Module-5

Overview and Channel Structure of LTE

Overview and Channel Structure of LTE: Radio Interface Architecture, LTE Design principles, Network Architecture, Radio Interface Protocols, Hierarchical Structure of LTE: Logical Channels, transport Channels and Physical Channels, Channel mapping, Downlink OFDMA Radio resources, Physical Resource Blocks for OFDMA, Uplink SC-FDMA Radio resources. [Text2: 6.1 to 6.4]

Text 2: Arunabha Ghosh, Jun Zhang, Jeffrey G. Andrews, Rias Muhamed, "Fundamentals of LTE", Pearson India Education Services Private Limited, 2018, ISBN: 978-93-530-6239-2.

5.1 The LTE Standard: Overview and Channel Structure of LTE

- The LTE project in 3GPP focusses on enhancing the UMTS Terrestrial Radio Access (UTRA).
- Another parallel project in 3GPP is the evolved packet core (EPC), which focuses on the core network evolution with flatter all IP, packet based architecture.
- A Radio Interface of a wireless network is the interface between the mobile terminal and the base station.
- UTRAN consists of two logical entities.
- The Node-B (radio base station).and the RNC (radio network controller).
- Radio Interface architecture of UTRAN and E-UTRAN are shown in figure 5.1. Compared to the traditional Node-B, the e-Node B supports features such as radio resource control, admission control, and mobility management; these were present in RNC (Radio Network Controller).
- E-UTRAN provides higher throughput and low latency over the radio interface.

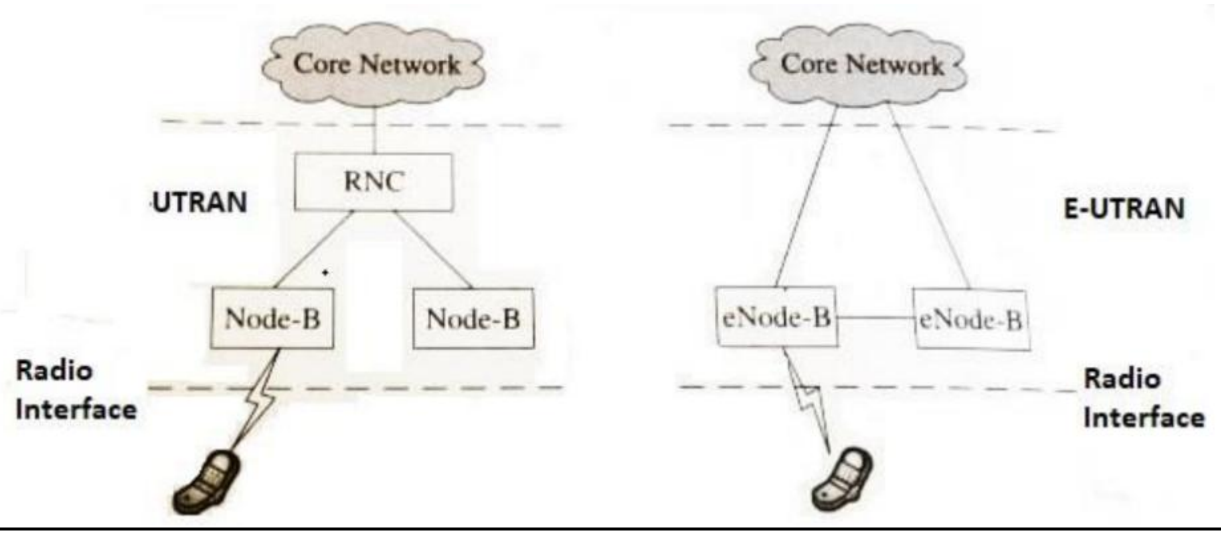


Fig. 5.1. Radio Interface architecture of UTRAN and E-UTRAN

5.2. Introduction to LTE

- LTE is the next step in the evolution of mobile cellular systems and was standardized as part of the 3GPP Release & specifications.

- Unlike 2G and 3G cellular systems that were designed mainly with voice services in mind, LTE was designed primarily for high-speed data services, which is why LTE is a packet-switched network from end to end and has no support for circuit-switched services.

- However, the low latency of LTE and its sophisticated quality of service (QoS) architecture allow a network to emulate a circuit-switched connection on top of the packet-switched framework of LTE.

5.2.1. Design Principles

The basic design principles that were agreed upon and followed in 3GPP while designing the LTE specifications include:

1. **Network Architecture:**

- Unlike 3G networks, LTE was designed to support packet- switched traffic with support for various QoS classes of services.

- Previous generations of networks such as UMTS/HSPA and IxRTT (Single carrier Radio Transmission Technology/EvDO-Evolution Data Optimized) also support packet-switched traffic but this was achieved by subsequent add-ons to the initial version of the standards.
- For example, HSPA, which is a packet-switched protocol (packet-switched over the air), was built on top of the Release 99 UMTS network and as a result carried some of the unnecessary burdens of a circuit-switched network.

- LTE supports packet switching for high data rate services from the start.

- The LTE radio access network, E-UTRAN, was designed to have the minimum number of interfaces (i.e., the minimum. number of network elements) while still being able to provide efficient packet-switched transport for traffic belonging to all the QoS classes such as conversational, streaming, real-time, non- real-time, and background classes.

2. **Data Rate and Latency:**

- The design target for **downlink and uplink peak data rates** for LTE are **100 Mbps and 50 Mbps,** respectively, when operating at the **20MHz frequency division duplex (FDD) channel size.**

- The user-plane latency is defined in terms of the time it takes to transmit a small IP packet from the UE to the edge node of the radio access network (also called as base station) or vice versa measured on the IP layer.

- The target for **one-way latency in the user plane is 5 ms** in an unloaded network, that is, if only a single UE is present in the cell.

- For the **control-plane latency**, the transition time from a camped state to an active state is less than 100ms, while the transition time between a dormant state and an active state should be less than 50 ms.

3. **Performance Requirements:**

The performance requirements for LTE are specified in terms of
i. Spectrum efficiency ii. Mobility iii. Coverage. iv. MBMS Service

i. **Spectrum Efficiency**: The average downlink user data rate and spectrum efficiency target is 3 to 4 times that of HSDPA (3G) network. For uplink the average user data rate and spectrum efficiency target is 2 to 3 times that of HSUPA network. The cell edge throughput should be 2 to 3 times that of HSDPA and HSUPA.

ii. **Mobility**: The mobility requirement for LTE is to be able to support mobility at different mobile terminal speeds. Maximum performance at lower mobile speeds of 0 to 15 km/hr.
With minor degradation in performance at higher mobile speeds up to 120 km/hr. LTE is also expected to be able to sustain a connection for mobile speeds up to 350 km/hr but with significant degradation in the system performance.

iii. **Coverage:** Good performance should be met up to 5 km. Slight degradation of the user throughput is tolerated cell ranges up to 30 km. Cell ranges up to 100 km should not be precluded by the specifications. The above coverage performance depends on user mobility.

iv. **MBMS Service:** LTE should also provide enhanced support for the Multimedia Broadcast and Multicast Service (MBMS) compared to UTRA (3G) operation.

4. Radio Resource Management(RRM): RRM requirements cover various aspects such as
- Enhanced support for end-to-end QoS
- Efficient support for transmission of higher layers
- Support for load sharing/balancing and policy management/enforcement across different access technologies.

4. **Deployment Scenario and Co-existence with 3G**: LTE shall support the following two deployment scenarios:

i. **Standalone deployment scenario**: where the operator deploys LTE either with no previous network deployed in the area or with no requirement for interworking with 2g and 3g networks.

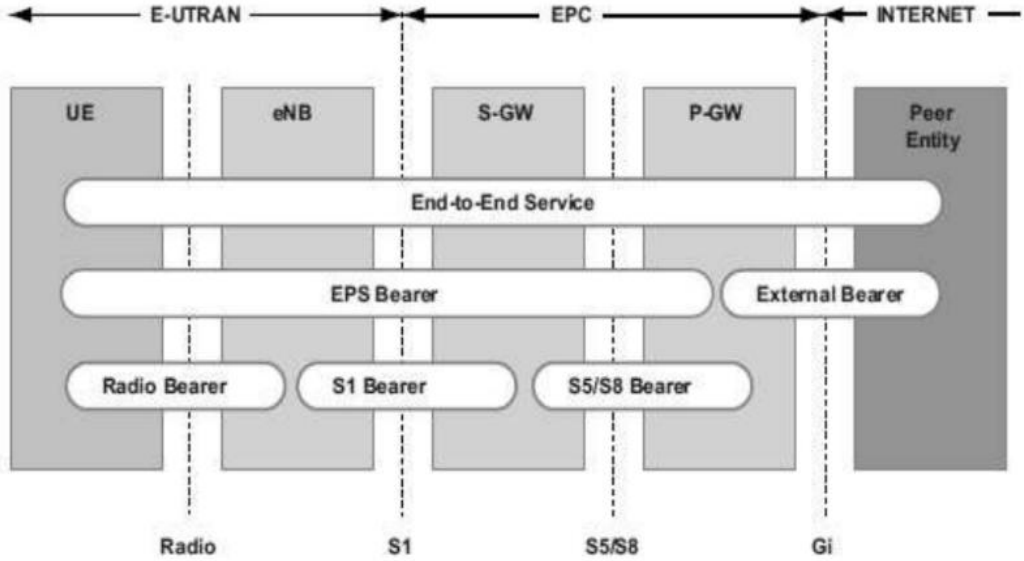
ii. **Integrating with existing UTRAN and/or GERAN deployment scenario**: where the operator already has either a UTRAN (3g) and/or a GERAN (2g) network deployed with full or partial coverage in the same geographical area.

6. Flexibility of Spectrum and Deployment:

- LTE was designed to be operable under a wide variety of spectrum scenarios, including its ability to coexist and share spectrum with existing 3G technologies.
- LTE was designed to have a scalable bandwidth from 1.4MHz to 20MHz.
- LTE was designed to operate in both FDD and TDD modes.

7. Interoperability with 3G and 2G Networks:

- Multimode LTE terminals, which support UTRAN and/or GERAN operation with Acceptable terminal complexity and network performance.



5.2.2 Network Architecture

- Figure 5.2 shows the end-to-end network architecture of LTE and the various components of the network.
- The entire LTE network is composed of
  - The radio access network (E-UTRAN) and
  - The core network (EPC).

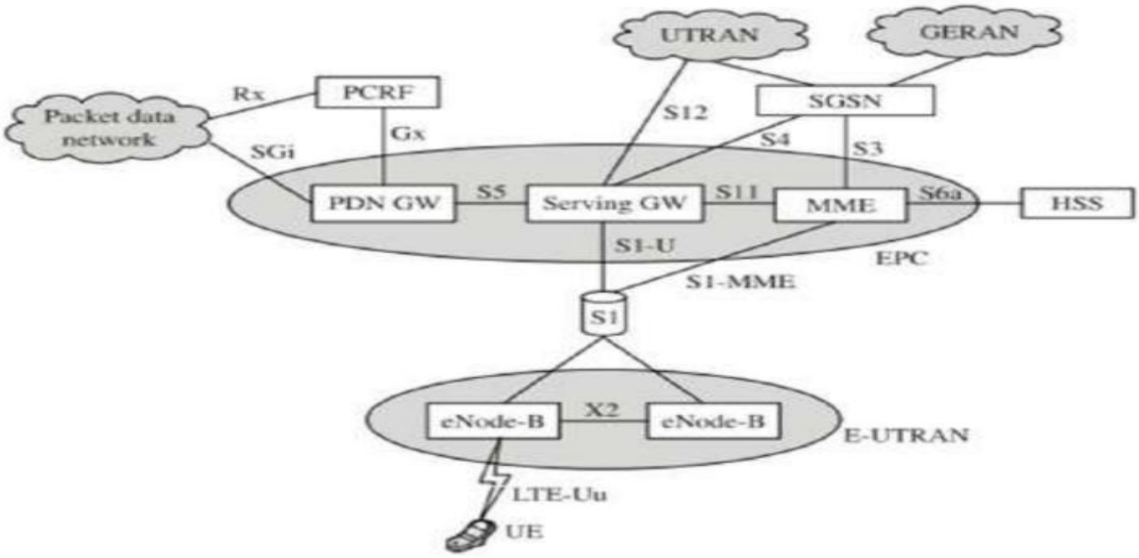


Figure 5.2 LTE end-to-end network architecture.

The main components of the E-UTRAN and EPC are

1. **UE (user Equipment):** It I also called mobile terminal. It is an access device for user. Provides measurements that indicate channel conditions to the network.

2. **ENode-B**: It also called the base station. It interface UE to EPC and is the first point of Contact for the UE. The eNode-B is the only logical node in the E-UTRAN, so it includes some functions such as

    a. Radio bearer management,
    b. Uplink and downlink dynamic radio resource management
    c. Data packet scheduling
    d. Mobility management.

3. **Mobility Management Entity (MME):** MME is similar in function to the control plane of legacy Serving GPRS Support Node (SGSN). It manages mobility aspects such as gateway selection and tracking area list management.

4. **Serving Gateway (Serving GW):** It terminates the interface toward E-UTRAN, and

    routes data packets between E-UTRAN and EPC. It perform local mobility anchor point for inter-eNode-B handovers and also provides an anchor for inter-3GPP mobility. The Serving GW and the MME may be implemented in one physical node or separate physical nodes. Other responsibilities include
    o Lawful intercept.
    o Charging, and some policy enforcement.

5. **Packet Data Network Gateway (PDN GW):** Following are the responsibilities of PDN GW
    - It terminates the SGi interface toward the Packet Data Network (PDN).
    - It routes data packets between the EPC and the external PDN, and is the key node for policy enforcement and charging data collection.
    - It also provides the anchor point for mobility with non-3GPP accesses.
    - The external PDN can be any kind of IP network as well as the IP Multimedia Subsystem (IMS) domain.
    - The PDN GW and the Serving GW may be implemented in one physical node or separated physical nodes.
6. **S1 Interface**: The S1 interface is the interface that separates the E-UTRAN and the EPC. It is split into two parts:
    i. The SI-U: It carries traffic data between the eNode-B and the Serving GW.
    ii. The S1-MME: It is a signaling-only interface between the eNode-B and the MME.

7. **X2 Interface**: The X2 interface is the interface between eNode-Bs. It always exists Between eNode-Bs that need to communicate with each other, for example, for support of handover. It consisting of two parts:
    i. The X2-C: It is the control plane interface between eNode-Bs.
    ii. The X2-U: It is the user plane interface between eNode-Bs.
8. **Policy and Charging Rules Function (PCRF):** It is for policy and charging control.
9. **Home Subscriber Server (HSS):** It is responsible for the service authorization and

User authentication.

10. **Serving GPRS Support Node (SGSN):** It is for controlling packet sessions and managing the mobility of the UE for GPRS networks.

5.2.3. Radio Interface Protocols

LTE radio interface is designed based on a layered protocol stack, which can be divided into **control plane and user plane** protocol stacks and is shown in figure 5.3. The packet flow in the user plane is shown in figure 5.4.

The LTE **radio interface protocol** is composed of the following layers

Radio Resource Control (RRC): The RRC layer performs the control plane functions including paging, maintenance and release of an RRC connection- security handling-mobility management, and QoS management.

Packet Data Convergence Protocol (PDCP):
The main functions of the **PDCP sub layer include IP packet header compression and decompression** based on the Robust Header Compression (ROHC) protocol, **ciphering of data and signaling and integrity protection** for signaling. There is only one PDCP entity at the eNode-B and the UE per bearer.

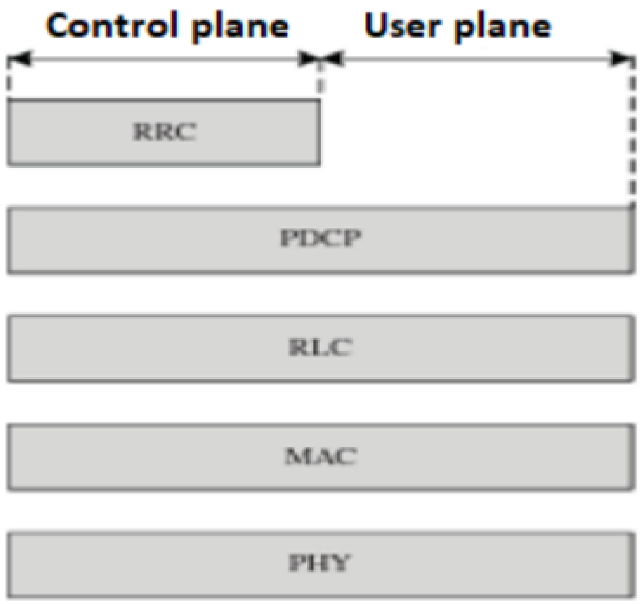


Fig. 5.3: The LTE radio interface protocol stack

Radio Link Control (RLC): The main functions of the RLC sublayer are segmentation and concatenation of data units, error correction through the Automatic Repeat request (ARQ) protocol, and in-sequence delivery of packets to the higher layers. It operates in three modes:

– The Transparent Mode (TM): The TM mode is the simplest one, without RIC header addition, data segmentation, or concatenation, and it is used for specific purposes such as random Access.

– The Unacknowledged Mode (UM): The UM mode allows the detection of packet loss and provides packet reordering and reassembly, but does not require retransmission of the missing protocol data units (PDUs)

– The Acknowledged Mode (AM): The AM mode is the most complex one, and it is configured to request retransmission of the missing PDUs in addition to the features supported by the UM mode.

There is only one RLC entity at the eNode-B and the UE per bearer.

Medium Access Control (MAC): The main functions of the MAC sublayer include **error correction through the Hybrid-ARQ (H-ARQ) mechanism, mapping between logical channels and transport channels, multiplexing/'demultiplexing of RLC PDUs on to transport blocks**, priority handling between logical channels of one UE, and priority handling between UEs by means of dynamic scheduling.

Physical Layer (PHY): The main function of PHY is the actual transmission and reception of data in the forms of transport blocks. The PHY is also responsible for various control mechanisms such as **signalling of H-ARQ feedback, signalling of scheduled allocations, and channel measurements.**

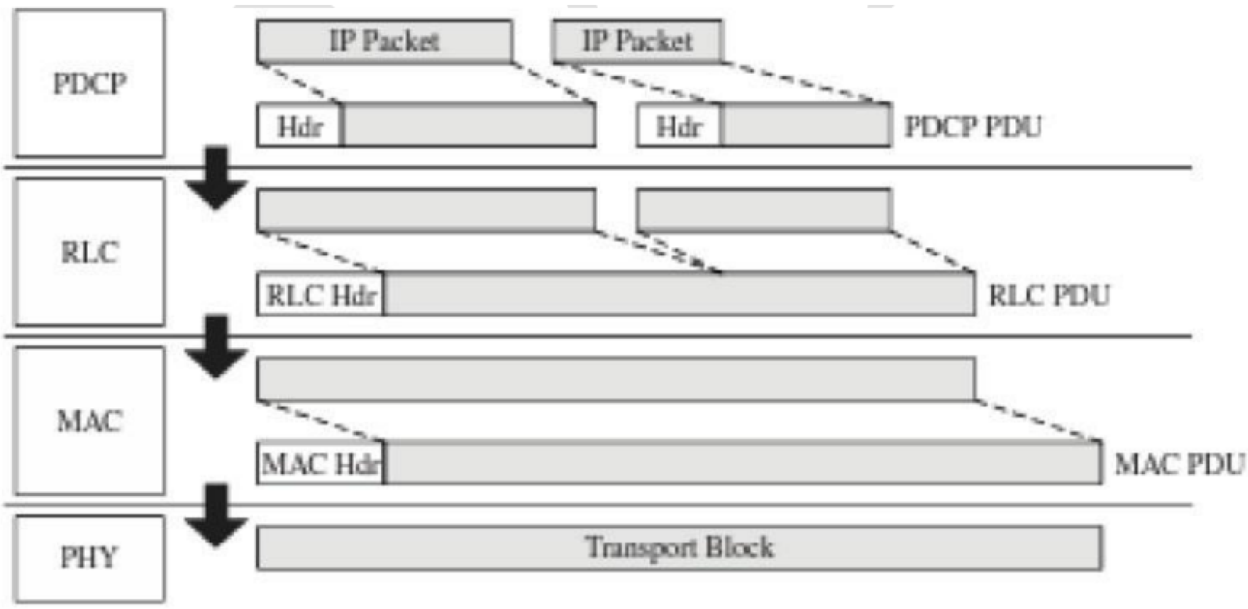


Fig. 5.4: The packet flow in the user plane

5.3. Hierarchical Channel Structure of LTE

- LTE adopts a hierarchical channel structure to efficiently support various QoS classes of services.
- There are three different channel types defined in LTE
  1. Logical channels
  2. Transport channels
  3. Physical channels
- Each channel type associated with a service access point (SAP) between different layers.

- These channels are used by the lower layers of the protocol stack to provide services to the higher layers. The radio interface protocol architecture and the SAPs between different layers are shown in Figure 5.5:

- The radio interface protocol architecture and the SAPs between different layers.

  - Logical channels provide services at the SAP between MAC and RLC layers
  - Transport channels provide services at the SAP between MAC and PHY layers
  - Physical channels are the actual implementation of transport channels over the Radio interface.

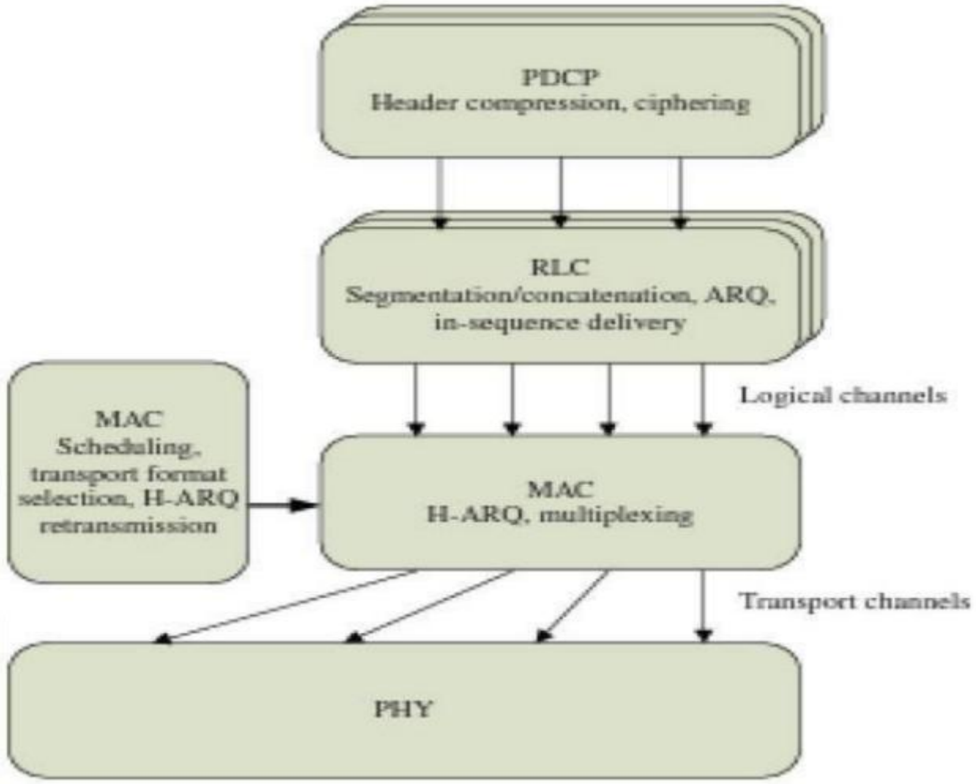


Fig. 5.5: The radio interface protocol architecture and the SAPs b/w different layers

5.3.1. Logical Channels: What to Transmit

Logical channels are used by the MAC to provide services to the RLC. Each logical channel is defined based on the type of information it carries. In LTE, there are two categories of logical channels depending on the service they provide: **logical control channels and logical traffic channels.**

- **Broadcast Control Channel (BCCH):** A downlink common channel used to broadcast system control information to the mobile terminals in the cell, including downlink system bandwidth, antenna configuration, and reference signal power. Due to the large amount of information carried on the BCCH, it is mapped to two different transport channels: **the Broadcast Channel (BCH) and the Downlink**

Shared Channel (DL-SCH).

- **Multicast Control Channel (MCCH):** A point-to-multipoint downlink channel used For transmitting control information to UEs in the cell. It is only used by UEs that Receive multicast/'broadcast services.

- **Paging Control Channel (PCCH):** A downlink channel that transfers paging information to registered UEs in the cell, for example, in case of a mobile-terminated communication session.

- **Common Control Channel (CCCH):** A bi-directional channel for transmitting Control information between the network and UEs when no RRC connection is available, implying the UE is not attached to the network such is in the idle state. Most commonly the CCCH is used during the random access procedure.

- **Dedicated Control Channel (DCCH):** A point-to-point, bi-directional channel that Transmitted dedicated control information between a UE and the network. This channel is used when the RRC connection is available, that is, the UE is attached to the network.

The logical traffic channels, which are to transfer user plane information, include:

Dedicated Traffic Channel (DTCH): A point-to-point, bi-directional channel used between a given UE and the network. It can exist in both uplink and downlink.

Multicast Traffic Channel (MTCH): A unidirectional point-to-multipoint data channel that transmits traffic data from the network to UEs. It is associated with multicast/broadcast service.

5.3.2 Transport Channels: How to Transmit

The transport channels are used by the PHY to offer services to the MAC.

A transport channel is basically characterized by how and with what characteristics data is transferred over the radio interface, that is, the channel coding scheme, the modulation scheme, and antenna mapping.

LTE defines two MAC entities: on in the UE and one in the E-UTRAN, which handle the following downlink/uplink transport channel.

Downlink Transport Channels

- **Downlink Shared Channel (DL-SCH):** Used for transmitting the downlink data, including both control and traffic data, and thus it is associated with both logical control and logical traffic channels. It supports H-ARQ, dynamic link adaption, dynamic and semi-persistent resource allocation, UE discontinuous reception and multicast/broadcast transmission.

- **Broadcast Channel (BCH):** A downlink channel scouted with the BCCH logical channel and is used to broadest system information over the entire coverage area of the cell. It has a fixed transport format defined by the specifications.

- **Multicast Channel (MCH):** Associated with MCCH and MTCH logical channels for the multicast/broadcast service. It supports **Multicast/Broadcast Single Frequency Network (MBSFN)** transmission, which transmits the same information on the same radio resource from multiple synchronized base stations to multiple UEs.

- **Paging Channel (PCH):** Associated with the PCCH logical channel. It is mapped to dynamically allocate physical resources, and is required for broadcast over the entire cell coverage area. It is transmitted on the Physical Downlink Shared Channel (PDSCH), and supports UE discontinuous reception.

Uplink Transport Channels

- **Uplink Shared Channel (UL-SCH):** The uplink counterpart of the DL-SCH. It can be associated to CCCH, DCCH, and DTCH logical channels. It supports H-ARQ, dynamic link adaption, and dynamic and semi-persistent resource allocation.

- **Random Access Channel (RACH):** A specific transport channel that is not mapped to any logical channel. It transmits relatively small amounts of data for initial loss or, in the case of RRC, state changes.

- **Downlink Control Information (DCI)**: It carries information related to downlink/uplink scheduling assignment, modulation and coding scheme, and **Transmit Power Control (TPC) command**, and is sent over the Physical Downlink Control Channel (PDCCH). The DCI supports 10 different formats, listed in Table 5.1. Among them, **Format 0 is for signalling uplink transmission allocation**, Format 3 and 3A for TPC and the remaining formats ire for signalling downlinks transmission allocation.

- **Control Format Indicator (CFI):** It indicates how many symbols the DCI spans in that sub frame. It takes values CFI = 1, 2, or 3, and is sent over the **Physical Control Format Indicator Channel (PCFICH).**

- **H-ARQ Indicator (HI):** It carries H-ARQ acknowledgment in response to up link transmissions, and is sent over the Physical Hybrid ARQ Indicator Chanel (PHICH). HI = 1 for a positive acknowledgement (ACK) and HI = 0 for a negative acknowledgment (NAK).

Table 5.1 DCI Formats

Format	Carried Information
Format 0	Uplink scheduling assignment
Format 1	Downlink scheduling for one codeword
Format 1A	Compact downlink scheduling for one codeword and random access procedure
Format 1B	Compact downlink scheduling for one codeword with precoding information
Format 1C	Very compact downlink scheduling for one codeword
Format 1D	Compact downlink scheduling for one codeword with precoding and power offset information
Format 2	Downlink scheduling for UEs configured in closed-loop spatial multiplexing mode
Format 2A	Downlink scheduling for UEs configured in open-loop spatial multiplexing mode
Format 3	TPC commands for PUCCH and PUSCH with 2-bit power adjustments
Format 3A	TPC commands for PUCCH and PUSCH with 1-bit power adjustments

5.3.3. Physical Channels: Actual Transmission:

- These channels are also used in both direction downlink and uplink directions.
- Each physical channel corresponds to a set of resources elements in the time frequency grid that carry information from higher layers.
- The basic entities of physical channel are resources elements and resources blocks.
- A resource element is a single subcarrier over one OFDM symbol and typically carry one symbol.
- A resource block is a collection of resource elements and in the frequency domain this represents smallest quanta of resources that can be allocated.

Downlink Physical Channel

Physical Downlink Control Channel (PDCCH): It carries information about the transport format and resource allocation related to the DL-SCH and PCH transport channels, and the H-ARQ information related to the DL-SCH. It also informs the UE about the transport format, resource allocation, and H-ARQ information related to UL-SCH. It is mapped from the DCI transport channel.

Physical Downlink Shared Channel (PDSCH): This channel carries user data and higher-layer signalling.
It is associated to DL-SCH and PCH.

Physical Broadcast Channel (PBCH): It-corresponds to the BCH transport channel and carries system information.

Physical Multicast Channel (PMCH): It carriers multicast/broadcast information for the MBMS service.

Physical Hybrid-ARQ Indicator Channel (PHICH): This channel carries H-ARQ ACK/NAKs associated with uplink data transmissions. It is mapped from the HI transport channel.

Physical Control Format Indicator Channel (PCFICH): It informs the UE about the number of OFDM symbols used for the PDCCH. It is mapped from the CFI transport channel.

Uplink Physical Channels

Physical Uplink Control Channel (PUCCH): It carries uplink control information including Channel Quality Indicators (CQI), ACK/NAKs for H-ARQ in response to downlink transmission, and uplink scheduling requests.

Physical Uplink Shared Channel (PUSCH): It carries user data and higher layer signaling. It corresponds to the UL-SCH transport channel.

Physical Random Access Channel (PRACH): This channel carries the random access preamble sent by UEs.

The physical signals defined in the LTE specifications are

Reference signal: It is defined in both downlink and uplink for channel for estimation that enable coherent demodulation.

Three different receive signal in downlink are

1. Cell-specific reference signals, associated with non-MBSFN (Multicast/Broadcast Single
2. Frequency Network) transmission.
3. MBSFN reference signals, associated with MBSFN transmission

UE-specific reference signals: There are two types of uplink reference signals:

Demodulation reference signal, associated with transmission of PUSCH or PUCCH

Sounding reference signal, to support uplink channel-dependent scheduling

Synchronization signal: It is split into a primary and a secondary synchronization signal, and is only defined in the downlink to enable acquisition of symbol timing and the precise frequency of the downlink signal.

5.3.4. Channel Mapping

From the description of different channel types, we see that there exists a good correlation based on the purpose and the content between channels in different layers.

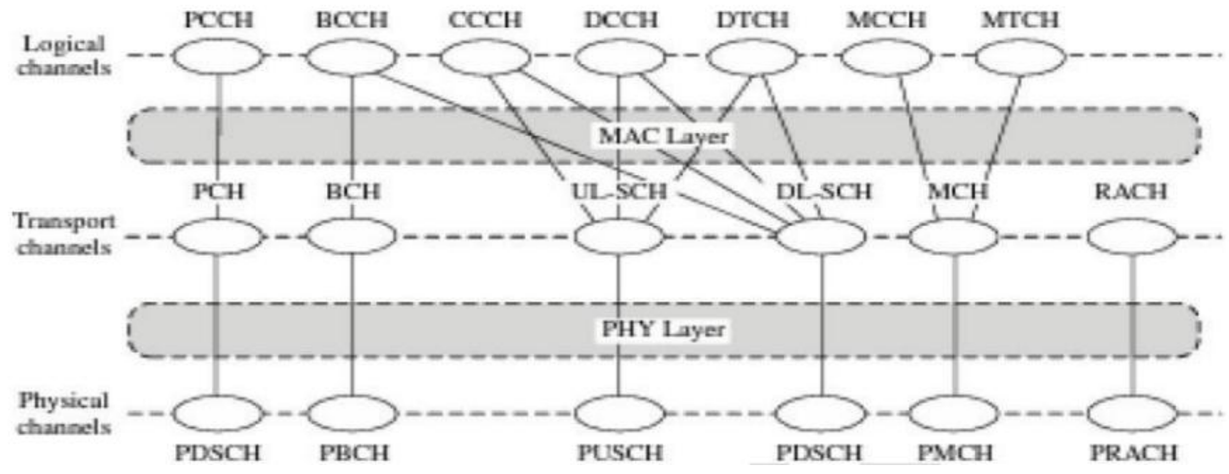


Fig. 5.6: Mapping between different channel types

This requires a mapping between the logical channels and transport channels at the MAC SAP (Service Access Points) and a mapping between transport channels and physical channels at the PHY SAP.

Such channel mapping is not arbitrary, and the allowed mapping between different channel types is shown in Figure 5.6, while the mapping between control information and physical channels is shown in Figure 5.7.
It is possible for multiple channels mapped to a single channel, for example, different logical control channels and logical traffic channels are mapped to the DL-SCH transport channel

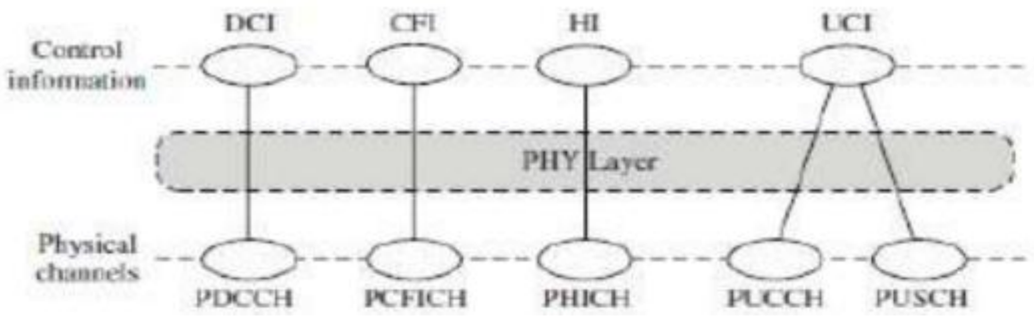


Fig. 5.7: Mapping of control information to physical channels

5.4. Downlink OFDMA Radio Resources

In LTE, the downlink and uplink use different transmission schemes due to different considerations.

Here, we describe downlink and uplink radio transmission schemes, respectively. In the downlink, a scalable **OFDM transmission/multi-access technique** is used that allows for high spectrum efficiency by utilizing multiuser diversity in a frequency selective channel.

On the other hand, SC- FDMA transmission, multi-access technique is used in the uplink since this reduces the peak-to-average power ratio (PAPR) of the transmitted signal.

The transceiver structure of OFDM with FFT/IFFT enables scalable bandwidth operation with a low complexity, which is one of the major objectives of LTE.

As each subcarrier becomes a flat fading channel, compared to single-carrier transmission OFDM makes it much easier to support multi-antenna transmission, which is a key technique to enhance the spectrum efficiency.

- OFDM enables multicast/broadest services on a synchronized single frequency network, that is, MBSFN, as it treats signals from different base stations is propagating through a multipath channel and can efficiently combine them.

The multiple access in the downlink is based on OFDMA. In each **TTI (Transmission Time Interval), a** scheduling decision is made where each scheduled UE is signed a certain amount of radio resources in the time and frequency domain. The radio resources allocated to different **UEs are orthogonal to each other**, which mean there is no intra-cell interference.

Further, we describe the **frame structure** and the radio **resource block structure** in the downlink, as well as the basic principles of **resource allocation** and the **supported MIMO modes.**

5.4.1. Frame Structure

Before going into details about the resource block structure for the downlink, we first describe the frame structure in the time domain, which is a common element shared by both downlink and uplink.

In LTE specifications, the size of elements in the time domain is expressed as a number of time units T = 1/(15000 x 2048) seconds. As the normal subcarrier spacing is defined to be Δf = 15kHz, T, can be regarded as the sampling time of an FFT-based OFDM transmitter/receiver implementation with FFT size N = 2048. Note that this is just for notation purpose, as different FFT sizes are supported depending on the transmission bandwidth. LTE supports both TDD and FDD.

Frame Structure Type 1

Frame stricture type 1 is applicable to **both full duplex and half duplex FDD**. There are three different kinds of units specified for this frame structure, illustrated in figure 5.8. The smallest one is called a slot, which is of length. T_{slot} = 1536* T_s= 0.5ms. Two consecutive slots are defined as a sub frame of length 1ms, and 20 slots, numbered from 0 to 19, constitute a radio frame of 10ms.

Channel-dependent scheduling and link adaptation operate of a sub frame level. Therefore, the subframe duration corresponds to the minimum downlink TTI, which is of 1 ms duration, compared to a 2 ms TTI for the HSPA and a minimum 10 ms TTI for the UMTS. A shorter TTI is for fast link adaptation and is able to reduce delay and better exploit the time-varying channel through channel-dependent scheduling.

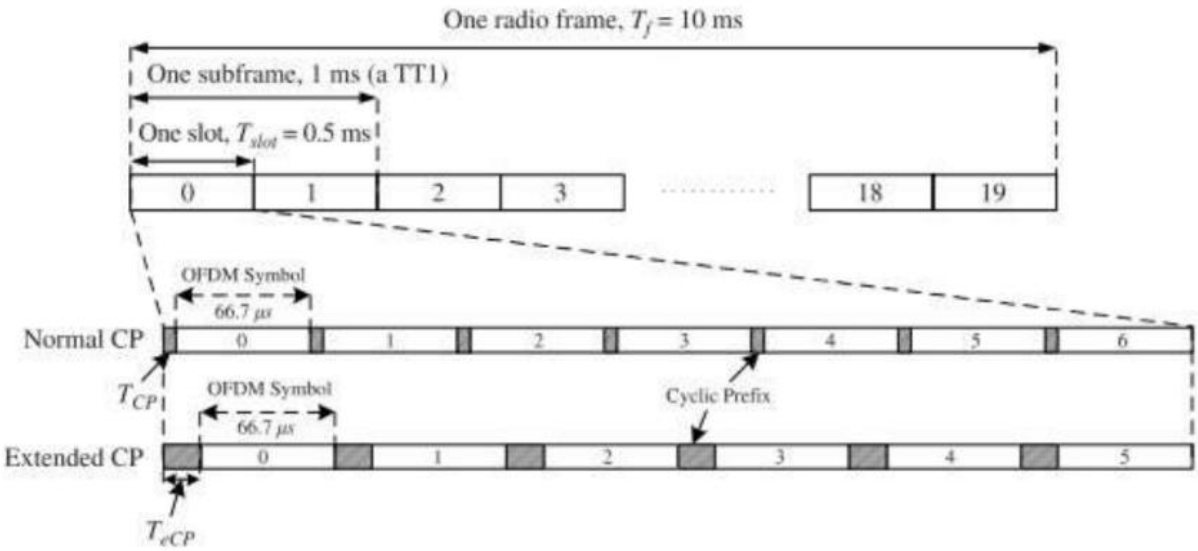


Figure 5.8: Frame structure type 1 . For the normal CP, T_{CP}=160.T_S = 5.2μs for the first OFDM symbols. And T_{CP} =144. T_s = 4.7μs for the remaining OFDM symbols, which together fill the entire slot of 0.5ms. For extended CP, T $_{eCP}$ =512. T_S = 16.7 μs.

Frame Structure Type 2:

Frame structure type 2 is applicable to the TDD mode. It is designed for coexistence with legacy systems such as the 3GPP TD-SCDMA-based standard. As shown in figure 5.9 each radio frame of frame structure type 2 is of length ; T_f = 30720 * T_s = 10 ms, which consists of two half-frames of length 5ms each.

Each half frame is divided into five subframes with 1ms duration.

There are special subframes consists of three fields

- **Downlink Pilot TimeSlot (DwPTS)**
- **Guard Period (GP)**
- **Uplink Pilot TiemSlot (UpPTS)**

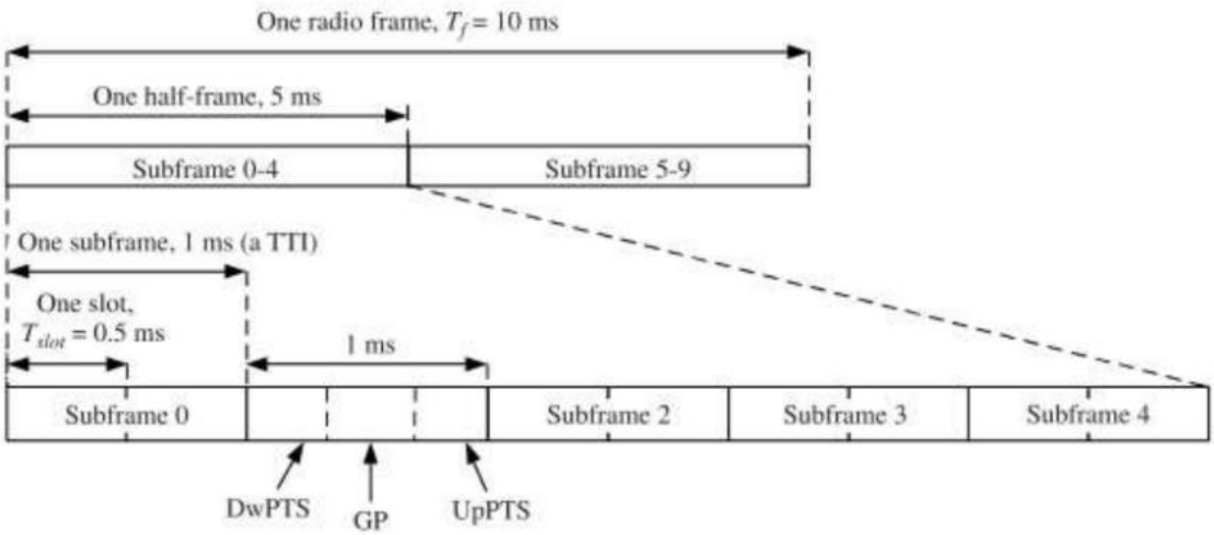


Figure 5.9: Frame structure type 2

The DwPTS field: This is the downlink part of the special subframe, and can be regarded is as on ordinary but shorter downlink sub frame for downlink data transmission. Its length can be varied from three up to twelve OFDM symbols.

The UpPTS field: This is the uplink part of the special subframe, and has a short duration with one or two OFDM symbols. It can be used for transmission of uplink sounding reference signals and random access preambles.

The GP field: The remaining symbols in the special sub frame that have not been allocated to DwPTS or UpPTS are allocated to the GP field, which is used to provide the guard period for the downlink-to-uplink and the uplink-to-downlink switch.

5.4.2 Physical Resource Blocks for OFDMA

The physical resource in the downlink in each slot is described by a time-frequency grid, called a resource grid, is illustrated in Figure5.27. Such a time-frequency plane representation is a common practice for OFDM systems, which makes it intuitive for radio resource allocation. Each column and each row of the resource grid correspond to one OFDM symbol and one OFDM subcarrier, respectively. The duration of the resource grid in the time domain corresponds to one slot in a radio frame. The smallest time frequency unit in a resource grid is denoted as a resource element. Each resource grid consists of a number of resource blocks, which describe the mapping of certain physical channels to resource elements. The detail of these resource units is described as follows.

Resource Grid

The structure of each resource grid is characterized by the following three parameters

- **The number of downlink resource blocks (N_{RB}^{DL}):** It depends on the transmission bandwidth and shall fulfill $N_{RB}^{min,DL} \le N_{RB}^{DL} \le N_{RB}^{max,DL}$, where $N_{RB}^{min,DL} = 6$ and $N_{RB}^{max,DL} = 110$ are for the smallest and largest downlink channel bandwidth,
- **The number of subcarriers in each resource block (N_{sc}^{RB}):** It depends on the subcarrier spacing Δf, satisfying $N_{sc}^{RB}\Delta f = 180\text{kHz}$, that is, each resource block is

  of 180kHz wide in the frequency domain. The values of N_{sc}^{RB} for different subcarrier spacings are shown in Table 6.4. There are a total of $N_{RB}^{DL} \times N_{sc}^{RB}$ subcarriers in each resource grid. For downlink transmission, the DC subcarrier is not used as it may be subject to a too high level of interference.
- **The number of OFDM symbols in each block (N_{symb}^{DL}):** It depends on both the CP length and the subcarrier spacing, specified in Table 6.4.

Therefore, each downlink resource grid has $(\boldsymbol{N_{RB}^{DL}})\boldsymbol{X}\ (\boldsymbol{N_{SC}^{RB}}\boldsymbol{X}(\boldsymbol{N_{symb}^{DL}})$resouces elements.

- Cell-specific reference signals support a configuration of 1, 2, or 4 antenna ports
- MBSFN reference signals are transmitted on antenna port p=4.
- UE-specific reference signals are transmitted on antenna port p=5.

Resource Element

Each resource element in the resource grid is uniquely identified by the index pair (k, l) in a slot, where $k = 0, 1, \ldots, N_{RB}^{DL} N_{sc}^{RB} - 1$ and $l = 0, 1, \ldots, N_{symb}^{DL} - 1$ are indices in the frequency and time domains, respectively. The size of each resource element depends on the subcarrier spacing Δf and the CP length.

Resource Block

The resource block is the basic element for radio resource allocation. The minimum size of radio resource that can be allocated is the minimum TTI in the time domain, that is, one subframe of 1ms, corresponding to two resource blocks. The size of each resource block is the same for all bandwidths, which is 180 kHz in the frequency domain.

There are two kinds of resource blocks defined for LTE:
physical and virtual resource blocks, which are defined for different resource allocation schemes and are specified in the following section.

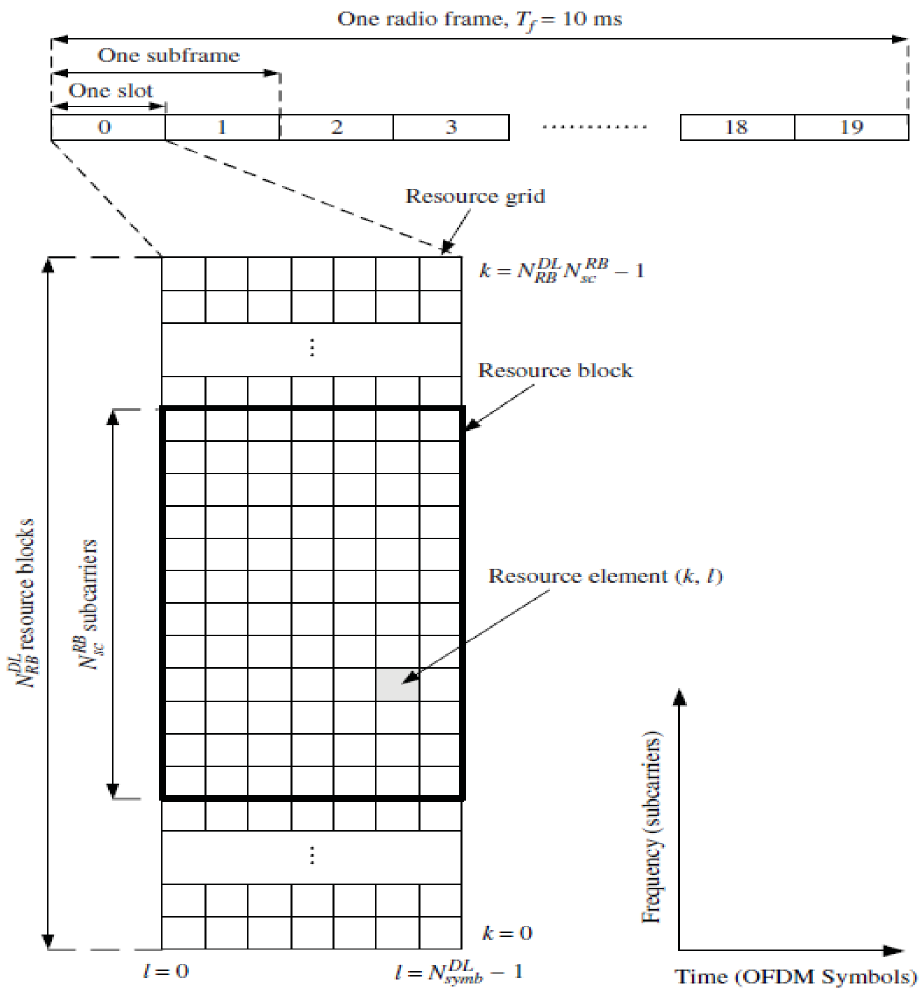


Fig. 5.10: The structure of the downlink resource grid

5.4.3 Resource Allocation

Resource allocation's role is to dynamically assign available time-frequency resource blocks to different UEs in an efficient way to provide good system performance. In LTE channel-dependent scheduling is supported, and transmission is based on the shared channel structure where the radio resource is shared among different UEs.

With OFDMA, the downlink resource allocation is characterized by the fact that each scheduled UE occupies a number of resource blocks while each resource block is assigned exclusively to one UE at any time. **Physical resource blocks (PRBs) and virtual resource blocks (VRBs)** are defined to support different kinds of resource allocation types.

The VRB is introduced to support both **block-wise transmission (localized) and transmission on non- consecutive subcarriers (distributed)** as a means to **maximize frequency diversity**. The LTE downlink supports three resource allocation types: type 0, 1, and 2. The downlink scheduling is performed at the eNode-B based on the channel quality information fed back from UEs, and then the downlink resource assignment information is sent to UEs on the PDCCH channel.

A PRB is defined as N^{DL}_{symb} consecutive OFDM symbols in the time domain and N^{RB}_{SC} Consecutive subcarriers in the frequency domain, as shown in figure 5.11. Therefore, each PRB corresponds to one slot in the time domain (0.5 ms) and 180 kHz in the frequency domain. PRBs are numbered from 0 to (N^{DL}_{RB} - 1) in the frequency domain. The PRB number η_{PRB} of a resource element (k, l) in a slot is given by

$$n_{PRB} = \left\lfloor \frac{k}{N^{RB}_{sc}} \right\rfloor.$$

The PRB is to support resource allocations of type 0 and type 1, which are defined for the DCI format 1, 2, and 2A.

In type 0 resource allocations, several consecutive PRBs constitute a resource block group (RBG), and the resource allocation is done in units of RBGs. Therefore, a bitmap indicating the RBG is sufficient to carry the resource assignment. The allocated RBGs to a certain UE do not need to be adjacent to each other, which provide frequency diversity. The RBG size P, that is, the number of PRBs in each RBG, depends on the bandwidth and is specified in Table 5.2. An example of type 0 resource allocation is shown in Figure 5.28, where P = 4 and RBGs 0, 3, 4,.. are allocated to a particular UE.

In type 1 resource allocations, all the RBGs are grouped into a number of RBG subsets, and certain PRBs inside a selected RBG subset are allocated to the UE.

There are a total of P RBG subsets, where P is the RBG size. An RBG subset p, where $0 \le p < P$, consists of every P-th RBG starting from RBG p.

Therefore the resource assignment information consists of three fields:

The first field indicates the selected RBG subset,

The second field indicates whether an offset is applied and

The third field contains the bitmap indicating PRBs inside the selected RBG subset.

Table5.2 :Resource Allocation RBG Size vs. Downlink System Bandwidth

Downlink Resource Blocks $\left(N_{RB}^{DL}\right)$	RBG Size (P)
≤ 10	1
$11-26$	2
$27-63$	3
$64-110$	4

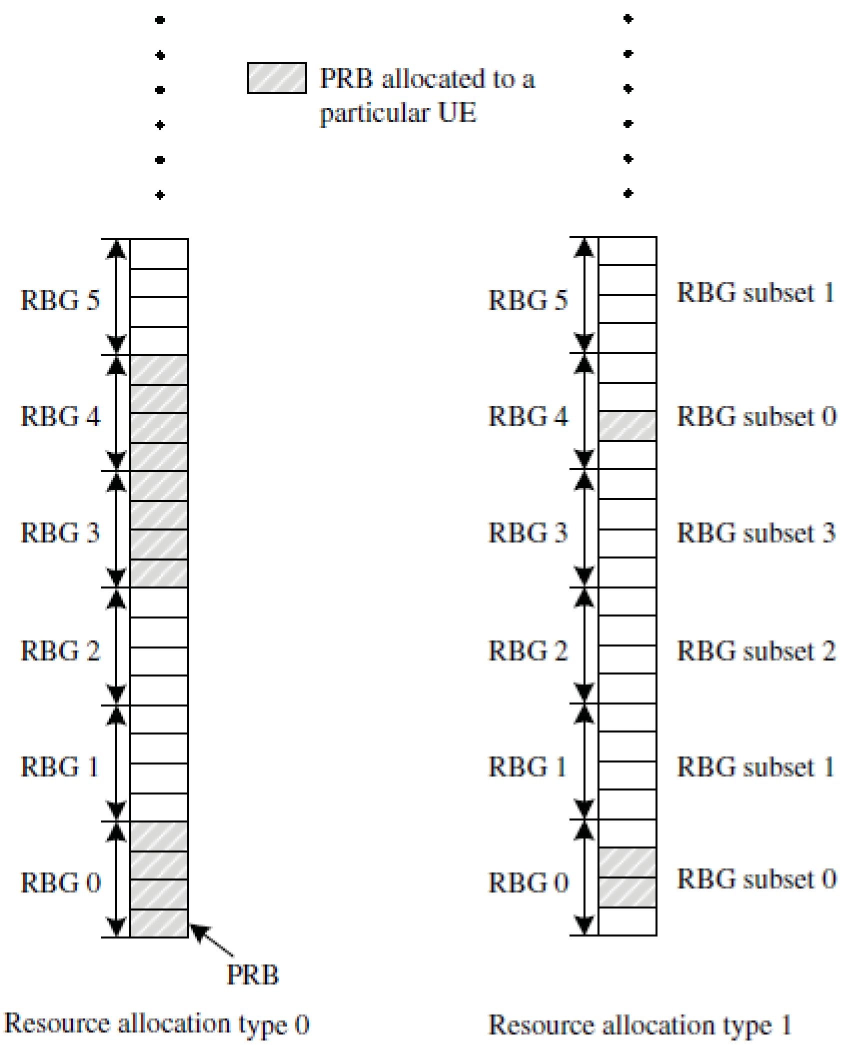


Fig. 5.11 Examples of resource allocation type 0 and type 1, where the RBG size P=4

This type of resource allocation is more flexible and is able to provide higher frequency diversity, but it also requires a larger overhead.

An example of type resource allocation is shown in Figure 5.12, where P = 4 and the RBG subset 0 selected for the given UE.

In type 2 resource allocations that are defined for the DCI format 1A, 1B, 1C and 1D, PRBs are not directly allocated. Instead, VRBs are allocated, which are then mapped onto PRBs. A VRB is of the same size as a PRB. There are two types VRBs ; VRBs of the localized type and VRBs of the distributed type.

5.4.4 Supported MIMO Modes

Multi antenna transmission and reception (MIIMO) is a physical layer technique that can improve both the reliability and throughput of the communication over wireless channels.
It is considered a key component of the LTE physical layer from the start.
The baseline antenna configuration in LTE is two transmit antennas at the cell site and two receive antennas at the UE.
The higher-order downlink MIMO is also supported with up to four transmit and four receive antennas.

The downlink transmission supports both single-user MIMO (SU-MIMO) and multiuser MIMO (MU-MIMO).
For SU-MIMO, one or multiple data streams are transmitted to a single UE through space-time processing: for MU-MIMO, modulation data streams are transmitted to different UEs using the same time-frequency resource.

The supported ST-MIMO modes are listed as follows:

- Transmit diversity with space frequency block codes (SFBC)
- Open-loop spatial multiplexing supporting four data streams
- Closed-loop spatial multiplexing, with closed-loop precoding as a special case when channel rank = 1.
- Conventional direction of arrival (DOA)-based beamforming

The supported MIMO mode is restricted by the UE capability. The PDSCH physical channel supports all the MIMO modes, while other physical channels support transmit diversity except PMCH, which only supports single-antenna-port transmission.

5.5. Uplink SC-FDMA Radio Resources.

For the LTE uplink transmission, SC-FDMA with a CP is adopted. SC-FDMA possesses most of the merits of OFDM while enjoying a lower PAPR. A lower PAPR is highly desirable in the uplink as less expensive power amplifiers are needed at UEs and the coverage is improved.

In LTE, the SC-FDMA signal is generated by the DFT-spread-OFDM. Compared to conventional OFDM, the SC-FDMA receiver has higher complexity, which however, is not considered to be an issue in the uplink given the powerful computational capability at the base station.

An SC-FDMA transceiver has a similar structure as OFDM, so the parameterization of radio resource in the uplink enjoys similarities to that in the downlink. Nevertheless, the uplink transmission has its own properties. Different from the downlink, only localized resource allocation on consecutive subcarriers is allowed in the uplink.

In addition, only limited MIMO modes are supported in the uplink.

5.5.1. Frame Structure

The uplink frame structure is similar to that for the downlink. The difference is that now we talk about SC-FDMA symbols and SC-FDMA subcarriers.

In frame structure type 1, an uplink radio frame consists of 20 slots of 0.5 ms each, and one subframe consists of two slots, as in Figure 5.8.

Frame structure type 2 consists of ten subframes, with one or two special subframes including DwPTS, GP, and UpPTS fields, as shown in Figure 5.9.

A CP is inserted prior to each SC-FDMA symbol. Each slot carries seven SC-FDMA symbols in the case of normal CP, and six SC-FDMA symbols in the case of extended CP.

5.5.2 Physical Resource Blocks for SC-FDMA

As SC-FDMA can be regarded as conventional OFDM with a DFT-based precoder, the f our grid for the uplink is similar to the one for the downlink, illustrated in figure 5.12, that is, it comprises a number of resource blocks in the time-frequency plane.

The number of resource blocks in each resource grid, NH depends on the uplink transmission bandwidth configured in the cell and should satisfy

$$N_{RB}^{min,UL} \leq N_{RB}^{UL} \leq N_{RB}^{max,UL},$$

where $N_{RB}^{min,UL} = 6$ and $N_{RB}^{max,UL} = 110$ correspond to the smallest and largest uplink Bandwidth.

There are $N_{sc}^{RB} \times N_{symb}^{RB}$ resource elements in each resource block.

5.5.3 Resource Allocation

- Similar to the downlink, shared-channel transmission and channel-dependent scheduling are supported in the uplink. Resource allocation in the uplink is also performed at the eNode-B.

- Based on the channel quality measured on the uplink sounding reference signals and the scheduling requests sent from UES, the eNode-B assigns a unique time frequency resource to a scheduled UE, which achieves orthogonal intra-cell transmission.
- Such intra-cell orthogonality in the uplink is preserved between UEs by using timing advance such that the transport blocks of different UEs are received synchronously at the eNode-B.

- This provides significant coverage and capacity gain in the uplink over UMTS, which employ's non-orthogonal transmission in the uplink and the performance is limited by inter-channel interference.

- In general, SC- FDMA is able to support both localized and distributed resource allocation.

- In the current specification, only localized resource allocation is supported in the uplink, which preserves the single-carrier property and can better exploit the multiuser diversity gain in the frequency domain.

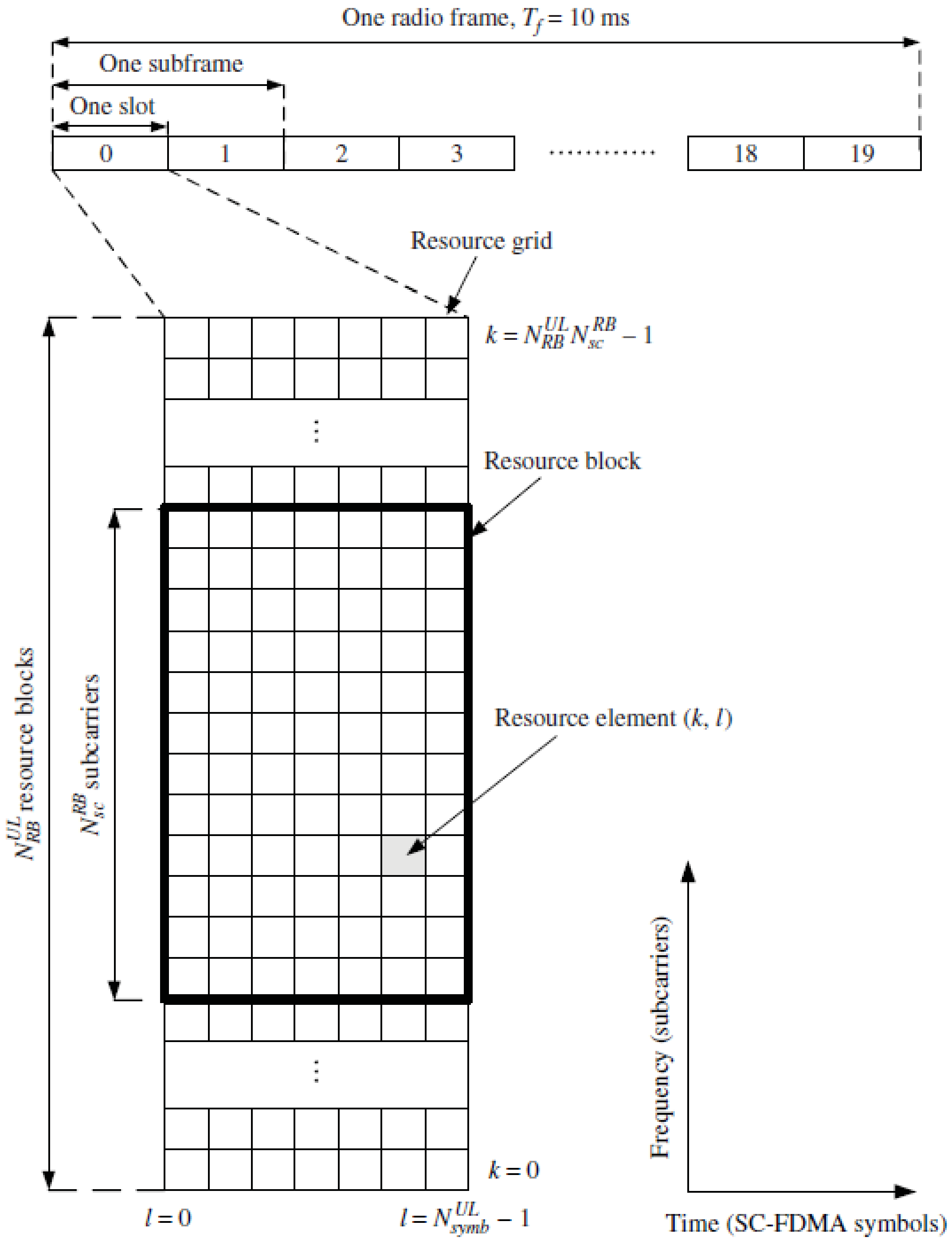


Fig. 5.12: The structure of the uplink resource grid

- Compared to distributed resource allocation, localized resource allocation is less sensitive to frequency offset and also requires fewer reference symbols.

- The resource assignment information for the uplink transmission is carried on the PDCCH with DCI format 0, indicating a set of contiguously allocated resource blocks.

- However, not all integer multiples of one resource block are allowed to be assigned to a UE, which is to simplify the DFT design for the SC-FDMA transceiver.

- Only factors 2, 3, and 5 are allowed. The frequency hopping is supported to provide frequency diversity, with which the UEs can hop between frequencies within or between the allocated subframes.

5.5.4. Supported MIMO Modes

- For the MIMO modes supported in the uplink, the terminal complexity and cost are among the major concerns.

- MU-MIMO is supported, which allocates the same time and frequency resource to two UEs with each transmitting on a single antenna. This is also called Spatial Division Multiple Access (SDMA).

- The advantage is that only one transmit antenna per UE is required. To separate streams for different UEs, channel state information is required at the eNode-B, which is obtained through uplink reference signals that are orthogonal between UEs.

- Uplink MU-MIMO also requires power control, as the near-far problem arises when multiple UEs are multiplexed on the same radio resource.

- For UEs with two or more transmit antennas, closed loop adaptive antenna selection transmit diversity shall be supported.

- Here UE only needs one transmit chain and amplifier. The antenna selection is based on feedback from eNode-B.

Question Bank

1. Discuss the basic design principles followed in designing LTE specification. **OR**
   Discuss the basic design principles while designing the LTE specifications. **OR**
   Explain the basic design principles of LTE.
2. Explain the LTE Radio Interface Protocols.
   OR
   Explain the LTE Radio Interface Protocol stack.
3. Explain the different logical channels supported in LTE.
4. Explain the Hierarchical Channel Structure of LTE.
5. Explain the transport channels in LTE.
6. Briefly explain downlink transport channel.

OR

Explain uplink transport channel.

OR

Explain uplink and downlink transport channel.

7. Explain the different physical signals in downlink.
8. Discuss the Broadcast channel and multicast channels.

   OR

   Explain Broadcast channel used in LTE.
9. Explain control information used in LTE-4G

   OR

   Explain uplink control information.
10. Explain the types of uplink reference signals used in physical channel.

    OR

    Explain the types of uplink reference signals.
11. With a neat diagram explain the mapping between the different channel types and mapping of control information to physical channels.
12. Explain multicast channels in downlink transport channel processing.
13. With a neat diagram explain briefly the frame structure used in LTE.

    OR

    With a neat sketch, explain briefly the frame structure used in LTE.
14. Write the Frame structure Type 2 and explain the various field's applications to TDD mode.
15. Write the Frame structure Type 1 and explain the various fields applications to TDD mode.
16. Write the structure of **downlink resource grid** and explain the types of resource allocation.
17. Write the structure of **uplink resource grid** and explain the types of resource allocation.