Module – 3

Module-3 covered by chapters 6, and 7 from the prescribed text book "*Fundamentals of LTE*" *by* Arunabha Ghosh, Jan Zhang, Jefferey Andrews, Riaz Mohammed.

6. Overview and Channel Structure of LTE:

- Introduction to LTE
- Channel Structure of LTE
- Downlink OFDMA Radio Resource
- Uplink SC-FDMA Radio Resource

7. Downlink Transport Channel Processing:

- Overview
- Downlink shared Channels
- Downlink Control Channels
- Broadcast channels
- Multicast channels
- Downlink physical channels
- H-ARQ on Downlink

- Following Acronyms are used in this module
  - *Mobile Terminal* ***(MT)***
  - *Base Station* ***(BS)***
  - *3rd Generation Partnership Project* ***(3GPP)***
  - *Radio Access Network* ***(RAN)***
  - *Core Network* ***(CN)***
  - *UMTS Terrestrial Radio Access Network* ***(UTRAN)***
  - *Universal Mobile Telecommunications Service* ***(UMTS)***
  - *Evolved Packet Core* ***(EPC)***
  - *Evolved Packet System* ***(EPS)***
  - *Evolved UMTS Terrestrial Radio Access* ***(E-UTRA)***
  - *Evolved UMTS Terrestrial Radio Access Network* ***(E-UTRAN)***
  - *Radio Network Controller* ***(RNC)***
  - *Evolved Node-B* ***(eNode-B)***
  - *High-Speed Packet Access* ***(HSPA)***
  - *GSM/EDGE Radio Access Network* ***(GERAN)***
  - *High Speed Downlink Packet Access* ***(HSDPA)***

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6.1 Overview of the LTE radio interface:

- The radio interface of a wireless network is the interface between the Mobile Terminal (MT) and the Base Station (BS)
- 3GPP divides the whole LTE network into a radio access network and a core network.
- 3GPP focuses to develop UTRA, i, e 3G RAN developed within 3GPP, and on optimizing 3GPP's overall radio access architecture.
- Another parallel project in 3GPP is the Evolved Packet Core (EPC), which focuses on the Core Network evolution with a flatter all-IP, packet-based architecture.
- The complete packet system consisting of LTE and EPC is called the Evolved Packet System (EPS).
- LTE is also referred to as Evolved UMTS Terrestrial Radio Access (E-UTRA), and the RAN of LTE is also referred to as Evolved UMTS Terrestrial Radio Access Network (E-UTRAN).
- The RAN architectures of UTRAN (3G) and E-UTRAN (LTE) are shown in Figure 6.1

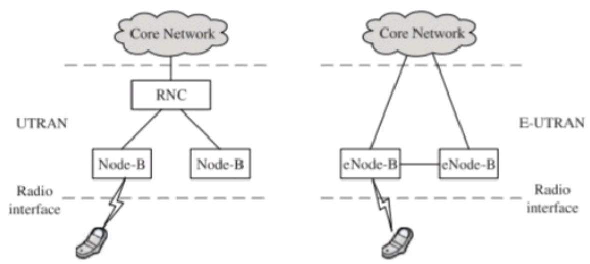

Figure 6.1 Radio interface architectures of UTRAN and E-UTRAN.

- The main architectural difference are, in E-UTRAN (4G) eNode-B is composed of RNC and Node-B of UTRAN (3G) and eNode-Bs are interconnected.
- The eNode-B supports additional features, such as
    1. *Radio resource control*
    2. *Admission control and*
    3. *Mobility management*
- The above three functions were originally performed in the RNC of UTRAN. This simpler structure simplifies the network operation and allows for higher throughput and lower latency over the radio interface.
- The LTE radio interface aims for a long-term evolution, so it is designed with a clean slate approach add-on to UMTS in order to increase throughput of packet switched services.

6.2 Introduction to LTE

- 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.
- The low latency of LTE and its sophisticated quality of service (QoS) architecture allow a net-work to emulate a circuit-switched connection on top of the packet-switched framework of LTE. For example voice over LTE or VoLTE.

6.1.1 Design Principles of LTE ***

- Following are the basic design principles that were agreed upon and followed in 3GPP while designing the LTE specifications. It includes

1. ***Network Architecture***
2. ***Data Rate and Latency***
3. ***Performance Requirements:*** *Spectrum Efficiency, Mobility, Coverage, MBMS service*
4. ***Radio Resource Management***
5. ***Deployment Scenario and Co-existence with 3G***
6. ***Flexibility of Spectrum and Deployment***
7. ***Interoperability with 3G and 2G Networks***

1. *Network Architecture*:

- Basically LTE has flat network architecture. It was designed to support purely packet-switched traffic with support for various QoS classes of services.
- LTE is different by use of clean slate design and supports packet switching for high data rate services from the start.
- The LTE radio access network, E-UTRAN, was efficiently designed to have the minimum number of interfaces and support 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*:

- *Data rate*: The design peak data rate target in LTE for downlink 100 Mbps and uplink 50 Mbps, when operating at the 20MHz channel size.
- *Latency*: The 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 100 ms, 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*

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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.

5. ***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.

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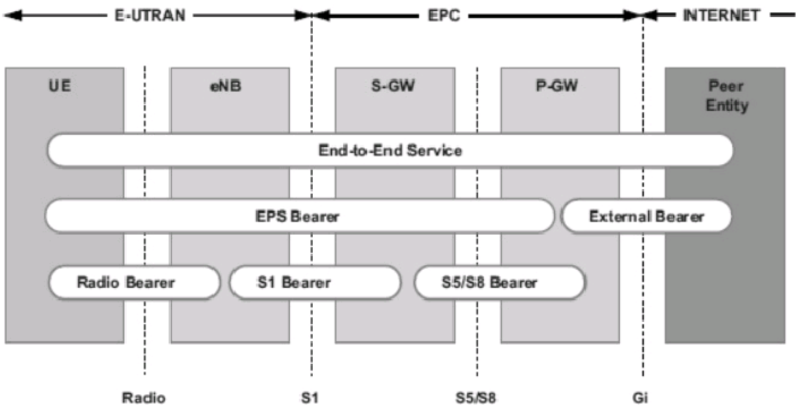
7. Interoperability with 3G and 2G Networks:

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



6.1.2 Network Architecture***

- Figure 6.2 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).*

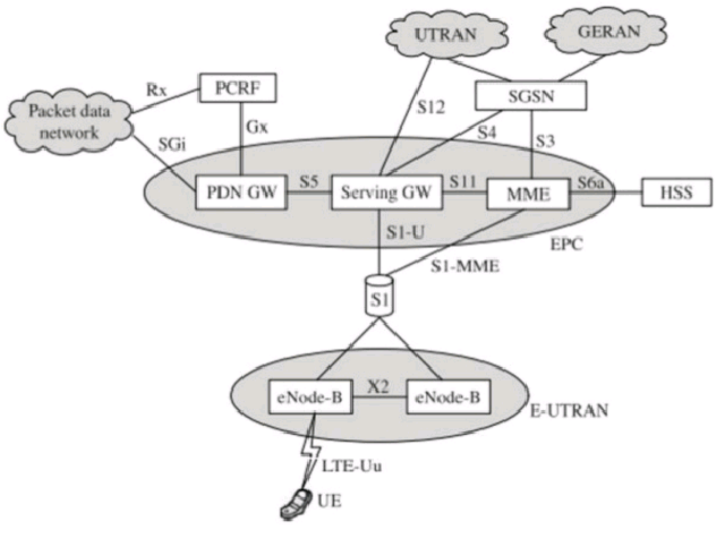


Figure 6.2 LTE end-to-end network architecture.

- 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
    - *Lawful intercept.*
    - *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.

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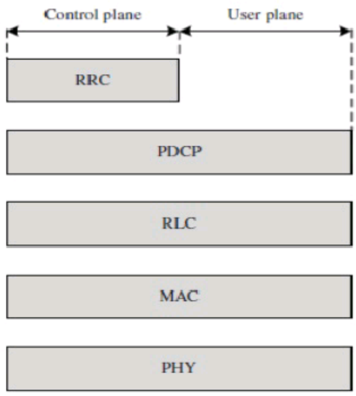
7. ***X2 Interface:*** The X2 interface is the interface between eNode-Bs. It always exists between eNode-Bs that need to communicate with each other, for example, for support of handover. It consisting of two parts:
    i. *The X2-C:* It is the control plane interface between eNode-Bs.
    ii. *The 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.

6.1.3 Radio Interface Protocols**

- The LTE radio interface is designed based on a layered protocol stack, which can be divided into ***Control Plane (CP)*** and ***User Plane (UP)*** protocol stacks and is shown in Figure 6.3.

Figure 6.3 The LTE radio interface protocol stack.



- The LTE radio interface protocol is composed of the following layers:

1. ***Radio Resource Control (RRC):*** This layer performs the control plane functions including
    - *Paging*
    - *Maintenance and release of an RRC connection*
    - *security handling*
    - *mobility and QoS management*
2. ***Packet Data Convergence Protocol (PDCP):*** There is only one PDCP entity at the eNode-B and the UE per bearer. The main functions of the PDCP sublayer include
    - *IP packet header compression and decompression based on the RObust Header Compression (ROHC) protocol*
    - *Ciphering of data and signaling*
    - *Integrity protection for signaling*

3. ***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.
   - In-sequence delivery of packets to the higher layers.

- It operates in three modes:
  1. ***The Transparent Mode (TM):*** The TM mode is the simplest one, without RLC header addition, data segmentation or concatenation and it is used for specific purposes such as random access.
  2. ***The Unacknowledged Mode (UM):*** This 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).
  3. ***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.

4. ***Medium Access Control (MAC):*** There is only one MAC entity at the eNode-B and at the UE. 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*
   - *Priority handling between UEs by means of dynamic scheduling.*
   - It responsible for transport format selection of scheduled UEs , which includes
     - *i. Selection of modulation format*
     - *ii. Code rate*
     - *iii. MIMO rank and power level.*

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

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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.

6.3 LTE Communication Channel* :**

- The information flows between the different protocols layers are known as *channels*. These are used to segregate the different types of data and allow them to be transported across different layers.
- These channels provide interfaces to each layers within the LTE protocol stack and enable an orderly and defined segregation of the data.
- Channels are distinguished based on kind of information they carry and by the way in which the information is processed.
- LTE uses three classes of channels(see fig 6.6):
    1. *Logical channels*: Define ***what type*** of information is transmitted.
    2. *Transport channels:* Define ***how this*** *information* transmitted.
    3. *Physical channels*: Define ***where to*** *send this information.*

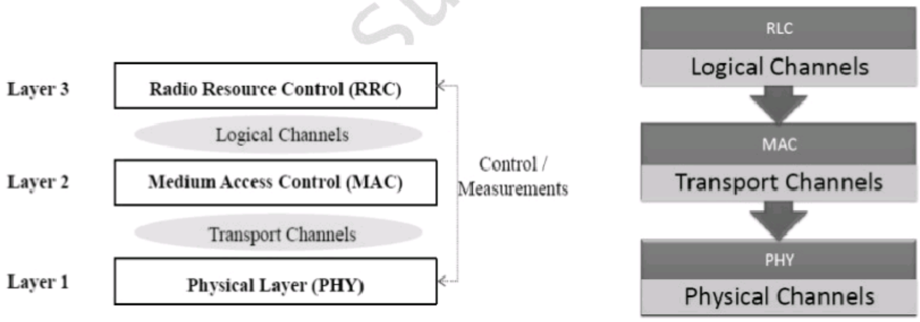

Figure 6.6: LTE channel structure

6.3.1 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:
    1. Logical Control Channels*: Which carries the signaling information in control plane*
    2. Logical Traffic Channels*: Which carries the date information in user plane*

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1. **The Logical Control Channels (LCC):** which are used to transfer control plane information. Control Channel can be either common channel or dedicated channel. A common channel means common to all users in a cell Point to multipoint while dedicated channels means channels can be used only by one user Point to Point. It include the following types:
   a. ***Broadcast Control Channel (BCCH):*** These channels are 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).
   b. ***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.
   c. ***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.
   d. ***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 as in the idle state. Most commonly the CCCH is used during the random access procedure.
   e. ***Dedicated Control Channel (DCCH):*** A point-to-point, bi-directional channel that transmits 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:
  a. ***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.
  b. ***Multicast Traffic Channel (MTCH):*** A unidirectional, point-to-multipoint data channel that transmits traffic data from the network to UEs. It is associated with the multicast/broadcast service.

6.3.2 Transport Channels: *How to Transmit*

- The transport channels are used by the PHY to offer services to the MAC.
- These 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*.
- Transport channels are classified in to
  1. *Downlink Transport Channels*
  2. *Uplink Transport Channels*

1. ***Downlink Transport Channels***

   a. ***Downlink Shared Channel (DL-SCH):***

   - These channel are 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.
   - By sharing the radio resource among different UEs the DL-SCH is able to maximize the throughput by allocating the resources to the optimum UEs.

   b. ***Broadcast Channel (BCH):***

   - A downlink channel associated with the BCCH logical channel and is used to broadcast system information over the entire coverage area of the cell.
   - It has a fixed transport format defined by the specifications.

   c. ***Multicast Channel (MCH):***

   - These channels are 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.

   d. ***Paging Channel (PCH):***

   - These are 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.

2. **Uplink Transport Channels**

   a. ***Uplink Shared Channel (UL-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.

   b. ***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 access or, in the case of RRC, state changes.

- The data on each transport channel is organized into transport blocks.
- The transmission time of each transport block, also called Transmission Time Interval (TTI).

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- In LTE TTI is 1 ms. TTI is also the minimum interval for link adaptation and scheduling decision.
- Without spatial multiplexing, at most one transport block is transmitted to a UE in each TTI; with spatial multiplexing, up to two transport blocks can be transmitted in each TTI to a UE.
- Besides transport channels, there are different types of control information defined in the MAC layer, which are important for various physical layer procedures. The defined control information includes

1. ***Downlink Control Information (DCI):***

- It carries information related to down-link/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 6.1.

Table 6.1 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

2. ***Control Format Indicator (CFI):***

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

3. ***H-ARQ Indicator (HI):***

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

4. ***Uplink Control Information (UCI):***

- It is for measurement indication on the downlink transmission, scheduling request of uplink, and the H-ARQ acknowledgment of downlink transmissions.
- The UCI can be transmitted either on the Physical Uplink Control Channel (PUCCH) or the Physical Uplink Shared Channel (PUSCH).

6.3.3 Physical Channels: *Actual Transmission*

- Each physical channel corresponds to a set of resource elements in the time-frequency grid that carry information from higher layers.
- The basic entities that make a physical channel are resource elements and resource blocks.
- Physical channels are classified into
    1. *Downlink Physical Channels*
    2. *Uplink Physical Channels*

1. Downlink Physical Channels

a. ***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.

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

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

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

e. ***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.

f. ***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.

2. Uplink Physical Channels

a. ***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.

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

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

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- Besides physical channels, there are signals embedded in the downlink and uplink physical layer, which do not carry information from higher layers. The physical signals defined in the LTE specifications are
  1. ***Reference signal***: It is defined in both downlink and uplink for channel estimation that enables coherent demodulation and for channel quality measurement to assist user scheduling.
  2. ***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

6.3.4 Channel Mapping

- These all three types of channel are present in Downlink as well as Uplink direction. Mapping of these channels is shown in below pictures.
- Need to exist a good correlation based on the purpose and the content between channels in different layers. This is achieved by
  1. Mapping between the logical channels and transport channels at the MAC SAP.
  2. Mapping between transport channels and physical channels at the PHY SAP.
- The allowed mapping between different channel types is shown in Figure 6.6 and mapping between control information and physical channels is shown in Figure 6.7.

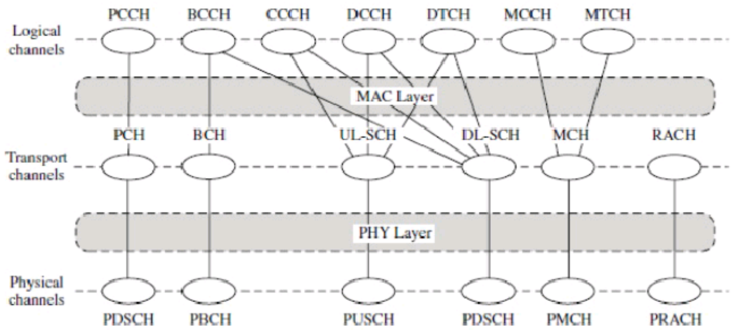

Figure 6.6 Mapping between different channel types.

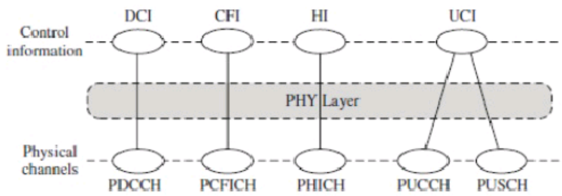

Figure 6.7 Mapping of control information to physical channels.

6.4 Downlink OFDMA Radio Resources***

- In LTE, the downlink and uplink use different transmission schemes due to different considerations.
- The multiple access in the downlink is based on OFDMA. In each TTI, a scheduling decision is made where each scheduled UE is assigned 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 means there is no intra-cell interference
- The following describes 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.

6.4.1 Frame Structure:

- Frames are the common time domain elements shared by both downlink and uplink in LTE.
- Typical parameters used in LTE specification for down link as shown in table 6.2

Table 6.2 Typical Parameters for Downlink Transmission

Transmission bandwidth [MHz]	1.4	3	5	10	15	20
Occupied bandwidth [MHz]	1.08	2.7	4.5	9.0	13.5	18.0
Guardband [MHz]	0.32	0.3	0.5	1.0	1.5	2.0
Guardband, % of total	23	10	10	10	10	10
Sampling frequency [MHz]	1.92 $1/2 \times 3.84$	3.84	7.68 2×3.84	15.36 4×3.84	23.04 6×3.84	30.72 8×3.84
FFT size	128	256	512	1024	1536	2048
Number of occupied subcarriers	72	180	300	600	900	1200
Number of resource blocks	6	15	25	50	75	100
Number of CP samples (normal)	9×6 10×1	18×6 20×1	36×6 40×1	72×6 80×1	108×6 120×1	144×6 160×1
Number of CP samples (extended)	32	64	128	256	384	512

- T_s is the basic time unit for LTE. T_s can be regarded as the sampling time of an FFT-based OFDM transmitter/receiver implementation with FFT size N_{FFT} = 2048.
- As the normal subcarrier spacing is defined to be $\Delta f = 15kHz$
- T_s is defined as $T_s = \frac{1}{(\Delta f \text{ x } N_{FFT})} = \frac{1}{(15000 \text{ x } 2048)}$ seconds or about 32.6 nanoseconds.
- Downlink and uplink transmissions are organized into frames of duration T_f = 307200 x T_s = 10ms
- The 10 ms frames divide into 10 subframes. Each subframe divides into 2 slots of 0.5 ms.
- For flexibility, LTE supports both FDD and TDD modes, but most of the design parameters are common to FDD and TDD in order to reduce the terminal complexity.

- LTE supports two kinds of frame structures:
  1. *Frame structure type 1*: It is for the FDD mode.
  2. *Frame structure type 2*: It is for the TDD mode.

1. Frame Structure Type 1

- Frame structure 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 Fig 6.8.

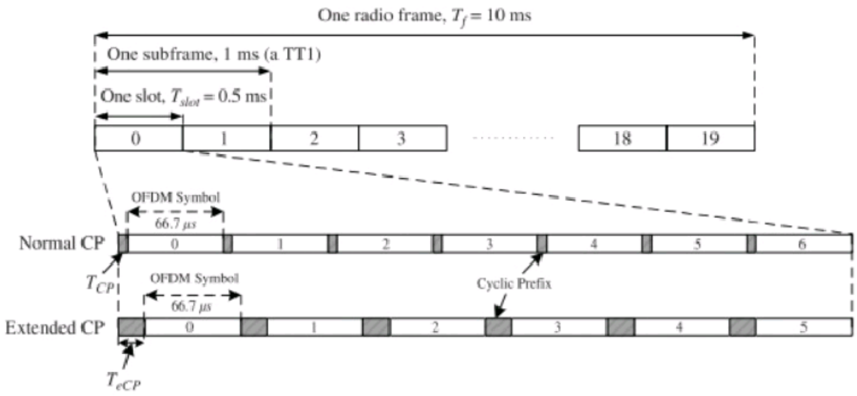

Figure 6.8 Frame structure type 1. For the normal CP, $T_{CP} = 160 \cdot T_s \approx 5.2\mu s$ for the first OFDM symbol, and $T_{CP} = 144 \cdot T_s \approx 4.7\mu s$ for the remaining OFDM symbols, which together fill the entire slot of 0.5 ms. For the extended CP, $T_{eCP} = 512 \cdot T_s \approx 16.7\mu s$.

- ***Description of the frame:***
  - *The smallest time unit is called a "slot" of length* $T_{slot} = 15360 \times T_s = 0.5ms$.
  - *Two consecutive slots are defined as a "subframe" of length* $1ms$.
  - *Ten subframes or 20 slots, numbered from 0 to 19, constitute a one radio frame of 10 ms.*
  - *Channel-dependent scheduling and link adaptation operate on a subframe level.*
  - *The subframe duration corresponds to the minimum downlink TTI, which is of 1 ms duration, compared to a 2 ms TTI for the UMTS (3G).*
  - *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.*
  - *Each slot carries a number of OFDM symbols including Cyclic prefix (CP). With subcarrier spacing* $\Delta f = 15kHz$ *, OFDM symbol time is* $\frac{1}{\Delta f} \approx 66.7\mu s$.
  - LTE defines two different CP lengths (see Fig 6.8):
    1. ***Normal CP:***
       - *It corresponds to seven OFDM symbols per slot.*
       - *The normal CP is suitable for urban environment and high data rate applications.*

- *The normal CP lengths are different for the first* ($T_{CP} = 160 \times T_s \approx 5.2\mu s$) *and subsequent OFDM symbols* $T_{CP} = 144 \times T_s \approx 4.7\mu s$) *which is to fill the entire slot of 0.5 ms.*
- *The numbers of CP samples for different bandwidths are shown in Table 6.2. For example, with 10MHz bandwidth, the sampling time is 1/(15000 x 1024) sec*

2. **Extended CP:**

- *It corresponding to six OFDM symbols per slot.*
- *The extended CP is for multicell multicast/broadcast and very-large-cell scenarios with large delay spread at a price of bandwidth efficiency.*
- *The extended CP lengths* $T_{eCP} = 512 \times T_s \approx 16.7\mu s$.
- *The number of CP samples for the extended CP is 256, which provides the required CP length of 256/ (15000 x 1024) = 1.67μs.*
- *In case of 7.5 kHz subcarrier spacing, there is only a single CP length, corresponding to 3 OFDM symbols per slot.*

---

2. Frame Structure Type 2

- Frame structure type 2 is applicable to the TDD mode. Type 2 structure shown in fig 6.9
- It is designed for coexistence with legacy systems such as the 3GPP TD-SCDMA-based standard.

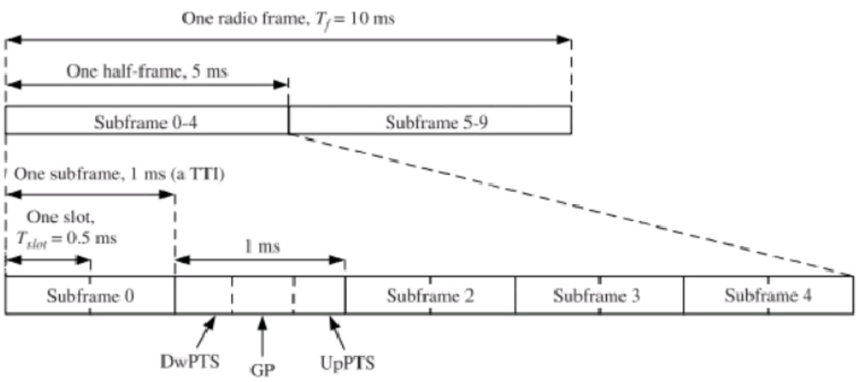

Figure 6.9 Frame structure type 2.

- ***Description of the frame type 2:***
- *Frame structure type 2 is of length* $T_f = 307200 \times T_s = 10ms$.
- *Each frame consists of two half-frames of length 5 ms each.*
- *Each half-frame is divided into five subframes with 1 ms duration.*

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6.3.2 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"*, as illustrated in Figure 6.10.
- 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.

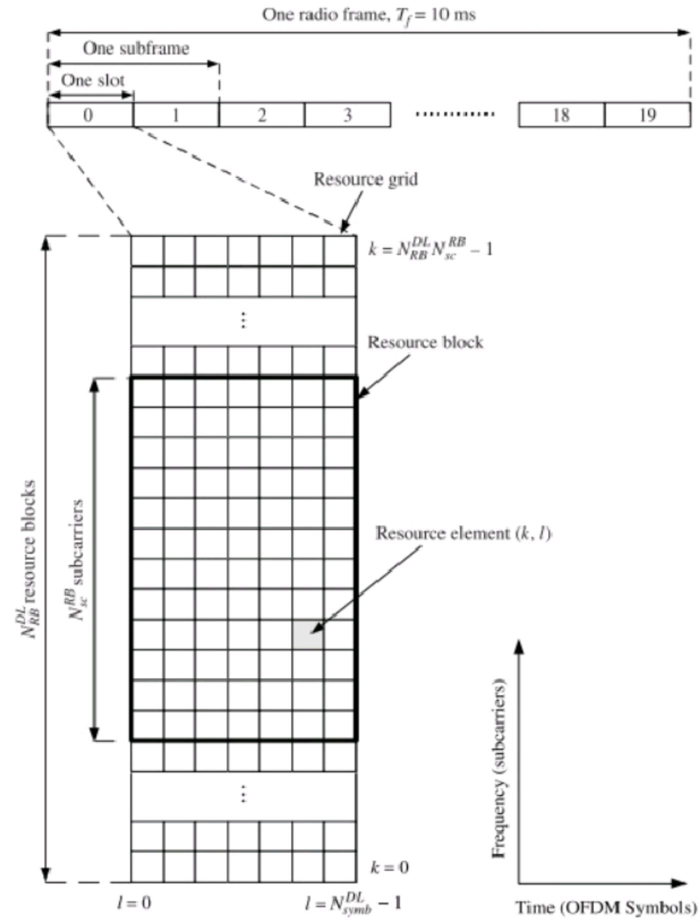

Fig 6.10: The structure of downlink resource grid

- **Resource Grid** : The structure of each resource grid is characterized by the following three parameters:
  1. ***The number of downlink resource blocks*** N_{RB}^{DL}: It depends on the transmission bandwidth and shall fulfill $N_{RB}^{min.DL} \leq N_{RB}^{DL} \leq N_{RB}^{max.DL}$, where $N_{RB}^{min.DL} = 6$ and $N_{RB}^{max.DL} = 110$ are for the smallest and largest downlink channel bandwidth, respectively. The values of N_{RB}^{DL} for several current specified bandwidths are listed in Table 6.2.
  2. ***The number of subcarrier in resource blocks*** N_{SC}^{RB} : It depends on the subcarrier spacing Δf, satisfying N_{SC}^{RB} Δf = 180 kHz, that is, each resource block of 180 kHz wide in the frequency domain. The values of N_{SC}^{RB} for different subcarrier spacing are shown in Table 6.4. There are a total of $N_{RB}^{DL} \times N_{SC}^{RB}$ subcarriers in each resource grid.
  3. ***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.
- Each downlink resource grid has $N_{RB}^{DL} \times N_{SC}^{RB} \times N_{symb}^{DL}$ resource elements.
- For example, with 10MHz bandwidth, Δf = 15 kHz, and normal CP, we get N_{RB}^{DL} = 50 from Table 6.2, N_{SC}^{RB} = 12 and N_{symb}^{DL} = 7 from Table 6.4, so there are 50 x 12 x 7 = 4200 resource elements in the downlink resource grid.

Configuration		N_{sc}^{RB}	N_{symb}^{DL}
Normal CP	$\Delta f = 15\text{kHz}$	12	7
Extended CP	$\Delta f = 15\text{kHz}$	12	6
	$\Delta f = 7.5\text{kHz}$	24	3

Table 6.4 Physical Resource Block Parameters for the Downlink

- In case of multi-antenna transmission, there is one resource grid defined per antenna port.
- An antenna port is defined by its associated reference signal, which may not correspond to a physical antenna.
- The set of antenna ports supported depends on the reference signal configuration in the cell.
- there are three different reference signals defined in the downlink, and the associated antenna ports are as follows:
  - Cell-specific reference signals support a configuration of 1, 2, or 4 antenna ports and the antenna port number p shall fulfill p = 0, p ∈ {0, 1}, and p ∈{0,1,2,3}, respectively.
  - MBSFN reference signals are transmitted on antenna port p = 4.
  - UE-specific reference signals are transmitted on antenna port p = 5.

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- **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,... , N $N_{RB}^{DL}N_{SC}^{RB} - 1$ and l = 0,1, ... , $N_{symb}^{DL} - 1$ 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 1 ms, 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.

6.4.3 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.
- Multiuser diversity can be exploited by assigning resource blocks to the UEs with favorable channel qualities.
- Resource allocation in LTE is able to exploit the channel variations in both the time and frequency domain, which provides higher multiuser diversity gain.
- 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-conse0cutive subcarriers (distributed) as a means to maximize frequency diversity.
- 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_{symb}^{DL} consecutive OFDM symbols in the time domain and N_{SC}^{RB}consecutive subcarriers in the frequency domain, as demonstrated in Figure 6.10.

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- 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 $N_{RB}^{DL} - 1$ in the frequency domain.
- The PRB number ηPRB of a resource element (k, l) in a slot is given by:

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

- ***Resource Allocation Type***: It specifies the way in which the scheduler allocate resource blocks for each transmission. Just in terms of flexibility, the way to give the maximum flexibility of resource block allocation would be to use a string of a bit map (bit stream), each bit of which represent each resource block. This way you would achieve the maximum flexibility, but it would create too much complication of resource allocation process or too much data (too long bit map) to allocate the resources
- The LTE downlink supports three resource allocation types: type 0, 1, and 2.
   1. ***Resource Allocation Type 0:*** *This is the simplest way of allocation resources. First it divides resource blocks into multiples of groups. This resource block group is called RBG (Resource Block Group). The number of resource block in each group varies depending on the system band width. It means RBG size gets different depending on the system bandwidth. The relationship between RBS size (the number of resource block in a RBG) and the system bandwidth as shown in Table 6.5.*

Table 6.5 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

- An exp of type 0, resource allocation is shown in Figure 6.11, where P = 4 and RBGs 0, 3, 4, … , are allocated to a particular UE.
   2. ***Resource Allocation Type 1:*** *Here 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 $0 \leq p \leq P$ consists of every P^{th} RBG starting from RBG p. Therefore, the resource assignment information consists of three fields:*
      1. *The first field indicates the selected RBG subset*
      2. *The second field indicates whether an offset is applied, and*

- *The third field contains the bitmap indicating PRBs inside the selected RBG subset. This type of resource allocation is more flexible and is able to provide higher frequency diversity, but it also requires a larger overhead.*

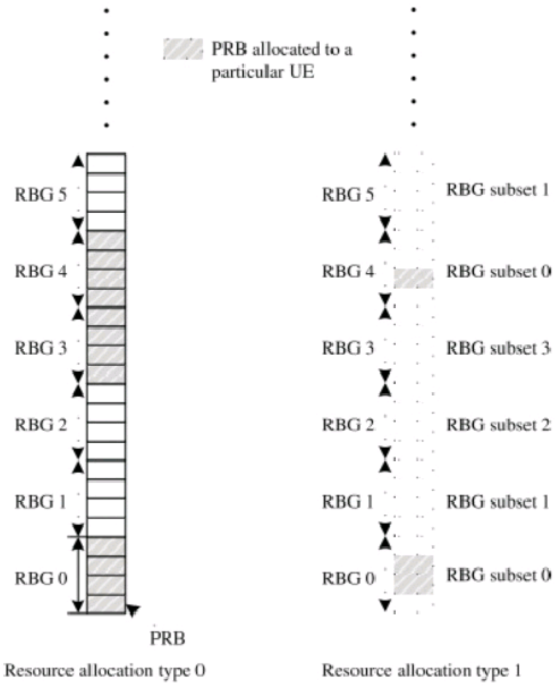

Figure 6.11 Examples of resource allocation type 0 and type 1, where the RBG size P= 4.

3. ***Resource Allocation Type 2:*** *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 of VRBs: VRBs of the localized type and VRBs of the distributed type. For each type of VRB, a pair of VRBs over two slots in a subframe are assigned together with a single VRB number,* ηVRB. VRBs of the localized type are mapped directly to physical resource blocks such that the VRB number ηVRB corresponds to the PRB number $\eta PRB = \eta VRB$. *For resource allocations of type 2, the resource assignment information indicates a set of contiguously allocated localized VRBs or distributed VRBs. A one-bit flag indicates whether localized VRBs or distributed VRBs are assigned.*

6.4.4 Supported MIMO Modes

- 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 DE through space-time processing; for MU-MIMO, modulation data streams are transmitted to different UEs using the same time-frequency resource.
- The supported SU-MIMO modes are listed as follows:
    1. Transmit diversity with space frequency block codes (SFBC)
    2. Open-loop spatial multiplexing supporting four data streams
    3. Closed-loop spatial multiplexing, with closed-loop preceding as a special case when channel rank = **1**
    4. 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.

6.5 Uplink SC-FDMA Radio Resources

- For the LTE uplink transmission, SC-FDMA with a CP is adopted.
- Nevertheless, the uplink transmission has its own properties. Different from the downlink, only localized resource allocation on consecutive subcarriers is allowed in the uplink.

6.5.1 Frame Structure

- *Frame structure type 1*: Uplink radio frame consists of 20 slots of 0.5 ms each, and one subframe consists of two slots, as in Figure 6.8.
- *Frame structure type 2*: It consists of ten subframes, with one or two special subframes including DwPTS, GP, and UpPTS fields, as shown in Figure 6.9.
- 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.

6.5.2 Physical Resource Blocks for SC-FDMA

- Figure 6.12, illustrated a number of resource blocks in the time-frequency plane.
- The number of resource blocks in each resource grid, N_{RB}^{UL} , depends on the uplink transmission bandwidth configured in

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

Where $N_{RB}^{min.UL} = 6\ and\ N_{RB}^{max.UL} = 110$ correspond to the smallest and largest uplink bandwidth, respectively.

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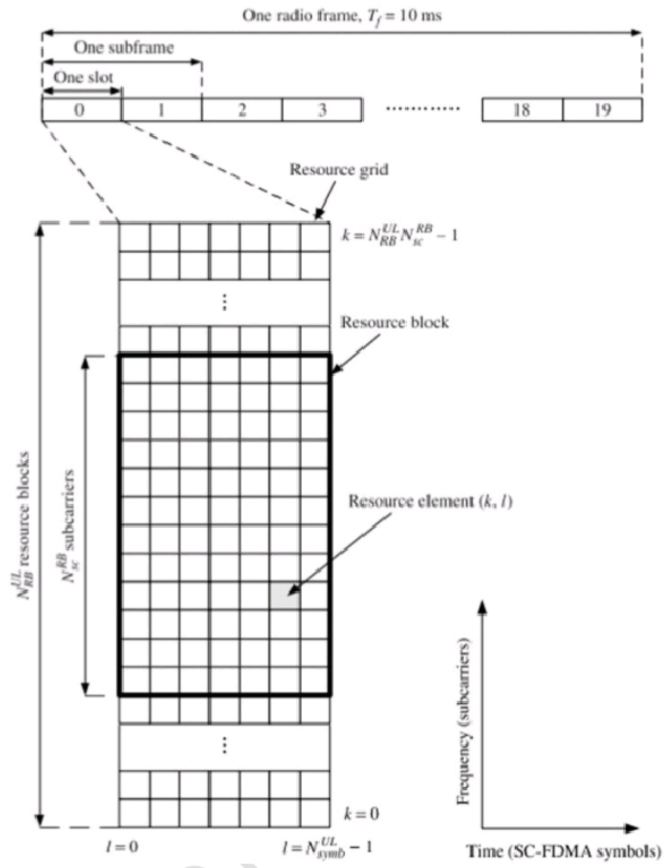

Figure 6.12: The structure of the uplink resource grid.

- There are $N_{SC}^{RB} \times N_{symb}^{RB}$ resource elements in each resource block. The values of N_{SC}^{RB} and N_{symb}^{UL} for normal and extended CP are given in Table 6.6.

Table 6.6 Physical Resource Block Parameters for Uplink

Configuration	N_{sc}^{RB}	N_{symb}^{UL}
Normal CP	12	7
Extended CP	12	6

- There is only one subcarrier spacing supported in the uplink, which is $\Delta f = 15$ kHz.
- The DC subcarrier is used in the uplink, as the DC interference is spread over the modulation symbols due to the DFT-based pre-coding.

- As for the downlink, each *resource element* in the resource grid is uniquely defined by the index pair (k, l) a slot, where k = 0, ... , $N_{RB}^{UL} \times N_{SC}^{RB}$— 1 and l = 0.......... $N_{symb}^{UL} - 1$ are the indices in the frequency and time domain, respectively.
- For the uplink, no antenna port is defined, as only single antenna transmission is supported in the current specifications.
- A PRB in the uplink is defined as N_{symb}^{UL} consecutive SC-FDMA symbols in the time domain and N_{SC}^{RB} consecutive subcarriers in the frequency domain, corresponding to one slot in the time domain and 180 kHz in the frequency domain.
- The relation between the PRB number ling in the frequency domain and resource elements (k, l) in a slot is given by:

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

6.5.3 Resource Allocation

- Resource allocation in the uplink is performed at the eNode-B.
- The eNode-B assigns a unique time-frequency resource to a scheduled UE based on the channel quality measured on the uplink sounding reference signals and the scheduling requests sent from UEs.
- Using timing advance such that the transport blocks of different UEs are received synchronously at the eNode-B.
- 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.
- 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.

6.5.4 Supported MIMO Modes

- The terminal complexity and cost are the major concerns in MIMO modes support in uplink.
- SC-FDMA support MU-MIMO, 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.

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- 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, resource allocation transmit diversity shall be supported.

Module 3: Chapter 7
Downlink Transport Channel Processing

7.1 Introduction:

- LTE uses a channels to provide effective, efficient data transport over the LTE radio interface.
- There are three categories into which the various data channels may be grouped.
  1. *Physical channels*: These are transmission channels that carry user data and control messages.
  2. *Logical channels*: Provide services for the Medium Access Control (MAC) layer within the LTE protocol structure.
  3. *Transport channels*: The physical layer transport channels offer information transfer to Medium Access Control (MAC) and higher layers. The PHY layer provides services to the MAC layer through transport channels.

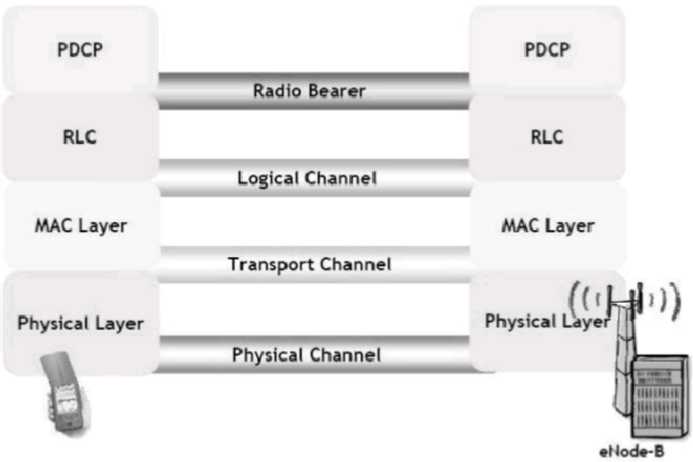

Fig 7.1 LTE channel Structure

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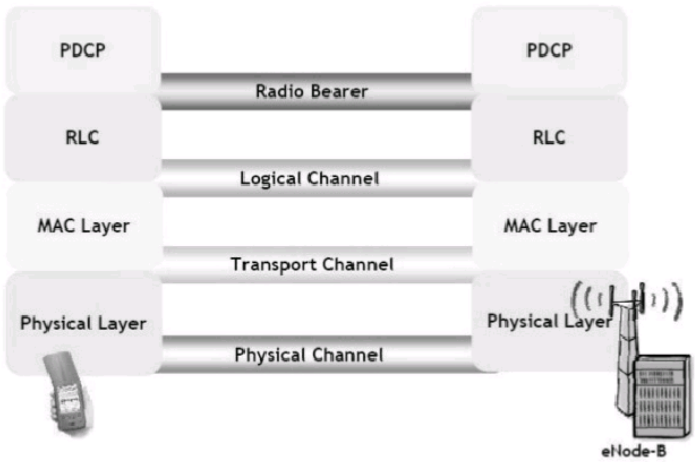

Fig 7.1 LTE channel Structure

- Following are Downlink Transport Channels:
  1. ***Broadcast Channel (BCH)characterized by:***
     - *Fixed, pre-defined transport format*
     - *Requirement to be broadcast in the entire coverage area of the cell.*
  2. ***Downlink Shared Channel (DL-SCH)characterized by:***
     - *Support for HARQ*
     - *Support for dynamic link adaptation by varying the modulation, coding and transmit power*
     - *Possibility to be broadcast in the entire cell*
     - *Possibility to use beamforming*
     - *Support for both dynamic and semi-static resource allocation*
     - *Support for UE discontinuous reception (DRX) to enable UE power saving.*
  3. ***Paging Channel (PCH)characterized by***:
     - *Support for UE discontinuous reception (DRX) to enable UE power saving (DRX cycle is indicated by the network to the UE)*
     - *Requirement to be broadcast in the entire coverage area of the cell*
     - *Mapped to physical resources which can be used dynamically also for traffic or other control channels.*
  4. ***Multicast Channel (MCH) (from Release 9)characterized by:***
     - *Requirement to be broadcast in the entire coverage area of the cell*
     - *Support for MBSFN combining of MBMS transmission on multiple cells*
     - *Support for semi-static resource allocation e.g., with a time frame of a long cyclic prefix.*
- ***Transport Blocks:*** Data and control streams coming from the MAC layer are organized in the form of transport blocks. Each transport block is a group of resource blocks with a common modulation and coding scheme. Downlink Shared Channel (DL_ SCH) are used to transmit transport block.
- ***The physical layer processing***: It mainly consists of coding and modulation, which maps each transport block to specific physical time-frequency resources.

7.2 Downlink Transport Channel Processing Overview

- The downlink physical layer processing mainly consists of
  1. *Channel coding process :* It involves mapping the incoming transport blocks from the MAC layer into different code words
  2. *Modulation process*: Modulation generates complex-valued OFDM baseband signals for each antenna port, which are then up converted to the carrier frequency.

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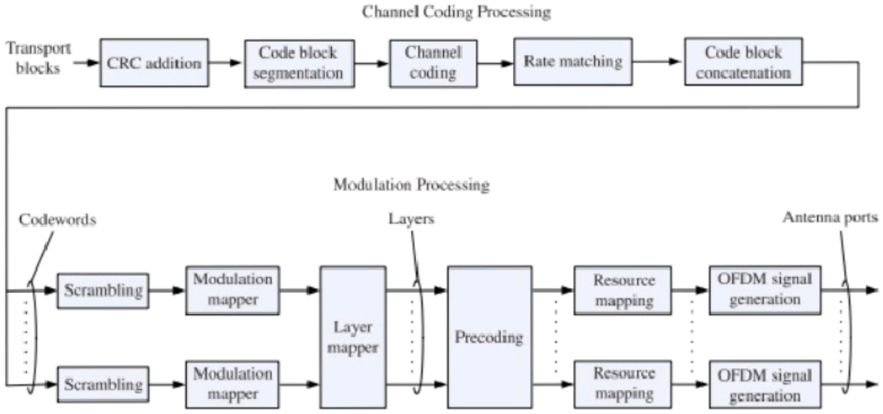


Figure 7.2 Overview of downlink transport channel processing.

7.2.1 Channel Coding Processing: The channel coding processing steps as shown in figure 7.2. The Channel Coding Processing procedure includes

1. ***CRC Addition***
2. ***Code Block segmentation***
3. ***Channel coding****: Tail-Biting Convolutional, Convolution Turbo Coding*
4. ***Rate Matching****: Sub-block interleaving, Bit collection and Bit selection*
5. ***Code Block Concatenation***

- The downlink channel coding processing is shown in Figure 7.2. Channel coding provides an error-control mechanism for data transmission using forward error correction (FEC) code and error detection based on cyclic redundancy check (CRC). In LTE, the coding rate at the channel encoder is fixed, and different effective coding rates for the whole transport block are achieved by repetition/puncturing during the rate matching procedure.

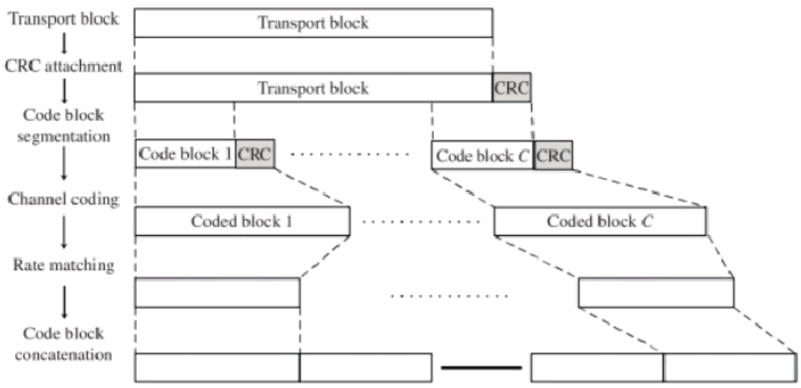
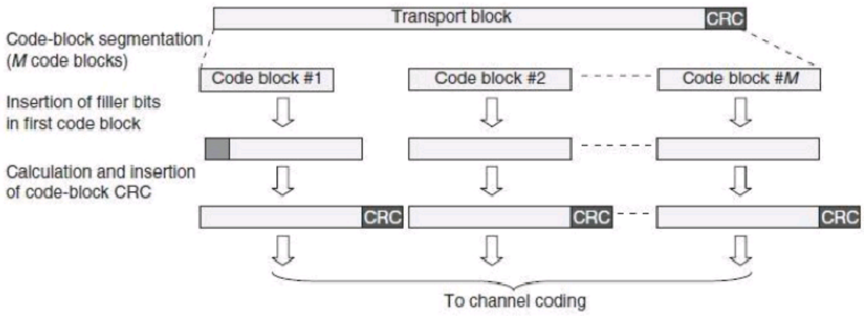


Figure 7.2 Channel coding processing.

1. **CRC Addition :**
    - The CRC is used to provide error detection on the transport block.
    - It generates cyclic generator polynomials, which are then added at the end of the transport block.
    - The 24-bit CRC is added to the each transport block for the downlink shared channel.
    - The CRC allows for receiver side detection errors in the decoded transport block.
    - The corresponding error indication is then used by the down link hybrid- ARQ protocol.

2. **Code Block Segmentation:**
    - Transport block is divided into smaller size code blocks in LTE, which is referred as code block segmentation in the LTE physical layer.



- In LTE there are two sizes defined for code block i.e. minimum and maximum code block size. These block sizes are based on block sizes as supported by the turbo interleaver module of CTC Encoder. They are as follows:
    - 40 bits of minimum code block size
    - 6144 bits of maximum code block size
- If input transport block length B is greater than the maximum code block size as supported by encoder then the input block is segmented into the one supported. This segmented block is referred as code blocks (c) and it is given by

$$C = \begin{cases} 1 & if \quad B \leq Z \\ \dfrac{B}{(Z-L)} & if\ B > Z \end{cases}$$

Where L is the number of CRC parity bits. Each of these C code blocks is then encoded independently. This is to prevent excessive complexity and memory requirement for de-coding at the receiver

- Each of these code blocks has a 24 bit CRC attached. This CRC is calculated similar to Transport Block CRC calculation.
- Filler bits are appended at the start of segment, this helps code block size to match a set of valid turbo interleaver block sizes.

3. Channel Coding

- In LTE, the channel encoders applied to transport channels include
  1. *Tail-biting convolutional coding*
  2. *Convolutional turbo coding*.
- The usage of channel coding schemes and coding rates for different downlink transport channels is specified in Table below

Transport Channel	Coding Scheme	Coding Rate
DL-SCH, PCH, MCH	Turbo coding	1/3
BCH	Tail-biting convolutional coding	1/3

- For control information, other channel coding schemes are supported, including block coding and repetition coding, specified in Table below

Control Information	Coding Scheme	Coding Rate
DCI	Tail-biting convolutional coding	1/3
CFI	Block coding	1/16
HI	Repetition coding	1/3

***A. Tail-Biting Convolutional Coding*:**

- The convolutional encoder used in LTE is a rate 1/3 encoder with a constraint length of 7 as shown in Figure 7.3.

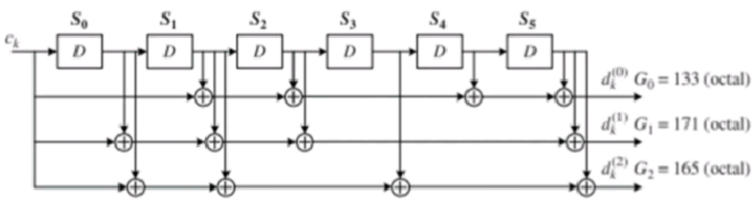


Figure 7.3 Rate 1/3 tail-biting convolutional encoder.

- Trellis termination must be performed at the end of each code block in order to restore the state of the encoder to the initial state for the next code block.
- If the initial and the final states of the encoder are known, then a lower block error rate can be achieved at the decoder while using a Viterbi algorithm.

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- Two of the most common approaches for trellis termination are
  a. Padding: *Here the end of the code block is padded with zeros. This forces the encoder to state '0' at the end of the code block, which is the starting state for the next code block. Main drawbacks of this method is that additional bandwidth is wasted due to the extra zeros that are added to the end of each code block.*
  b. Tail biting: *It is more efficient method, where the information bits from the end of each code block are appended to the beginning of the code block. Once these appended bits are passed through the encoder, it ensures that the start and end states of the encoder are the same. With tail biting, all the input bits are afforded the same amount of error protection, and there is no code-rate loss compared to zero padding, but the decoding algorithm becomes more complicated.*

B. Convolution Turbo Coding:

- It is a Parallel Concatenated Convolutional Code (PCCC) with two eight-state constituent encoders and one turbo code internal interleaver, with a coding rate of 1/3.
- The encoder used for the turbo codes is systematic and therefore recursive in nature.
- LTE employs a new contention-free internal interleaver based on Quadrature Permutation Polynomial (QPP)
- The QPP interleaver requires a small parameter storage and allows highly flexible parallelization due to its maximum contention-free property, which substantially reduces the encoder-decoder complexity
- The structure of the encoder is illustrated in Figure 7.4.

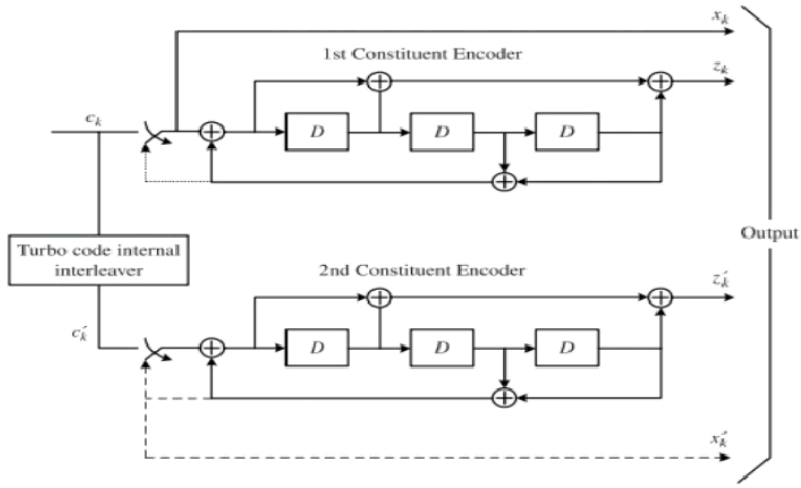


Figure 7.4 Structure of rate 1/3 turbo encoder (dotted lines apply for trellis termination only)

- The transfer function of the eight-state constituent code for the PCCC is

$$G(D) = \left[1, \frac{g_1(D)}{g_0(D)}\right],$$

where

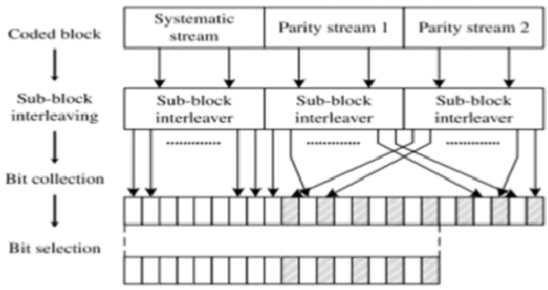
$$g_0(D) = 1 + D^2 + D^3,$$
$$g_1(D) = 1 + D + D^3.$$

- The initial values of the shift registers shall be all zeros when starting to encode the input bits.
- Due to the recursive nature of the encoder, the trellis termination is performed by taking the recursive bit and performing a modulo 2 addition with itself as shown in Figure 7.4.
- For each K-bit input code block, the output of the turbo encoder consists of three K-bit data streams:
  a. *One systematic bit stream*
  b. *Two parity bit streams.*
- 12 tail bits due to trellis termination are added to the end of the output streams, so each bit stream has K + 4 bits. Therefore, the actual coding rate is slightly lower than 1/3.

4. Rate Matching

- The main task of the rate-matching is to extract the exact set of bits to be transmitted within a given TTI.
- The rate-matching for Turbo coded transport channels is defined for each code block: there are three basic steps composing a rate-matching, As illustrated in Figure 7.5.
- Rate matching is defined per coded block and consists of the following stages:
  a. *Interleaving b. Bit collection c. Bit selection*

Figure 7.5 Rate matching for coded transport channels.



a. Interleaving: *It is performed at Sub-block level in order to spread out the occurrence of bursty errors across the code block, which improves the overall performance of the decoder. It is performed independently for each bit stream, done by a block interleaver with inter-column permutations. The inter-column permutation patterns are different for turbo coding and convolutional coding.*

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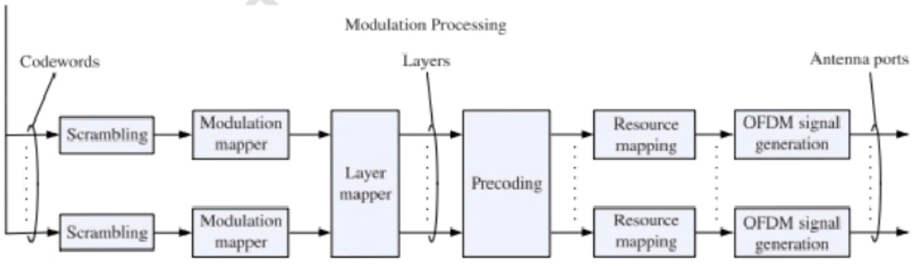
b. Bit Collection: *Bit collection stage is required to place the systematic and parity bits in the right order as needed by the decoder. A virtual circular buffer is formed by collecting bits from the interleaved streams. The systematic bits are placed at the beginning, followed by bit-by-bit interlacing of the two interleaved parity streams, as shown in Figure 7.5.*

c. Bit Selection: *The bit selection extracts consecutive bits from the circular buffer to the extent that fits into the assigned physical resource. To select the output bit sequence, the sequence length L should first be determined, Then L bits are read from the virtual circular buffer. The starting point of the bit selection depends on the redundancy version of the current transmission, which is different for different retransmissions associated with the H-ARQ process. This means that from one H-ARQ transmission to the next even though the number of bits L is the same, the parity bits that are punctured or repeated can be different. During bit selection if the end of the buffer is reached, the reading continues by wrapping around to the beginning of the buffer. With K input bits to the channel encoder, the effective coding rate is K/L, which can achieve any continuum of coding rates.*

d. Code Block Concatenation: *It is needed only for turbo coding when the number of code blocks is larger than one. It consists of sequentially concatenating the rate matching outputs for different code blocks, forming the code word input to the modulation processing.*

7.1.2 Modulation Processing

- Modulation takes in one or two code words, depending on whether spatial multiplexing is used, and converts them to complex-valued OFDM baseband signals for each antenna port.



- The modulation processing consists of
  - ***Scrambling***
  - ***Modulation Mapping***
  - ***Layer Mapping and Pre-coding***
  - ***Resource Mapping***
  - ***OFDM Signal Generation.***

1. ***Scrambling*** : A scrambler (or randomizer) is an algorithm that converts an input string into a seemingly random output string of the same length , thus avoiding long sequences of bits of the same value
   - There are two main reasons scrambling is used:

1. *To enable accurate timing recovery on receiver equipment without resorting to redundant line coding. It facilitates the work of a timing recovery circuit, an automatic gain control and other adaptive circuits of the receiver.*
2. *For energy dispersal on the carrier, reducing inter-carrier signal interference.*
   - Before modulation, the code word is scrambled by a bit-level scrambling sequence.
   - The block of bits for code word q is denoted as $b^{(q)}(0), \ldots \ldots b^{(q)}\left(M_q^{(q)} - 1\right)$, *Where* $M_q^{(q)}$ is the number of bits transmitted in one sub-frame.
   - The scrambling sequence $c^{(q)}$ is a pseudo-random sequence defined by a length-31 Gold sequence [3]. The scrambled bits are generated using a modulo 2 addition as:

$$\tilde{b}^{(q)}(i) = \left(b^{(q)}(i) + c^{(q)}(i)\right) \bmod 2, \quad i = 0, 1, \ldots, M_b^{(q)} - 1.$$

to two codewords can be transmitted in the same subframe, so $q = 0$ if spatial tiplexing is not used or q ∈{0,1} if spatial multiplexing is used.

ept the multicast channel, for all other downlink transport channels and control rmation, the scrambling sequences are different for neighboring cells so that inter-cell rference is randomized, which is one of the approaches for interference mitigation.

ion Mapping:

each codeword q, the block of scrambled bits $b^{(q)}(0), \ldots \ldots b^{(q)}\left(M_q^{(q)} - 1\right)$ are modulated into a block of complex-valued modulation symbols $d^{(q)}(0), \ldots \ldots d^{(q)}\left(M_s^{(q)} - 1\right)$ where $M_s^{(q)}$ e number of the modulation symbols in each codeword and depends on the modulation me. The relation between $M_s^{(q)}$ and $M_q^{(q)}$ is as follows:

$$M_s^{(q)} = \frac{M_b^{(q)}}{Q_m},$$

re is the number of bits in the modulation constellation, with Qin = 2 for QPSK, Q_m = 4 for QAM, and Q,,, = 6 for 64QAM.

- The supported data-modulation schemes in LTE include QPSK, 16QAM, and 64QAM, and BPSK is applied for the PHICH physical channel.

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- Different physical channels employ different modulation listed in Table 7.3.

Table 7.3 Modulation Schemes for Different Physical Channels

Physical Channel	Modulation Schemes
PDSCH	QPSK, 16QAM, 64QAM
PMCH	QPSK, 16QAM, 64QAM
PBCH	QPSK
PCFICH	QPSK
PDCCH	QPSK
PHICH	BPSK

3. Layer Mapping and Precoding

- Mapping and pre-coding are associated with MIMO. An illustrated in figure 7.6

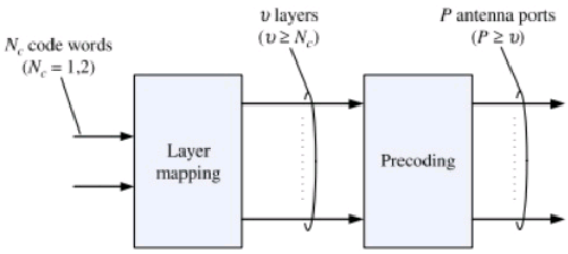

Figure 7.6 Layer mapping and precoding.

- ***Layer Mapping***: This is the process where each *codeword* is mapped to one or multiple *layers*. A *codeword* is defined as the output of each channel coding associated with a single transport block coming from the MAC layer. For MIMO transmission with multiple codewords on different spatial channels. In LTE, up to four transmit/receive antennas are supported, the number of codewords is limited to two. *A layer* corresponds to a data stream of the spatial multiplexing channel. Each codeword is mapped into one or multiple layers
- ***Pre-coding***: This is process where the layer data are allocated to multiple antenna ports. An antenna port is defined by its associated reference signal. The number of transmit antenna ports at the eNode-B is sent to UEs through the PBCH channel, which can be 1, 2, or 4 in LTE. Antenna ports are divided into three groups:
  1. *Antenna ports 0-3:* These ports are cell specific, which are used for downlink MIMO transmission.
  2. *Antenna port 4:* It is MBSFN specific and is used for MBSFN transmission.
  3. *Antenna port 5:* It is UE specific, which is used for beamforming to a single UE using all physical antennas.
- Cell-specific ports and the UE-specific port cannot be simultaneously used.

- Layer mapping is different for different MIMO modes, described as follows.
  1. *Single antenna port*: One codeword is mapped to a single layer.
  2. *Transmit diversity*: One codeword is mapped to two or four layers.
  3. *Spatial multiplexing*: Are codewords are mapped to v layers, the detailed mapping is in Table 7.4. Note that the case of a single codeword mapped to two layers occurs only when the initial transmission contains two codewords and a codeword mapped onto two layers needs to be retransmitted. Both open-loop (OL) and closed-loop (CL) spatial multiplexing modes are supported in LTE.

Table 7.4 Codeword-to-Layer Mapping for Spatial Multiplexing

Number of Layers	Codeword 0	Codeword 1
1	Layer 0	
2	Layer 0	Layer 1
2	Layer 0, 1	
3	Layer 0	Layer 1,2
4	Layer 0,1	Layer 2,3

- The precoder is either fixed or selected from a predefined codebook based on the feedback from UEs. The general form for precoding is

$$y(i) = W(i) * x(i)$$

Where $W(i)$ is the precoding matrix of size $P \times v$.

- Different physical channels support different MIMO modes, specified in Table 7.5. The PDSCH channel supports all the specified MIMO modes, while the PMCH channel only supports single-antenna-port transmission (antenna port 4).

Table 7.5 Supported MIMO Modes for Different Physical Channels

Physical Channel	Single Antenna Port	OL Transmit Diversity	Spatial Multiplexing
PDSCH	✓	✓	✓
PDCCH	✓	✓	
PBCH	✓	✓	
PMCH	✓		
PHICH	✓	✓	
PCFICH	✓	✓	

4. Resource Mapping

- For each of the antenna ports used for transmission of physical channels.
- The block of complex-valued symbols $y_p(0), \ldots \ldots y_p\left(M_s^{(ap)} - 1\right)$ shall be mapped in sequence.
- Starting with $y_p(0)$, to resource blocks assigned for transmission.
- The mapping to resource element (k, l) on antenna port p not reserved for other purposes.

5. OFDM Baseband Signal Generation

- The continuous-time signal $s_l^{(p)}(t)$ on antenna port p in OFDM symbol l in a downlink slot is generated as:

$$s_l^{(p)}(t) = \sum_{k=-\lfloor N_{RB}^{DL} N_{sc}^{RB}/2 \rfloor}^{-1} a_{k^{(-)},l}^{(p)} \cdot e^{j2\pi k \Delta f (t - N_{CP,l} T_s)} + \sum_{k=1}^{\lceil N_{RB}^{DL} N_{sc}^{RB}/2 \rceil} a_{k^{(+)},l}^{(p)} \cdot e^{j2\pi k \Delta f (t - N_{CP,l} T_s)} \quad (7.4)$$

for $0 \le t \le (N_{CP,l} + N) \times T_s$, where $k^{(-)} = k + \lfloor N_{RB}^{DL} N_{sc}^{DL}/2 \rfloor$ and $k^{(+)} = k + \lfloor N_{RB}^{DL} N_{sc}^{DL}/2 \rfloor - 1$, and for 20MHz bandwidth the value of N is given by:

$$N = \begin{cases} 2048, & \text{if } \Delta f = 15\text{kHz} \\ 4096, & \text{if } \Delta f = 7.5\text{kHz}. \end{cases} \quad (7.5)$$

The cyclic prefix (CP) length $N_{CP,l}$ depends on the CP type and the subcarrier spacing, listed in Table 7.6.

Table 7.6 Values of $N_{CP,l}$

Configuration		CP Length $N_{CP,l}$
Normal CP	$\Delta f = 15$kHz	160 for $l = 0$ 144 for $l = 1, 2, \ldots, 6$
Extended CP	$\Delta f = 15$kHz $\Delta f = 7.5$kHz	512 for $l = 0, 1, \ldots, 5$ 1024 for $l = 0, 1, 2$

- The OFDM signal generation with multiple users are illustrated in figure 7.8

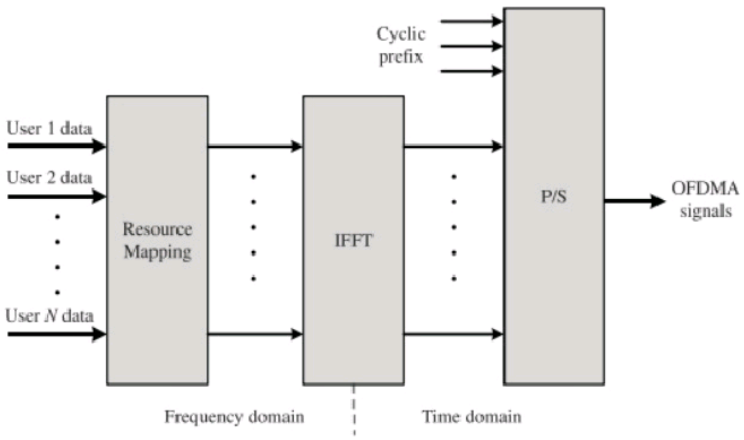

Figure 7.8 OFDMA signal generation with N users, where P/S denotes the parallel-to-serial converter.

7.2 Downlink Shared Channels (DL-SCH)

- The DL-SCH is carried on the Physical Downlink Shared Channel (PDSCH).
- Data transmission in the PDSCH is based on the concept of shared-channel transmission, where the resource blocks available for PDSCH, is treated as a common resource that can be dynamically shared among different UEs.
- The dynamic multiplexing of LTEs on the PDSCH is done by the scheduler on $1ms$ interval.
- The channel mapping around the DL-SCH is shown in Figure 7.9.

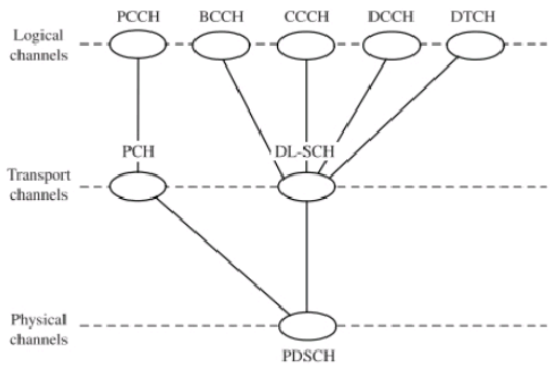

Figure 7.9 Channel mapping around the downlink shared channel.

- DL-SCHs carry both traffic and control data from logical channels, and the Paging Channel (PCH) is also carried on the PDSCH (See figure 7.9).

7.2.1 Channel Encoding and Modulation

- *Channel Coding of DL-SCH:*
  - It uses the rate 1/3 convolutional turbo code.
  - Rate matching is used in order to achieve an effective channel coding rate that matches the payload capacity.
  - For MIMO spatial multiplexing with two codewords, different modulation and coding can be used for each codeword, which requires individual signaling.

- *Modulation scheme of DL-SCH*:
  - It includes QPSK, 16QAM, and 64QAM and is chosen based on the Channel Quality Indicator (CQI) provided by the UE and various other parameters.
  - The transport block size, the redundancy version, and the modulation order are indicated in the Downlink Control Information (DCI).
  - Channel coding for the PCH transport channel is the same as that for the DL-SCH channel. Both of which are mapped to the PDSCH physical channel.

7.2.2 Multi-antenna Transmission

- The PDSCH supports all the MIMO modes specified in LTE.***
- There are seven transmission modes defined for data transmission on the PDSCH channel:
  1. ***Single-antenna port (port 0):*** One transport block is transmitted from a single physical antenna corresponding to antenna port 0.
  2. ***Transmit diversity***: One transport block is transmitted from more than one physical antenna, that is, ports 0 and 1.
  3. ***Open-loop (OL) spatial multiplexing***: One or two transport blocks are transmitted from two or four physical antennas. In this case, precoding is fixed based on RI feedback.
  4. ***Closed-loop (CL) spatial multiplexing***: One or two transport blocks are transmitted from two or four physical antennas. The precoding is adapted based on the Precoding Matrix Indicator (PMI) feedback from the UE.
  5. ***Multiuser MIMO:*** Two UEs are multiplexed onto two or four physical antennas with one transport block to each UE.
  6. ***Closed-loop rank-1 precoding***: It is a special case of the Closed Loop spatial multiplexing with single-layer transmission, that is, a P x 1 precoder is applied.
  7. ***Single-antenna port (port 5):*** A single transport block is transmitted from two or more physical antennas. The eNode-B performs beamforming to a single UE using all physical antennas. Beamforming can be used to improve the received signal power and/or reduce the interference signal power, which is especially important for cell edge users.
- Transmission mode 1 can be classified as a Single-Input-Single-Output (SISO) mode that does not require any layer mapping and precoding.
- Transmission modes 2-6 can be classified as MIMO modes, which require explicit layer mapping and precoding.
- Transmission MIMO modes classified into

  i. Open Loop(OL) Transmission MIMO modes: *OL MIMO technique requires no feedback from UEs, so it is suitable for scenarios where accurate feedback is difficult to obtain or the channel changes rapidly enough, such as the high mobility scenario. This mode includes*
  (a). OL transmit diversity (b) OL Spatial multiplexing

  ii. Closed Loop (CL) Transmission MIMO modes: *CL MIMO transmission requires explicit feedback from UEs. UE determines precoding matrix based on its current MIMO channel and sends this information to the eNode-B using the uplink control channel. This mode includes*
  (a) CL Spatial Multiplexing (RI > 1)
  (b) CL Rank-1 Precoding (RI = 1)

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7.3 Downlink Control Channels

- Downlink control channels are carried over the Physical Downlink Control Channel (PDCCH).
- Control information from the MAC layer, including
  1. *Downlink Control Information (DCI).*
  2. *Control Format Indicator (CFI).*
  3. *H-ARQ Indicator (HI).*
- Channel mapping between control information and physical channels in the downlink is shown in Figure 7.11.
- There is a specific physical channel for each type of control information. On the physical layer the PDCCH and the PDSCH are time multiplexed and
  – PDCCH is carried over the first few OFDM symbols of each subframe
  – PDSCH is carried over the rest of the OFDM symbols.
  – The number of OFDM symbols allocated for PDCCH can vary from one to four and is conveyed by the CFI.
  – The CFI is carried on yet another control channel known as the Physical Control Format Indicator Channel (PCFICH), which is always carried in a predetermined format over the first OFDM symbol of each subframe.
  – This predetermined format of PCFICH allows each UE to decode the CFI without ambiguity and thus determine the number of OFDM symbols in the beginning of earth subframe that are used as the control region.

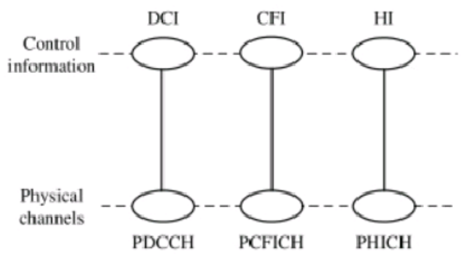

Figure 7.11 Channel mapping for control information in the downlink

7.3.1 Downlink Control Information (DCI) Formats:

- DCI is the most important as it carries detailed control information for both downlink and uplink transmissions.
- The DCI carries the downlink scheduling assignments, uplink scheduling grants, power control commands, and other information necessary for the scheduled UEs to decode and demodulate data symbols in the downlink or encode and modulate data symbols in the uplink.

- In Table 6.1, LTE defines ten different DCI formats for different transmission scenarios, summarized as follows:

Table 6.1 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

- By considering format 0 and format 1 as examples, the different fields of DCI format are explained in Table 7.10 and Table 7.11, respectively.

Table 7.10 Fields of DCI Format 0

Information Type	Number of Bits	Purpose
Flag for format 0/1A differentiation	1	Indicates format 0 or format 1A
Hopping flag	1	Indicates whether PUSCH frequency hopping is performed
Resource block assignment and hopping resource allocation	$\lceil \log_2(N_{RB}^{DL}(N_{RB}^{DL}+1)/2) \rceil$	Indicates assigned resource blocks
Modulation and coding scheme and redundancy version	5	For determining the modulation order, redundancy version and the transport block size
New data indicator	1	Indicates whether the packet is a new transmission or a retransmission
TPC command for scheduled PUSCH	2	Transport Power Control (TPC) command for adapting the transmit power on the PUSCH
Cyclic shift for demodulation reference signal	3	Indicates the cyclic shift for the demodulation reference signal for PUSCH
UL index	2	Indicates the scheduling grant and only applies to TDD operation with uplink-downlink configuration 0
Downlink Assignment Index (DAI)	2	For ACK/NAK reporting and only applies to TDD operating with uplink-downlink configurations 1-6
CQI request	1	Requests an aperiodic CQI from the UE

Table 7.11 Fields of DCI Format 1

Information Type	Number of Bits	Purpose
Resource allocation header	1	Indicates whether it is of resource allocation type 0 or 1
Resource block assignment	Depends on resource allocation type	Indicates assigned resource blocks
Modulation and coding scheme	5	For determining the modulation order and the transport block size
H-ARQ process number	3 (TDD), 4 (FDD)	Indicates the H-ARQ process
New data indicator	1	Indicates whether the packet is a new transmission or a retransmission
Redundancy version	2	Identifies the redundancy version used for coding the packet
TPC command for PUCCH	2	TPC command for adapting the transmit power on the PUCCH
Downlink Assignment Index (DAI)	2	For ACK/NAK reporting and only applies to TDD operation

7.3.2 Control Format Indicator (CFI).

- The CFI is a parameter used on the LTE air interface. It defines the amount of symbols in each subframe allocated to PDCCH. The CFI takes values CFI = 1, 2 or 3 OFDM symbols as shown in Table 7.13

Table 7.13 Number of OFDM Symbols Used for PDCCH

Subframe	Number of OFDM Symbols for PDCCH When $N_{RB}^{DL} > 10$	Number of OFDM Symbols for PDCCH When $N_{RB}^{DL} \leq 10$
Subframe 1 and 6 for frame structure type 2	1,2	2
MBSFN subframes on a carrier supporting both PMCH and PDSCH for one or two cell-specific antenna ports	1,2	2
MBSFN subframes on a carrier supporting both PMCH and PDSCH for four cell-specific antenna ports	2	2
MBSFN subframes on a carrier not supporting PDSCH	0	0
All other cases	1,2,3	2,3,4

- For example system bandwidths $N_{RB}^{DL} > 10$, the DCI spans 1, 2, or 3 OFDM symbols, given by the value of the CFI; for system bandwidths $N_{RB}^{DL} \leq 10$, the DCI spans 2, 3, or 4 OFDM symbols, given by CFI+1.
- Finally, the CFI is mapped to the PCFICH physical channel carried on specific resource elements in the first OFDM symbol of the subframe.
- The PCFICH is transmitted when the number of OFDM symbols for PDCCH is greater than zero. The PCFICH shall be transmitted on the same set of antenna ports as the PBCH.

7.3.3 H-ARQ Indicator (HI)

- LTE uses a hybrid automatic repeat request (HARQ) scheme for error correction.
- The eNodeB sends a HARQ indicator to the UE to indicate a positive acknowledgement (ACK) or negative acknowledgement (NACK) for data sent using the uplink shared channel.
- The channel coded HARQ indicator codeword is transmitted through the Physical Hybrid Automatic Repeat Request Indicator Channel (PHICH).
- H-ARQ Indicator: H-ARQ indicator of '0' represents a NACK and a '1' represents an ACK.
- A repetition code with rate 1/3 and BPSK modulation is applied used for encoding and mapping the H-ARQ Indicator.
- Multiple PHICHs mapped to the same set of resource elements constitute a PHICH group, where PHICHs within the same group are separated through different orthogonal sequences with a spreading factor of four.

7.4 Broadcast Channels (PBCH)***

- Broadcast channels carry *system information* such as downlink system bandwidth, antenna configuration, and reference signal power.
- Due to the large size of the *system information field*, it is divided into two portions:
  1. *Master Information Block (MIB)*: It is transmitted on the PBCH. The PBCH contains basic system parameters necessary to demodulate the PDSCH. The transmission of the PBCH is characterized by a fixed pre-determined transport format and resource allocation
  2. *System Information Blocks (SIB)*: It is transmitted on the PDSCH. Which contains the remaining SIB.
- *Coding and Modulation types for PBCH*:
  - Error detection is provided through a 16-bit CRC.
  - The tail-biting convolutional coding with rate 1/3 is used, and the coded bits are rate matched to 1920 bits for the normal CP and to 1728 bits for the extended CP.
  - The modulation scheme is QPSK. No H-ARQ is supported.
  - PBCH supports single-antenna transmission and OL transmit diversity.

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- In the subframes where PMCH is transmitted on a carrier supporting a mix of PDSCH and PMCH transmissions, up to two of the first OFDM symbols of a subframe can be reserved for non-MBSFN transmission and shall not be used for PMCH transmission.
- In a cell with four cell-specific antenna ports, the first OFDM symbols of a subframe are reserved for non-MBSFN transmission in the subframes in which the PMCH is transmitted.
- The non-MBSFN symbols shall use the same CP as used for subframe 0.
- PMCH shall not be transmitted in subframes 0 and 5 on a carrier supporting a mix of PDSCH and PMCH transmissions.

7.6 Downlink Physical Signals: It including downlink *reference signals* and *synchronization signals*.

7.6.1 Downlink Reference Signals:

- Downlink *reference signals* consist of known reference symbols that are intended for downlink channel estimation at the UE needed to perform coherent demodulation.
- To facilitate the channel estimation process, scattered reference signals are inserted in the resource grid at pre-determined intervals.
- The time and frequency intervals are mainly determined by the characteristics of the channels, and should make a tradeoff between the estimation accuracy and the overhead.
- There are three different types of downlink reference signals:
  1. Cell-specific reference signals
  2. MBSFN reference signals
  3. UE-specific reference signals.

1. ***Cell-Specific Reference Signals:***
   - The reference sequence is generated from a pseudo-random sequence, with different initializations for different types of reference signals
   - Cell-specific reference signals are transmitted in all downlink subframes in a cell supporting non-MBSFN transmission.
   - There is one reference signal transmitted per downlink antenna port.
   - Cell-specific reference signals are defined separately for antenna ports 0, 1, 2, and 3 as shown in Figure 7.12.
   - Only the first two OFDM symbols can be used for cell-specific reference symbols. Therefore, in LTE a maximum of four antennas can be used while transmitting the cell specific reference signal.
   - Cell specific reference signal are defined only for normal subcarrier spacing of $\Delta f = 15kHz$.

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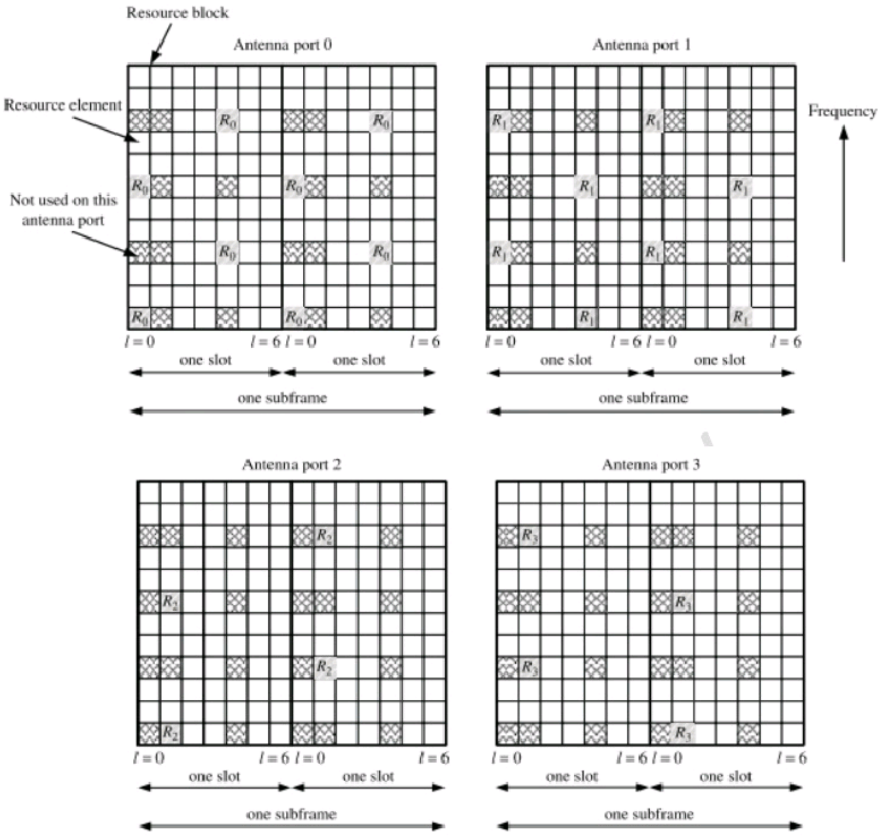

Figure 7.12 An example of mapping of downlink cell-specific reference signals, with four antenna ports and the normal CP. R_p denotes the resource element used for reference signal transmission on antenna port p.

- *Reference Signal(RS) mapping in time domain*:
  - For the antenna port p ∈ {0, 1}, the RS are inserted within the first and the third last OFDM symbols in each slot, which are the 1st and 5th OFDM symbols for the normal CP and the 1st and 4th OFDM symbols for the extended CP.
  - For p ∈ {2, 3}, the RSs are only inserted in the 2nd OFDM symbol. So antenna ports 0 and 1 have twice as many reference symbols as antenna ports 2 and 3. This is to reduce the reference signal overhead but also causes an imbalance in the quality of the respective channel estimates.
- *Reference Signal(RS) mapping in time domain:*
  - The spacing between neighboring reference symbols in the same OFDM symbol is five subcarriers, that is, the reference symbols are transmitted every six subcarriers.
  - There is a staggering of three subcarriers between the 1st and 2nd reference symbols.

2. *MBSFN Reference Signals*

- MBSFN RSs are only transmitted in subframes allocated for MBSFN transmission, which is only defined for extended CP and transmitted on antenna port 4.
- *In the time domain*: For even-numbered slots, the RSs are inserted in the 3rd OFDM symbol for $\Delta f = 15kHz$ and in the second OFDM symbol for $\Delta f = 7.5\ kHz$. for odd-numbered slots, the reference symbols are inserted in the 1st and 5th OFDM symbols for $\Delta f = 15kHz$. and in the first and third OFDM symbols for $\Delta f = 7.5\ kHz$.
- *In the frequency domain*: The RSs are transmitted every two subcarriers for $\Delta f = 15\ kHz$ and every four subcarriers for $\Delta f = 7.5\ kHz$. In the 0th OFDM symbols, the reference symbols are transmitted from the 2nd and the 3rd subcarrier for $\Delta f = 15\ kHz$ and $\Delta f = 7.5\ kHz$.
- Based on these rules, an example of the resource mapping of MBSFN reference signals is shown in Figure 7.13 with the extended CP, and $\Delta f = 15\ kHz$.
- *Note:* The density of the MBSFN reference signal in the frequency domain is three times higher than that of the cell-specific reference signal.

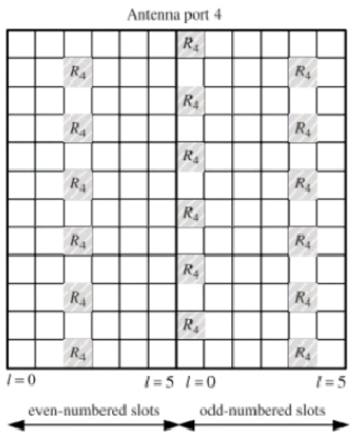

Figure 7.13 An example of mapping of MBSFN reference signals, with the extended CP and $\Delta f =$ 15kHz.

3. *UE- Specific Reference Signals*

- UE-specific reference signals support single-antenna-port transmission with beam forming for the PDSCH and are transmitted on antenna port 5.
- They are transmitted only on the resource blocks upon which the corresponding PDSCH is mapped.
- The UE-specific signal is not transmitted in resource elements in which one of the other physical signals or physical channels is transmitted.

- An example of resource mapping of UE-specific reference signals is shown in Figure 7.14 with the normal CP. In the even-numbered slots, the reference symbols are inserted in the fourth and seventh OFDM symbols: in the odd-number slots, the reference symbols are inserted in the third and sixth OFDM symbols. There is a frequency shift of two subearriers in neighboring reference symbols.

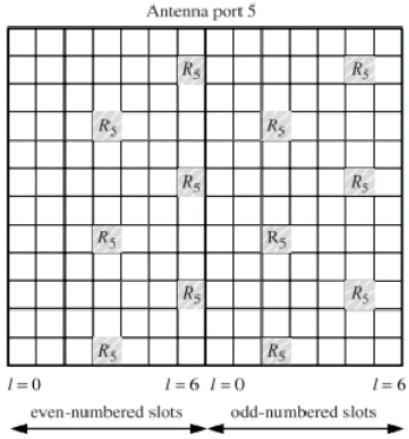

Figure 7.14 An example of mapping of UE-specific signals, with the normal CP.

7.6.2 Synchronization Signals

- The downlink synchronization signals are sent to facilitate the cell search procedure, during which process the time and frequency synchronization between the UE and the eNode-B is achieved and the cell ID is obtained.
- There are a total of 504 unique physical-layer cell IDs, which are grouped into 168 physical-layer cell-ID groups. A physical-layer cell ID is uniquely defined as:

$$N_{ID}^{(1)} = 3N_{ID}^{(1)} + N_{ID}^{(2)}$$

Where $N_{ID}^{(1)} = 0,1 \ldots \ldots 167$ represents the physical-layer cell-ID group and $N_{ID}^{(2)}$ = 0, 1, 2 represents the physical-layer ID within the cell-ID group. Each cell is assigned a unique physical-layer cell ID.

- The synchronization signals are classified as
  1. *Primary synchronization signals (P-SS):* P-SS signals identify the *symbol timing* and the cell ID index $N_{ID}^{(2)}$.
  2. *Secondary synchronization signals(S-SS).* These signals are used for detecting the cell-ID group index $N_{ID}^{(1)}$and the frame timing.
- The secondary synchronization signal can only be detected after detecting the primary synchronization signal.

- The synchronization signals are designed in such a way to make the cell search procedure fast and of low complexity.
- The sequence used for the primary synchronization signal is generated from a frequency-domain Zadoff-Chu sequence.
- The Zadoff-Chu sequence possesses the Constant Amplitude Zero Auto-Correlation (CAZAC) property, which means low peak-to-average power ratio (PAPR). This property is desirable for synchronization signals as it improves coverage, which is an important design objective.
- Both primary and secondary synchronization signals are transmitted on the 62 sub-carriers centered on the DC subcarrier, with five reserved subcarriers on either side in the frequency domain, so there are a total of 72 subcarriers occupied by synchronization signals, corresponding to the narrowest bandwidth supported by LTE (1.4MHz).
- In the time domain, both primary and secondary synchronization signals are transmitted twice per 10 ms in predefined slots.
- For frame structure type 1, the primary and secondary synchronization signals are mapped to the last and the OFDM symbols in slot 0 and 10.
- For frame structure type 2, the primary synchronization signal is mapped to the third OFDM symbol in slot 2 and 12 and the secondary synchronization signal is mapped to the last OFDM symbol in slot 1 and 11.
- The difference in the location of the synchronization signal enables the UE to detect the duplex mode of the cell.
- The resource mapping for synchronization signals is illustrated in Figure 7.15.

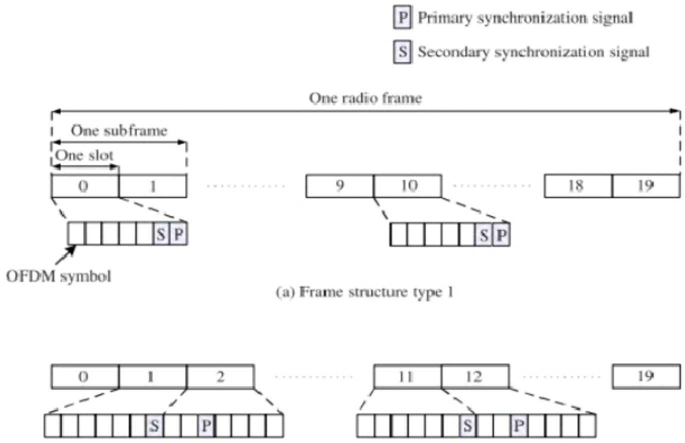

Figure 7.15 The mapping of primary and secondary synchronization signals to OFDM symbols for frame structure type 1 and type 2, with the normal CP. 'P' and 'S' denote primary and secondary synchronization signals, respectively.

7.7 H-ARQ in the Downlink

- It is an acknowledgement processes in LTE for a received error packet.
- In the case of LTE both Type I Chase Combining (CC) H-ARQ and Type II Incremental Redundancy (IR) H-ARQ schemes have been defined.
- The H-ARQ operation is part of the MAC layer, while the PHY layer handles soft combining.
- ***At the receiver:*** Turbo decoding is first applied on the received code block. If this is a retransmission, which is indicated in the DCI, the code block will be combined with the previously received versions for decoding. If there is no error detected in the output of the decoder, an ACK signal is fed back to the transmitter through the PUCCH physical channel and the decoded block is passed to the upper layer; otherwise, an NAK signal is fed back and the received code block is stored in the buffer for subsequent combining.
- ***At the transmitter:*** For each (re)transmission, the same turbo-encoded data is transmitted with different puncturing, so each of these (re)transmissions has a different redundancy version and each is self-decodable. Puncturing is performed during the rate matching process. The rate matcher can produce four different redundancy versions of the original coded block. H-ARQ transmissions are indexed with the redundancy version rv_{idx}, which indicates whether it is a new transmission (rv_{idx} =0) or the $rv_{idx}th$ retransmission (rv_{idx} = 1, 2, or 3).
- Time interval between two successive H-ARQ transmissions, which is typically 8 ms in LTE.
- N-channel Stop-and-Wait protocol is used for downlink H-ARQ operation. An N-channel Stop-and-Wait protocol consists of N parallel H-ARQ processes. When one or more of the processes are busy waiting for the H-ARQ ACK /NAK, the processes that are free can be used to transmit other transport blocks.
- The maximum number of H-ARQ processes in the downlink is determined by the UL/DL configuration, specified in Table 7.17, which ranges from 4 to 15.

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Table 7.17 Maximum Number of Downlink H-ARQ Processes for TDD

TDD UL/DL Configuration	Maximum Number of H-ARQ Processes
0	4
1	7
2	10
3	9
4	12
5	15
6	6

- Figure 7.16 an example of a 10-msec frame with eight H-ARQ processes.

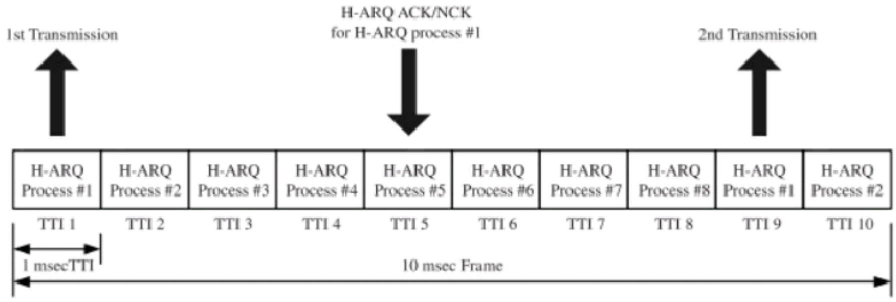

Figure 7.16 An example of a 10-msec frame with eight H-ARQ processes. The H-ARQ process 1 is transmitted in the first TTI, for which the H-ARQ ACK/NAK is received in the 5-th TTI, and then the H-ARQ process 1 is transmitted again in the 9-th TTI.

- The H-ARQ process 1 is transmitted in the first TTI, for which the H-ARQ ACK/NAK is received in the 5-th TTI, and then the H-ARQ process 1 is transmitted again in the 9-th TTI.
- Each H-ARQ process is associated with an 11-ARQ process ID.
- When spatial multiplexing is used, both transport blocks are associated with the same H-ARQ process.
- Figure 7.16 shows a 10 msec frame with TTI index 1 transmitting the H-ARQ process 1, TTI index 2 transmitting the H-ARQ process 2, and so on.
- The H-ARQ ACK/NAK for the 11-ARQ process 1 is received in TTI index 5.2 , Then in TTI index 9 the H-ARQ process 1 is transmitted again, either a new transmission if an ACK is received or a retransmission if an NAK is received.
- LTE downlink applies the asynchronous H-ARQ protocol, where the H-ARQ processes can be transmitted in any order without fixed timing. Therefore, in the example in Figure 7.16, the retransmission of H-ARQ process 1 does not necessarily occur in the 9^{th} TTI.
- The asynchronous H-ARQ makes it possible to reflect channel quality measurements at the instance of retransmission, which is able to provide a higher throughput with re-scheduling or changing the modulation and coding scheme, called adaptive RQ.
- In addition, asynchronous operation makes it possible for the eNode-B to avoid potential collision of H-ARQ retransmissions with other high priority scheduled transmissions such as persistent scheduling.
- Meanwhile, the asynchronous 11-ARQ requires more overhead, as the receiver does not know ahead of time what is being transmitted and when the retransmission occurs.