Cellular systems: from 2G to 4G


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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.
• Enhanced full rate codec based on ACELP (Algebraic Code Excited Linear Prediction) $\leftarrow 13$Kbit/s
• Adaptive MultiRate $\leftarrow$ new generation codec that adapts to available channels (half rate or full rate) and changes rate depending on channel propagation conditions
• Tandem Free Operation $\leftarrow$ 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
• Location services \( \leftrightarrow \) triangolarization among BTS allows to achieve a localization around 100m

• Number portability \( \leftrightarrow \) user can maintain its own telephone number even when changing telecom operator

• Cordless telephony system \( \leftrightarrow \) to use a MS as cordless, connecting to a Home Base Station (HBS) and from there to the cellular operator network

• SIM application toolkit \( \leftrightarrow \) 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 \( \leftrightarrow \) Mobile Execution Environment; CAMEL (customized applications for mobile networks enhanced logic).
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Voice
Fax
SMS
Call fwd.
Call restriction

1991

Circuit switching data
Call hold/waiting
Multi-party call
Advice of charge
Half rate speech coding

GPRS, EDGE
Enhanced Full Rate codec, AMR codec
Voice broadcast service, Voice call group service
Number portability
Cordless telephony service
Location services
SIM application toolkit, CAMEL, MeXe

1995

2G

2G+

2G+ innovation
• 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 22,8 Kbit/s of GSM
  – Features
    ✓ Carrier bandwidth: 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)
• 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
• 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
• 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.)
• 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
• **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,...
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
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
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.
Medium Access Control

- Same timeslot can be shared by multiple information flows
- Some MS can have (temporarly) allocated multiple timeslots
  - MAC + scheduling
• 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
• 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
• 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
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
Un. of Rome “La Sapienza”

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• **Objective:** overcome bandwidth/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

<table>
<thead>
<tr>
<th>Traffic class</th>
<th>Conversational class</th>
<th>Streaming class</th>
<th>Interactive class</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fundamental</td>
<td>Preserve time</td>
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<td>Request response</td>
<td>Destination is not expecting the</td>
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<tr>
<td>characteristics</td>
<td>relation between</td>
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<td>pattern</td>
<td>data within a certain time</td>
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</table>

| Example of the     | Voice, videotelephony,|
| application         | video games           |
|                     | Streaming multimedia  |
|                     | Web browsing, network games |
|                     | Background download of emails |
• Hierarchical organization: Macrocell → Microcell → Picocell
• 3G bandwidth: 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
• 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
• 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
• 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

Application
  IP
  PDCP
  RLC
  MAC
  L1

GTP-U GPRS Tunneling Protocol
UDP
PDCP Packet Data Convergence Protocol

RLS Radio Link Control
ATM Asynchronous Transfer Mode
AAL5 ATM Adaption Layer

Relay
  GTP - U
  RLC
  UDP / IP
  MAC
  AAL5
  L1
  ATM

Relay
  GTP - U
  UDP / IP
  AAL5
  L1 / L2

IP
GTP - U
UDP / IP
L1 / L2

UE
U'  
I'  
PS
SGSN
Gn
GGSN
Gi
• 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

sender

receiver

From Kurose Ross-Computer Networking
CDMA: two-sender interference

Chipping codes must be orthogonal

Other requirements such as the fact signals arrive with comparable power

 Receivers 1
Cellular systems: 4G


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• 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

Regulation and licences
ITU-R, FCC, regional regulators

Technology and standards

High cost of spectrum
Licences, spectrum almost completely allocated
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• GSM/GPRS/EDGE ← TDMA/FDMA based, designed for voice, extended for data

Specification through consensus in Working Groups part of Technical Specification Groups ← accounting for performance, implementation cost, complexity, backward compatibility
Project Co-ordination Group (PCG)

- TSG GERAN
  - GSM / EDGE
  - Radio Access Network
    - GERAN WG1
      - Radio Aspects
    - GERAN WG2
      - Protocol Aspects
    - GERAN WG3
      - Terminal Testing

- TSG RAN
  - Radio Access Network
    - RAN WG1
      - Radio Layer 1 (Physical Layer)
    - RAN WG2
      - Radio Layers 2 and 3
    - RAN WG3
      - RAN interfaces and O&M requirements
    - RAN WG4
      - Radio Performance and Protocol Aspects
    - RAN WG5
      - Mobile Terminal Conformance Tests

- TSG SA
  - Service and System Aspects
    - SA WG1
      - Services
    - SA WG2
      - Architecture
    - SA WG3
      - Security
    - SA WG4
      - Codes
    - SA WG5
      - Telecom Management

- TSG CT
  - Core Network (CN) and Terminals
    - CT WG1
      - Layer 3 protocols (Terminal – CN)
    - CT WG3
      - Interworking with external networks
    - CT WG4
      - Supplementary Services
    - CT WG5
      - Smart Card Application Aspects

Note: The GERAN working groups, maintaining and developing the GSM/EDGE specifications, were adopted later into 3GPP from ETSI.
- UMTS ← CDMA based, up to high frequency, MIMO, multiservice support
• 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
• 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
• The high-level network architecture of LTE is comprised of following three main components:
  – The User Equipment (UE).
  – The Evolved Packet Core (EPC).
E-UTRAN handles radio communication between the UE and EPC. It comprises only evolved base station, eNB or eNodeB.
E-UTRAN handles radio communication between the UE and EPC. It comprises only evolved base station, either eNB or eNodeB.
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

Network architecture

- Broadcasting of system information
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Cell selection based on cell priority
Second criterion: radio link quality
• 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
**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

- Flexible measurements configuration
- Event based reporting
- Periodic reporting
- Optimized to save energy
- 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: transports 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
• Standardized interfaces among network elements
• 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
• 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
  – \textit{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
  – \textit{persistent scheduling}: resources are semi-statically configured and allocated to a UE for a longer time period
• 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

User 1  User 2  User 3  User 4

Frequency

Time
• 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).
Brings to the home the QoS and high spectrum utilization features of LTE technology
• 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.