Cellular systems: from 2G to 4G

Wireless Systems, a.a. 2014/2015

Un. of Rome "La Sapienza"

Chiara Petrioli[†]

[†] *Department of Computer Science – University of Rome "Sapienza" – Italy*

2G+ Cellular systems

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- Challenges:
  - Widespread Internet usage raises demand for data communication (not only voice!)
  - Packet Switching vs. Circuit Switching
  - Data rates must increase
  - Data encoding quality must increase
  - Need to extend the functionalities of a mobile operator systems to allow to provide more complex services
  - → First answers to these needs already provided by 2G+ systems (EDGE, GPRS)
  - → Evolutionary approach: systems have been built over GSM approach with very limited impact on the cell operator core network.
  - → A non evolutionary approach is under discussion for 5G systems.

2G+ innovation

- Enhanced full rate codec based on ACELP (Algebraic Code Excited Linear Prediction)←13Kbit/s
- Adaptive MultiRate←new generation codec that adapts to available channels (half rate or full rate) and changes rate depending on channel propagation conditions
- Tandem Free Operation←limits use of transcoding (which implies degradation of voice quality), allowing multiplexing of flows of coded speech signal (e.g. using full rate or enhanced full rate codecs) on the PCM channels in case of MS-MS communication.
- Enhanced data rates achieved through improvements of phy layer, and allocation of multiple slots to the same MS

2G+ innovation

- Location services ←triangolarization among BTS allows to achieve a localization around 100m
- Number portability← user can maintain its own telephone number even when changing telecom operator
- Cordless telephony system ←to use a MS as cordless, connecting to a Home Base Station (HBS) and from there to the cellular operator network
- SIM application toolkit←change of paradigm. The ME is no longer the master and the SIM the slave. The SIM can initiate communication with the ME; downloads via the radio link to the SIM are possible.
  - SIM can ask the ME to perform actions such as:
    - ✓ Set up of a call to a number in the SIM;
    - ✓ Send telephone numbers the ME is dialing to the SIM that can analyze, modify and bar the call
    - ✓ Tone generation
    - ✓ Pass to the SIM information
    - ✓ Execute a command sent by the SIM
    - ✓ Launch the microbrowser in the ME redirecting it to a particular WEB address
- Environments for application/service support, customization, personalization ←Mobile Execution Environment; CAMEL (customized applications for mobile networks enhanced logic).

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2G+ innovation

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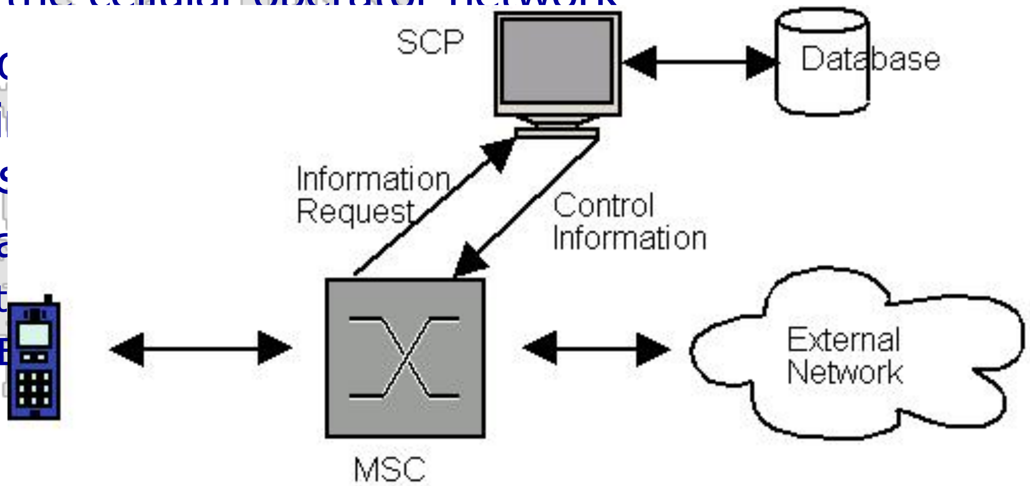

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2G+ innovation

2G → ← 2G+ →

1991 — 1995

Voice	Circuit switching data	GPRS, EDGE
Fax	Call hold/ waiting	Enhanced Full Rate codec, AMR codec
SMS	Multi-party call	Voice broadcast service, Voice call group service
Call fwd.	Advice of charge	Number portability
Call restriction	Half rate speech coding	Cordless telephony service
		Location services
		SIM application toolkit, CAMEL, MeXe

- Improvements on the radio interface have increased the MS achievable data rate without changing the mobile cellular system architecture
- EDGE is a radio access technology:
  - 3/8 shifted 8PSK modulation (phase modulation) →three times more bits per symbol
  - with channel encoding EDGE achieves a gross data rate of 59,2 Kbit/s vs. the 22,8Kbit/s of GSM
  - Features
    - ✓ Carrier bandwdith: 200 kHz
    - ✓ Timeslots per frame: 8; frame duration: 4,615 ms
    - ✓ radio interface symbol rate: 270ksymbols/s (vs. 270kbits/s in GSM)
    - ✓ Normal burst: 384 payload bits (116 in GSM)
    - ✓ Max gross bit rate per time slot: 59,2 kbit/s (22,8 Kbit/s in GSM)

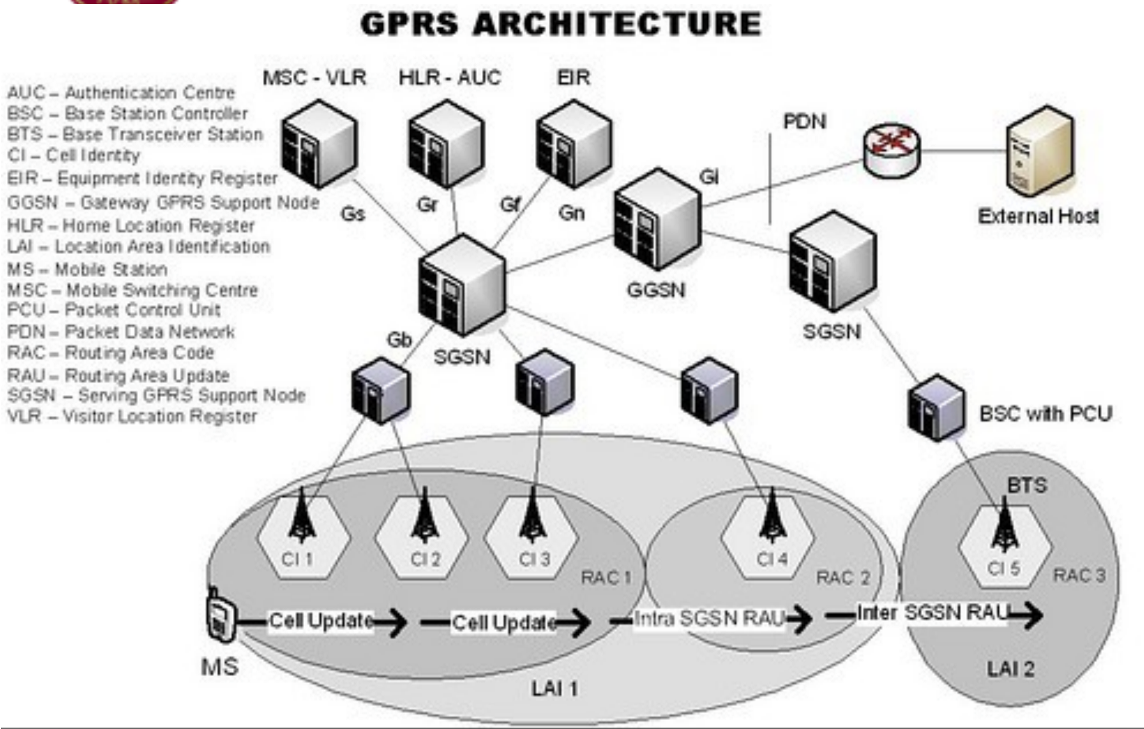
GPRS
General Packet Radio Service

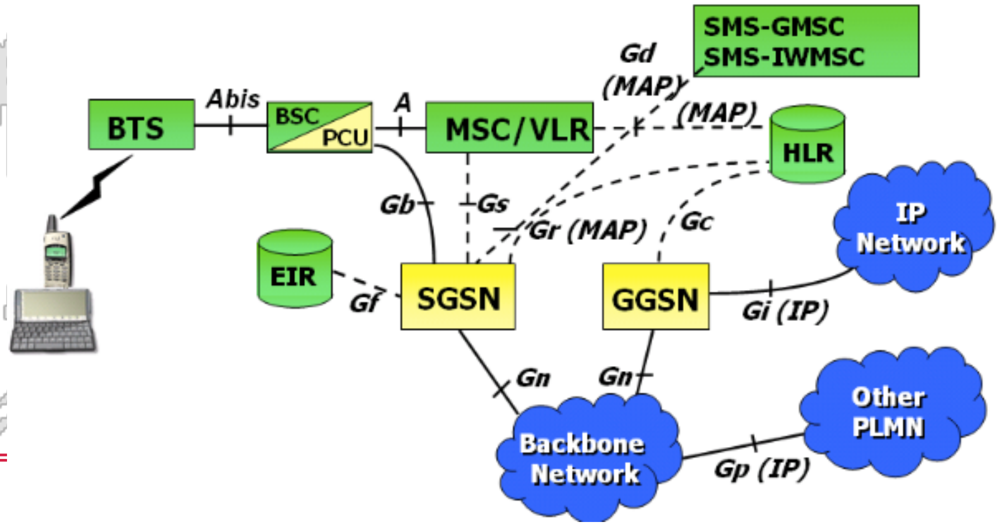
- Internet widespread use has raised the need to combine circuit switched and packet switched communication in cellular systems, and support data transmission (not only voice)
- The technology which has first supported this evolution is GPRS (General Packet Radio Service)
- IP backbone used for packet switching, integrated with the circuit switching networks

What changes in the architecture

- Added nodes to support packet switching data communication
- GSN (GPRS Support Node) are IP routers supporting mobility management)
  - SGSN (or Serving GPRS Support Node) route IP packets from/to a set of MS under their area
    - ✓ Area splitted in finer grain routeing areas (localization is finer grain, at least at the routeing area level)
  - GGSN (or Gateway GPRS Support Node) interfaces the cellular network with external packet data networks
  - SGSNs and GGSN interconnected through an IP backbone
  - Network elements must be associated IP addresses
- At the BSSS level a new functional entity is added denoted PCU or Packet Control Unit to manage data transmission over the radio links

What changes in the architecture





Additional network elements

- PCU – Packet Control unit
  - Deals with dynamic resource allocation between GSM CS and GPRS, and to interconnect MS and SGSN for packet data exchange
    - ✓ **Segmentation and reassembly**
    - ✓ **Physical channel scheduling**
    - ✓ **Error detection and management (ACK/NAK, buffering, retransmissions)**
    - ✓ Access request management and resource allocation
    - ✓ Channel management (power control, congestion management, broadcasting of control messages etc.)

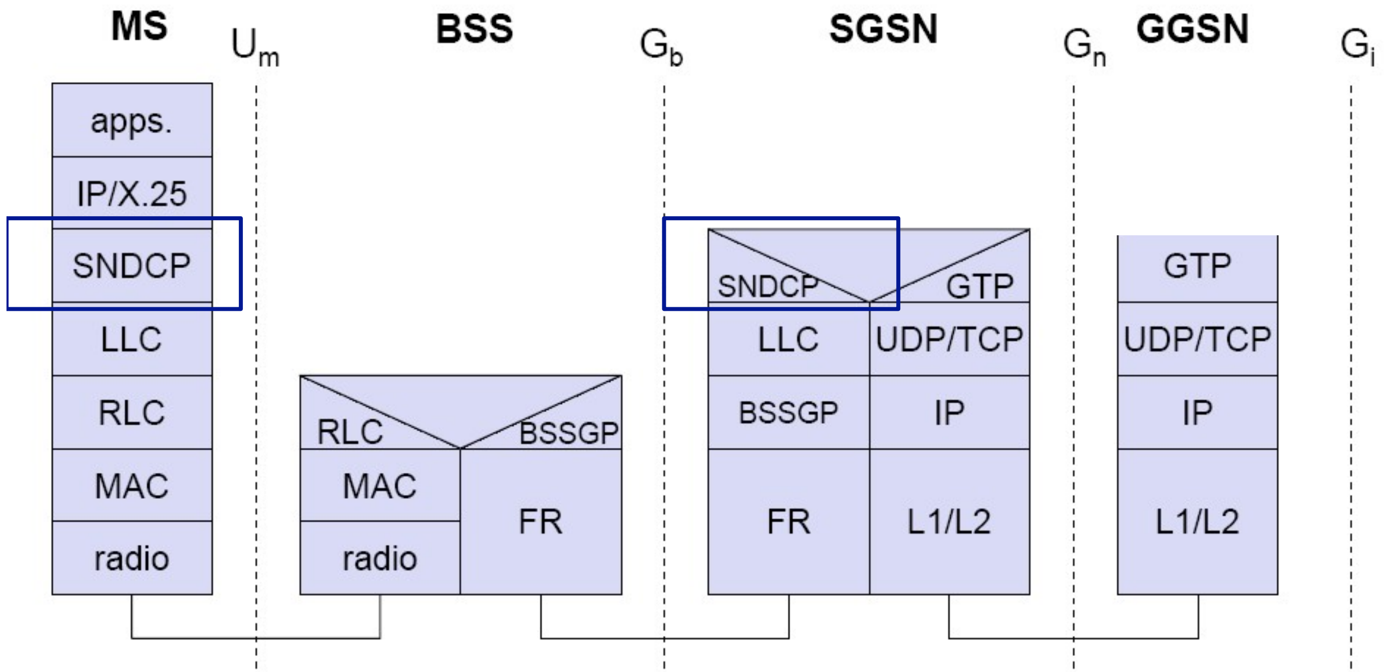
Additional network elements

- SGNS-Serving GPRS Support Node
  - Handles user authentication and checks it is entitled to access the service; coordinates encryption.
  - Performs mobility management (it has associated a location register)
  - Together with BSS radio resource management it reserves radio resources needed to support the requested **QoS**
  - Gathers information useful for billing
  - Routes information flows from/to the MS
  - Performs **encapsulation and tunneling of packets**
  - Performs logical connections management to/from the MS

Additional network elements

- GGSN-Gateway GPRS Support Node
  - It interfaces the cellular operator network with external packet data networks
  - Performs routing tasks, encapsulation/decapsulation, analyzes and filters arriving messages, and gathers info needed for accounting and billing
  - Stores in its location register the address of the SGSN who are serving the different MS, MS user profiles, and active/standby MS **PDP context**
    - ✓ Upon request it creates the PDP context: used protocol (e.g., IPv4), MS IP address, requested QoS,…

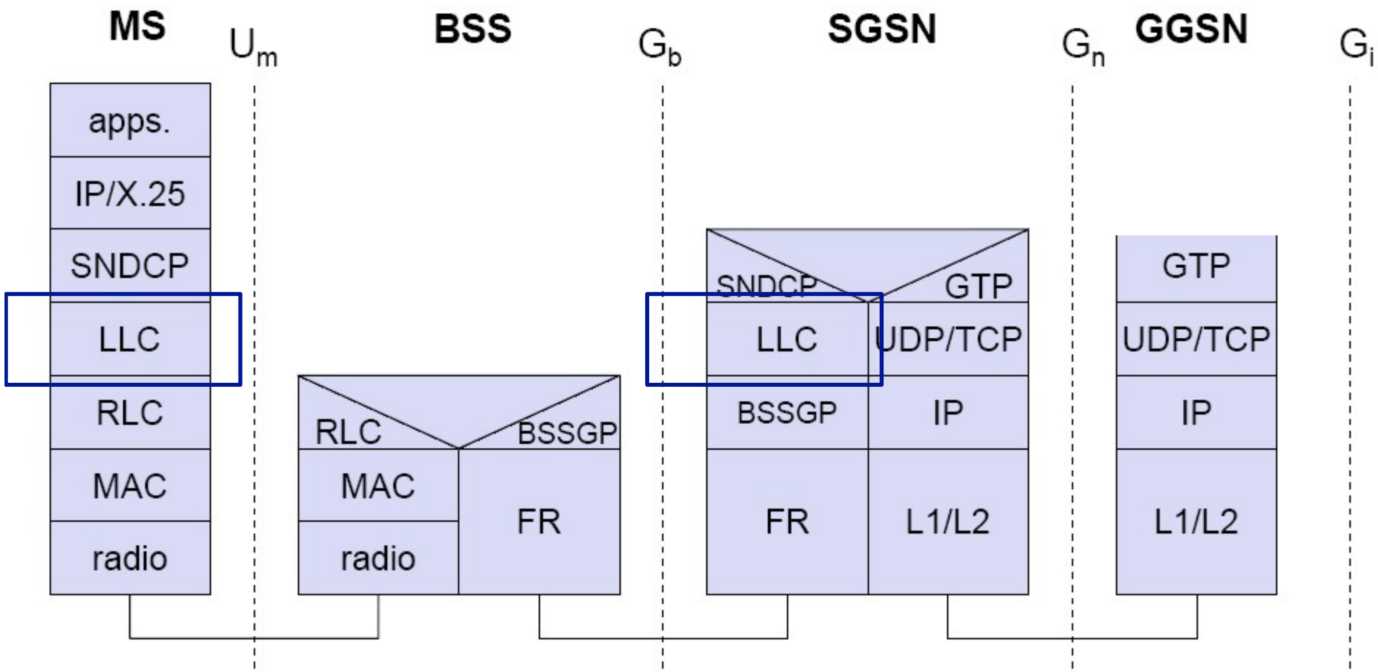
GPRSs protocol Architecture



Subnetwork dependent convergence protocol:

- provides to different L3 protocols support for variable size PDU transmission, with QoS support
- Information and header compression
- Segmentation and reassembly
- Multiplexing

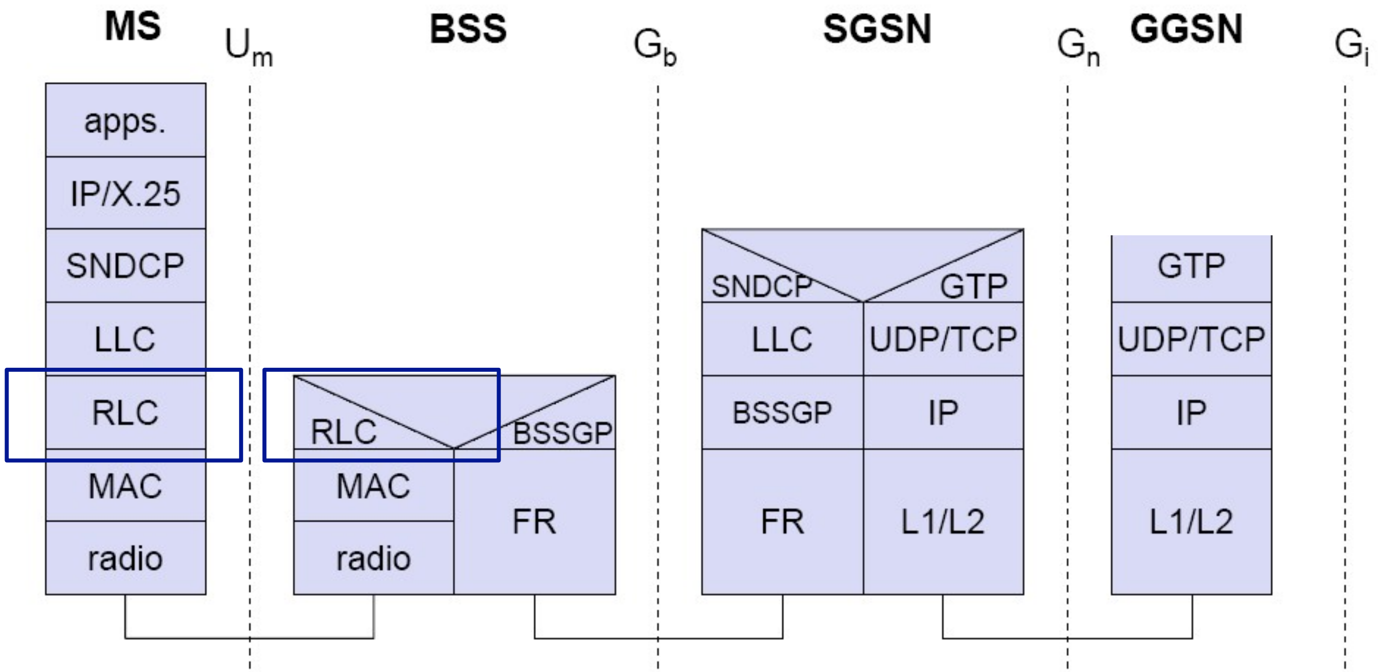
GPRSs protocol Architecture



Logical Link Control:

- Logical connection is maintained when moving from one cell to another one controlled by the same SGSN
- Can operate in two modes: acknowledged/unacknowledged

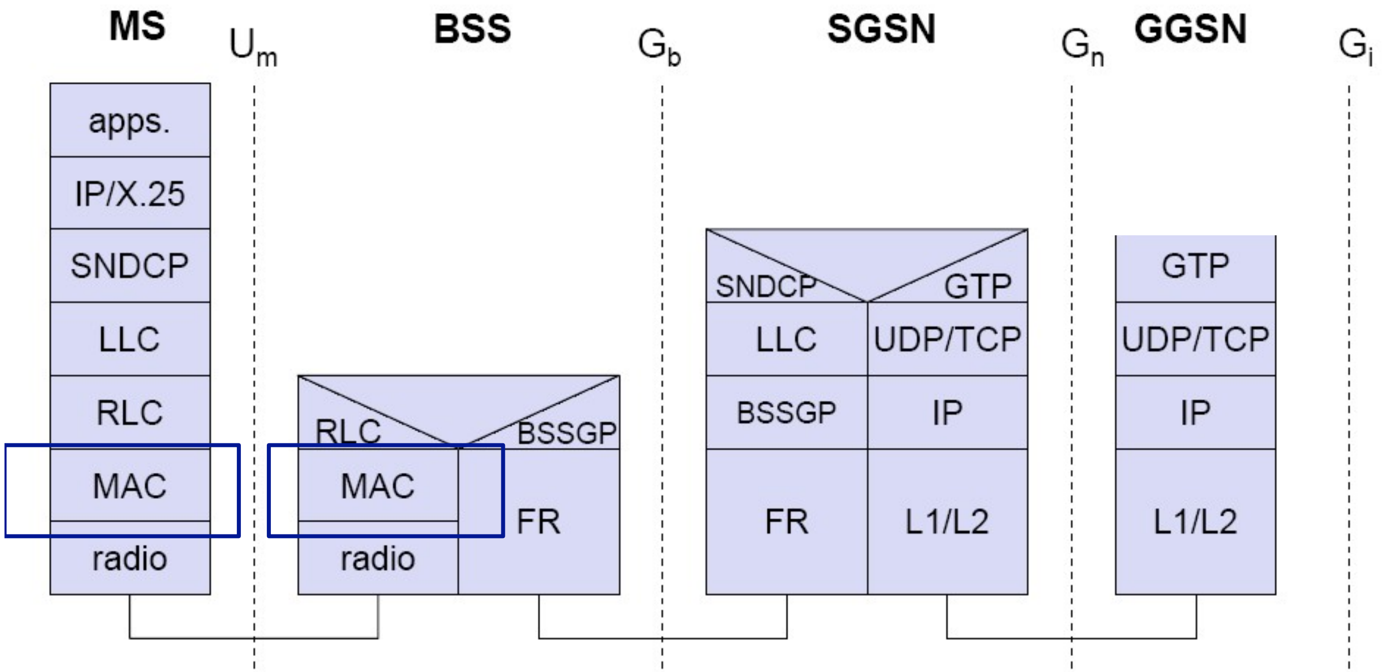
GPRSs protocol Architecture



Radio Link Control:

- Reliable connection between MS and BSS
  - Fragmentation and reassembly of LLC frames to insert them into RLC blocks
  - Backward error correction (retransmission of blocks not correctly received)
    - Transmission of up to 64 blocks without ACKs; Cumulative ACKs; Selective NAKs.

GPRSs protocol Architecture



Medium Access Control

- Same timeslot can be shared by multiple information flows
- Some MS can have (temporarly) allocated multiple timeslots
  - MAC + scheduling

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Physical and logical channels

- PDCH –Packet Data Channel← Physical channels allocated for data transmission
- Same FDMA/TDMA structure as in GSM
- PDCH is allocated only for the time needed to transmit data and then released.
- More information flows (up to 8) can be multiplexed over the same PDCH
- PDCH supports transmission of radio blocks
  - RLC/MAC block + Block Check Sequence
  - 456 bits transmitted in 4 normal bursts → 4 slots in consecutive frames
- More slots can be allocated in parallel to the same MS

Physical and logical channels

- Resource allocation:
  - the network allocates resources as a Temporary Flow Block (TBF), which has associated an identity (Temporary Flow Identity-TFI)
  - Before an MS can communicate it has to request a TBF
  - Once PDU have been transmitted the TBF is released
  - Statistical multiplexing: the network must allocate resources so that different flows can be multiplexed over the same physical channel
    - ✓ when communicating in downlink the network piggybacks the information or which MS should communicate in uplink in the next frame
    - ✓ scheduling

Physical and logical channels

- Control channels:
  - Packet Common Control Channels
    - ✓ PPCH - Packet Paging Channel
    - ✓ PRACH - Packet Random Access
    - ✓ PACGH - Packet Access Grant Channel
    - ✓ PNCH - Packet Notification Channel → downlink channel used to notify a group of MS that there is traffic for them (point to multipoint – multicast)
  - [Packet Broadcast Control Channel – PBCCH]
  - Dedicated control channels
    - ✓ PACCH – Packet Associated Control Channel. Bidirectional channel over which control information associated to one or more PDTCH are transmitted
      - info transmitted: power control, ACK/NAK, reassignment of resources, assignment of a downlink PDTCH for MS using an uplink PDTCH,…
    - ✓ Packet Timing Advance Control Channel

Mobility management

- MS can be idle (unreachable), in standby or ready (active)
  - Standby: updates when changing routing area; paging needed
  - Active: updated at the cell level; no paging. PDP context activation/deactivation to transmit data.
- Location update and routing area updates integrated whenever possible
- Implicit detach + periodic updates
- Procedures are similar to what seen in GSM (but involve the new network elements)

Cellular systems: 3G systems

Universal Mobile Telecommunication System

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Chiara Petrioli[†]

[†] *Department of Computer Science – University of Rome "Sapienza" – Italy*

3G objective

- Objective: overcome bandwdith/data rate limitations of 2G/2G+ systems (reaching Mbps)
- Full support of a variety of services and of multimedia applications
  - different classes of traffic
  - Heterogeneous QoS demands
  - QoS support

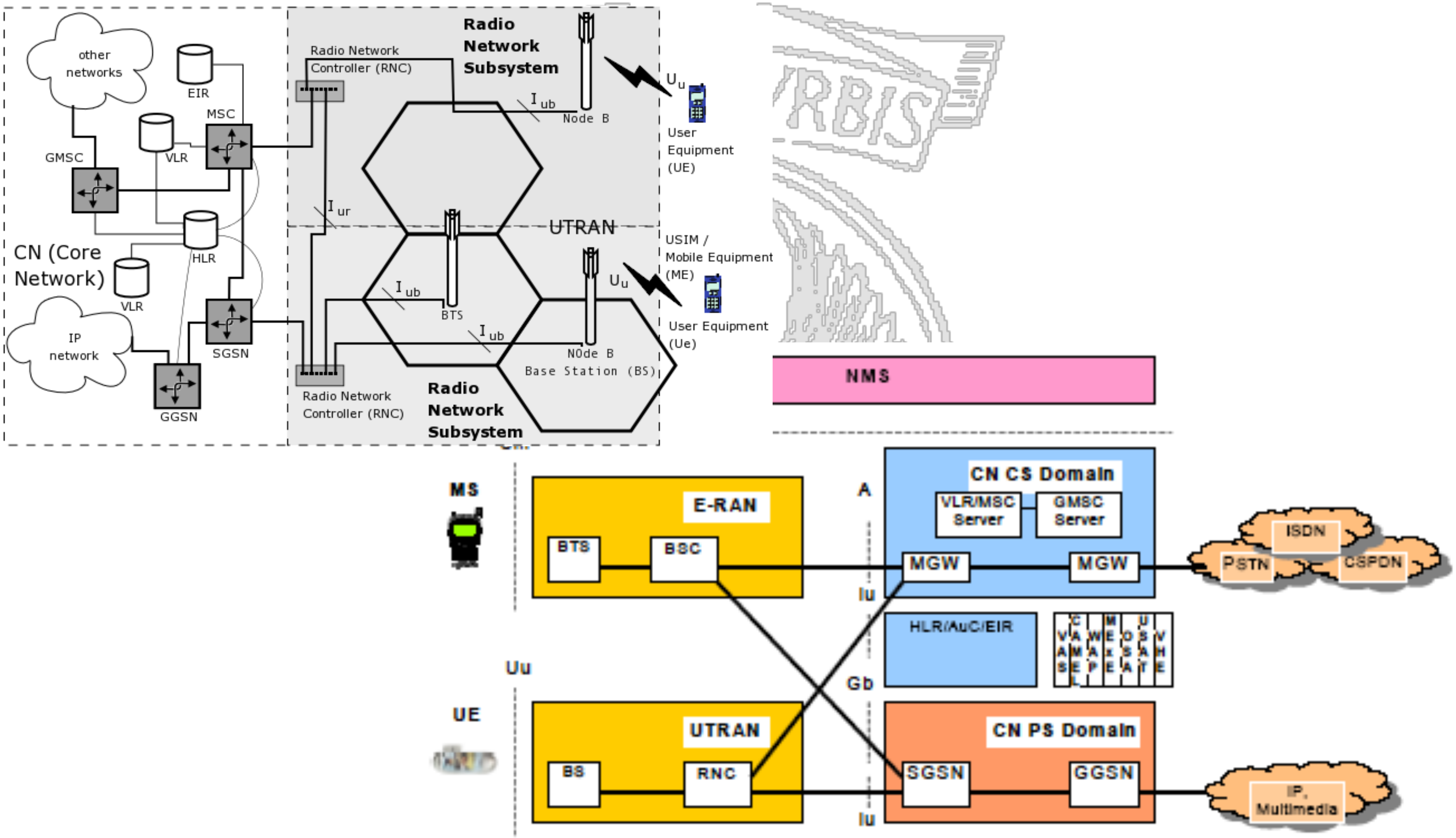
Traffic class	Conversational class	Streaming class	Interactive class	Background
Fundamental characteristics	Preserve time relation between information entities of the stream Conversational pattern (stringent and low delay)	Preserve time relation between information entities of the stream	Request response pattern Preserve data integrity	Destination is not expecting the data within a certain time Preserve data integrity
Example of the application	Voice, videotelephony, video games	Streaming multimedia	Web browsing, network games	Background download of emails

- Integration of mobile and satellite communications

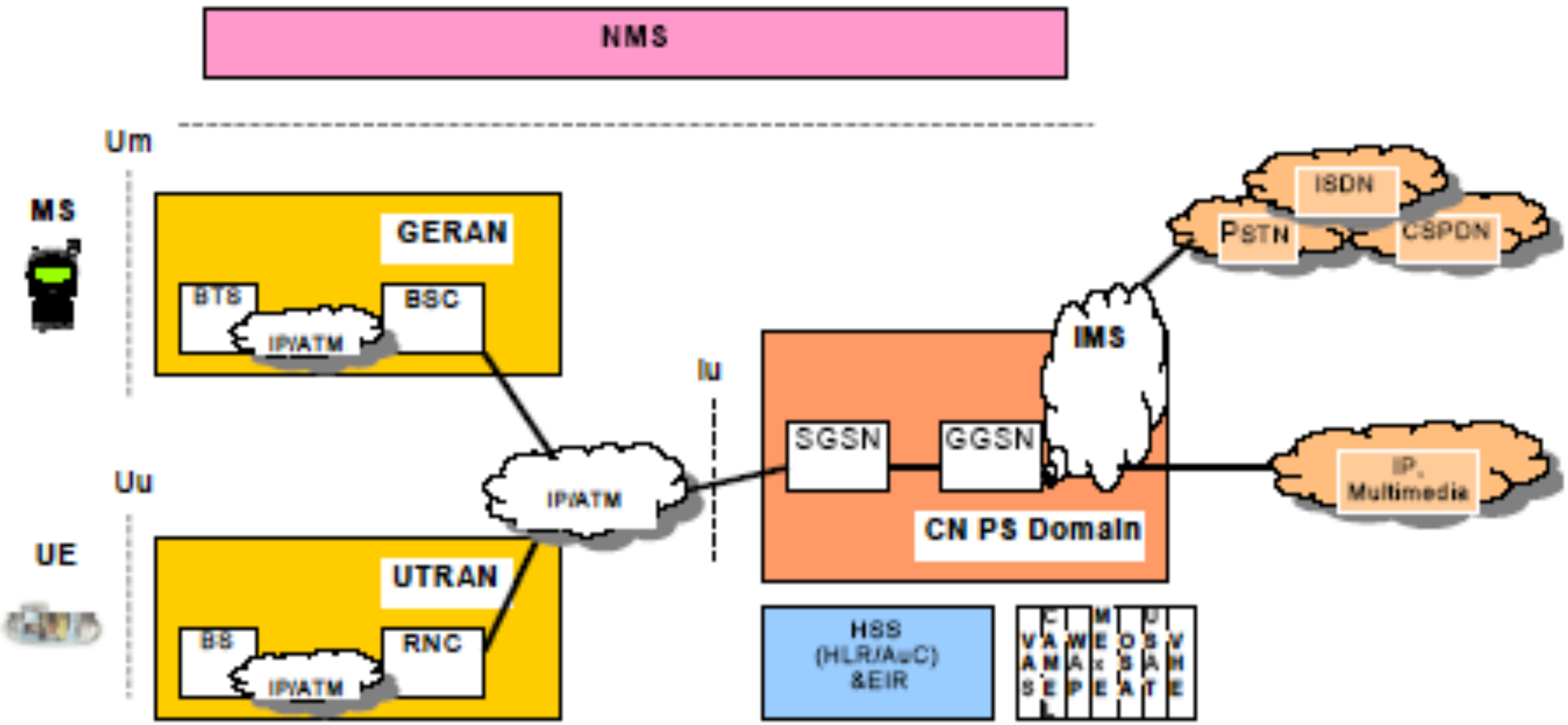
3G features

- Hierarchical organization: Macrocell→Microcell→Picocell
- 3G bandwdith: 1885-2025Mhz; 2110-2200Mhz (155MHz for terrestrial and 75Mhz for satellite networks)
  - Splitted into 5MHz channels
  - TDD and FDD to divide resources among uplink and downlink
  - Support also of asymmetric services
  - Increase of bandwidth to 500MHz planned from the beginning

3G architecture



Towards ALL IP networks



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UTRAN functions

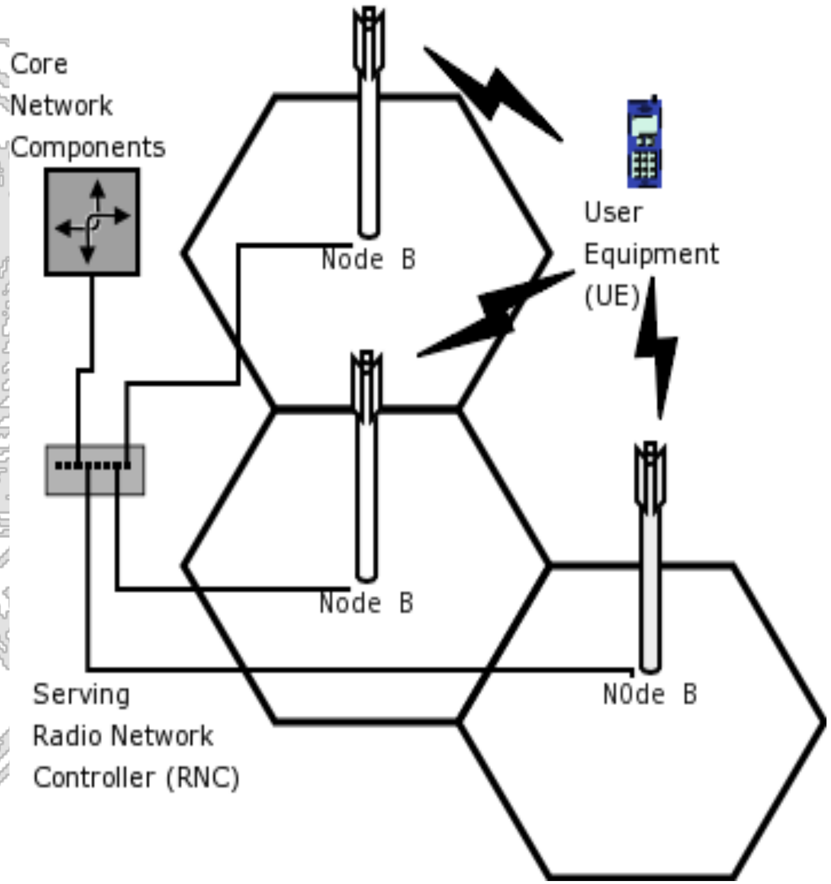
- UTRAN functions
  - Controls cell capacity and interference in order to provide an optimal utilization of the wireless interface resources
  - Includes Algorithms for Power Control, Handover, **Packet Scheduling, Call Admission Control and Load Control**
  - Encryption of the radio channel
  - Congestion control to handle situations of network overload
  - System information broadcasting
  - Micro and macro diversity

UTRAN functions

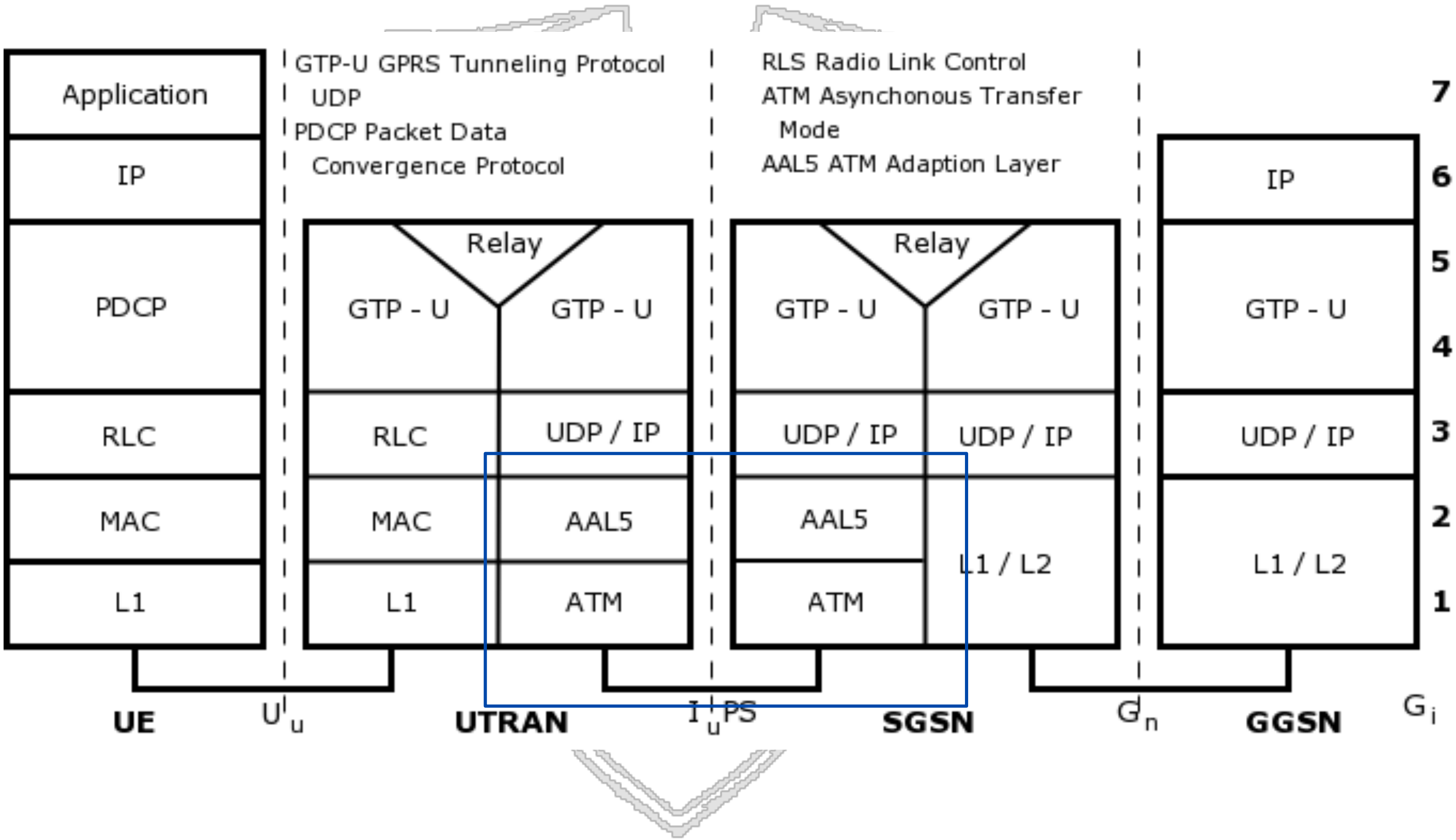
- Network based functions
  - Packet Scheduling
    - ✓Controls the UMTS packet access
    - ✓Handles all non real time traffic, (packet data users)
    - ✓Decides when a packet transmission is initiated and the bit rate to be used
  - Load Control
    - ✓Ensures system stability and that the network does not enter an overload state
  - Admission control to avoid network overload
    - ✓Decides whether or not a call is allowed to generate traffic in the network

Macrodiversity

- Same data stream is sent over different physical channels
- Uplink – UE sends its data to different Node B
- Data stream is reassembled, reconstructed in Node B, SRNC or NC
- Downlink – receiving same data from different cells on different spread codes



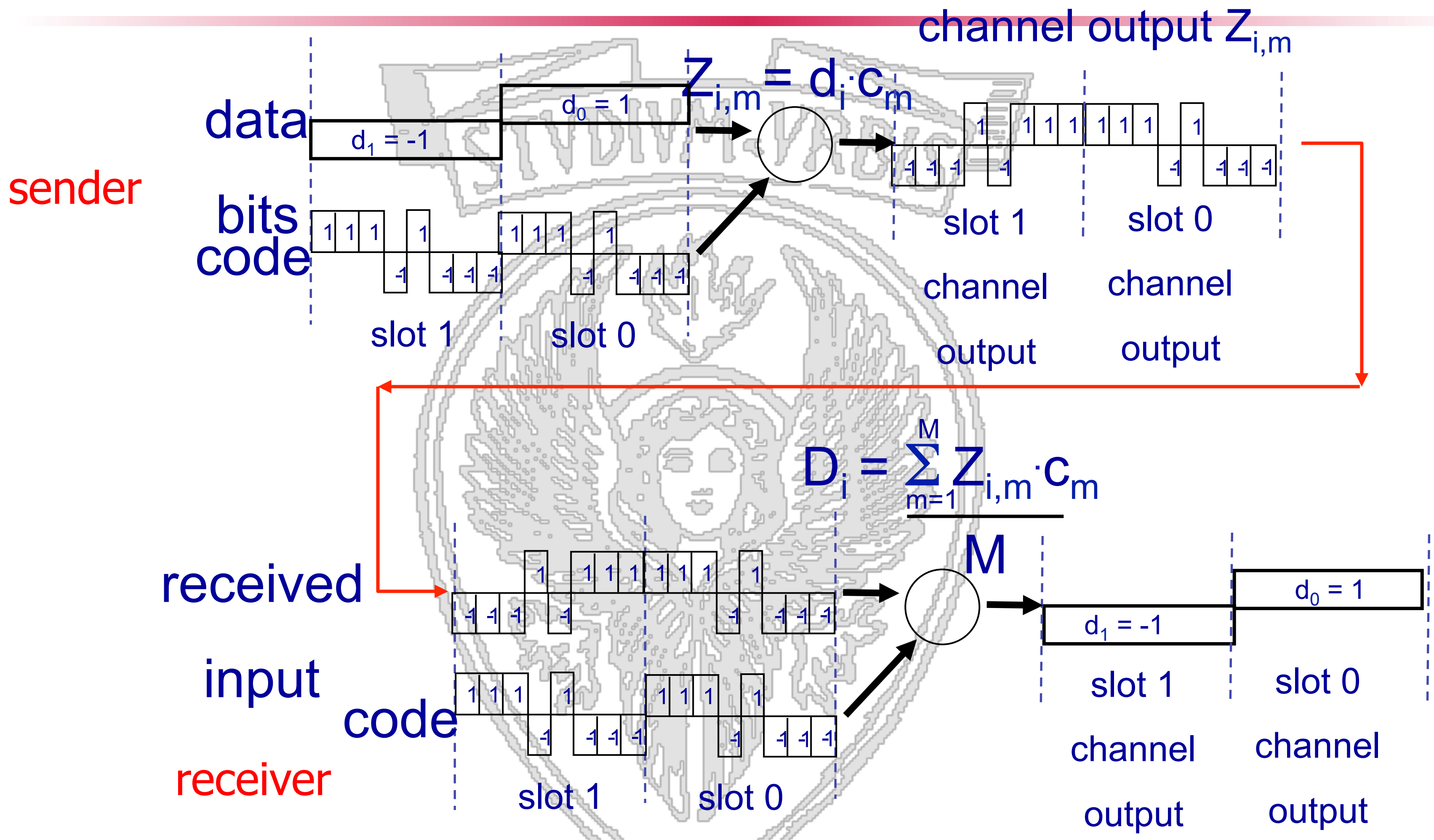
UMTS protocol stack



CDMA

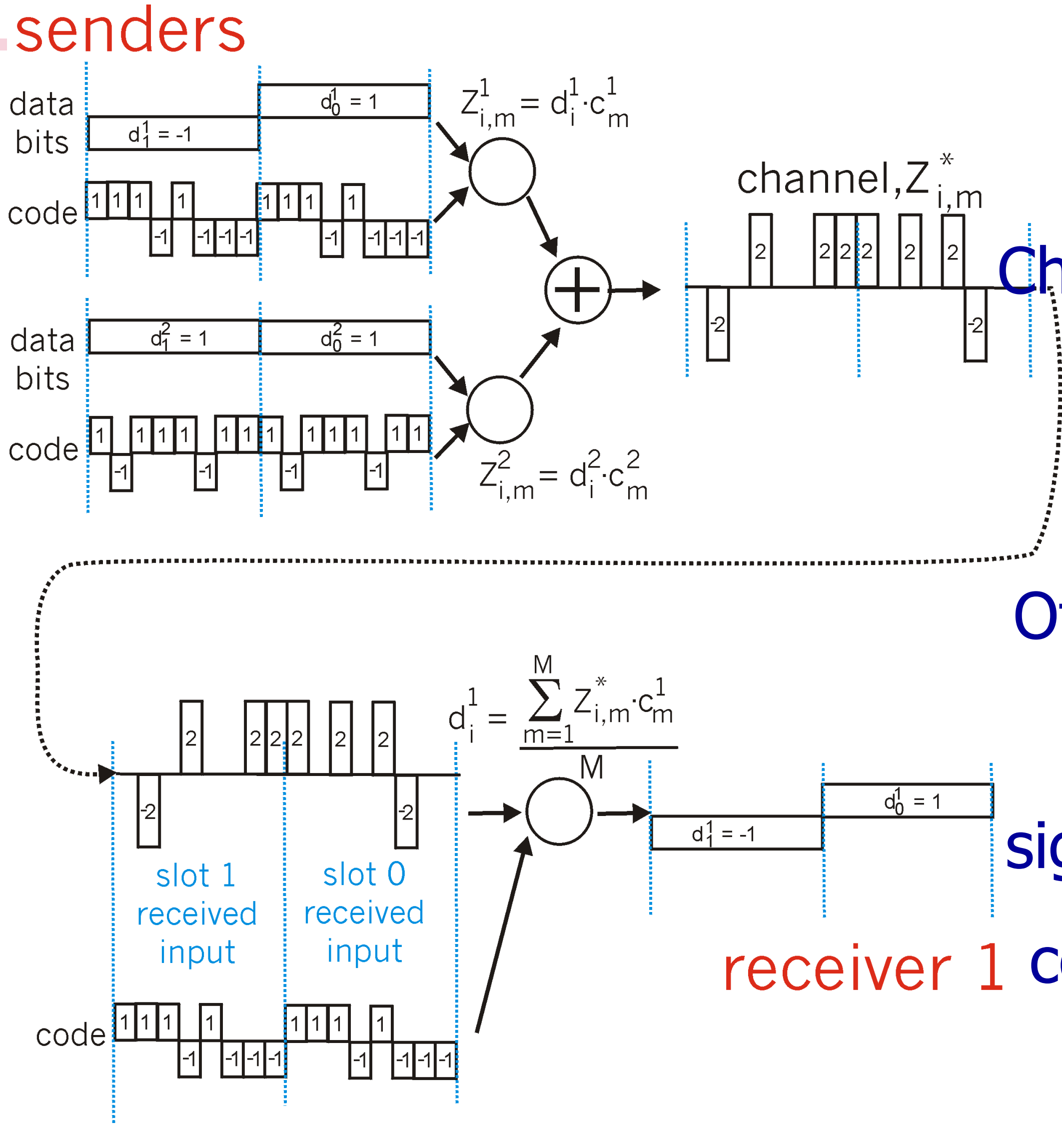
- unique "code" assigned to each user; i.e., code set partitioning
- all users share same frequency, but each user has own "chipping" sequence (i.e., code) to encode data
- *encoded signal* = (original data) X (chipping sequence)
- *decoding:* inner-product of encoded signal and chipping sequence
- allows multiple users to "coexist" and transmit simultaneously with minimal interference (if codes are "orthogonal")

CDMA Encode/Decode



From Kurose Ross-Computer Networking

CDMA: two-sender interference



Chipping codes must be orthogonal

Other requirements such as the fact signals arrivere with comparable power

Cellular systems: 4G

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Emerging needs

- Requirements for LTE (2005)
  - Increased user data rates
  - Uniformity of service provisioning (even at cell edge)
  - Improved spectral efficiency
  - Greater flexibility of spectrum usage
  - Reduced delays (connection establishment and transmission latency)
  - Low energy consumption at the mobile
  - Seamless mobility and simplified network architecture
- Cellular systems aggregated data rate:

Bandwidth * Spectral efficiency

Bandwidth: Regulation and licences — ITU-R, FCC, regional regulators

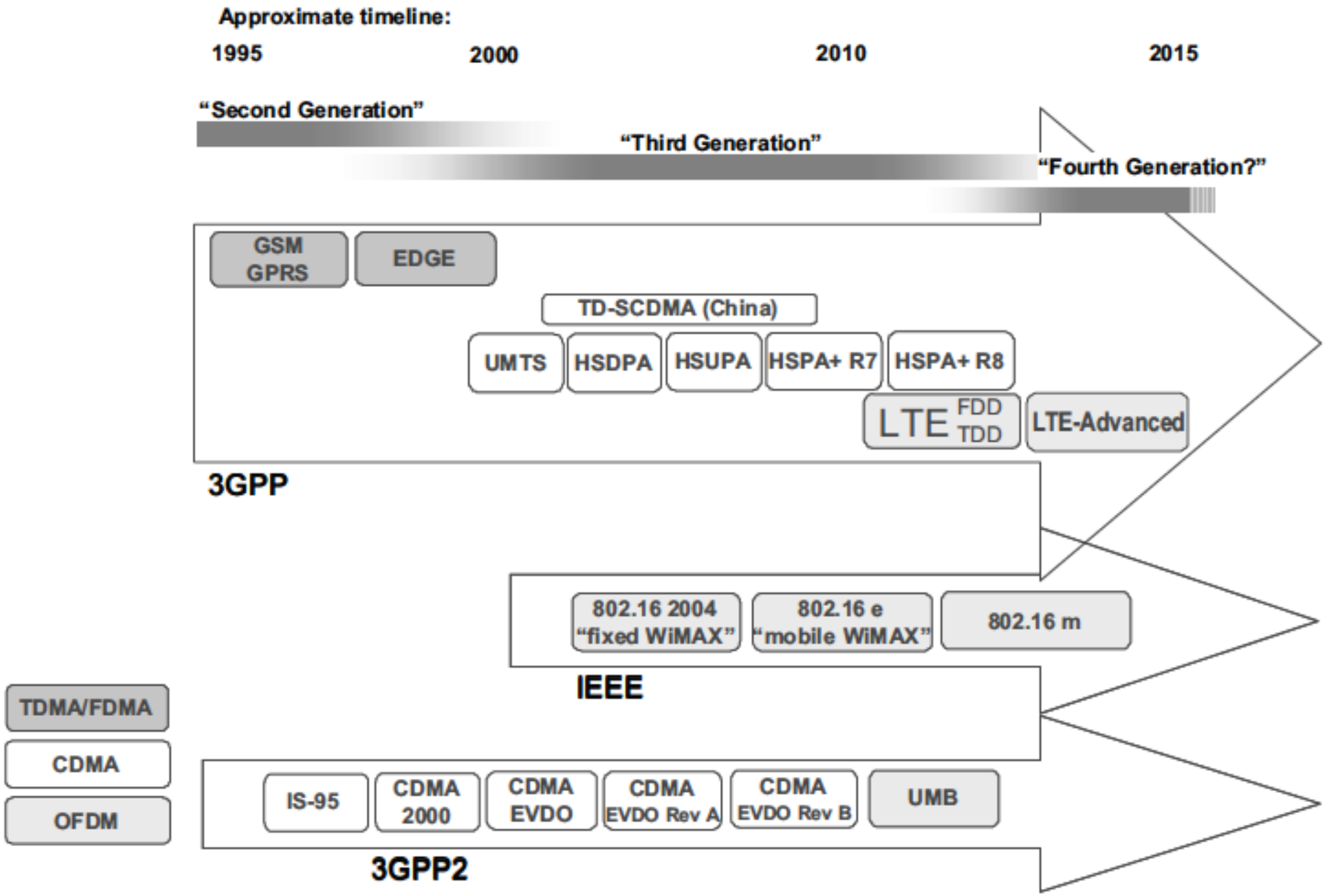
High cost of spectrum — Licences, spectrum almost completely allocated

Spectral efficiency: Technology and standards

		Absolute requirement	Comparison to Release 6	Comment
Downlink	Peak transmission rate	> 100 Mbps	7 × 14.4 Mbps	LTE in 20 MHz FDD, 2 × 2 spatial multiplexing. Reference: HSDPA in 5 MHz FDD, single antenna transmission
	Peak spectral efficiency	> 5 bps/Hz	3 bps/Hz	
	Average cell spectral efficiency	> 1.6 – 2.1 bps/Hz/cell	3 – 4 × 0.53 bps/Hz/cell	LTE: 2 × 2 spatial multiplexing, Interference Rejection Combining (IRC) receiver [3]. Reference: HSDPA, Rake receiver [4], 2 receive antennas
	Cell edge spectral efficiency	> 0.04 – 0.06 bps/Hz/user	2-3 × 0.02 bps/Hz	As above, 10 users assumed per cell
	Broadcast spectral efficiency	> 1 bps/Hz	N/A	Dedicated carrier for broadcast mode
Uplink	Peak transmission rate	> 50 Mbps	5 × 11 Mbps	LTE in 20 MHz FDD, single antenna transmission. Reference: HSUPA in 5 MHz FDD, single antenna transmission
	Peak spectral efficiency	> 2.5 bps/Hz	2 bps/Hz	
	Average cell spectral efficiency	> 0.66 – 1.0 bps/Hz/cell	2 – 3 × 0.33 bps/Hz	LTE: single antenna transmission, IRC receiver [3]. Reference: HSUPA, Rake receiver [4], 2 receive antennas
	Cell edge spectral efficiency	> 0.02 – 0.03 bps/Hz/user	2 – 3 × 0.01 bps/Hz	As above, 10 users assumed per cell
System	User plane latency (two way radio delay)	< 10 ms	One fifth	
	Connection set-up latency	< 100 ms		Idle state → active state
	Operating bandwidth	1.4 – 20 MHz	5 MHz	(initial requirement started at 1.25 MHz)
	VoIP capacity	NGMN preferred target expressed in [2] is > 60 sessions/MHz/cell		

Standard Evolution

- GSM/GPRS/EDGE ← TDMA/FDMA based, designed for voice, extended for data



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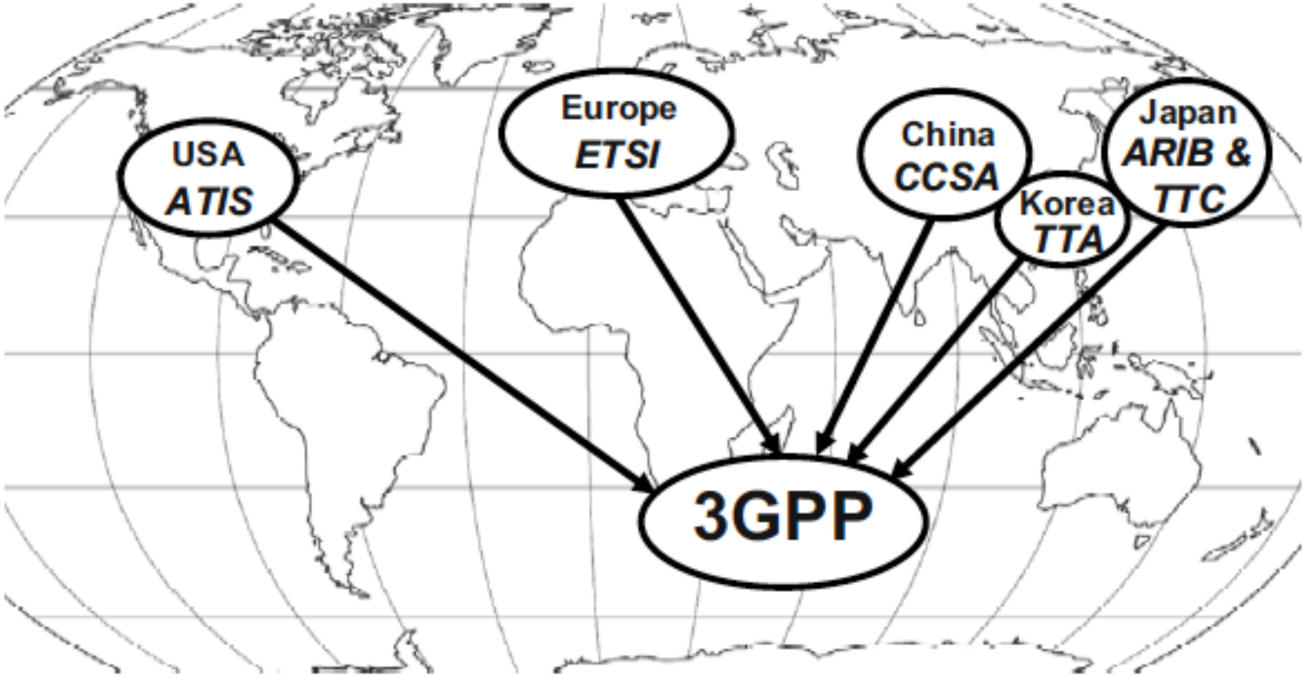
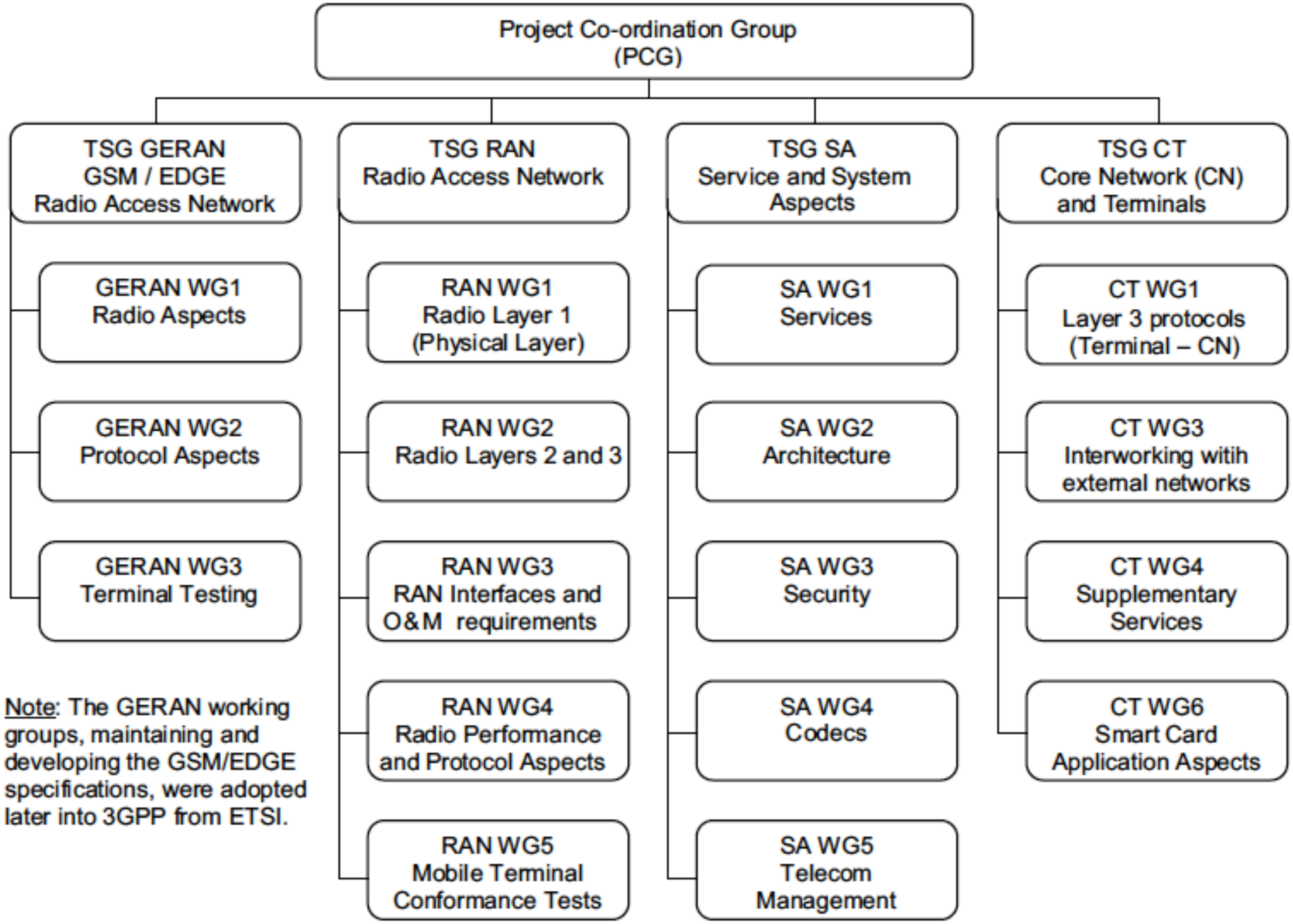


Specification through consensus in Working Groups part of

Technical Specification Groups ←accounting for performance, implementation cost, complexity, backward compatibility

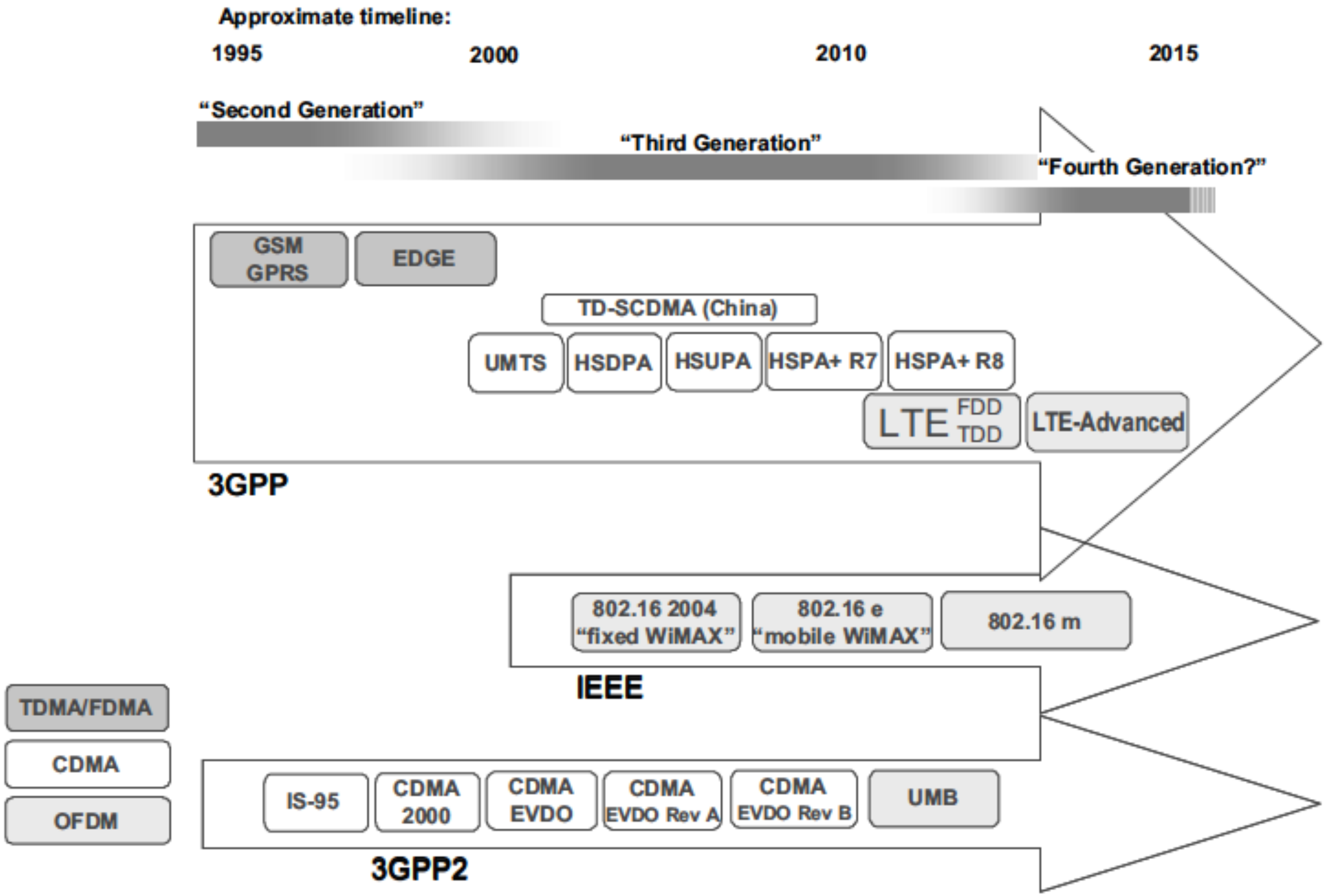
Standardization



Note: The GERAN working groups, maintaining and developing the GSM/EDGE specifications, were adopted later into 3GPP from ETSI.

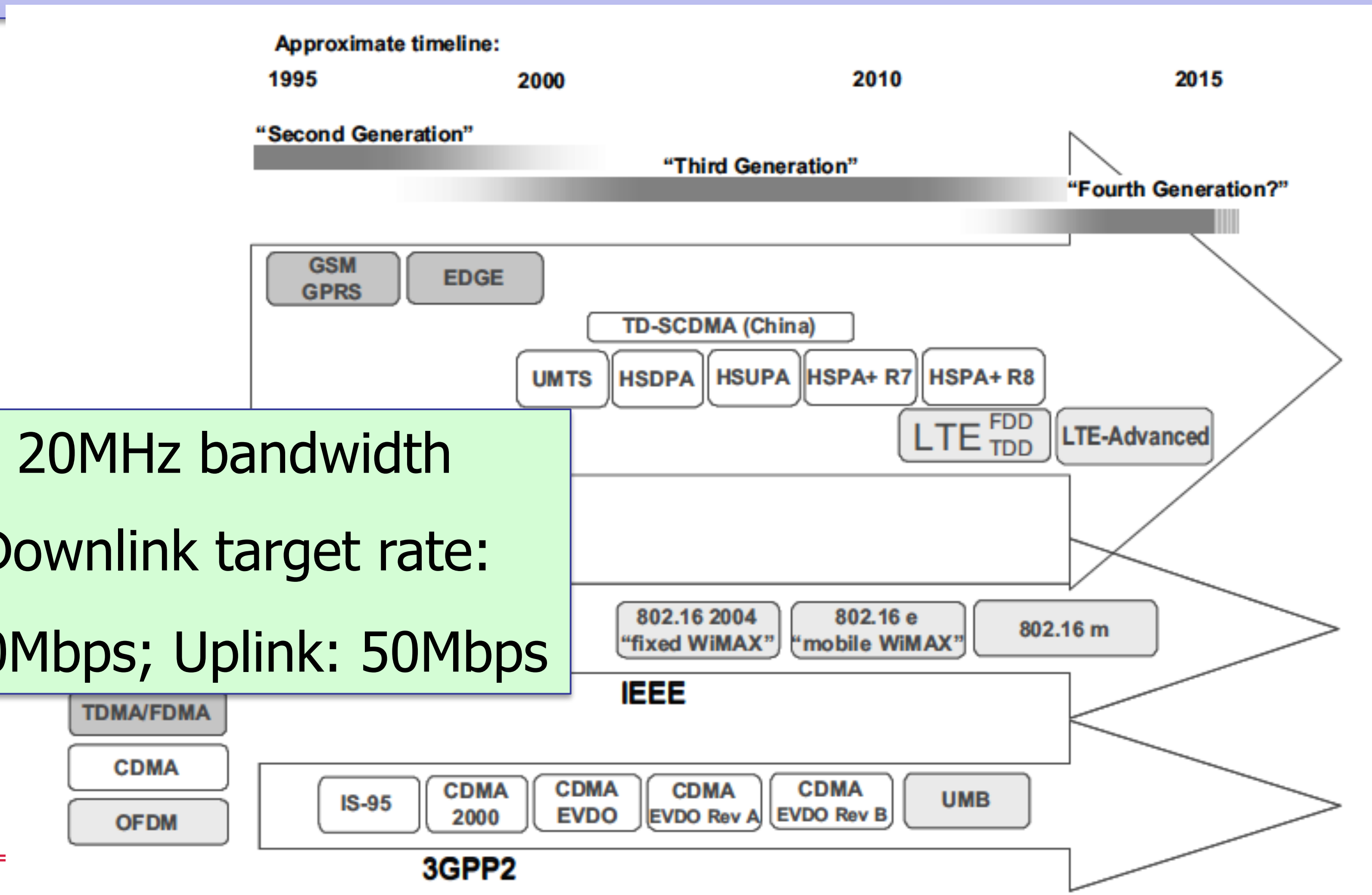
Standard Evolution

- UMTS ← CDMA based, up to high frequency, MIMO, multiservice support



Standard Evolution

- LTE←OFDM based, designed from the very beginning based on a packet switched model, complete realization of the multiservice model



20MHz bandwidth

Downlink target rate:

100Mbps; Uplink: 50Mbps

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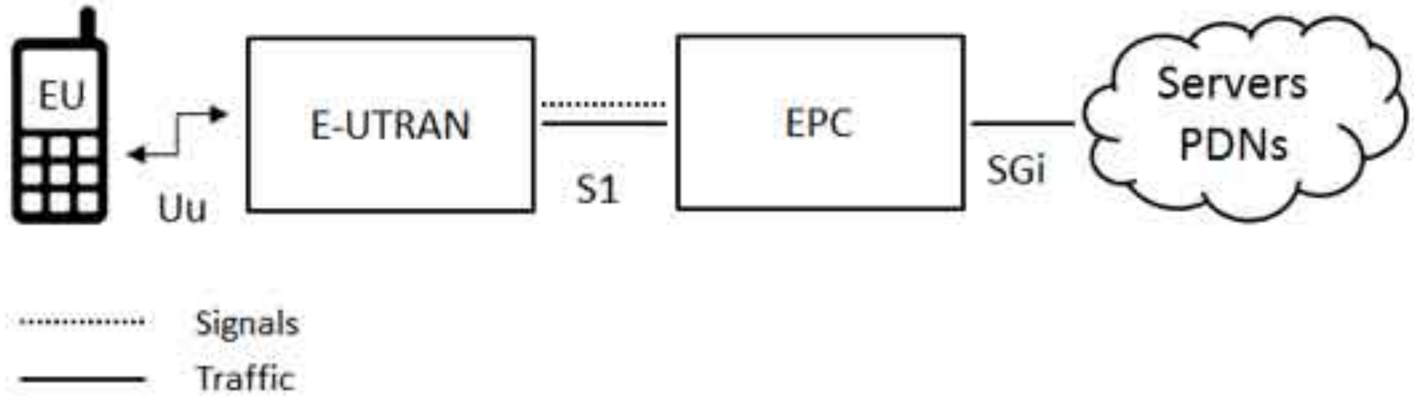
- Requirements for LTE
  - Able to operate in a wide range of frequency bands and sizes of spectrum allocations (from 1.4 up to 20MHz per carrier)
  - Fast connection time (less than 100ms), at least 200 active state users per cell supported by control signaling up to 5MHz and at least 400 users per cell for wider spectrum allocation, one way packet latency =5ms in light traffic.
  - Increased peak rate, uniform performance (requirements on cell edge performance as 5° percentile of performance)
  - Support of mobility up to 350-500Km/h, cells radius 5-100Km
  - Flexible interoperation with other radio access technologies (service continuity in the migration phase), in particular earlier 3GPP technologies, and non 3GPP technologies (WiFi, CDMA 2000, WiMax)
  - Low terminal complexity and power consumption
  - Cost effective deployment
    - ✓ One type of node, the BS, named eNodeB
    - ✓ Open interfaces, multivendor interoperability
    - ✓ Self optimization and easy management
    - ✓ Packet switched services
    - ✓ Easy deployment and configuration of home base station

Technologies for LTE

- Multicarrier technology
  - OFDMA for downlink+ SC-FDMA for uplink
    - ✓ Flexible, adaptable, robust
    - ✓ Low complexity receivers
- Multiantenna technology
- Packet switching
  - System architecture evolution
    - ✓ Concept of Evolved packet system bearer to route IP packets from a gateway of the Packet Data Network to the User Equipment
      - Internet traffic, VoIP traffic
    - ✓ Bearer = IP packet flow with a given QoS between the gateway and the UE (set up and released by the radio access and the evolved packet core together)
      - Multiple bearers can be established for an end user providing different QoS

Network architecture

- The high-level network architecture of LTE is comprised of following three main components:
  - The User Equipment (UE).
  - The Evolved UMTS Terrestrial Radio Access Network (E-UTRAN).
  - The Evolved Packet Core (EPC).



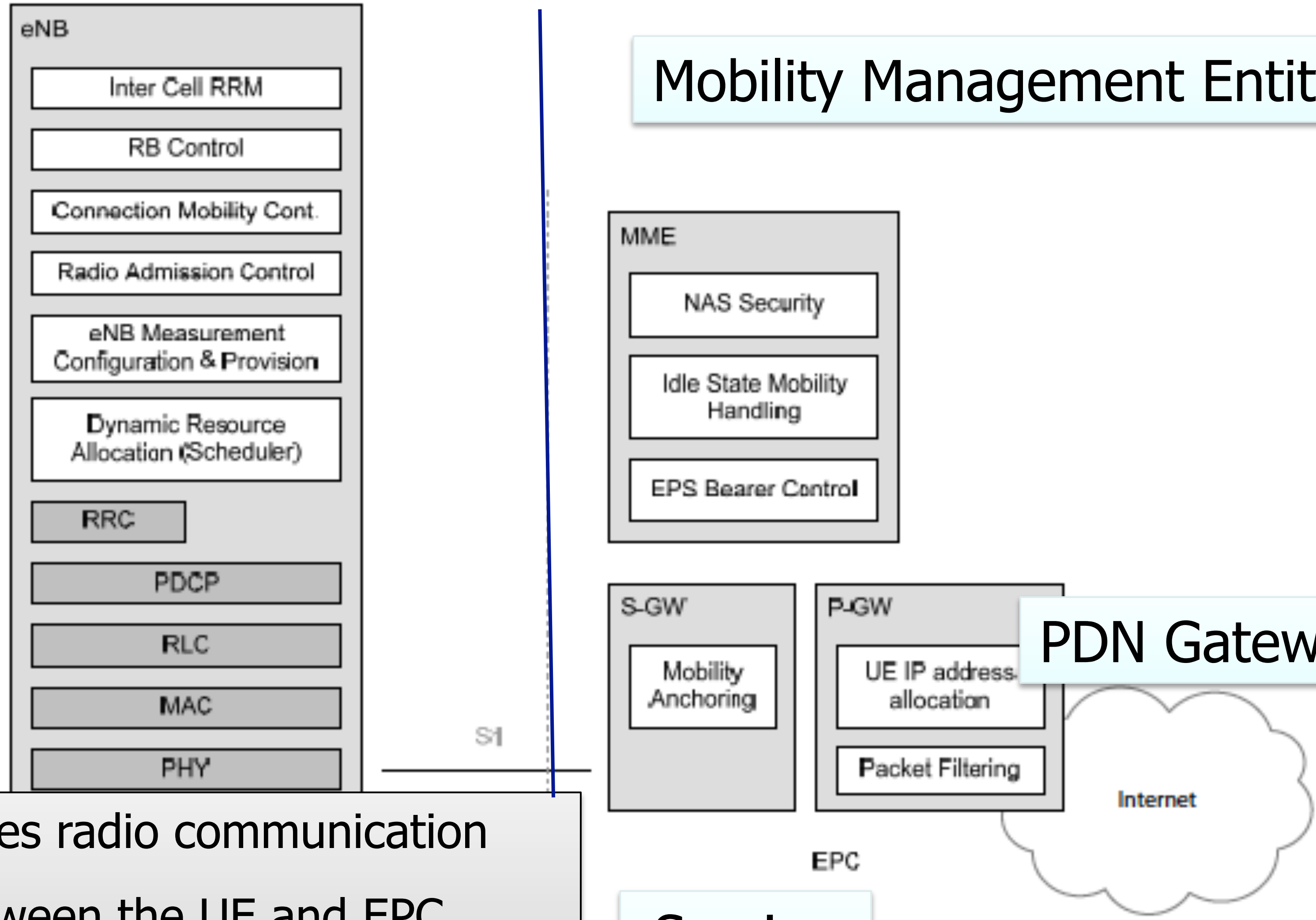
Access Network

Core network

Network architecture

Mobility Management Entity

E-UTRAN



PDN Gateway

Handles radio communication

between the UE and EPC

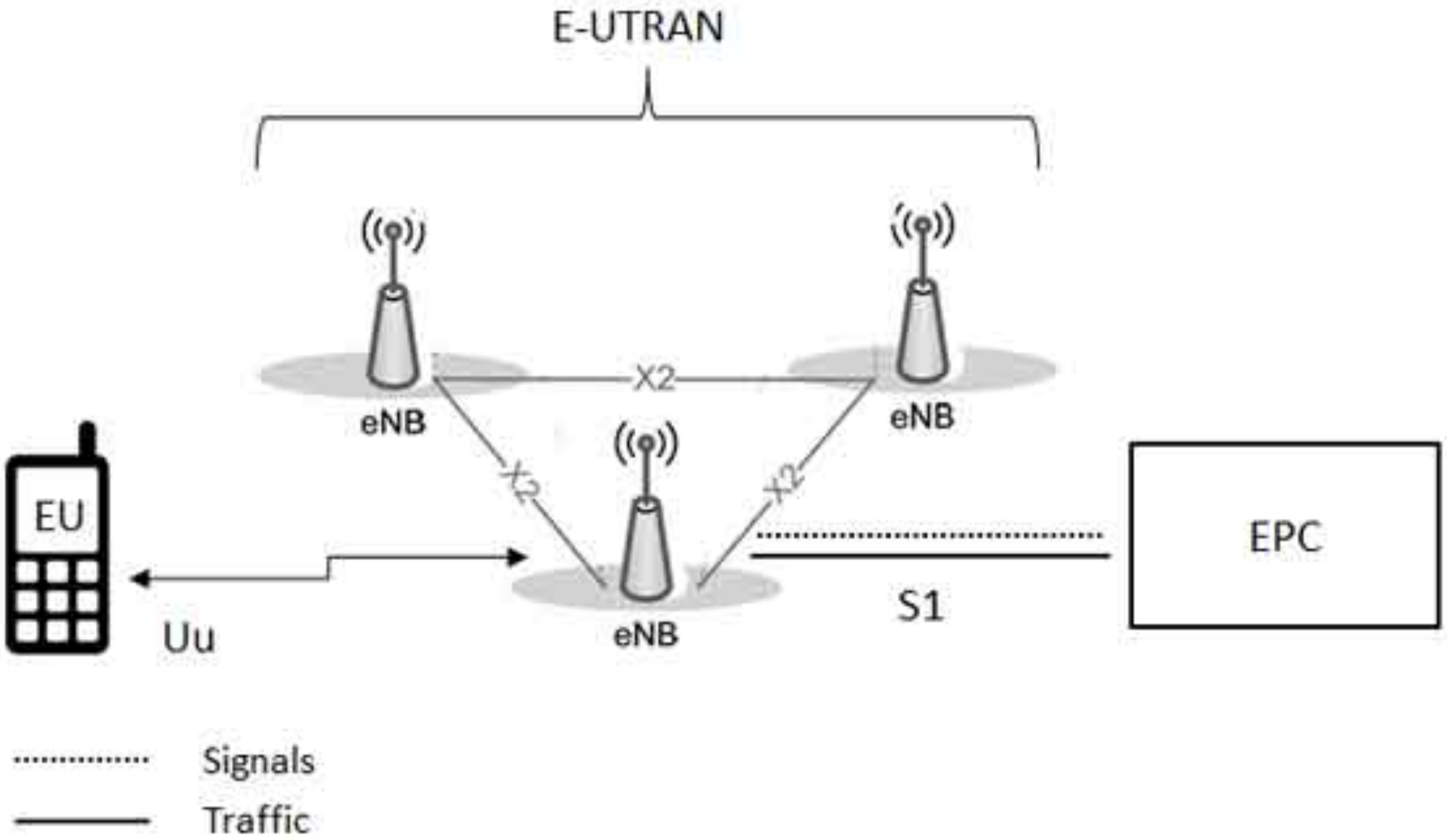
Comprises only evolved base station

→eNB or eNodeB

Serving Gateway

Network architecture

E-UTRAN



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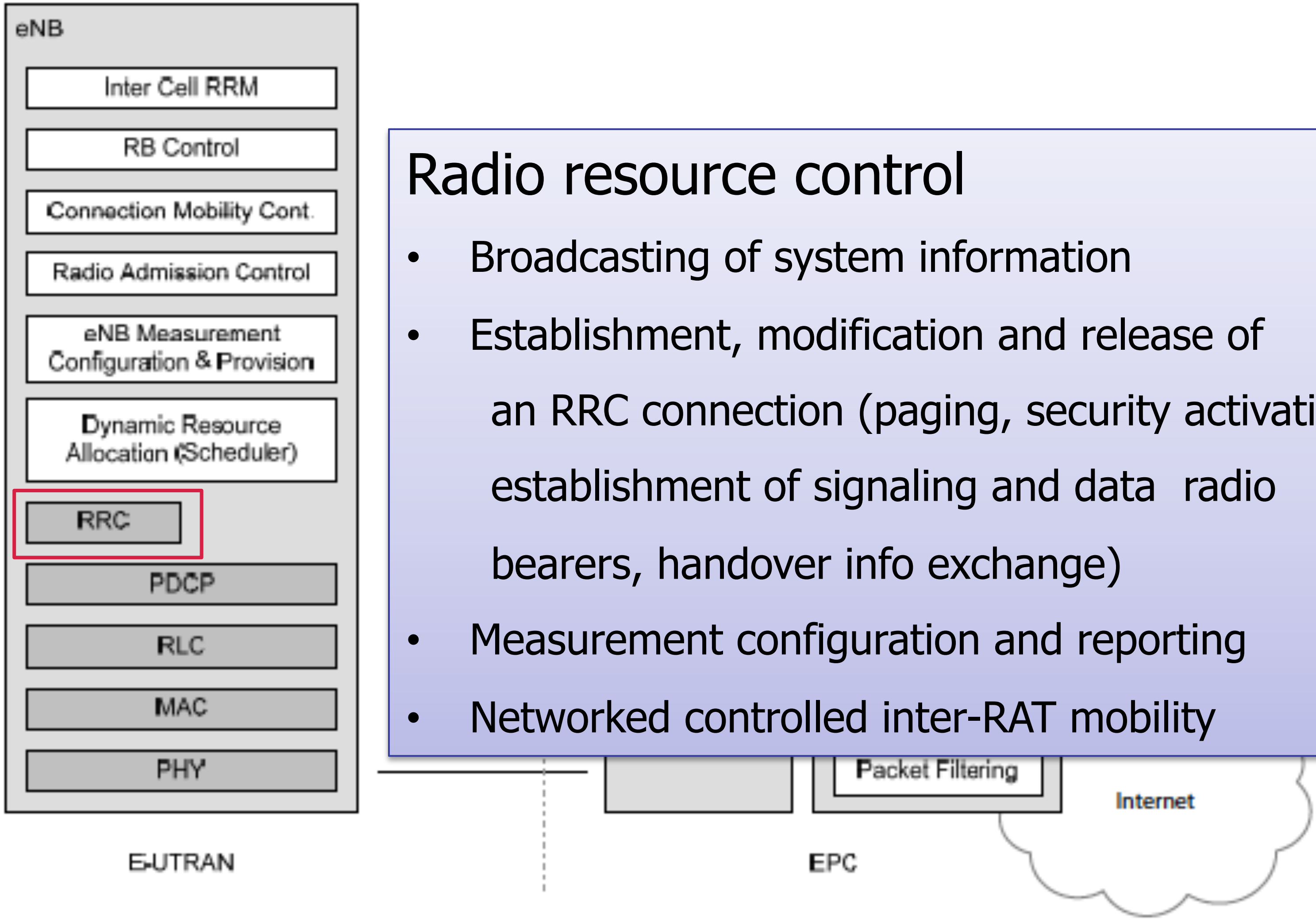
Network architecture



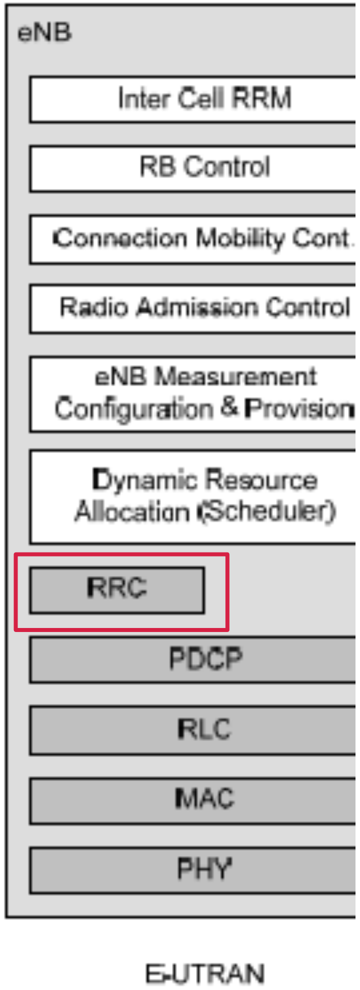
Radio resource control

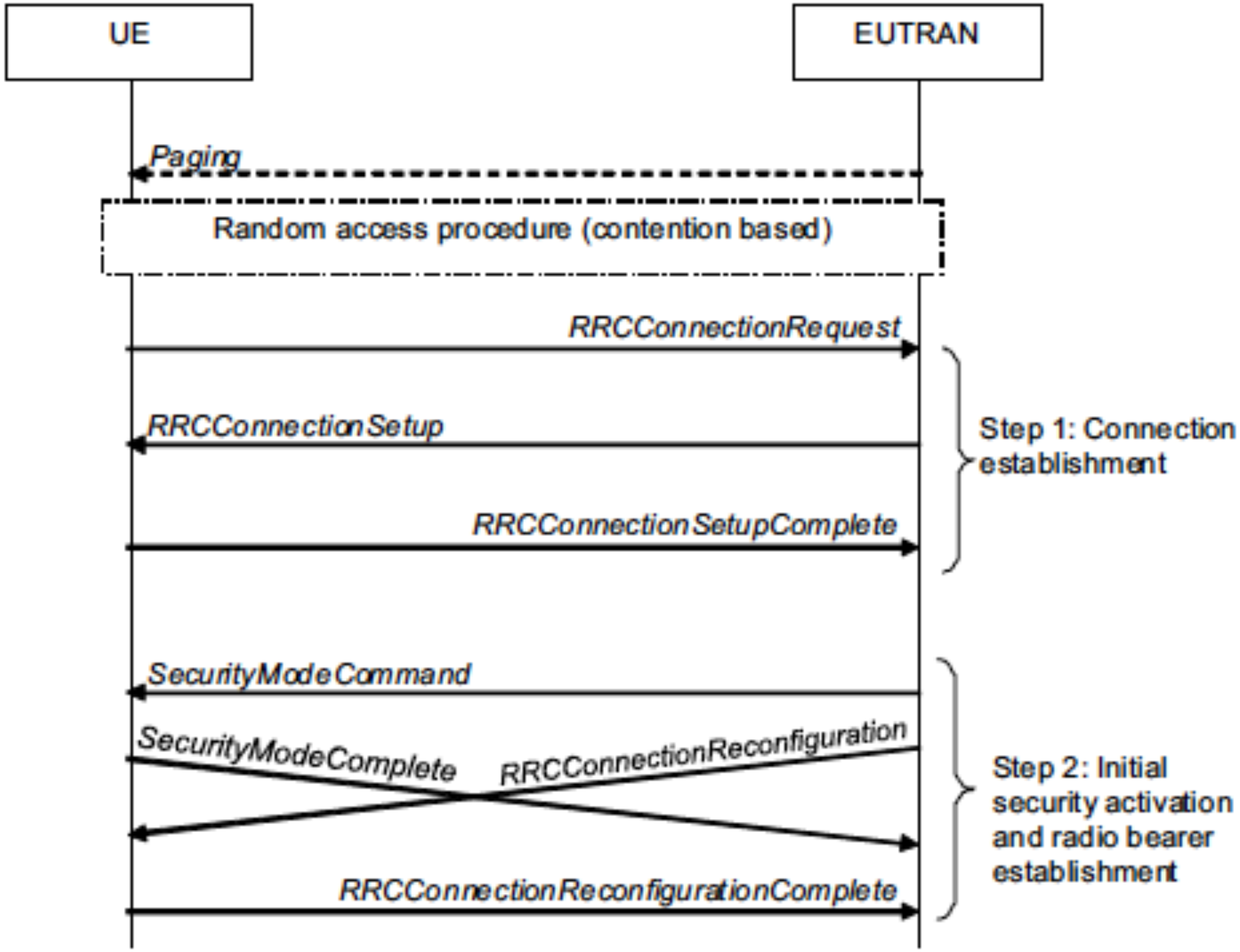
- Broadcasting of system information
- Establishment, modification and release of an RRC connection (paging, security activation, establishment of signaling and data radio bearers, handover info exchange)
- Measurement configuration and reporting
- Networked controlled inter-RAT mobility

Access Network

Core network

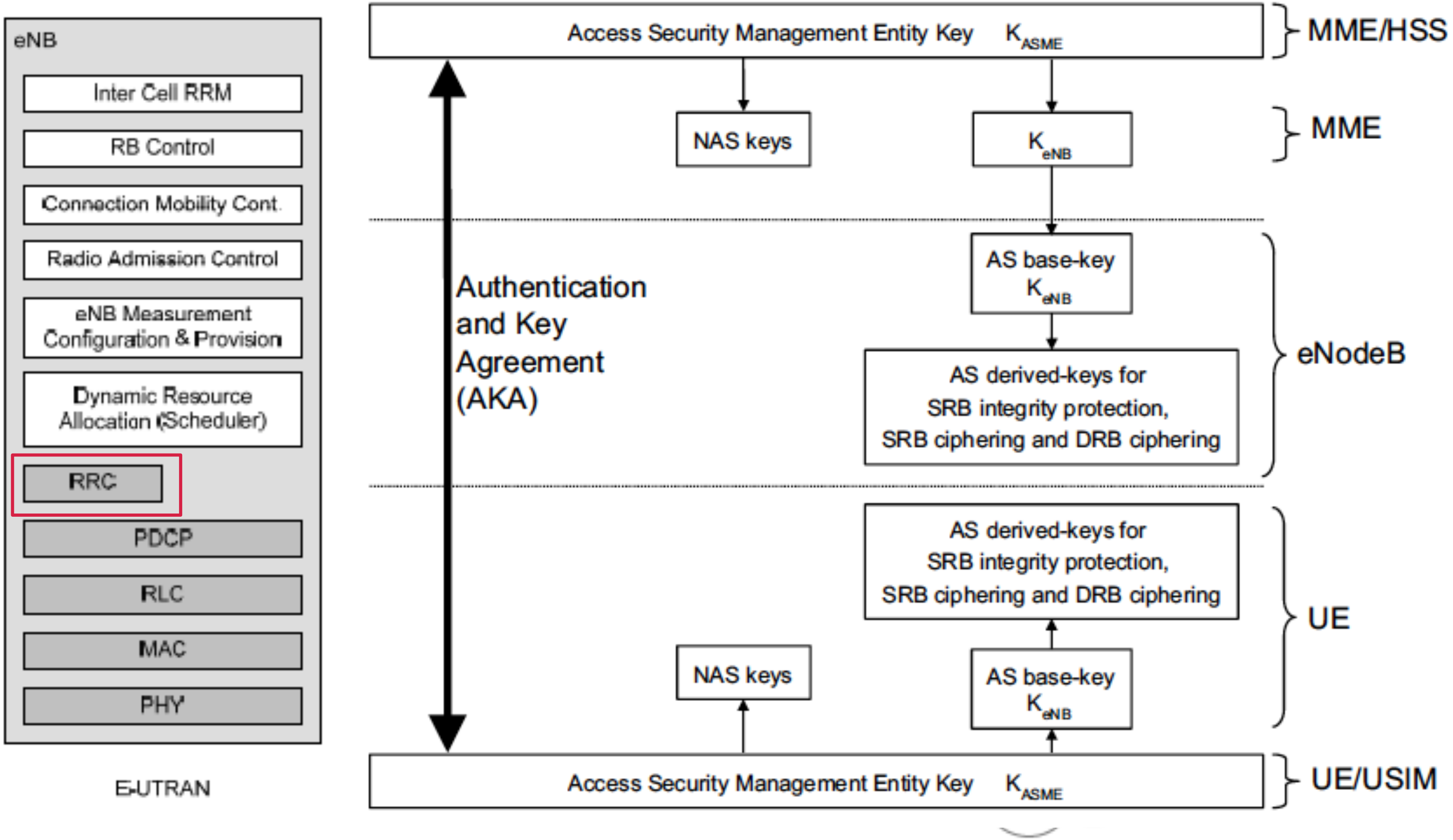
Network architecture





Access Network

Network architecture



Access Network

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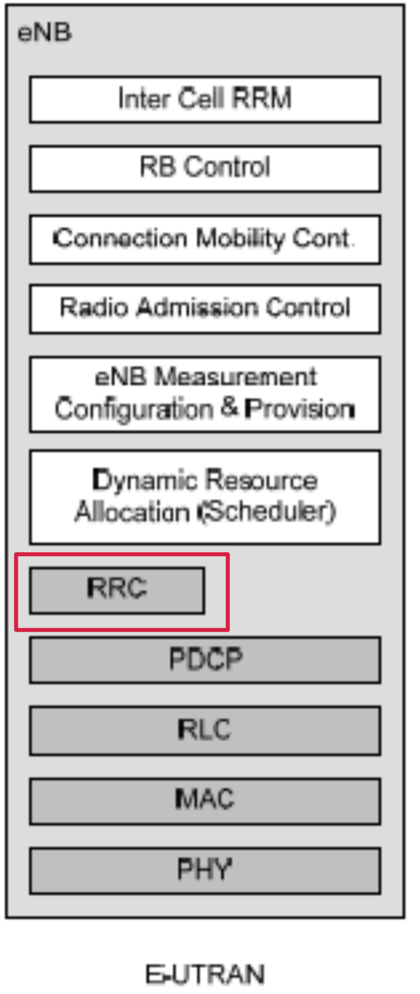
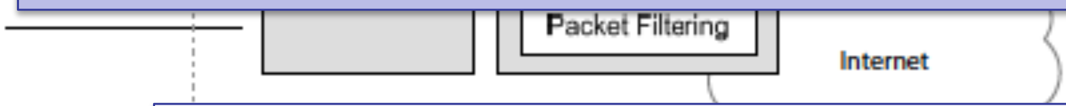


Radio resource control

- Broadcasting of system information
- Establishment, modification and release of an RRC connection (paging, security activation, establishment of signaling and data radio bearers, handover info exchange)
- Measurement configuration and reporting
- Networked controlled inter-RAT mobility

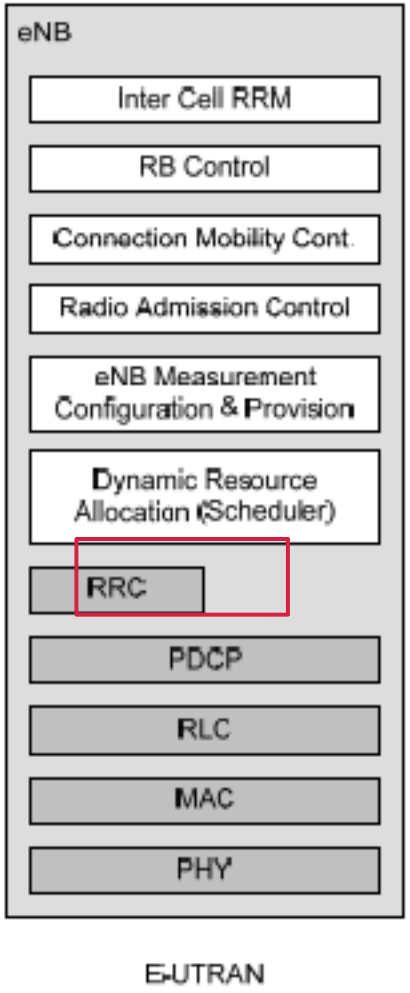


Cell selection based on cell priority

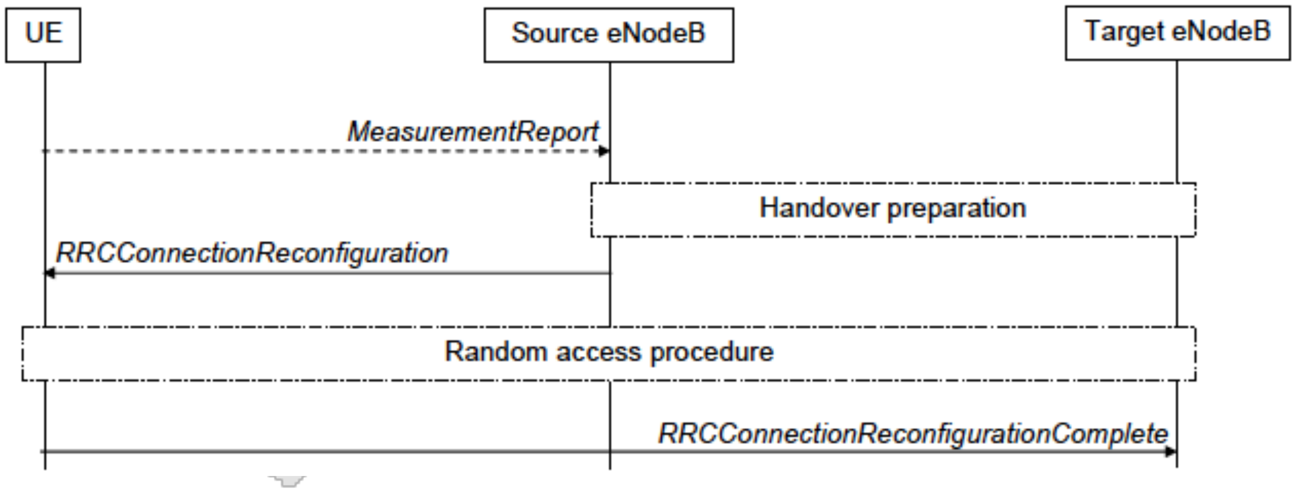
Second criterion: radio link quality

Access Network

Network architecture



- Hard handover
- UE provides measurements
- eNodeN controlling the source cell requests one or more target eNodeB to prepare for handover (and provides UE radio resource information/context info)
- Target eNodeB generates RRC "message of handover which is forwarded by source eNodeB to the UE
- UE initiates a random access procedure to connect to the new cell



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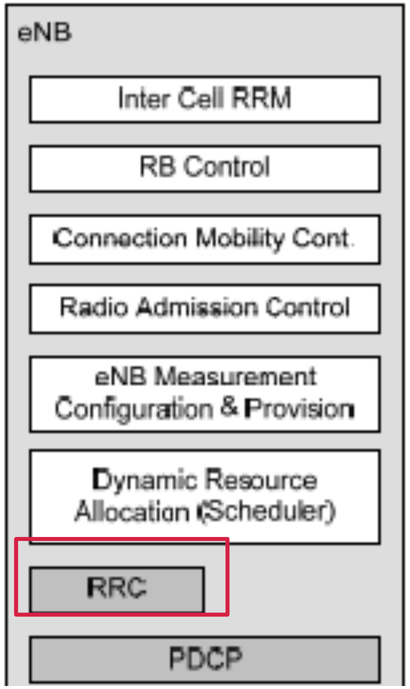
Network architecture



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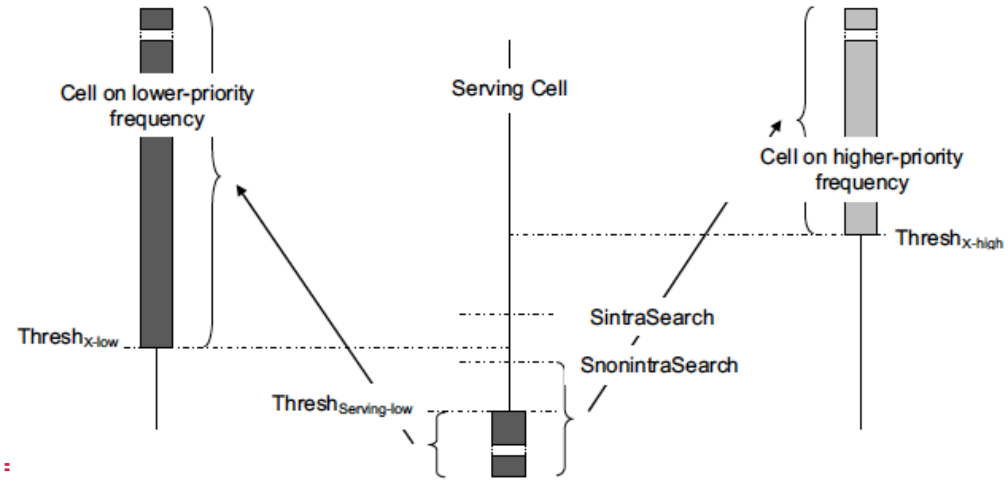
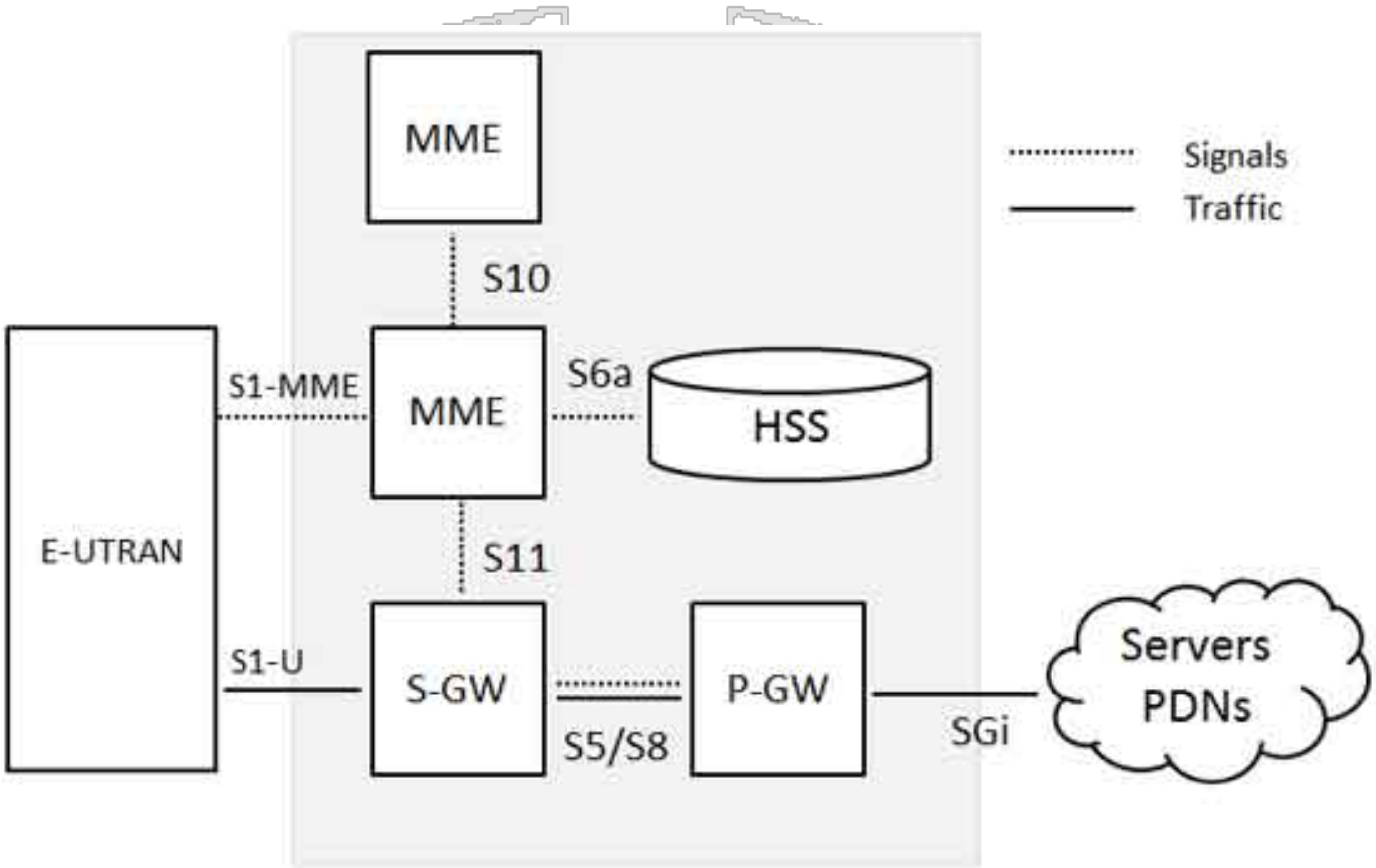


- Flexible measurements configuration
- Event based reporting
- Periodic reporting
- Optimized to save energy

Network architecture

- HSS (Home Subscriber Server)
  - User subscription data, PDNs to which the user can connect, identity of the MME the user is connected to, authentication center
  - HLR+AuC
- P-GW: IP address allocation to UE+ QoS enforcement in downlink+interworking with non 3GPP technologies
- S-GW:tranports the IP data traffic between the User Equipment and the external networks.
- MME (Mobility Management Entity): connection set up including paging within a tracking area; security

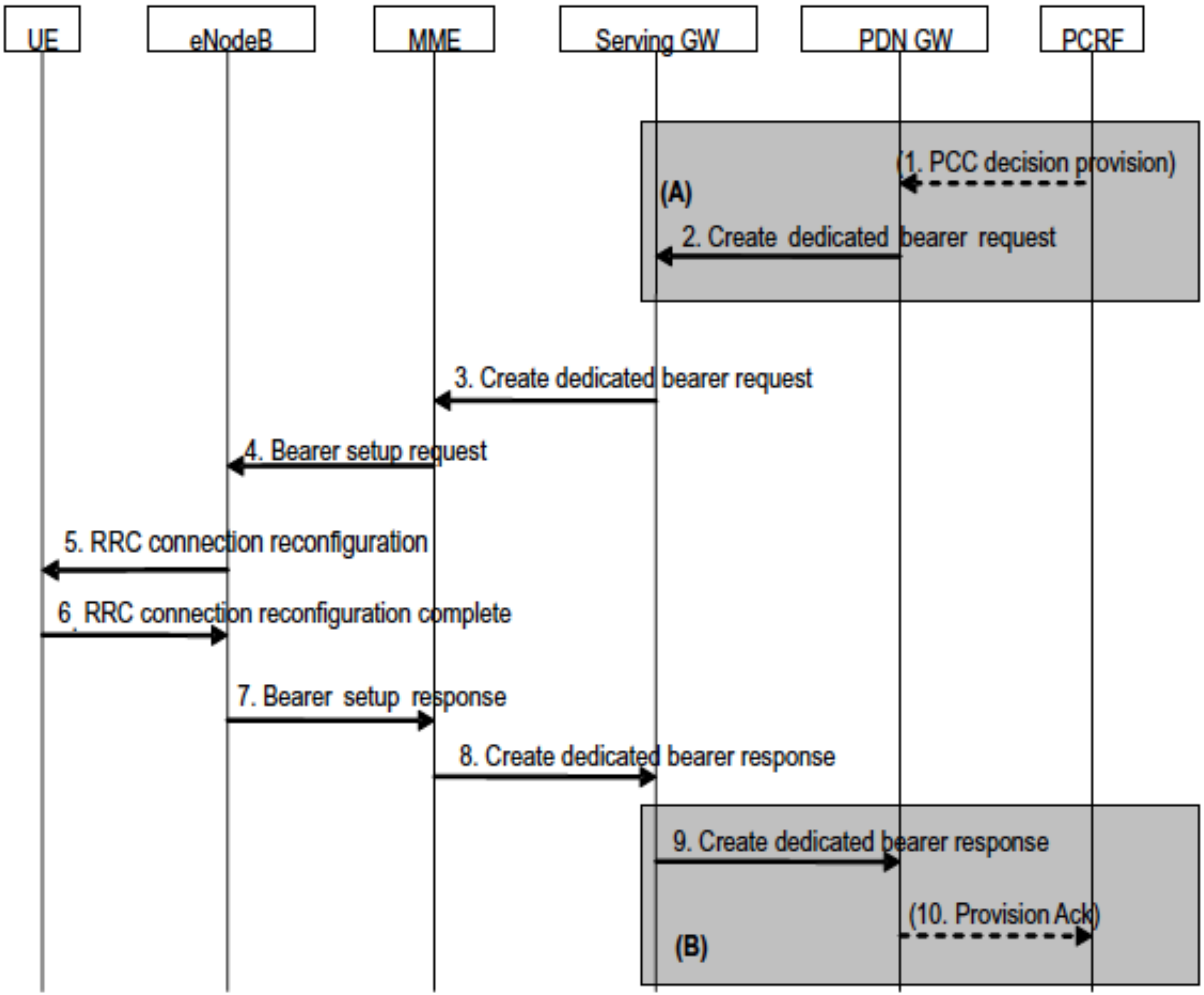
Network architecture



- Standardized interfaces among network elements

QoS and bearers

- Bearers
  - Minimum guaranteed bit rate
  - Non GBR bearers
- The eNodeB in the access network ensures the necessary QoS for a bearer over the radio interface
- Each bearer has an associated QoS Class Identifier and an Allocation and Retention Priority(the latter used for call admission)
  - QCI: priority, packet delay budget, acceptable packet loss rate
  - Determining how to perform scheduling, which queue management policy to use, with which priority

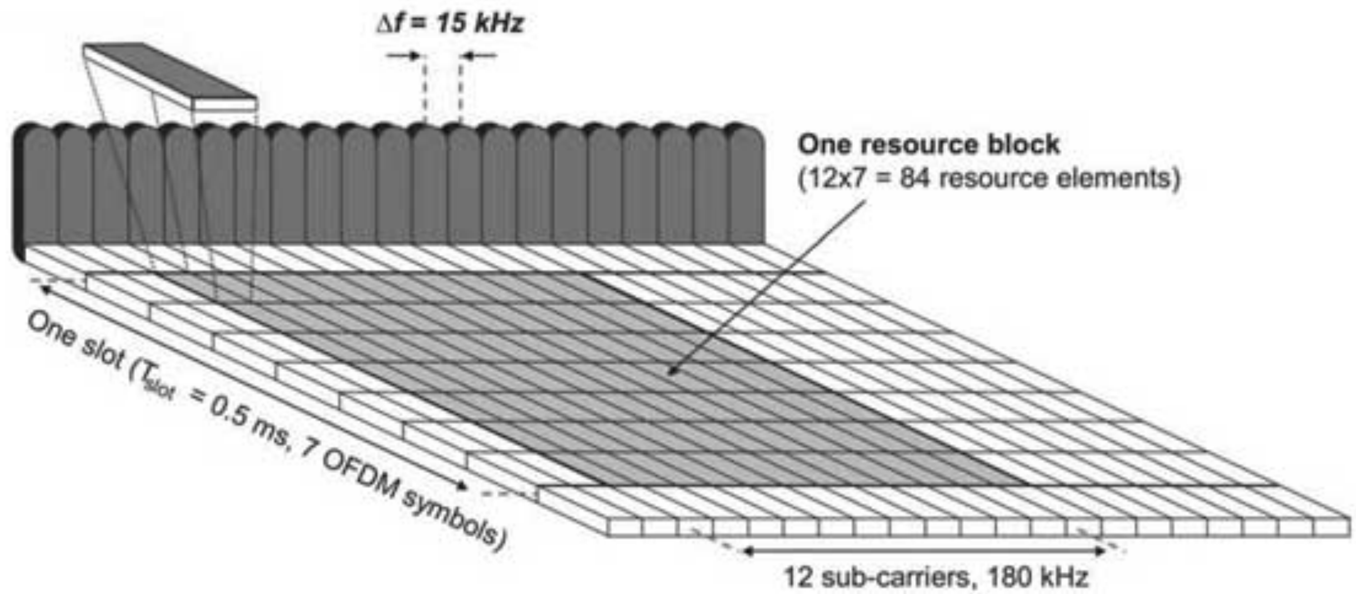

UE
eNodeB
MME
Serving GW
PDN GW
PCRF
(1. PCC decision provision)
(A)
2. Create dedicated bearer request
3. Create dedicated bearer request
4. Bearer setup request
5. RRC connection reconfiguration
6. RRC connection reconfiguration complete
7. Bearer setup response
8. Create dedicated bearer response
9. Create dedicated bearer response
(10. Provision Ack)
(B)

Scheduling

- The scheduler in the eNodeB distributes the available radio resources in one cell among the UEs, and among the radio bearers of each UE.
- eNodeB allocates downlink or uplink radio resources to each UE based on the downlink data buffered in the eNodeB and on Buffer Status Reports (BSRs) received from the UE, and based on channel quality indicator reports.
- eNodeB considers the QoS requirements of each configured radio bearer
  - *dynamic scheduling*: assignment of downlink transmission resources and uplink grant messages for the allocation of uplink transmission resources;
    - ✓ valid for specific single subframes, tx on Physical Downlink Control Channel
  - *persistent scheduling*: resources are semi-statically configured and allocated to a UE for a longer time period

Resource blocks and OFDMA

- LTE is based on orthogonal frequency-division multiplexing (OFDM)
- The OFDM symbols are grouped into resource blocks. The resource blocks have a total size of 180kHz in the frequency domain and 0.5ms in the time domain.



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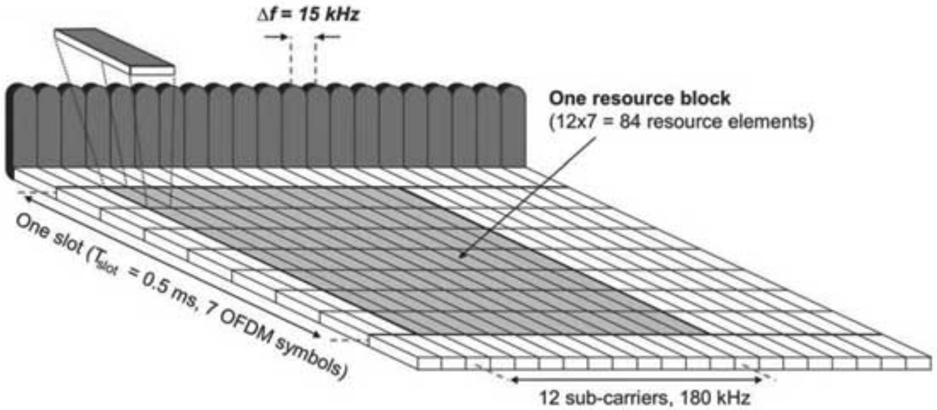
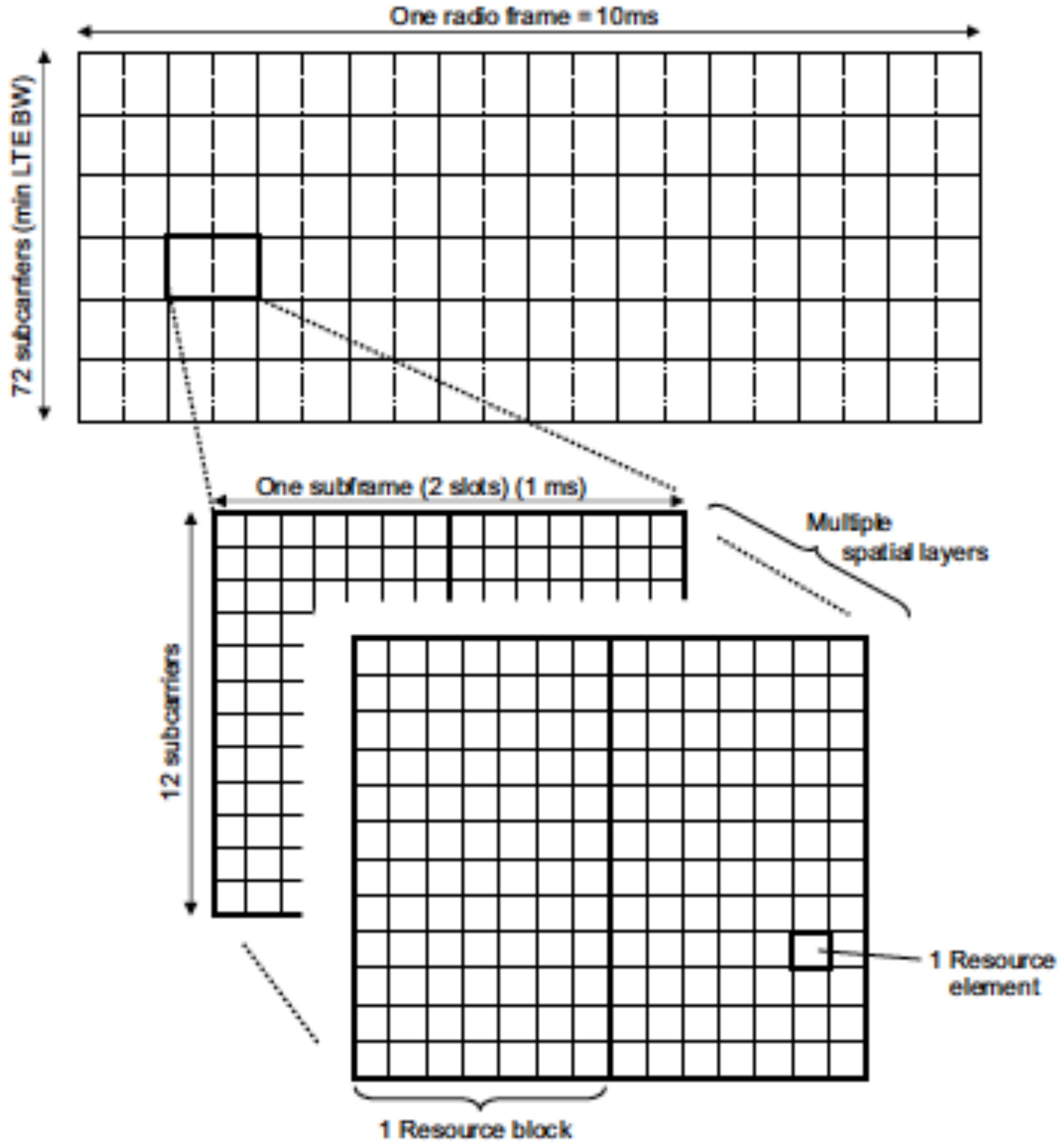
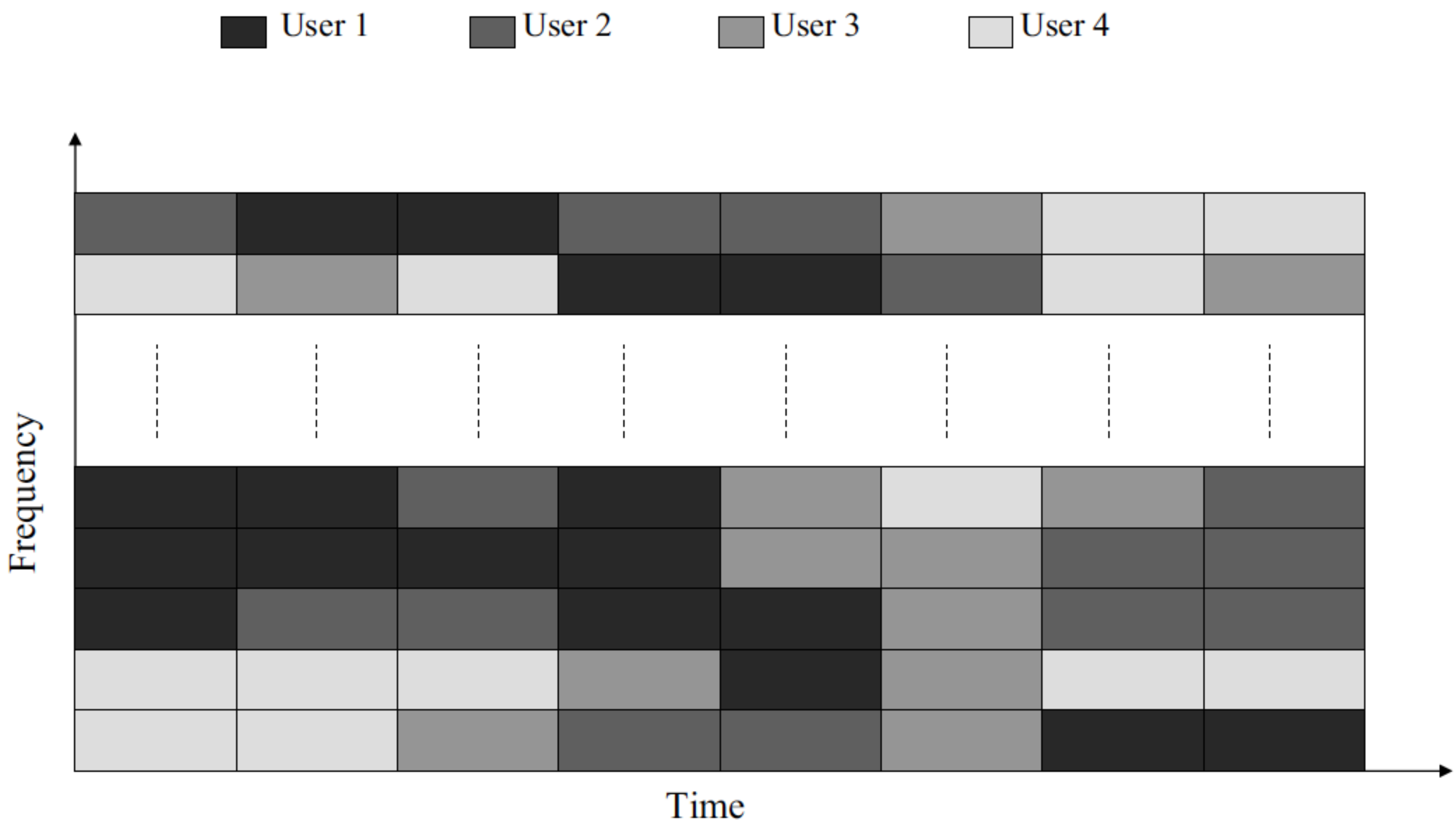


- Each user is allocated a number of so-called resource blocks in the time-frequency grid.
- The more resource blocks a user gets, and the higher the modulation used in the resource elements, the higher the bit-rate.
- Advanced scheduling techniques are used
- Based on feedback information about the frequency-selective channel conditions from each user, adaptive user-to-subcarrier assignment can be performed, enhancing considerably the total system spectral efficiency

Resource blocks



Resource block allocation
An example

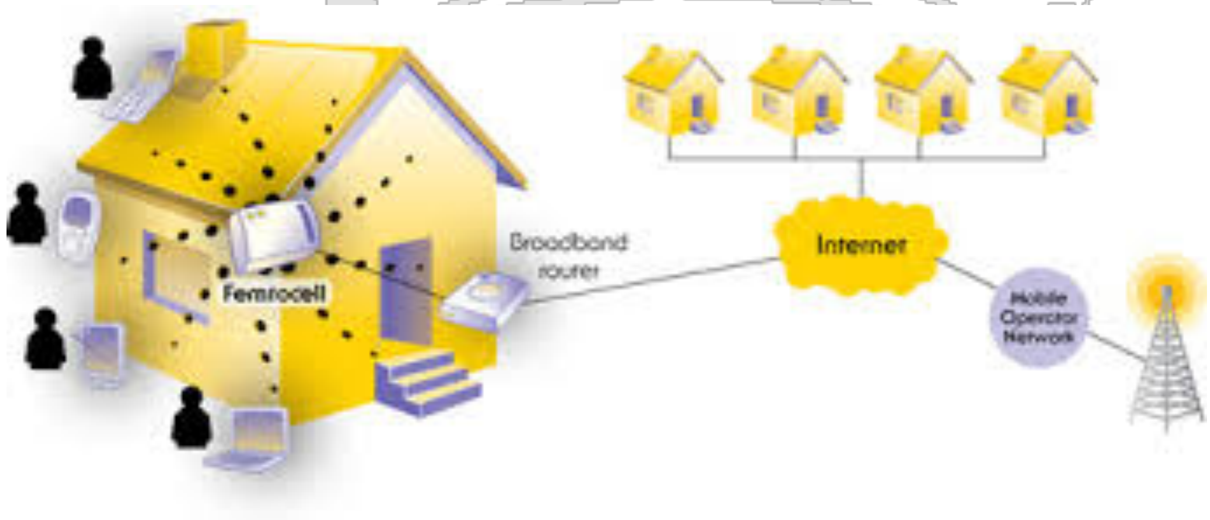


Phy layer adaptation

- Modulation scheme, code rate are dynamically selected based on predicted channel conditions

- Channel Quality Indicator provided as feedback by the UEs are used to estimate different channels conditions (based on user perceived quality of transmitted reference signals)

The femto cell concept



Brings to the home the QoS and high spectrum utilization features of LTE technology

LTE summary

- LTE brings up to 50 times performance improvement and much better spectral efficiency to cellular networks.
- 300Mbps peak downlink and 75 Mbps peak uplink.
- LTE supports flexible carrier bandwidths, from 1.4 MHz up to 20 MHz as well as both FDD and TDD.
- All LTE devices have to support MIMO transmissions, allowing the base station to transmit several data streams over the same carrier simultaneously
- All interfaces between network nodes are now IP based
- Quality of Service (QoS) mechanism have been standardized on all interfaces
- Works with GSM/EDGE/UMTS systems utilizing existing 2G and 3G spectrum and new spectrum. Supports hand-over and roaming to existing mobile networks.