# Evolved Packet System: Introduction, Physical Layer, Scheduling, and Random Access Channel

Vahid Shah-Mansouri, Fall 1397
School of ECE, University of Tehran

# Reference

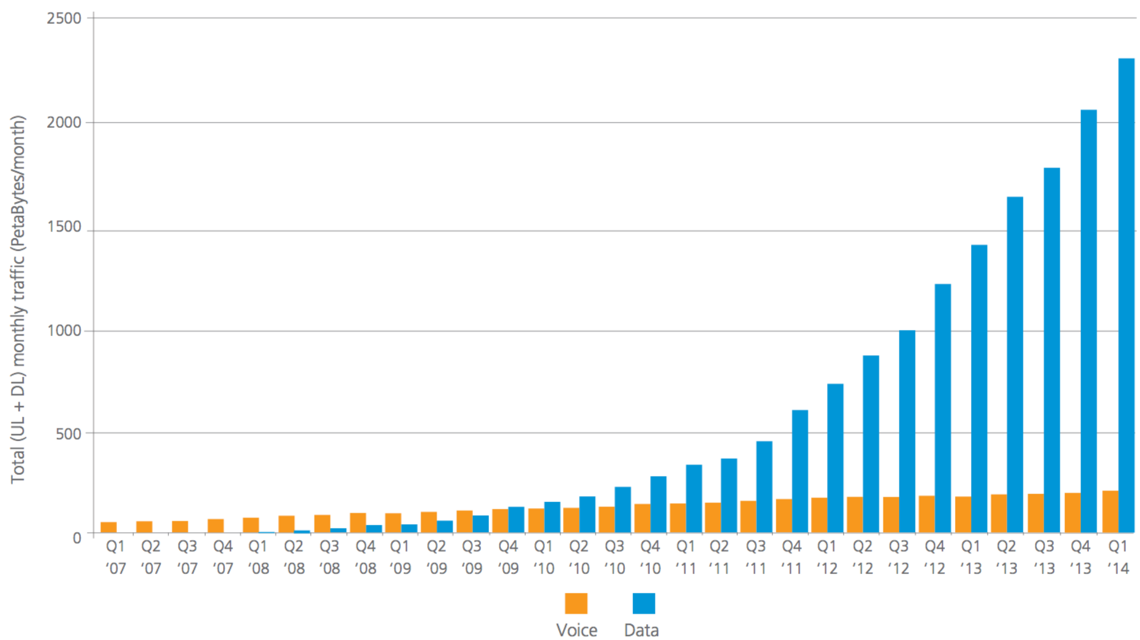
- S. Sesia, I. Toufik, and M. Baker, "LTE: The UMTS Long Term Evolution," 2nd Edition, John Wiley & Sons Ltd, 2011.

# Content

- Introduction to SAE
- LTE Physical Layer
- LTE Scheduling
- LTE Random Access Channel

# Why a New Generation?

- Data traffic is becoming dominant in cellular networks than voice traffic.
- Data is not native to 3G/2G; it is an addendum.
- UMTS core network is designed for circuit switched traffic.
- IP appears after GGSN.
- UTRAN can hardly reach beyond 40 Mbps.
- Goals for the first release of LTE was to reach 100 Mbps DL and 50Mbps uplink.



Total Monthly Mobile Voice and Data as Measured by Ericsson

# 3GPP Long Term Evolution

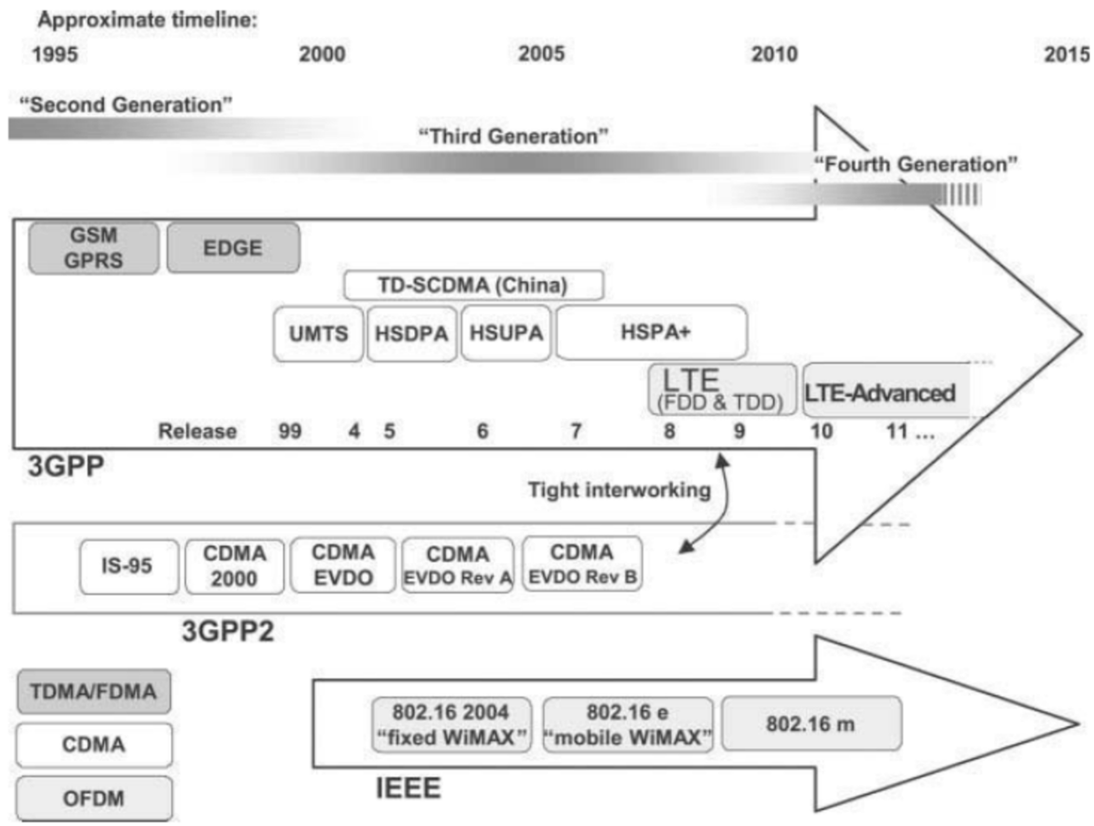
- LTE was designed from the scratch with the assumption that all services would be packet-switched !
- LTE is referred mainly to the access network evolution of UMTS.
- The non-radio aspects of the 3GPP 4G system is called System Architecture Evolution (SAE) which includes the Evolved Packet Core (EPC) network.
- Together, LTE and SAE comprise the Evolved Packet System (EPS), where both the core network and the radio access are fully packet-switched.

# LTE Access Link Goal

- High data rates
  - Downlink: >150 Mbps
  - Uplink: >50 Mbps
- Low delay/latency
  - User plane RTT: < 10 ms
  - Channel set-up: < 100 ms idle-to-active (fewer nodes, shorter messages, quicker node resp.)
- High spectral efficiency
- Spectrum flexibility
  - Operation in a wide-range of spectrum allocations, new and existing
  - Wide range of Bandwidth: 1.4, 1.6, 3.0/3.2, 5, 10, 15 and 20 MHz, FDD and TDD
- Simplicity – Less signaling, Auto Configuration
- Reduced OPEX and CAPEX
  - A key element for any operator is to reduce costs. It is therefore essential that any new design reduces both the capital expenditure (CAPEX) and the operational expenditure (OPEX).

# Standardization Roadmap

- Introduction of LTE did not stop enhancement of 3G by 3GPP.



# Performance Requirement Targets for LTE Release 8

| | | Absolute requirement | Release 6 (for comparison) | Comments |
|---|---|---|---|---|
| Downlink | Peak transmission rate | > 100 Mbps | 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 | 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 | 0.02 bps/Hz/user | 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 | 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 | 0.33 bps/Hz/cell | 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 | 0.01 bps/Hz/user | As above, 10 users assumed per cell |
| | | | | |
| System | User plane latency (two way radio delay) | < 10 ms | | LTE target approximately one fifth of Reference. |
| | 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 | | |

# Operating Bands

Table 1. FDD and TDD defined in 3GPP (April 2011).[5]

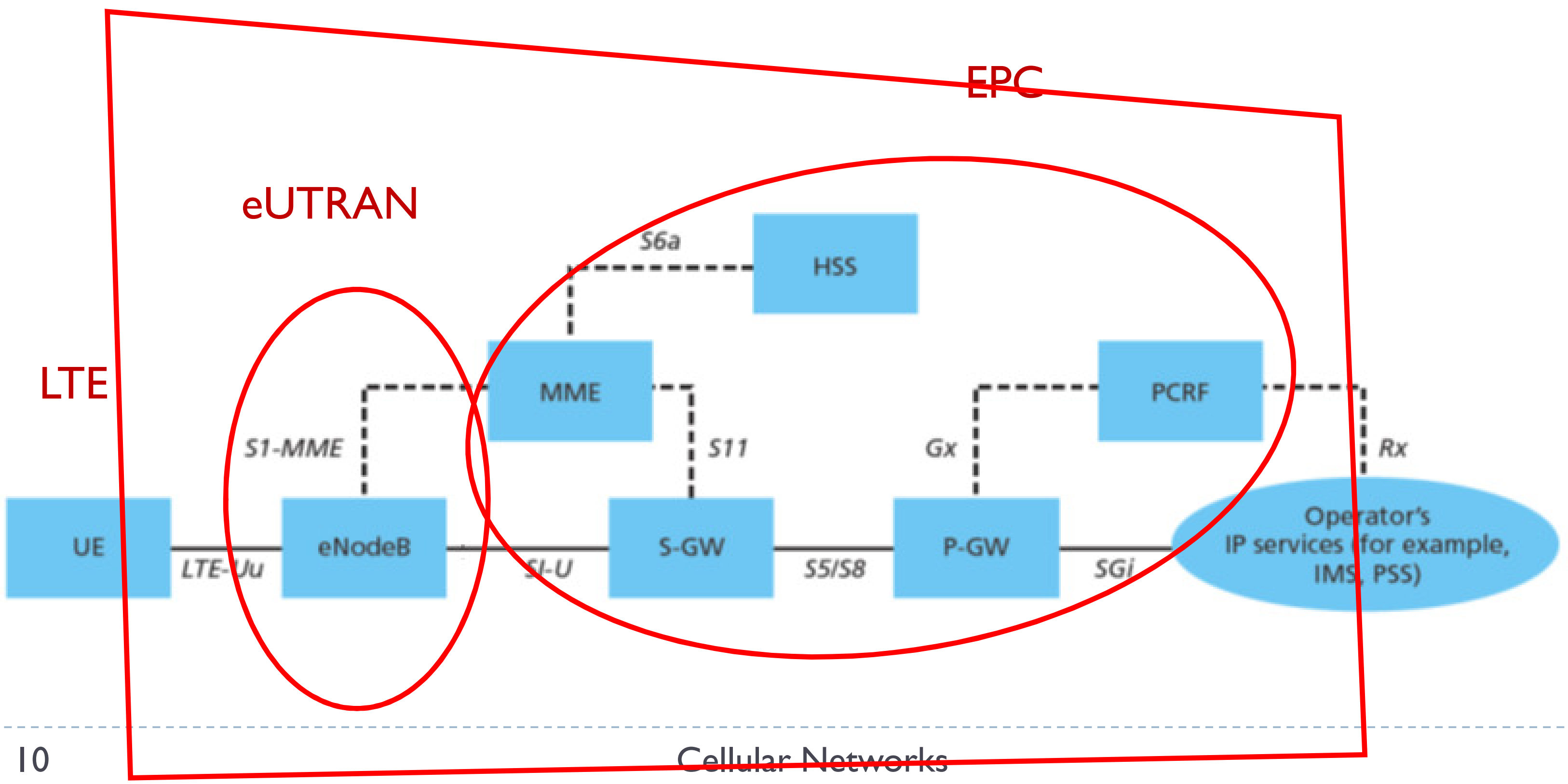
| E UTRA Operating Band | Uplink (UL) Operating Band | Downlink (DL) Operating Band | Duplex Mode |
|---|---|---|---|
| 1 | 1920 MHz – 1980 MHz | 2110 MHz – 2170 MHz | FDD |
| 2 | 1850 MHz – 1910 MHz | 1930 MHz – 1990 MHz | FDD |
| 3 | 1710 MHz – 1785 MHz | 1805 MHz – 1880 MHz | FDD |
| 4 | 1710 MHz – 1755 MHz | 2110 MHz – 2155 MHz | FDD |
| 5 | 824 MHz – 849 MHz | 869 MHz – 894MHz | FDD |
| 6[1] | 830 MHz – 840 MHz | 875 MHz – 885 MHz | FDD |
| 7 | 2500 MHz – 2570 MHz | 2620 MHz – 2690 MHz | FDD |
| 8 | 880 MHz – 915 MHz | 925 MHz – 960 MHz | FDD |
| 9 | 1749.9 MHz – 1784.9 MHz | 1844.9 MHz – 1879.9 MHz | FDD |
| 10 | 1710 MHz – 1770 MHz | 2110 MHz – 2170 MHz | FDD |
| 11 | 1427.9 MHz – 1447.9 MHz | 1475.9 MHz – 1495.9 MHz | FDD |
| 12 | 699 MHz – 716 MHz | 729 MHz – 746 MHz | FDD |
| 13 | 777 MHz – 787 MHz | 746 MHz – 756 MHz | FDD |
| 14 | 788 MHz – 798 MHz | 758 MHz – 768 MHz | FDD |
| 15 | Reserved | Reserved | |
| 16 | Reserved | Reserved | |
| 17 | 704 MHz – 716 MHz | 734 MHz – 746 MHz | FDD |
| 18 | 815 MHz – 830 MHz | 860 MHz – 875 MHz | FDD |

| E UTRA Operating Band | Uplink (UL) Operating Band | Downlink (DL) Operating Band | Duplex Mode |
|---|---|---|---|
| 19 | 830 MHz – 845 MHz | 875 MHz – 890 MHz | FDD |
| 20 | 832 MHz – 862 MHz | 791 MHz – 821 MHz | FDD |
| 21 | 1447.9 MHz – 1462.9 MHz | 1495.9 MHz – 1510.9 MHz | FDD |
| ... | | | |
| 24 | 1626.5 MHz – 1660.5 MHz | 1525 MHz – 1559 MHz | FDD |
| ... | | | |
| 33 | 1900 MHz – 1920 MHz | 1900 MHz – 1920 MHz | TDD |
| 34 | 2010 MHz – 2025 MHz | 2010 MHz – 2025 MHz | TDD |
| 35 | 1850 MHz – 1910 MHz | 1850 MHz – 1910 MHz | TDD |
| 36 | 1930 MHz – 1990 MHz | 1930 MHz – 1990 MHz | TDD |
| 37 | 1910 MHz – 1930 MHz | 1910 MHz – 1930 MHz | TDD |
| 38 | 2570 MHz – 2620 MHz | 2570 MHz – 2620 MHz | TDD |
| 39 | 1880 MHz – 1920 MHz | 1880 MHz – 1920 MHz | TDD |
| 40 | 2300 MHz – 2400 MHz | 2300 MHz – 2400 MHz | TDD |
| 41 | 2496 MHz – 2690 MHz | 2496 MHz – 2690 MHz | TDD |
| 42 | 3400 MHz – 3600 MHz | 3400 MHz – 3600 MHz | TDD |
| 43 | 3600 MHz – 3800 MHz | 3600 MHz – 3800 MHz | TDD |

Note 1: Band 6 is not applicable.

# EPS Overall Architecture

- EPS provides the user with IP connectivity to a packet data network (PDN) for accessing the Internet, as well as for running services such as VoIP.

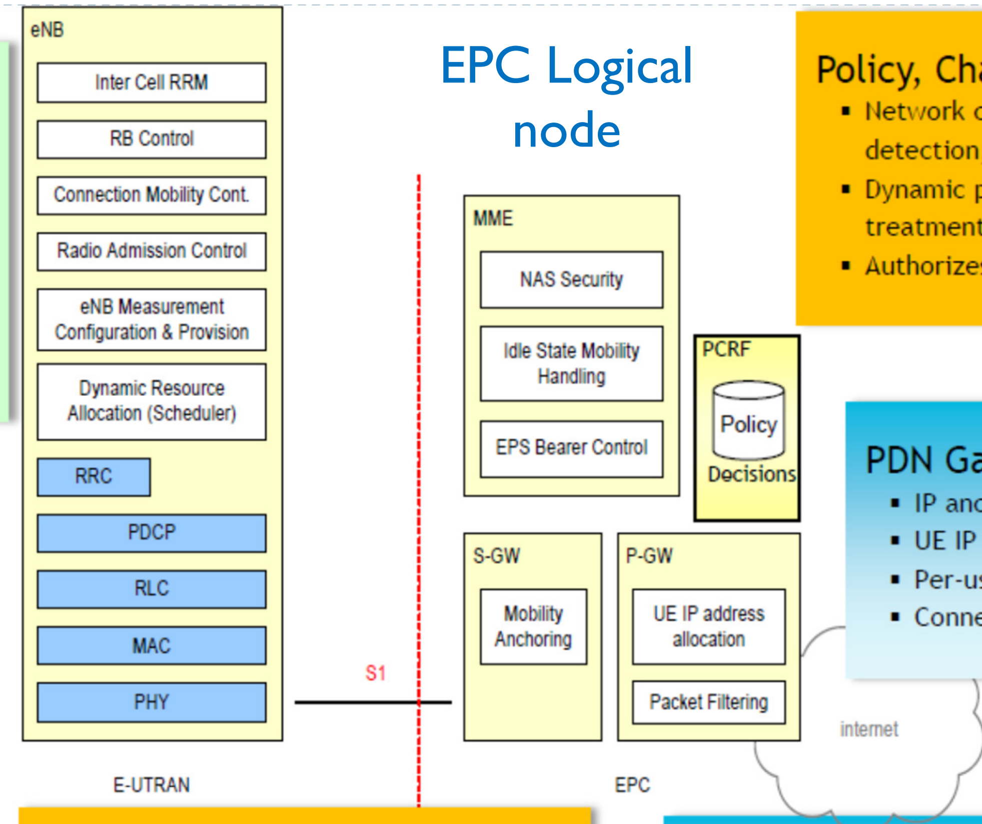


# EPC-eUTRAN Functionalities

**eNodeB:**
**all radio access functions**
- Radio admission control
- Scheduling of UL and DL data
- Scheduling and transmission of paging and system broadcast
- IP header compression (PDCP)
- Outer-ARQ (RLC)

eUTRAN
Logical node

EPC Logical node



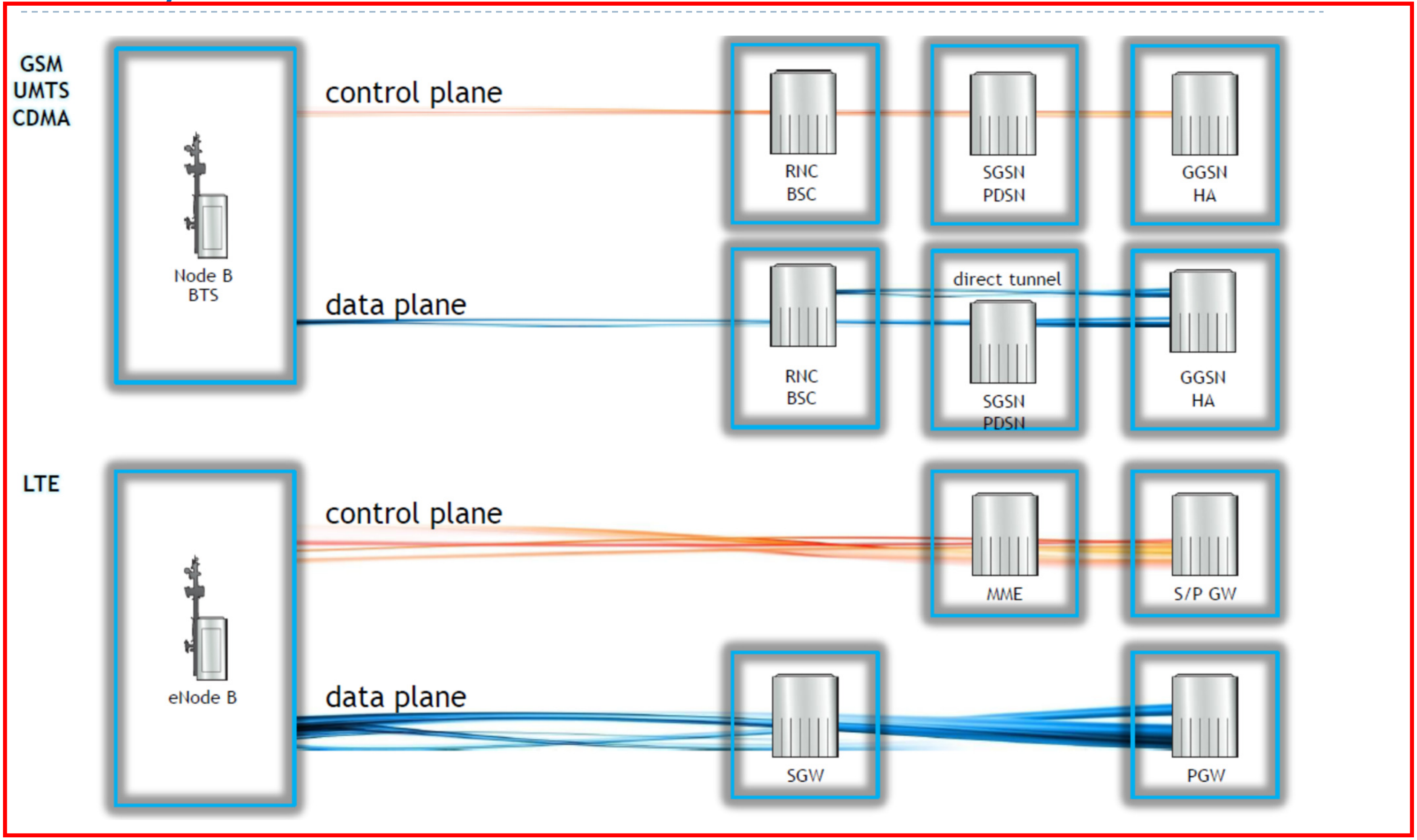

## Policy, Charging & Rules Function
- Network control of Service Data Flow (SDF) detection, gating, QoS & flow based charging
- Dynamic policy decision on service data flow treatment in the PCEF (xGW)
- Authorizes QoS resources

## PDN Gateway
- IP anchor point for bearers
- UE IP address allocation
- Per-user based packet filtering
- Connectivity to packet data network

## Mobility Management Entity
- Authentication
- Tracking area list management
- Idle mode UE reachability
- S-GW/PDN-GW selection
- Inter core network node signaling for mobility between 2G/3G and LTE
- Bearer management functions

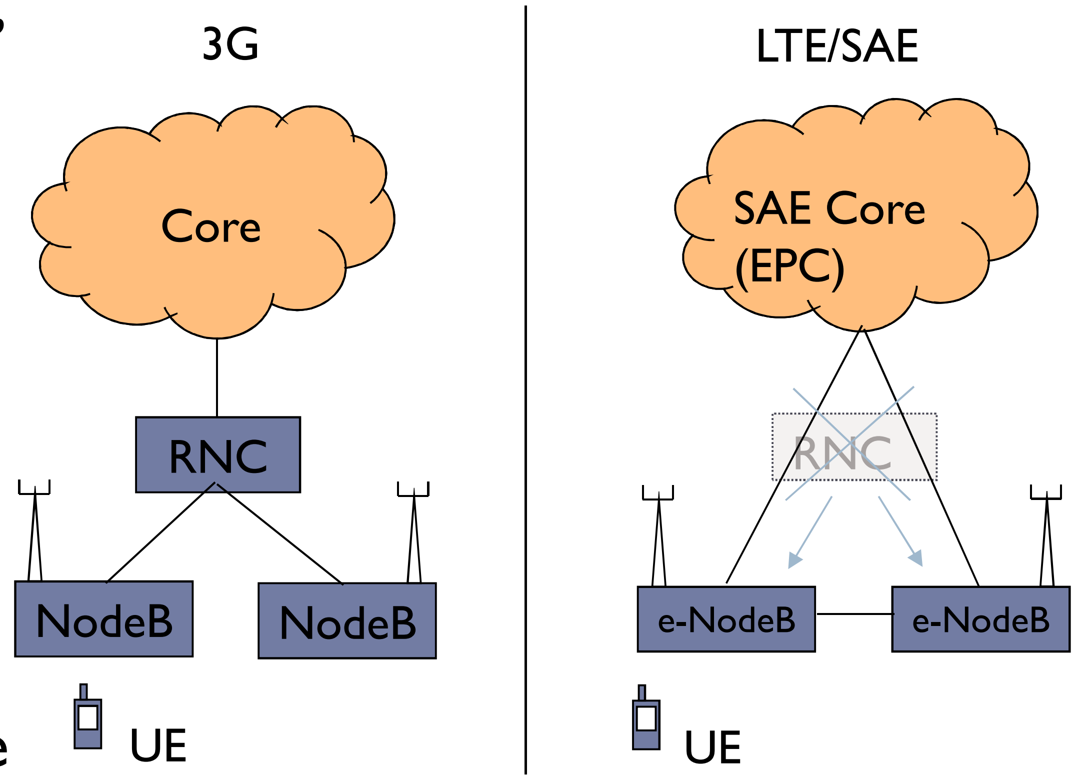
## Serving Gateway
- Local mobility anchor for inter-eNB handovers
- Mobility anchoring for inter-3GPP handovers
- Idle mode DL packet buffering
- Lawful interception
- Packet routing and forwarding

# LTE/EPC versus UMTS



# Evolved UTRAN

- The access network of LTE, E-UTRAN, simply consists of a network of eNodeBs.
- Therefore, there is no centralized radio resource management element like the RNC.
- RNC tasks are pushed to eNodeB or MME/SGW.
- The E-UTRAN architecture is said to be flat.



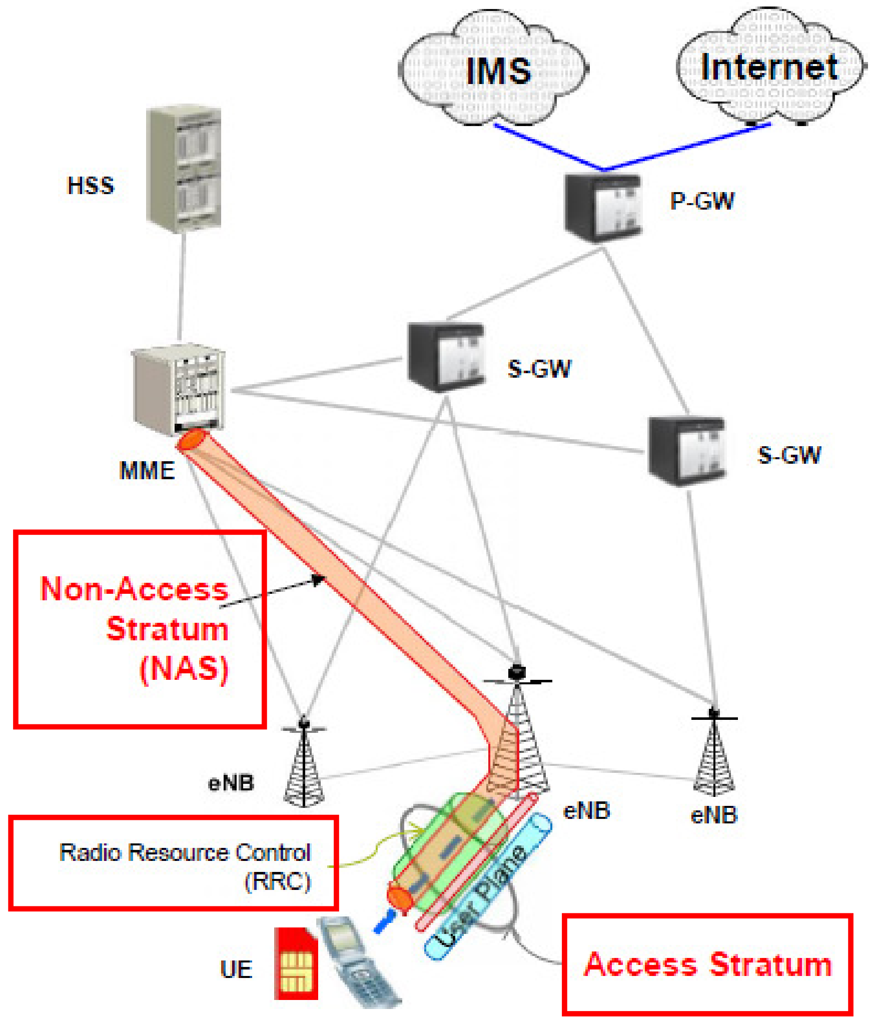
# Evolved UTRAN

- The eNodeBs are normally inter-connected with each other by means of an interface known as X2.
- eNBs are connected to the EPC by means of the S1 interface
  - To the MME by means of the S1-MME interface and
  - To the S-GW by means of the S1-U interface.
- The protocols which run between the eNBs and the UE are known as the Access Stratum (AS) protocols.

- The E-UTRAN is responsible for radio-related functions:
  - Radio Resource Management: This covers all functions related to the radio bearers such as radio bearer control, radio admission control, radio mobility control, scheduling and dynamic allocation of resources.
  - Header Compression
  - Security
  - Positioning: The E-UTRAN provides the necessary measurements and other data to the E-SMLC and assists the E-SMLC in finding the UE position.

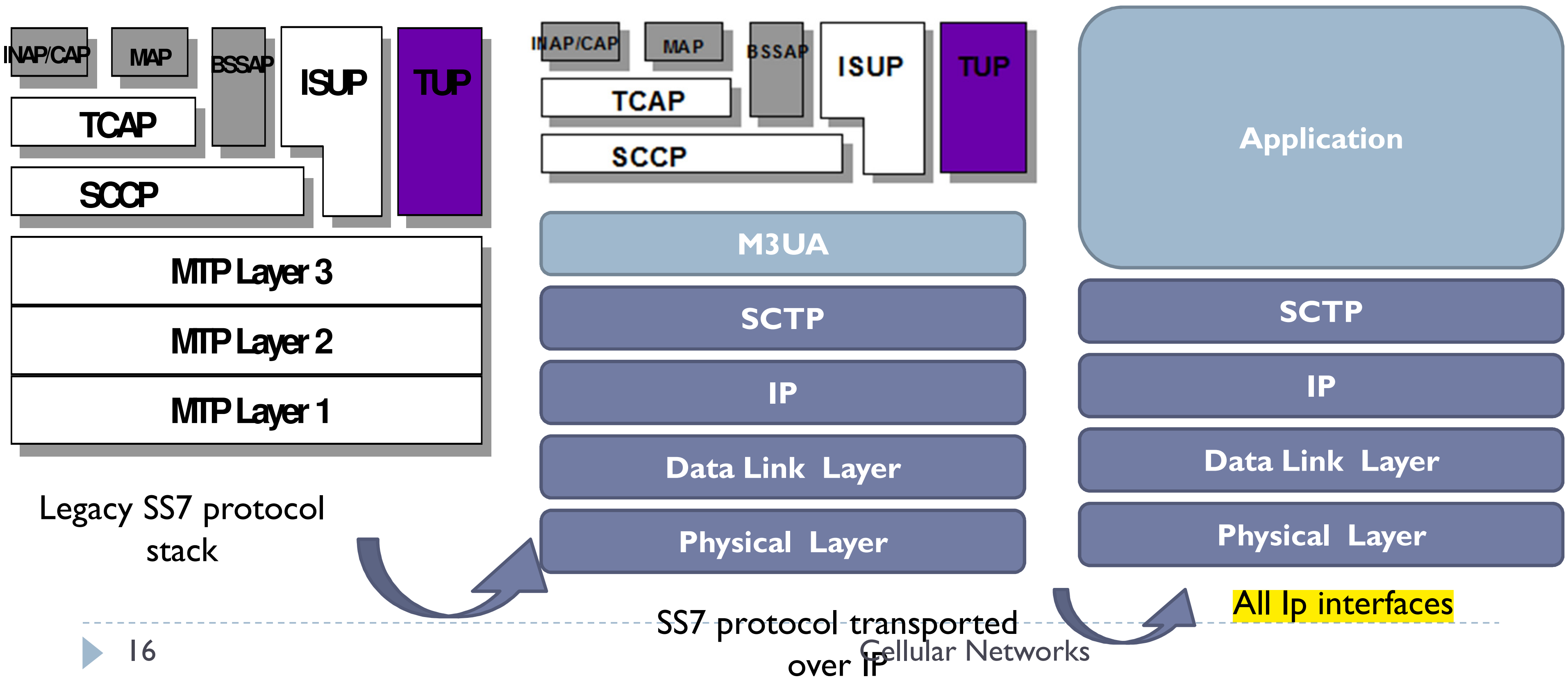
# Access Stratum vs Non-Access Stratum

- On the signaling plane, the UE communicates with two entities in the infrastructure:
  - the eNB and
  - the MME (via the eNB).
- Access-stratum (AS):
  - UE <-> eNB.
  - AS consists of both user plane and control-plane.
  - The user-plane protocol is PDCP and control-plane protocol is RRC.
- Non-access Stratum (NAS):
  - UE <-> MME.
  - NAS is only in the control plane.
  - The protocol is called the NAS protocol.

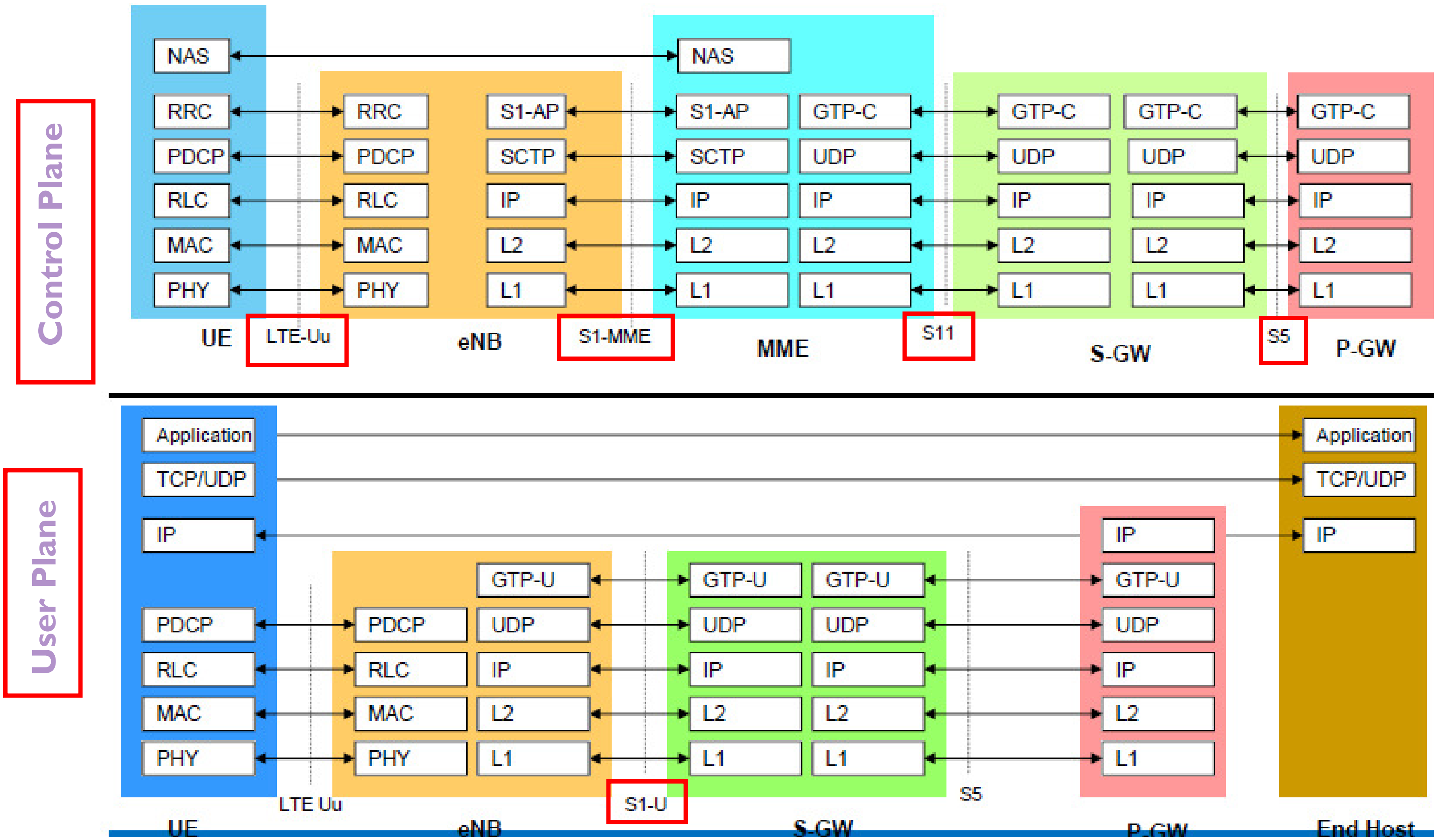


# All-IP Operation

- In 2G and 3G networks, legacy SS7 protocol stack is the main player.
- For voice traffic in GPRS and 3G, SS7 is used over IP.
- In 4G, all traffic is transported over IP.

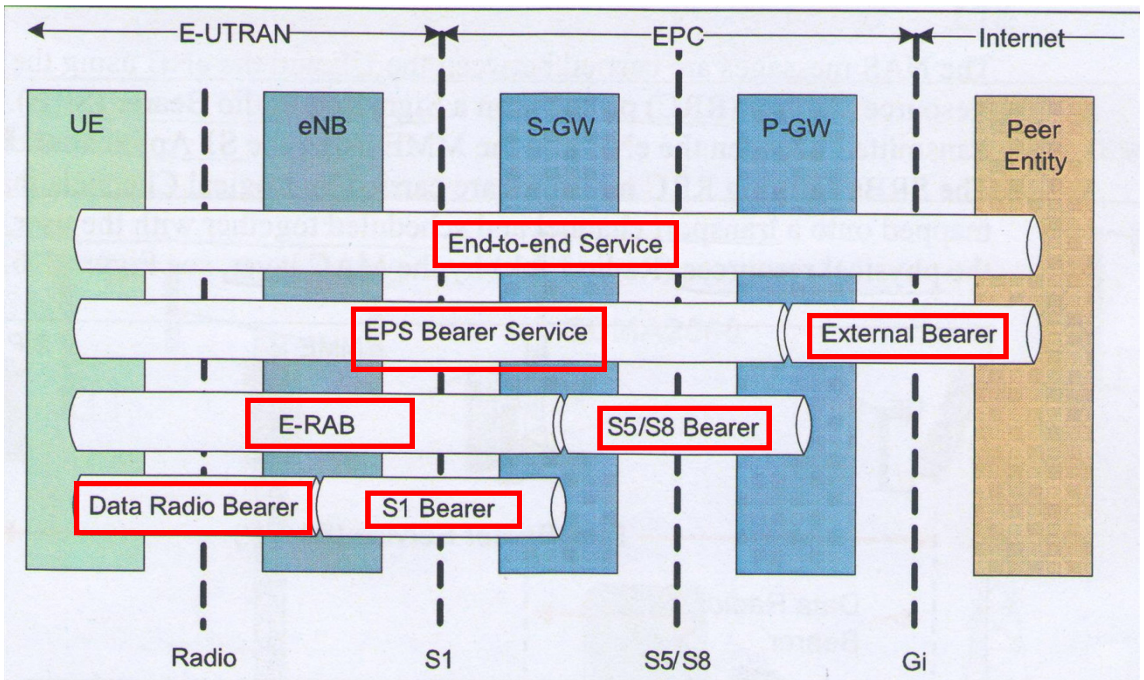


# All-IP Operation



# SAE QoS Provisioning

- SAE bearer is the connection between the UE and the core network edge node (PDN-GW).
- Each bearer carries end-to-end services and is associated with a QoS.




User Plane Bearer Service

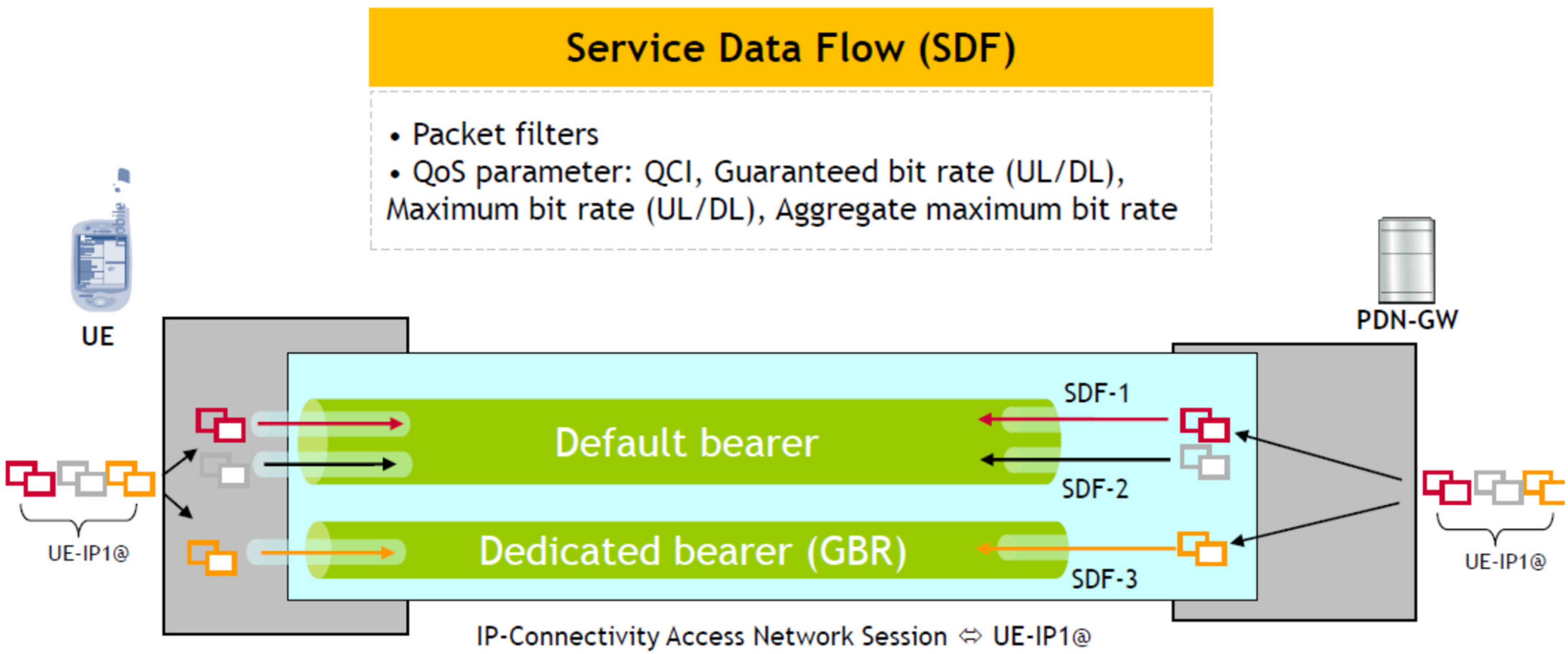
# SAE QoS Provisioning

- Service Data Flow (SDF) = IP flow
- SDFs are mapped to bearers by IP routing elements (gateways)
- Each bearer (SDF) is recognized by following parameters:
  - QoS Class Identifier (QCI)
    - A scalar that is used as a reference to node specific parameters that control packet forwarding treatment (e.g., scheduling weights, admission thresholds, queue management thresholds, link layer protocol configuration, etc.), and that have been pre-configured by the operator owning the access node.
  - Allocation and Retention Priority (ARP)
    - The primary purpose or ARP is to decide if a bearer establishment/modification request can be accepted or rejected in case or resource limitation
  - Guaranteed Bit Rate (GBR)
  - Maximum Bit Rate (MBR)
  - Aggregate Maximum Bit Rate (AMBR) (for non-GBR bearers)

# SAE QoS Provisioning

| QCI | Resource Type | Priority | Packet Delay Budget | Packet Error Loss Rate | Example Services |
|---|---|---|---|---|---|
| 1 | Guaranteed Bit Rate (GBR) | 2 | 100 ms | $10^{-2}$ | Conversational voice |
| 2 | | 4 | 150 ms | $10^{-3}$ | Conversational video (live streaming) |
| 3 | | 3 | 50 ms | $10^{-3}$ | Real-time gaming |
| 4 | | 5 | 300 ms | $10^{-6}$ | Non-conversational video (buffered streaming) |
| 5 | Non-GBR | 1 | 100 ms | $10^{-6}$ | IMS signalling |
| 6 | | 6 | 300 ms | $10^{-6}$ | Video (buffered streaming) TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc.) |
| 7 | | 7 | 100 ms | $10^{-3}$ | Voice, video (live streaming), interactive gaming |
| 8 | | 8 | 300 ms | 10-6 | "Premium bearer" for video (buffered streaming), TCP-based (e.g., www, e-mail, chat, ftp, p2p file sharing, progressive video, etc) for premium subscribers |
| 9 | | 9 | 300 ms | 10-6 | "Default bearer" for video, TCP-based services, etc. for non-privileged subscribers |

# SAE QoS Provisioning



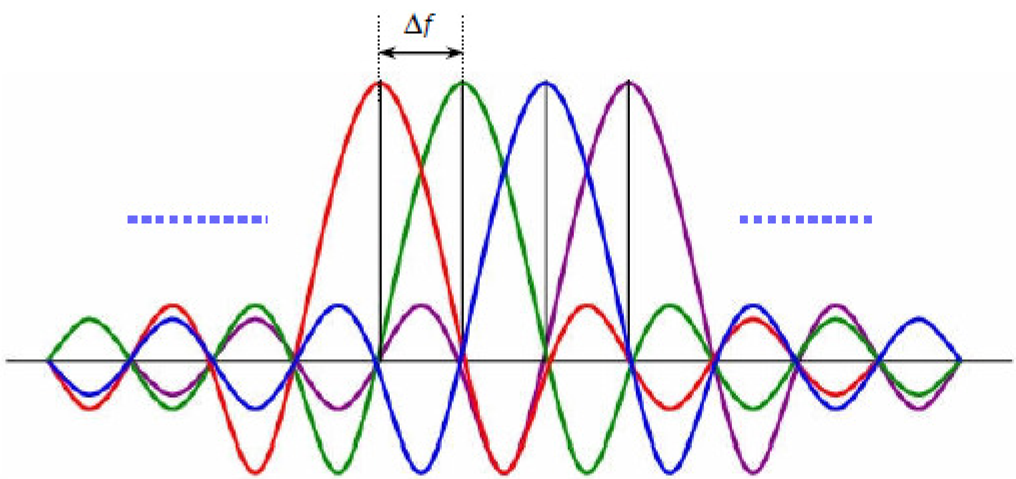
# LTE Physical Layer

# LTE PHY Key Features

- The design of the LTE physical layer (PHY) is heavily influenced by the requirements for high peak transmission rate (100 Mbps DL/50 Mbps UL) and multiple channel bandwidths (1.25-20 MHz).
  - Multiple access scheme
    - DL: OFDMA with CP (Cyclic Prefix)
    - UL: Single Carrier FDMA (SC-FDMA) with CP
  - Adaptive modulation and coding
    - DL/UL modulations: QPSK, 16QAM, and 64QAM
    - Convolutional code and Rel-6 turbo code
  - Advanced MIMO spatial multiplexing techniques
    - (2 or 4)x(2 or 4) downlink and uplink supported
  - Support for both FDD and TDD

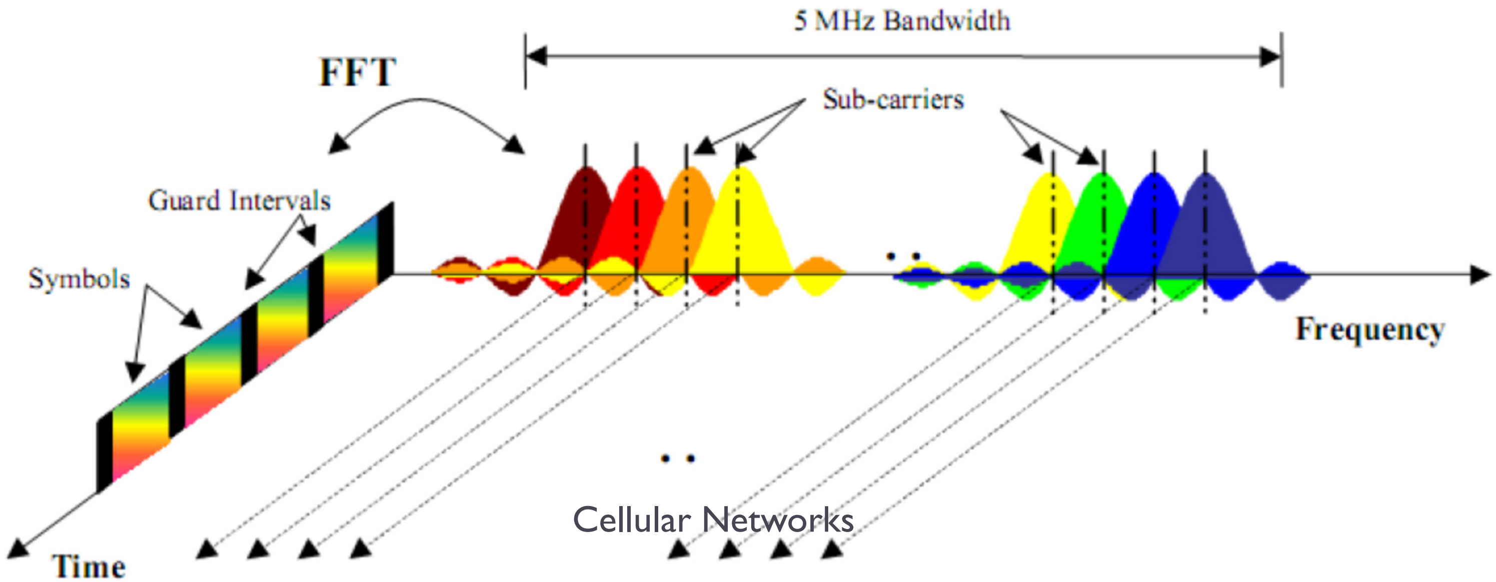
# OFDM

- The OFDM technology is based on using multiple narrow band sub-carriers spread over a wide channel bandwidth.
- The sub-carriers are mutually orthogonal in the frequency domain which mitigates inter-symbol interference (ISI).
- Each of these sub-carriers experiences ‘flat fading’.
- This obviates the need for complex frequency equalizers which are featured in 2G/3G technologies.



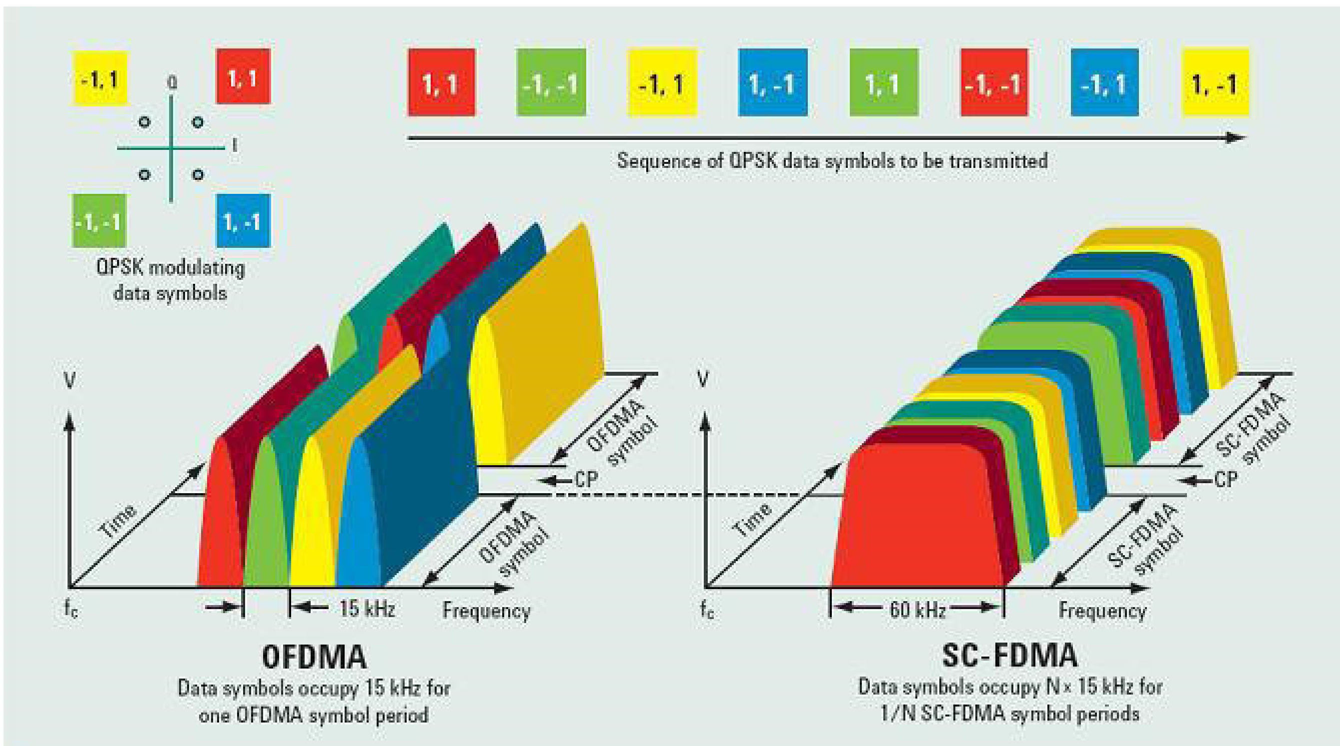
# OFDM Generation

- The information data stream is parallelized and spread across the sub-carriers for transmission.
- The process of modulating data symbols and combining them is equivalent to an Inverse Fourier Transform operation (IFFT).
- In the receiver, the reverse operation is applied to the OFDM symbol to retrieve the data stream – which is equivalent to a Fast Fourier Transform operation (FFT).



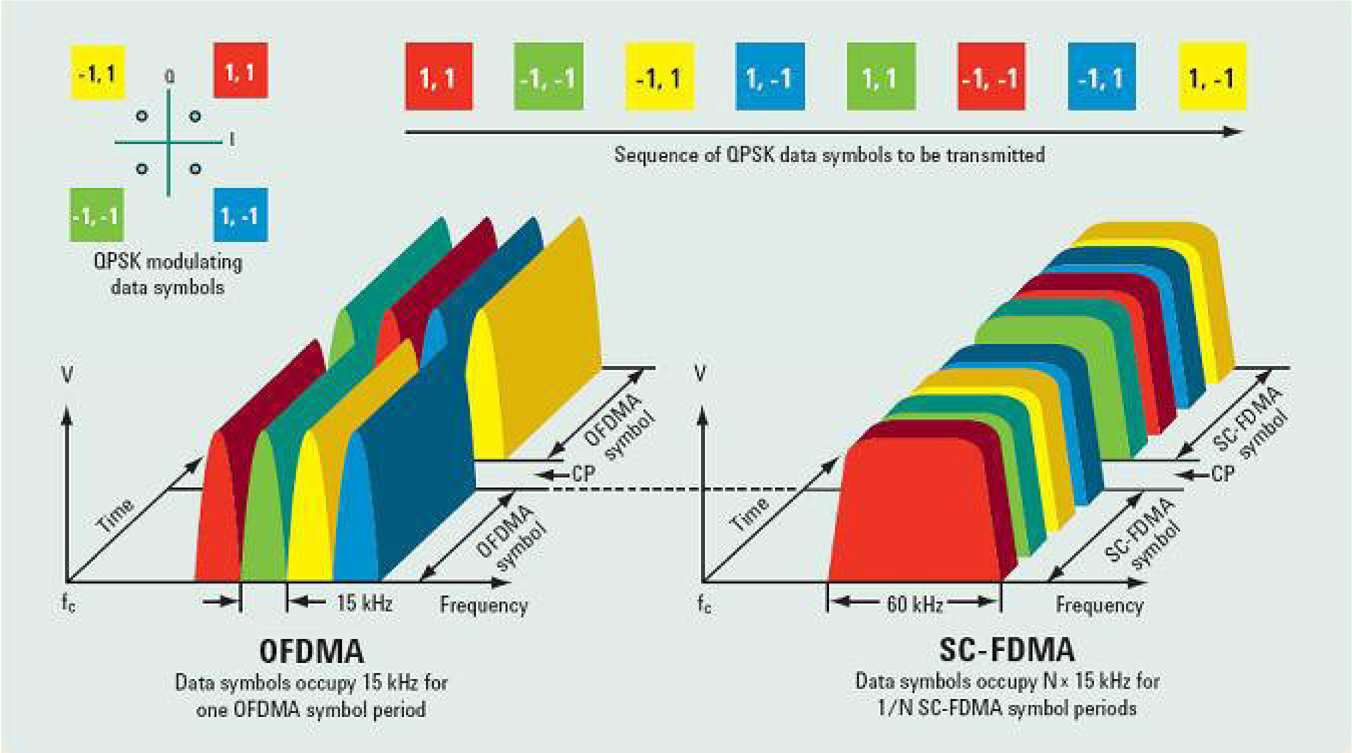
# OFDMA

- The downlink physical layer of LTE is based on OFDMA.
- Multiple access is achieved in OFDMA by assigning subsets of subcarriers to individual users

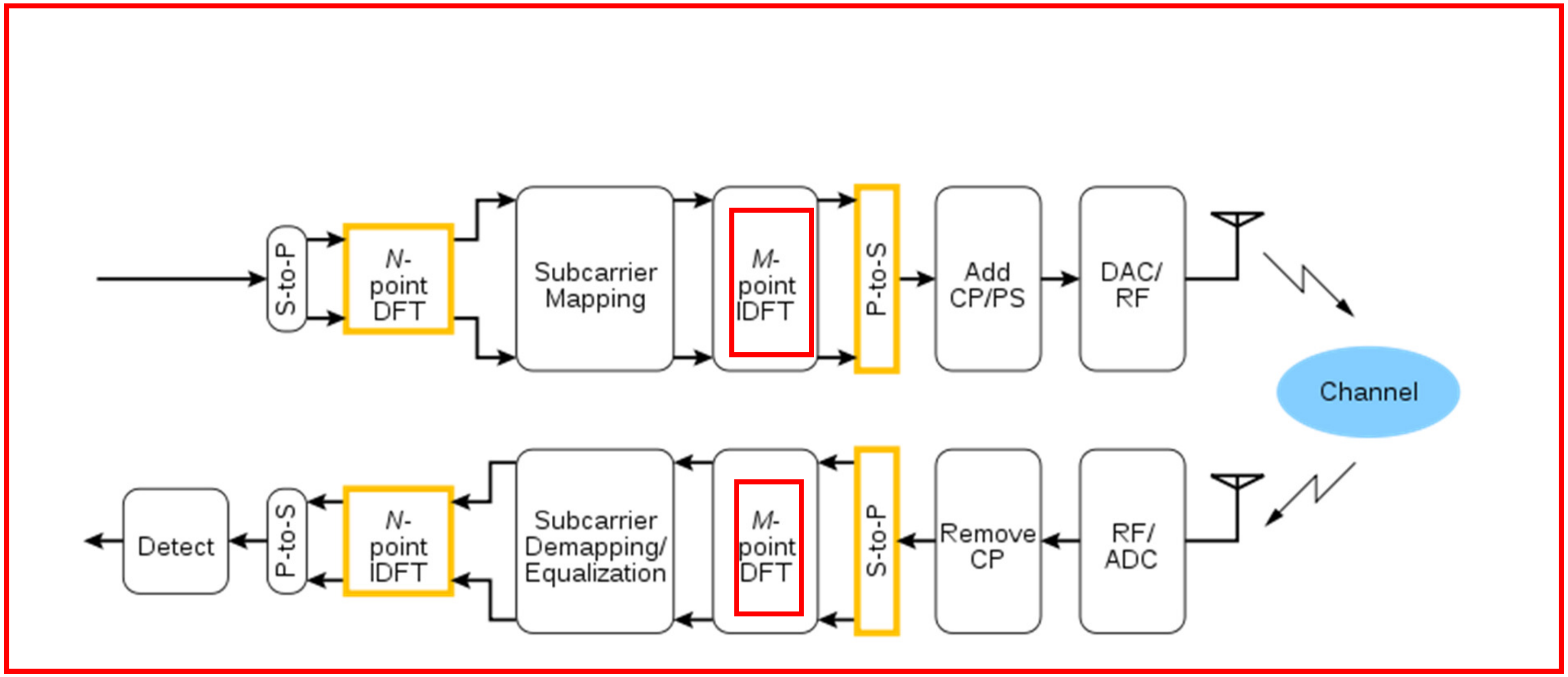


# OFDM

- OFDMA has certain drawbacks
  - High sensitivity to frequency offset
  - High peak-to-average power ratio (PAPR).
- Single carrier FDMA is the solution for uplink.



# OFDMA – SC-FDMA



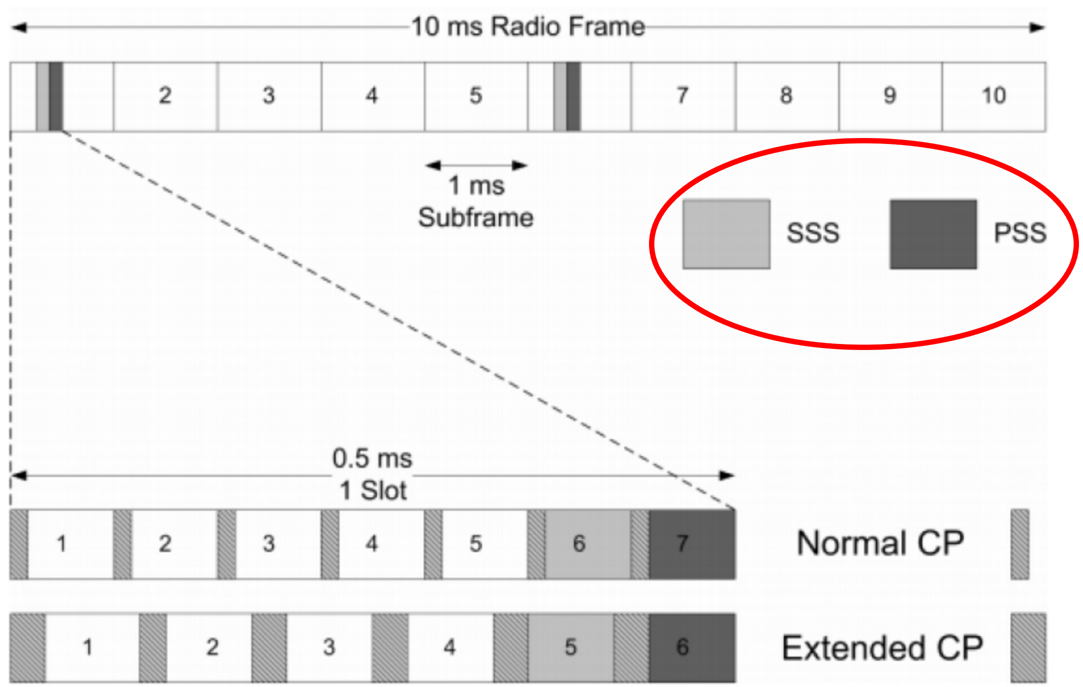

* $N < M$
* S-to-P: Serial-to-Parallel
* P-to-S: Parallel-to-Serial

**SC-FDMA:** ▢ + ▢

**OFDMA:** ▢

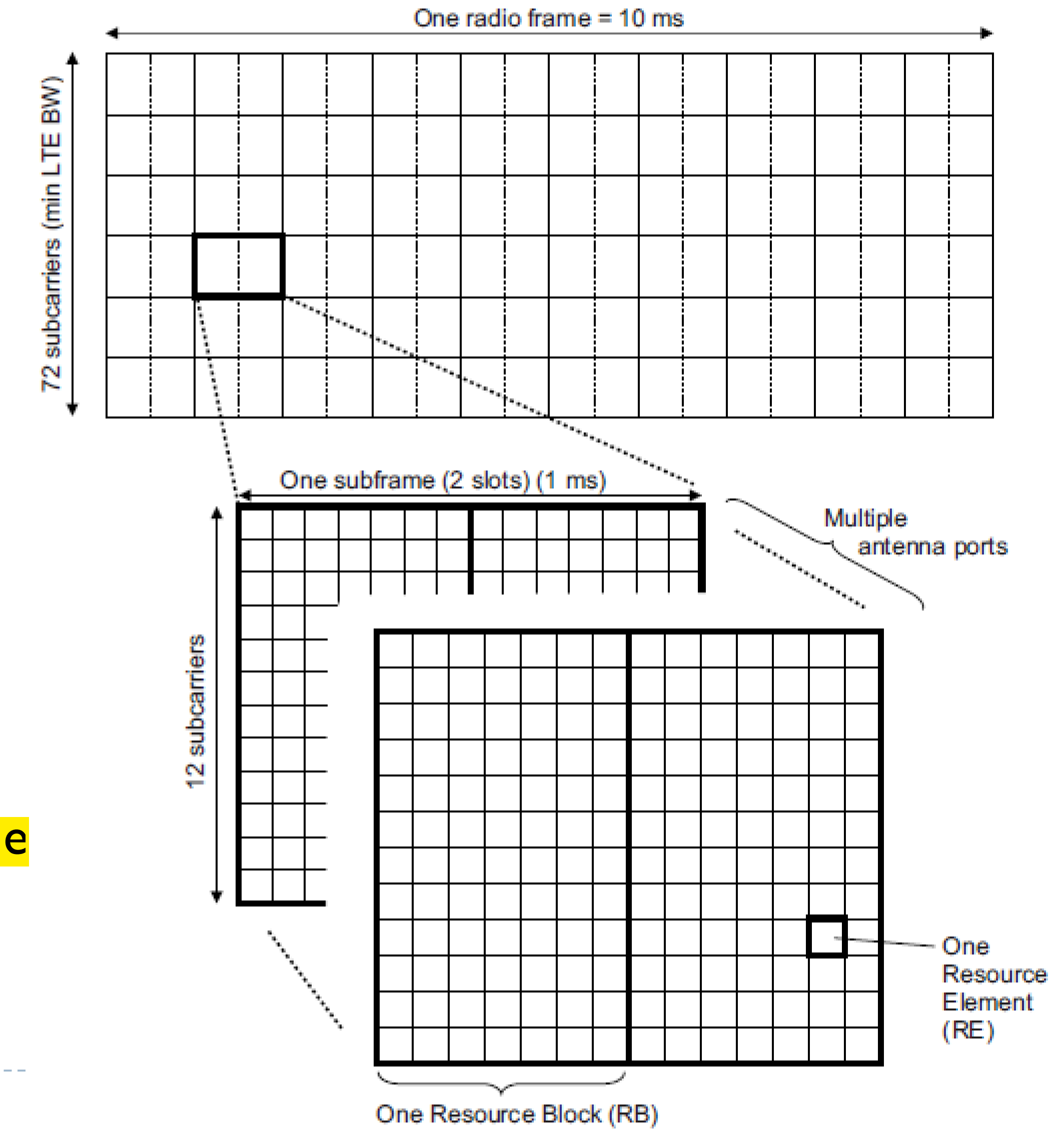
# Frame Structure

- The radio frame in LTE has a length of 10 ms.
- Each frame is divided into 10 equally sized subframes of 1 ms.
- Each subframe consists of two equally sized slots of 0.5 ms.
- Each slot consists of a number of OFDM symbols which can be either seven (normal cyclic prefix) or six (extended cyclic prefix).

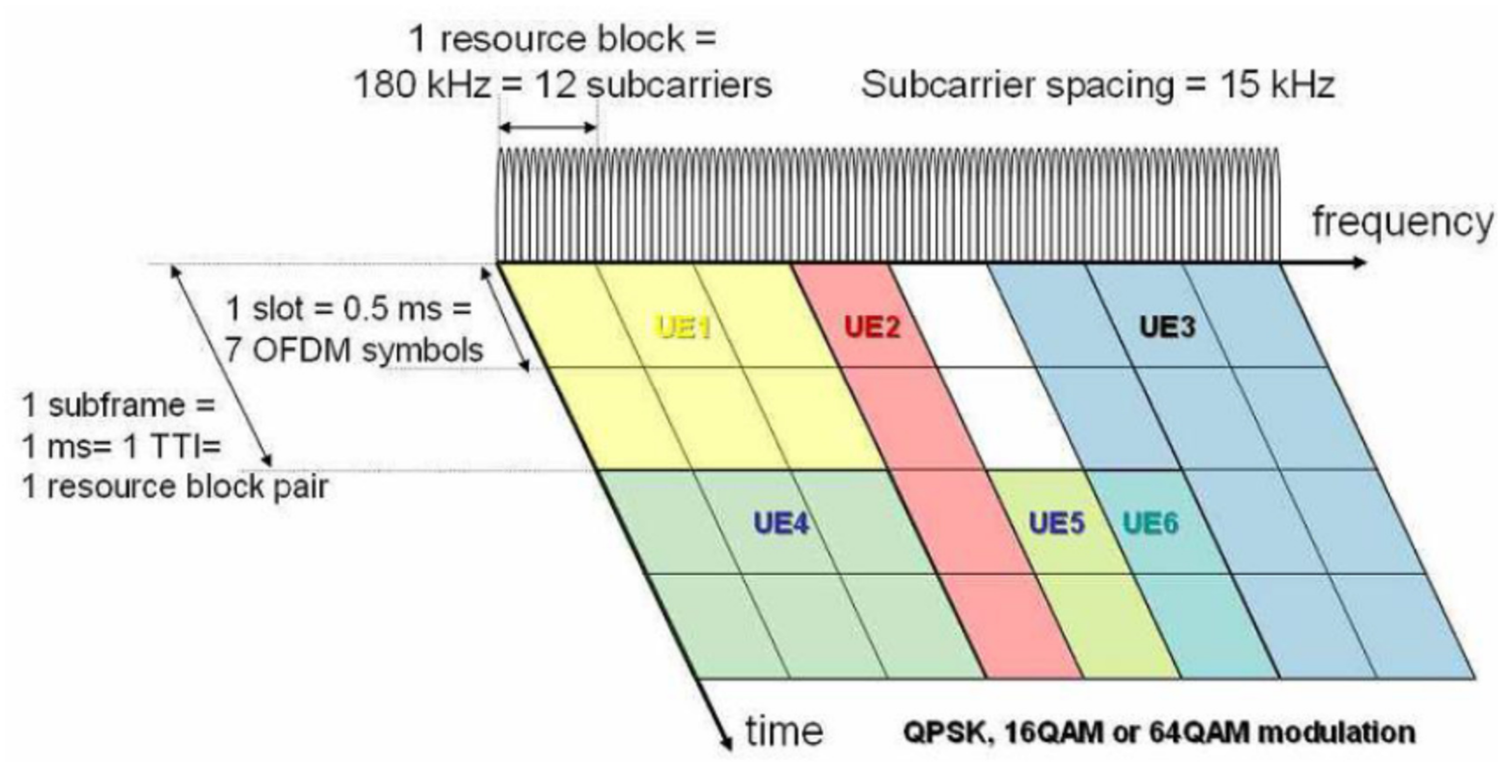


# Resource Block and Element

- The sub-carrier frequency spacing is 15 KHz.
- The minimum LTE bandwidth consists of 72 subcarriers (1.08 MHz).
- One symbol transmission in one subcarrier is called resource element (RE).
- 12 subcarriers (180Khz) in one time slot builds a resource block (RB).
- Scheduling is done on a subframe (RB pair) basis for both the downlink and uplink.



# OFDMA Time-Frequency Multiplexing



# LTE Scheduling

# Scheduling in LTE

- The core of the LTE transmission scheme is the use of shared-channel transmission with the overall time–frequency resource dynamically shared between users.
- The scheduler controls, for each time instant, to which users the different parts of the shared resource should be assigned.
- To support downlink scheduling, a terminal may provide the network with channel-state reports indicating the instantaneous downlink channel quality in both the time and frequency domains.

# Scheduling in LTE

- The goal of a resource scheduling algorithm in the eNodeB is to allocate the RBs and transmission powers for each subframe in order to optimize a function of a set of performance metrics:
  - example maximum / minimum / average throughput, maximum / minimum / average delay, total/per-user spectral efficiency or outage probability.
- In the downlink, the resource allocation strategy is constrained by the total transmission power of the eNodeB.
- In the uplink, the main constraints on transmission power in different RBs arises from a multicell view of inter-cell interference and the power headroom of the UEs.

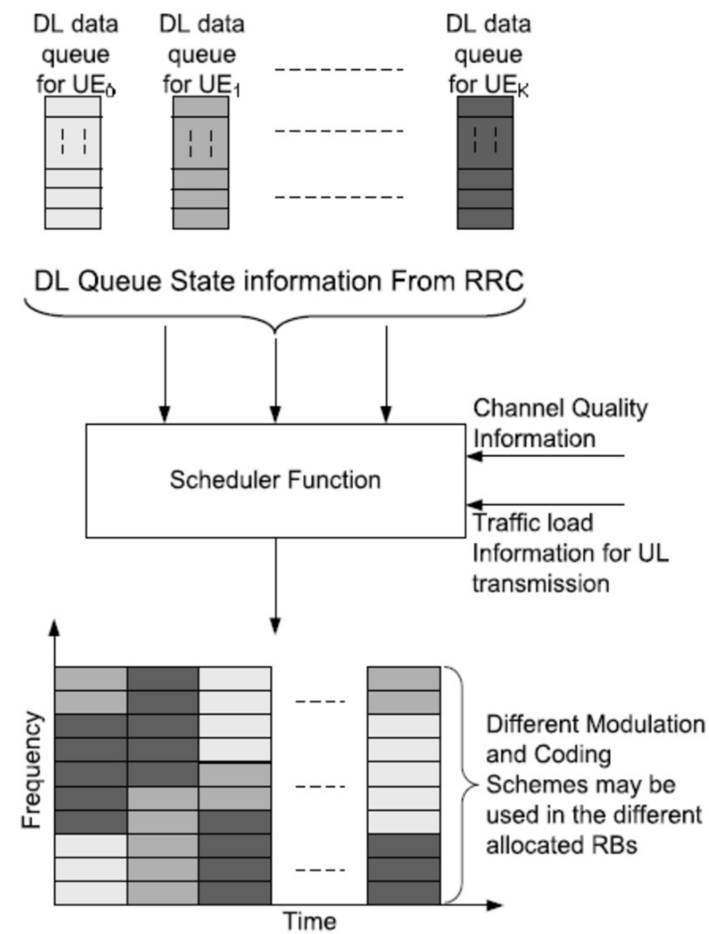
# Scheduling in LTE

- **Dynamic Scheduling**
  - Suitable for bursty traffic.
  - eNB allocates downlink/uplink radio resources to the UE using resource allocation information called **downlink/uplink assignment**
  - The down-link assignment and the uplink grant are signalled separately to the UE through the Physical Downlink Control CHannel (PDCCH), masked with the UE's C-RNTI.

- **Semi-Persistent Scheduling (SPS)**
  - a VoIP service periodically generates many small-sized packets at short intervals.
  - reducing the number of the downlink assignment and the uplink grant is required to increase the number of supportable simultaneous VoIP calls in a cell
  - SPS is used to allocate radio resources for a long time period with a minimized load on the PDCCH.

# Scheduling in LTE

- Scheduling algorithms can make use of two types of measurement information to inform the scheduling decisions:
  - Channel State Information (CSI)
  - Traffic measurements (volume and priority).
  - Power headroom



# Channel Quality Indicators (CQI)

- CQI is measured by the UE and eNB to measure the quality for scheduling.
- For this purpose, reference signals are transmitted via the eNB (CQI reference resource).
- Reference signals are transmitted with specific power, modulation, and coding schemes.
- The type of modulations, coding and transmit power are introduced in SIB2.
- Reference signals are transmitted on various RBs.

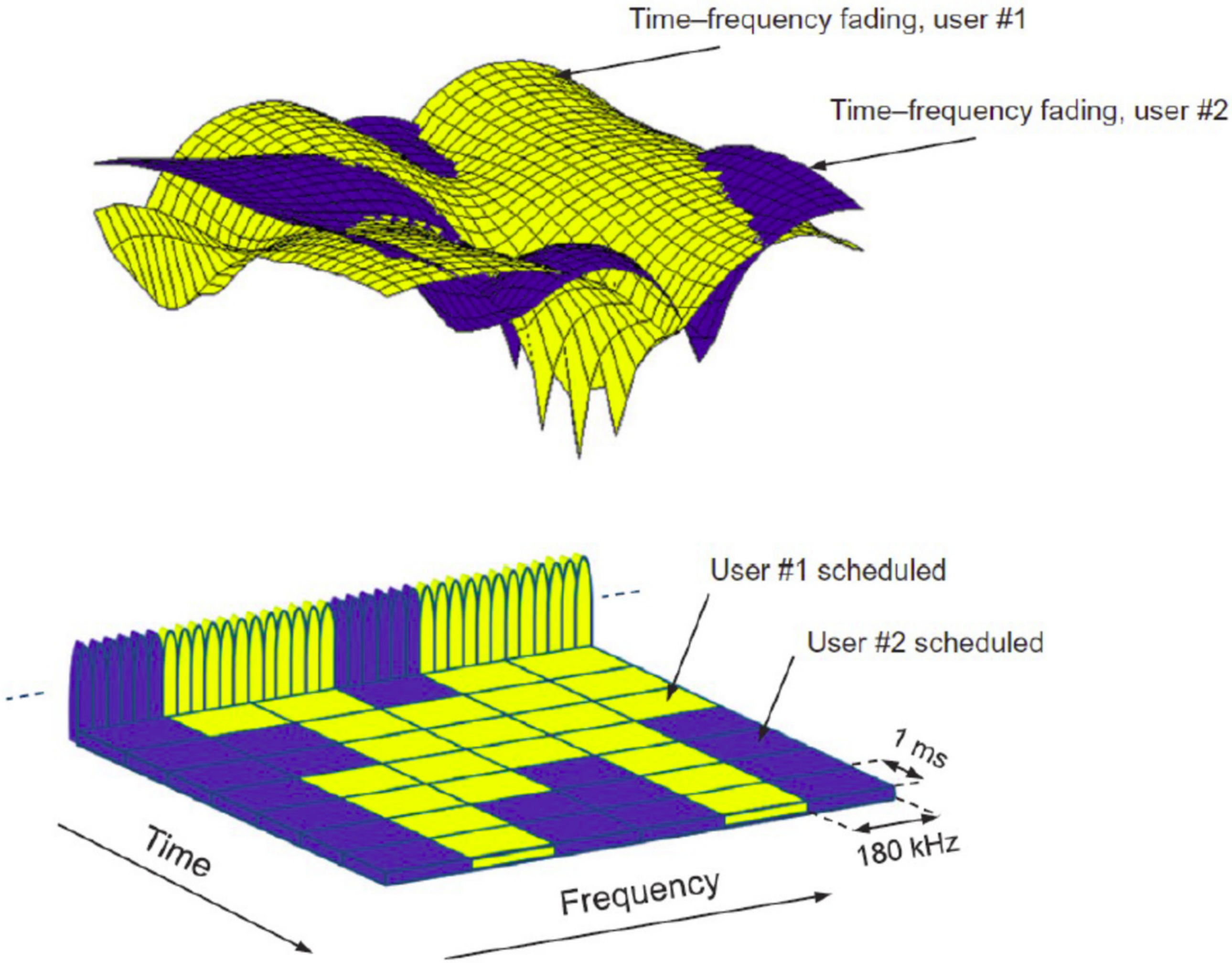
# CQI Reporting

- CQI ie reported
  - Periodic
    - Period is defined by the eNB. The Physical Uplink Control CHannel is used for periodic CQI.
  - Aperiodic
    - Aperiodic CQI reporting on the PUSCH is scheduled by the eNodeB by setting a CQI request bit in an uplink resource grant sent on the Physical Downlink Control CHannel (PDCCH).

# CQI reporting

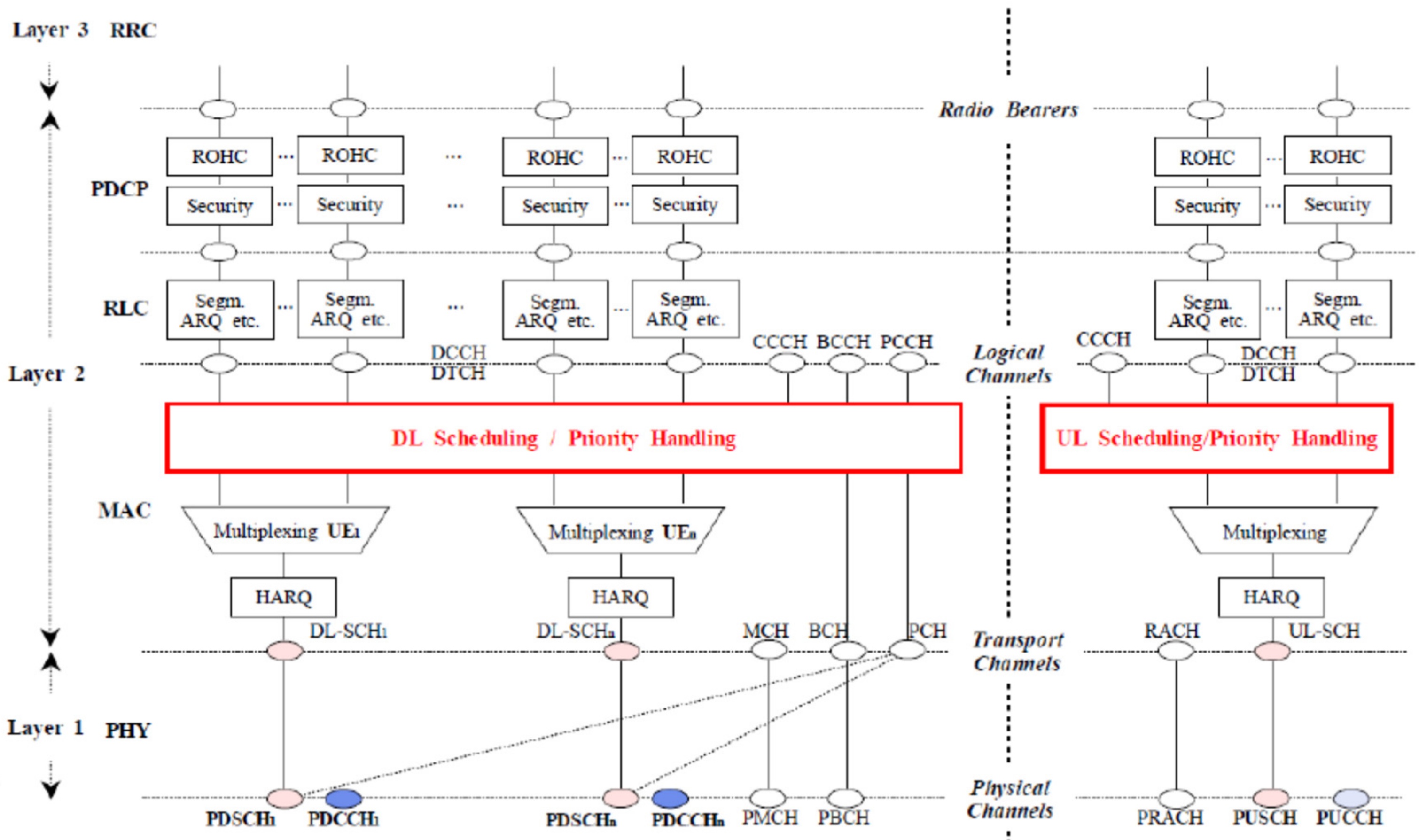
- The frequency granularity of the CQI reporting is determined by eNB:
  - **Wideband**: The UE reports one wideband CQI value for the whole system bandwidth.
  - **eNB configured subbands**: The UE reports a wideband CQI value for the whole system bandwidth as well as a CQI value for each subband.
  - **UE-selected subbands:** The UE selects a set of M preferred sub-bands of size k which has better channel quality and report them plus wideband reports.

# Scheduling in LTE



# LTE Scheduling

- In LTE, scheduling is performed at the MAC and per logical channels.



# Buffer Status Reporting

- The BSR indicates how much data are buffered in the UE's memory.
- For uplink radio resource allocation, a UE needs to send the BSR to the eNB to indicate the amount of data in the UE that need to be transmitted.
- Two formats are defined for the BSR: **Long BSR** and **Short BSR**
- The Long BSR is used to deliver buffer status information for the four Logical Channel Groups (LCGs)
- The Short BSR is used to deliver buffer status information for only one LCG. Which BSR format is used depends on what triggers the BSR, how many LCGs have data to send, and how much space is available in the MAC PDU.

# Buffer Status Reporting

- The above states that the amount of data is indicated not per logical channel but per LCG.
- By grouping logical channels with similar attributes into at most four LCGs and by making the UE report the buffer status per LCG, LTE strikes a good balance between reporting efficiency and reporting accuracy

# Buffer Status Reporting

- A BSR can be triggered in any of the following situations:
  - When data arrive for a logical channel which has higher priority than the logical channels whose buffers are not empty.
  - When data become available for the UE's buffer, which is empty.
  - When the retxBSR-Timer expires and there is still data in the UE's buffer.
  - When a periodicBSR-Timer expires. This BSR is called a Periodic BSR. This is used for the UE to periodically deliver updated buffer status information to the eNB.

# Scheduling Request (SR)

- The SR procedure starts when a regular BSR is triggered but uplink radio resource to transmit the BSR is not available in the UE.
- During the SR procedure, the UE performs either transmission of the SR over the PUCCH or initiates the Random Access (RA) procedure, depending on whether the UE is configured with the PUCCH resource for SR or not.
- The RA procedure is initiated only when the PUCCH resource for SR is not configured.
- It is not always possible for the eNB to configure the UE with the PUCCH resource for SR because the PUCCH resource in a cell is limited.
- Thus, there is a trade-off between resource allocation delay (due to RACH procedure) and the PUCCH load.
- The PUCCH resource for SR is allocated by the eNB in a periodic manner. The periodicity of the PUCCH resource allocated for SR is called SR periodicity. The SR periodicity impacts upon the delay for the UE to obtain uplink resource.

# Power Headroom Reporting (PHR)

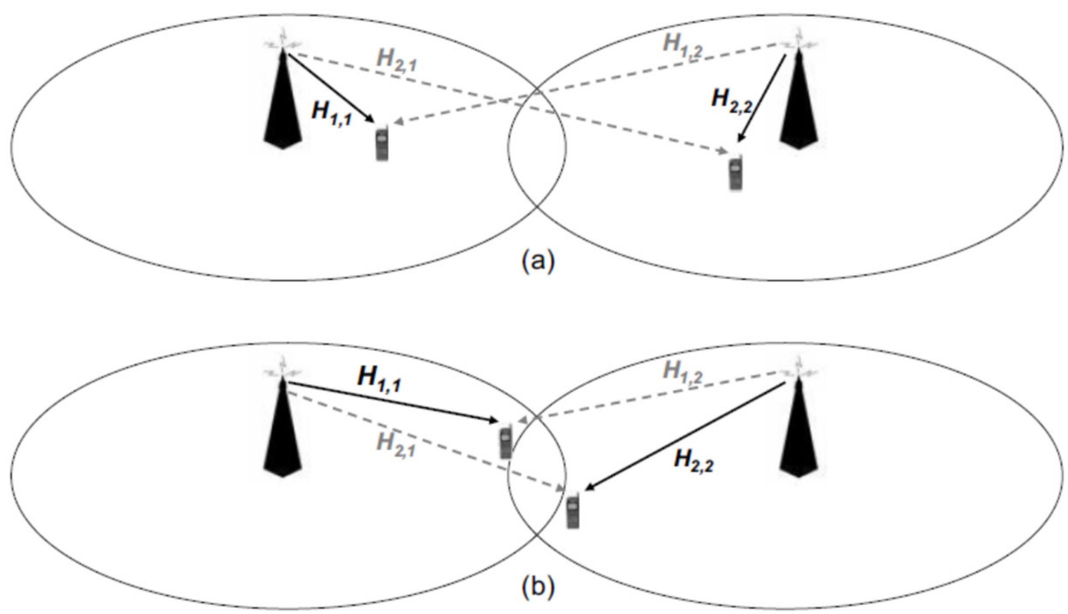
- With a given maximum power, if the UE is allocated more resources than it can support, the decoding error rate at the eNB will increase.
- Thus, it is important that the eNB has an accurate power status for the UE and allocates a suitable amount of radio resource.
- The Power Headroom Report (PHR) is used to provide the eNB with information about the difference between the nominal maximum transmit power and the estimated required power for uplink transmission.

# Inter-Cell Interference Coordination

- LTE is designed to operate with a one-cell frequency reuse, implying that the same time-frequency resources can be used in neighboring cells.
- From an overall system-efficiency point-of-view, having access to the entire available spectrum in each cell and operating with one-cell reuse is always beneficial.
- However, it may also lead to relatively large variations in the signal-to interference ratio, and thus also in the achievable data rates, over the cell area with potentially only relatively low data rates being available at the cell border.
- Thus, system performance, and especially the cell-edge user quality, can be further enhanced by allowing for some coordination in the scheduling between cells.

# Inter-Cell Interference Coordination

- The basic aim of such inter-cell interference coordination (ICIC) is to, if possible, avoid scheduling transmissions to/from terminals at the cell border simultaneously in neighboring cells.
- To support such interference coordination, the LTE specification includes several messages that can be communicated between base stations (eNodeBs) using the so-called X2 interface.

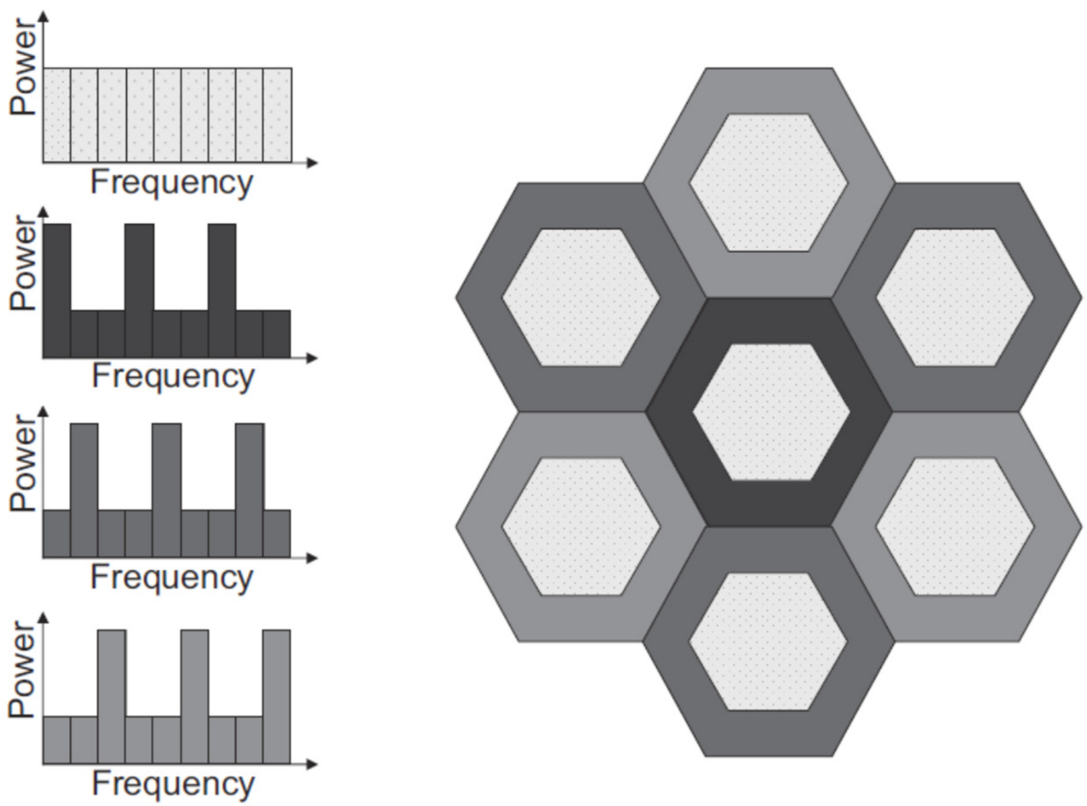


# Partial Frequency Reuse

- From a practical point of view, this result can be exploited in the eNodeB scheduler by treating users in different ways depending on whether they are cell-centre or cell-edge users.
- Each cell can then be divided into two parts – inner and outer.
- In the inner part, where users experience a low level of interference and also require less power to communicate with the serving cell, a frequency reuse factor of 1 can be adopted.
- For the outer part, scheduling restrictions are applied: when the cell schedules a user in a given part of band, the system capacity is optimized if the neighbouring cells do not transmit at all; alternatively, they may transmit only at low power (probably to users in the inner parts of the neighbouring cells) to avoid creating strong interference to the scheduled user in the first cell.

# Partial Frequency Reuse

- This effectively results in a higher frequency reuse factor at the cell-edge; it is often referred to as 'partial frequency reuse' or 'soft frequency reuse.



# ICIC Methods

- In general, ICIC may be static or semi-static, with different levels of associated communication required between eNodeBs.
- Static ICIC:
  - the coordination is associated with cell planning, and reconfigurations are rare. This largely avoids signalling on the X2 interface, but it may result in some performance limitation since it cannot adaptively take into account variations in cell loading and user distributions.
- Semi-static ICIC
  - typically refers to reconfigurations carried out on a time-scale of the order of seconds or longer. The inter-eNodeB communication methods over the X2 interface can be used.

# X2 Signaling to Support ICIC

- In relation to the downlink transmissions, a bitmap termed the Relative Narrowband Transmit Power (RNTP) indicator can be exchanged between eNodeBs over the X2 interface.
- Each bit of the RNTP indicator corresponds to one RB in the frequency domain and is used to inform the neighbouring eNodeBs if a cell is planning to keep the transmit power for the RB below a certain upper limit or not.
- The value of this upper limit, and the period for which the indicator is valid into the future, are configurable.
- This enables the neighbouring cells to take into account the expected level of interference in each RB when scheduling UEs in their own cells.

# X2 Signaling to Support ICIC

- The reaction of the eNodeB in case of receiving an indication of high transmit power in an RB in a neighbouring cell is not standardized.
- A typical response could be to avoid scheduling cell-edge UEs in such RBs.
- In the definition of the RNTP indicator, the transmit power per antenna port is normalized by the maximum output power of a base station or cell.
- For the uplink scheduling, "High Interference Indicator (HII)", is considered to announce the RB usage.
- The HII is not sent more often than every 20 ms.

# X2 Signaling to Support ICIC

- A reactive indicator, known as the 'Overload Indicator' (OI), can be exchanged over the X2 interface to indicate physical layer measurements of the average uplink interference plus thermal noise for each RB.
- The OI can take three values, expressing low, medium, and high levels of interference plus noise.
- In order to avoid excessive signalling load, it cannot be updated more often than every 20 ms.

# Carrier Aggregation

- In LTE release 10, the transmission bandwidth can be further extended by means of so-called carrier aggregation (CA), where multiple component carriers are aggregated and jointly used for transmission to/from a single terminal.
- Each aggregated carrier is referred to as a component carrier.
- The component carrier can have a bandwidth of 1.4, 3, 5, 10, 15 or 20 MHz and a maximum of five component carriers can be aggregated, hence the maximum aggregated bandwidth is 100 MHz.

# LTE Random Access Procedure

# Why Random Access Procedure

- RACH Procedure is used for
  - initial access to the network to receive dedicated traffic channels

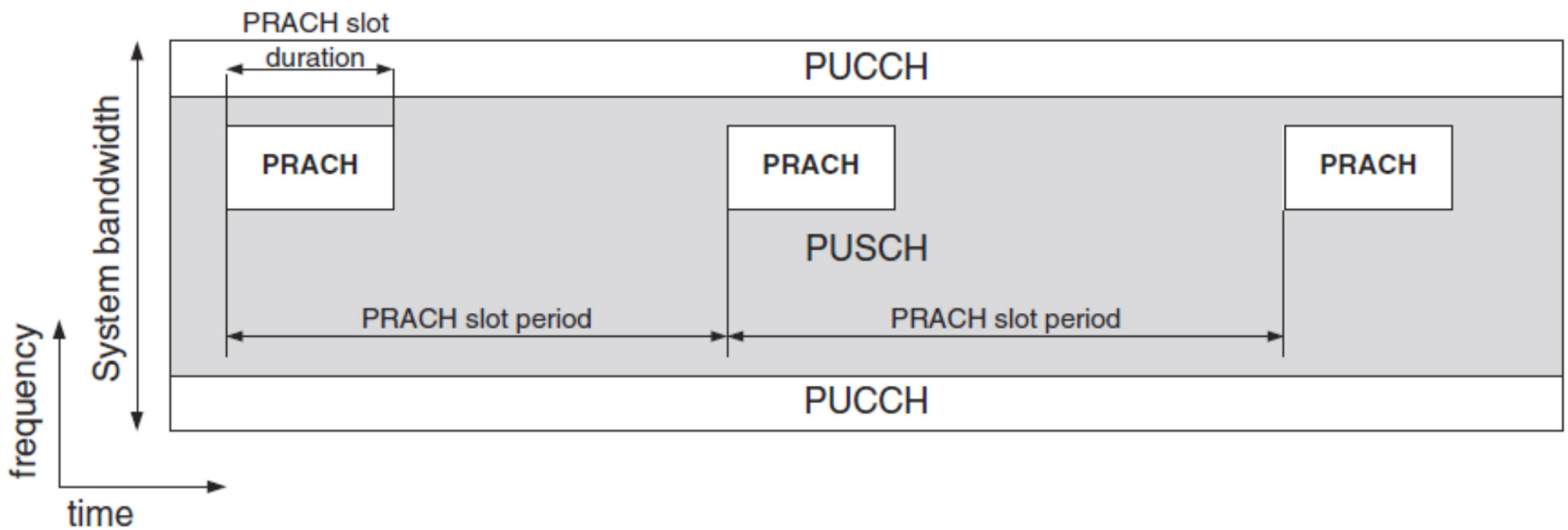
    OR
  - Time synchronization between the UE and eNB.
- Random access procedure is required if
  - A UE in RRC_CONNECTED state, but not uplink-synchronized, needing to send new uplink data or control information (e.g. an event-triggered measurement report);
  - A UE in RRC_CONNECTED state, but not uplink-synchronized, needing to receive new downlink data, and therefore to transmit corresponding ACK.
  - A UE in RRC_CONNECTED state, handing over from its current serving cell to a target cell;
  - A transition from RRC_IDLE state to RRC_CONNECTED.

# Physical Uplink Channels

- Physical Uplink Shared Channel (PUSCH)
  - Uplink data and some control information data.
- Physical Uplink Control Channel (PUCCH)
  - ACK/NACK, CQI/PMI, SR transmission
- If UE has application data or RRC signalling then, user control information (UCI) is carried over PUSCH. If UE does not have any application data or RRC signalling then UCI is carried over PUCCH.
- Physical Random Access Channel (PRACH)

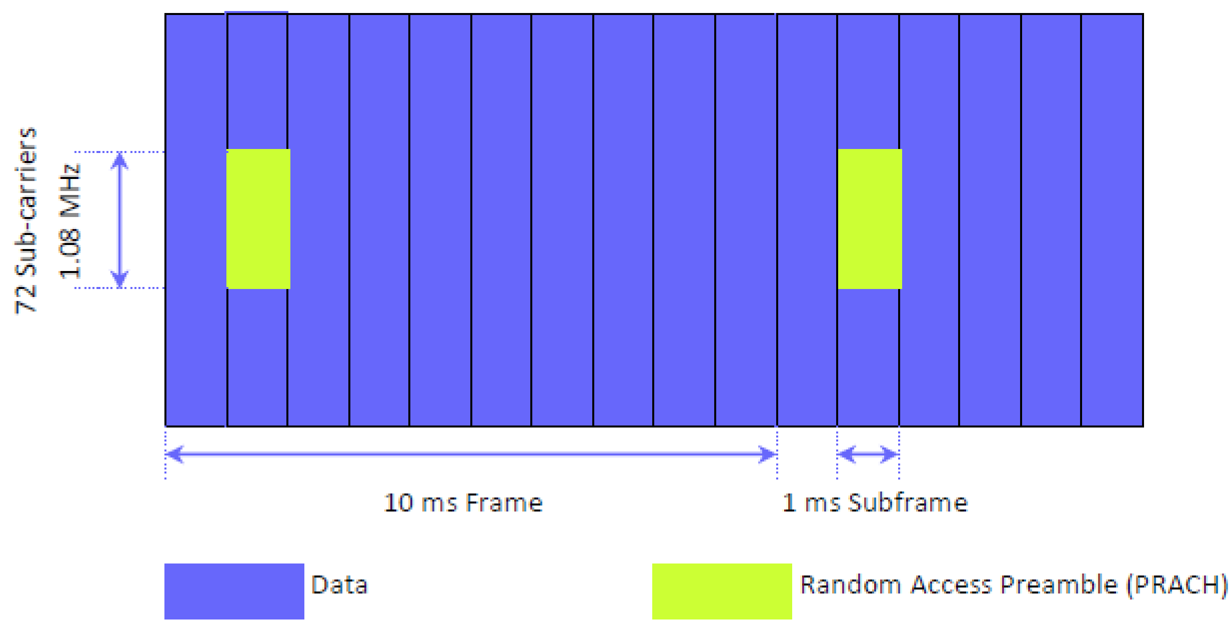
# PRACH

- The random access procedure is mapped at the physical layer onto the PRACH.



# Importance of Random Access

- RACH is repeated in the LTE for an eNB with specific rate.
- Each RACH can accommodate limited number of devices.
- For applications such as Machine Type Communications, there are large number of devices (in order of 10,000) generating small amount of data.
- The cell or core bandwidth can handle such traffic but random access becomes a critical bottleneck.



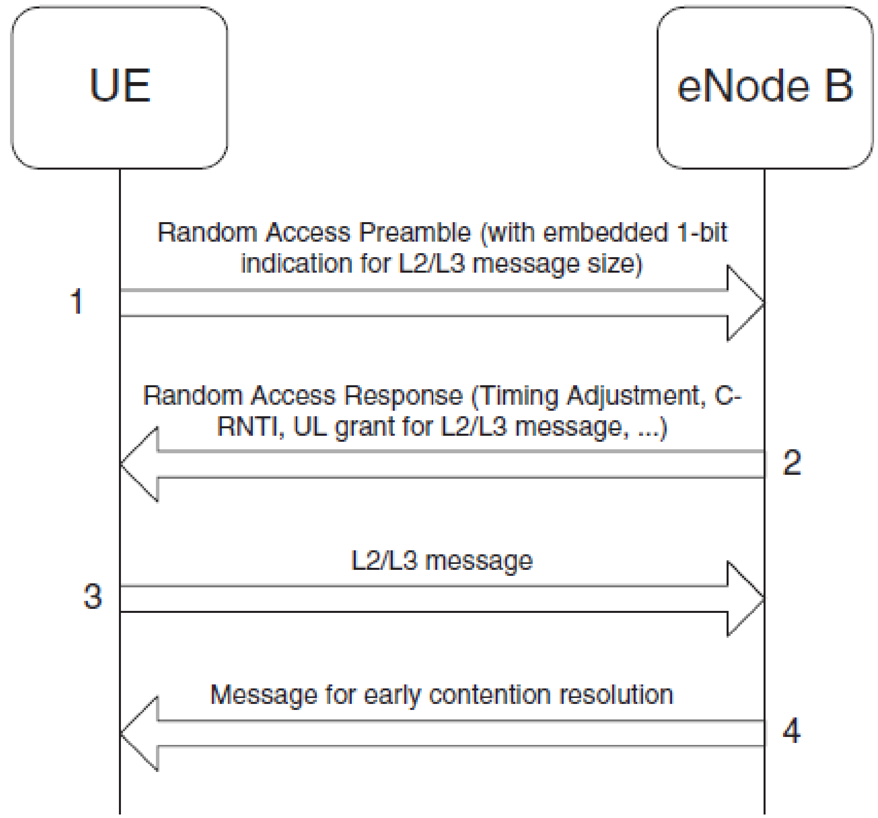
| PRACH Configuration Index | Preamble Format | System frame number | Subframe number | PRACH Configuration Index | Preamble Format | System frame number | Subframe number |
|---|---|---|---|---|---|---|---|
| 0 | 0 | Even | 1 | 32 | 2 | Even | 1 |
| 1 | 0 | Even | 4 | 33 | 2 | Even | 4 |
| 2 | 0 | Even | 7 | 34 | 2 | Even | 7 |
| 3 | 0 | Any | 1 | 35 | 2 | Any | 1 |
| 4 | 0 | Any | 4 | 36 | 2 | Any | 4 |
| 5 | 0 | Any | 7 | 37 | 2 | Any | 7 |
| 6 | 0 | Any | 1, 6 | 38 | 2 | Any | 1, 6 |
| 7 | 0 | Any | 2 ,7 | 39 | 2 | Any | 2 ,7 |
| 8 | 0 | Any | 3, 8 | 40 | 2 | Any | 3, 8 |
| 9 | 0 | Any | 1, 4, 7 | 41 | 2 | Any | 1, 4, 7 |
| 10 | 0 | Any | 2, 5, 8 | 42 | 2 | Any | 2, 5, 8 |
| 11 | 0 | Any | 3, 6, 9 | 43 | 2 | Any | 3, 6, 9 |
| 12 | 0 | Any | 0, 2, 4, 6, 8 | 44 | 2 | Any | 0, 2, 4, 6, 8 |
| 13 | 0 | Any | 1, 3, 5, 7, 9 | 45 | 2 | Any | 1, 3, 5, 7, 9 |
| 14 | 0 | Any | 0, 1, 2, 3, 4, 5, 6, 7, 8, 9 | 46 | N/A | N/A | N/A |
| 15 | 0 | Even | 9 | 47 | 2 | Even | 9 |
| 16 | 1 | Even | 1 | 48 | 3 | Even | 1 |
| 17 | 1 | Even | 4 | 49 | 3 | Even | 4 |
| 18 | 1 | Even | 7 | 50 | 3 | Even | 7 |
| 19 | 1 | Any | 1 | 51 | 3 | Any | 1 |
| 20 | 1 | Any | 4 | 52 | 3 | Any | 4 |
| 21 | 1 | Any | 7 | 53 | 3 | Any | 7 |
| 22 | 1 | Any | 1, 6 | 54 | 3 | Any | 1, 6 |
| 23 | 1 | Any | 2 ,7 | 55 | 3 | Any | 2 ,7 |
| 24 | 1 | Any | 3, 8 | 56 | 3 | Any | 3, 8 |
| 25 | 1 | Any | 1, 4, 7 | 57 | 3 | Any | 1, 4, 7 |
| 26 | 1 | Any | 2, 5, 8 | 58 | 3 | Any | 2, 5, 8 |
| 27 | 1 | Any | 3, 6, 9 | 59 | 3 | Any | 3, 6, 9 |
| 28 | 1 | Any | 0, 2, 4, 6, 8 | 60 | N/A | N/A | N/A |
| 29 | 1 | Any | 1, 3, 5, 7, 9 | 61 | N/A | N/A | N/A |
| 30 | N/A | N/A | N/A | 62 | N/A | N/A | N/A |
| 31 | 1 | Even | 9 | 63 | 3 | Even | 9 |

## Contention based vs Contention Free

- RACH procedure is carried out via transmission of a code called *preamble* in the PRACH.
- There are limited number of orthogonal preambles.
- A device can have a dedicated code which results in a contention free RACH procedure.
- Otherwise, the device needs to choose randomly from the pool of preambles which results in contention.

# Contention Based Random Access Procedure

- It is inherently contention-based:
  - Step 1: Preamble transmission;
  - Step 2: Random access response;
  - Step 3: Layer 2 / Layer 3 (L2/L3 message;
  - Step 4: Contention resolution message.



# Step 1: Preamble Transmission

- The UE selects one of the 64 - $N_{cf}$ available PRACH contention-based signatures, where $N_{cf}$ is the number of signatures reserved by the eNB for contention-free RACH.
- The initial preamble transmission power setting is based on an open-loop estimation with full compensation for the path-loss.
- The UE estimates the path-loss by averaging measurements of the downlink Reference Signal Received Power (RSRP).

# Step 2: Random Access Response

- The Random Access Response (RAR) is sent by the eNB on the Physical Downlink Shared CHannel (PDSCH).
- RAR includes:
  - Identity of the detected preamble
  - Temporary ID known as "Cell Radio Network Temporary Identifier" (C-RNTI)
  - A timing alignment instruction to synchronize subsequent uplink transmissions from the UE.
  - An initial uplink resource grant for transmission of the Step 3 message
  - Backoff timer
- The UE expects to receive the RAR within a time window broadcasted by the eNB.
- The earliest is 2 ms after the tried RACH.
- The minimum delay for the transmission of another preamble after the end of the RAR window is 3 ms.

# Step 3: Layer 2/Layer 3 (L2/L3) Message

- This message is the first scheduled uplink transmission on the PUSCH
- It makes use of Hybrid Automatic Repeat reQuest (HARQ).
- It conveys the actual random access procedure message, such as an RRC connection request, tracking area update, or scheduling request but no Non-Access Stratum (NAS) message.
- It is addressed to the temporary C-RNTI allocated in the RAR at Step 2.
- In case of a preamble collision having occurred at Step 1, the colliding UEs will receive the same temporary C-RNTI through the RAR and will also collide in the same uplink time-frequency resources when transmitting their L2/L3 message.

# Step 4: Contention Resolution Message

- The contention resolution message uses HARQ.
- It is addressed to the C-RNTI and, in the latter case, echoes the UE identity contained in the L2/L3 message.
- In case of a collision followed by successful decoding of the L2/L3 message, the HARQ feedback is transmitted only by the UE which detects its own UE identity (or C-RNTI).
- Other UEs understand there was a collision, transmit no HARQ feedback, and can quickly exit the current random access procedure

# RACH Preamble

- Zadoff–Chu (ZC) sequences are used as RACH preambles.
- ZC sequences are non-binary unit-amplitude sequences.
- The ZC sequence of odd-length $N_{ZC}$ is given by

$$a_u(n) = \exp\left[-j\frac{\pi u\, n\,(n+1)}{N_{ZC}}\right]$$

For any value of *u, the* above equation provides $N_{ZC}$ codes by varying *n* from 0 to $N_{ZC}$-1.

# RACH Preamble

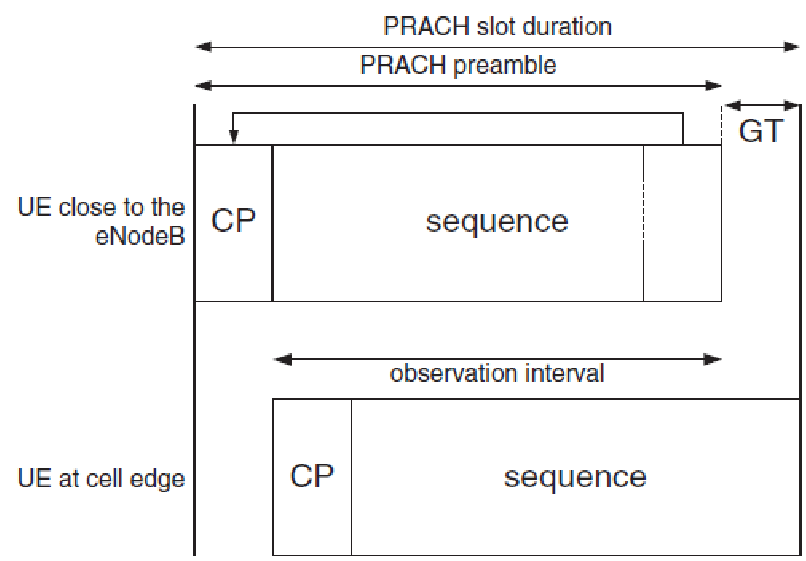
- ZC codes properties:
  - A ZC sequence has constant amplitude. The constant amplitude property limits the Peak-to-Average Power Ratio.
  - ZC sequences of any length have 'ideal' cyclic autocorrelation. The correlation with its circularly shifted version is a delta function.

$$r_{kk}(\sigma) = \sum_{n=0}^{N_{ZC}-1} a_k(n) a_k^*[(n+\sigma)] = \delta(\sigma)$$

  - If $N_{ZC}$ is prime, the Discrete Fourier Transform of a Zadoff–Chu sequence is another Zadoff–Chu sequence.
  - The cross-correlation between two Zadoff–Chu sequences provided that $|u_1-u_2|$ is relative prime to $N_{ZC}$ is $1/\sqrt{N_{ZC}}$.

# Cyclic Prefix and Guard Time

- Due to different propagation delays, two sequences transmitted by two UEs may be received at different times.
- To absorb propagation delay, Guard Time (GT) is used.
- We then copy a section from the end of the symbol to the beginning, known as Cyclic Prefix (CP).
- At the receiver, we remove CP from the beginning without knowing the delay offset.



# Time Advance (TA) Calculation

- RACH is carried out on a non-synchronized channel.
- eNB samples the whole timeslot and removes CP time from the beginning and GT from the end.
- The received preambles is a cyclically shifted version of the transmitted preamble.
- Thanks to the cyclic shift behavior of the ZC code, the sampled preamble is also a ZC code.
- However, to avoid confusion between two preambles, we cannot use all the codes from one root. We need some distance between the used codes.
- TA can be calculated from the shifts in the preamble.

# Sequence Duration

- Trade-off between sequence length and overhead
- Compatibility with the maximum expected round-trip delay.
  - The lower bound for TSEQ must allow for unambiguous round-trip time estimation for a UE located at the edge of the largest expected cell including the maximum delay spread.

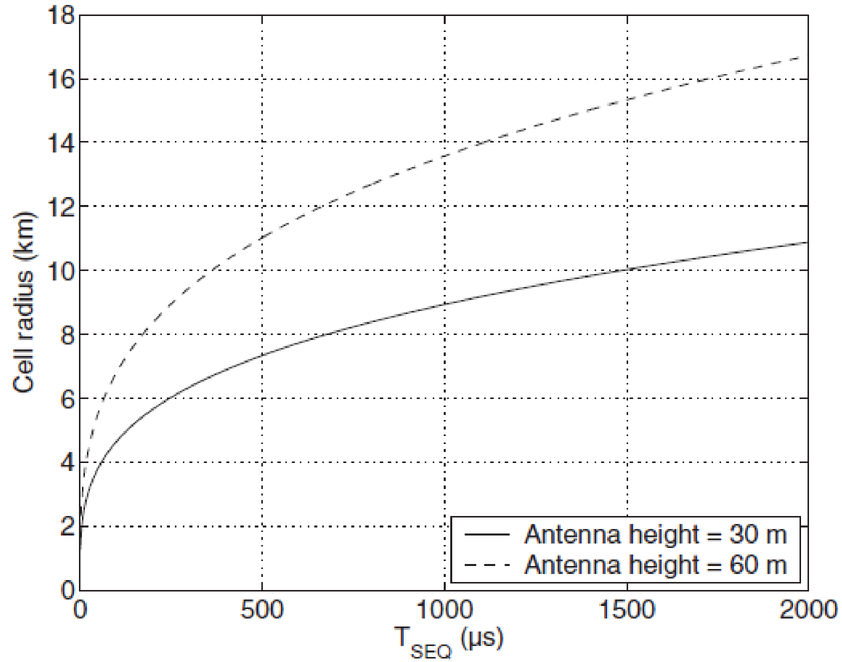
$$T_{SEQ} \geq \frac{RTD}{C} + \text{maximum delay spread}$$

# Sequence Duration

- Coverage performance

$$\text{RACH SNR}=\frac{E_p}{N_0}=\frac{T_{SEQ}P_{RA}(r)}{N_0 N_f}$$

- $P_{RA}(r) = P_{max} + G_a - L(r) - LF - PL$ (dB)
  - $P_{RA}$: signal power
  - $L(r)$ : Okumura-Hata empirical model of distance-dependent path-loss
  - $Ga$: eNodeB Receiver Antenna Gain (including cable loss)
  - $P_{max}$: UE transmitted power
  - LF: Log-normal fade margin (0 db)
  - $P_L$: Penetration loss



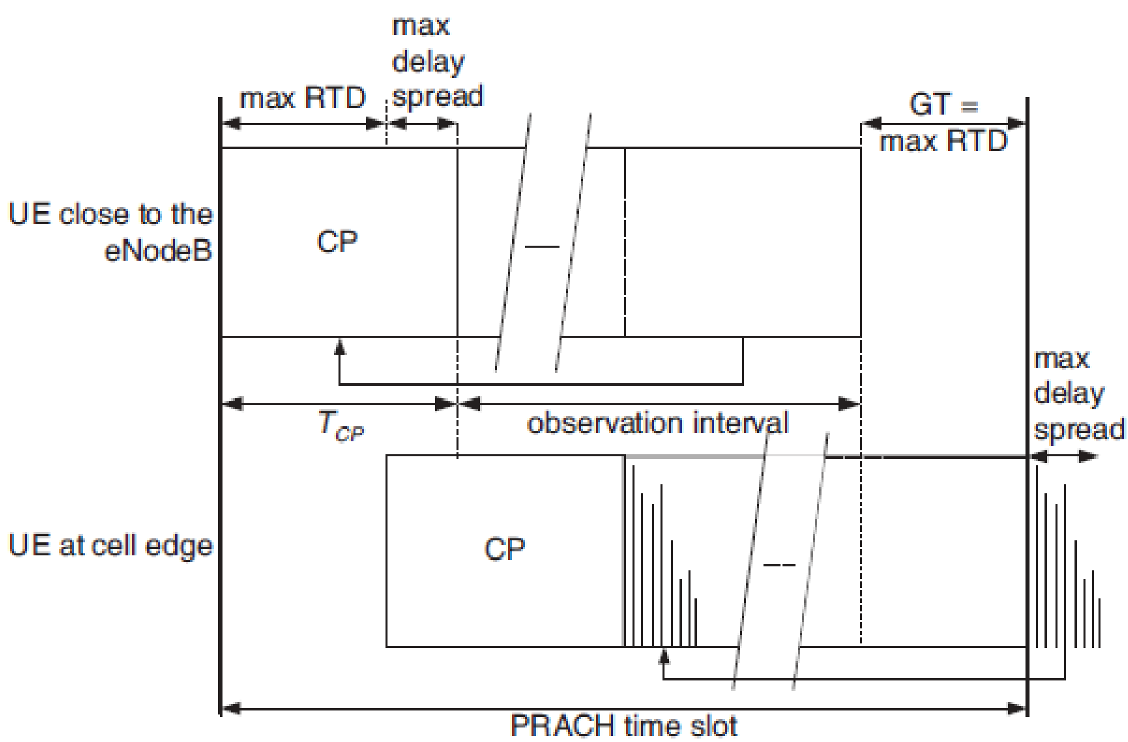
# PRACH Formats

- There are four preamble formats possible for PRACH and is broadcast in the System Information.

| Preamble format | $T_{SEQ}$ (µs) | $T_{CP}$ (µs) | Usage |
|---|---|---|---|
| 0 | 800 | 103.13 | Normal 1 ms random access burst with 800 µs preamble sequence, for small to medium cells (up to ~14 km) |
| 1 | 800 | 684.38 | 2 ms random access burst with 800 µs preamble sequence, for large cells (up to ~77 km) without a link budget problem |
| 2 | 1600 | 203.13 | 2 ms random access burst with 1600 µs preamble sequence, for medium cells (up to ~29 km) supporting low data rates |
| 3 | 1600 | 684.38 | 3 ms random access burst with 1600 µs preamble sequence, for very large cells (up to ~100 km) |

# CP and GT Duration

- Since we remove the first $T_{CP}$ seconds of the symbol, the remaining part should contain information.
- Therefore, $T_{CP} \geq \max \mathrm{RTD} + \max$ delay spread.



# CP and GT Duration

- Since we remove the first $T_{CP}$ seconds of the symbol, the remaining part should contain information.
- Therefore, $T_{CP} \geq \max \text{RTD}$ +max delay spread.

| Preamble format | Number of allocated subframes | CP duration in µs | GT duration in µs | Max. delay spread (µs) | Max. cell radius (km) |
|---|---|---|---|---|---|
| 0 | 1 | 103.13 | 96.88 | 6.25 | 14.53 |
| 1 | 2 | 684.38 | 515.63 | 16.67 | 77.34 |
| 2 | 2 | 203.13 | 196.88 | 6.25 | 29.53 |
| 3 | 3 | 684.38 | 715.63 | 16.67 | 100.16 |

# Cyclic Shift Dimensioning (low speed cells)

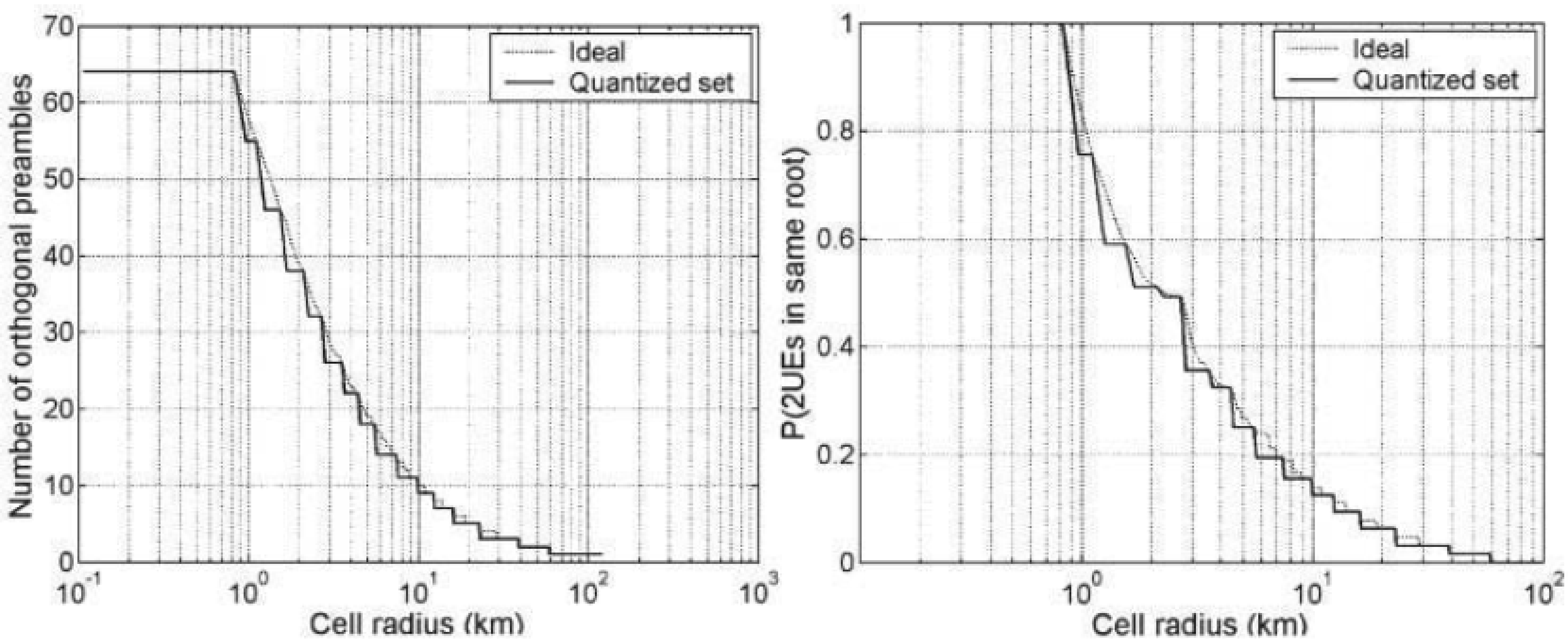
- The $N_{ZC}$ is chosen as 839 for LTE RACH.
- For one root sequence, 839 cyclic shifts of the sequence provide 839 orthogonal sequences.
- LTE mandates use of 64 preambles.
- Various propagation delays do not allow use of all 839 preambles for one root.
- Let $N_{CS}$ denote the minimum required distance between sequences derived from one root sequence.
- If r is the maximum cell radius in km, $\tau_{ds}$ shows the delay spread in $\mu s$, $n_g$ is the number of additional guard samples due to the receiver pulse shaping filter, then we have

$$N_{CS} \geq \left\lfloor \left(\frac{20}{3} r + \tau_{ds}\right) \frac{N_{ZC}}{T_{SEQ}} \right\rfloor + n_g$$

| Cell scenario | Number of cyclic shifts per ZC sequence | Number of ZC root sequences | Cyclic shift size $N_{CS}$ (samples) | Cell radius (km) |
|---|---|---|---|---|
| 1 | 64 | 1 | 13 | 0.7 |
| 2 | 32 | 2 | 26 | 2.5 |
| 3 | 18 | 4 | 46 | 5 |
| 4 | 9 | 8 | 93 | 12 |

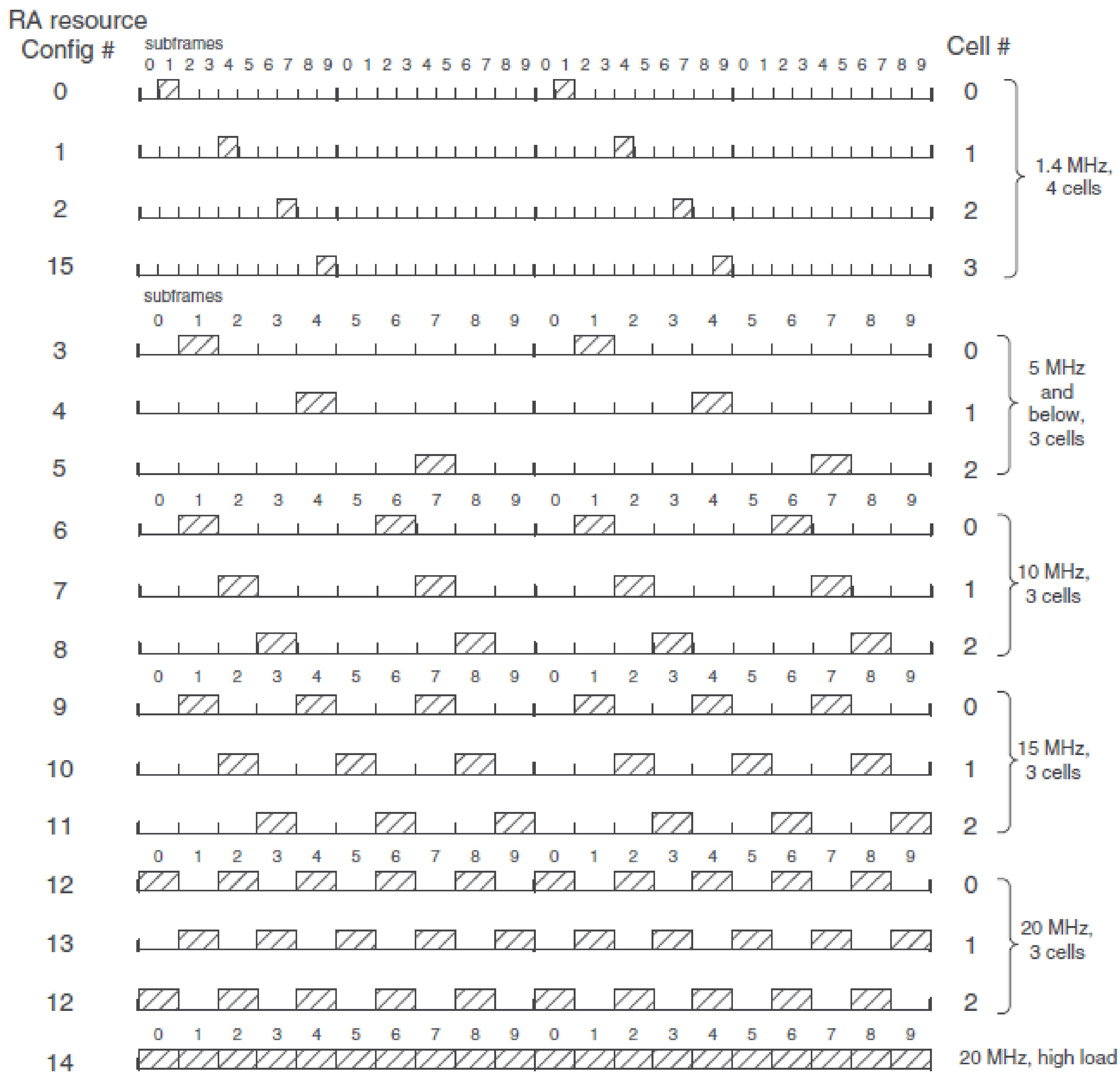
# Cyclic Shift Dimensioning

- When different roots are used, the preambles are not orthogonal anymore.
- The chance that orthogonal preambles are chosen by different UEs approaches zero as cell radius increases.



# PRACH Resource Configurations

- Depending on the RAN load, the number of PRACHs in eUTRAN can vary.
- Higher number of PRACHs, higher chance for initial access but lower resources for uplink data transfer.
- 5 Different configuration types are defined in the standard.



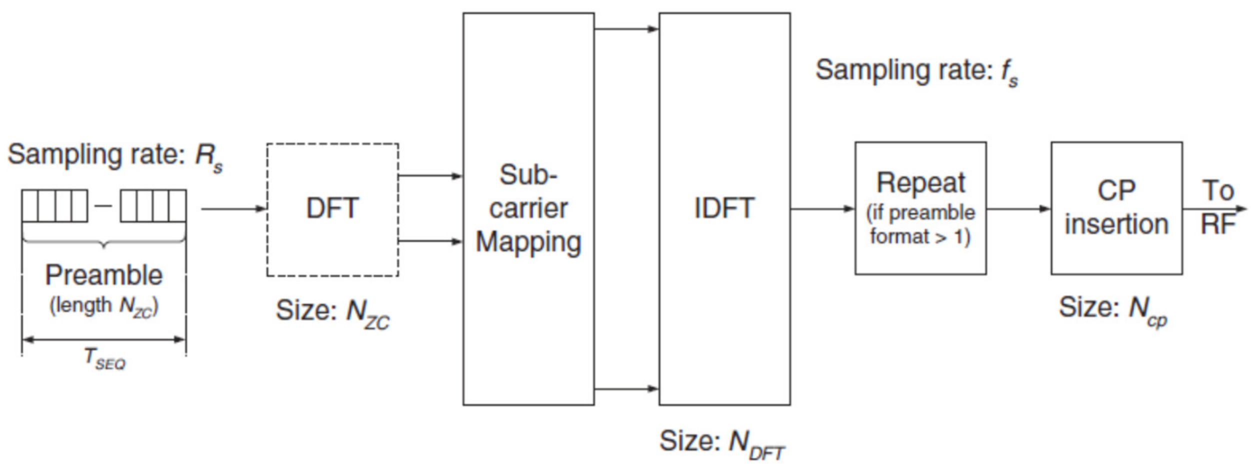
RA resource Config #
subframes
Cell #
0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9
0
1
2
15
1.4 MHz, 4 cells
3
4
5
5 MHz and below, 3 cells
6
7
8
10 MHz, 3 cells
9
10
11
15 MHz, 3 cells
12
13
12
20 MHz, 3 cells
14
20 MHz, high load

# PRACH Implementation

| CM group | Sub-group no. | $N_{CS}$ (High-Speed) | Logical index (i.e. re-ordered) | Physical root sequence index $u$ (in increasing order of the corresponding logical index number) |
|---|---|---|---|---|
| Low | 0 | - | 0~23 | 129, 710, 140, 699, 120, 719, 210, 629, 168, 671, 84, 755, 105, 734, 93, 746, 70, 769, 60, 779, 2, 837, 1, 838 |
| | 1 | 15 | 24~29 | 56, 783, 112, 727, 148, 691 |
| | 2 | 18 | 30~35 | 80, 759, 42, 797, 40, 799 |
| | 3 | 22 | 36~41 | 35, 804, 73, 766, 146, 693 |
| | 4 | 26 | 42~51 | 31, 808, 28, 811, 30, 809, 27, 812, 29, 810 |
| | ... | ... | ... | ... |
| | 15 | 23 7 | 384~455 | 3, 836, 19, 820, 22, 817, 41, 798, 38, 801, 44, 795, 52, 787, 45, 794, 63, 776, 67, 772, 72<br>767, 76, 763, 94, 745, 102, 737, 90, 749, 109, 730, 165, 674, 111, 728, 209, 630, 204, 635, 117, 722, 188, 651, 159, 680, 198, 641, 113, 726, 183, 656, 180, 659, 177, 662, 196, 643, 155, 684, 214, 625, 126, 713, 131, 708, 219, 620, 222, 617, 226, 613 |
| High | 16 | 23 7 | 456~513 | 230, 609, 232, 607, 262, 577, 252, 587, 418, 421, 416, 423, 413, 426, 411, 428, 376, 463, 395, 444, 283, 556, 285, 554, 379, 460, 390, 449, 363, 476, 384, 455, 388, 451, 386, 453, 361, 478, 387, 452, 360, 479, 310, 529, 354, 485, 328, 511, 315, 524, 337, 502, 349, 490, 335, 504, 324, 515 |
| | ... | ... | ... | ... |
| | 29 | 18 | 810~815 | 309, 530, 265, 574, 233, 606 |
| | 30 | 15 | 816~819 | 367, 472, 296, 543 |
| | 31 | - | 820~837 | 336, 503, 305, 534, 373, 466, 280, 559, 279, 560, 419, 420, 240, 599, 258, 581, 229, 610 |

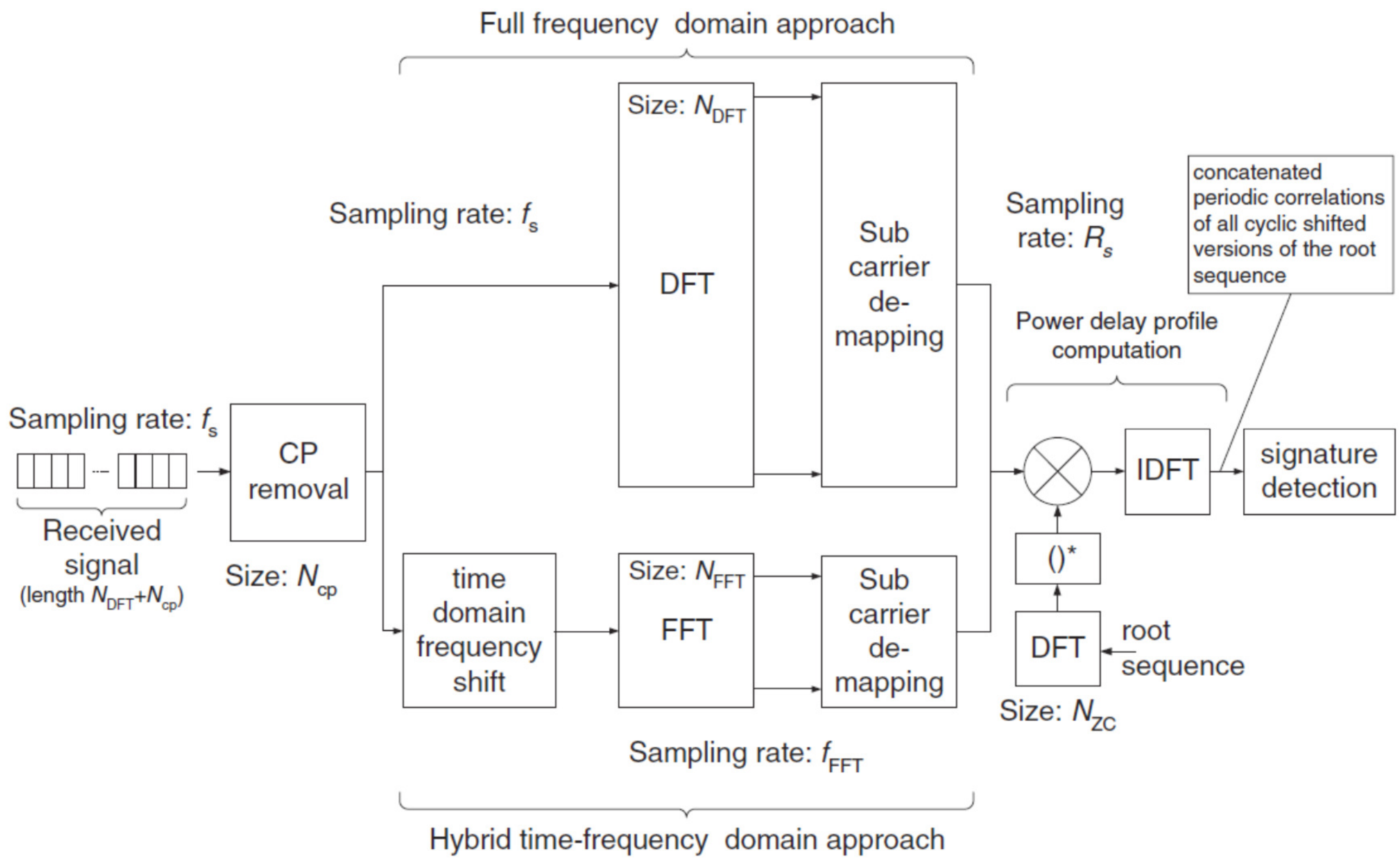
# UE Preamble Transmission

- The PRACH preamble can be generated at the system sampling rate, by means of a large IDFT.




- The DFT block is optional as the sequence can be mapped directly in the frequency domain at the IDFT input

# eNB Reception



# Offered Load

- Assume the acceptable collision probability for an UE is $p$.
- From slotted ALOHA systems, we know the probability that a transmission is successful in a slot with offered load $G$ is $e^{-G}$. The ALOHA throughput is $Ge^{-G}$.
- To have collision probability $p$, the offered load *per preamble* is $G = \ln(\frac{1}{1-p})$.
- For $M$ preambles in a PRACH, the throughput is $M(1-p)\ln(\frac{1}{1-p})$
- Example:
  - Collision probability 0.1
  - Number of available preambles: 30
  - Resource configuration: 3
  - Offered load per seconds: # of PRACH/sec × # of preambles × $\ln\left(\frac{1}{1-p}\right)$=316.
  - Accommodate users: 285.

# RACH Throughput

- The number of UEs in a RACH: *N*
- The number of preambles: *M*
- Load per preamble: *G*=*N*/*M*,
- RACH Throughput = $Ne^{-\frac{N}{M}}$
- Maximum throughput is achieved for *N*=*M* which is $Ne^{-1}$
- UE Success probability: $e^{-1}$
- UE collision probability $1 - e^{-1}$
- Maximum capacity of one preamble: $e^{-1}$
- How to control the number of UEs trying in one RACH?

# Access Class Barring

- In LTE, all UEs are members of one out of ten randomly allocated mobile populations, defined as Access Classes (AC) 0 to 9.
- The population number is stored in the SIM/USIM.
- In addition, UEs may be members of one or more out of 5 special categories (Access Classes 11 to 15), also held in the SIM/USIM.
- These are allocated to specific high priority users as follows.
  - Class 15 - PLMN Staff;
  - Class 14 - Emergency Services;
  - Class 13 - Public Utilities (e.g. water/gas suppliers);
  - Class 12 - Security Services;
  - Class 11 - For PLMN Use.
  - Class 10 - Emergency calls

# Access Class Baring (ACB) factor

- When the eNB is overloaded, it will bar some ACs randomly by broadcasting the ACB information. ACB information contains the following information:
  - Which ACs are barred
  - ACB factor (0.05 ~ 0.95)
  - ACB Time (4~512 sec)
- ACB factor plays persistent probability role for users of their class.
- For users initiating emergency calls (AC 10) their access is controlled by AB-BarringForEmergency (boolean): barring or not
- For UEs with AC 11- 15, their access is controlled by AC-BarringForSpecialAC (boolean): barring or not.
- ACB is updated in SIB2 every 160ms.