared to cm-waves (i.e. < 6 GHz) => BS will send narrow beams towards Ues
  - Possible collaboration with a cm-wave cell: mm-wave cell for capacity, cm-wave cell for coverage

Non Orthogonal Multiple Access NOMA

- Example of single-carrier NOMA (SC-NOMA) with two users and SIC (successive interference cancelation [WYNED16]:
- BS will transmit the signals s1 (for user 1) and s2 (for user 2) multiplexed on the same sub-carrier, but with different powers (bigger for user 2)
- User 1 will decode first the signal s2 and will remove it from the received signal
- Then it will decode its own signal s1
- User 2 will decode its signal s2

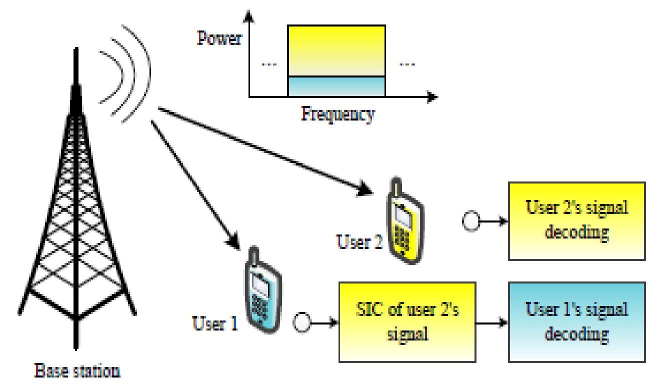


Fig. 3. A downlink NOMA model with one base station and two users.

Fig 3 from [WYNED16]

NOMA can use power domain multiplexing (like in example) or code domain multiplexing
NOMA has a better spectral efficiency than OMA, but with increased complexity at receivers

5G core network improvements

- 5G core network (CN) will use SDN, NFV, CDN (contend delivery network):
  - Resources will be closer to users: smaller cells, caching
- Slicing network (infrastructure as a service):
  - A common infrastructure (CN plus radio resources) shared between several network operators and several clients
- Cloud computing: e.g. simpler BS, with part of the BS functionality moved into the cloud

SDN concept

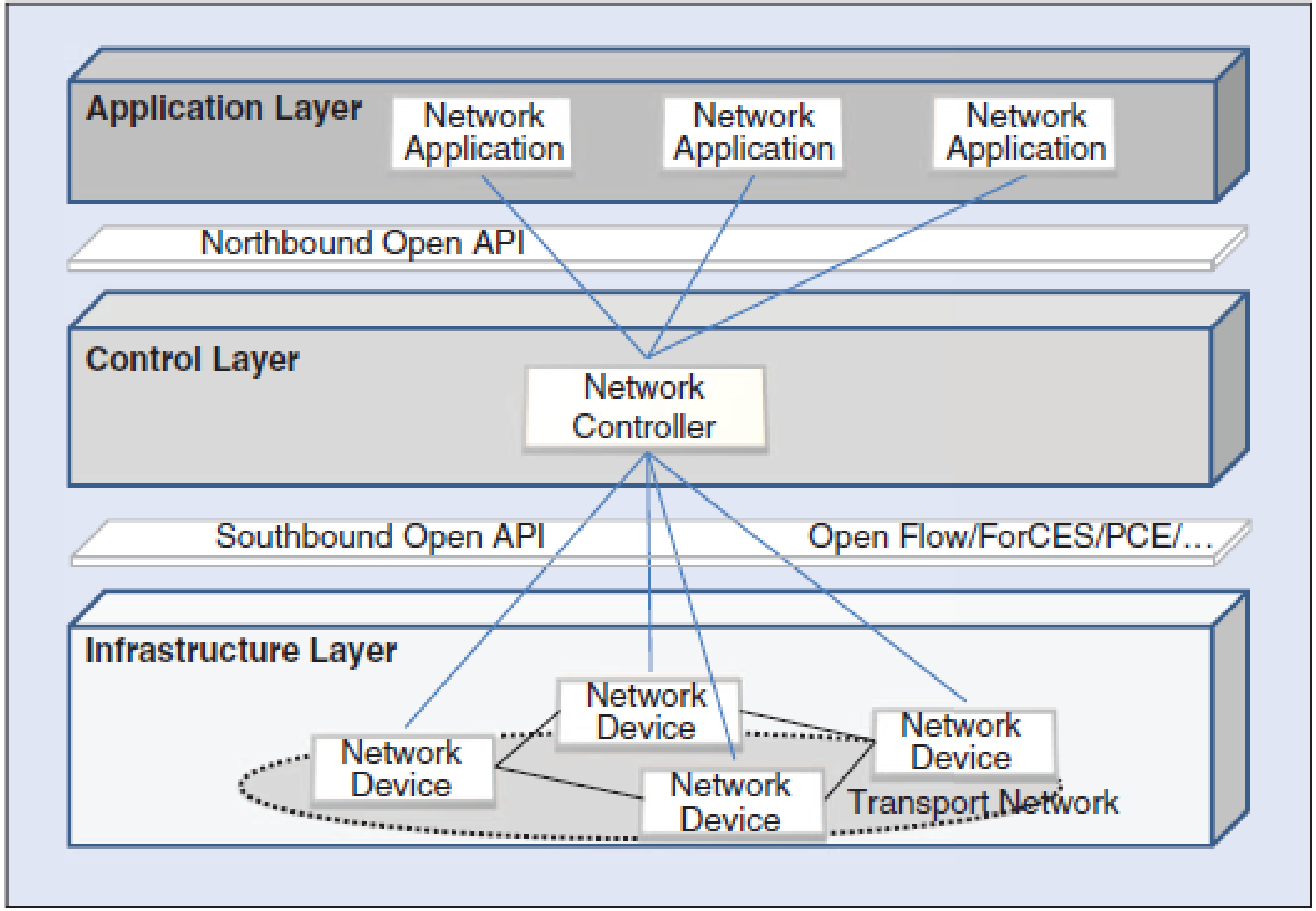


FIGURE 4 SDN layering concept overview.

SDN layering concept. Fig 4 from [PGKT+13]

SDN concept

- Data (forwarding) and control plane are separated
- The network contains a centralized controller
  - It allocates traffic to network elements
  - It maintains the state of the entire network
  - It uses the northbound interface to provide a unified view of the network resources for the applications
  - For the southbound interface between the network controller and the network devices, the most used protocol is Open flow (defined by Open Network Foundation – ONF) [MABPP+08]

The NFV concept

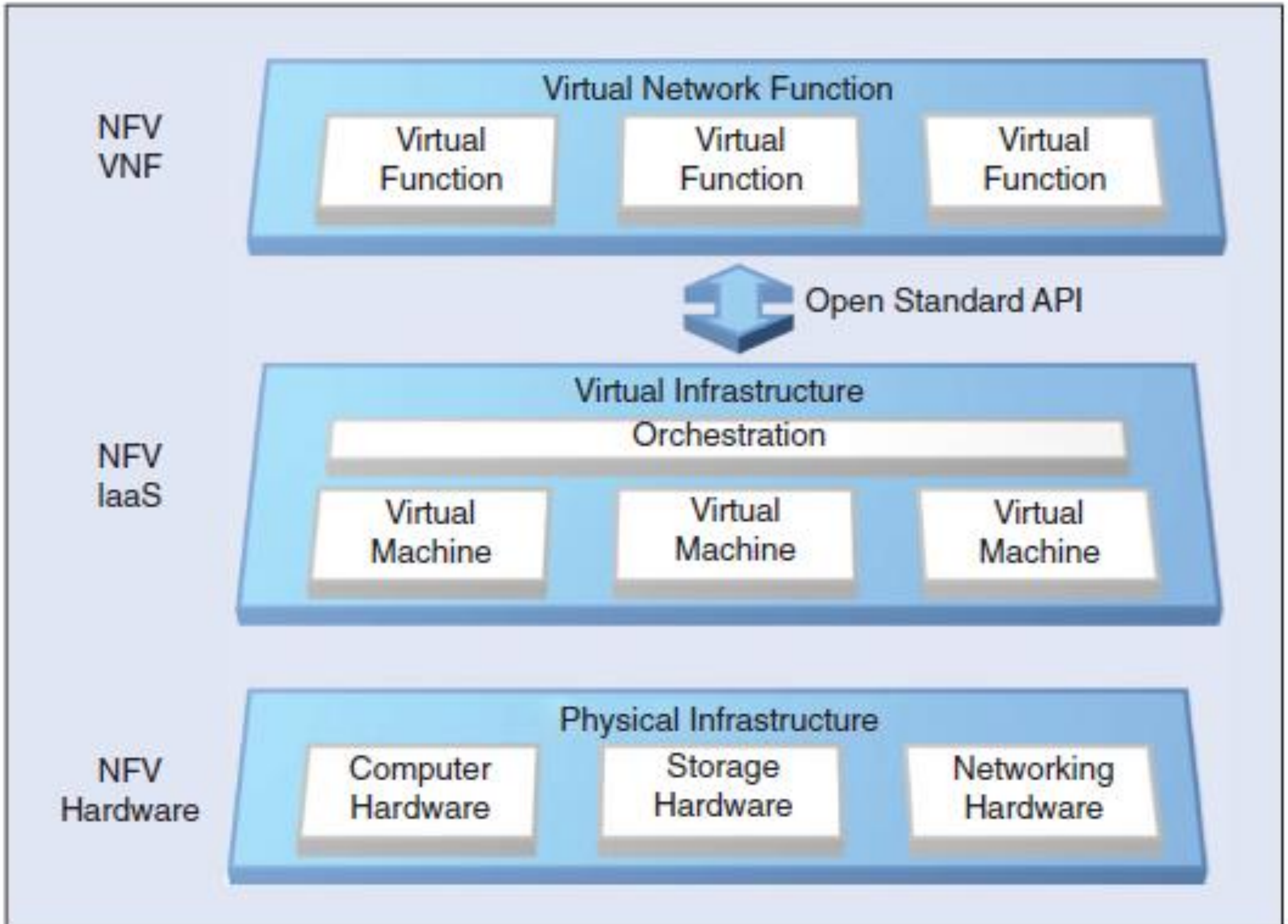


FIGURE 5 NFV concept overview.

NFV concept. Fig 5 from [PGKT+13]

The NFV concept

- NFV enables to implement network functions on standard hardware devices like servers, storage equipments and switches
- Network functions are implemented in software packages running in virtual machines (VMs)
- Architecture:
  - Virtual infrastructure: VMs running on hardware devices, organized by orchestration
  - separation of software that defines the network functions from hardware
  - Automated orchestration: automates installation and management of virtualized network functions on generic hardware elements
- NFV reduces the cost and time to market for network equipment
- It creates challenges concerning performance, reliability, security.

D2D

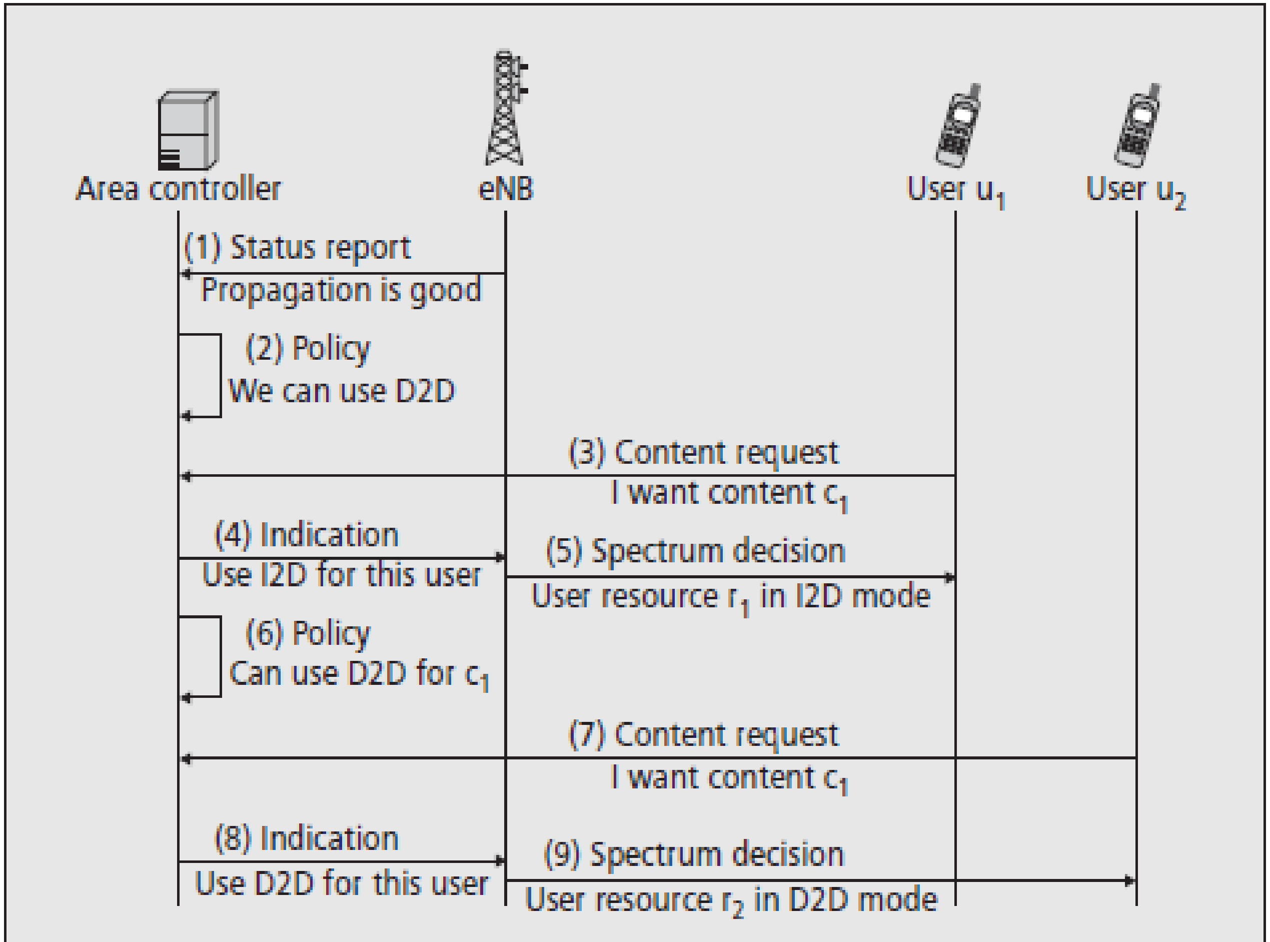


Figure 1. System model, summarizing the entities involved in heterogeneous networks, and interaction diagram highlighting the role of each entity.

A scenario when both infrastructure to device (I2D) and D2D information transfer are used. For D2D user u2 obtains the file from user u1. Figure 1 from [MCC14]

The MMPF Scheduling algorithm from [MCC14]

for all user u **do**
  compute u's score, given by

$$\frac{u\text{'s rate}}{\text{data downloaded by } u}$$

for all RB r **do**
  let u^* be the user with the highest score
  if the content needed by u^* is available through d2d **then**
    let s^* be the closest user to u^* having the content she needs
    schedule RB r for transfer $s^* \to u^*$ through d2d
  else
    let b^* be macro- or micro-BS covering u^* with the best RSSI
    schedule RB r for transfer $b^* \to u^*$ through i2d

Figure 2. The MMPF algorithm.

The multi-modal proportional fairness (MMPF) algorithm pseudo-code (fig 2 from [MCC14])

MMPF

- Line 2 computes user score as a function of user's radio link quality (user's rate) and data downloaded by it
- If a user downloaded more data, it will receive a smaller score, which ensures the fairness part
- RB = resource block (like PRB in LTE)
- If the content wanted by user is available to another user, in close range, it is taken from that user (by D2D)
- Otherwise it is taken from the network (by I2D = infrastructure to device), from the cell with the best radio link quality (RSSI = received signal strength indicator)

NFV, SDN, CDN

- NFV – Network Function Virtualization
  - Means to implement network functions in software that runs on standard hardware equipments (servers, storage elements, switches)
  - Dedicated hardware equipment (e.g. SGSN, GGSM, firewalls, etc) will be replaced with this general purpose hardware equipment
  - NFV will reduce the cost, time to market, but rises performance challenges
- SDN - Software Defined Networks:
  - Idea is to separate data and control plane
  - Network management is simplified and new services can be introduced easily
- CDN – Content Delivery Networks [Wikipedia]
  - Delivers information (webpages) to users based on their geographical location
  - CDN server behave like a caching system: requested information is copied from the original server to servers that are geographically closer to the requiring users

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