ΕΠΛ 427:
ΚΙΝΗΤΑ ΔΙΚΤΥΑ ΥΠΟΛΟΓΙΣΤΩΝ
(MOBILE NETWORKS)

Δρ. Χριστόφορος Χριστοφόρου

Πανεπιστήμιο Κύπρου - Τμήμα Πληροφορικής

3GPP Long Term Evolution (LTE)

Topics Discussed

- LTE Motivation and Goals
- Introduction to LTE
- LTE Network Architecture
- Air Interface in LTE
- Symbols, Slots, Resource Blocks and Frames (OFDM)
- LTE Channel Structure (Downlink, Uplink)
- LTE Channel Model (Downlink, Uplink)
- MIMO Transmission & Adaptive Modulation and Coding

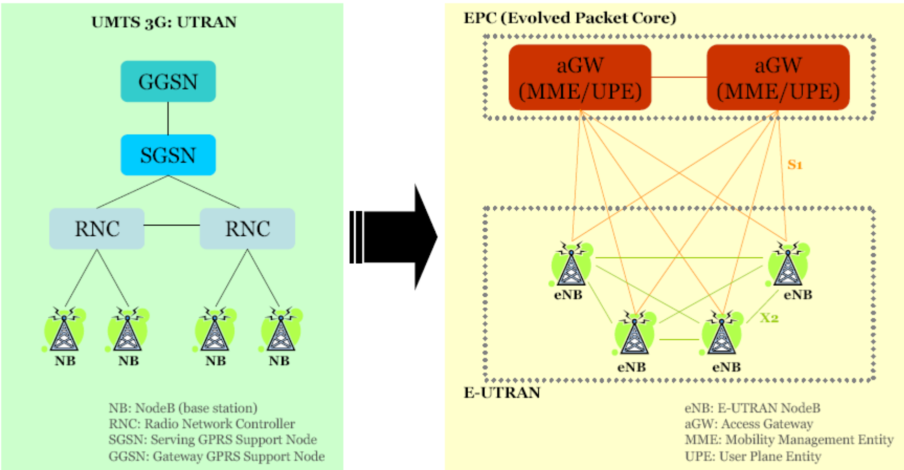
LTE Motivation and Goals

- **The main goal of LTE is to improve Data Rates and QoS.**
  - **The driving force towards the definition of the LTE is** the **Need for Higher Data Rates**
- In addition, **Networks Operators** are looking for **Backward Compatibly, Lower Complexity** and **Cost Reduction, support for higher mobility (i.e., higher speeds), better Spectral Efficiency** and **Improved System Latency (lower delays** and thus **increased User Experience)**

  - **The simplification of the Core Network Architecture (adopted an All-IP approach), the simplification of the Radio Network Architecture (becoming Flat), and the new air interface (OFDM) chosen for LTE, helped to support all these goals.**

Introduction to LTE

- **Despite constant evolution, 3G (UMTS) is approaching a number** of **inherent design limitations** in a manner similar to what GSM and GPRS did a decade ago.
- Therefore, the **3GPP decided to once again redesign both the Radio Network and the Core Network.**
- The result is commonly referred to as **'Long-Term Evolution'** or **LTE** for short.



Mobility Management Entity (MME)

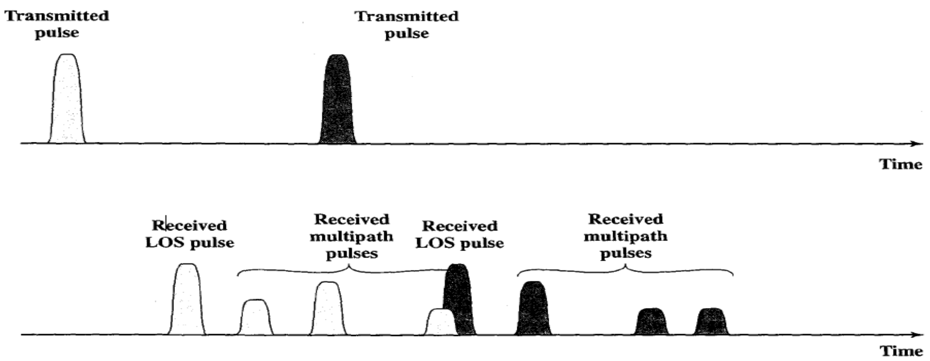
User Plane Entity (UPE)

Introduction to LTE

- **When UMTS was designed**, it was **a brave approach to specify an air interface with** a **Carrier Bandwidth of 5 MHz**.
- **WCDMA, the air interface chosen at that time, performed very well within this bandwidth limit**.
- Unfortunately, **WCDMA does not scale very well (due to the fact that a single carrier is used to transfer the data)**.
  - That is because in order to **attain higher transmission speeds**, the time **between subsequent symbols has to decrease.**
  - **For example assuming 1 bit is sent per symbol:**
    - **64 Kbps→ Subsequent Symbol time: 0.000015625 sec**
    - **256 Kbps→ Subsequent Symbol Time: 0.00000390625 seconds**

Introduction to LTE

- The **shorter the time between subsequent Symbols**, the **greater the impact** of **InterSymbol Interference (ISI)**, which degrades the quality of the signal considerably.



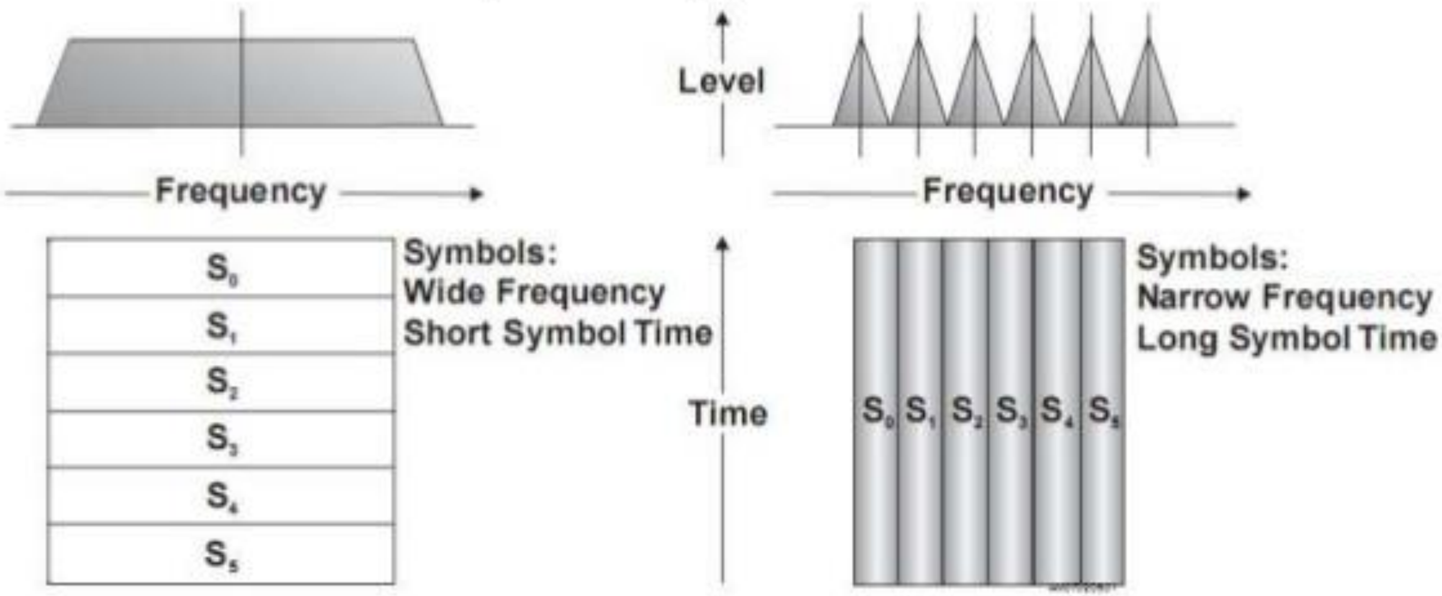
- **Therefore, with LTE**, a **completely different air interface (based on OFDM; Orthogonal Frequency Division Multiplexing) has been specified to significantly increase the data rates in the air interface while at the same time overcome the effects of ISI**.

Introduction to LTE

- **Instead of spreading one signal over the complete carrier bandwidth (single carrier transmission)**, like WCDMA does, **LTE uses Orthogonal Frequency Division Multiplexing (OFDM)** that **transmits the data over many narrowband carriers** of **180 kHz each (multicarrier transmission scheme)**.
  - **Instead of** a **single fast transmission**, a **data stream is split into many slower data streams** that are **transmitted simultaneously (using many different carriers)**.
  - As a consequence, the **achievable data rate compared to UMTS is similar in the same bandwidth** but the **ISI multipath effect is greatly reduced** because of the **Longer time between subsequent symbols**.

Introduction to LTE

OFDM Concept: Single-Carrier Vs. OFDM



Single-Carrier Mode:

- Serial Symbol Stream Used to Modulate a Single Wideband Carrier
- Serial Datastream Converted to Symbols (Each Symbol Can Represented 1 or More Data Bits)

OFDM Mode:

- Each Symbol Used to Modulate a Separate Sub-Carrier

Introduction to LTE

- **Example - Single Carrier Vs Multicarrier transmission**
  - **Let assume a data stream of 256 kbps send in the same channel using the same carrier (single carrier) and that one bit is sent per symbol**
  - **This means that in one second, 256000 symbols must be transmitted in the carrier so as to achieve the 256Kbps bit rate.**
  - **Therefore, this gives 0.00000390625 seconds between consecutive symbols (1 second / 256000 symbols).**

Introduction to LTE

- **Example - Single Carrier Vs Multicarrier transmission**
  - **Now lets split this data stream into eight (8) lower data rate streams and send each stream using a different carrier (i.e., a different channel; multicarrier transmission). Also we assume that one bit is sent per symbol.**
  - **Thus, each one of the carriers (i.e., the channels) will now transmit 32Kbps (256Kbps/8).**
  - **This means that in one second, the number of symbols that have to be transmitted is 32000 (per carrier).**

Introduction to LTE

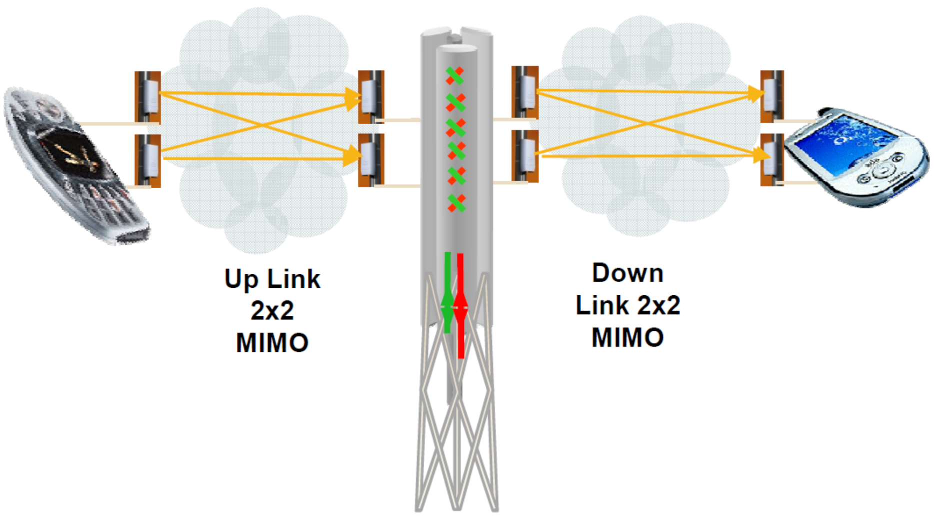
- **Example - Single Carrier Vs Multicarrier transmission**
  - **This increases the time between consecutive symbols to 0.00003125 seconds (1 second / 32000 symbols) thus reducing significantly the effects of InterSymbol Interference (ISI) – *Note that if the time between* consecutive *symbols is much greater than the delay spread then the ISI is mitigated.***
  - **However, all the carriers used to send the lower data rate streams will transmit the data simultaneously and therefore the achievable data rate will be the same as with the single carrier transmission (i.e., 8 x 32Kbps = 256Kbps)**

Introduction to LTE

- **Several bandwidths have been specified for LTE:**
  - **Flexible bandwidth Allocation from 1.4 MHz up to 20 MHz (Note that for WCDMA the bandwidth that can be used is fixed to 5 MHz).**
  - In a **20 MHz carrier bandwidth, data rates beyond 100 Mbit/s** can be achieved **under very good signal conditions (using Adaptive Modulation and Coding and MIMO transmissions)**.

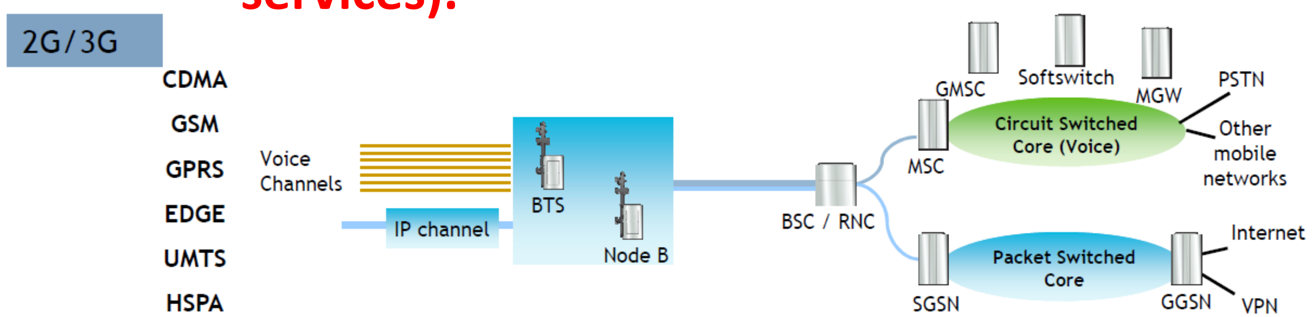
Introduction to LTE

- In addition to the **flexible bandwidth support**, **all LTE devices have to support Multiple Input Multiple Output (MIMO) transmissions, which allows the Base Station to transmit/receive several data streams simultaneously**.
  - **Under very good signal conditions**, the **data rates that can be achieved** this way are **beyond those that can be achieved with a single-stream transmission**.

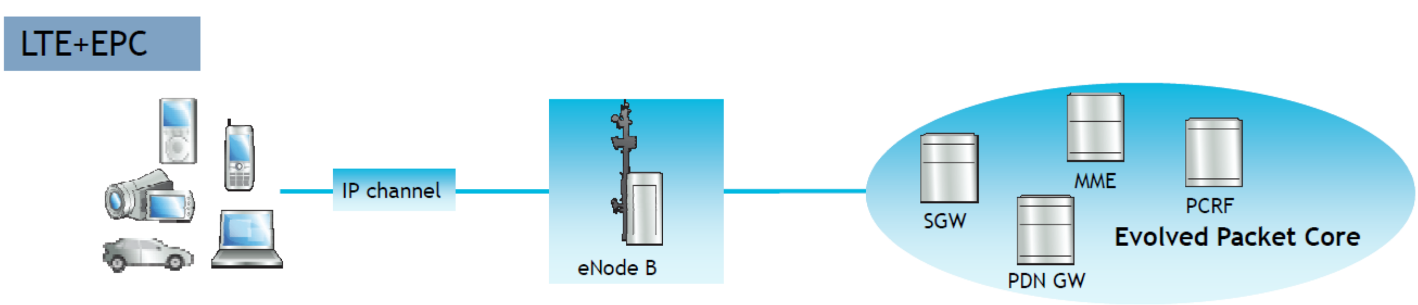


Introduction to LTE

- The **second major change** of **LTE compared to previous systems** is the **adoption of an all-IP approach**.
  - While **UMTS used a traditional Circuit-Switched packet core** for **voice services**, **for SMS** and other services inherited from GSM/GPRS/EDGE, **LTE solely relies on an IP-based Core Network (only Packet Switched services).**



PCRF (Policy Control and Charging Rules Function)

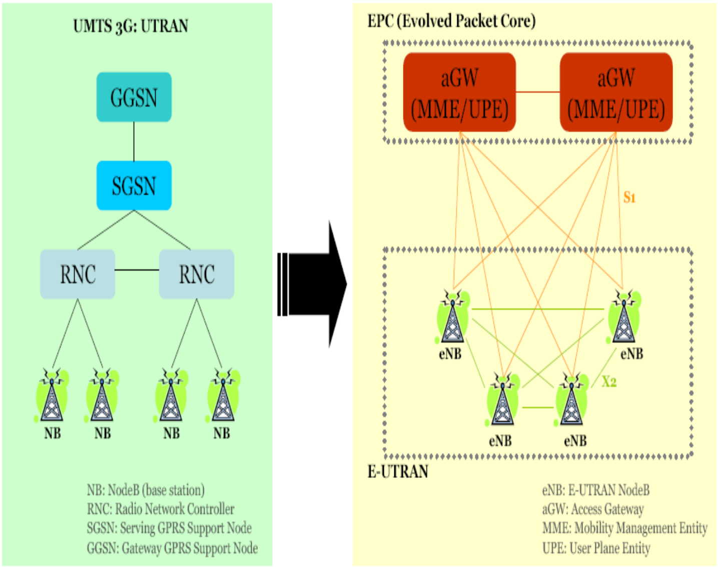


An All IP-based Core Network

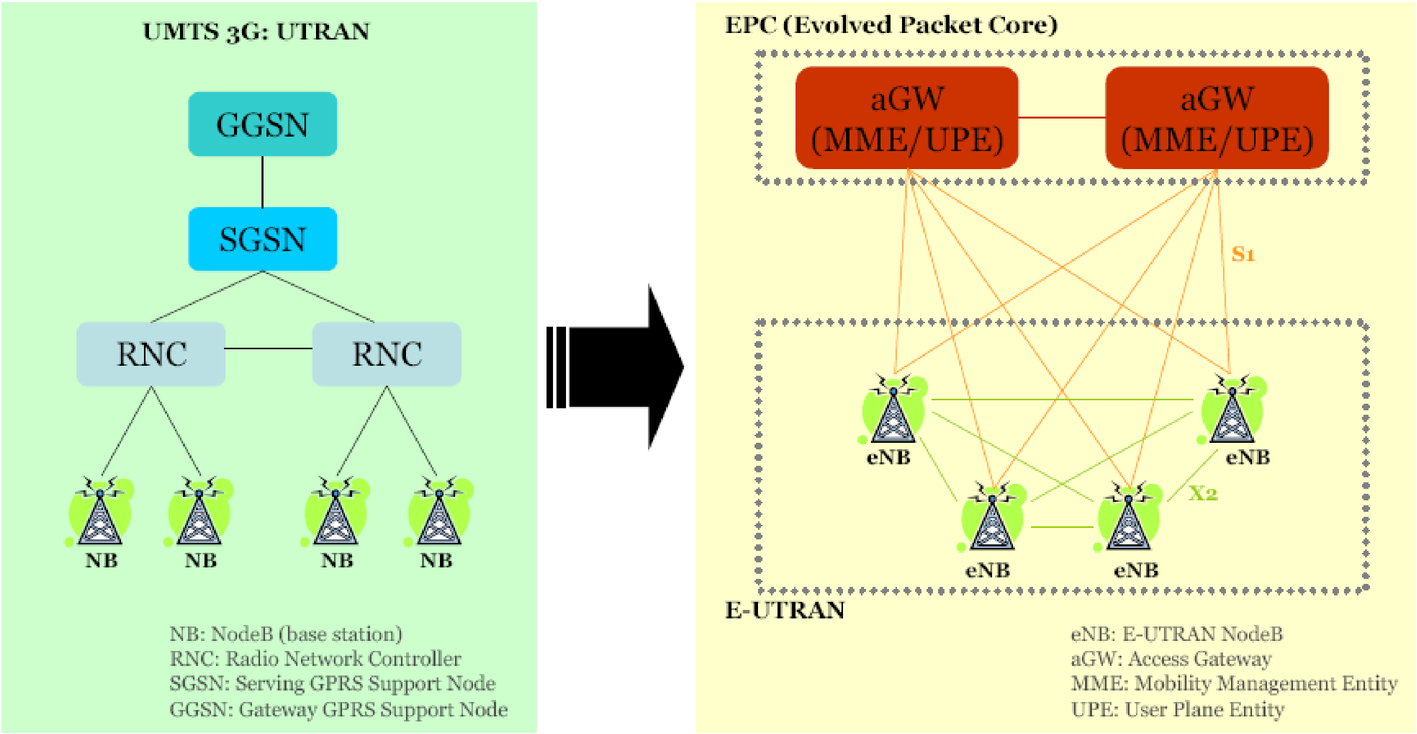
Evolved Packet Core (EPC)

Introduction to LTE

- To further **simplify the network architecture** and to **reduce user data delay**, **fewer logical and physical network components (e.g., the RNC in the Radio Network of LTE is removed)** have been defined in LTE.
  - In practice, this has **resulted in Round-Trip delay times** of **less than 25–30 milliseconds (used to be 150 ms for UMTS).**
  - This **improved User Experience** since **with faster signaling, faster Mobility Management procedures** and **faster Connection Times to the network as well as lower Packet Delays and jitter** are **achieved.**



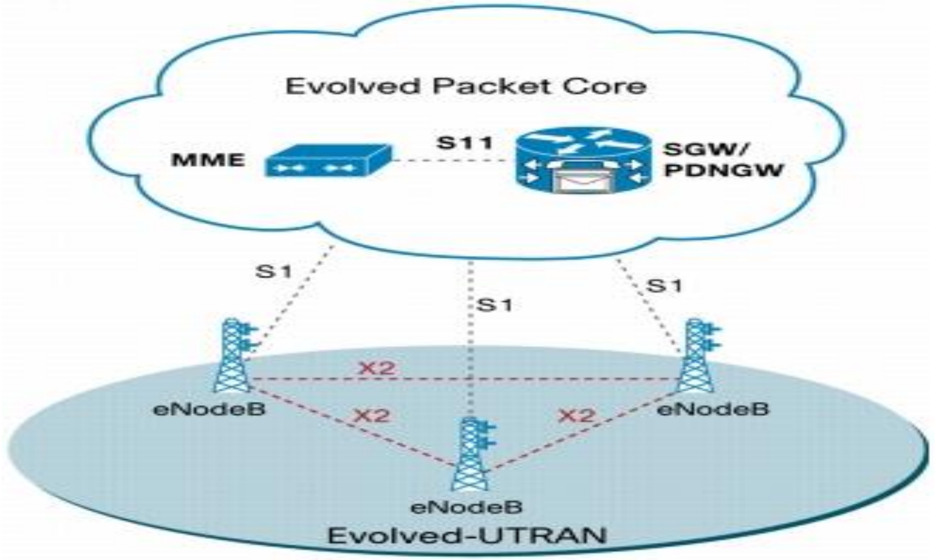
Introduction to LTE



The main difference between UMTS and LTE: The **removing of RNC network element** and the **introduction of X2 interface for communication between the BSs (eNBs)**, which **makes the radio network architecture more simple and flat**, **leading lower networking cost**, **higher networking flexibility** and **lower latency**.

Introduction to LTE

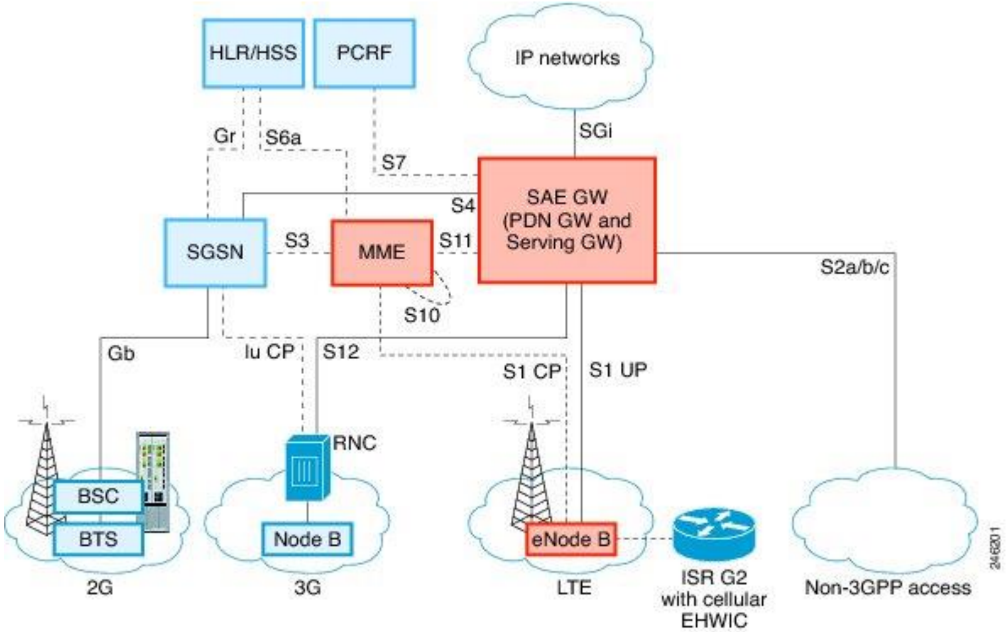
- Also, **all interfaces (S1, X2, S11, etc.) between network nodes in LTE are based on IP**.
- An **All-IP network architecture greatly simplifies the design and implementation** of the **LTE air interface**, the **Radio Network** and the **Core Network**.



Introduction to LTE

- On the **Network side**, **interfaces and protocols** have been put in place so that **Data sessions (i.e., active data connections) can be moved seamlessly between LTE, UMTS, GSM and other Non-3GPP Access (i.e., WiMAX)** when **the user roams in and out of areas covered by different air interface technologies**.

- **Thus, LTE-capable devices must also support GSM, GPRS, EDGE** and **UMTS interfaces**.



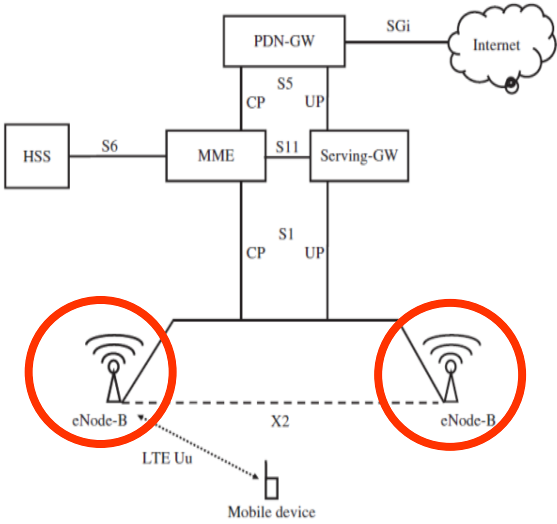
LTE Network Architecture
LTE Mobile Devices

- **In the LTE specifications**, as in UMTS, **the Mobile Device** is **referred to as the User Equipment (UE)**
- **For LTE, five (5) different UE classes (categories) have been defined**
- In the **Downlink**, **all the LTE UEs** support **64-QAM modulation**
- In the **Uplink**, **only the support of the slower but more reliable 16-QAM is required for UE Classes 1 to 4**.
  - **However, Class 5** devices have to **support 64-QAM**
- Also **all the LTE UEs have to support MIMO transmission**
  - **2x2 MIMO** for first LTE UEs
  - **4x4 MIMO** for Class 5

LTE UE categories

Category	1	2	3	4	5
Maximum downlink datarate (20 MHz carrier)	10	50	100	150	300
Maximum uplink datarate	5	25	50	50	75
Number of receive antennas	2	2	2	2	4
Number of MIMO downlink streams	1	2	2	2	4
Support for 64 QAM in the uplink direction	No	No	No	No	Yes

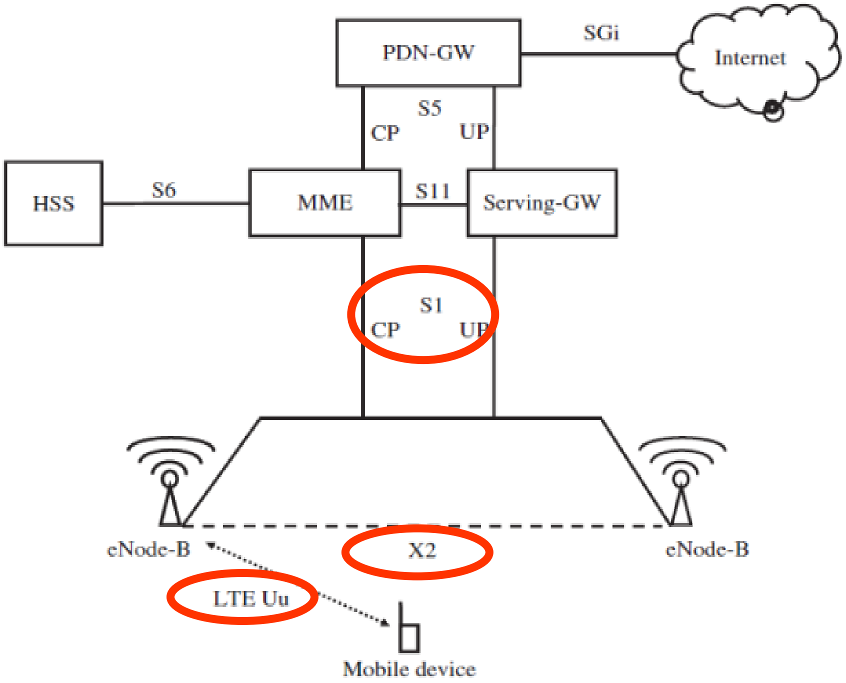
LTE Network Architecture
The eNode-B



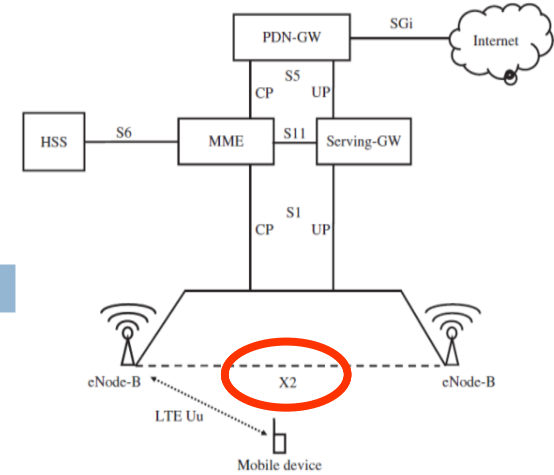
- The **most complex device** in the **LTE network** is the **Base Station, referred to as eNode-B (eNB)**.
- **Unlike in UMTS, LTE Base Stations are autonomous units.**
  - In **LTE, it was decided** to **integrate most of the functionality (i.e., Radio Resource Management) that was previously part of the Radio Network Controller into the Base Station** itself.
  - For example, **the eNode-B decides on its own to handover ongoing data transfers** to a **neighboring eNode-B**, **a novelty in 3GPP systems**.

LTE Network Architecture
The eNode-B

- The **air interface between the eNodeB and the LTE UE** is referred to as the **LTE Uu interface (this interface implements the OFDM physical Channels)**
- The **interface between the eNodeB and the Core Network** is referred to as the **S1 interface.**
- The **interface between two eNodeBs** is referred to as the **X2 interface.**



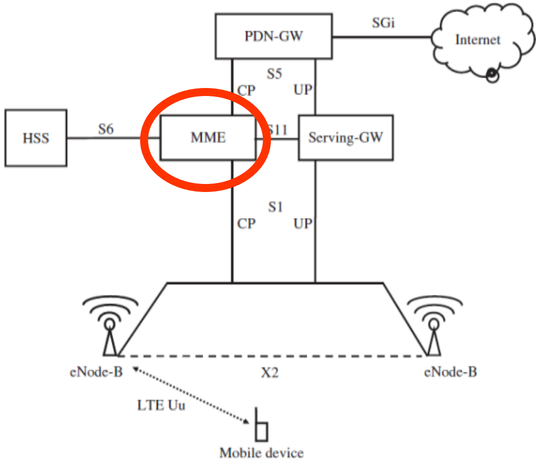
LTE Network Architecture
The eNode-B



- **As LTE Base Stations** are **autonomous units**, they **communicate directly with each other over the X2 interface** for **two purposes**:
  1. **Handovers are now controlled by the eNodeBs themselves. If the Target cell is known and reachable over the X2 interface, the cells communicate directly with each other. Otherwise, the S1 interface and the CN are employed to perform the handover.**
  2. **The X2 interface can be used for Inter-Cell Interference Coordination (ICIC). For example, as Mobile Devices can report, the noise level at their current location and the perceived source (i.e., the eNodeB that causes the noise), to their Serving eNodeB, the X2 interface can then be used by the Serving eNodeB to contact the neighboring eNodeB, in case the Neighbouring eNodeB causes a lot of noise, and agree on methods to mitigate or reduce the noise problem.**

LTE Network Architecture

The Mobility Management Entity (MME)

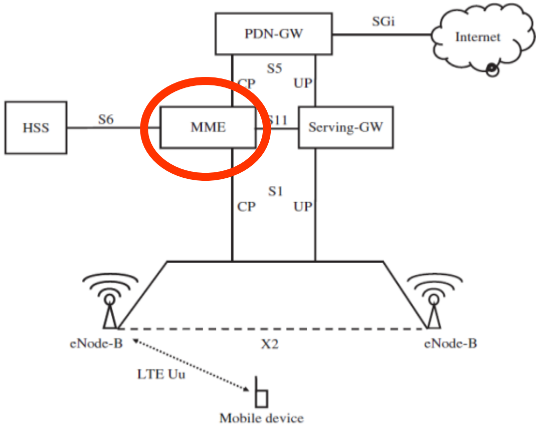


- The **eNode-Bs autonomously handle users** and **their radio connections once they are established. However overall User Control is centralized in the Core Network**.
  - This is **necessary as there needs to be a single point over which data, between the user and the Internet, flows**.
  - Further, a **centralized user database (Home Subscriber Server (HSS)) is required**, which **can be accessed from anywhere** in **the Home Network** and al**so from networks abroad in case the user is roaming**.

- The **network node responsible for all signaling exchanges between the Base Stations** and **the Core Network as well as between the Users** and **the Core Network** is **the Mobility Management Entity (MME).**

LTE Network Architecture

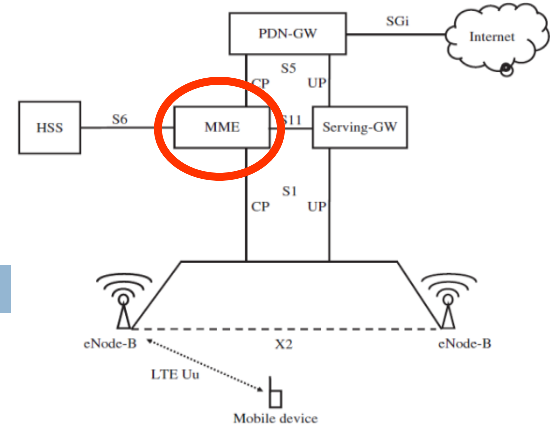
The Mobility Management Entity (MME)



- The **MME is mainly responsible for:**
  - **User's Authentication:** When a **subscriber first attaches to the LTE network** the **MME requests authentication information from Home Subscriber Server (HSS)** and **authenticates the subscriber**.
  - **Establishment of bearers: Establishment of IP tunnels (dedicated to an LTE UE) between the eNode-B and the Packet Data Network Gateway (PDN-GW)** which is the **Gateway to the Internet.**
    - Note that the **establishment of the OFDM physical channels** over the air interface **between the eNode-B and the UE** is a **responsibility of the eNodeB**.

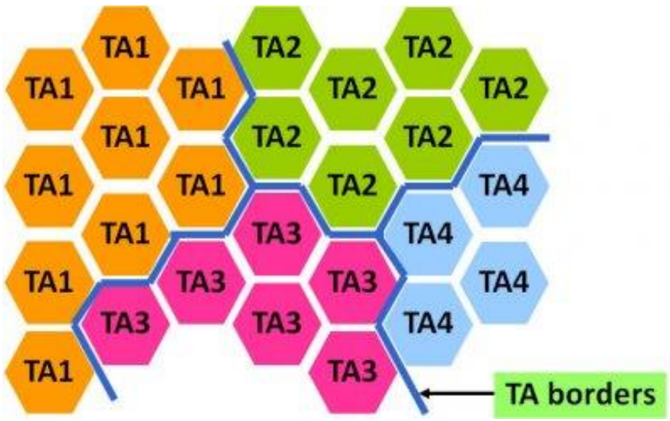
LTE Network Architecture

The Mobility Management Entity (MME)



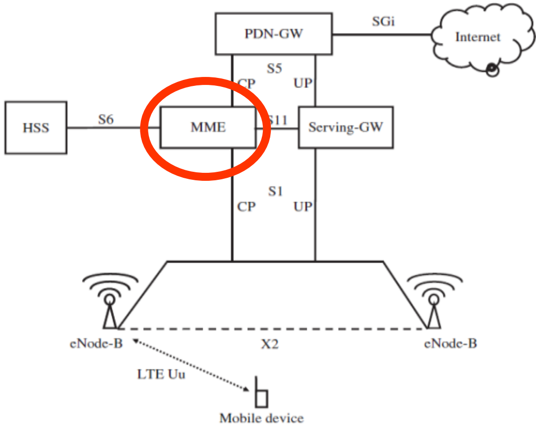
- The **MME is mainly responsible for:**
  - **Mobility Management: Locate the UE**, by **sending a Paging signal to the group of Base Stations** that belong to the **Tracking Area (TA)*** the UE is **currently roaming**.
  - **Handover support:** In case **no X2 interface** is available **between the eNodeBs**, the **MME helps to forward the handover messages between the two eNode-Bs involved**.

**** Tracking Area (TA): This Area includes a group of Bases Stations (Cells). If the LTE UE is idle, will have to inform the MME about any location update only when it enters a new Tracking Area (TA).***



LTE Network Architecture

The Mobility Management Entity (MME)



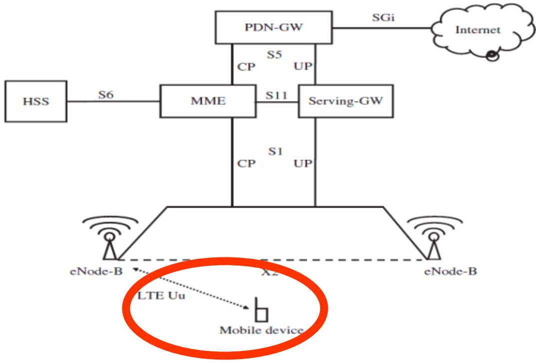
- The **MME is mainly responsible for:**
  - **Interworking with other radio networks:** When a Mobile Device **reaches the limit of the LTE coverage area**, the **eNode-B can decide** to **handover the mobile device** to a **GSM** or **UMTS network** or **instruct it to perform a cell change to a suitable cell**. In both cases, **the MME is the overall managing instance** and **communicates** with the **GSM** or **UMTS network components** during this operation.
  - **Billing and Charging:** To charge mobile subscribers for their use of the system, **billing records are created**, **on the MME**. These are **collected and sent to a charging system**, which **once a month generates** an **invoice that is then sent to the customer**.

Key Features of LTE

Most Important Key Features of LTE:

- **Multicarrier Transmission**
  - Orthogonal Frequency Division Multiple Access (OFDMA) in the Downlink (DL) Direction
  - Single Carrier - FDMA (SC-FDMA) in the Uplink (UL) Direction
- **Adaptive Modulation and Coding**
  - DL and UL modulations: QPSK, 16QAM, and 64QAM
  - Coding: Convolutional code and Rel-6 Turbo Code
- **Advanced MIMO Spatial Multiplexing**
  - (2 or 4) x (2 or 4) MIMO Downlink and Uplink supported.
- **Hybrid-Automatic Repeat ReQuest (HARQ)**
  - For fast reporting and retransmission of packets that received with errors, aiming to minimize the resulting packet delay and jitter.

Air Interface in LTE



- The **major evolution in LTE** compared to previous 3GPP wireless systems is the **completely revised air interface (based on OFDMA).**
- **When UMTS was designed an air interface, based on WCDMA, with** a **Carrier Bandwidth of 5 MHz was specified**.
- With today's **Hardware** and **Processing capabilities**, **Higher data rates can be achieved** by **using an Increased Carrier Bandwidth**.

Air Interface in LTE

- UMTS, however, **does not scale in this regard** as the **WCDMA transmission scheme (being a single carrier transmission scheme)** is **not ideal for wider channels**.
  - When the **carrier bandwidth is increased**, the **symbols need to become shorter (and thus the time between consecutive symbols needs to be reduced)** to take **advantage of the additional bandwidth (as more bits will be sent at the same amount of time)**.
  - **By increasing the transmission speed** (i.e., Data Rate), which results in a **decrease of the symbol time**, the **negative effect** of the **InterSymbol Interference (ISI) increases**.
  - **As a consequence, CDMA is not suitable for carrier bandwidths beyond 5 MHz**.
- **Thus, Multicarrier Transmission** has been **defined for LTE** to **mitigate the problems of Multipath (Fast) Fading and InterSymbol Interference (ISI)** to some degree **at the expense of rising complexity**.

Air Interface in LTE
OFDMA for Downlink Transmission

- **Instead of sending a data stream at a very high speed over a single carrier as in UMTS, OFDMA splits the data stream into many slower data streams that are transported over many subcarriers simultaneously.**
  - **Carrier Bandwitdh: 180 KHz**
  - **Subcarrier Spacing (bandwidth): 15 kHz**
  - The **advantage** of **many slow but parallel data streams** is that **symbols' duration can be sufficiently long (even 10 times greater than the Delay Spread caused)** to **avoid the effects of multipath transmission (i.e., InterSymbol Interference (ISI))**

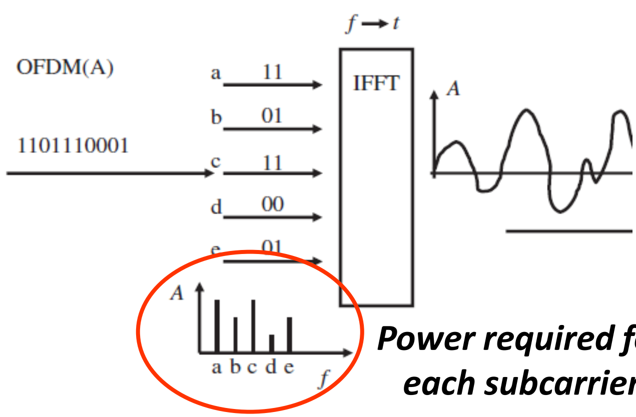
Air Interface in LTE
OFDMA for Downlink Transmission

- **Note that regardless of the overall channel bandwidth (i.e., 1.4 MHz, 5 MHz, 10 MHz, 20 MHz, etc.) the subcarrier spacing (i.e., bandwidth) remains the same (i.e., 15 KHz)**
  - For example, for a **Wider Bandwidth**, the **number of subcarriers is increased** while the **individual subcarrier bandwidth (which is 15KHz) remains the same**.

Bandwidth (MHz)	Number of subcarriers
1.25	76
2.5	150
5	300
10	600
15	900
20	1200

Air Interface in LTE
SC-FDMA for Uplink Transmission

- **For Uplink data transmissions, the use of OFDMA is not ideal because of its high Peak to Average Power Ratio (PAPR) when the signals from multiple subcarriers are combined.**
  - In practice, the **amplifier in a radio transmitter circuit has to support the Peak Power output required to transmit the data**
  - **This Peak Power output value defines the power consumption** of the **transmitting device.**
    - **Note that the Average output power required for the signal to reach the Receiver is much lower.**
    - **Hence, it can be said that the PAPR of OFDMA is very high.**



Power required for each subcarrier

With OFDMA, Data stream is divided into lower data rate streams and transmitted in a number of subcarriers (a, b, c, d, e)

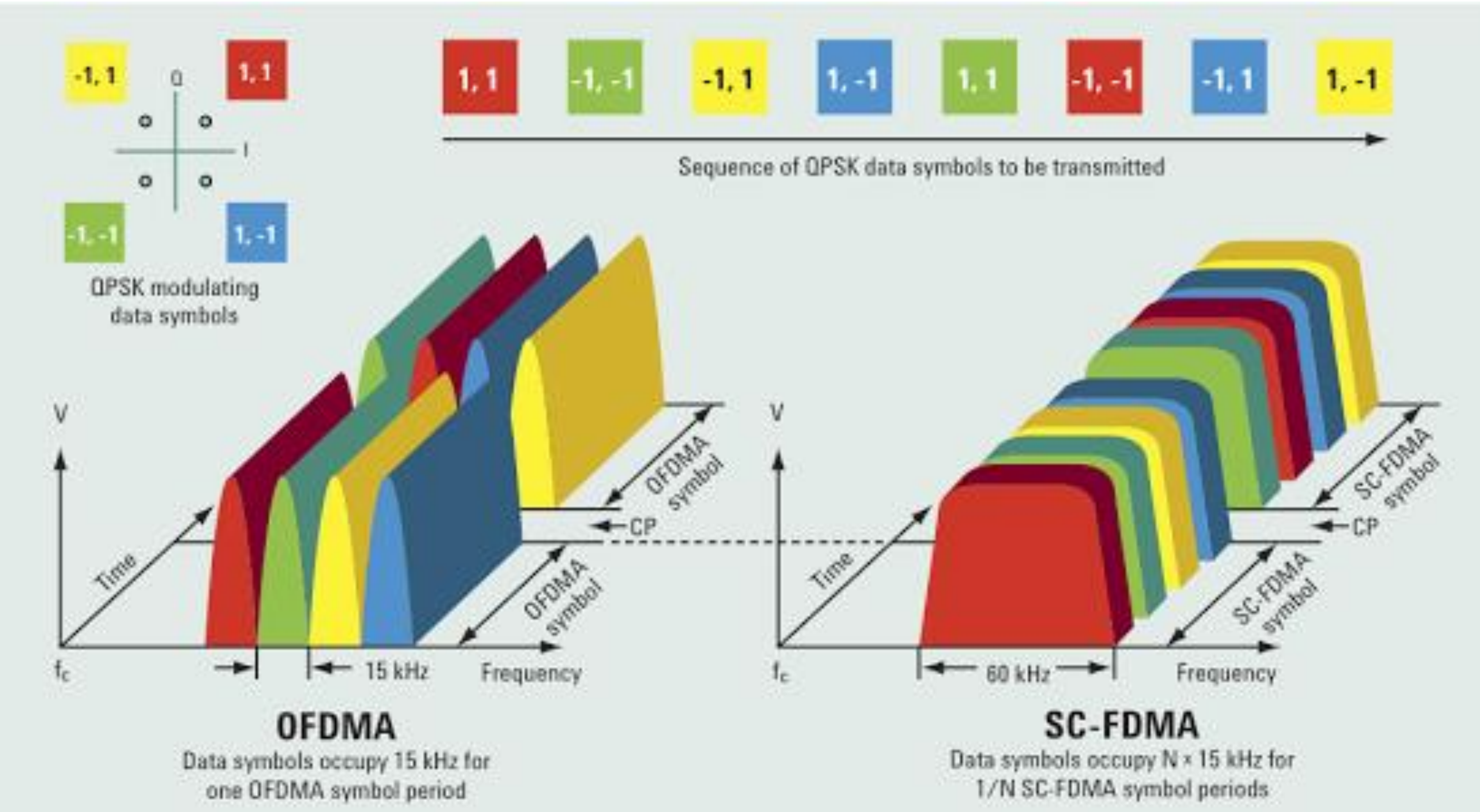
Air Interface in LTE
SC-FDMA for Uplink Transmission

- **For a Base Station, a high PAPR can be tolerated as power is not a problem (power is abundant).**
- **However, for a Mobile Device that is Battery driven, the transmitter should be as efficient as possible.**
- **3GPP has hence decided to use a different transmission scheme, referred to as Single-Carrier Frequency Division Multiple Access (SC-FDMA).**
- **SC-FDMA** is a **misleading term** as **SC-FDMA is essentially a multicarrier scheme similar to OFDMA.**

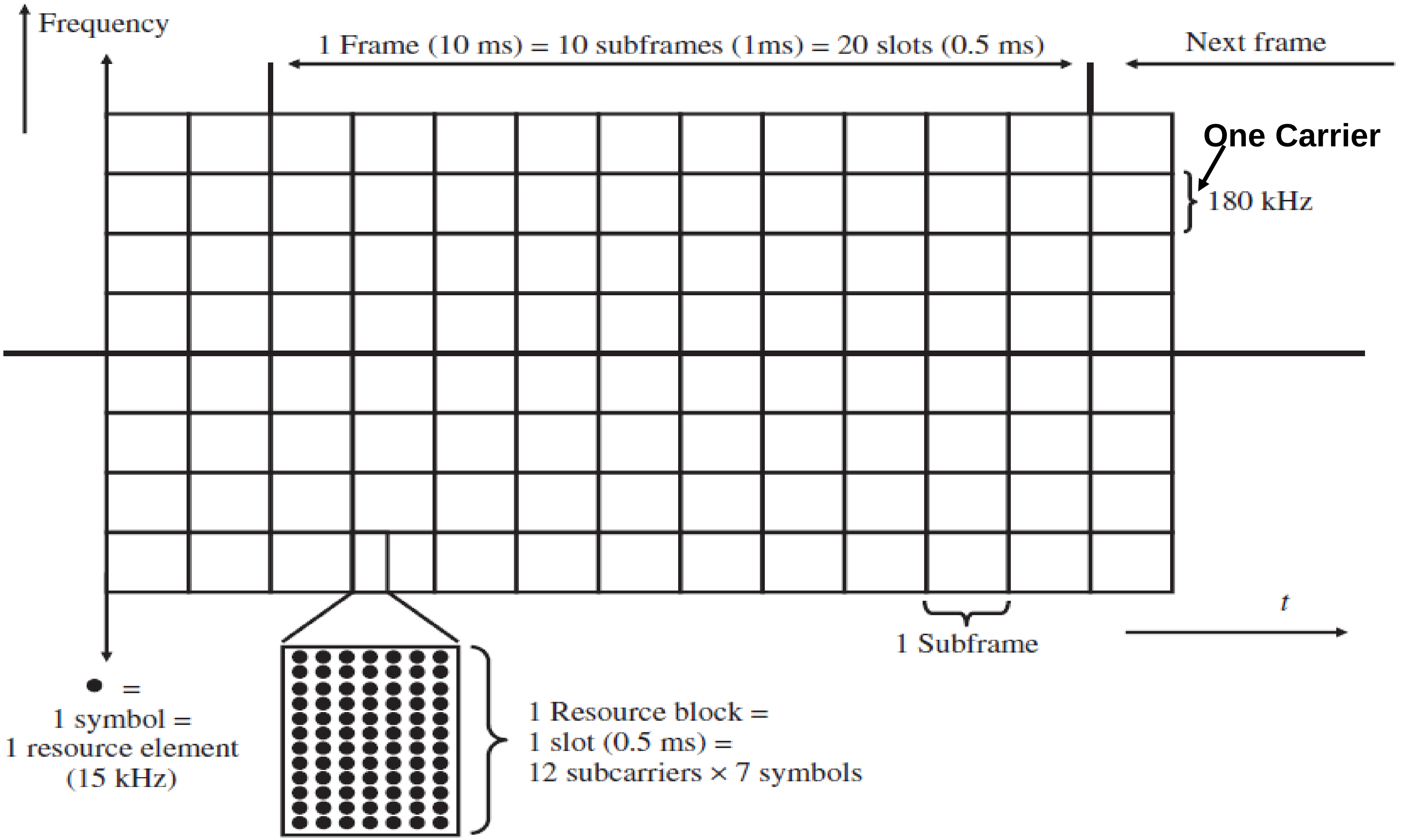
Air Interface in LTE
SC-FDMA for Uplink Transmission

- **SC-FDMA contains some additional transmission processing steps beneficial for reducing the PAPR required.**
  - **During these steps, the information of each bit is distributed onto all subcarriers used for the transmission reducing in this way the power differences between the subcarriers → In this way a much lower PAPR than that obtained with OFDMA is achieved** (by approximately **2 dB**)**.**
  - **However, the tradeoffs are additional processing complexity during the transmission and lower transmission date rates in the uplink.**

OFDMA Vs SC-FDMA

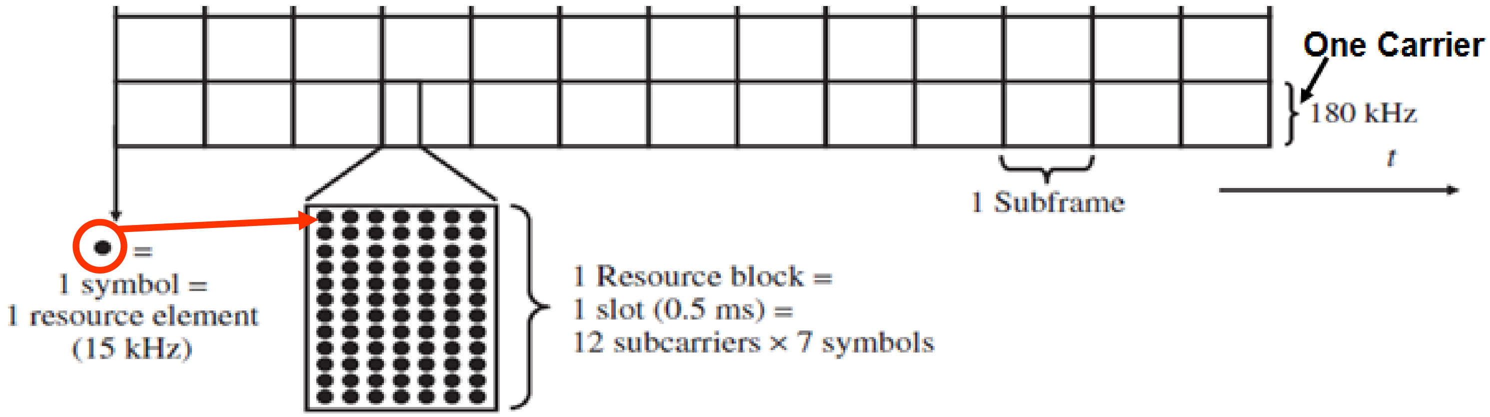


Symbols, Resource Blocks, Slots, Subframes and Frames



Symbols, Resource Blocks, Slots, Subframes and Frames

- The smallest transmission unit on each subcarrier (of 15KHz wide) is the symbol with a length of 66.667 microseconds (10^{-6} seconds)
  - Several bits can be transmitted per symbol depending on the Modulation Scheme used.
  - If radio conditions are excellent, 64-QAM (Quadrature Amplitude Modulation) is used to transfer 6 bits ($2^6 = 64$) per symbol.
  - Under less ideal signal conditions, 16-QAM or QPSK (Quadrature Phase Shift Keying) modulation is used to transfer 4 or 2 bits per symbol.
  - A symbol is also referred to as a Resource Element (RE).

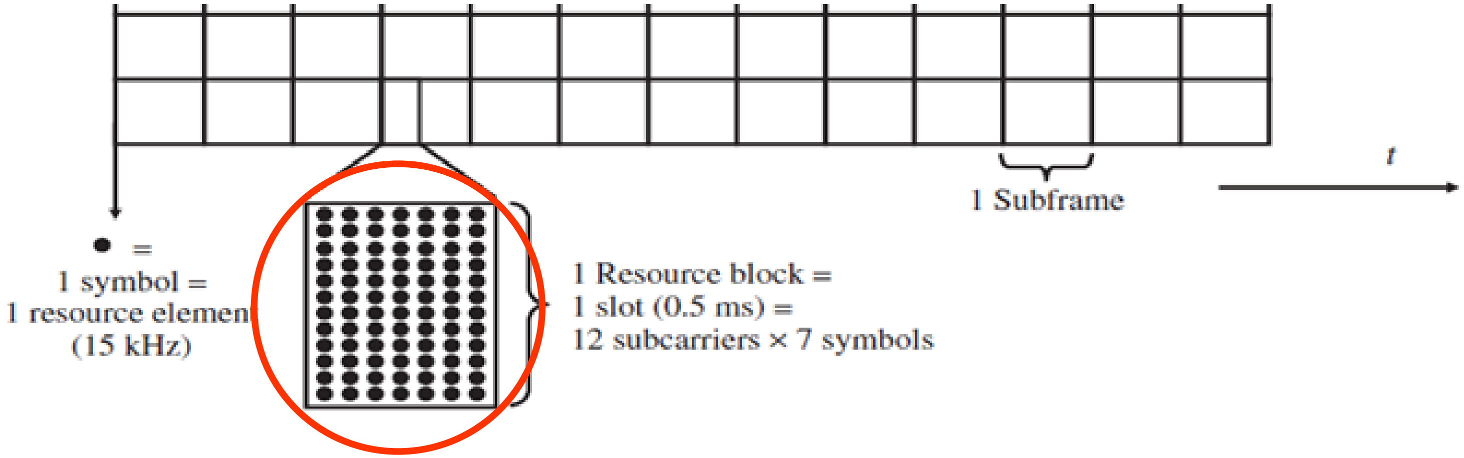


Symbols, Resource Blocks, Slots, Subframes and Frames

- **As the overhead involved in assigning each individual symbol to a certain user would be too great,** the **symbols are grouped together into a number of different steps. These are:**
  - **Resource Block (RB; 1 slot time that is 0.5 ms)**
  - **Subframe (2 slots → 2 subsequent RBs): Subframe represents the LTE scheduling time. That is every 1 ms the eNodeB schedules the parallel RBs to one or more Users.**
  - **LTE Radio Frame (10 Subframes; 20 slots → 20 subsequent RBs)**

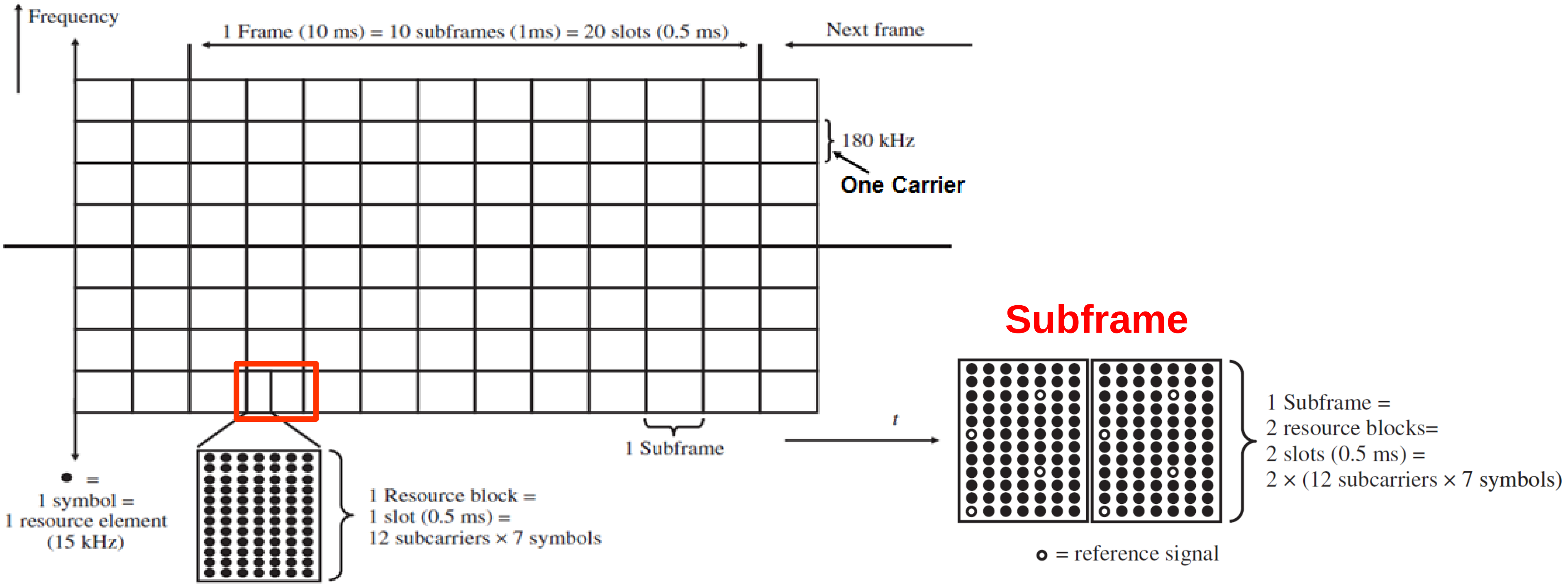
Symbols, Resource Blocks, Slots, Subframes and Frames

- **Resourse Block (RB)**
  - **Seven (7) consecutive symbols on 12 subcarriers are grouped into a Resource Block (RB).**
  - **A Resource Block (RB) occupies exactly one slot with a duration of 0.5 milliseconds**



Symbols, Resource Blocks, Slots, Subframes and Frames

- **Subframe**
  - **Two (2) slots form a Subframe** with a **duration of 1 millisecond (10^{-3} sec)**
  - **A Subframe represents the LTE scheduling time, which means that at each millisecond the eNode-B decides as to which users are to be scheduled and which Resource Blocks (RBs) are assigned to which user.**

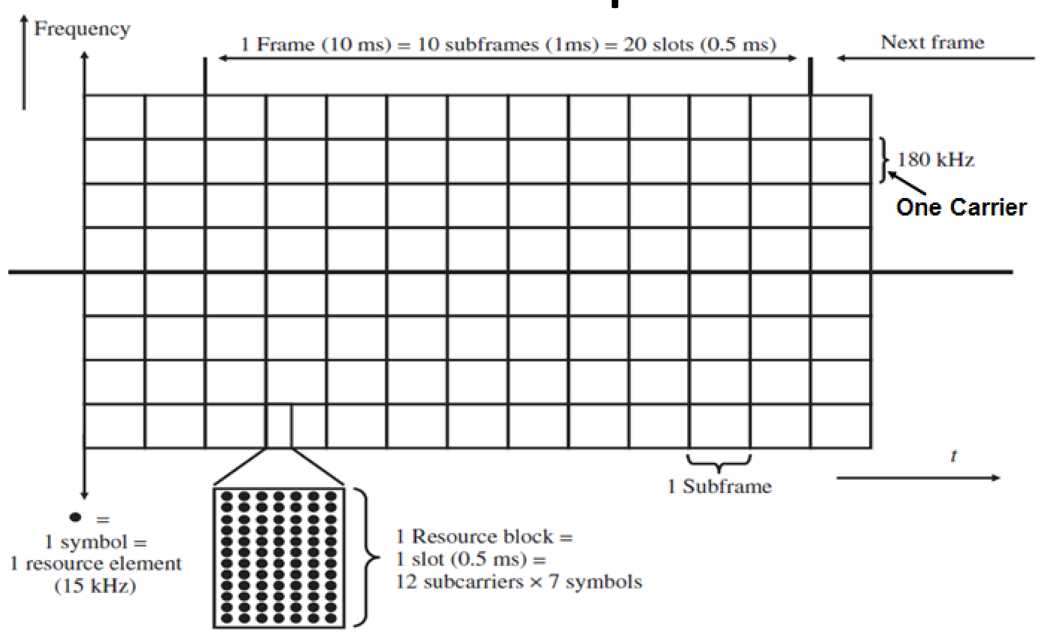


Symbols, Resource Blocks, Slots, Subframes and Frames

Bandwidth (MHz)	Number of subcarriers
1.25	76
2.5	150
5	300
10	600
15	900
20	1200

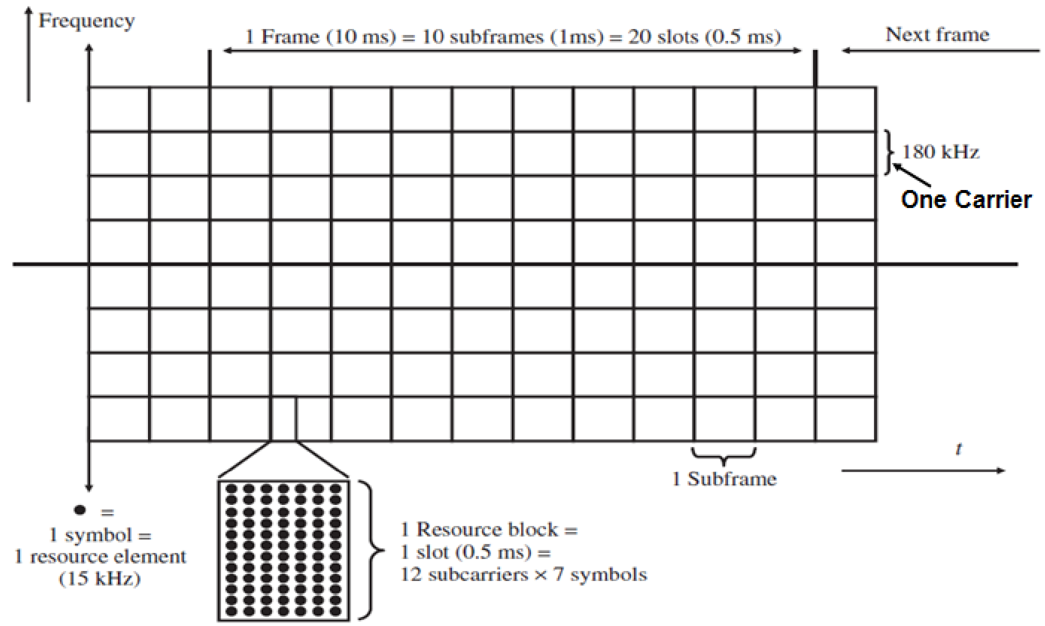
- The **number of parallel Resource Blocks (RBs)** in each **Subframe period** depends on the **system Bandwidth**.
- For example, if a **10-MHz bandwidth carrier** is used, **600 subcarriers are available**. As a **Resource Block (RB)** includes **12 subcarriers**, a **total of 50 parallel RBs** are **available in each slot of a Subframe.**
  - As a Subframe is **formed by two slots** (and each slot includes one RB), **100 RBs** can be **scheduled for one or more users** per **Subframe time**.

Note that on the figure on the right (for simplification) only eight parallel Resource Blocks are shown in the y-axis. On a 10-MHz carrier, for example, 50 Resource Blocks are used in parallel in each slot of a Subframe.



Symbols, Resource Blocks, Slots, Subframes and Frames

- **LTE Radio Frame**
  - **Finally, 10 Subframes are combined into an LTE Radio Frame, which has a length of 10 milliseconds.**
  - **LTE Radio Frames are also used for the scheduling of periodic System Information (SI) conveying information that is required by all UEs that are currently in the cell.**



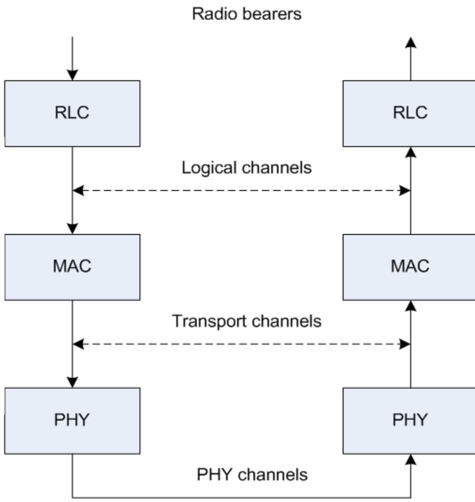
System information blocks and content overview

Message	Content
MIB	Most essential parameters required for initial access
SIB 1	Cell identity and access-related parameters and scheduling information of system information messages containing the other SIBs
SIB 2	Common and shared channel configuration parameters
SIB 3	General parameters for intrafrequency cell reselection
SIB 4	Intrafrequency neighbor cell reselection information with information about individual cells
SIB 5	Interfrequency neighbor cell reselection parameters
SIB 6	UMTS inter-RAT cell reselection information to UMTS
SIB 7	GSM inter-RAT cell reselection information to GSM
SIB 8	CDMA2000 inter-RAT cell reselection information
SIB 9	If the cell is a femto cell, i.e. a small home eNode-B, this SIB announces its name
SIB 10	Earthquake and tsunami warning system (ETWS) information
SIB 11	Secondary ETWS information
SIB 12	Commercial mobile alert system (CMAS) information

LTE Channel Structure

Type of Channels

Note: LTE defines same type of channels as WCDMA/HSPA



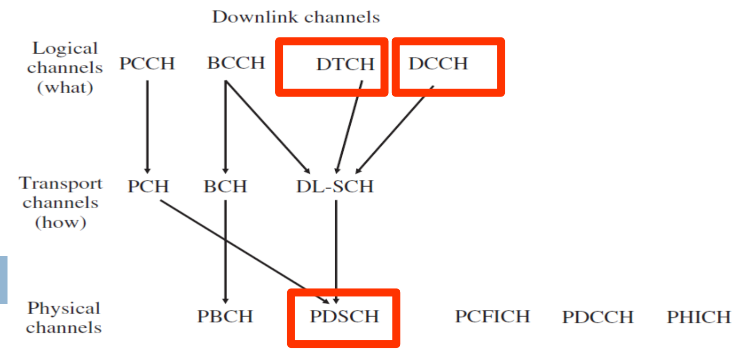
- **Logical channels**
  - **Formed by RLC (Radio Link Control) layer**
  - **Characterized by the type of information it carries (what) (i.e., Control channel used to carry Control Information, a traffic channel is used for the user data)**
- **Transport channels**
  - **Formed by MAC (Medium Access Control) layer**
  - **Characterized by how the data will be transmitted (i.e., defines the Transport Format (TF)*) over the Radio Interface (i.e., the Physical Layer).**
- **Physical channels**
  - **Formed by PHY (Physical Layer – OFDM Channels)**
  - **Consist of a group of RBs that will be assigned to the users (the data in the RBs will be transmitted based on the TF selected by the MAC layer)**

Transport Format (TF): Specifies how the data is to be transmitted over the radio interface (e.g., Modulation Scheme, Coding, Antenna Mapping (e.g., type of MIMO used))

LTE Channel Model Downlink Direction

- All Downlink **Control Signaling** and **User Data traffic** are organized in:
  - **Logical channels → Determines the Data and type of data that will be transmitted; e.g., Control signaling, User Traffic**
  - **Transport channels → Determines how the data will be transmitted; e.g., Multiplexing, Transport Format that will be used**
  - **Physical channels → Determines the RBs that will be assigned to the users for the data to be transmitted**

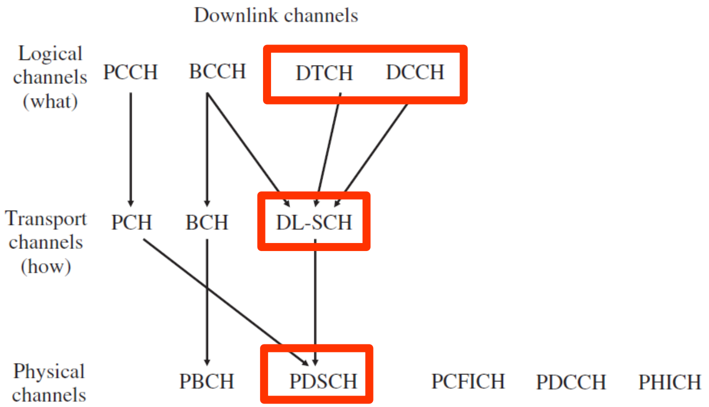
LTE Channel Model Downlink Direction



- **On the** **Logical Layer**, **data (user traffic) for each user** is transmitted in a **Logical Dedicated Traffic Channel (DTCH)**
  - **Each User has an individual DTCH.**
- **A UE that has been assigned a DTCH** also **requires a Dedicated Control Channel (DCCH)** for the **management of the connection**.
  - **Here, the control signaling that is required, for example, for handover control, channel reconfiguration, is sent.**

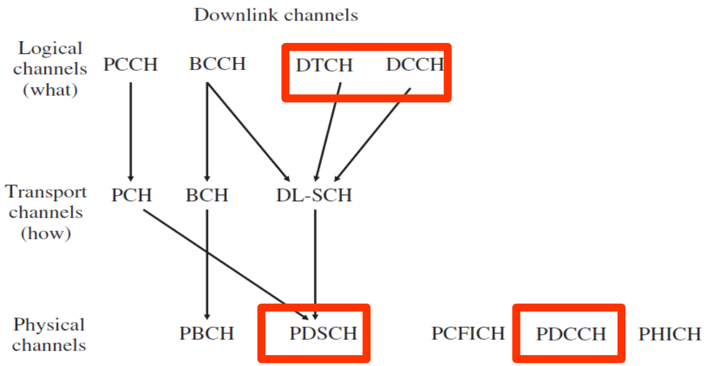
- **On the air interface** (i.e., on the **Physical layer**), **all Dedicated Channels** are **mapped to a single shared channel** that **occupies all Resource Blocks (RBs)** **that will be assigned to the users** (this channel is the **Physical Downlink Shared Channel (PDSCH)**).

LTE Channel Model Downlink Direction



- The **DTCH** and the **DCCH assigned to each user** are **mapped** to **individual Resource Blocks** in the **Physical Downlink Shared Channel (PDSCH)** in two steps.
- **In the first step, the logical DTCH and DCCH of each user are multiplexed (into a data stream) to the Transport layer in the Downlink Shared Channel (DL-SCH) and the Transport Format (Modulation, Coding and MIMO used) that will be used during their transmission is determined.**
- **In the second step, this data stream is then mapped to the Physical Downlink Shared Channel (PDSCH) (i.e., to the Resource Blocks that are allocated to the users)**
  - **Which Resource Blocks** are **assigned** to **which user** is **decided** by the **scheduler in the eNodeB for each Subframe**, that is, **once per millisecond.**

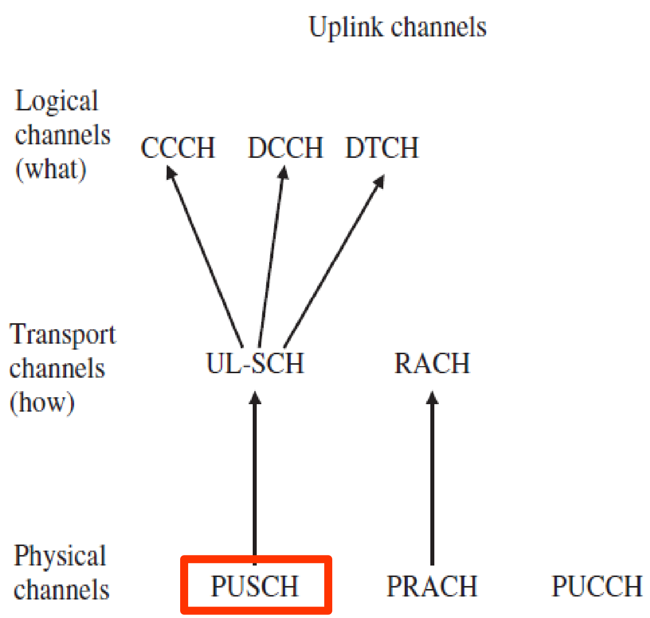
LTE Channel Model Downlink Direction



- **Note that ALL the DTCH and DCCH of all the users** are **mapped to a single PDSCH.**
- Therefore, a **mechanism is required to indicate to each UE**:
  - **When and where (i.e., which RBs in the Subframe), what kind of data (i.e., traffic or control) is scheduled for them and how (i.e., the Transport Format (TF) that will be used) data are transmitted to them** on the **PDSCH in the Downlink Direction.**
  - **Which RBs is allowed to use in the Uplink direction**.
- This is done via **Physical Downlink Control Channel (PDCCH)** messages.

LTE Channel Model Uplink Direction

- In the **Uplink direction**, a similar channel model is used as in the downlink direction.
- The **most important channel** is the **Physical Uplink Shared Channel (PUSCH)**.
- The **PUSCH** main task is to **carry** the **User Data Traffic** and **Control Signaling as well as Downlink Signal Quality Feedback.**
  - **Signal Quality Feedback will be considered by the eNodeB to adapt the Transport Format that will be used in the Downlink for the specific UE (for the subsequent RBs) according to its downlink channel conditions.**



LTE Channel Model
Uplink Direction

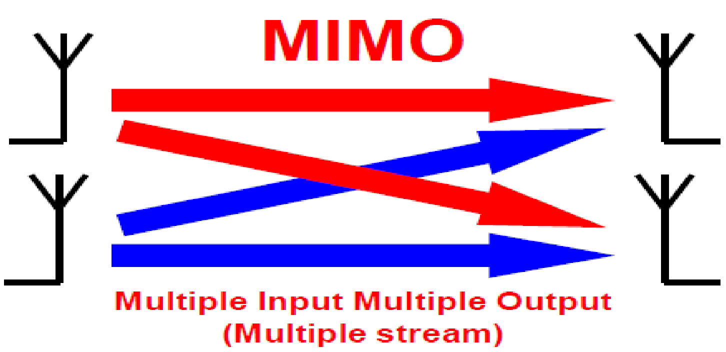
- When a **Mobile Device** **has been granted resources** **(i.e., RBs have been reserved and assigned for it in the next 1ms)**, the **PUSCH** is used for **transmitting the** **user data traffic** **(over the DTCH)** and also for **transmitting** **Control Signaling Data** **(over the DCCH)**
  - The **Control Signaling Data** is **required to**
    - **Maintain the Uplink connection** and
    - **Optimize the data transmission** **over the** **Downlink connection**.

LTE Channel Model Uplink Direction

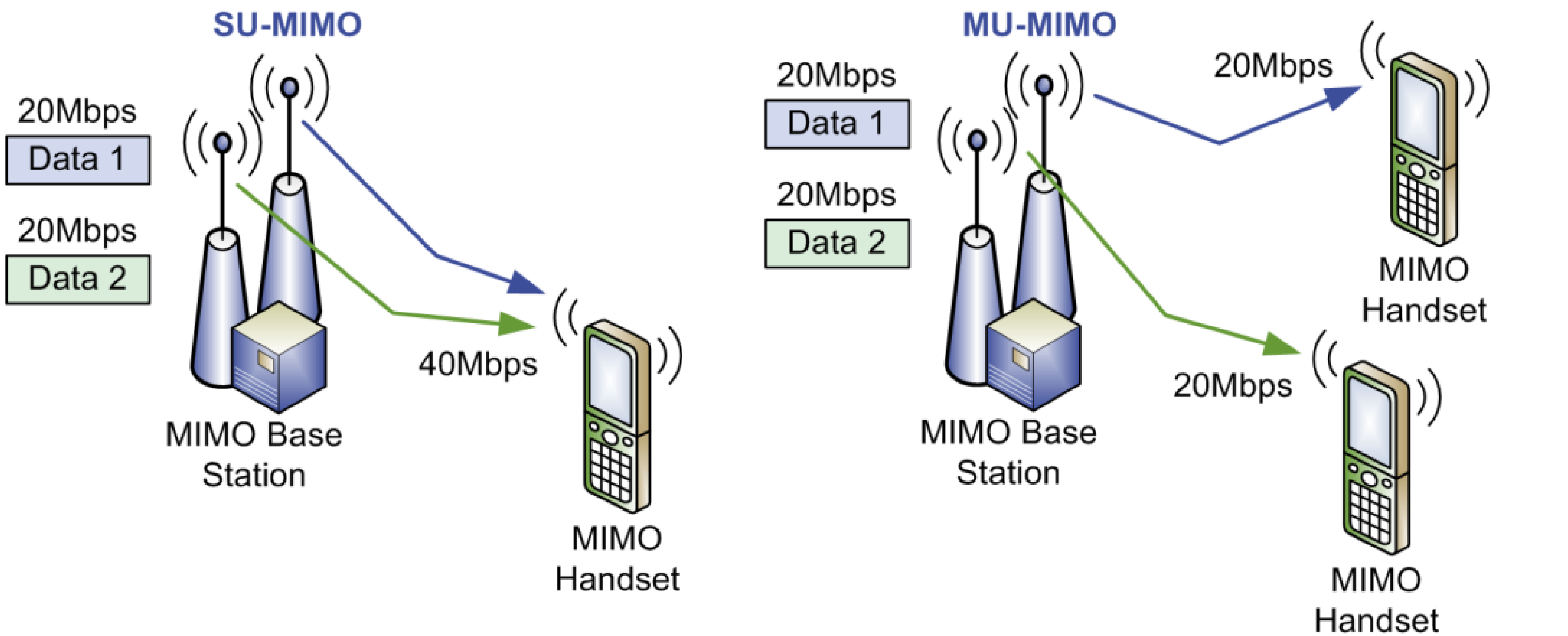
- The **main Control Signaling Data sent in the PUSCH is**:
  - The **Channel Quality Indicator (CQI)** that the **eNode-B considers to adapt the Modulation and Coding Scheme** for the **Downlink direction.**
  - **MIMO-related parameters (Rank Indicator (RI)) that the eNode-B can use for adapting the MIMO transmission in the Downlink direction (i.e., number of independent data streams the UE can receive based on its channel conditions).**
    - **Rank 1 signifies a single-stream transmission (i.e., a single stream is sent over multiple antennas which boost the SNR at the UE)**
    - **Rank 2 signifies a two-stream MIMO transmission (i.e., two independent data streams are sent over the same air interface increasing the achievable throughput).**

MIMO Transmission & Adaptive Modulation and Coding

- In addition to **Adaptive Modulation and Coding,** LTE allows **the use** of **Multi-Antenna techniques**, also referred to as **Multiple Input Multiple Output (MIMO)** in **the Downlink direction**.
- The **basic idea behind MIMO techniques** is to **send several independent data streams** over the **same air interface channel simultaneously (e.g., Spatial Multiplexing)**.
- **In Spatial Multiplexing, a high-data rate signal is split into multiple lower-rate streams and each stream is transmitted from a different transmit antenna in the same frequency channel.**



MIMO Transmission & Adaptive Modulation and Coding



Single User – MIMO (SU-MIMO): *"Conventional" MIMO.* One user gets the full benefit of the increased throughput.

Multi User – MIMO (MU-MIMO): The BS schedules two users to be served at the same time.

MIMO Transmission & Adaptive Modulation and Coding

- **Higher Order Modulation scheme** (i.e., **64QAM**) and **two stream operation MIMO (Rank 2)** is **only used for** the **Physical Downlink Shared Channel (PDSCH)** and **only to transmit those Resource Blocks assigned to users that experience very good signal conditions**.
  - **For other channels (i.e., the BCH which carries the Master Information Block (MIB) including the most essentials parameters required for initial access)**, **only single-stream operation** with a **Robust Modulation (i.e., QPSK) and Coding is used** → This is done because the **eNode-B has to ensure** that the **data transmitted over those channels can reach all Mobile Devices independent of their location and current signal conditions**.

MIMO Transmission & Adaptive Modulation and Coding

- **Once the interference gets too strong (this is indicated in the CQI sent by the UE to the eNodeB), the Modulation scheme has to be lowered, that is, instead of using 64-QAM and two stream operation MIMO together, the Modulation is reduced to 16-QAM and single stream operation MIMO.**
  - **The Transport Format and the MIMO transmission that will be used depends on the characteristics of the downlink channel, and it is the eNodeB's task to make a proper decision on how to transmit the data.**

MIMO Transmission & Adaptive Modulation and Coding

- **Only in very ideal conditions, that is, no interference and very short distances between the Transmitter and the Receiver, can 64-QAM and MIMO be used simultaneously.**
- **As Modulation and Coding and the use of MIMO can be adapted every millisecond (scheduling time of RBs to the UEs) on a per device basis, the system can react very quickly to changing radio conditions (e.g., like the Fast Power Control used in UMTS).**

MIMO Transmission & Adaptive Modulation and Coding

- **In the LTE specifications, the term 'Rank' is often used to describe the use of MIMO. E.g.,**
  - **Rank 1 signifies a single-stream transmission (i.e., a single stream is sent over multiple antennas which boost the SNR at the UE)**
  - **Rank 2 signifies a two-stream MIMO transmission (i.e., two independent data streams are sent over the same air interface increasing the achievable throughput).**

MIMO Transmission & Adaptive Modulation and Coding

- **The UE, every one millisecond, based on its downlink channel conditions, sends to the eNode-B (along with other control information) a Rank Indicator (RI) and a Channel Quality Indicator (CQI).**
  - **The RI informs the eNode-B about the number of data streams that can be sent over the channel from the receiver's point of view.**
  - **The CQI information is considered by the eNode-B to decide as to which modulation (QPSK, 16-QAM, 64-QAM) and which coding rate, that is, the ratio between user data bits and error detection bits in the data stream that should be used for the transmission.**

Ερωτήσεις;

Additional Slides

3GPP Evolution

- **2G: Started years ago with GSM (Mainly voice, SMS) → ~ 1992**
- **2.5G: Added Packet Services (GPRS, EDGE) → ~ 2000**
- **3G: Added 3G (WCDMA) Air Interface (UMTS) → ~ 2001**
  - **3G Architecture evolved to:**
    - **Support of both 2G/2.5G and 3G Access**
    - **Support Handover between GSM and UMTS technologies**
  - **3G Extensions to Increase Bit Rates and User Experience: → ~ 2006**
    - **HSPA (up to 14.4 Mbps), HSPA+ (up to 42 Mbps)**
- **4G (3.9G – 4G; Heterogeneous Networks): Redesigned the Radio Network (based on OFDMA Air Interface; Flat Architecture) and the Core Network (New All-IP Core Network with fewer nodes) ~ 2012**
  - **Long Term Evolution (LTE) and Long Term Evolution Advanced (LTE Advanced)**
- **5G: Future Networks. Demands for new architectures, methodologies** and **technologies, to support the high data traffic and massive device support foreseen by 2020.**

3GPP Evolution (UMTS Releases)

Release	Standardized	Commercial	Major features
3GPP R99	1999 (WCDMA)	2000	**UMTS/WCDMA**, **Packet Data Bearer services**, 64 kbit/s CS, 384 kbit/s PS, Call services: Compatible with GSM
3GPP R5	2002 (WCDMA)	2006	**HSDPA, IP Multimedia Subsystem (IMS),** IPv6, IP transport in UTRAN, Improvements in GERAN,
3GPP R6	2004 (WCDMA)	2007	**Multimedia Broadcast and Multicast System (MBMS), HSUPA**, Improvements in IMS, Fractional DPCH
3GPP R7	2007 (WCDMA)	2008	**64 QAM , DL MIMO, VoIP over HSPA**, CPC - Continuous Packet Connectivity, FRLC - Flexible RLC
3GPP R8	2008 (WCDMA)	2010	**HSPA+, HSUPA 16QAM**
3GPP R8 (LTE)	2008 **(OFDM)**	2010	**New air interface** (**OFDM/SC-FDMA**), **New Core Network**

- Through 3GPP standardization efforts, **3G continues to progress gracefully evolving into 4G** starting from **Release 7** and **Release 8**.
  - **Data Rates:** R99: 0.4Mbps UL, 0.4Mbps DL, R5: 0.4Mbps UL, 14Mbps DL, R6: 5.7Mbps UL, 14Mbps DL, R7: 11Mbps UL, 28Mbps DL, R8: 50Mbps UL on LTE, 160 Mbps DL on LTE, 42Mbps DL on HSPA

3GPP Evolution

- **With Release 7 and Release 8** there are **two branches of the standards:**
  - **HSPA**: **Gradual performance improvements** at **lower incremental costs (as the same infrastructure is used)**
  - **LTE**: **Revolutionary changes** with **significant performance improvements, but with higher cost.**
    - **First step Towards IMT advanced, specifying the requirements towards a 4G Wireless Networks.**

3GPP Evolution (LTE Releases)

Release	Standardized	Major features
3GPP R8 (LTE)	2008	Multi antenna support (MIMO), Channel Dependent Scheduling, Bandwidth Flexibility, ICIC (Intercell Interference Coordination), Hybrid ARQ, FDD + TDD support
3GPP R9 (LTE)	2009	Dual Layer Beam Forming, Network based UE positioning, MBSFN (Multicast/Broadcast Single Frequency Network)
3GPP R10 (LTE) LTE Advanced	2010	Multi Antenna Extension, Relaying, Carrier Aggregation, Heterogeneous Networks (HetNet's)

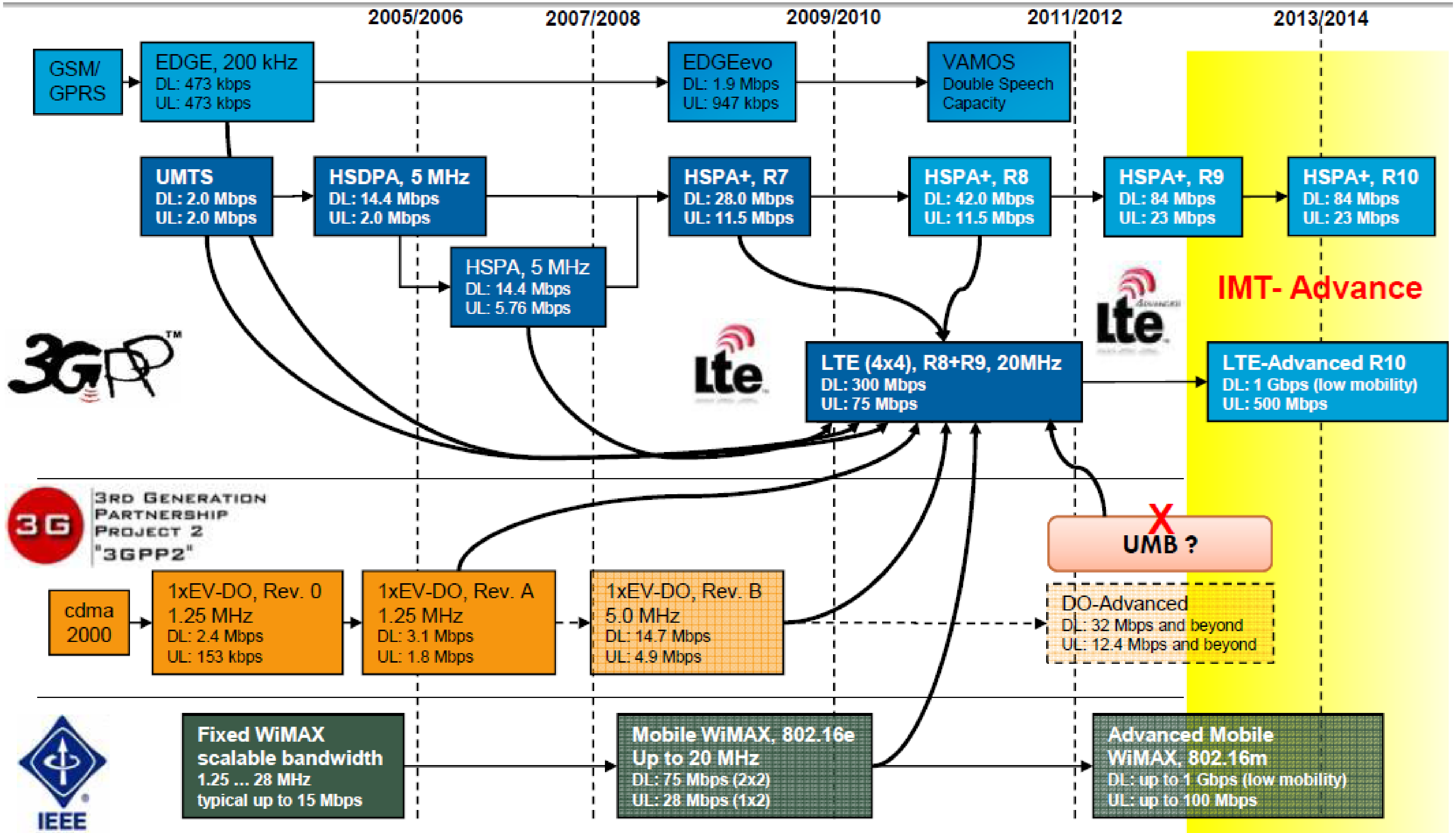
- **LTE has an "Evolution Path" of its own**
- **The evolution is towards LTE Advanced (4G)**

LTE Main Features

Parameter	Details
Peak DL speed with 64QAM in Mbps	100 (SISO), 172 (2x2 MIMO), 326 (4x4 MIMO)
Peak UL speeds(Mbps)	50 (QPSK), 57 (16QAM), 86 (64QAM)
Data Type	All Packet Switched data → Voice must use VoIP. No Circuit Switched Services (Voice or Data) are supported.
Flexible Channel Bandwidth (MHz)	1.4, 3, 5, 10, 15, 20 (Higher Bandwidth → Higher Data Rates)
Duplex Schemes	FDD and TDD
Mobility	Maximum Performance for low mobility users (0 - 15 km/h) High Performance for 15 - 120 km/h Maximum supported speed 500km/h
Reduced Latency	User plane (data traffic): < 5ms Control plane (control traffic): < 50ms
Spectral Efficiency (compared to Release 6 HSPA)	Downlink: 3 - 4 times better throughput than Rel 6 HSDPA Uplink: 2 - 3 times better throughput Rel 6 HSUPA
Access Schemes	OFDMA (Downlink) SC-FDMA (Uplink)
Modulation Types Supported	QPSK, 16QAM, 64QAM (Uplink and Downlink)

3GPP Evolution

LTE-Advanced: Technology Evolution Towards 4G

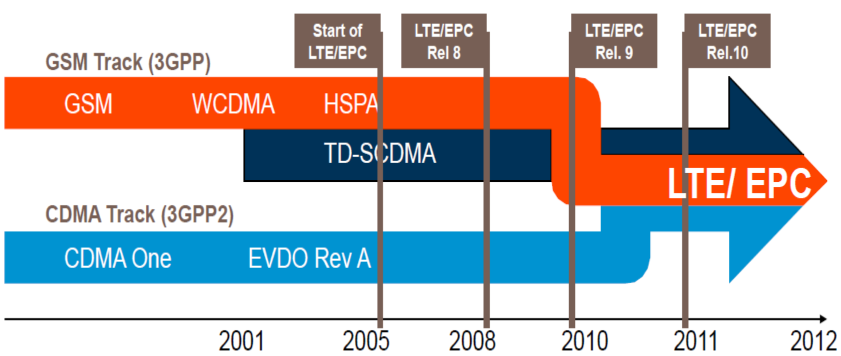


Multipath Fading

- Multipath fading can be observed when radio waves bounce off objects on the way from transmitter to receiver, and hence the receiver does not see one signal but several copies arriving at different times.
- As a result, parts of the signal of a previous transmission step (symbol) that has bounced off objects and thus took longer to travel to the receiver overlap with the radio signal of the current transmission step that was received via a more direct path.
- The shorter a transmission step (i.e., the shorter the symbol time), the more the overlap that can be observed and the more difficult it gets for the receiver to correctly interpret the received signal.

Introduction to LTE

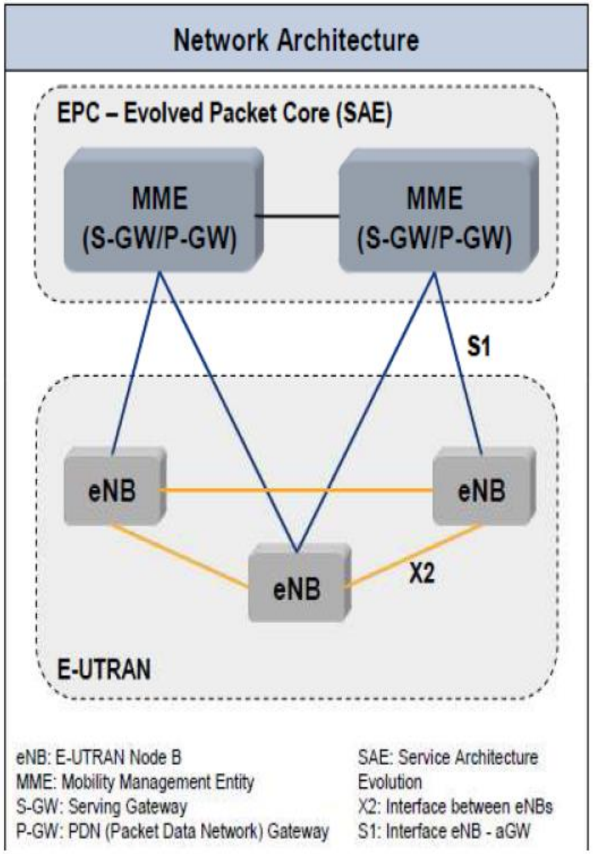
- **Long Term Evolution (LTE)**, as specified in **3GPP Release 8 (standardized on 2008 and commercialized on 2010)**, was a **new beginning** and also a **foundation for further enhancements**.
- **With 3GPP Release 10, new ideas (e.g., Carrier Aggregation – up to 100 MHz Carrier Bandwidth, 8 x 8 MIMO, etc.)** to **further push the limits are specified** as part of the **LTE-Advanced project** to comply with the **International Telecommunication Union's (ITU's) IMT-Advanced requirements for 4G Wireless Networks (Heterogeneous Networks)**



		LTE	LTE-Advanced	IMT-Advanced
		3GPP Release 8	3GPP Release 10	International Telecommunications Union "True 4G"
Peak Data Rate	DL	300 Mbps	1 Gbps	100 Mbps (high mobility) 1 Gbps (low mobility)
	UL	75 Mbps	500 Mbps	
Peak Spectrum Efficiency [bps/Hz]	DL	15	30	15
	UL	3.75	15	6.75
Tx Bandwidth	UL & DL	Up to 20 MHz	Up to 100 MHz	Up to 40 MHz

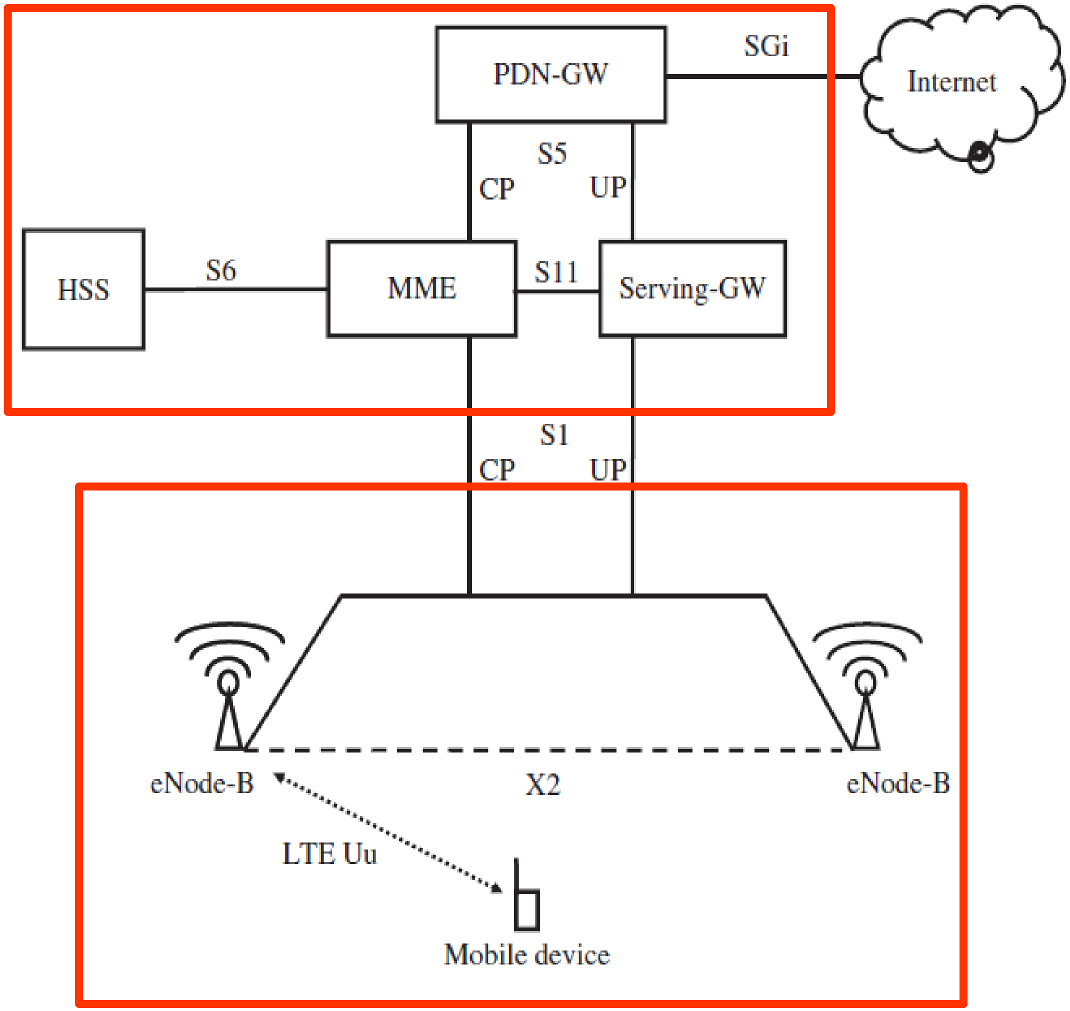
LTE Network Architecture

- **Long Term Evolution** (LTE) encompasses the **evolution of the radio access** through the **E-UTRAN** and the **Non-Radio aspects** under the term **System Architecture Evolution (SAE)**
- **At a high-level, the LTE network is comprised of the:**
  - **Core Network (CN), called Evolved Packet Core (EPC) in SAE.**
  - **Radio Access Network called Enhanced UTRAN (E-UTRAN)**
- **CN is responsible for the overall control of the UE and the establishment of the bearers. → A bearer is an IP packet flow with a defined QoS between the Gateway (in the Core Network) and the User Equipment (UE)**



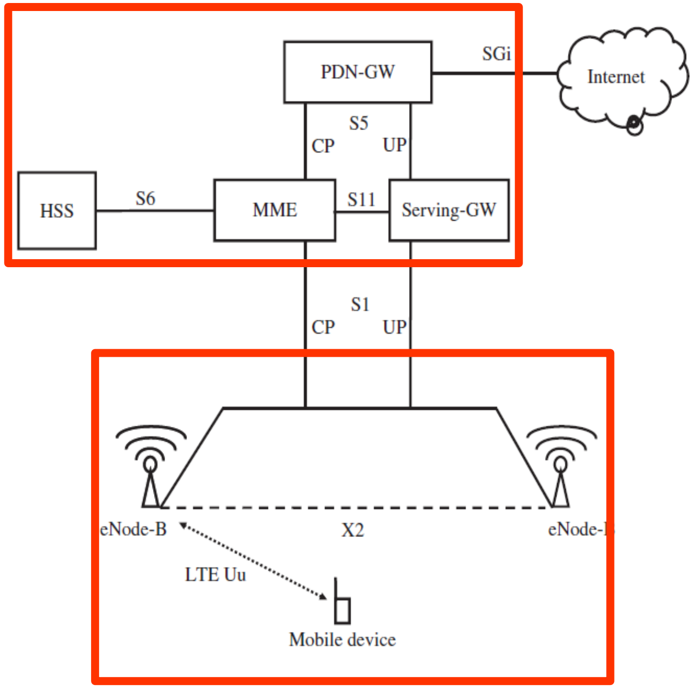
LTE Network Architecture
Service Architecture Evolution (SAE)

- The general **LTE network architecture** is **similar to that of UMTS**.
- In principle, the network is separated into a **Radio Network part** and a **Core Network part**.
- However, the **number of logical network nodes**, has been **reduced** to **simplify** the **overall architecture** and **reduce cost** and **latency** in the network.

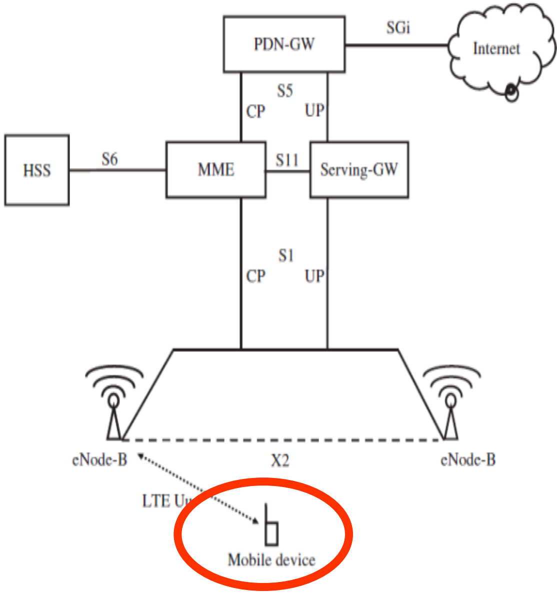


LTE Network Architecture
Service Architecture Evolution (SAE)

- **The main logical nodes in the Evolved Packet Core (EPC) are:**
  - Packet Data Network Gateway **(PDN-GW)**
  - Serving Gateway **(S-GW)**
  - Mobility Management Entity **(MME)**
- **EPC also includes other nodes and functions,** such as **the Home Subscriber Server (HSS)**
- **E-UTRAN** solely **contains the evolved Base Stations,** called **eNodeB** or **eNB**
- The **LTE Mobile Device** is **referred as** the **User Equipment (UE)**



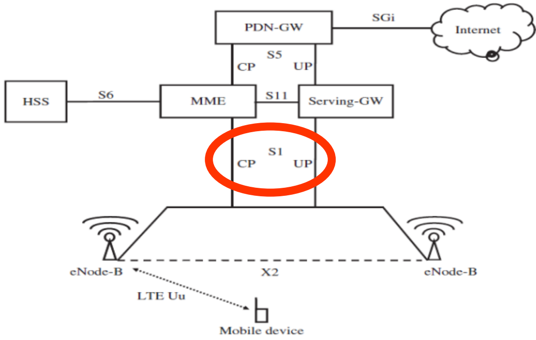
LTE Network Architecture
LTE Mobile Devices



- **Most** **LTE-capable devices** also **support other radio technologies** such as **GSM** and **UMTS**.
- As a consequence, **most LTE devices support not only one or more LTE frequency bands** but also **those for the other technologies**.
  - This is a **challenge for antenna and transmitter design** due to the **small size of devices** and **limited battery capacity**.

LTE Frequency Bands in Europe	Downlink (DL) (MHz)	Uplink (UL) (MHz)	UL/DL separation (duplex gap in MHz)	Duplex mode	Maximum carrier bandwidth (MHz)
Europe					
7	2620–2690	2500–2570	50	FDD	20
3	1805–1880	1710–1785	20	FDD	20
1	2110–2170	1920–1980	130	FDD	20
20	791–821	832–862	10	FDD	20

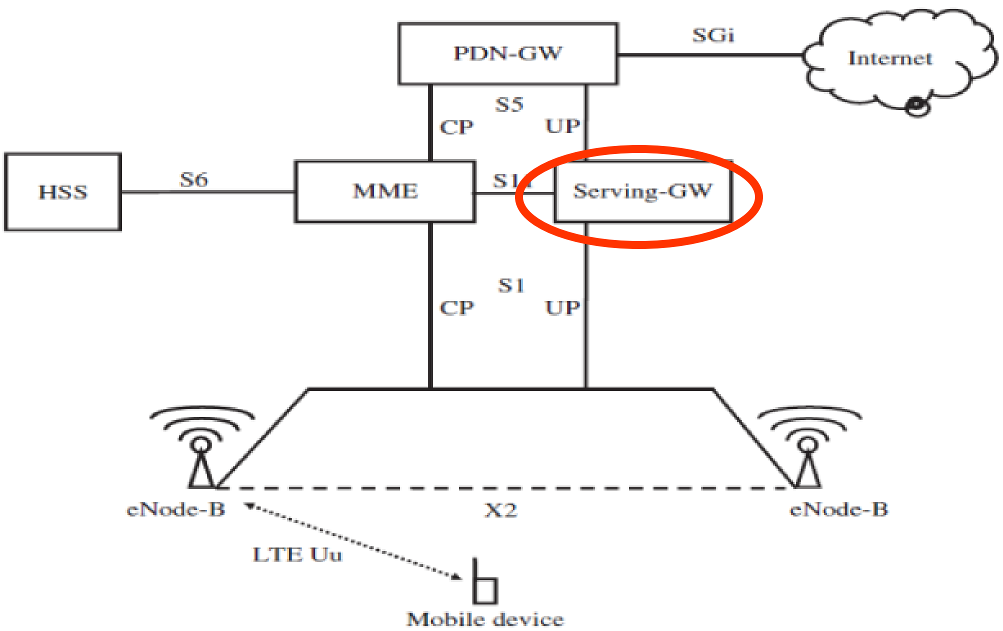
LTE Network Architecture
The eNode-B



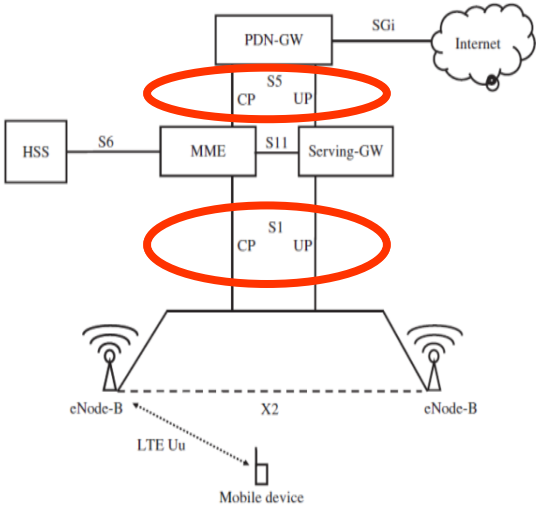
- The **S1-CP (S1 Control Plane) part of the interface is mainly used for transferring Control (signaling) messages that concern the users of the system. E.g.,**
  - For **authentication**, for **supplying keys for encrypting data on the air interface** and for the **establishment of the S1-UP between the eNode-B and the Core Network**.
  - **Also once the S1-UP is in place**, the **S1-CP** is used to **maintain the connection**, to **perform a handover of the UE to another LTE, UMTS or GSM Base Station as required**.
- The **S1-UP (S1 User Plane) part of the interface is used for transferring the user data**.

LTE Network Architecture
The Serving Gateway (S-GW)

- The **S-GW** is responsible for **managing User Data tunnels between** the **eNode-Bs** in **the Radio Network** and the **Packet Data Network Gateway PDN-GW** (which is the gateway router to the Internet),
  - I.e., it **Routes** and **forwards** user data packets.



LTE Network Architecture
The Serving Gateway (S-GW)

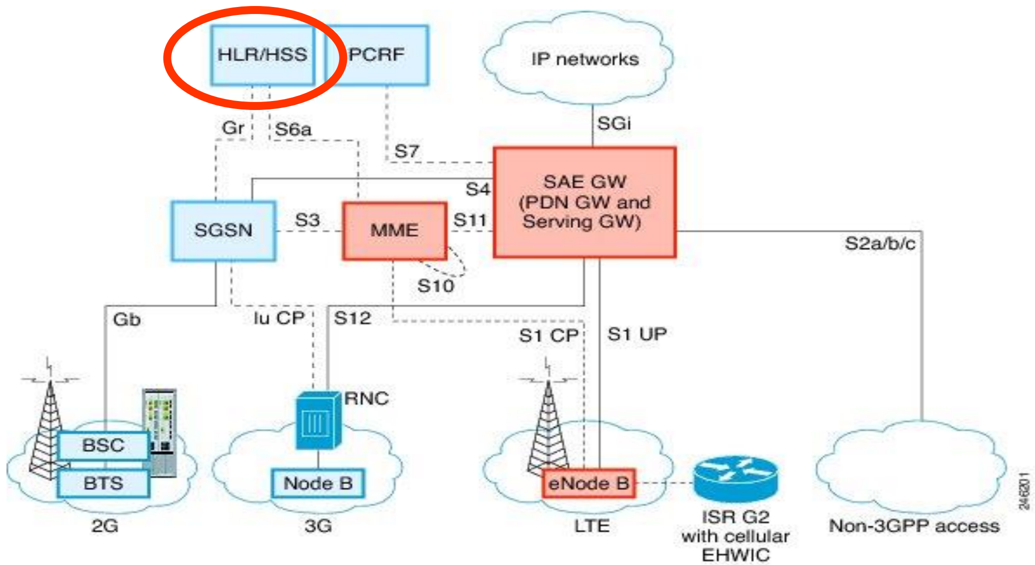


- Acts as the anchor for **Mobility** for the **User Plane** during an **inter- eNB** handovers **(i.e., routes the User Data Traffic to the new eNB after a Handover)**.
  - **S1** and **S5 User Plane tunnels for a single user** are **independent of each other** and **can be changed as required**.
  - If, for example, a **handover is performed to an eNode-B under the control of the same MME/S-GW**, **only the S1 UP tunnel needs to be modified to redirect the user's data stream to and from the new Base Station**.
  - If the connection is **handed over to an eNode-B** that is **under the control of a new MME/S-GW**, the **S5 UP tunnel (between the PDN-GW and the S-GW) has to be modified as well**, so as **the user's data stream to be redirected to the new MME/S-GW**.

LTE Network Architecture

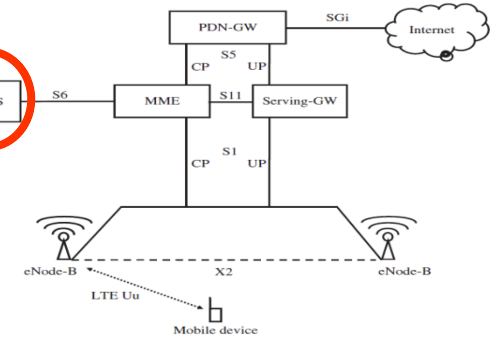
The Home Subscriber Server (HSS)

- LTE **shares its subscriber database with GSM and UMTS** (In these systems, the database is referred to as the **Home Location Register (HLR)**)
- **In LTE, the name of the database has been changed to HSS**
- **In practice**, the **HLR** and the **HSS** are **physically combined** to **enable seamless roaming between the different Radio Access Networks (RATs).**
- **Each subscriber has a record in the HLR/HSS and most properties are applicable for communicating over all Radio Access Networks (2G, 3G, LTE, etc.).**



LTE Network Architecture

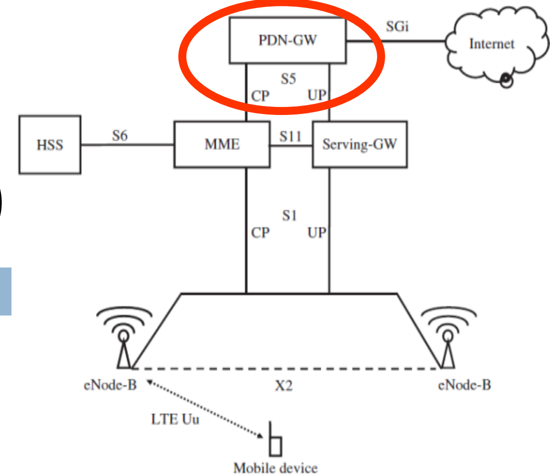
The Home Subscriber Server (HSS)



- **The** **most important user parameters** **in the HSS are:**
  - The user's **International Mobile Subscriber Identity (IMSI),** which **uniquely identifies a subscriber**. The **IMSI implicitly includes** the **Mobile Country Code (MCC)** and **Mobile Network Code (MNC)** and is thus **used when the user is roaming abroad** to **find the Home Network** of the user **to contact the HSS**. A **copy of the IMSI** is **stored on the SIM card** of the subscriber;
  - **Authentication information** that is used to **authenticate the subscriber** and to **generate encryption keys** for the connection.
  - **Current Location** of the user (i.e., **ID of current Serving Network** if the user is **roaming to a Foreign Network**, **ID of the Tracking Area (TA) if the user is roaming in his/her Home Network, etc.**)

LTE Network Architecture

The Packet Data Network Gateway (PDN-GW)

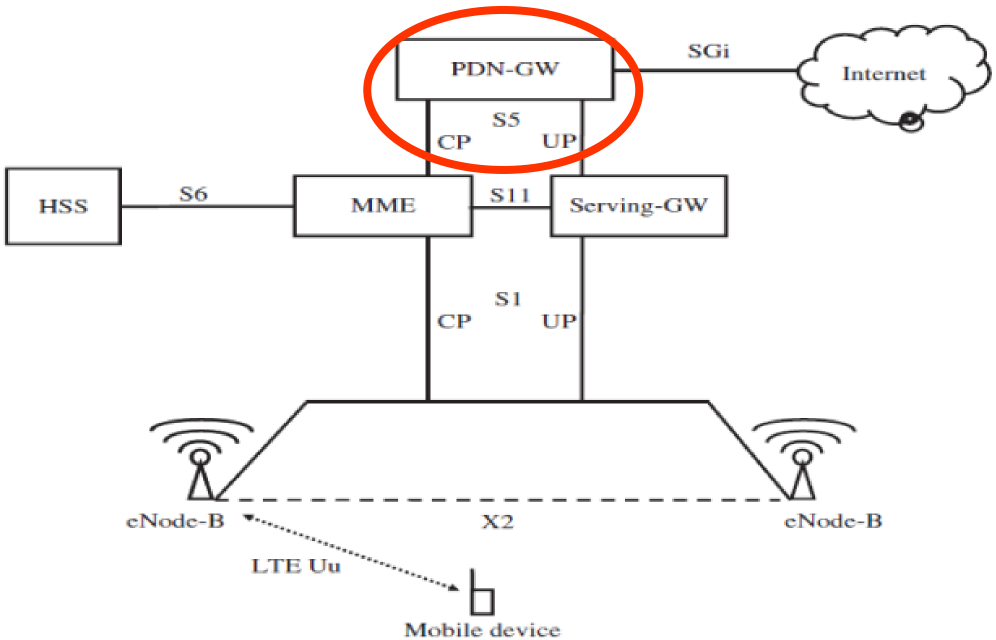


- **PDN-GW provides connectivity between** the **UE and the Internet** and **other external Packet Data Networks (PDNs)** by **being the point of Exit and Entry for UE traffic.**
- **PDN-GW** connects to the **S-GW** using the **S5 UP interface and to the MME using the S5 CP interface**.
- On the **S5 User Plane (UP)**, this means that
  - **Data packets destined for a user** are **encapsulated into an S5 User Plane (UP) tunnel** and **forwarded to the S-GW**, which is **currently responsible for this user**.
  - The **S-GW** then **forwards the data packets over the S1 interface** to **the eNode-B that currently serves the user**,
  - Finally, the **eNode-B sends the data packets over the air interface to the user's Mobile Device**.

LTE Network Architecture

The Packet Data Network Gateway (PDN-GW)

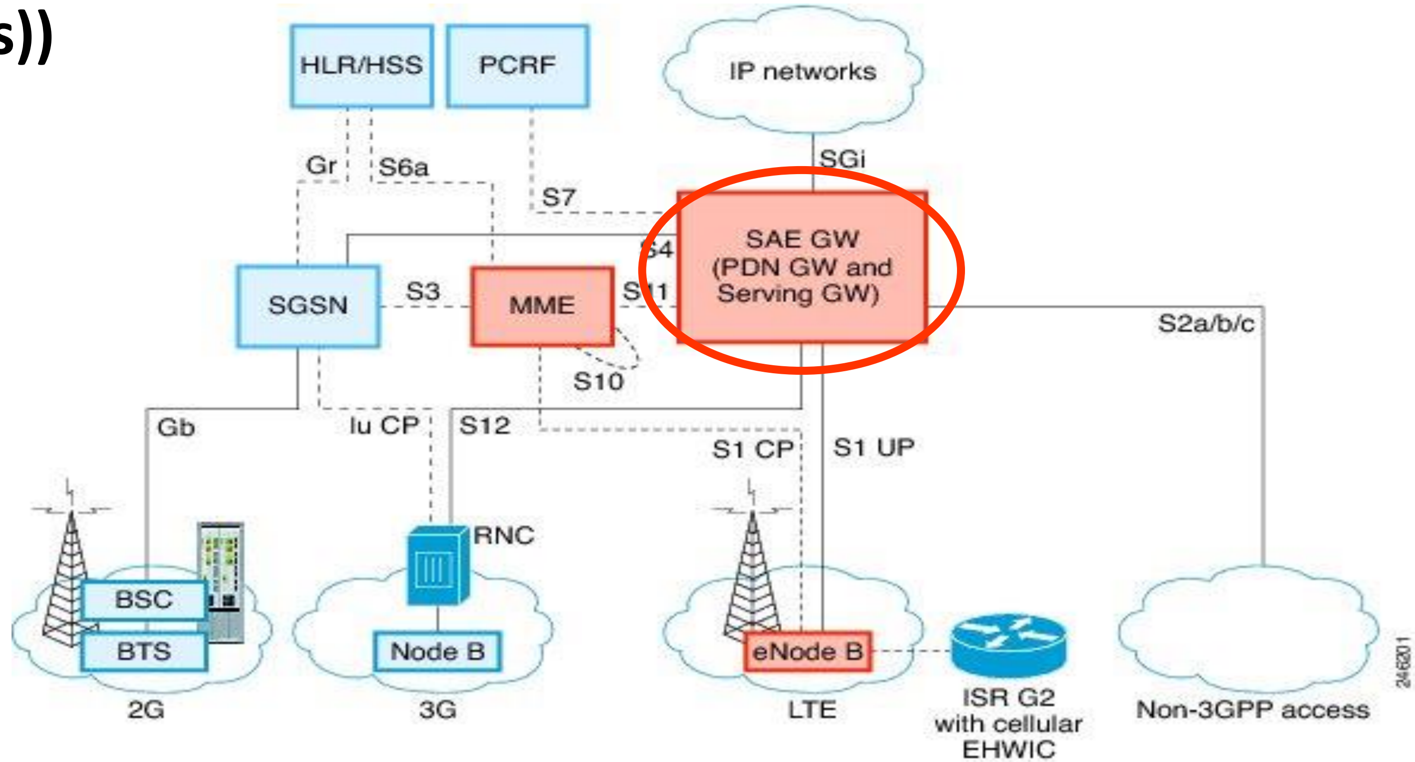
- The **PDN-GW** is also **responsible** for **assigning IP addresses to Mobile Devices.**
  - When the **MME authenticates the subscriber** it **requests an IP address from the PDN-GW for the Mobile Device** (This **is done through** the **S5 Control Place (CP) interface**)



LTE Network Architecture

The Packet Data Network Gateway (PDN-GW)

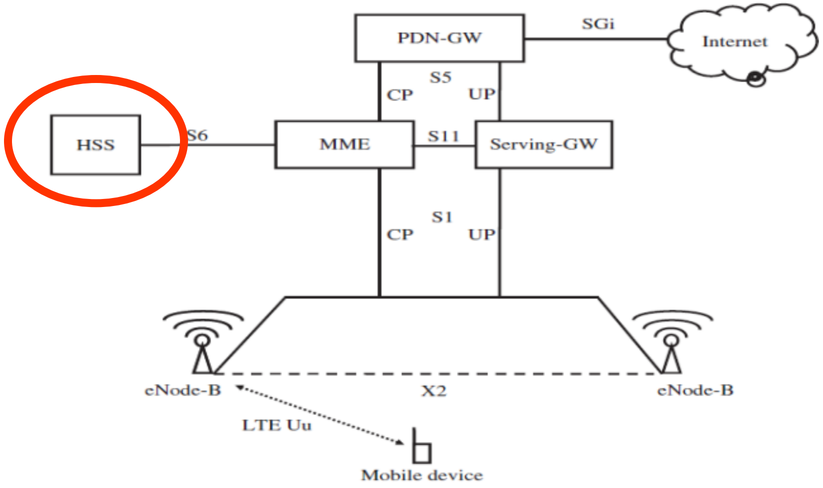
- The **PDN-GW acts as the anchor for mobility between 3GPP** (i.e., legacy systems as **GSM**, **GRPS**, **UMTS**) **and Non-3GPP access technologies such as WiMAX** (i.e., **PDN-GW facilitates handovers between different Radio Access Technologies (RATs)**)



LTE Network Architecture

The Packet Data Network Gateway (PDN-GW)

- The PDN-GW plays an **important part** in **International Roaming scenarios**.
  - For example, for a **user traveling abroad** and connected into a **Foreign Network**, the **MME/S-GW** in the **Foreign Visited network will contact the PDN-GW** in the **user's Home Network** to **query the HLR\HSS database** for **user authentication purposes**.



LTE Requirements

- **Outlined in 3GPP TR 29.913 and described in seven different areas**
  - **Capabilities**
  - **System performance**
  - **Deployment related aspects**
  - **Architecture and migration**
  - **Radio Resource Management**
  - **Complexity**
  - **General aspects**

LTE Requirements

- **Capabilities**
  - **DL data rate > 100 Mbps in 20 MHz**
  - **UL data rate > 50 Mbps in 20MHz**
  - **Rate scales linearly with spectrum**
  - **Latency User plane: < 5ms**
  - **Latency Control plane: < 50ms**
  - **Support for 200 mobiles in 5MHz, 400 mobiles in more than 5MHz**

LTE Requirements

- **System Performance (Baseline is HSPA Rel. 6)**
  - **Maximum performance for low mobility users (0-15km/h)**
  - **High performance up to 120 km/h**
  - **Maximum supported speed 500km/h**
  - **Cell range**
    - **5 km - optimal size**
    - **30km sizes with reasonable performance**
    - **up to 100 km cell sizes supported with acceptable performance**

Throughput requirements relative to baseline

Performance measure	DL target relative to base line	UL target relative to baseline
Average throughput per MHz	3-4 times	2-3 times
Cell edge user throughput per MHz	2-3 times	2-3 times
Spectrum efficiency (bit/sec/Hz)	3-4 times	2-3 times

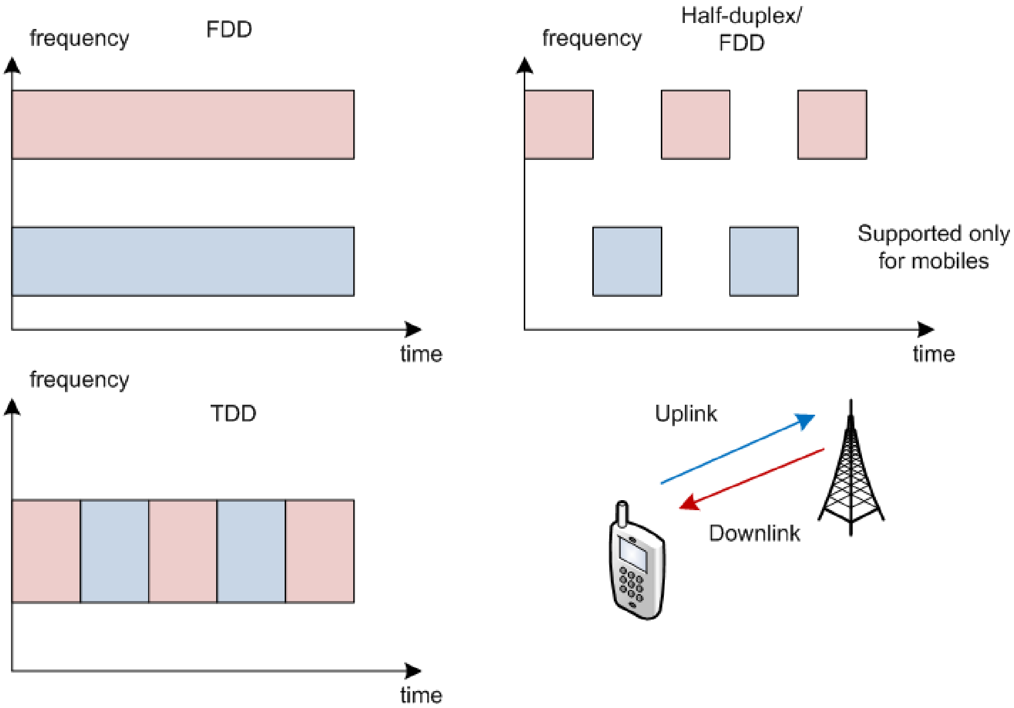
LTE Requirements

- **Deployment Related Aspects**
  - **LTE may be deployed as standalone or together with WCDMA/HSPA and/or GSM/GPRS**
  - **Co-existence with legacy standards (users can transparently start a call or transfer of data in an area using an LTE standard, and, when there is no coverage, continue the operation without any action on their part using GSM/GPRS or W-CDMA-based UMTS)**
  - **Handover interruption time targets specified**

	Non-real time services (ms)	Real time services (ms)
LTE to WCDMA	500	300
LTE to GSM	500	300

LTE Requirements

- **Spectrum Flexibility**
  - **Support both FDD and TDD duplex schemes**
  - **Channel bandwidth from 1.4 - 20MHz**
  - **IMT 2000 bands (co-existence with WCDMA and GSM)**



LTE Requirements

- **Architecture and Migration**
  - Single RAN architecture
  - RAN is fully packet based with support for real time conversational class
  - RAN architecture should minimize “single points” of failure
  - RAN should simplify and reduce number of interfaces
  - Radio Network Layer and Transport Network Layer interaction should not be precluded in interest of performance
  - QoS support should be provided for various types of traffic

LTE Requirements

- **Radio Resource Management**
  - **Support for enhanced end to end QoS**
  - **Support for load sharing between different radio access technologies (RATs)**

- **Complexity**
  - **LTE should be less complex than WCDMA/HSPA**

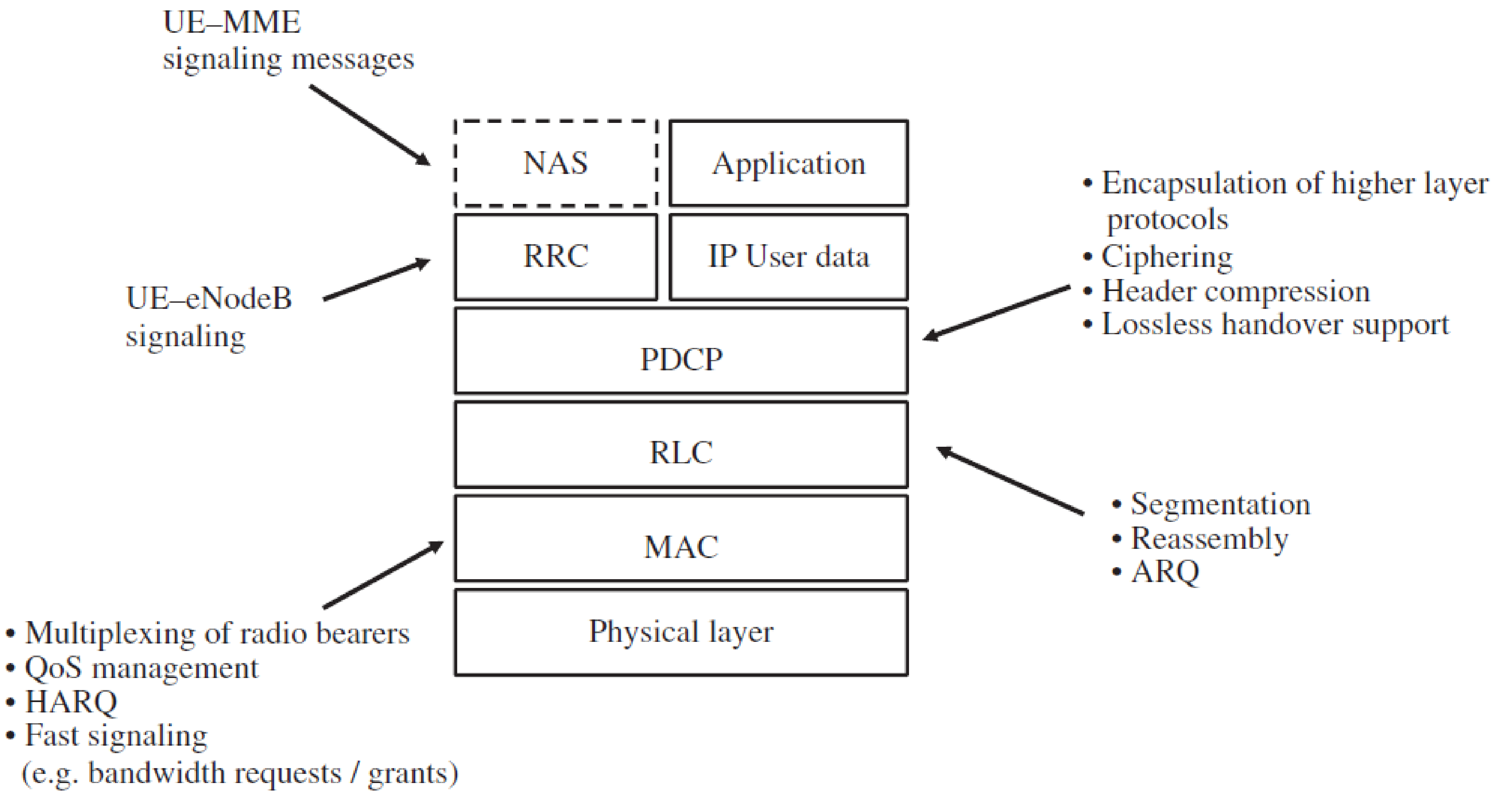
LTE Channel Structure
Radio Link Control (RLC) Layer

- **Depending on the Scheduler Decision, a certain amount of data is selected for transmission from the RLC SDU (Service Data Units) buffer and the SDUs are segmented/concatenated to create the RLC PDU (Protocol Data Unit). Thus, for LTE the RLC PDU size varies dynamically.**
- **Each RLC PDU includes a header, containing, among other things, a sequence number used for in-sequence delivery and also by the Retransmission mechanism for retransmissions**
- **Further, it is responsible for monitoring packets' sequence numbers and detecting and retransmitting lost packets (ARQ).**
- **Although the RLC is capable of handling transmission errors, error-free delivery is in most cases handled by the MAC-based Hybrid-ARQ protocol.**

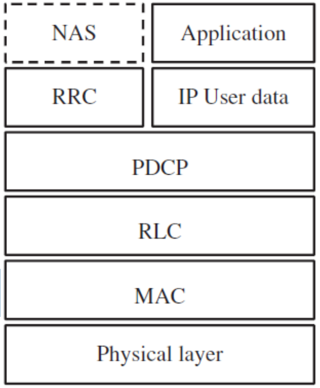
LTE Channel Structure
Medium Access Control (MAC) Layer

- **Data on a Transport channel is organized into Transport blocks.**
- **Each Transmission Time Interval (TTI), at most one Transport Block of a certain size is transmitted over the radio interface to/from a Mobile Terminal (*in absence of Spatial Multiplexing; Applied with MIMO transmissions*)**
- **Each Transport Block has an associated Transport Format (TF) which specifies how the block is to be transmitted over the radio interface (i.e., Transport-Block size, Modulation Scheme, Antenna Mapping (e.g., type of MIMO used; 2x2, 4x2 etc.))**
- **By varying the Transport Format, the MAC layer can realize different data rates. Rate Control is therefore also known as Transport-Format Selection.**
- **In addition, the MAC layer is responsible for the HARQ packet retransmission functionality.**

Protocol Layer Overview
Air interface protocol stack and main functions

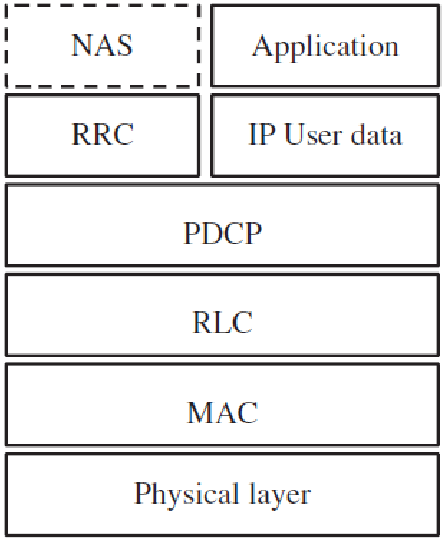


Protocol Layer Overview



- **Control Protocols (NAS and RRC):**
  - **The top layer is the Nonaccess Stratum (NAS) protocol that is used for mobility management and other purposes between the Mobile Device and the MME.**
  - **NAS messages are tunneled through the radio network, and the eNode-B just forwards them transparently. NAS messages are always encapsulated in Radio Resource Control (RRC) messages over the air interface.**
  - **The other purpose of RRC messages is to manage the air interface connection and they are used, for example, for handover or bearer modification signaling.**
  - **As a consequence, an RRC message does not necessarily have to include a NAS message.**

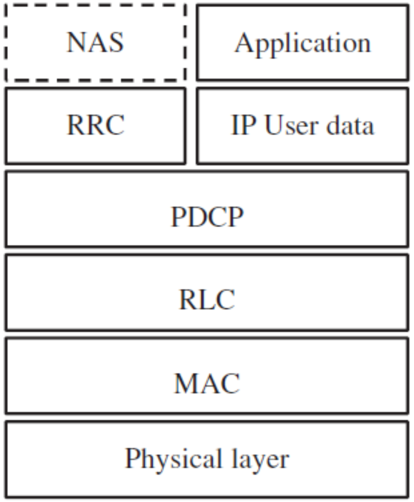
Protocol Layer Overview



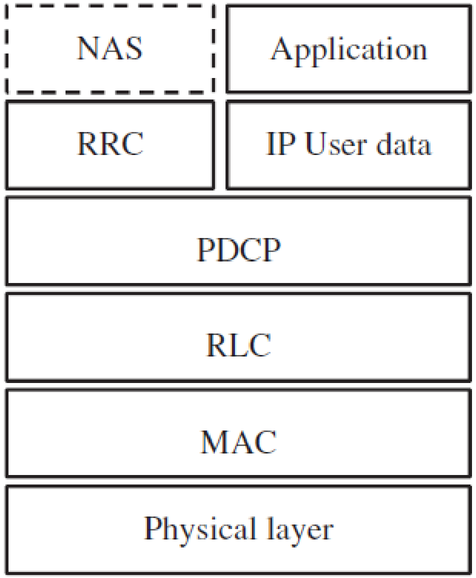
- **Use Data plane Protocols:**
  - **Here, IP packets are always transporting user data and are sent only if an application wants to transfer data.**
- **The first unifying protocol layer to transport IP, RRC and NAS signaling messages is the Packet Data Convergence Protocol (PDCP) layer.**
  - **PDCP is responsible for encapsulating IP packets and signaling messages, for ciphering, header compression and lossless handover support.**

Protocol Layer Overview

- **One layer below is the Radio Link Control (RLC).**
  - **It is responsible for segmentation and reassembly of higher layer packets to adapt them to a packet size that can be sent over the air interface.**
  - **Further, it is responsible for detecting and retransmitting lost packets (ARQ).**



Protocol Layer Overview

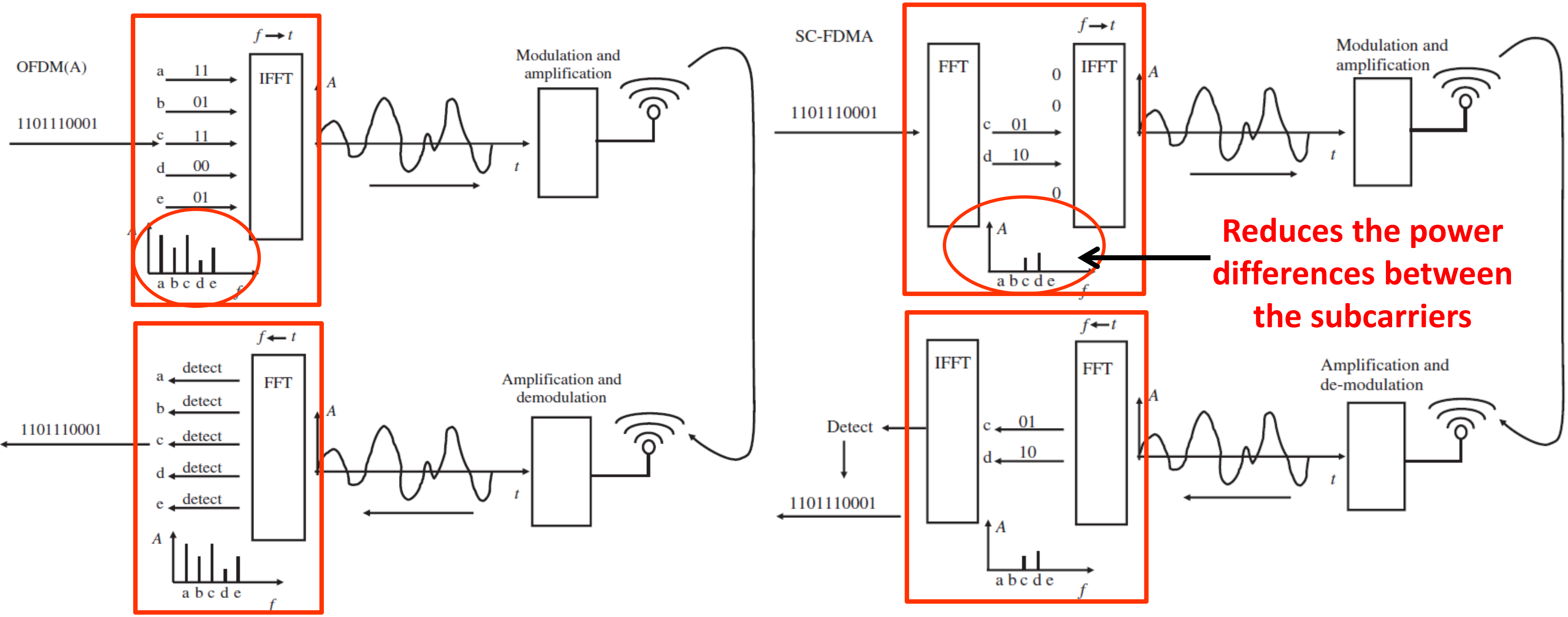


- Just above the physical layer is the Medium Access Control (MAC)
  - It multiplexes data from different radio bearers and ensures QoS by instructing the RLC layer about the number and the size of packets to be provided.
  - In addition, the MAC layer is responsible for the HARQ packet retransmission functionality.
  - And finally, the MAC header provides fields for addressing individual mobile devices and for functionalities such as bandwidth requests and grants, power management

Air Interface in LTE
SC-FDMA for Uplink Transmission

- **The number of subcarriers used for distributing the user's data in the Uplink mainly depends on:**
  - **The user's Uplink signal conditions (measured at the eNodeB)**
  - **The transmission power capabilities of the Mobile Device and**
  - **The number of simultaneous users in the uplink (that will share the subcarriers).**

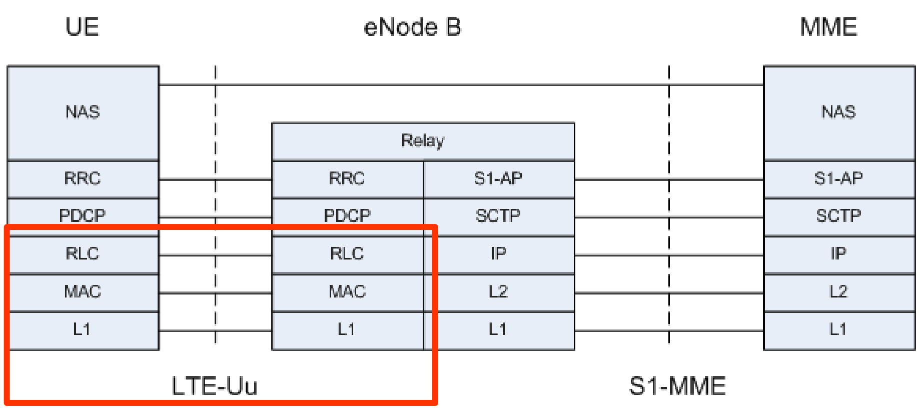
OFDMA Vs SC-FDMA



- **With SC-FDMA**, instead of dividing the data stream and putting the resulting substreams directly on the individual subcarriers (like OFDMA does), **the time-based signal is first converted to a frequency-based signal** with an **Fast Furrier Transform (FFT) function**.
- This **distributes the information of each bit onto all subcarriers that will be used for the transmission** and **thus reduces the power differences between the subcarriers** → **Reduces the Peak to Average Power Ratio (PAPR).**
- This **frequency vector is then fed to the IFFT** as in OFDMA, which **converts the information back into a time-base signal** which **is modulated, amplified** and **transmitted**.

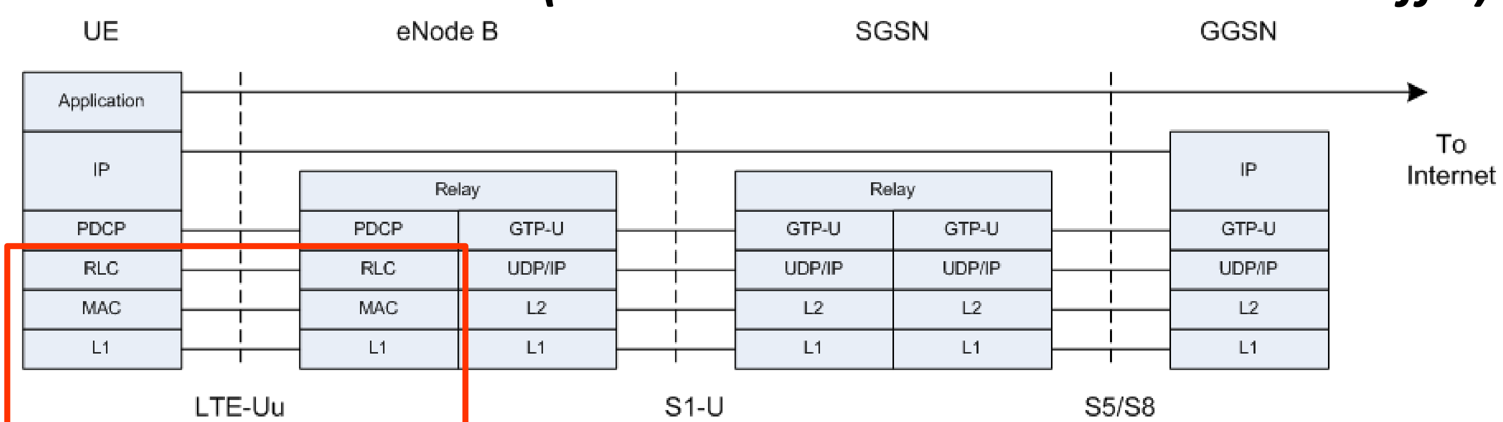
LTE Channel Structure
LTE Protocol Layer Overview

***Control Plane Channels** (Channels that carries signaling (control) traffic)*



- NAS – Non Access Stratum
- RRC – Radio Resource Control
- PDCP – Packet Data Convergence Protocol
- **RLC – Radio Link Control (Forms the Logical Channels)**
- **MAC – Medium Access Control (Forms the Transport Channels)**
- **L1 – Physical Layer (Forms the Physical Channels)**

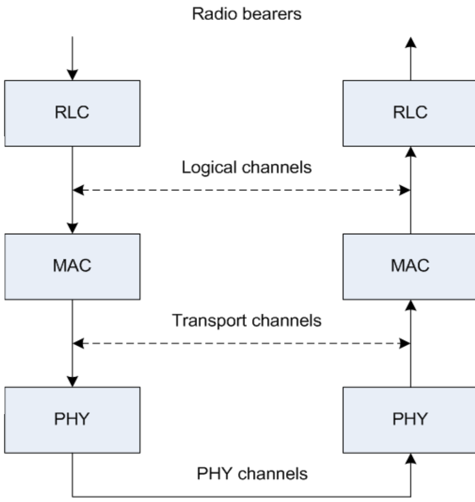
***User Plane Channels** (Channels that carries user data traffic)*



LTE Channel Structure

Type of Channels

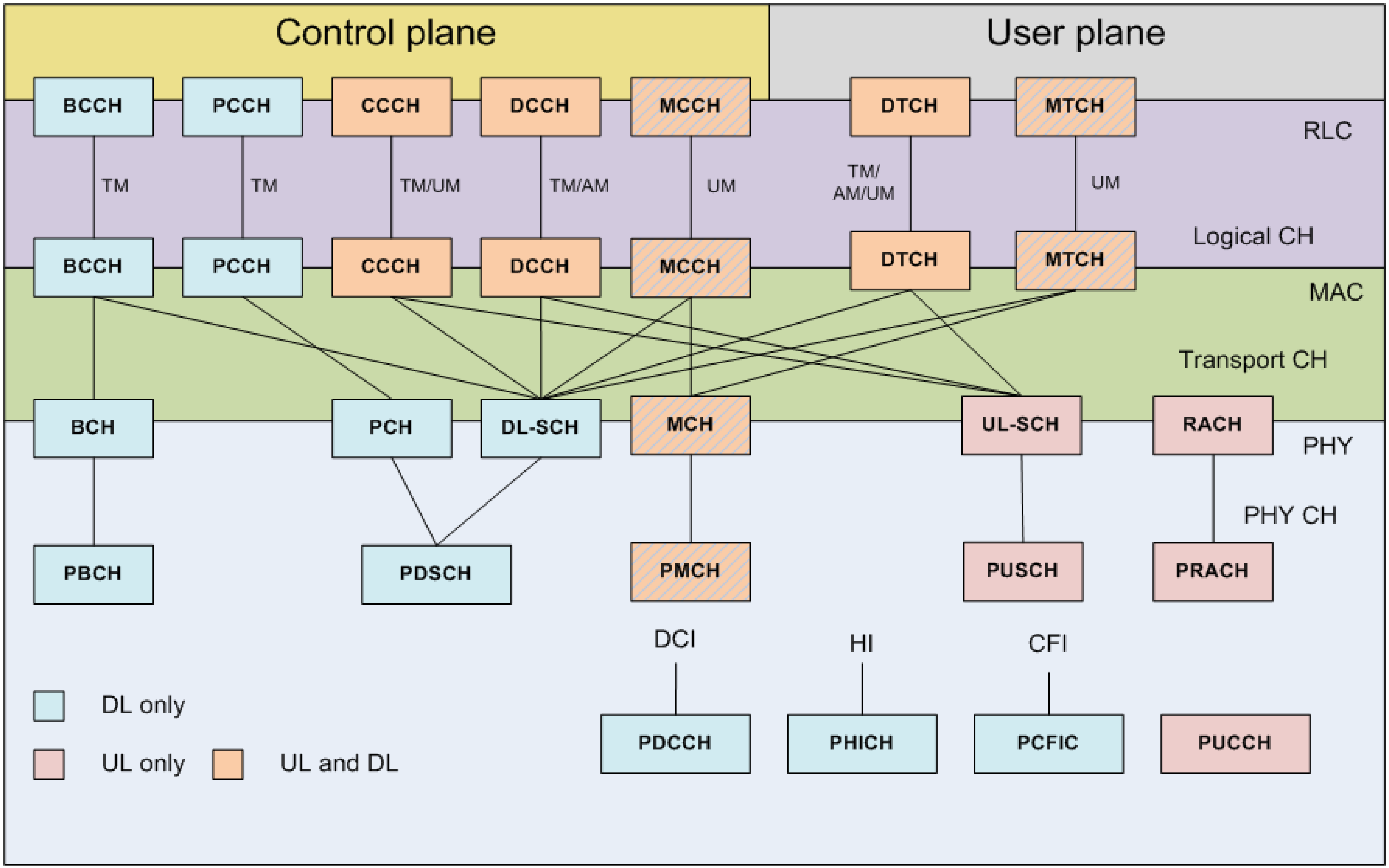
Note: LTE defines same type of channels as WCDMA/HSPA



- **Logical channels**
  - **Formed by RLC (Radio Lick Control) layer**
  - **Characterized by the type of information it carries (what) (i.e., Control channel used to carry Control Information, a traffic channel is used for the user data)**
- **Transport channels**
  - **Formed by MAC (Medium Access Control) layer**
  - **Characterized by how the data will be transmitted (i.e., the defines the Transport Format (TF)*) over the Radio Interface (i.e., the Physical Layer).**
- **Physical channels**
  - **Formed by PHY (Physical Layer – OFDM Channels)**
  - **Consist of a group of RBs that will be assigned to the users (the data in the RBs will be transmitted based of the TF selected by the MAC layer)**

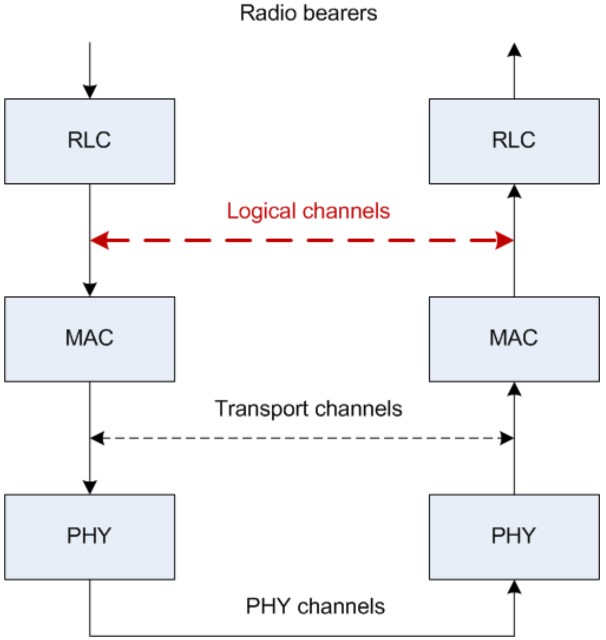
Transport Format (TF): Specifies how the data is to be transmitted over the radio interface (i.e., e.g., Modulation Scheme, Antenna Mapping (e.g., type of MIMO used; 2x2, 4x2 etc.))

LTE Channel Mapping



LTE Logical Channels

- BCCH – Broadcast Control CH
  - System information sent to all UEs
- PCCH – Paging Control CH
  - Paging information when addressing UE
- CCCH – Common Control CH
  - Access information during call establishment
- DCCH – Dedicated Control CH
  - User specific signaling and control
- DTCH – Dedicated Traffic CH
  - User data
- MCCH – Multicast Control CH
  - Signaling for multi-cast
- MTCH – Multicast Traffic CH
  - Multicast data

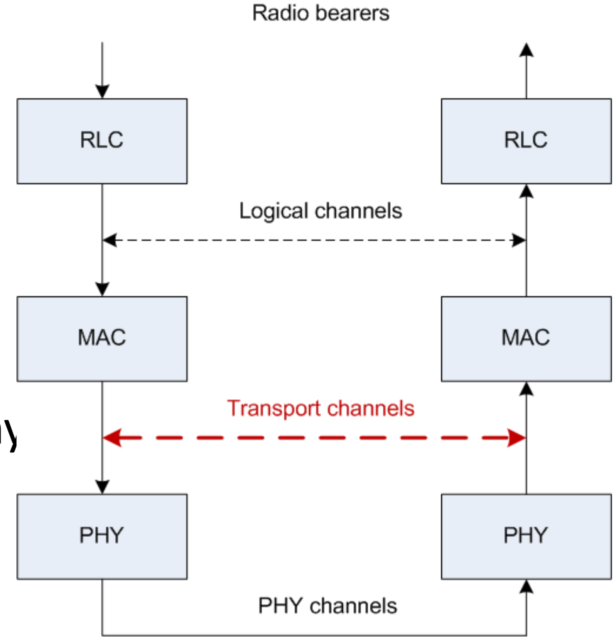


LTE Channels

Red – Common,
Green – Shared,
Blue – Dedicated

LTE Transport channels

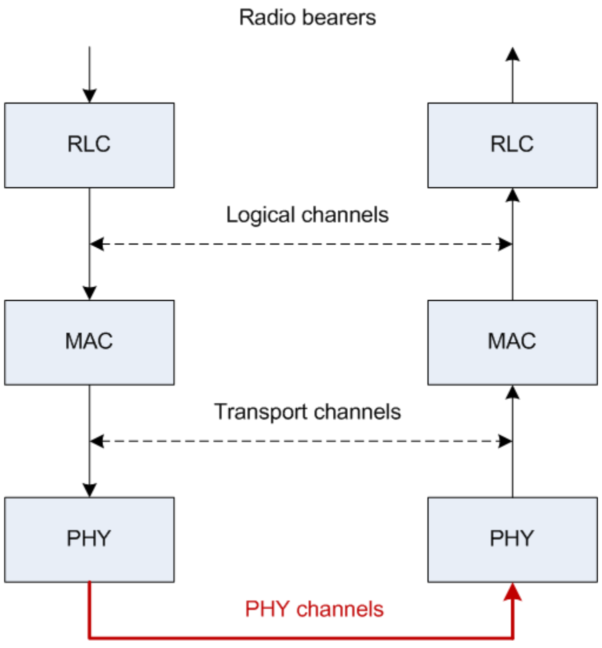
- BCH – Broadcast CH
  - Transport for BCCH
- PCH – Paging CH
  - Transport for PCH
- DL-SCH – Downlink Shared CH
  - Transport of user data and signaling. Used by many logical channels
- MCH – Multicast channel
  - Used for multicast transmission
- UL-SCH – Uplink Shared CH
  - Transport for user data and signaling
- RACH – Random Access CH
  - Used for UE's accessing the network



Red – **Common,**
Green – **Shared**

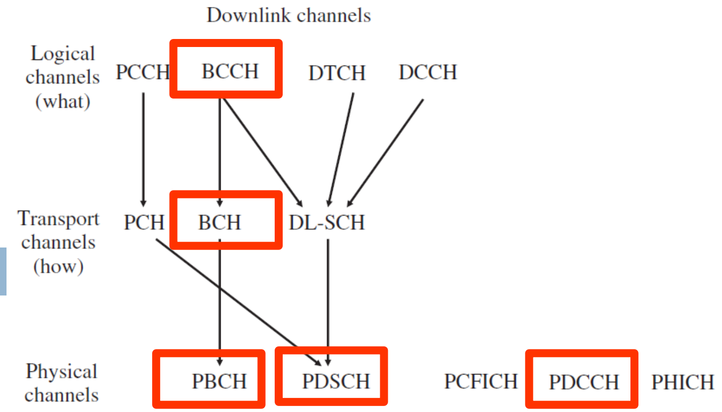
LTE Physical Channels

- PDSCH – Physical DL Shared CH
  - Uni-cast transmission and paging
- PBCH – Physical Broadcast CH
  - Broadcast information necessary for accessing the network
- PMCH – Physical Multicast Channel
  - Data and signaling for multicast
- PDCCH – Physical Downlink Control CH
  - Carries mainly scheduling information
- PHICH – Physical Hybrid ARQ Indicator
  - Reports status of Hybrid ARQ
- PCIFIC – Physical Control Format Indicator
  - Information required by UE so that PDSCH can be demodulated (format of PDSCH)
- PUSCH – Physical Uplink Shared Channel
  - Uplink user data and signaling
- PUCCH – Physical Uplink Control Channel
  - Reports Hybrid ARQ acknowledgements
- PRACH – Physical Random Access Channel
  - Used for random access



Red – Common,
Green – Shared

LTE Channel Model Downlink Direction

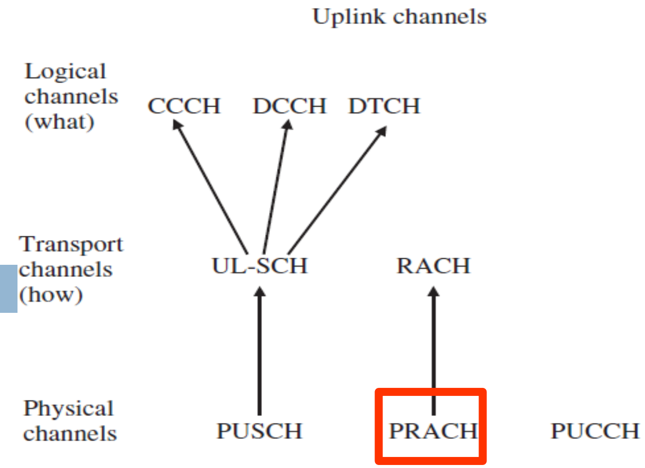


- LTE uses **System Information (SI) messages** to convey information that is **required by all UEs that are currently in the cell.**
- **Master Information Block (MIB)** is **transported over** the **Broadcast Channel (BCH).**
- **All other SI is scheduled in the PDSCH** and **their presence is announced on the PDCCH in a search space that has to be observed by all UEs.**

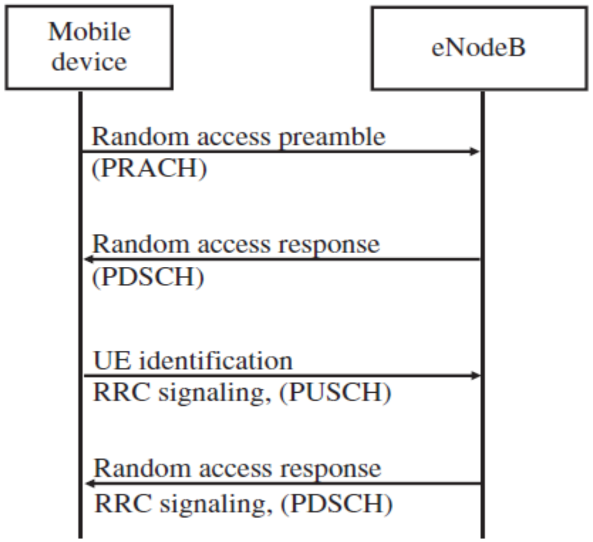
System information blocks and content overview

Message	Content
MIB	Most essential parameters required for initial access
SIB 1	Cell identity and access-related parameters and scheduling information of system information messages containing the other SIBs
SIB 2	Common and shared channel configuration parameters
SIB 3	General parameters for intrafrequency cell reselection
SIB 4	Intrafrequency neighbor cell reselection information with information about individual cells
SIB 5	Interfrequency neighbor cell reselection parameters
SIB 6	UMTS inter-RAT cell reselection information to UMTS
SIB 7	GSM inter-RAT cell reselection information to GSM
SIB 8	CDMA2000 inter-RAT cell reselection information
SIB 9	If the cell is a femto cell, i.e. a small home eNode-B, this SIB announces its name
SIB 10	Earthquake and tsunami warning system (ETWS) information
SIB 11	Secondary ETWS information
SIB 12	Commercial mobile alert system (CMAS) information

LTE Channel Model Uplink Direction



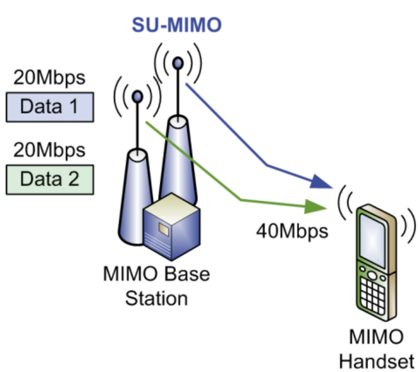
- **Before a Mobile Device can send data in the uplink direction**, it needs to **synchronize with the network** and has to **request the assignment of resources (i.e., Resource Blocks)** on the **PUSCH**.
- **Synchronizing and requesting initial uplink resources** is performed with a **Random Access Procedure** on the **Physical Random Access Channel (PRACH)**.
  - In these cases, a **contention-based procedure is performed** as it is possible that **several devices try to access the network with the same Random Access Channel (RACH) parameters at the same time.**

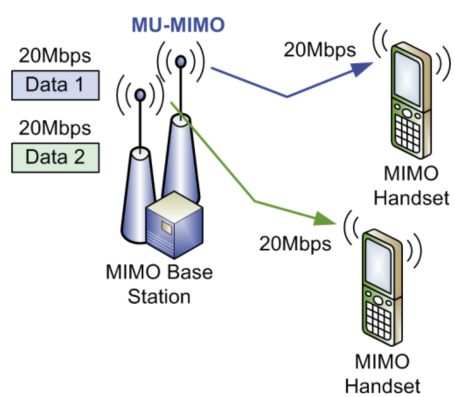


MIMO Transmission & Adaptive Modulation and Coding

- In 3GPP Release 8, **the** **use of two or four simultaneous streams** is specified → **In practice, up to two data streams are used today.**
  - **In 3GPP Release 10 (LTE Advanced) the use of up to eight simultaneous data streams is specified; 8 x 8 MIMO)**
- **In theory, the use of two independent transmission paths can double the achievable throughput and four independent transmission paths can quadruple the throughput.**
- **In practice, however, throughput gains will be lower because of the signals interfering with each other.**

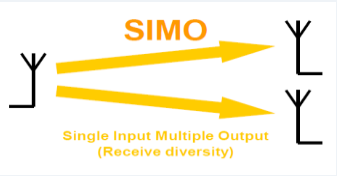
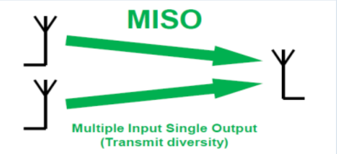
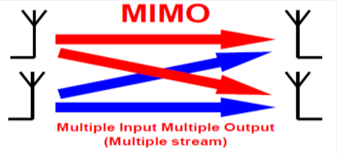
Single User – MIMO (SU-MIMO): *"Conventional" MIMO.* One user gets the full benefit of the increased throughput.





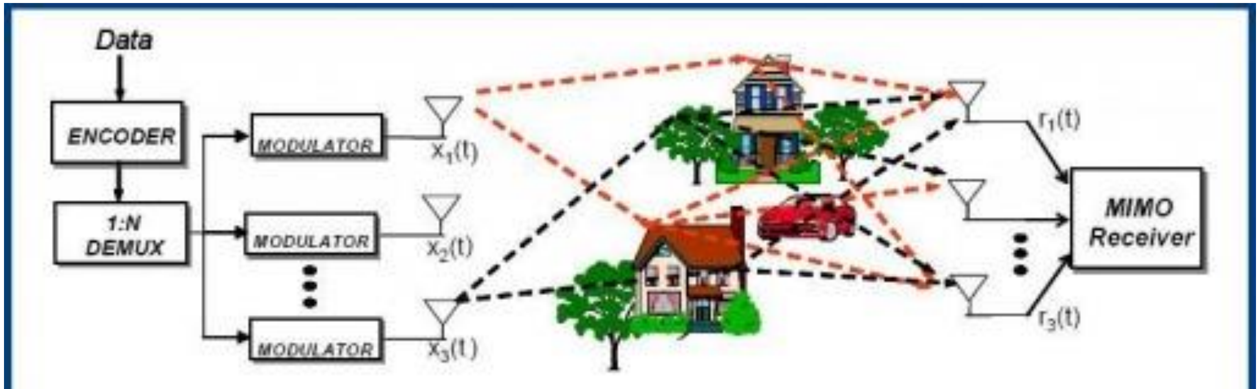
Multi User – MIMO (MU-MIMO): The BS schedules two users to be served at the same time.

MIMO Transmission & Adaptive Modulation and Coding

Multi-antenna types		
SISO	Single-input-single-output means that the transmitter and receiver of the radio system have only one antenna.	
SIMO	Single-input-multiple-output means that the receiver has multiple antennas while the transmitter has one antenna. **(Receive Diversity)**	
MISO	Multiple-input-single-output means that the transmitter has multiple antennas while the receiver has one antenna. (**Transmit Diversity)**	
MIMO	Multiple-input-multiple-output means that both the transmitter and receiver have multiple antennas. **(Spatial Multiplexing)**	

MIMO Transmission & Adaptive Modulation and Coding

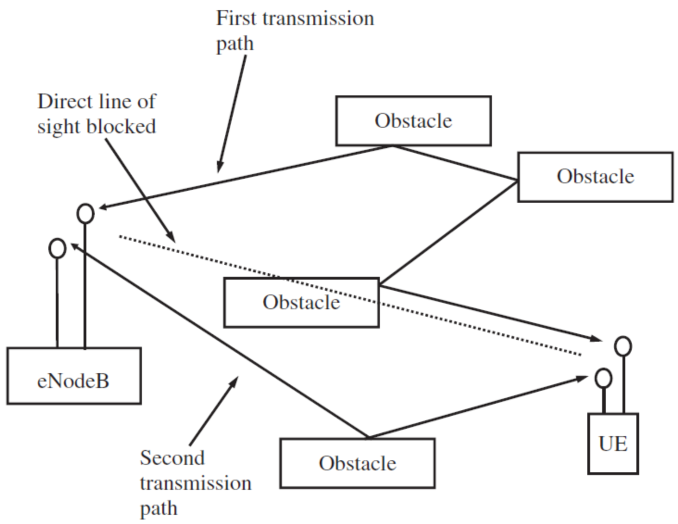
- **Transmitting simultaneous data streams over the same channel** is **possible only if the streams remain largely independent of each other on the way from the Transmitter to the Receiver.** This can be achieved if **two basic requirements are met**.
- **First Requirement for MIMO Transmission:**
  - **On the transmitter side, two or four independent hardware transmit chains are required to create the simultaneous data streams.**
  - **In addition, each data stream requires its own antenna. For two streams, two antennas are required.**



A Generic MIMO system

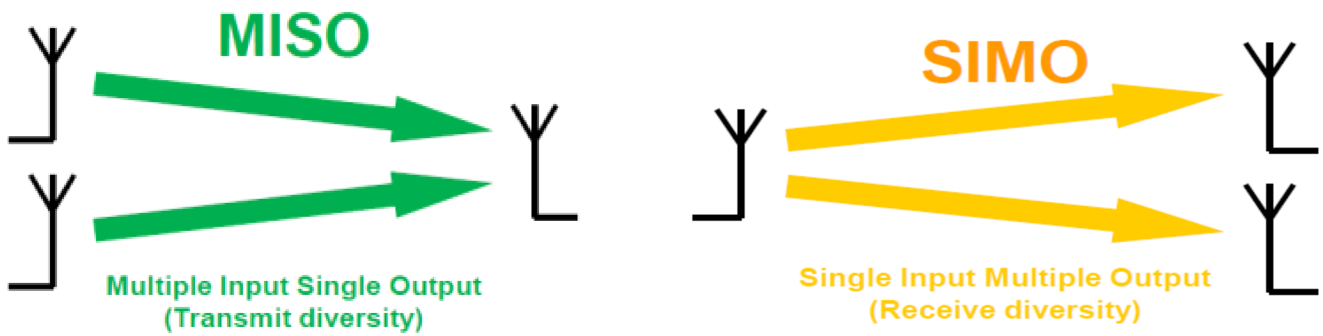
MIMO Transmission & Adaptive Modulation and Coding

- **Second Requirement for MIMO Transmission:**
  - **The signals have to remain as independent as possible on the transmission path between the Transmitter and the Receiver.**
  - This can be achieved if the **simultaneous transmissions reach the Mobile Device via several independent paths**
  - **However, the simultaneous transmissions interfere with each other to some degree, which reduces the achievable speeds.**



MIMO Transmission & Adaptive Modulation and Coding

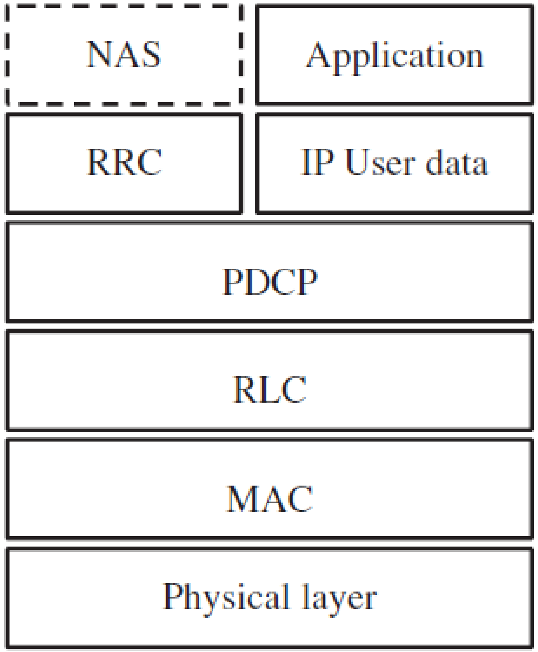
- Multiple antennas can also be used for Transmit and Receive diversity (e.g., MISO and SIMO transmission types)
- Here, the same data stream is transmitted (or received) over several antennas.
- This does not increase the transmission speed beyond what is possible with a single stream but it helps the receiver to better decode the signal and, as a result, enhances data rates (throughput) beyond what would be possible with a single transmit (or receive) antenna.



Hybrid Automatic Repeat Request (HARQ)

- **Despite Adaptive Modulation and Coding schemes, it is always possible that some of the transmitted data packets are not received correctly.**
  - **In fact, it is even desired that not all packets are received correctly as this would indicate that the modulation and coding scheme is too conservative and hence capacity on the air interface is wasted.**
  - **In practice, the air interface is utilized best if about 10% of the packets have to be retransmitted because they have not been received correctly.**

Hybrid Automatic Repeat Request (HARQ)



- **The challenge of this H-ARQ approach is to report transmission errors quickly and to ensure that packets are retransmitted as quickly as possible to minimize the resulting packet delay and jitter.**
- **Further, the Modulation and Coding scheme used during the transmission must be adapted quickly to keep the error rate within reasonable limits.**
- **The HARQ scheme is used in the Medium Access Control (MAC) layer for fast reporting and retransmission and can achieve an overall round-trip delay times of the complete LTE system of less than 20 milliseconds (much better values that those achieved by HSDPA ~ 80 - 100 ms)**