R N S Institute of Technology
Dept. of Electronics and Communication Engineering
15EC81: Wireless Cellular and LTE 4G Broadband

1 Course Syllabus

Mod 1 : Evolution of Cellular systems, LTE features & Wireless fundamentals

Mod 2 : Multi carrier modulation, OFDMA, Multiple Antenna Transmission & Reception

Mod 3 : Channel structure of LTE & Downlink Transport Channel Processing

Mod 4 : Uplink Channel Transport Processing & Physical Layer Procedures

Mod 5 : Radio Resource Management & Mobility Management

2 Course Outcomes

At the end of the course, you will be able to:

CO1 : Understand the system architecture and functional standard specified in LTE 4G

CO2 : Understand the modulation techniques for LTE and communication using multiple antenna.

CO3 : Analyze the role of LTE radio interface protocols and its channel structure.

CO4 : Test the performance of resource management and packet data processing and transport algorithm.

CO5 : Demonstrate the UTRAN handling process from setup to release including the mobility management for a variety of all data cell scenarios.

Module 1

Part 1: Evolution of Cellular Technologies & LTE Features

1 Topics Covered

1. Evolution of Mobile Broadband
2. First Generation Cellular Systems
3. 2G Digital Cellular Systems
4. 3G Broadband Wireless Systems
5. Beyond 3G:HSPA+, WiMAX, LTE
6. Key Requirements of LTE Design
7. Key Enabling Technologies and Features of LTE
8. LTE Network Architecture

2 Evolution of Mobile Broadband

- Before 1892 - Theoretical basis for radio communication - Nikola Tesla, Jagadish Bose & Alexander Popov
- 1897 - Marconi demonstrated radio communication & awarded patent for it.
- 1934 - AM Radio Systems used in US.
- 1935 - Edwin Armstrong demonstrated FM.
- 1948 - Claude Shannon published theory on Channel Capacity: $C = Blog_2(1 + SNR)$
- 1960 to 70 - Bell labs developed Cellular concept.
- 1983 - AMPS (Advanced Mobile Phone Service) launched in Chicago.
- 1991 - First Commercial GSM in Europe.
- 1995 - First Commercial launch of CDMA (IS - 95).
- 2001 - NTT DoCoMo launched first commercial 3G service.
- 2005 - IEEE 802.16e standard, the air - interface for mobile WiMAX, completed & approved.

- 2007 - First Apple iPhone launched.
- 2009 - 3GPP Release 8 LTE/SAE specifications completed.

3 First Generation Cellular Systems

- The United States, Japan and parts of Europe led the development of cellular wireless systems.
- These systems were characterized by analog modulation schemes & were designed primarily for delivering voice services.
- Japan's Nippon Telephone & Telegraph Company (NTT) implemented the world's first commercial cellular system in 1979.
- Europe's Nordic Mobile Telephone (NMT - 400) system implemented automatic handover & international roaming.
- The more successful first generation systems were AMPS in the United States.
- Major First Generation Cellular Systems are
  - **AMPS** (Advanced Mobile Phone Service)
  - **ETACS** (Extended Total Access Communication Systems) in Europe
  - **NTACS** (Nippon Total Access Communication Systems) in Japan
  - **NMT - 450 / NMT - 900**

4 2G Digital Cellular Systems

- Improvements in processing abilities of hardware platforms enabled the development of 2G wireless systems.
- 2G systems were also focused on voice transmission, but used digital modulation techniques.
- Shifting from Analog to Digital enabled several improvements in system performance.
  1. System capacity was improved through the use of spectrally efficient digital speech codecs.
  2. Multiplexing techniques were used to accommodate several users on the same frequency channel.
  3. Frequency re-use enabled by better error performance of digital modulation.
- Major 2G Cellular Systems are

1. GSM : Introduced in 1990
2. blackIS - 54 / IS - 136: Introduced in 1991
3. IS - 95: Introduced in 1993

- Besides providing improved voice quality, capacity & security, 2G systems also enabled new application.

  That is **Short Message Service (SMS)**
- In addition to SMS, 2G systems also supported low data rate wireless data applications.
- These systems supported circuit switched data services.

5 3G Broadband Wireless Systems

- The circuit - switched paradigm based on which 2G systems were built, made these systems very inefficient for data, hence only low - data rates were supported.
- 3G systems employed packet data services. Hence provided much higher data rates.
- Voice quality significantly increased.
- 3G systems also supported **multimedia, Web browsing, e - mail & interactive games.**

  Major 3G Standards are
  - IMT - 2000
  - Wideband CDMA (W - CDMA)
  - CDMA 2000 (3G evolution of IS-95)
  - EV - DO (EVolution Data Only)
  - HSPA (High Speed Packet Access)

6 Beyond 3G

- From 2009, mobile operators around the world started planning their next step in the evolution of their networks.
- Major technologies are
  - **HSPA+**
  - **WiMAX**
  - **LTE**

7 Key Requirements of LTE Design

LTE was designed with the following objectives in mind to effectively meet the growing demand.

1. Performance on par with Wired Broadband.
    - High throughput and Low latency
    - Data rate targets: 100 Mbps for Downlink & 50 Mbps for Uplink
2. Flexible Spectrum Usage.
    - Operators can deploy LTE in 700 MHz, 900 MHz, 1800 MHz & 2.6 GHz Bands.
    - LTE supports a variety of channel bandwidths: 1.4, 3, 5, 10, 15 & 20 MHz.
3. Co-existence and Interworking with 3G Systems as well as Non-3GPP Systems.
4. Reducing Cost per Megabyte.

8 Key Enabling Technologies & Features of LTE

To meet its service and performance requirements, LTE design incorporates several important enabling radio & core network technologies. They are:

1. Orthogonal Frequency Division Multiplexing (OFDM)
2. Single Carrier Frequency Domain Equalization (SC-FDE) and SC-FDMA
3. Channel Dependent Multi-user Resource Scheduling
4. Multi antenna Techniques
5. IP - Based Flat Network Architecture

8.1 Orthogonal Frequency Division Multiplexing (OFDM)

- OFDM has emerged as a technology of choice for achieving high data rates.
- It is the core technology used by a variety of systems including **Wi-Fi & WiMAX.**
- The following advantages of OFDM led to its selection for LTE:
    - Elegant solution to multipath interference.
    - Reduced computational complexity.
    - Graceful degradation of performance under excess delay.

  - Exploitation of frequency diversity.
  - Enables efficient multi-access scheme.
  - Facilitates use of MIMO.
  - Efficient support of broadcast services.

8.2 SC-FDE and SC-FDMA & Channel Dependent Multi-user Resource Scheduling

- Single Carrier Frequency Domain Equalization (SC-FDE) is conceptually similar to OFDM but instead of using IFFT, it uses QAM symbols with cyclic prefix.

- The uplink of LTE implements a multi-user version of SC-FDE, called SC-FDMA, which allows multiple users to use parts of the frequency spectrum.

- OFDMA allows for allocation in both time & frequency and it is possible to design algorithms to allocate resources in a flexible and dynamic manner.

8.3 Multi-antenna Techniques

- The LTE standard provides extensive support for implementing advanced multi-antenna solutions to improve link robustness, system capacity and spectral efficiency.

- Multiantenna techniques supported in LTE include:
  - Transmit diversity
  - Beam forming
  - Spatial multiplexing
  - Multi-user MIMO

8.4 IP - Based Flat Network Architecture

- The access network of LTE, E-UTRAN, simply consists of a network of eNodeBs, as illustrated in Figure.

- For normal user traffic (as opposed to broadcast), there is no centralized controller in E-UTRAN; hence the E-UTRAN architecture is said to be **flat.**

- The eNodeBs are normally inter-connected with each other by means of an interface known as X2, and to the EPC by means of the S1 interface.

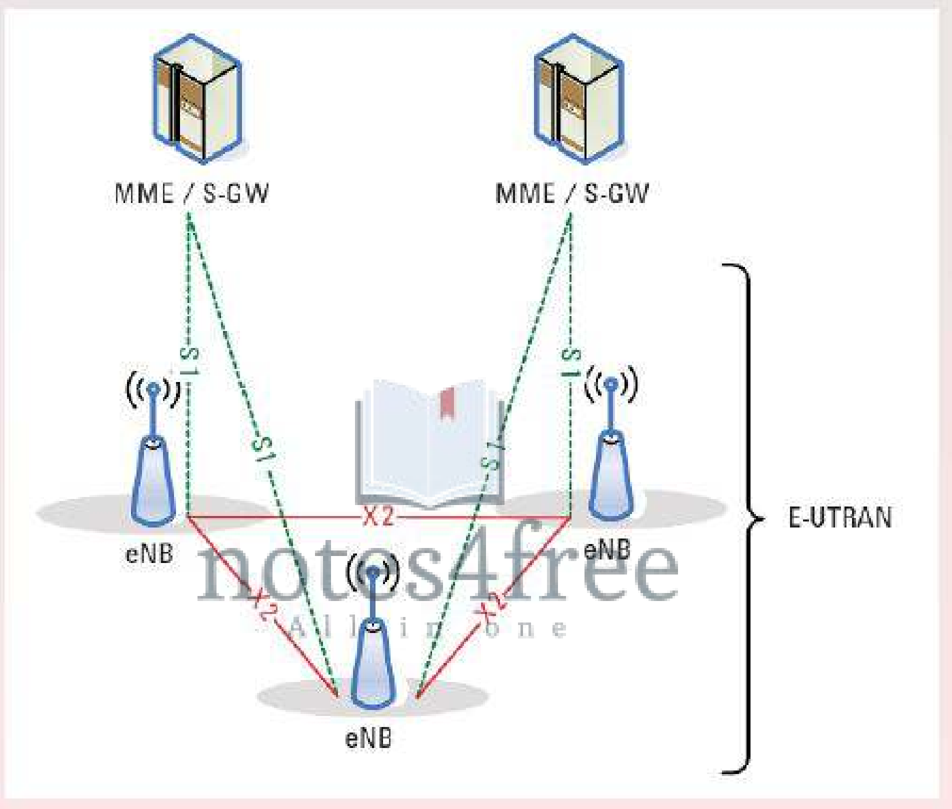


Figure 1: Overall E-UTRAN architecture.

- The protocols which run between the eNodeBs and the UE are known as the Access Stratum (AS) protocols.
- The E-UTRAN is responsible for all radio-related functions.

9 LTE Network Architecture

- LTE includes the evolution of:
  - the radio access through the E-UTRAN (Evolved - Terrestrial Radio Access Network)
  - the non-radio aspects under the term **System Architecture Evolution (SAE)**
- Entire system composed of both LTE and SAE is called the **Evolved Packet System (EPS)**
- At a high-level, the network is comprised of:
  - Core Network (CN), called **Evolved Packet Core (EPC)** in SAE
  - access network (E-UTRAN)
- A *bearer* (a messenger) is an IP packet flow with a defined QoS between the gateway and the User Terminal (UE).
- CN is responsible for overall control of UE and establishment of the bearers.

9.1 Evolved Packet Core Architecture

- Main logical nodes in EPC are:
  - Packet Data Network Gateway **(PGW)**
  - Serving Gateway **(SGW)**
  - Mobility Management Entity **(MME)**
- EPC also includes other nodes and functions, such as:
  - Home Subscriber Server **(HSS)**
  - Policy Control and Charging Rules Function **(PCRF)**
- EPS only provides a bearer path of a certain QoS, control of multimedia applications is provided by the IP Multimedia Subsystem **(IMS)**, which is considered outside of EPS.
- E-UTRAN solely contains the evolved base stations, called **eNodeB or eNB**

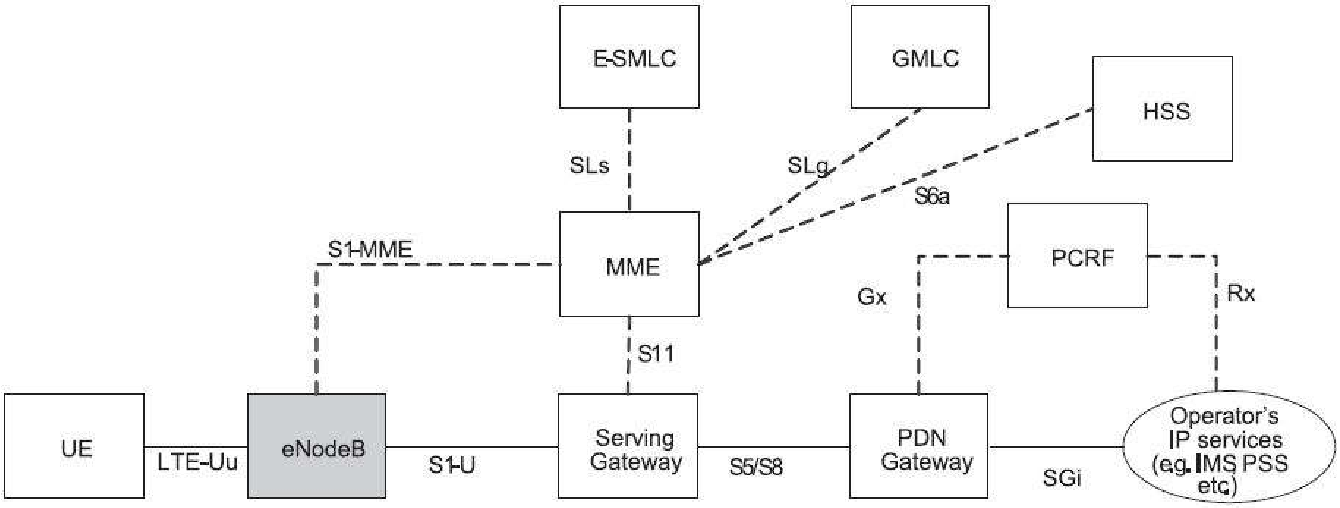


Figure 2: Evolved Packet Core Architecture

9.2 Four new elements of EPC

1. Serving Gateway (SGW)
    - It acts as a demarcation point between the RAN & core network.
    - It manages user plane mobility.
2. Packet Data Network Gateway (PGW)
    - It acts as the termination point of the EPC toward other networks such as Internet, private IP network or the multimedia service.
    - It provides functions such as user IP address allocation, policy enforcement, packet filtering & charging support.
3. Mobility Management Entity (MME)
    - It performs the signaling and control functions to manage the user terminal.
4. Policy & Charging Rules Function (PCRF)
    - It is a concatenation of Policy Decision Function (PDF) and Charging Rules Function (CRF).

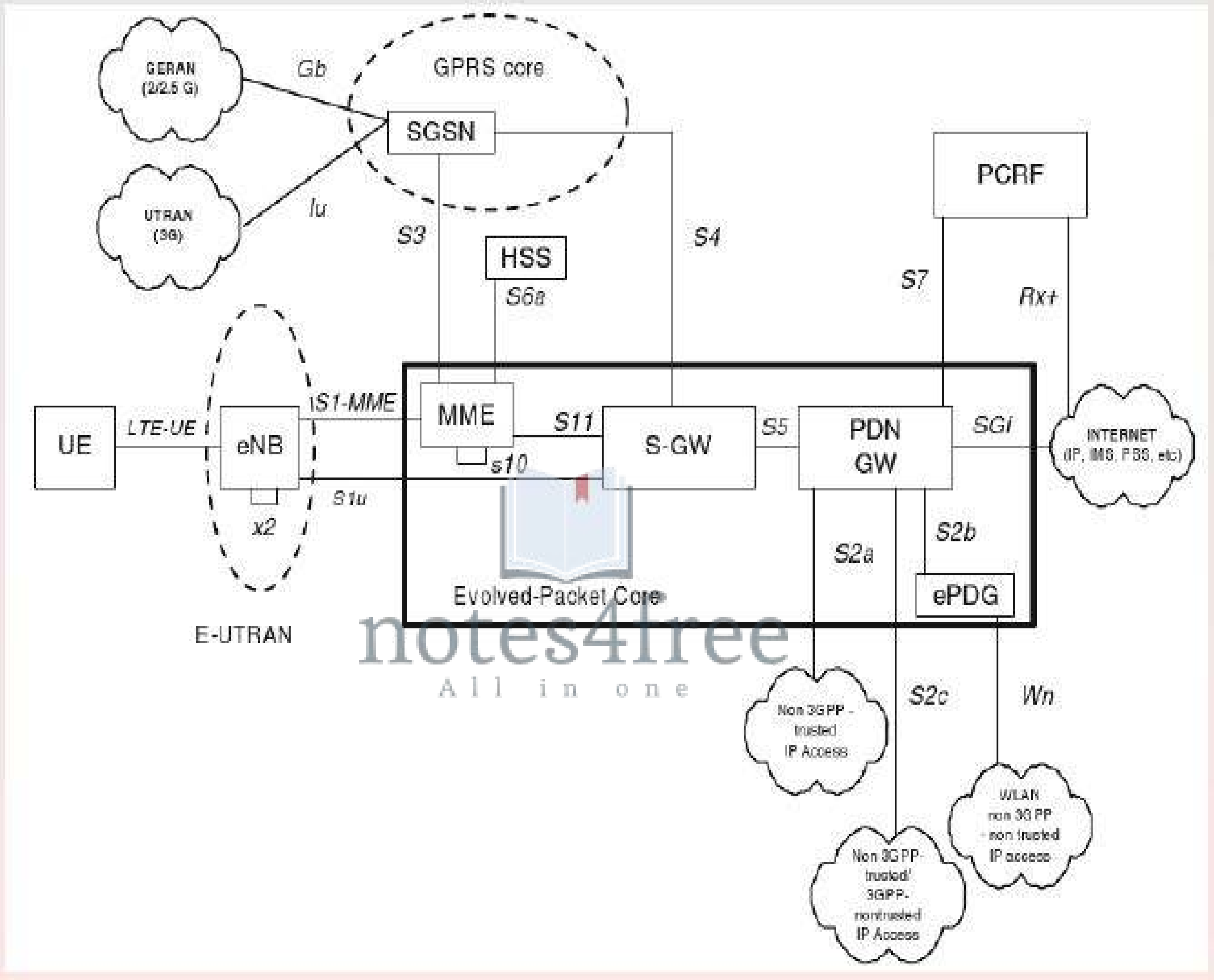


Figure 3: Evolved Packet Core Architecture

10 Home Work Exercise Questions

1. List out the features of major First Generation Systems.
2. List out the features of major 2G systems.
3. Draw GSM Network architecture and explain its sub-components.
4. Explain CDMA (IS-95) and its evolution.
5. Compare the features of major 3G Standards.
6. Write a note on HSPA.
7. What were the key requirements of LTE design? Briefly explain them.
8. Discuss the key enabling technologies of LTE.
9. What are the advantages of OFDM that has led to its selection for LTE?
10. Explain the IP - based Flat Network Architecture.
11. With a neat block diagram, explain the LTE Network Architecture and describe briefly the four new elements provided in it.

Module 1

Part 2: Wireless Fundamentals

Topics Covered

1. The Broadband Wireless Channel
2. Cellular Systems
3. Fading
4. Modeling of Broadband Fading Channels
5. Mitigation of Narrowband Fading
6. Mitigation of Broadband Fading

1 The Broadband Wireless Channel

In this topic we discuss the fundamental factors affecting the received signal in a wireless system, And how they can be modeled using the different parameters.

- Here we introduce the overall channel model, and discuss the large - scale trends that affect this model.
- In discrete-time, the overall channel model is described using a simple **tap-delay line (TDL).**

$$h[k,t] = h_0\delta[k,t] + h_1\delta[k-1,t] + \cdots + h_v\delta[k-v,t]$$

- Here, the discrete-time channel is time - varying and has **non - negligible** values over a span of $(v+1)$ channel taps.
- Here its assumed that the channel is sampled at a frequency $f_s = \dfrac{1}{T}$ where T is the symbol period.
- Hence, the duration of the channel is **vT**.
- Assuming that the channel is static over a period of (v+1)T seconds, the output of the channel can be described as

$$y[k,t] = \sum_{k=-\infty}^{\infty} h[j,t]x[k-j] = h[k,t] * x[k]$$

where x[k] is an input sequence of data symbols with rate $\frac{1}{T}$

- In a simple notation, the channel can be represented as a time-varying (v+1) x 1 column vector.

$$\text{i.e., } h(t) = \begin{bmatrix} h_0(t) \\ h_1(t) \\ \vdots \\ h_v(t) \end{bmatrix}$$

- Although this tapped-delay line model is general and accurate, it is difficult to design a communication system for the channel without knowing some of the key attributes about h(t).

1.1 Path Loss

- The first obvious difference between wired and wireless channels is the amount of transmitted power that actually reaches the receiver.
- Assuming an isotropic antenna is used, as shown in figure below
- The propagated signal energy expands over a spherical wavefront.
- Therefore, the energy received at an antenna a distance **d** away is inversely proportional to the sphere surface are, $4\pi d^2$
- The *free space path loss formula* or **Friis formula**, is given more precisely as

$$P_r = P_t \frac{\lambda^2 G_t G_r}{(4\pi d)^2}$$

where P_r and P_t are the received & transmitted powers and λ is the wavelength.

- As observed in Friis formula, $P_r \propto \lambda^2$, which means that $P_r \propto \frac{1}{f_c^2}$
- Clearly, higher frequencies suffer greater power loss than lower frequencies.
- As a result, lower carrier frequencies are generally more desirable, and hence very crowded.

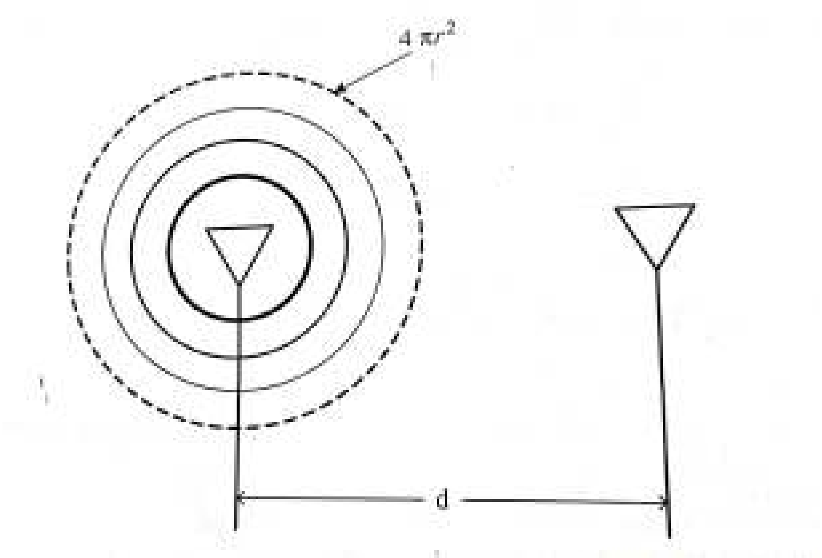


Figure 1: Free space propagation

- Therefore, bandwidth at higher carrier frequencies is more plentiful, more consistently available on a global basis, and almost always **less expensive.**
- Hence, a high-rate, low-cost system would generally prefer to operate at higher frequencies.
- But, the terrestrial propagation environment is not free space.
- The reflections from the Earth or other objects would actually increase the received power since more energy would reach the receiver.
- However, because a reflected wave often experiences a 180-degrees phase shift, at relatively large distances the reflection serves to create **destructive interference.**
- Therefore, the common 2 - ray approximation for path loss is:

$$P_r = P_t \frac{G_t G_r h_t^2 h_r^2}{d^4}$$

which is significantly different from free-space path loss in several aspects.

1.1.1 Empirical Path Loss Formula

- In order to more accurately describe different propagation environments, empirical models are often developed using experimental data.

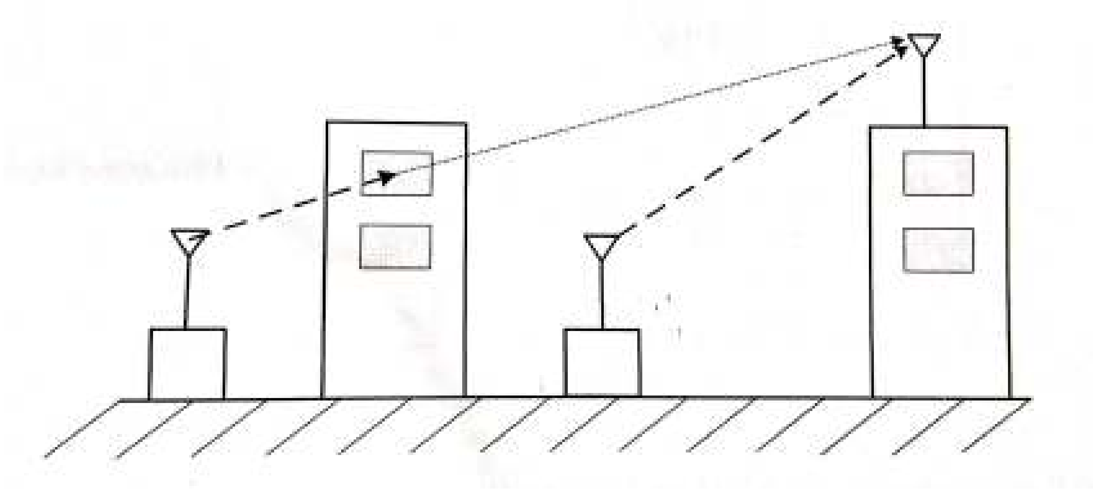


Figure 2: Shadowing can cause large deviations from path loss predictions.

- One of the simplest and most common is

$$P_r = P_t P_0 (\frac{d_0}{d})^{\alpha}$$

where α is the path loss exponent and the measured path loss P_0 at a reference distance of d_0

1.2 Shadowing

- Obstacles located between Transmitter & Receiver cause temporary degradation in received signal strength.
- Modeling the locations of all objects in every possible communication environment is generally impossible.
- Therefore, a random effect, called as **shadowing**, is introduced to measure these variations.
- With shadowing, the empirical path loss formula becomes

$$P_r = P_t P_0 \chi (\frac{d_0}{d})^{\alpha}$$

where χ is a sample of the shadowing random process.

- Hence, the received power is also now modeled as a random process.
- The shadowing value χ is typically modeled as a lognormal random variable, that is

$$\chi = 10^{x/10}, where x \sim N(0, \sigma_s^2)$$

where $N(0, \sigma_s^2)$ is a Gaussian (Normal) distribution with mean 0 and variance σ_s^2

- Thus, shadowing is an important effect in wireless networks because it causes the received SINR to vary dramatically over long time scales.
- In some given cell, reliable high-rate communication may be nearly impossible.

2 Cellular Systems

- In cellular systems, the service area is subdivided into smaller geographic areas called **cells**.
- Each cell is served by its own base station (BS).
- In order to minimize interference between cells, the transmit power level of each BS is regulated to be just enough to provide the required signal strength at the cell boundaries.
- The same frequency channels can be reassigned to different cells, as long as those cells are spatially isolated.
- The reuse of the same frequency channels should be intelligently planned in order to maximize the geographic distance between the co-channel base stations.

Some advantages of Cellular systems are:

- Cellular systems allow the overall system capacity to increase by simply making the cells smaller & turning down the power.
- Cellular systems support user mobility, seamless call transfer from one cell to another is provided.
- The handoff process provides a means of the seamless transfer of a connection from one BS to another.
- Small cells give a large capacity & reduce power consumption.
- Primary drawbacks are, **system needs more Base Stations, and their associated hardware costs, and the need for frequent handoffs.**

2.1 Cell Sectoring

- The performance of wireless cellular systems is significantly limited by co-channel interference (CCI).
- This comes from other users in the same cell or from other cells.

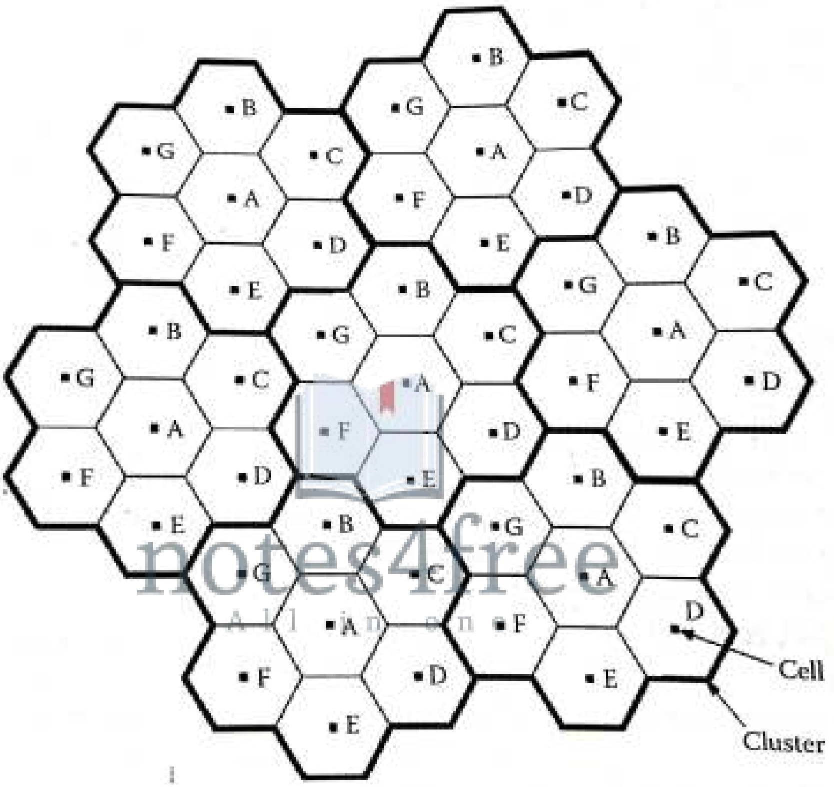
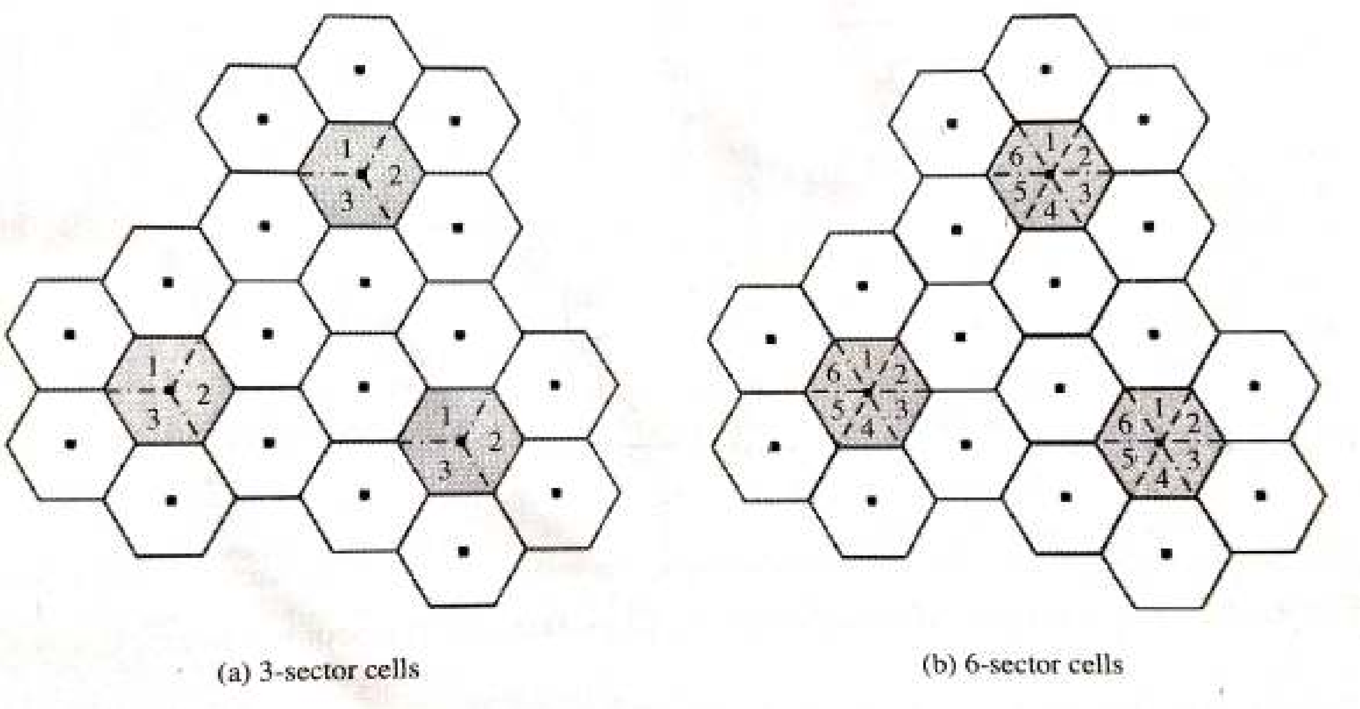


Figure 3: Standard figure of a hexagonal cellular system with f = 1/7



(a) 3-sector cells

(b) 6-sector cells

Figure 4: 3-Sector (120-degree) and 6-Sector (60-degree) cells.

- In Cellular Systems, Other Cell Interference (OCI) is a decreasing function of the radius of the cell (R) & the distance to the center of the neighbouring co-channel cell and an increasing function of transmit power.
- Since the SIR is so bad in most of the cell, it is desirable to find techniques to improve it without sacrificing so much bandwidth.
- A popular technique is to **sectorize** the cells, which is effective if frequencies are reused in each cell.

Directional antennas are used instead of omni-directional antenna at the base station.

3 The Broadband Wireless Channel: Fading

- One of the most disturbing aspects of wireless channels is the fading phenomenon.
- Unlike path loss or shadowing, which are large-scale attenuation effects due to distance or obstacles, fading is caused by the reception of multiple versions of the same signal.
- The multiple received versions are caused by reflections that are referred to as *multipath.*

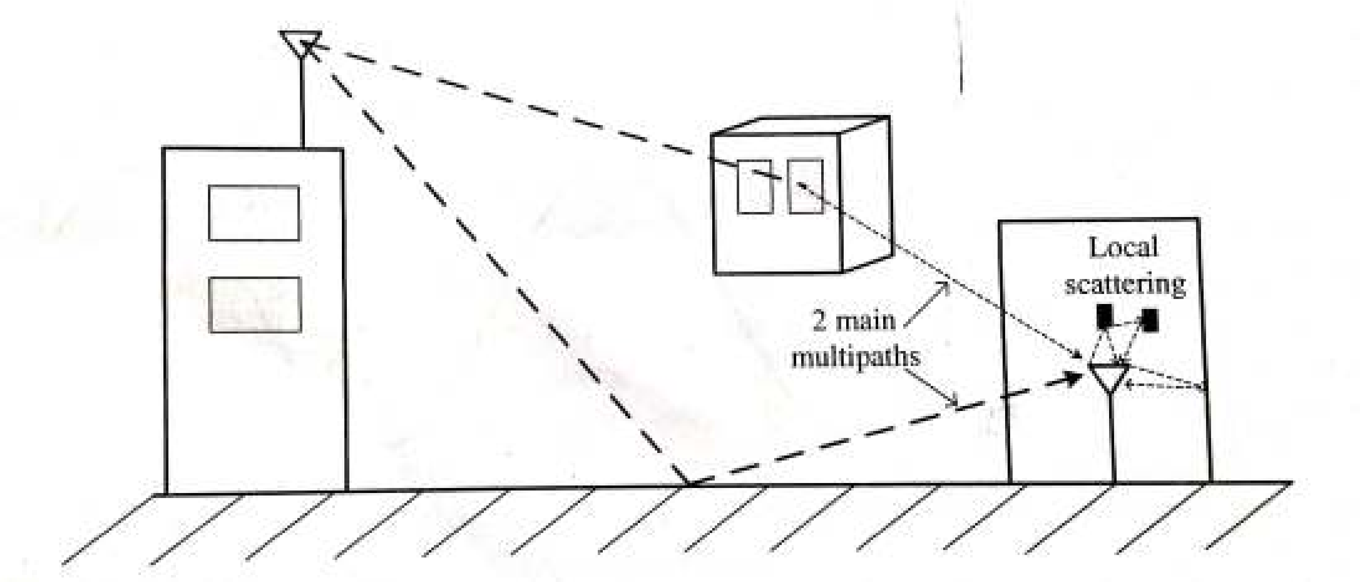


Figure 5: The channel may have a few major paths with quite diffrent lengths, and then the receiver may see a number of locally scattered versions of those paths.

- Depending on the phase difference between the arriving signals, the interference can be either constructive or destructive.
- This causes a very large observed difference in the amplitude of the received signal even over very short distances.

  Let us consider the time-varying tapped-delay line channel model.
- As either the Tx^r or Rx^r move relative to each other, the channel response $\mathbf{h(t)}$ will change.
- Movement in the propagation environment will also cause the channel response to change over time.
- This channel response can be thought of as having two dimensions:
  a delay dimension τ & a time dimension t
- Since the channel is highly variant in both the τ & **t** dimensions, in order to be able to discuss what the channel response is we must use statistical methods.
- The most important & fundamental function used to statistically describe broadband fading channels is the two-dimensional auto correlation function, $A(\Delta\tau, \Delta t)$.

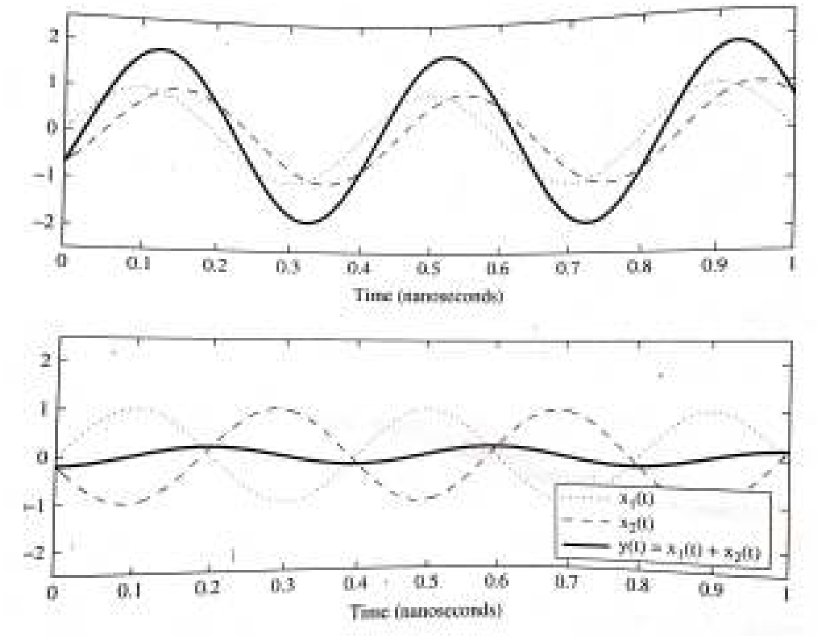


Figure 6:

And it is defined as

$$
\begin{aligned}
A(\Delta\tau, \Delta t) &= E[h(\tau_1, t_1)h^*(\tau_2, t_2)] \\
&= E[h(\tau_1, t)h^*(\tau_2, t + \Delta t)] \\
&= E[h(\tau, t)h^*(\tau + \Delta\tau, t + \Delta t)]
\end{aligned}
$$

- The channels described by this auto correlation function are referred to as **Wide Sense Stationary Uncorrelated Scattering (WSSUS).**
- This is the most popular model for wide band fading channels.

  From the auto correlation function, following wireless channel parameters can be estimated.

  1. Delay Spread, τ
  2. Coherence Bandwidth, B_c
  3. Doppler Spread, $f_D = \dfrac{f_c v}{c}$
  4. Coherence Time, T_c
  5. Angular Spread, θ_{rms}
  6. Coherence Distance, D_c

4 Modelling Broadband Fading Channels

- In order to design and benchmark wireless communication systems, it is important to develop channel models that incorporate their variations in time, frequency and space.
- The two main classes of models are **Statistical model** & **Empirical model.**
- Statistical models are simpler and are useful for analysis & simulations.
- The empirical models are more complicated, but usually represent a specific type of channel more accurately.

4.1 A Pedagogy for Developing Statistical Models

The methods for modelling wireless channels are broken into three steps:

Step 1 : First consider just a single channel sample corresponding to a single principle path between the Tx^r & Rx^r, that is

$$h(\tau, t) \rightarrow h_0\delta(\tau, t)$$

Attempt to quantify: How is the value of $|h_0|$ statistically distributed?

Step 2 : Next consider how this channel sample h_0 evolves over time, that is:

$$h(\tau, t) \rightarrow h_0(t)\delta(\tau)$$

Attempt to quantify: How does the value $|h_0|$ change over time?

Step 3 : Finally, $h(\tau, t)$ is represented as a general time varying function.

4.2 Statistical Channel Models

- The received signal in a wireless system is the superposition of numerous reflections or multi path components.
- In this section, we will overview statistical methods that can be used to characterize the amplitude & power of received signal $r(t)$ when all the reflections arrive at about the same time.
- The following statistical models are considered in this section:
  1. Rayleigh Fading Model
  2. Line-of-Sight Channels - The Rician Distribution
  3. A more general model: Nakagami - m Fading

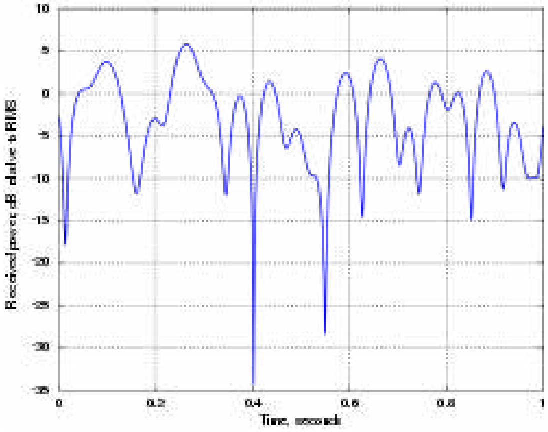


Figure 7: One second of Rayleigh fading with a maximum Doppler shift of 10 Hz.

4.3 Rayleigh Fading Model

- Rayleigh fading is a reasonable model when there are many objects in the environment that scatter the radio signal before it arrives at the receiver.
- The in-phase (cosine) and quadrature (sine) components of received signal r(t) follow two independent time - correlated Gaussian random processes.
- The distribution of the envelope amplitude $|r| = \sqrt{r_I^2 + r_Q^2}$ is **Rayleigh distribution.**

$$f_{|r|}(x) = \frac{2x}{P_r} e^{-x^2/P_r}; x \geq 0$$

- The received power $|r|^2 = r_I^2 + r_Q^2$ is **exponentially distributed.**

$$f_{|r|^2}(x) = \frac{1}{P_r} e^{-x/P_r}; x \geq 0$$

- The GRVs r_I and r_Q each have zero mean and variance $\sigma^2 = P_r/2$.
- The phase of $r(t)$ is defined as $\theta_r = \tan^{-1}(\frac{r_Q}{r_I})$
- This phase is **uniformly distributed** from 0 to 2π, or equivalently from $[-\pi, \pi]$

4.4 LoS Channels - The Rician Distribution

- An important assumption in the Rayleigh fading model is that, the arriving reflections have a mean of zero.
- For LoS signal, the received envelope distribution is more accurately modelled by a Rician distribution.
- It is given by

  $$f_{|r|}(x) = \frac{x}{\sigma^2} e^{-(x^2+\mu^2)/2\sigma^2} I_0\left(\frac{x\mu}{\sigma^2}\right); x \geq 0$$

  where μ^2 is the power of the LoS component and
  I_0 is the 0^{th} order, modified Bessel function of the first kind.
- The Rician phase distribution θ_r is not uniform in $[0, 2\pi]$ and is not distributed by a straight forward expression.
- It is more generalization of the Rayleigh distribution.

4.5 A more general model: Nakagami - m Fading

- The Nakagami distribution is relatively new, being first proposed in 1960.
- It has been used to model attenuation of wireless signals traversing multiple paths and to study the impact of fading channels on wireless communications.
- The Probability Density Function (PDF) of Nakagami - m fading is parameterized by m and is given as

  $$f_{|r|}(x) = \frac{2m^m x^{2m-1}}{\Gamma(m) P_r^m} e^{-mx^2/P_r}; m \geq 0.5$$

- The power distribution for Nakagami fading is

  $$f_{|r|^2}(x) = \left(\frac{m}{P_r}\right)^m \frac{x^{m-1}}{\Gamma(m)} e^{-mx/P_r}; m \geq 0.5$$

4.6 Empirical Channel Model

- Actual environments are too complex to model accurately.
- In practice, most simulation studies use empirical models that have been developed based on measurements taken in various real environments.

- In 1968, **Okumura** conducted extensive measurements of base station to mobile signal attenuation throughout Tokyo and developed a set of curves giving median attenuation relative to free space path loss.
- To use this model one needs to use the empirical plots given in his paper. This is not very convenient to use.
- So in 1980, **Hata** developed closed-form expressions for Okumura's data.

4.7 LTE Channel Models for Path Loss : Hata Model

According to **Hata model** the path loss in an urban area at a distance d is:

$$L_U = 69.55 + 26.16log_{10}(f_c) - 13.82log_{10}(h_B) - a(h_r) + [44.9 - 6.55log_{10}(h_B)]log_{10}(d)$$

where
L_U = Path loss in Urban areas (dB)
h_B = Height of BS antenna (meters)
f_c = Carrier Frequency (MHz)
$a(h_r)$ = Antenna height correction factor
d = Distance between BS & MS (Kms)

4.8 COST Hata Model

- Hata model is intended for large cells with BS being placed higher than the surrounding rooftops.
- Both Okumura & Hata models are designed for **150-1500 MHz** and are applicable to the first generation cellular systems.
- The European Cooperative for Scientific and Technical (COST) research extended the Hata model to 2 GHz as follows:

$$P_{L,Urban} = 46.3 + 33.9log_{10}(f_c) - 13.82log_{10}(h_t) - a(h_r) + [44.9 - 6.55log_{10}(h_t)]log_{10}(d) + C_m$$

- This model is restricted to the following range of parameters:

Carrier Frequency	1.5 GHz to 2 GHz
Base Antenna Height	30 m to 300 m
Mobile Antenna Height	1 m to 10 m
Ditance d	100 m to 20 Km

- COST Hata model is designed for large and small macro-cells, i.e., base station antenna heights above rooftop levels adjacent to base station.

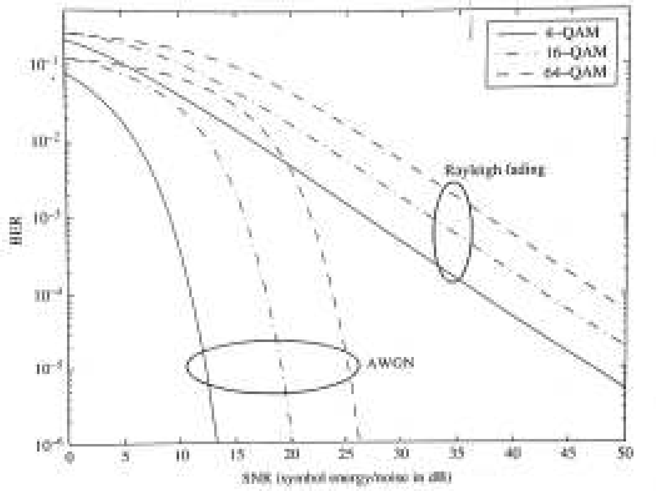


Figure 8: SNR vs. BER

5 Mitigation of Narrowband Fading

5.1 The Effects of Unmitigated Fading

- The probability of bit error (BER) is the principle metric of interest for the physical (PHY) layer of a communication system.
- For a QAM - based modulation system, the BER in an AWGN (no fading) can be approximated by the following bound:
  $P_b \leq 0.2e^{-1.5SNR/(M-1)}$
- The BER decreases rapidly (exponentially) with SNR.
- So decreasing SNR linearly causes the BER to increase exponentially.

5.2 Techniques to mitigate fading

The following techniques are used to mitigate the effects of fading.

1. Diversity - Spatial Diversity
2. Coding and Interleaving - Using ECCs or FECs
3. Automatic Repeat Request (ARQ)
4. Adaptive Modulation and Coding (AMC)

5.2.1 Spatial Diversity

- Diversity is the key to overcome performance loss from fading channels.
- Spatial diversity is a powerful form of diversity, and particularly desirable since it does not include redundancy in time or frequency.
- It is usually achieved by having two or more antennas at the receiver and / or the transmitter.
- The simplest form of space diversity consists of two receive antennas, where the stronger of the two signals is selected.
- This type of diversity is called as **Selection Diversity.**

6 Mitigation of Broadband Fading

- Since the data rate R is proportional to 1/T, high data rate systems almost invariably have multi path delay spread & hence experience very serious inter symbol interference (ISI).
- Choosing a technique to effectively reduce ISI is a central design decision for any high data rate system.
- OFDM is the most popular choice for reducing ISI in high rate systems, including WiFi, WiMAX and LTE.

Mod: 2

Multiple Antenna Transmission & Reception

- Multicarrier modulation enables richer, more efficient use of multiple antennas & receivers in wideband channels.

- Multiple antenna techniques can be grouped into 3 different categories.

  (1) Diversity

  (2) Interference Suppression

  (3) Spatial Multiplexing.

-(1) Spatial Diversity.

It allows a number of different versions of the signal to be transmitted and/or received, and provides considerable resilience against fading.

-(2) Interference Suppression

It uses the spatial dimensions to reject the interference from other users, either through the physical antenna gain pattern or through other forms of array processing such as linear precoding, post coding or interference cancellation.

-(3) Spatial Multiplexing

It allows two or more independent streams of data to be sent simultaneously in the same bandwidth, and hence is useful primarily for increasing the data rate.

All 3 of these different approaches are often collectively referred to as multiple input-multiple output (MIMO) communication.

Spatial Diversity

- Spatial diversity is more essential for reliable wireless systems.
- The advantage of spatial diversity is that no additional bandwidth or power is needed.

Instead, it is exploited through two or more antennas, which are separated by enough distance so that the fading is approximately decorrelated between them.

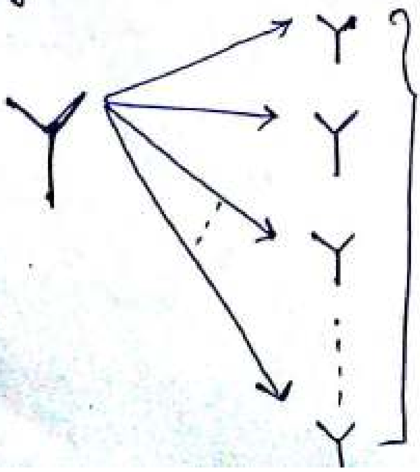
- When multiple antennas are used, there are two forms of gain available.

(i) Diversity Gain → Because of multiple independent channels b/w Tx^r & Rx^r. It depends on product of statistical characteristics of those channels.

(ii) Array Gain
↓
It does not rely on statistical diversity b/w the different channels. Instead, it depends on combined energy of each of the antennas.

Due to array gain, even if the channels are completely correlated, the received SNR increases linearly with the number of receive antennas.

Eg: Consider a $1 \times N_r$ system.



Perfectly correlated.
$\therefore h_i = h$.

In correlated flat fading, each antenna $i \in (1, N_r)$ receives a signal that can be characterized as

$$y_i = h_i x + n_i$$

$$= hx + n_i$$

SNR on a single antenna is $\gamma_i = \frac{|h_i \mathcal{E}_x|^2}{\sigma^2}$

$$\gamma_i = \frac{|h|^2}{\sigma^2},$$

where σ^2 is the noise power & we assume the signal energy as 1. ie, $\mathcal{E}_x = E|x|^2 = 1$.

If all the receive antenna paths are added, the resulting signal is

$$y = \sum_{i=1}^{N_r} y_i = N_r \cdot h x + \sum_{i=1}^{N_r} n_i .$$

and the combined SNR, assuming that just the noise on each branch is uncorrelated, is given by

$$\gamma_\Sigma = \frac{|N_r h|^2}{N_r \cdot \sigma^2} = \frac{N_r^2 \cdot |h|^2}{N_r \cdot \sigma^2} = \frac{N_r \cdot |h|^2}{\sigma^2} .$$

$\Rightarrow \gamma_\Sigma \propto N_r$

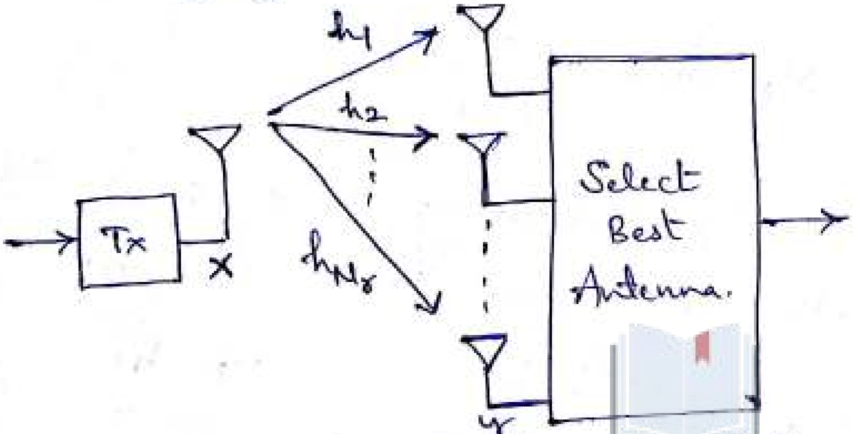
Hence, the received SNR also increases linearly with the number of receive antennas, even if those antennas are correlated.

Receive Diversity

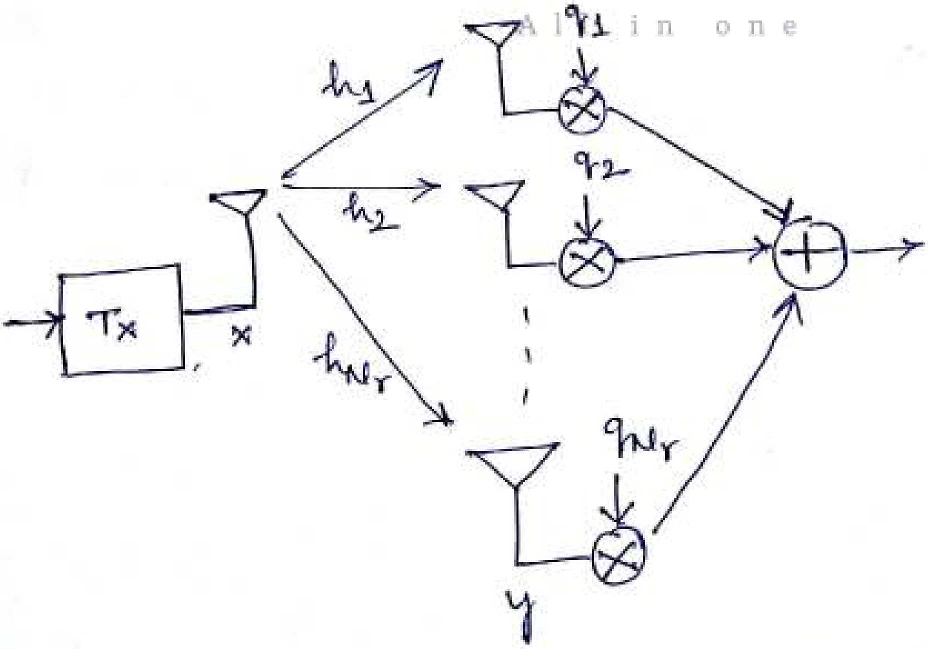
- The most common form of spatial diversity is receive diversity, often with just two Rx antennas. $(N_r = 2)$.

- In this section, we will overview two of the widely used combining algorithms.

(1) Selection Combining (SC) (2) Maximal Ratio Combining (MRC)



Selection Combining (SC)



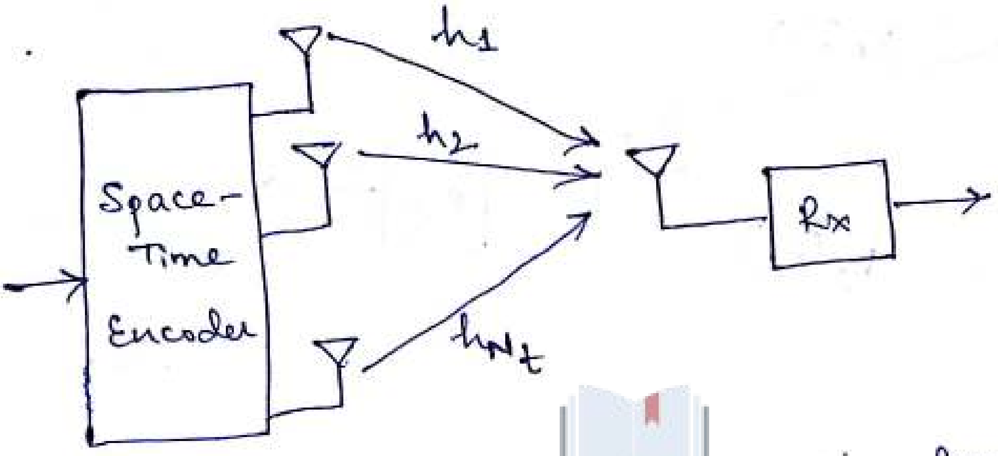
Maximal Ratio Combining (MRC)

Here $q_i = |q_i| e^{j\phi_i}$ is a complex factor.

Transmit Diversity

- It is a more recent development than receive diversity.
- Multiple antenna transmit schemes are often categorized into two classes:

(1) open-loop (2) closed-loop.



Open-loop transmit diversity.

2×1 Space-Frequency Block Coding (SFBC)

The simplest SFBC corresponds to two transmit antennas and a single receive antenna.

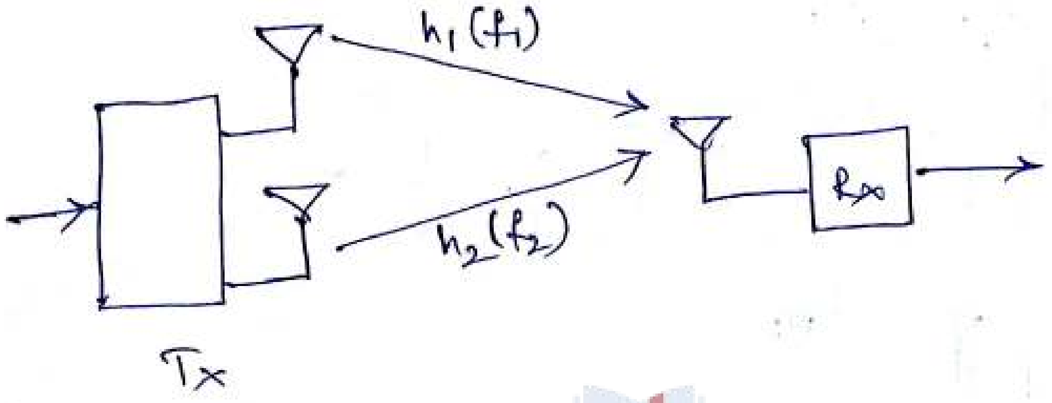
If two symbols to be transmitted are s_1 and s_2, the Alamouti code sends the following over two subcarriers f_1 and f_2.

		Antennas	
		1	2
Sub carrier	f_1	s_1	s_2
	f_2	$-s_2^*$	s_1^*

Assuming a flat fading channel on each subcarrier, then

$h_1(f_1)$ → is the complex channel gain from Tx Antenna 1 to Rx Antenna.

$h_2(f_2)$ → is the complex channel gain from Tx Antenna 2 to Rx Antenna.



$$r(f_1) = h_1(f_1)\, s_1 + h_2(f_2)\, s_2 + n(f_1)$$

$$r(f_2) = h_1(f_1)\,(-s_2^*) + h_2(f_2)\, s_1^* + n(f_2)$$

Assuming channel is constant over the two adjacent subcarriers, ie,

$$h_1(f_1) = h_1(f_2) = h_1$$
$$h_2(f_1) = h_2(f_2) = h_2$$

$$\therefore\ r(f_1) = h_1 s_1 + h_2 s_2 + n(f_1)$$

$$r(f_2) = h_1(-s_2^*) + h_2 s_1^* + n(f_2)$$
$$= -h_1 s_2^* + h_2 s_1^* + n(f_2)$$

$$\left.\begin{aligned} y_1 &= h_1^* r(f_1) + h_2 r^*(f_2) \\ y_2 &= h_2^* r(f_1) - h_1 r^*(f_2) \end{aligned}\right\}$$ Using diversity combining scheme + assuming channel is known at Rx^r.

$$\therefore y_1 = h_1^* \left(h_1 s_1 + h_2 s_2 + n(f_1)\right) + h_2\left(-h_1^* s_2 + h_2^* s_1 + n^*(f_2)\right)$$

$$y_1 = \left(|h_1|^2 + |h_2|^2\right) s_1 + h_1^* n(f_1) + h_2 n^*(f_2)$$

III^ly

$$y_2 = \left(|h_1|^2 + |h_2|^2\right) s_2 + h_2^* n(f_1) - h_1 n^*(f_2)$$

Resulting SNR

$$\gamma_\Sigma = \frac{\left(|h_1|^2 + |h_2|^2\right)^2}{|h_1|^2\sigma^2 + |h_2|^2\sigma^2} \cdot \frac{\mathcal{E}_x}{2}$$

$$= \frac{|h_1|^2 + |h_2|^2}{\sigma^2} \cdot \frac{\mathcal{E}_x}{2}$$

$$\gamma_\Sigma = \frac{\sum_{i=1}^{2} |h_i|^2}{\sigma^2} \frac{\mathcal{E}_x}{2}.$$

Here $E|s_1|^2 = E|s_2|^2 = \frac{\mathcal{E}_x}{2}$ since each are sent twice.

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)***

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

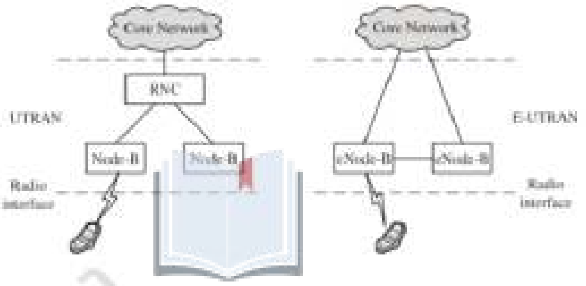


Figure 6.1 Radio interface architectures of UTRAN and E-UTRAN.

- 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 network 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

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.

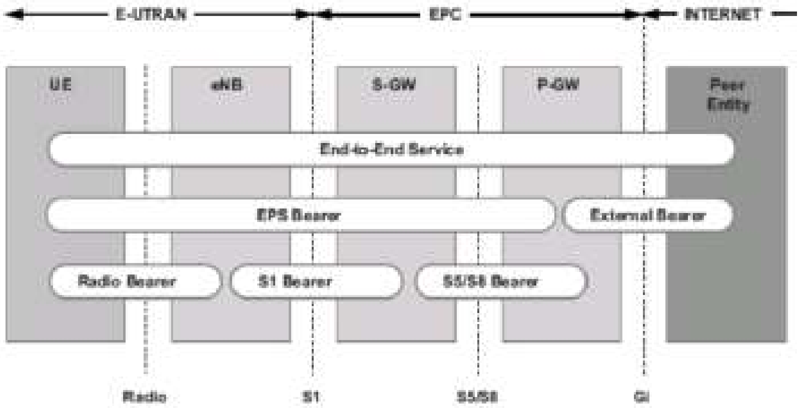
iv. *MBMS Service:* LTE should also provide enhanced support for the Multimedia Broadcast and Multicast Service (MBMS) compared to UTRA (3G) operation.

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.

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).*

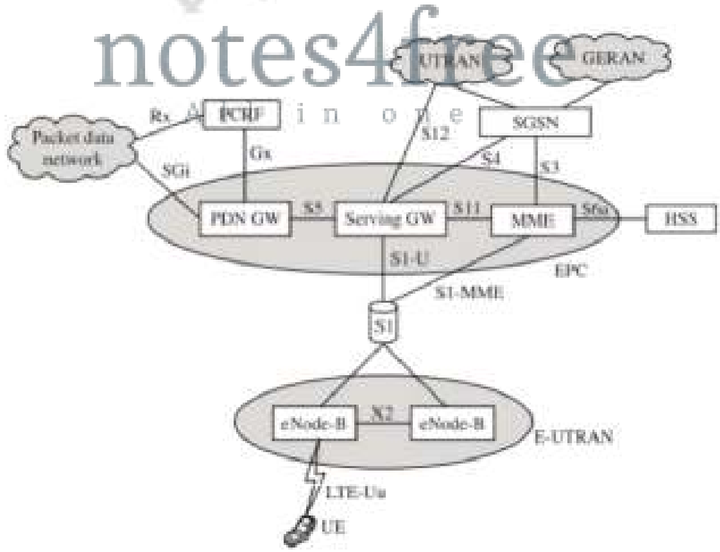


Figure 6.2 LTE end-to-end network architecture.

- 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.

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.

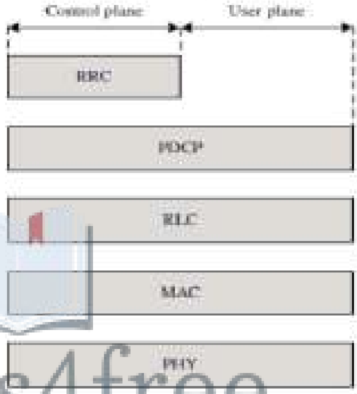


Figure 6.3 The LTE radio interface protocol stack.

- 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
        1. *Selection of modulation format*
        2. *Code rate*
        3. *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.*

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*

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).

- 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.

- 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.

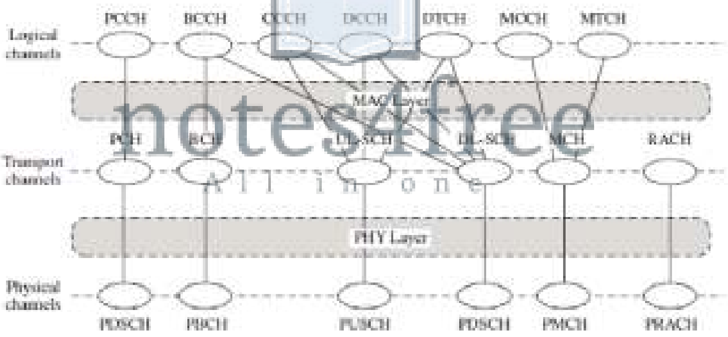


Figure 6.6 Mapping between different channel types.

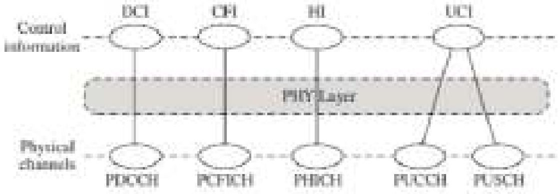


Figure 6.7 Mapping of control information to physical channels.

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 × 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 $T_f = 307200 \text{ x } T_s = 10\text{ms}$
- 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.

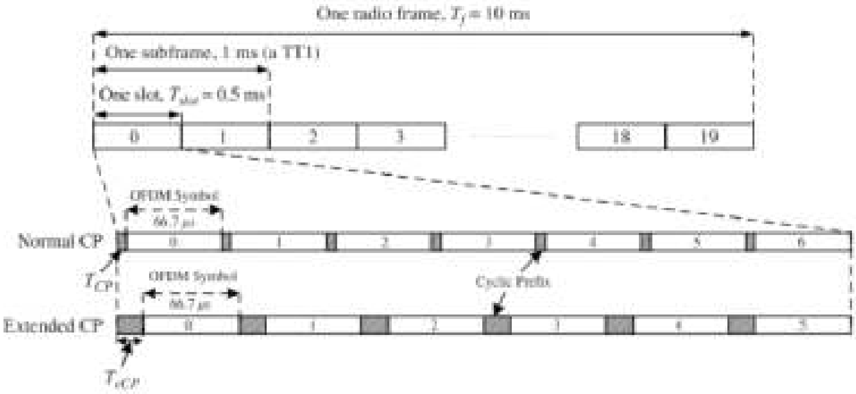


Figure 6.8 Frame structure type 1. For the normal CP, $T_{CP} = 160 \cdot T_s \approx 5.2\mu s$ for the first OFDM symbol, and $T_{CP} = 144 \cdot T_s \approx 4.7\mu s$ for the remaining OFDM symbols, which together fill the entire slot of 0.5 ms. For the extended CP, $T_{eCP} = 512 \cdot T_s \approx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

- ***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) = $1.67\mu s$.*
- *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.

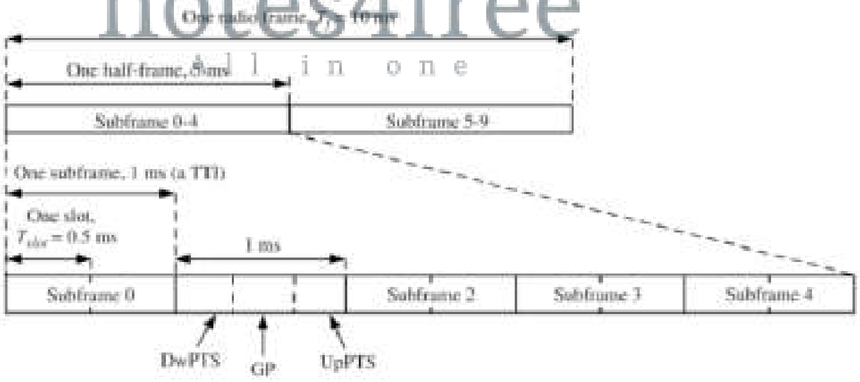


Figure 6.9 Frame structure type 2.

- ***Description of the frame type 2:***
- *Frame structure type 2 is of length $T_f = 30720 \times T_s = 10ms$.*
- *Each frame consists of two half-frames of length 5 ms each.*
- *Each half-frame is divided into five subframes with 1 ms duration.*

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.

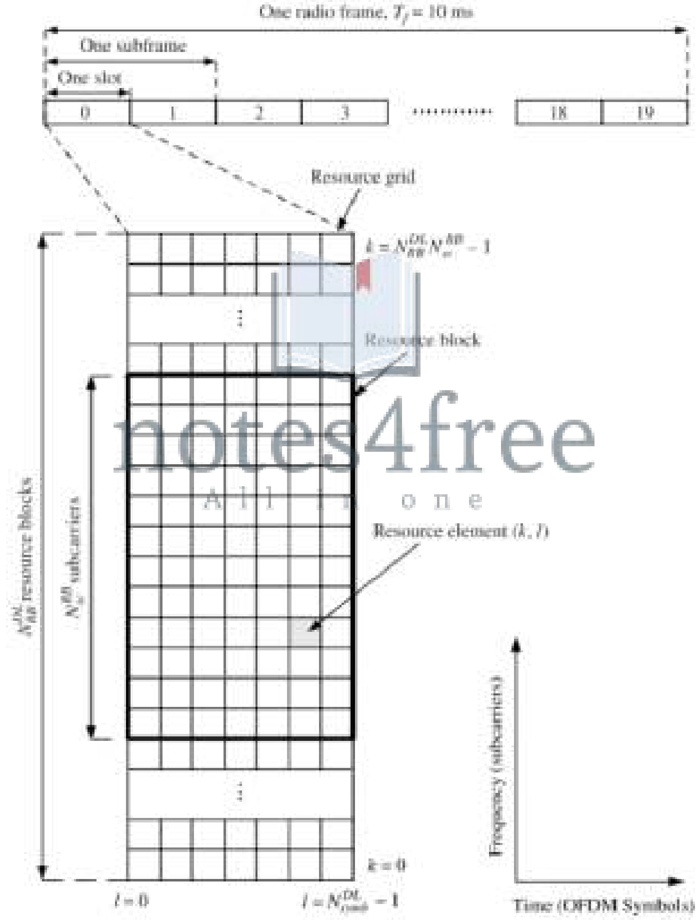


Fig 6.10: The structure of downlink resource grid

- **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 $N_{SC}^{RB}\ \Delta f$ = 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.

- **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.

- 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.*

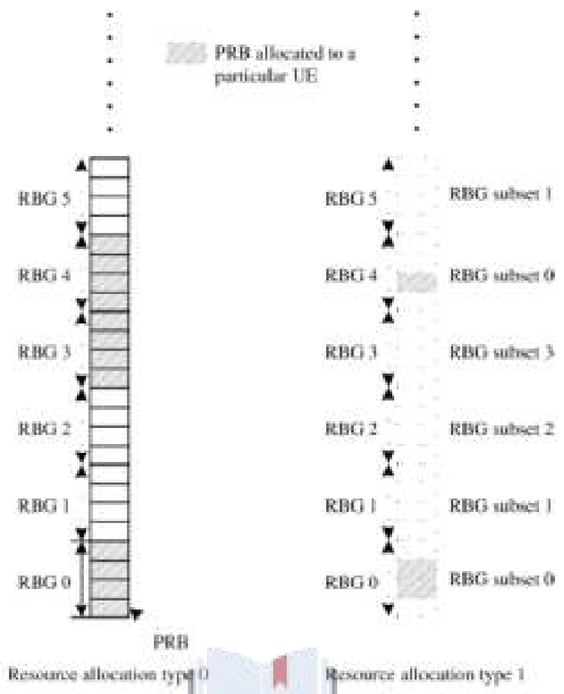


Figure 6.11 Examples of resource allocation type 0 and type 1, where the RBG size P= 4.

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.

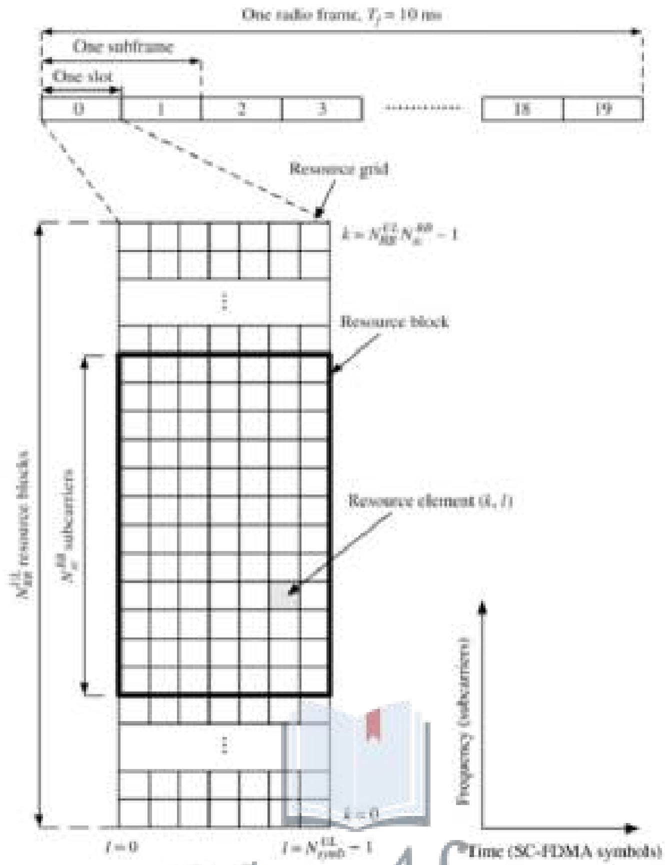


Figure 6.12: The structure of the uplink resource grid.

- 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 Δf = **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.

- 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.

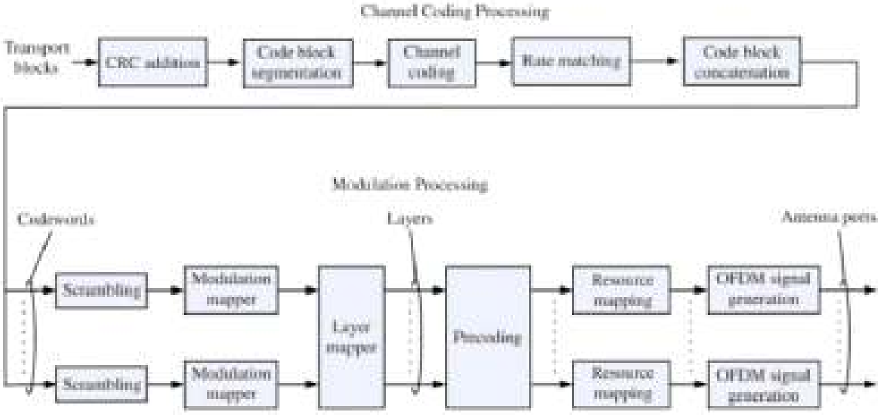


Figure 7.2 Overview of downlink transport channel processing.

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.

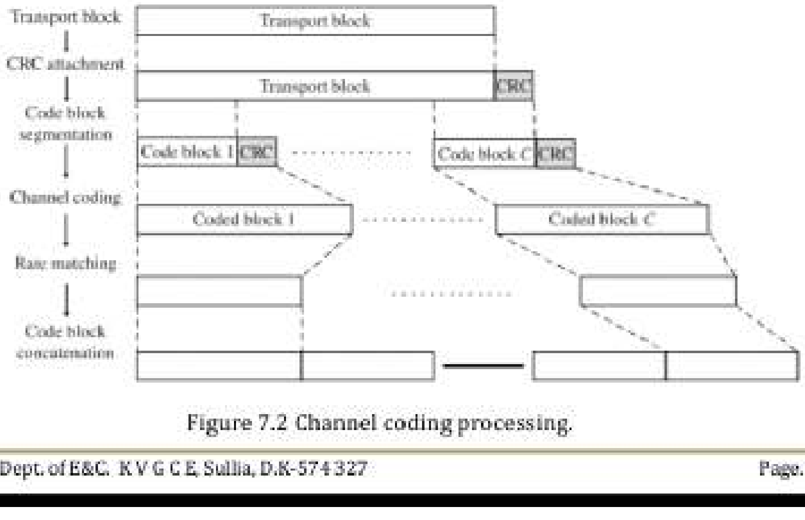
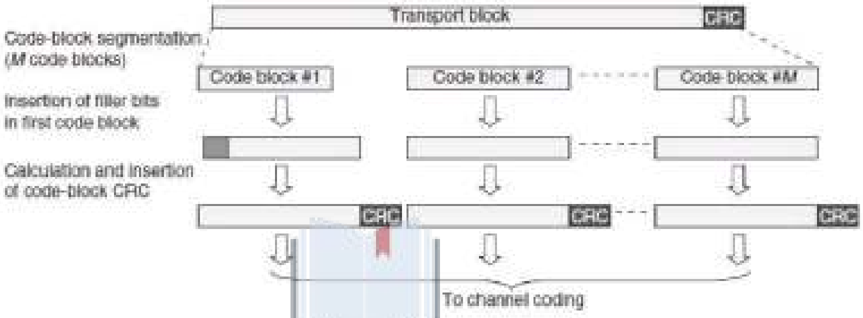


Figure 7.2 Channel coding processing.

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 decoding 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.

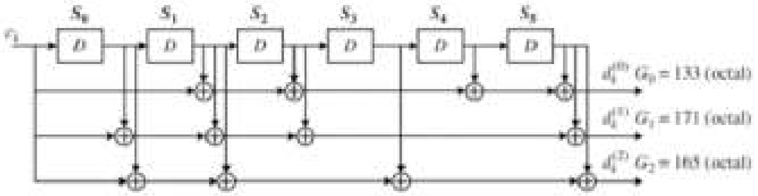


Figure 7.3 Rate 1/3 tail-biting convolutional encoder.

- 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.

- 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.

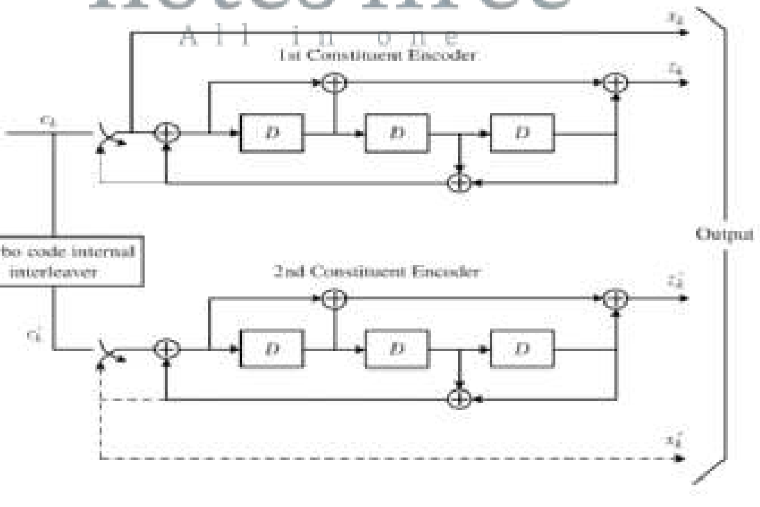


Figure 7.4 Structure of rate 1/3 turbo encoder (dotted lines apply for trellis termination only)

- 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*

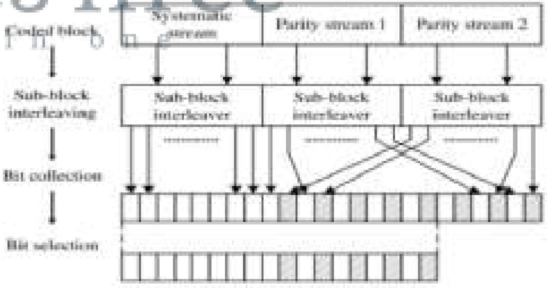


Figure 7.5 Rate matching for coded transport channels.

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.*

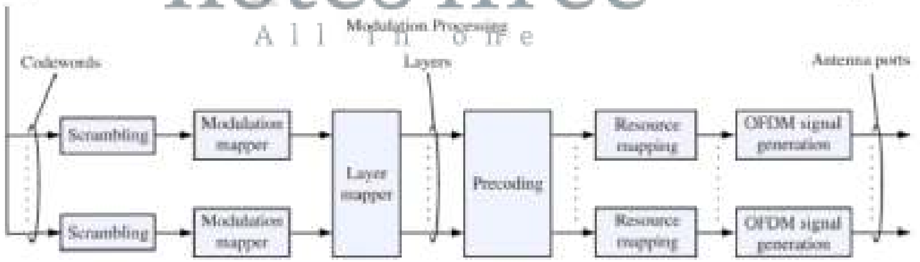
b. Bit Collection: *Bit collection stage is required to place the systematic and parity bits in the right order as needed by the decoder. A virtual circular buffer is formed by collecting bits from the interleaved streams. The systematic bits are placed at the beginning, followed by bit-by-bit interlacing 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 eme. The relation between $M_s^{(q)}$and $M_q^{(q)}$ is as follows:

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

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

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

- 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

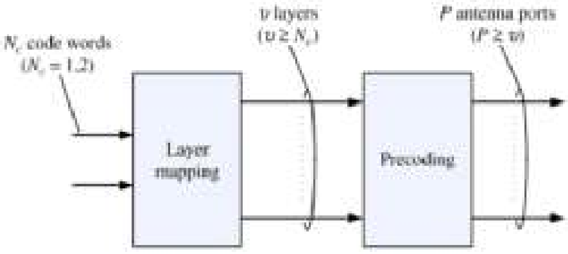


Figure 7.6 Layer mapping and precoding.

- ***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

$$y(i) = W(i) \cdot x(i)$$

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:

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

for $0 \leq t \leq (N_{CP,l} + N) \times T_s$, 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:

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

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

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

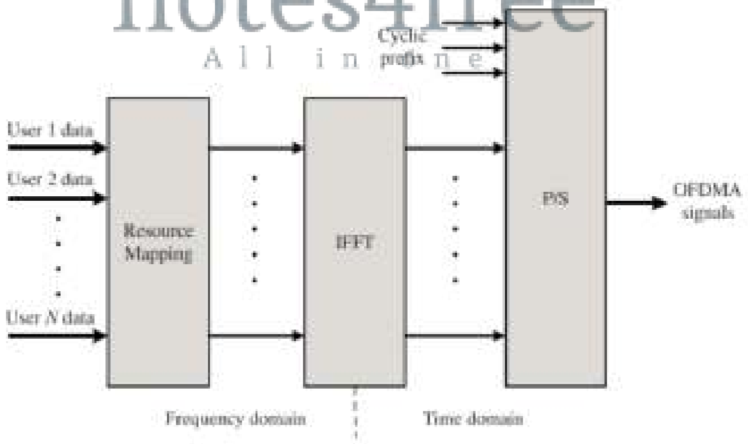


Figure 7.8 OFDMA signal generation with N users, where P/S denotes the parallel-to-serial converter.

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.

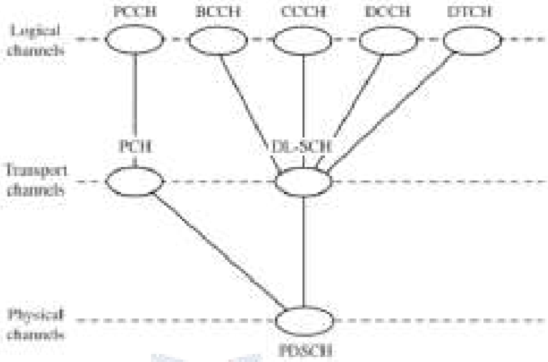


Figure 7.9 Channel mapping around the downlink shared channel.

- 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)

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.

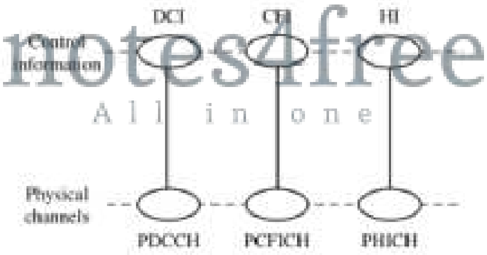


Figure 7.11 Channel mapping for control information in the downlink

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.

- 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 $\Delta f = 15kHz$.

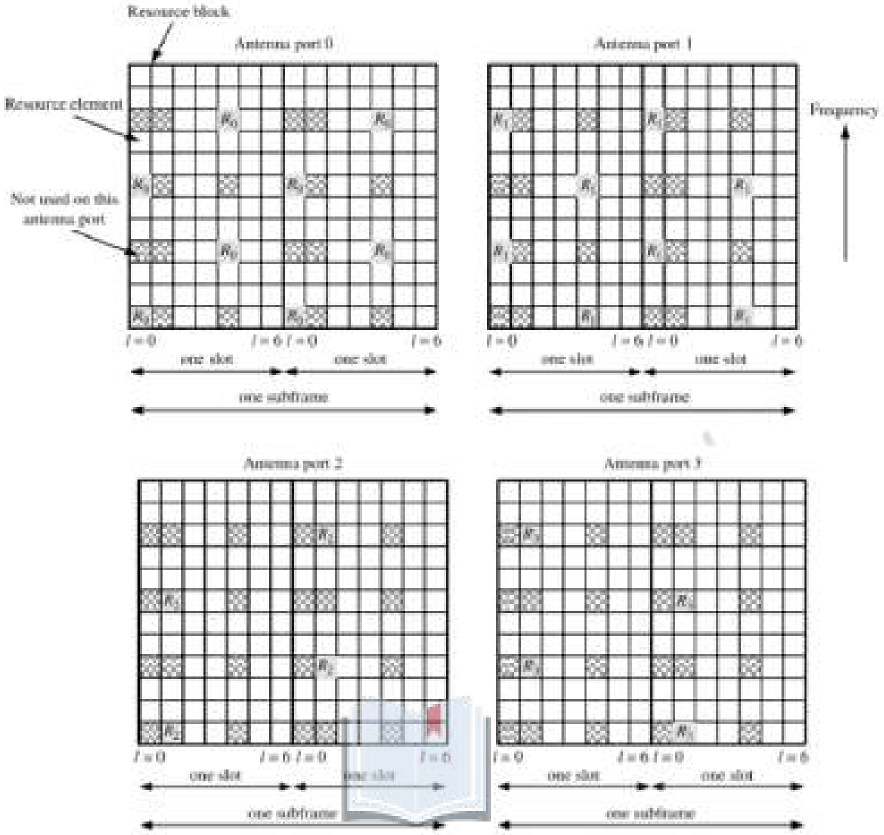


Figure 7.12 An example of mapping of downlink cell-specific reference signals, with four antenna ports and the normal CP. R_p denotes the resource element used for reference signal transmission on antenna port p.

- *Reference Signal(RS) mapping in time domain*:
  - For the antenna port $p \in \{0, 1\}$, 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 $p \in \{2, 3\}$, 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.

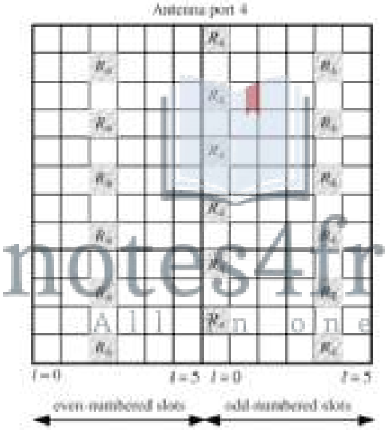


Figure 7.13 An example of mapping of MBSFN reference signals, with the extended CP and $\Delta f =$ 15kHz.

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 subcarriers in neighboring reference symbols.

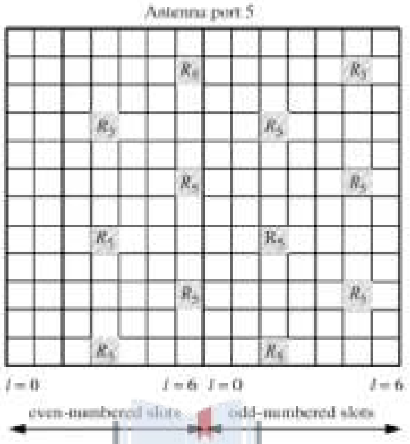


Figure 7.14 An example of mapping of UE-specific signals, with the normal CP.

7.6.2 Synchronization Signals

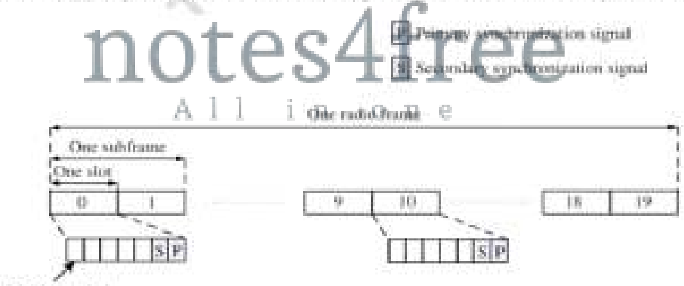
- The downlink synchronization signals are sent to facilitate the cell search procedure, during which process the time and frequency synchronization between the UE and the eNode-B is achieved and the cell ID is obtained.
- There are a total of 504 unique physical-layer cell IDs, which are grouped into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

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

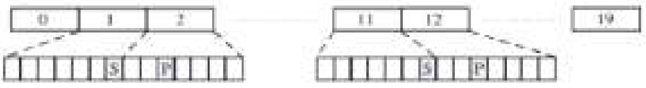
Where $N_{ID}^{(1)} = 0,1 \ldots \ldots 167$ represents the physical-layer cell-ID group and $N_{ID}^{(2)} = 0, 1, 2$ represents the physical-layer ID within the cell-ID group. Each cell is assigned a unique physical-layer cell ID.

- 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.



(a) Frame structure type 1



(b) Frame structure type 2

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.

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.

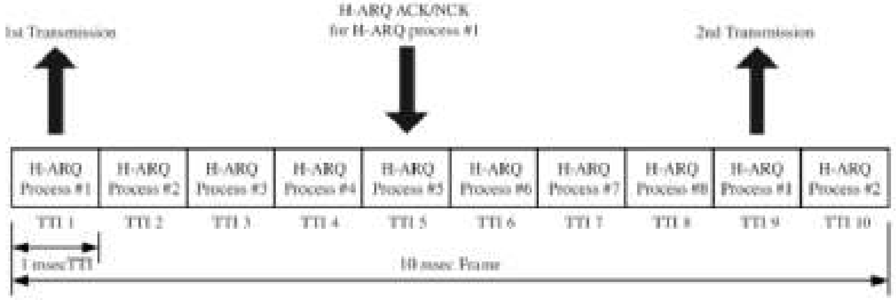


Figure 7.16 An example of a 10-msec frame with eight H-ARQ processes. The H-ARQ process 1 is transmitted in the first TTI, for which the H-ARQ ACK/NAK is received in the 5-th TTI, and then the H-ARQ process 1 is transmitted again in the 9-th TTI.

- 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.

Module – 4

Module-4 covered by chapters 8 and 9 from the prescribed text book *"Fundamentals of LTE" by* Arunabha Ghosh, Jan Zhang, Jefferey Andrews, Riaz Mohammed.

8. Uplink Channel Transport Processing:

- Uplink Channel Transport Processing Overview
- Uplink shared channels
- Uplink Control Information
- Uplink Reference signals
- Random Access Channels
- H-ARQ on uplink

9. Physical Layer Procedures:

- Hybrid – ARQ procedures
- Channel Quality Indicator CQI feedback
- Pre-coder for closed loop MIMO Operations
- Uplink channel sounding
- Buffer status Reporting in uplink
- Scheduling and Resource Allocation
- Cell Search
- Random Access Procedures
- Power Control in uplink

Module 4

Chapter 8: Uplink Transport Channel Processing

8.1 Background:

- Low complexity and high power efficiency are among the major factors for the transmitter design in the uplink.
- To achieve above requirement LTE uplink is based on SC-FDMA.
- SC-FDMA based uplink, each UE can only be allocated contiguous resource blocks.
- The uplink only supports a limited number of MIMO modes compared to the downlink.
- Similarities between the downlink and uplink transport channel processing are
  - The same channel coding processing is applied on both downlink and uplink shared channels
  - The time-frequency structure of the uplink resource blocks is similar to that of the downlink.

8.2 Uplink Transport Channel Processing Overview

The transport channel processing in the uplink include two distinct steps

1. Channel coding
2. Modulation, as shown in Figure 8.1.

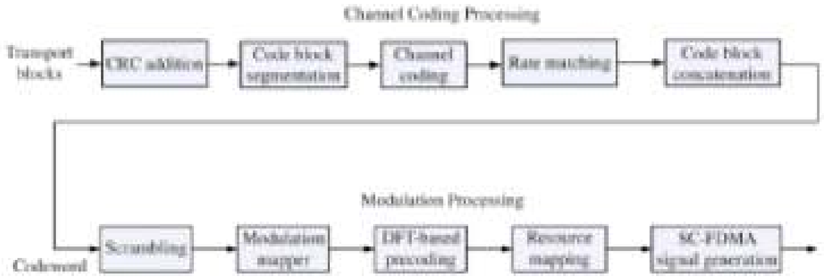


Figure 8.1 Overview of uplink transport channel processing

1. ***Channel Coding Processing:***
   - The channel coding processing in the uplink includes
     - *CRC addition and Code block segmentation*
     - *Channel coding and Rate matching and*
     - *Code block concatenation* (See figure 8.1)
   - The usage of the channel coding scheme and coding rate for the uplink shared channel and control information is specified in Table 8.1 and Table 8.2, respectively.

Table 8.1 Usage of Channel Coding Scheme and Coding Rate for Uplink Transport Channels

Transport Channel	Coding Scheme	Coding Rate
UL-SCH	Turbo coding	1/3

Table 8.2 Usage of Channel Coding Scheme and Coding Rate for Uplink Control Information

Control Information	Coding Scheme	Coding Rate
UCI	Block coding	Variable
	Tail-biting convolutional coding	1/3

- The turbo encoder used for uplink shared channels.
- Control information, the channel coding scheme depends on the type of control information and also on the type of the physical channel that carries the control information.
- The control information in the uplink can be mapped either to the Physical Uplink Shared Channel (PUSCH) or the Physical Uplink Control Channel (PUCCH).

2. *Modulation Processing:*

- Modulation processing in the uplink includes scrambling and modulation mapping.
- In uplink a UE specific scrambling is applied in order to randomize the interference.
- Since spatial multiplexing is not supported in the uplink there is no layer mapping or MIMO precoding.
- The main difference from the downlink, the generation of the SC-FDMA baseband signal is illustrated in Figure 8.2

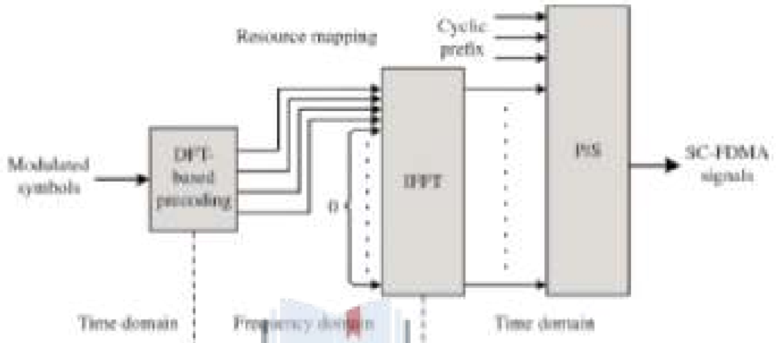
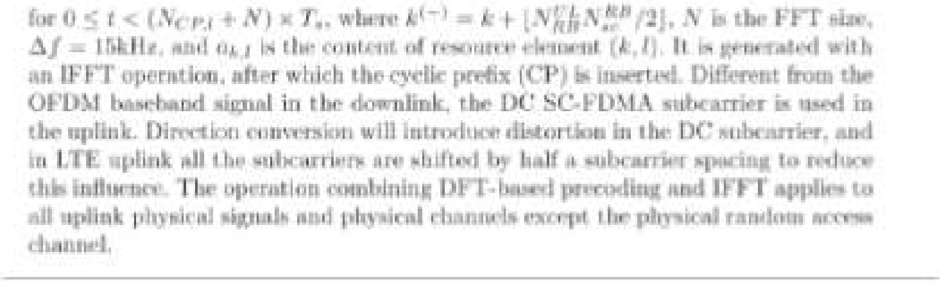


Figure 8.2 Generation of SC-FDMA baseband signals, where P/S denotes the parallel-to-serial converter.

- *Generation Of SC-FDMA baseband signal:*
  a. First, the DFT-based precoding is applied to the block of complex-valued modulation symbols, which transforms the time-domain signal into the frequency domain.
  b. In LTE, the DFT size is constrained to a tradeoff between the complexity of the implementation and the flexibility on the assigned bandwidth and also depends on the number of resource blocks assigned to the UE.
  c. The output of the DFT-based precoder is mapped to the resource blocks that have been allocated for the transmission of the transport block.
  d. In LTE, only localized resource allocation is supported in the uplink, that is, contiguous resource blocks are assigned to each UE.
  e. The baseband signal $S_l(t)$ in SC-FDMA symbol l in an uplink slot is defined by:

$$s_l(t) = \sum_{k=-\lfloor N_{RB}^{UL} N_{sc}^{RB}/2 \rfloor}^{\lceil N_{RB}^{UL} N_{sc}^{RB}/2 \rceil - 1} a_{k^{(-)},l} \cdot e^{j2\pi(k+1/2)\Delta f(t - N_{CP,l}T_s)} \qquad (8.1)$$



for $0 \leq t < (N_{CP,l} + N) \times T_s$, where $k^{(-)} = k + \lfloor N_{RB}^{UL} N_{sc}^{RB}/2 \rfloor$, N is the FFT size, $\Delta f = 15\text{kHz}$, and $a_{k,l}$ is the content of resource element (k,l). It is generated with an IFFT operation, after which the cyclic prefix (CP) is inserted. Different from the OFDM baseband signal in the downlink, the DC SC-FDMA subcarrier is used in the uplink. Direction conversion will introduce distortion in the DC subcarrier, and in LTE uplink all the subcarriers are shifted by half a subcarrier spacing to reduce this influence. The operation combining DFT-based precoding and IFFT applies to all uplink physical signals and physical channels except the physical random access channel.

8.2 Uplink Shared Channels:

- The description of transport channel processing for Uplink Shared Channels (UL-SCH) below. The UL-SCH is the only transport channel that carries traffic data.
- The channel mapping around the UL-SCH is shown in Figure 8.3.

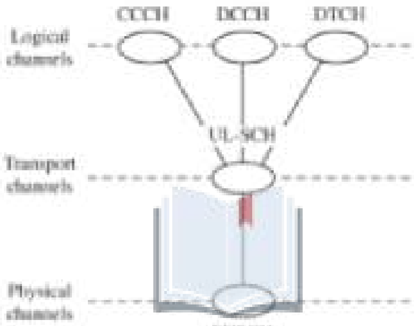


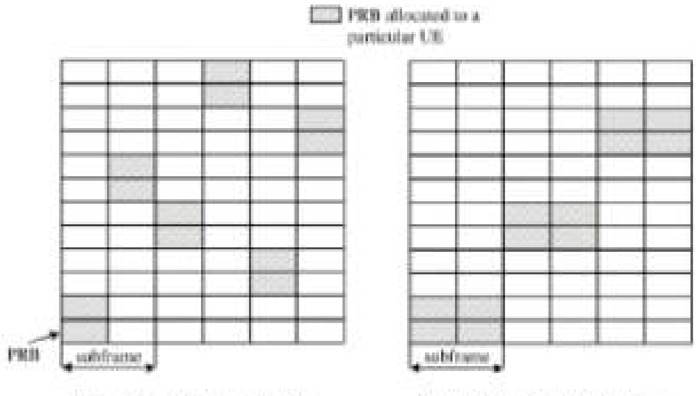
Figure 8.3 Channel mapping around the uplink shared channel.

- Uplink Shared Channels(UL-SCH) processing includes
  1. *Channel Encoding and Modulation*
  2. *Frequency hopping*
  3. *Multi-antenna transmission*

1. Channel Encoding and Modulation for UL-SCH:

- The channel coding scheme: *UL-SCH uses 1/3 turbo encoder is used to encode the transport block. Effective code rates other than 1/3 are achieved by either puncturing or repetition of the encoded bits, depending on the transport block size, the modulation scheme, and the assigned radio resource. The encoded symbols are scrambled prior to modulation. UE-specific scrambling is applied in the uplink.*
- Modulation for UL-SCH: *The UL-SCH supports QPSK, 16QAM, and 64QAM modulation schemes. The QPSK and 16QAM modulation schemes are mandatory and support for the 64QAM modulation is optional and depends on the UE capability.*

2. ***Frequency Hopping:***
    - LTE supports frequency hopping on PUSCH, which provides additional frequency diversity gain in the uplink.
    - Frequency hopping can also provide interference averaging when the system is not 100% loaded. In LTE both intra-subframe and inter-subframe frequency hopping are supported, as illustrated in Figure 8.4.



Intra-subframe frequency hopping

Inter-subframe frequency hopping

Figure 8.4 Illustrations of frequency hopping on PUSCH.

- *Intra-subframe hopping:* The UE hops to another frequency allocation from one slot to another within the same subframe.
- *Inter-subframe hopping:* The frequency resource allocation changes from one subframe to another.
- Higher layers determine if the hopping is "inter-subframe" or "intra- and inter-subframe."
- Intra-subframe hopping provides higher frequency diversity gain since this gain can be extracted over a single H-ARQ transmission, which always spans only one subframe.
- In the case of "inter-subframe" hopping, multiple H-ARQ transmissions are needed in order to extract the frequency diversity gain.
- Single bit Frequency Hopping (FH) field in the corresponding PDCCH with DCI format 0 is set to 1, the UE shall perform PUSCH frequency hopping.
    - ***No frequency hopping:*** If uplink frequency hopping is disabled (FH = 0), the set of physical resource blocks to be used for transmission is given by $n_{PRB} = n_{VRB}$. Where n_{VRB} is the virtual resource block index obtain from uplink scheduling grant.
    - ***Frequency hopping:*** set FH = 1, there are two frequency hopping types.
        1. *Type I hopping:* It uses an explicit offset in the second slot, determined by parameters in DCI format 0.

8.3 Uplink Control Information (UCI)

- UCI is to assist physical layer procedures by providing the following types of physical layer control information:
  a. Downlink CQI: *It is used to assist the adaptive modulation and coding and the channel-dependent scheduling of the downlink transmission. The CQI indicates highest modulation and coding rate that can be supported in the downlink.*
  b. H-ARQ acknowledgment (H-ARQ-ACK): *It is associated with the downlink H-ARQ process.*
  c. Scheduling Request (SR): *It is used to request radio resources for the uplink transmission.*
  d. Precoding Matrix Indicator (PMI): *It is for downlink MIMO transmission.*
  e. Rank Indication (RI): *RI indicates the maximum number of layers that can be used for spatial multiplexing in the downlink, while PMI indicates the preferred precoding matrix.*
- *The channel mapping for control information:* It is shown in figure 8.5, which has three different physical control channels, there is only one physical control channel defined for the UCI—the PUCCH. The UCI can also be mapped onto PUSCH when the UE has been assigned uplink radio resources.

Figure 8.5 Channel mapping for control information in the uplink.

8.3.1 Channel Coding for Uplink Control Information

- The channel coding for UCI therefore depends on whether it is carried on the PUCCH or PUSCH.
- Different types of control information are encoded differently, which allows individual adjustments of transmission energy using different coding rates.
- ***UCI on PUCCH:*** When the UCI is transmitted on the PUCCH, three channel coding scenarios are considered:
  1. *Encoding CQI/PMI but not H-ARQ-ACK:* The CQI/PMI is encoded using $(20, N_{CQI})$ code, with codewords being a linear combination of the 13 basis sequences. Denote a_i, $i = 1, \dots N_{CQI}$ as the input channel quality bits, and the encoding is performed as:

$$b_i = \sum_{n=0}^{N_{CQI}} (a_n \cdot M_{i,n}) \bmod 2, \; i = 0, 1, \dots, 19. \qquad (8.2)$$

2. *Encoding H-ARQ-ACK and SR:* The H-ARQ-ACK bits and SR indication are received from higher layers. Each positive acknowledgement (ACK) is encoded as a binary '1' while each negative acknowledgment (NAK) is encoded as a binary '0'.
3. *Encoding both CQI/PMI and H-ARQ-ACK.:* When CQI/PMI and H-ARQ-ACK are transmitted in the same subframe, the following coding scheme is used:
    - *With the normal CP*: The CQI/PMI is encoded using the $(20, N_{CQI})$ code and then the H-ARQ-ACIC bits are added at the end of the resulting codeword.
    - *With the extended CP*: The CQI/PMI and H-ARQ-ACK are jointly encoded using the same $(20, N_{CQI})$ code as that for encoding CQI/PMI alone, with N as the sum of CQI/PMI bits and H-ARQ-ACK bits.

- Based on different types of control information carried on the PUCCH, there are six different PUCCH formats defined in LTE, as shown in Table 8.4. The parameter M_{bit} is the number of encoded bits for each PUCCH format.

Table 8.4 Supported PUCCH Formats

PUCCH Format	Contents	M_{bit}
1	Scheduling Request (SR)	N/A
1a	H-ARQ-ACK, H-ARQ-ACK+SR	1
1b	H-ARQ-ACK, H-ARQ-ACK+SR	2
2	CQI/PMI or RI, (CQI/PMI or RI)+H-ARQ-ACK (extended CP)	20
2a	(CQI/PMI or RI)+H-ARQ-ACK (normal CP)	21
2b	(CQI/PMI or RI)+H-ARQ-ACK (normal CP)	22

- ***UCI on PUSCH with UL-SCH Data:***
    - The UCI can be multiplexed with the UL-SCH data on the PUSCH channel and there is no need to send SR.
    - In this case, the channel coding for H-ARQ-ACK, RI, and CQI/PMI is done independently.
    - Different coding rates can be achieved by allocating different numbers of coded symbols, depending on the amount of allocated radio resource.
    - ***Coding for H-ARQ-ACK:*** For the FDD mode, there is one or two H-ARQ-ACK bits. For the TDD mode, two ACK/NAK feedback modes are supported with different information bits:
        - *ACK/NAK bundling*: It consists of one or two bits of information.
    - *Both FDD and TDD ACK/NAK multiplexing with NBARQ < 2:* The output sequence from the channel encoder is obtained by concatenating multiple encoded H-ARQ-ACK blocks.

  - *TDD with ACK/NAK bundling*: The output sequence from the channel encoder is obtained by scrambling the concatenation of multiple encoded H-ARQ-ACK blocks with a specified scrambling sequence.
  - *TDD with ACK/NAK multiplexing with NHARQ > 2*: The H-ARQ-ACK bits are encoded using a linear combination of a set of basis sequences.
- ***Coding for RI***: The mapping between the RI bits and the channel rank is shown in Table 8.5. N_{RI} denote as the number of RI bits encoded into a $N_{RI}Q_m$ codeword, and then multiple concatenated RI blocks are concatenated to form a bit sequence.

Table 8.5 RI Mapping

RI Bits	Channel Rank
0	1
1	2
0, 0	1
0, 1	2
1, 0	3
1, 1	4

- ***Coding for CQI/PMI***: The coding scheme for CQI/PMI depends on the total number of CQI and PMI bits. After channel encoding, the CQI encoded sequence is multiplexed with the UL-SCH data, the output of which is interleaved with the RI and H-ARQ-ACK encoded sequence as depicted in Figure 8.6. The multiplexing ensures that control and data information bits are mapped to different modulation symbols.

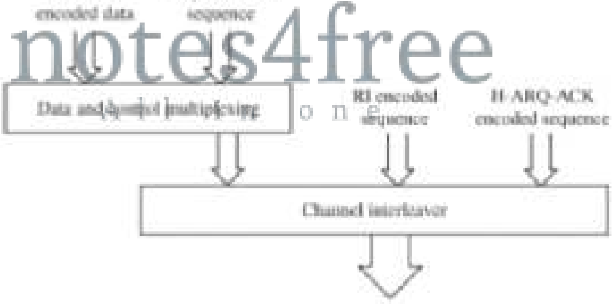


Figure 8.6 Multiplexing of data and control information on the PUSCH channel.

- ***UCI on PUSCH without UL-SCH Data:*** For this case, the channel coding for CQI, RI, and H-ARQ-ACK information is performed in the same manner as if the UCI is transmitted with UL-SCH data, and then the coded sequences are interleaved. The same interleaves as in Figure 8.6 is applied without the UL-SCH data.

8.3.2 Modulation of PUCCH

- When the UCI is transmitted on the PUSCH, the modulation scheme is determined by the scheduler in the MAC layer.
- The modulation scheme and the number of bits per subframe for different PUCCH formats are specified in Table 8.6.

Table 8.6 Modulation for Different PUCCH Formats

PUCCH Format	Modulation Scheme	M_{bit}
1	N/A	N/A
1a	BPSK	1
1b	QPSK	2
2	QPSK	20
2a	QPSK+BPSK	21
2b	QPSK+QPSK	22

- All PUCCH formats use a cyclic shift of a based sequence to transmit in each SC-FDMA symbol, so UCI from multiple UEs can be transmitted on the same radio resource through code division multiplexing (CDM). Two classes of PUCCH formats. They are

1. ***PUCCH Formats 1, Ia, and Ib:***
   - These format are used to transmit H-ARQ-ACK and/or SR, without CQI bits.
   - When both ACK/NAK and SR are transmitted in the same subframe, a UE shall transmit the ACK/NAK on its assigned ACK/NAK PUCCH resource for a negative SR transmission and transmit the ACK/NAK on its assigned SR PUCCH resource for a positive SR transmission. As shown in Table 8.4, one or two explicit bits are transmitted, respectively, the modulation for which is described in Table 8.7.

Table 8.7 Modulation Symbol $d(0)$ for PUCCH Formats 1*a* and 1*b*

PUCCH Format	$b(0),\ldots,b(M_{bit}-1)$	$d(0)$
1a	0	1
	1	−1
1b	00	1
	01	−j
	10	j
	11	−1

2. ***PUCCH Formats 2, 2a, and 2b:***
   - Format 2, 2a, or 2b is used when $M_{bits} \geq 20$, as mentioned in table 8.4
   - The block of the first 20 bits, b(0), , b(19), shall be scrambled with a UE-specific scrambling sequence, producing a block of scrambled bits b(0),......... b(19). Then the scrambled bits will be QPSK modulated, resulting in a block of complex-valued Table 8.8 Modulation symbol d(10) for PUCCH formats 2a and 2b complex-valued symbols is multiplied with a length-12

cyclically shifted version of a Zadoff-Chu sequence. This allows FUCCHs from multiple UEs to be transmitted on the same resource block with CDM.

Table 8.8 Modulation symbol $d(10)$ for PUCCH formats 2a and 2b

PUCCH Format	$b(20),b(M_{bit}-1)$	$d(10)$
2a	0	1
	1	−1
2b	00	1
	01	−j
	10	j
	11	−1

- The modulation of these H-ARQ-ACK bits are described in Table 8.8. The resulting modulated symbol d(10) will be used in the generation of the reference signal for PUCCH format 2a and 2b, from which the eNode-B can decode the ACK/NAK information.

8.3.3 Resource Mapping

- PUCCH is time-division multiplexed with the PUSCH from the same UE. This is done in order to retain the single-carrier property of SC-FDMA.
- PUCCH can be FDM with the PUSCH from other UEs in the same subframe.
- For frame structure type 2 (the TDD mode), the PUCCH is not transmitted in the UpPTS field, which is only for the transmission of uplink sounding reference signals or random access.
- The PUCCH uses one resource block in each of the two slots in a subframe.
- The physical resource blocks to be used for PUCCH transmission in slot n_s are given by:

$$n_{PRB} = \begin{cases} \lfloor \frac{m}{2} \rfloor & \text{if } (m + n_s \bmod 2) \bmod 2 = 0 \\ N_{RB}^{UL} - 1 - \lfloor \frac{m}{2} \rfloor & \text{if } (m + n_s \bmod 2) \bmod 2 = 1 \end{cases} \tag{8.3}$$

Where the parameter m depends on the PUCCH format:

- The mapping of PUCCH to physical resource blocks in one subframe is shown in Figure 8.7 for different values of m.

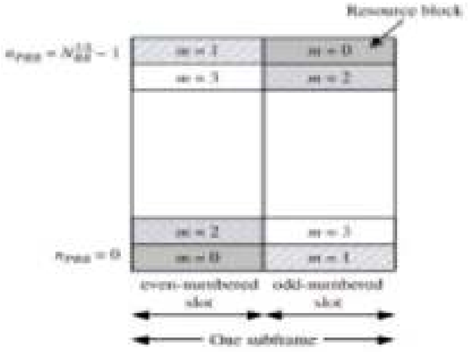


Figure 8.7 Mapping to physical resource blocks for PUCCH.

- PUCCH is transmitted at the bandwidth edge, which is to provide the contiguous bandwidth in the middle for data transmission as only localized resource allocation is allowed in the uplink.
- The frequency hopping between different slots provides frequency diversity.
- The PUCCH symbols are mapped to resource elements not used for RS transmission.

8.4 Uplink Reference Signals

- In LTE there are two types of reference signals defined in the uplink:
  1. *Demodulation reference signals*: These reference signals are used for coherent demodulation of data and control information at the eNode-B. As PUCCH cannot be transmitted simultaneously with PUSCH, there are demodulation reference signals defined for each of them, that is, there are demodulation reference signals for PUSCH and demodulation reference signals for PUCCH.
  2. *Sounding reference signals:* There are wideband reference signals for the eNode-B to measure uplink CQI for uplink resource allocation. They are not associated with the transmission of PUSCH or PUCCH.

8.4.1 Reference Signal Sequence:

- Both the demodulation reference signal and the sounding reference signal are defined by a cyclic shift of the same base sequence.
- The generation of the base sequence depends on the reference signal sequence length, which which is $M_{sc}^{RS} = mN_{sc}^{RB}$ with $1 \le m \le N_{RB}^{max,UL}$ where m in is the size of the resource blocks assigned to the UE.
  - If $m \geq 3$ (the UE is assigned three resource blocks or more), the base sequence is based on prime-length Zadoff-Chu sequences that are cyclically extended to the desired length.
  - For $m = 1$ or $m = 2$, the base sequence is of the form $e^{j\varphi(n)\pi/4}$, where $0 \le n \le M_{sc}^{RS} - 1$ and the value of $\varphi(n)$ is given in [1].
  - The reference signal in the uplink is always UE-specific.

8.4.2 Resource Mapping of Demodulation Reference Signals

- For PUSCH, the demodulation reference signal sequence is mapped to resource elements (k, l) with $l = 3$ for normal CP and $l = 2$ for extended CP, with increasing order first in k and then in the slot number.
- An example of demodulation reference signal mapping for PUSCH is shown in Figure 8.8, with the normal CP.
- PUCCH supports six different formats, and the resource mapping to SC-FDMA symbols for different formats is listed in Table 8.9.

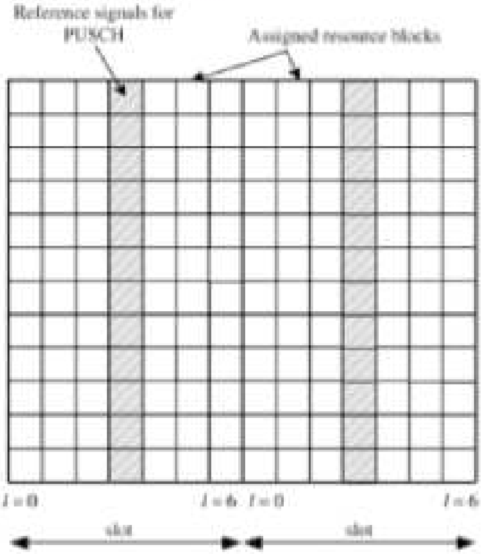


Figure 8.8 Resource mapping of demodulation reference signals for PUSCH with the normal CP.

Table 8.9 Demodulation Reference Signal Location for Different PUCCH Formats

PUCCH Format	Set of Values for l	
	Normal Cyclic Prefix	Extended Cyclic Prefix
1, 1a, 1b	2,3,4	2,3
2	1,5	3
2a, 2b	1,5	N/A

- The number of PUCCH demodulation reference symbols are different for different formats, which is related to the number of control symbols for each format.
- There are 10 CQI/PMI modulated symbols for PUCCH format 2/2a/2b, and there are 2 reference symbols in each slot as shown in Table 8.9, so there are a total of 14 symbols that fill the whole subframe, which is of 14 SC-FDMA symbols.
- PUCCH format 1/1a/1b has fewer information bits than PUCCH format 2/2a/2b, there are more reference symbols for format 1/1a/1b than there are for format 2/2a/2b, which can be used to improve the channel estimation performance.

8.4.3 Resource Mapping of Sounding Reference Signals

- In FDD mode, it is transmitted in the last SC-FDMA symbol in the specified subframe.
- In the TDD mode, the sounding reference signal is transmitted only in configured uplink subframes or the UpPTS field in the special subframe.
- The subframes in which the sounding reference signals are transmitted are indicated by the broadcast signaling, and there are 15 different configurations.

- The bandwidth of sounding reference signals is configured by higher layers and also depends on the system bandwidth. An example of resource mapping of sounding reference signals is shown in Figure 8.10.

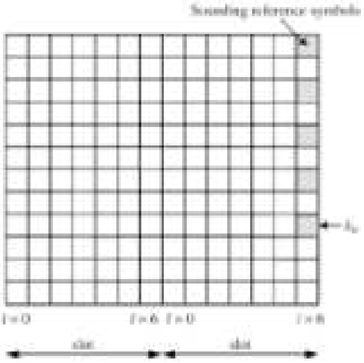


Figure 8.10 An example of resource mapping of sounding reference signals, with the normal CP.

8.5 Random Access Channels (RCH)

- The uplink random access procedure is used during initial access or to re-establish uplink synchronization.
- As shown in Figure 8.11, the random access preamble consists of a CP of length T_{cp} and a sequence part of length T_{SEQ}.

Figure 8.11 The random access preamble format.

- Guard Time (GT) is also needed to account for the round trip propagation delay between the UE and the eNode-B.
- The values of T_{cp} and T_{SEQ} depend on the cell size and base station implementation. There are five different preamble formats defined in LTE, specified in Table 8.10

Table 8.10 Random Access Preamble Parameters

Preamble Format	T_{CP}	T_{SEQ}
0	$3168 \cdot T_s$	$24576 \cdot T_s$
1	$21024 \cdot T_s$	$24576 \cdot T_s$
2	$6240 \cdot T_s$	$2 \cdot 24576 \cdot T_s$
3	$21024 \cdot T_s$	$2 \cdot 24576 \cdot T_s$
4	$448 \cdot T_s$	$4096 \cdot T_s$

- *Format 0:* It is for normal cells.
- *Format 1:* It is also known as the extended format, is used for large cells.

- *Format 2 and format 3:* These are use repeated preamble sequences to compensate for increased path loss, and are used for small cells and large cells, respectively.
- *Format 4:* It is defined for frame structure type 2 only.
- The network configures the set of preamble sequences that the UE is allowed to use.
- In each cell, there are 64 available preambles, which are generated from one or several root Zadoff-Chu sequences.
- There is no intra-cell interference from multiple random access attempts using different preambles in the same cell due to Zadoff-Chu sequences.
- The Physical Random Access Channel (PRACH) resources within a radio frame are indicated by a PRACH configuration index, which is given by higher layers.
- In the frequency domain, the random access burst occupies a bandwidth corresponding to six consecutive resource blocks (72 subcarriers) in a subframe or a set of consecutive subframes.
- The PRACH uses a different subcarrier spacing (Δf_{RA}) than other physical channels, which is listed in Table 8.11 together with the preamble sequence length N_{zc}.

Table 8.11 Parameters for Random Access Preamble

Preamble Format	Δf_{RA}	N_{ZC}	φ
0–3	1.25 kHz	839	7
4	7.5 kHz	139	2

- The continuous-time random access signal is defined by:

$$s(t) = \beta \sum_{k=0}^{N_{ZC}-1} \sum_{n=0}^{N_{ZC}-1} x_{u,v}(n) \cdot e^{-j\frac{2\pi nk}{N_{ZC}}} \cdot e^{j2\pi(k+\varphi+K(k_0+1/2))\Delta f_{RA}(t-T_{CP})}, \qquad (8.4)$$

where $0 \le t \le (T_{SEQ} + T_{CP})$ and

- β is an amplitude scaling factor for power control;
- $x_{u,v}(n)$ is the uth root Zadoff-Chu sequence with cyclic shift v;
- φ is a fixed offset determining the frequency-domain location of the random preamble within the physical resource blocks, given in Table 8.11;
- $K = \Delta f / \Delta f_{RA}$ accounts for the difference in subcarrier spacing between the random access preamble and uplink data transmission;
- $k_0 = n_{PRB}^{RA} N_{sc}^{RB} - N_{RB}^{UL} N_{sc}^{RB}/2$ controls the random access preamble location in the frequency domain, with $0 \le n_{PRB}^{RA} \le (N_{RB}^{UL} - 6)$ as the physical resource block number configured by higher layers.

8.6 H-ARQ in the Uplink

- The H-ARQ retransmission protocol is also used in the LTE uplink, so the eNode-B has the capability to request retransmissions of incorrectly received data packets.
- Uplink H-ARQ process, the corresponding ACK/NAK information is carried on the PHICH.
- LTE uplink applies the synchronous H-ARQ protocol, that is, the retransmissions are scheduled on a periodic interval
- Synchronous retransmission is preferred in the uplink because it does not require to explicitly signal the H-ARQ process number so there is less protocol overhead.
- The number of H-ARQ processes and the time interval between the transmission and retransmission depend on the duplexing mode and the H-ARQ operation type.
- There are two types of H-ARQ operation in the uplink:
  1. *The non-subframe bundling operation (normal H-ARQ operation)*
  2. *Subframe bundling operation (also called TTI[3] bundling)*

8.6.1 The FDD Mode: For the FDD mode

- There are eight parallel H-ARQ processes in the uplink for the non-subframe bundling operation, and four H-ARQ processes for the subframe bundling operation.
- For the FDD mode with the normal H-ARQ operation, upon detection of an NAK in subframe n, the UE retransmits the corresponding PUSCH in subframe n + 4
- For the FDD mode with the subframe bundling operation, upon detection of an NAK in subframe n - 5, the UE retransmits the corresponding first PUSCH transmission in the bundle in subframe n + 4.

8.6.2 The TDD Mode: For the TDD mode,

- The number of H-ARQ processes is determined by the DL/UL configuration, listed in Table 8.12.
- For TDD UL/DL configurations 1-6 and the normal H-ARQ operation, upon detection of an NAK in subframe n, the UE retransmits in subframe n + k, with k given in Table 8.13.

Table 8.12 Number of Synchronous UL H-ARQ Processes for TDD

TDD UL/DL Configuration	Number of H-ARQ Processes for Normal H-ARQ Operation	Number of H-ARQ Processes for Subframe Bundling Operation
0	7	3
1	4	2
2	2	N/A
3	3	N/A
4	2	N/A
5	1	N/A
6	6	3

- *For TDD UL/DL configuration 0 and the normal H-ARQ operation*: Upon detection of an NAK in subframe n, the UE will retransmit in subframe n + 7 or n + k with k given in Table 8.13, which depends on the UL index field in DCI and the value of n.

Table 8.13 The Value of *k* for TDD Configurations 0–6

TDD UL/DL Configuration	DL Subframe Number *n*									
	0	1	2	3	4	5	6	7	8	9
0	4	6				4	6			
1		6			4		6			4
2				4					4	
3	4								4	4
4									4	4
5									4	
6	7	7				7	7			5

- *For TDD UL/DL configurations 1 and 6 with subframe bundling*: Upon detection of an NAK in subframe n. — *l* with 1 given in Table 8.14, the UE retransmits the corresponding first PUSCH transmission in the bundle in subframe $n + k$, with *k* given in Table 8.13.

Table 8.14 The Value of *l* for TDD Configurations 0, 1, and 6

TDD UL/DL Configuration	DL Subframe Number *n*									
	0	1	2	3	4	5	6	7	8	9
0	9	6				9	6			
1		2			3		2			3
6	5	5				6	6			8

- *For TDD UL/DL configuration 0 and the subframe bundling operation*: Upon detection of an NAK in subframe $n - l$ with l given in Table 8.14, the UE retransmits in subframe n + 7 or $n + k$ with k given in Table 8.13, depending on the UL index field in DCI and the value of n.

Chapter 9

Physical Layer Procedures and Scheduling

1. Introduction:

- The physical layer procedures that provide crucial services to higher layers.
- The physical layer procedures or functions in LTE includes
  - *Hybrid-ARQ (H-ARQ) and Channel Quality Indicator (CQI)*
  - *Dynamic channel-dependent scheduling and MIMO transmission.*
  - *Precoding for MIMO closed-loop operations.*
  - *The Rank Indicator (RI) and Precoder Matrix Indicator (PMI) feedback.*
  - *Cell search and Random accesses procedures.*
  - *Power control in uplink.*

9.2 Hybrid-ARQ (H-ARQ) Feedback

- In LTE, the H-ARQ protocol is applied to improve the transmission reliability over the wireless channel.
- HARQ = ARQ+FEC (Forward Error Correction)/Soft Combining.
- Soft Combining is an error correction technique in which the bad packets are not discarded but stored in a buffer. The basic idea is that 2 or more packets received with insufficient information can be combined together in such a way that total signal can be decoded.
- A mechanism H-ARQ is implemented to correct the error packets in the PHY layer.
- Principle of H-ARQ: *Works at PHY layer but controlled by MAC layer. If the received data has an error then the receiver buffers the data and requests a re-transmission from the sender. When the receiver receives the re-transmitted data, it then combines it with buffered data prior to channel decoding and error detection. This helps the performance of the re-transmissions.*
- Two methods of H-ARQ protocol uses in LTE
  1. *Asynchronous adaptive H-ARQ protocol*: Used by down link transmission
     - The retransmissions can take place whenever in time, due to scheduling purposes.
     - Need an appropriate signaling to make the transmitter aware of which HARQ process we are considering.
     - The TTI and resource allocation for the retransmission is dynamically determined by the scheduler.
     - Asynchronous HARQ increases flexibility because re-transmissions doesn't have to be scheduled during every sub-frame.
  2. *Synchronous adaptive H-ARQ protocol*: Used by uplink transmission
     - Re-transmissions are scheduled at fixed time intervals.
     - Generates lower over-head as it doesn't need to include HARQ process Id in the outgoing data

       3. Always works in cycle even if no resources are allocated during a specific sub frame; which means that the 1st process will repeat itself after every 8 ms.
- The H-ARQ feedback is different for FDD and TDD mode.

9.2.1 *H-ARQ Feedback for Downlink (DL) Transmission:* Procedures are

- UEs need to feedback the associated ACK/ NAK information on PUCCH or PUSCH.
- One ACK/NAK bit is transmitted in case of single-codeword downlink transmission, while two ACK/NAK bits are transmitted in case of two-codeword downlink transmission.
- H-ARQ retransmission happens when the channel is static or experiences little or no variation between subsequent H-ARQ transmissions.

- *H-ARQ feedback for FDD mode*: Procedure are
  1. UE transmits H-ARQ-ACK in subframe *n* for a PDSCH transmission in subframe $n - 4$.
  2. The reason for the 4 subframe delay in the transmission of an ACK/NACK message is due to the processing delay of about 3 ms at the receiver.
  3. Both H-ARQ-ACK and Scheduling Request (SR) are transmitted in the same subframe.
  4. UE shall transmit the H-ARQ-ACK on its associated H-ARQ-ACK PUCCH resource for a negative SR transmission.
  5. UE transmit the H-ARQ-ACK on its assigned SR PUCCH resource for a positive SR transmission.
- H-ARQ feedback for TDD mode: Procedure are
  1. In this mode, the time association between the data transmission and the ACK/NACK cannot be maintained due to the variable numbers of DL and UL subframes being present in a frame.
  2. The UL and DL delay between data and ACK is dependent on the TDD configuration chosen. Hence, a fixed delay between a transmission and the HARQ ACK/NACK is not possible in TDD-LTE.
  3. For TDD, two ACK/NAK feedback modes are supported by higher layer configuration:
     - *ACK/NAK bundling using PUCCH format 1a or 1b, which is the default mode and consists of one or two bits of information*
     - *ACK/NAK multiplexing using PUCCH format 1b, which consists of between one and four bits of information*
- In TDD, the delay between the transmission and the HARQ ACK/NACK depends on both the TDD configuration and the subframe in which the data was transmitted.
- For example, in configuration 1 which is shown below in Figure 9.1, there are some DL subframes for which the nearest UL subframe (greater than a separation of 4 or more subframes) is 7 subframes away. In the Figure 8.12 shown below, this can be seen clearly for the DL data transmission case.

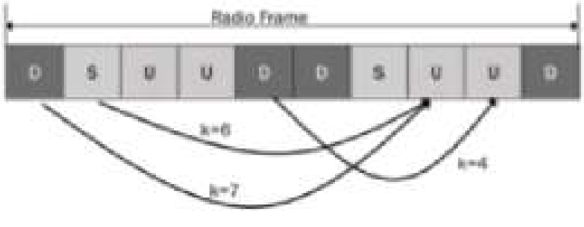


Figure 9.1: HARQ ACK/NACK Timing for configuration 1

9.3 Channel Quality Indicator (CQI) Feedback: It includes

1. *Introduction*
2. *CQI estimation*
3. *CQI feedback modes*

9.3.1 Introduction: *CQI is an indicator carrying the information on how good/bad the communication channel quality is. The CQI basically includes CQI, PMI (Precoding Matrix Indicators), RI (Rank Indicator) components. The requirement for each of these components depend on transmission mode. All transmission modes need UE to provide CQI feedback.*

- *CQI reporting contains information sent from a UE to the eNode-B to indicate a suitable downlink transmission data rate,* i.e., a Modulation and Coding Scheme (MCS) value.
- CQI is a 4-bit integer and is based on the observed signal to-interference-plus-noise ratio (SNIR) at the UE.
- The CQI estimation process takes into account the UE capability such as the number of antennas and the type of receiver used for detection.
- The CQI reported value are used by the eNode-B for downlink scheduling and link adaptation, which are important features of LTE.
- LTE supports wideband and subband CQI reporting.
  1. A wideband CQI reporting:
     - *The wideband report provides one CQI value for the entire downlink system bandwidth.*
     - *It is a value of single 4-bit integer that represent an effective SINR as observed by the UE.*
     - *It is most efficient in terms of uplink bandwidth consumption since it requires only a single 4-bit feedback.*
     - *With wideband CQI, the variation in the SINR across the channel due to frequency selective nature of the channel is masked out.*
     - *It is not suitable for frequency selective scheduling.*
     - *It is the preferred mode to use for high speeds where the channel changes rapidly since frequent subband reporting would exhaust a large portion of the uplink bandwidth.*
     - *Wideband CQI is also the preferred mode for services such as VoIP where a large number of simultaneous UEs are supported and latency is more critical than the overall throughput since VoIP is typically a low data rate application with very strict latency requirement.*
  2. A subband CQI reporting:
     - *To support frequency selective scheduling, each UE needs to report the CQI with a fine frequency granularity, which is possible with subband CQI reporting.*

  - *A subband CQI report consists of a vector of CQI value, where each CQI value is representative tithe SINR observed by the UE over a sub-band.*
  - *A subband is a collection of n adjacent Physical Resource Blocks (PRBs) where the value tint can be 2, 3, 4, 6, or 8 depending on the channel bandwidth and the CQI feedback mode.*
  - *It requires more uplink bandwidth but is more efficient since it allows for a frequency selective scheduling, which maximizes the multiuser diversity gain.*

- Note:

  (1). *One of the critical aspects of designing the CQI feedback mechanism for LTE is the optimization between the downlink system performance and the uplink bandwidth consumed by the feedback mechanism.*

  (2). *The LTE standard does not specify how to select between wideband and subband CQI reporting depending on the UE speed or the QoS requirements of the application. It is left up to the equipment manufacturer to develop their proprietary algorithms in order to accomplish this.*

9.3.2 A Primer on CQI Estimation

- Downlink cell-specific *Reference Signals (RS)* are used by each UE to estimate the MIMO LTE channel from the eNode-B.
- The estimated MIMO channel along with the known reference signal is then used to calculate the other-cell interference level.
- The important thing is to understand that reference signals are sent in both UL and DL while the CQI is sent in UL only (either on PUCCH or PUSCH) but it reports the DL signal strength based on the channel estimation.
- The UE uses the estimated channel and interference plus noise variance to compute the SINR on the physical resource element (PRE) carrying the reference signal.
- The UE computes SINR samples over multiple OFDM symbols and subcarriers, which are then used to calculate an effective SINR. The effective SINR is given as:

$$\mathrm{SINR}_{\mathrm{eff}} = \alpha_1 I^{-1}\left(\frac{1}{N}\sum_{k=1}^{N} I\left(\frac{\mathrm{SINR}_k}{\alpha_2}\right)\right)$$

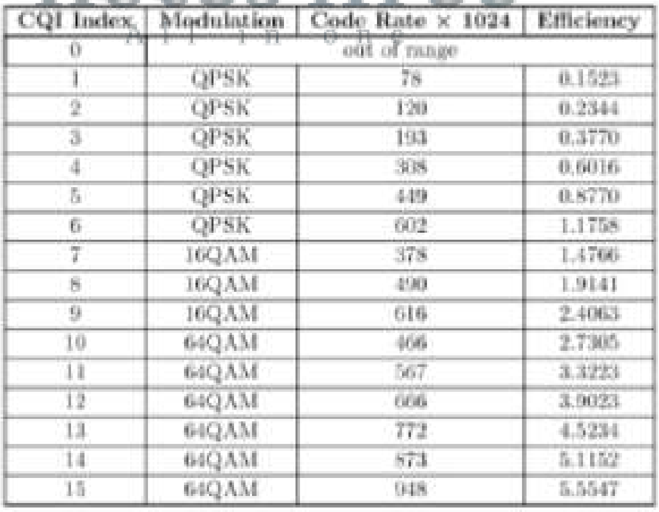
  Where N is the number of samples. α_1 *and* α_2 adapt to different modulation and coding schemes.

- Exponential Effective SINR Mapping (EESM) and the mutual information-based methods are preferred since they have been shown to give a more accurate estimate of the channel quality.

- In the case of wideband CQI feedback, the UE measures the SINR from the reference signal over all the PRBs, and then computes its CQI based on the effective SINR across the entire channel bandwidth.
- In subband CQI the UE measures the SINR over the PRBs contained in the given subband, and then computes the CQI.
- If a UE reports a CQI value for a particular subband, it is called *subband feedback*.
- If a UE reports a single CQI value for whole system bandwidth, it is called *wideband feedback*.
- Based on the estimated effective SINR, the UE picks the CQI index that indicate the highest MCS level (modulation and code rate) that can be supported with a 10% BLER on the first H-ARQ transmission.
- The CQI feedback is used by the eNode-B to select an optimum PDSCH transport block with a combination of modulation scheme and transport block size corresponding to the CQI index that could be received with target block error probability after the first H-ARQ transmission.
- The target block error probability is left open as an implementation choice, typical values are in the range of 10-25%.
- The supported CQI indices and their interpretations are given in Table 9.3. In total, there are 16 CQI values, which require a 4-bit CQI feedback. In Table 9.3, the efficiency for a given CQI index is calculated as: efficiency = Q_m × code rate,

  Where Q_m, is the number of bits in the modulation constellation. Taking CQI index 4 as an example, as $Q_m = 2$ for QPSK. We have efficiency = $2 \times \frac{308}{1024} = 0.6016\,bits/symbol$.

Table 9.3 4-Bit CQI Table



CQI Index	Modulation	Code Rate × 1024	Efficiency
0	out of range		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

9.3.3 CQI Feedback Modes

- There are two reporting CQI feedback modes in the time domain
    1. Periodic reporting: *The UE reports CQI, PMI, and RI with reporting periods configured by the higher layer. PUCCH is used for this report.*
    2. Aperiodic reporting: *It can be used to provide large and more detail reporting in a single reporting instance via PUSCH. Report Timing is triggered by DCI*
- Note: *In cases where both periodic reporting on the PUCCH and the aperiodic reporting PUSCH happen to be on the same subframe, the UE will only transmit the aperiodic report over the PUSCH and ignore the periodic PUCCH report.*
- Both periodic and aperiodic reporting modes support wideband and subband CQI reporting.
- In LTE there are two distinct reporting mechanisms for subband CQI feedback when the aperiodic reporting mode is used:
    1. *Higher Layer Configured Subband Report*: In this case, the UE reports the subband CQI for each band in a single feedback report. The size of a band is specified by a higher layer message and is contingent on the system bandwidth.
    2. *UE Selected Subband Report*: In this case, the UE reports the subband CQI for the 'M' bands with the highest CQI values. The CQI for the rest of the bands is not reported.
- The average per sector downlink throughput for various wideband and subband CQI feedback modes as shown Figure 9.2. These result are typical of a 10MHz FDD system in a multicell.

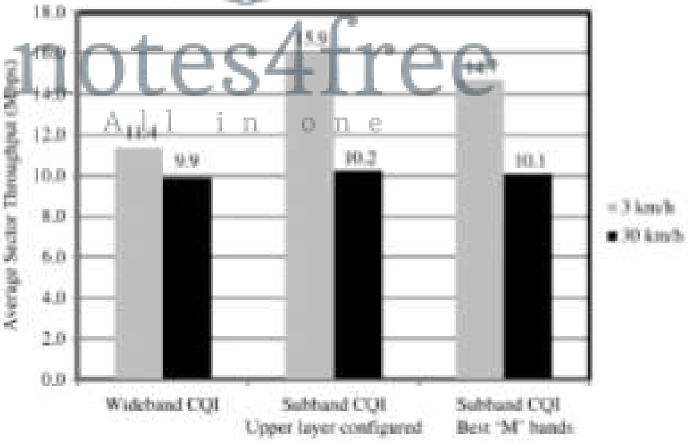


Figure 9.1: The average downlink throughput per sector for various CQI feedback

- Each reporting class supports a number of different reporting modes. Where each reporting mode is characterized by a specific CQI feedback type and a PMI feedback type. Which are listed in Table 9.4 and Table 9.5 for periodic reporting and aperiodic reporting respectively.

Table 9.4 CQI and PMI Feedback Types for Periodic PUCCH Reporting Modes

PUCCH CQI Feedback Type	PMI Feedback Type	
	No PMI	Single PMI
Wideband (Wideband CQI)	Mode 1-0	Mode 1-1
UE Selected (Subband CQI)	Mode 2-0	Mode 2-1

Table 9.5 CQI and PMI Feedback Types for Aperiodic PUSCH Reporting Modes

PUSCH CQI Feedback Type	PMI Feedback Type		
	No PMI	Single PMI	Multiple PMI
Wideband (Wideband CQI)			Mode 1-2
UE Selected (Subband CQI)	Mode 2-0		Mode 2-2
Higher Layer-Configured (Subband CQI)	Mode 3-0	Mode 3-1	

- There are seven transmission modes in the downlink and each of them supports a specific subset of the reporting mode the details of which are shown in Table 9.6.

Table 9.6 The Supporting CQI Reporting Modes for Different Transmission Modes

Transmission Mode	Periodic Reporting Mode	Aperiodic Reporting Mode
1. Single-antenna port, port 0	Modes 1-0, 2-0	Modes 2-0, 3-0
2. Transmit diversity	Modes 1-0, 2-0	Modes 2-0, 3-0
3. Open-loop spatial multiplexing	Modes 1-0, 2-0	Modes 2-0, 3-0
4. Closed-loop spatial multiplexing	Modes 1-1, 2-1	Modes 1-2, 2-2, 3-1
5. Multiuser MIMO	Modes 1-1, 2-1	Mode 3-1
6. Closed-loop Rank = 1 precoding	Modes 1-1, 2-1	Modes 1-2, 2-2, 3-1
7. Single-antenna port, port 5	Modes 1-0, 2-0	Modes 2-0, 3-0

- **Periodic CQI Reporting:** UE is semi-statically configured by higher layers. UE periodically feedback CQI on the PUCCH in one of the reporting mode given in Table 9.4. Note that
- Mode 1-0 and 2-0 do not report PMI and they are used for OL MIMO modes and single-antenna port transmission.
- Mode 1-1 and mode 2-1 report a single PMI for CL NIIMO modes, i.e., only the wideband PMI is reported.
- The periodic CQI feedback is useful for scheduling and adaptive modulation and coding, and can also be used to check or change semi-static parameters such as the MIMO mode or transmission mode. Considering the reporting for CQI/PMI and RI, there are four different reporting types supported for each of these reporting modes as given in Table 9.7:
    1. Type 1: report supports CQI feedback for the UE selected subbands.
    2. Type 2: report supports wideband CQI and Phil feedback.
    3. Type 3: report supports RI feedback.
    4. Type 4: report supports wideband CQI.

Table 9.7 PUCCH Report Type Payload Size Per Reporting Mode

PUCCH Report Type	Mode State	PUCCH Reporting Modes			
		Mode 1-1 (bits/BP)	Mode 2-1 (bits/BP)	Mode 1-0 (bits/BP)	Mode 2-0 (bits/BP)
1. Subband CQI	RI= 1	NA	4+L	NA	4+L
	RI > 1	NA	7+L	NA	4+L
2. Wideband CQI/PMI	2 TX Antennas RI= 1	6	6	NA	NA
	4 TX Antennas RI= 1	8	8	NA	NA
	2 TX Antenna RI > 1	8	8	NA	NA
	4 TX Antennas RI > 1	11	11	NA	NA
3. RI	2-layer spatial multiplexing	1	1	1	1
	4-layer spatial multiplexing	2	2	2	2
4. Wideband CQI	RI= 1	NA	NA	4	4

- **Aperiodic CQI Reporting**
  - The UE shall perform aperiodic CQI, PMI and RI reporting using the PUSCH channel in subframe n + k. The value of it is specified as follows:
    a. For FDD, k = 4.
    b. For TDD UL/DL configuration 1-6, k, is given in Table 9.10.
    c. For TDD UL/DL configuration 0:

Table 9.10 The Values of k for TDD Configuration 0–6

TDD UL/DL Configuration	DL Subframe Number n									
	0	1	2	3	4	5	6	7	8	9
0	4	6				4	6			
1		6			4		6			4
2				4					4	
3	4								4	4
4									4	4
5									4	
6	7	7				7	7			5

  - As shown in Table 9.5, there are three different aperioclic CQI feedback types:
    1. Wide-band feedback
    2. Higher layer-configured subband feedback,
    3. UE-selected subband feedback.
    4. Five reporting modes.
    5. Modes 2-0 arid 3-0 are for single-antenna-port transmission and OL MIMO modes, while Mode 3-1 with single PMI and Modes 1-2 and 2-2 with multiple P511 are for CL MEMO modes.

- Aperiodic CQI reporting supporting both Wideband and subband feedback.
    i. *Wideband feedback*: a UE selects a preferred precoding matrix for each subband, assuming transmission only in that subband. Then each UE reports one wideband CQI value for each codeword, assuming the use of the selected precoding matrix in each subband, and it also reports the selected PMI for each subband.
    ii. *Higher Layer-Configured Subband Feedback*: There are two different reporting modes with higher layer-configured subband feedback: Mode 3-0 (without PMI) and Mode3-1 (with single PMI). The supported subband size k is the same as that for the periodic reporting, as in Table 9.8. As a separate CQI is reported for each subband, this reporting type provides the finest frequency granularity but also has the highest overhead.

9.4 Precoder for Closed-Loop MIMO Operations

9.4.1 Introduction:

- MIMO transmission is a key technique in LTE and can provide a significant *throughput and gains*, especially with the spatial multiplexing mode.
- The amount of feedback required to provide the full CSI (*Channel State Information*) to the eNode-B is large, particularly in multicarrier systems.
- In order to mitigate the feedback issue, limited *feedback mechanisms* are used in LTE.
- The UE chooses the optimum rank and precoder for downlink transmission based on a predefined set of precoders, also known as a "*Codebook*".
- Instead of indicating the full precoding matrix, the UE only needs to indicate the *index of the precoding matrix* from the codebook.
- RI is reported by the UE to indicate the number of layers, i.e., the number of data streams used in spatial multiplexing.
- For CL MEMO modes, i.e., the transmission modes 4, 5, and 6, the preferred precoding matrix in the predefined codebook needs to be reported, which is provided by the PMI.

9.4.2 Precoder Estimation for Multicarrier Systems

- The precoder estimation at the UE can be done based on a few different metrics. The most common metric is the capacity-based one.
- The precoder is chosen to maximize the MIMO capacity of the effective channel, which includes the radio channel and the precoder.
- CL MIMO system, the interference is dynamic in nature, as the precoders used at interfering cells change from one TTI to the next. Thus, choosing a precoder based on the instantaneous interference seen by a UE can lead to suboptimal performance.

- It is better to choose the precoder based on long-term characteristic of the interference such as the interference variance at each receive antenna.
- For the l^{th} subcarrier, the achievable rate for Minimum mean square error (MMSE) receiver is

$$\begin{aligned} R_l &= \sum_{k=1}^{M} \log_2(1 + \mathrm{SINR}_k) \\ &= -\sum_{k=1}^{M} \log_2 \left(\left(\mathbf{I}_M + \frac{\rho}{M} \mathbf{F}^H \mathbf{H}^H \mathbf{H} \mathbf{F} \right)^{-1}_{k,k} \right), \end{aligned} \tag{9.9}$$

where $M = 1$ to 4, depending on the number of layers, and $\mathbf{H}$ and $\mathbf{F}$ are the channel matrix and precoding matrix, respectively. For a multicarrier system, the sum capacity over a subband with N subcarriers is

$$R_{\mathrm{sum}} = \sum_{l=1}^{N} R_l. \tag{9.10}$$

- The precoder is chosen to maximize R_{sum} for a given subband (subband PMI) or the entire bandwidth (wideband PMI).

9.4.3 Precoding Matrix Index (PMI) and Rank Indication (RI) Feedback

- The RI report is determined from the supported set of RI values for the corresponding eNode-B and the UE antenna configuration.
- The value of RI can be 1 or 2 for two-antenna ports and from 1 to 4 for four-antenna ports.
- The mapping between RI bits and the channel rank is shown in Table 9.13.

Table 9.13 RI Mapping

RI Bits	Channel Rank
0	1
1	2
0, 0	1
0, 1	2
1, 0	3
1, 1	4

- UEs need to report RI for both CL and OL MIMO modes.
- For the CL spatial multiplexing, the RI report, together with the PMI, informs the eNode-B to select the suitable precoder.
- For OL MIMO, the RI report supports selection between transmit diversity (RI = 1) and OL spatial multiplexing (RI > 1).
- Only wideband RI reporting is supported, i.e., only a single RI is reported for the whole bandwidth, as subband RI reporting provides little performance gain.

- In addition, as the channel rank normally changes slowly, the reporting period for RI is longer than CQI in periodic reporting.
- PMI reports the channel-dependent preceding matrix for CL NEMO mode.

9.5 Uplink Channel Sounding

- Channel sounding is mainly used for uplink channel quality measurement at the eNode-B.
- The Sounding Reference Symbol (SRS) is transmitted by the UE in the uplink for the eNode-B to estimate the channel state information, which includes the MIMO channel of the desired signal. SINR, noise. Interference level, etc.
- The SRS can also be used for uplink timing estimation and uplink power control.
- The SRS transmission is always in the last SC-FDMA symbol in the configured subframe, on which PUSCH data transmission is not allowed.
- The eNode-B can either request an individual SRS transmission from a SE or configure a UE to periodically transmit SRS.
- The periodicity may take any value of 2, 5, 10, 20, 40, 80, 160, and 320 ms.
- The UE-specific SRS parameters include
    - The starting physical resource block assignment
    - Duration of SOS transmission
    - SRS periodicity and SRS subframe offset
    - SRS bandwidth
    - Frequency hopping bandwidth and cyclic shift.
- The above parameters are semi-statically configured by higher layers.
- A UE shall not transmit SRS in the following scenarios:
    - *If SRS and PUCCH format 2/2a/2b transmissions happen to coincide in the same subframe*
    - *Whenever SRS and ACK/NAK and/or positive SR transmissions happen to coincide in the same subframe unless the parameter Simultaneous-AN-and-SRS is TRUE*

9.6 Buffer Status Reporting in Uplink

- A Buffer Status Report (BSR) is sent from the UE to the serving eNode-B to provide information about the amount of pending data in the uplink buffer of the UE.
- The buffer status along with other information, such as priorities allocated to different logical channels is useful for the uplink scheduling process to determine which UEs or logical channels should be granted radio resources at a given time.
- A BSR is triggered if any of the following events occurs:

a. *Regular BSR:* Uplink data for a logical channel becomes available for transmission, and either the data belongs to a logical channel with higher priority than the priorities of the data available for transmission for any of the logical channels.

b. *Padding BSR*: Uplink resources are allocated and the number of padding bits is equal to or larger than the size of the BSR MAC control element.

c. A serving cell change occurs, in which case the BSR is referred to as *"regular BSR."*

d. The retransmission BSR timer expires and the UE has data available for transmission, in which case the BSR is referred to as *"regular BSR."*

e. *Periodic BSR*: BSR timer expires, in which case the BSR is referred to as "periodic BSR."

- The buffer status is reported on a per radio bearer' (logical channel) group basis.
- There are two BSR formats used in the LTE uplink: short BSR that reports only one radio bearer group, and long BSR that reports multiple radio bearer groups.
- For regular and periodic BSR, if more than one radio bearer group has data available for transmission in the TTI where the BSR is transmitted, long BSR is reported: otherwise. Short BSR is reported. For padding BSR:
    a. When the number of padding bits is equal to or larger than the size of the short BSR plus its subheader but smaller than the size of the long BSR plus its subheader truncated BSR with the highest priority logical channel is reported if more than one logical channel group has buffered data: otherwise, short BSR is reported.
    b. If the number of padding bits is equal to or larger than the size of the long BSR plus its subheader, long BSR is reported.
- When the BSR procedure determines that at least one BSR has been triggered, and then if the UE has been allocated uplink resources, a buffer status report is transmitted.
- If a regular BSR has been triggered and the UE has no allocated uplink resource, a scheduling request for a BSR transmission is triggered.
- A MAC PDU shall contain at most one MAC BSR control element, even when multiple events trigger.
- In this case, the regular BSR and the periodic BSR shall have precedence over the padding BSR. All triggered BSRs shall be cancelled in the following two scenarios:

1. *The uplink grant can accommodate all pending data available for transmission but is not sufficient to additionally accommodate the BSR MAC control element*
2. *A BSR is include in a MAC PDU for transmission.*

9.7 Scheduling and Resource Allocation

- The main aim of scheduling and resource allocation is to efficiently allocate the available radio resources to UEs to optimize a certain performance metric with QoS requirement constraints.
- Scheduling algorithms for LTE can be divided into two categories:

1. ***Channel-dependent scheduling***:
   - Dynamic channel-dependent scheduling is one of the key feature to provide high spectrum efficiency in LTE.
   - The allocation of RBs to a UE is based on the channel condition, e.g., proportional fairness scheduler, max Carrier Interfernce scheduler.
   - To better exploit the channel selectivity, the packet scheduler is located in the eNode-B, which allocates physical layer resource for both the DL-SCH and UL-SCH transport channels every TTI.
   - Scheduling depends heavily on the channel information available at the eNode-B, which is provided by the uplink CQI reporting for the downlink channel and by channel sounding in the uplink channel.
   - The scheduler should also take account of the traffic volume and the QoS requirement of each UE and associated radio bearers.
   - Due to the use of OFDMA/SC-FDMA, LTE is able to exploit the channel variation in both the time and frequency domain, which is a major advantage compare to HSPA (3G).
2. ***Channel dependent scheduling***:
   - The objective of channel-dependent scheduling is to exploit multiuser diversity to improve the spectrum efficiency.
   - Here allocate resource blocks to a UE is random and not based on channel condition, e.g., round-robin scheduler.
   - It should also consider such issues as fairness and QoS requirements.
   - In addition, scheduling is tightly integrated with link adaptation and the H-ARQ process.
   - The scheduling algorithm is not standardized and it is vendor specific.

- In a multicarrier system such as LTE, channel-dependent scheduling can be further divided into two categories:
  1. ***Frequency diverse scheduling***: The UE selection is based on wideband CQI. However, the PRB allocation in the frequency domain is random. It can exploit time selectivity and frequency diversity of the channel.
  2. ***Frequency selective scheduling:*** The UE selection is based on both wideband and subband CQI, and the PRB allocation is based on the subband CQI. This can exploit both time and frequency selectivity of the channel.

9.7.1 Signaling for Scheduling in Downlink and Uplink

- eNode-B scheduler dynamically controls time-frequency resources are allocated to a certain UE in both downlink and uplink.
- The resource assignments, including the assigned time/frequency resources and respective transmission formats, are conveyed through downlink control signaling.
- The minimum size of radio resource that can be allocated to a UE corresponds to two resource blocks, which is 1 ms duration in the time domain and 180 kHz in the frequency domain.
- Both localized and distributed resource allocations are supported in the downlink, while in the uplink UEs are always assigned contiguous resources.
- In addition, there is a strict constraint on the UE transmit power in the uplink.

- ***Signaling for Downlink Scheduling:*** *Producers are*
  - The channel state information (CSI) at the eNode-B for the downlink scheduling is obtained through CQI reporting from UEs.
  - Based on the CQI, eNode-B dynamically allocates resources to UEs at each TTI.
  - A UE always monitors the PDCCH for possible allocations and decode the PDCCH with CRC.
  - The UE shall decode the PDCCH and any corresponding PDSCH according to the respective combinations defined in Table 9.16.

Table 9.16 PDCCH and PDSCH Configured by C-RNTI

UE DL Transmission Mode	DCI Format	Transmission Scheme of PDSCH
Mode 1	DCI format 1A	Single-antenna port, port 0
	DCI format 1	Single-antenna port, port 0
Mode 2	DCI format 1A	Transmit diversity
	DCI format 1	Transmit diversity
Mode 3	DCI format 1A	Transmit diversity
	DCI format 2A	OL spatial multiplexing or transmit diversity
Mode 4	DCI format 1A	Transmit diversity
	DCI format 2	CL spatial multiplexing or transmit diversity
Mode 5	DCI format 1A	Transmit diversity
	DCI format 1D	Multiuser MIMO
Mode 6	DCI format 1A	Transmit diversity
	DCI format 1B	Closed-loop Rank = 1 precoding
Mode 7	DCI format 1A	If the number of PBCH antenna ports is one, single-antenna port (port 0); otherwise, transmit diversity
	DCI format 1	Single-antenna port, port 5

9.7.2 Multiuser MIMO Signaling

- If MU-MINO is used in the uplink, then it is transparent to the UE with the exception that two UEs should transmit orthogonal reference signals in order for the eNode-B to separate them.
- The uplink resource allocation is indicated on PDCCH using DCI format 0, which contains a 3-bit field to indicate the cyclic shift in the reference signal to be used by each UE.
- When MU-MIMO is used in the downlink, two rank-1 UEs are multiplexed on the same physical resource.
- In this case the power for each UE is reduced by 3 dB. This is indicated by the power offset field in DCI format ID which is used for MU-MIMO scheduling.

9.8 Cell Search***

- Cell Search means the collective term representing the combined procedure of Measurement, Evaluation and Detection process.
- This is very tightly related to Cell Selection process because UE goes through this search process first before it goes through the cell selection.
- Also this process influence greatly on energy consumption of UE during the idle mode.
- When a UE powers on, it needs to acquire time and frequency synchronization with a cell and detect the physical-layer cell ID of that cell through the cell search procedure or synchronization procedure.
- During cell search, different types of information need to be identified by the UE, including *symbol and frame timing, frequency, cell identification, transmission bandwidth, antenna configuration, and the cyclic prefix length.*
- LTE uses a hierarchical cell search scheme similar to WCDMA, demonstrated in Figure 9.4.

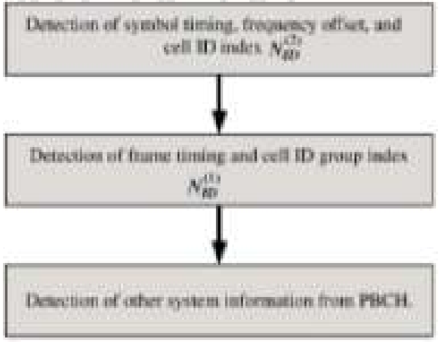


Figure 9.4 The cell search process.

- **Cell search procedure**: *A cell search is nothing but a procedure that a UE shall perform in order to get more details about the nearby eNodeB/cell. So this is the first step that a UE shall do, as soon as it is powered on. The cell search procedure, is the UE's way of acquiring cell specific information and this, the UE has to perform once or several times based on the condition of the network.*
- ***Cell Search step 1***: The UE detects the symbol timing and the cell ID index $N_{ID}^{(2)}$from the primary synchronization signal. This is achieved through matched filtering between the received signal and the primary synchronization sequences. Three orthogonal sequences defined for the primary synchronization signal, the cell ID index $N_{ID}^{(2)}$, can be detected by identifying the received sequence. Frequency and Time synchronization can be performed based on the primary synchronization signal. OFDM symbol timing can be detected, but as there are two primary synchronization signals transmitted in each frame that are indistinguishable, frame timing cannot be detected.
- ***Step 2***: The UE detects the cell ID group index $N_{ID}^{(1)}$ and frame timing from the secondary synchronization signal. The index $N_{ID}^{(1)}$; is detected by identifying the shift in the m-sequence in the received signal. For detecting the frame timing, the pair of secondary synchronization signals in a radio frame has a different structure than primary synchronization signals.
- ***Step 3:*** After the cell search, the UE can detect the broadcast channel to obtain other physical layer information, e.g., system bandwidth, number of transmit antennas, and system frame number.
- ***Step 4:*** The system information is divided in to Master Information Block (MIB) transmitted on the PBCH and System Information Blocks (SIB) transmitted on the PDSCH. At this stage, the UE detects MIB from the PBCH. To maintain the uplink intra-cell orthogonality, uplink transmissions from different UEs should arrive at the eNode-B within a cyclic prefix. This is achieved through the timing advance procedure.
- ***Step 5:*** The timing advance is obtained from the uplink received timing and scot by the eNode-B to the UE. The UE advances or delays its timing of transmissions to compensate for propagation delay and thus time-aligns its transmissions with other UEs. The timing advance command is on a per-need basis with a granularity in the step size of $0.52\mu s$

9.9 Random Access Procedures (RACH:

- In order to be synchronized with the network, RACH procedure is used by UE.
- Suppose a UE wants to access the network, so first it will try to attach or synchronize with the network. In LTE a separate channel PRACH (Physical Random Access Channel) is provided for initial access to the network.

- The UEs also obtain uplink timing information from the initial handshake.
- In LTE, there are two random access mechanisms:

1. Non-synchronized random access: *Non-synchronized random access is used ohm the UE uplink has not been time synchronized, or when the UE uplink loses synchronization. Its main purpose is to obtain synchronization of the uplink, notify the eNode-B that the UE has data to transmit, or transmit a small amount of control information and data packets.*
2. Synchronized random access: *Synchronized random access is used when uplink synchronization is present. Its main purpose is to request resources for uplink data transmission from the eNode-B scheduler.*

- ***Non-synchronized random access procedure:***
    - Prior to initiation of the non-synchronized random access procedure, each UE obtains the following information broadcast from eNode-B:
        - Random access channel parameters
        - Including POACH configuration
        - Frequency position and preamble forma
        - Parameters for determining the root sequences and their cyclic shifts in the preamble sequence set for the cell.
    - The non-synchronized random access procedure consists of following steps is depicted in the figure 9.5 and described as follows.

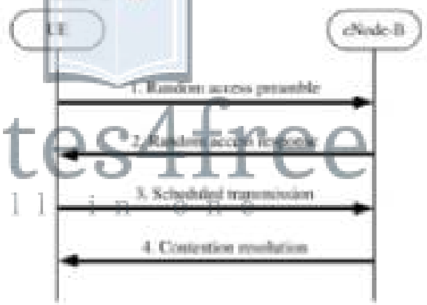


Figure 9.5 The non-synchronized random access procedure.

1. Multiple UEs transmit randomly selected random access code.
2. eNode - B conducts a multiuser detection process and allocates resources to the detected UEs.
3. Each UE transmits detailed information losing allocated resources.
4. The eNode-B transmits the contention-resolution message on the DL-SCH. When the previous steps are finished successfully, eNode-B and each UE initiate data communication.

Step 1: Random Access Preamble Transmission:

- The UE randomly selects a random access preamble transmitted by eNodeB, and transmits on the PRACH physical channel.
- Open-loop power control is used to determine the initial transmit power level.
- Multiple UEs may transmit their random access preambles simultaneously through the same channel, and the eNode-B monitors the random access channel and conducts multiuser detection identifying each RACH transmission.
- The RACH signals from the different UEs are based on the Zadoff-Chu sequence with different cyclic shift resulting in a zero cross-correlation between them.
- The eNode-B also calculates the timing correction for the uplink transmission for each UE.

Step 2: Random Access Response:

- eNode-B transmits the corresponding random access response on the DL-SCH, which contains the identity of the detected preamble, the timing correction for uplink transmission, a temporary identity for transmission in following steps, and an initial uplink resource grant.
- The random access response message can also include a backoff indicator to instruct the UE to back off for a period of time before retrying another random access attempt.
- The uplink scheduling grant for the following uplink transmission contains 20 bits, and the content is illustrated in Table 9.20.

Table 9.20 The Content of Random Access Response Grant

Information Type	Number of Bits	Purpose
Hopping flat	1	Indicates whether PUSCH frequency hopping is applied in the following step.
Fixed-size resource block assignment	10	Indicates the assigned radio resource for the following transmission.
Truncated modulation and coding scheme	4	Determines the modulation and coding scheme.
TPC command for scheduled PUSCH	3	Adjusts the transit power of PUSCH.
UL delay	1	Adjusts the uplink transmission timing.
CQI request	1	Used in non-contention-based random access procedure to determine whether an aperiodic CQI report is included in the corresponding PUSCH transmission.

- Once the random access preamble is transmitted, it will monitor the PDCCH for random access response identified by the Random Access Radio Network Temporary Identifier (RA-RNTI), as the time-frequency slot carrying the preamble is associated with an RA-RNTI.
- If the received random access response matches the transmitted preaanble, the UE may stop monitoring.

***Step 3: Scheduled Transmission*:**

- After step 2, the UE is uplink synchronized and can transmit additional messages on scheduled UL-SCH.
- This step is to assist contention resolution.
- If the UEs that perform random access attempts in the same time-frequency resource use different preambles.
- Different UEs can be identified by the eNode-B and there is no collision. However. it is possible that multiple UEs select the same preamble, which causes a collision.
- To resolve the contention for access, the UE that detects a random access preamble transmits a message containing a terminal identity.
- If the UE is connected to a cell, Cell Radio Network Temporary Identifier (C-RNTI) will be tool, which is a unique UE ID at the cell level; otherwise, a core network identifier is used. In step 1 the H-ARQ protocol is supported to improve the transmission reliability.

***Step 4: Contention Resolution*:**

- In this step, the eNode-B transmits the contention-resolution message on the DL-SCH, which contains the identity of the winning UE.
- The UE that observes a match between this identity and the identity transmitted in step 3 declares a success and completes its random access procedure.
- If this UE has not been assigned a C-RNTI, the temporary identity is then set as its C-RNTI.
- The H-ARQ protocol is supported in this step and the UE with successful access will transmit an H-ARQ acknowledgment.

9.10 Power Control in Uplink:

- As compared to Downlink, in case of Uplink in LTE, Power control is used. As the battery of the phone (UE) is power limited compared to base station power in the DL.
- Uplink power control is used mainly for the following two reasons.
    1. *Limit intracell and intercell interference*
    2. *Reduce UE power consumption*
- In LTE, the power control in the uplink is to control the interference caused by UEs to neighboring cells while maintaining the required SINR at the serving cell.
- The power control scheme for the PUSCH transmission in the uplink. Usually in Uplink. Power control is done in two ways. One is

1. ***Conventional Power Control (CPC)*:** Conventional power control in the uplink is to achieve the same SINR for different UEs at the base station, also known as *full compensation*. But it suffers low spectral efficiency as the common SINR is limited by the cell-edge UEs.

MODULE-5

Radio Resource Management and Mobility Management:

PDCP overview, MAC/RLC overview, RRC overview, Mobility Management, Inter-cell Interference Coordination(Sec 10.1 – 10.5 of Text).

Data Flow, Radio Resource Management, and Mobility Management

Building on the physical layer procedures discussed in previous chapters, in this chapter we describe higher-layer protocols and mobility management in LTE. Radio re source management and inter-cell interference mitigation techniques will also be discussed in this chapter. However, before discussing higher-layer protocols, we first introduce the concept of bearer for Quality of Service (QoS) control and the protocol architecture of LTE.

PDCP Overview :

A PDCP entity is associated either with the control plane or with the user plane depending on which radio bearer it is carrying data for 7. Each radio bearer is associated with one PDCP entity, and each PDCP entity is associated with one or two RLC entities depending on the radio bearer characteristic (uni-directional or bi-directional) and the RLC mode. PDCP is used only for radio bearers mapped on DOCH and DTCH types of logical channels.

The main services and functions of the PDCP sub layer for the user plate and control plane 5 shown in Figure 1 are as follows.

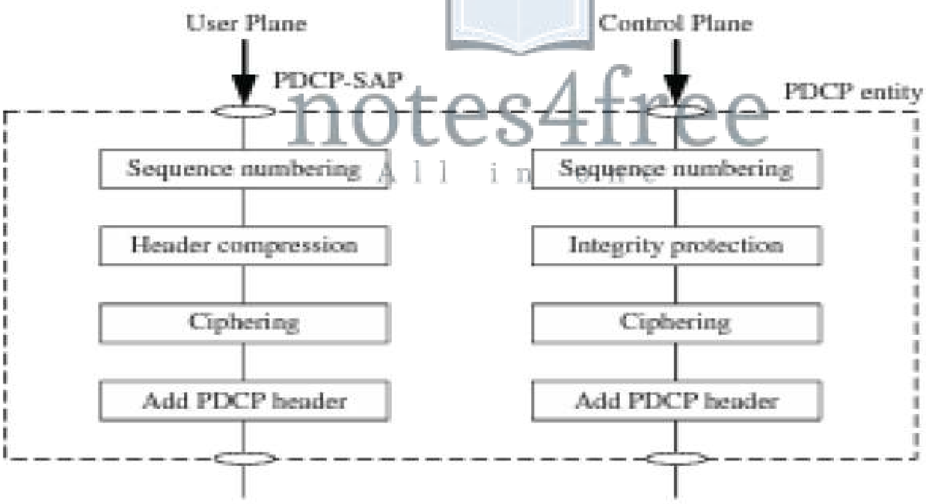


Figure 1: PDCP functions for the user plane and the control plane.

For the user plane:

1. Header compression and decompression of IP data flows with the Robust Header Compression (ROHC) protocol.
2. Ciphering and deciphering of user plane data .

3. In-sequence delivery and reordering of upper-layer PDUs at handover.
4. Buffering and forwarding of upper-layer PDUs from the serving eNode-B to the target eNode-B during handover .
5. Timer-based discarding of SDUs in the uplink .

For the control plane:

1. Ciphering and deciphering of control plane data.
2. Integrity protection and integrity verification of control plane data.
3. Transfer of control plane data.

The PDCP PDUs can be divided into two categories:

The PDCP data PDU is used in both the control and user plane to transport higher-layer packets. It is used to convey either user plane data containing a compressed/'un compressed IP packet or control plate data containing one RRC merge and a Message Authentication Code for Integrity (MAC-I) field for integrity protection, which will be described in detail later in this section.

The PDCP control PDU is used only within the user plane to convey a PDCP status report during handover and feedback information for header compression. Thus, unlike a PDCP data PDU, the PDCP control PDU does not carry any higher layer SDU but rather is used for peer-to-peer signalling between the PDCP entities at two ends.

The constructions of the PDCP data PDU formants from the PDCP SDU for the user plane and the control plane are shown in Figure . The various types of PDCP PDU carried on the user and control plane are shown in Table 1. There are three different types of PDCP data PDUs, distinguished by the length of the Sequence Number (SN).

The PDCP SN is used to provide robustness against packet loss and to guarantee sequential delivery at the receiver. The PDCP data PDU with the long SN is used for the Un acknowledge Mode (UM) and Acknowledged Mode (AM) and the PDCP data PDU with the short SN is used for the Transparent Mode (TM). Besides the SN field and the ciphered data, the PDCP data PDU for the user plane contains a "D/C' field that is

Figure 2: PDCP formats for the user plane and the control plane

PDCP PDU Type	SN Length	Applicable RLC Mode
User plane PDCP data PDU (long SN)	12 bits	AM/UM
User plane PDCP data PDU (short SN)	7 bits	UM
Control plane PDCP data PDU	5 bits	AM/UM
PDCP control PDU for ROHC feedback	N/A	AM/RM
PDCP control PDU for PDCP status report	N/A	AM

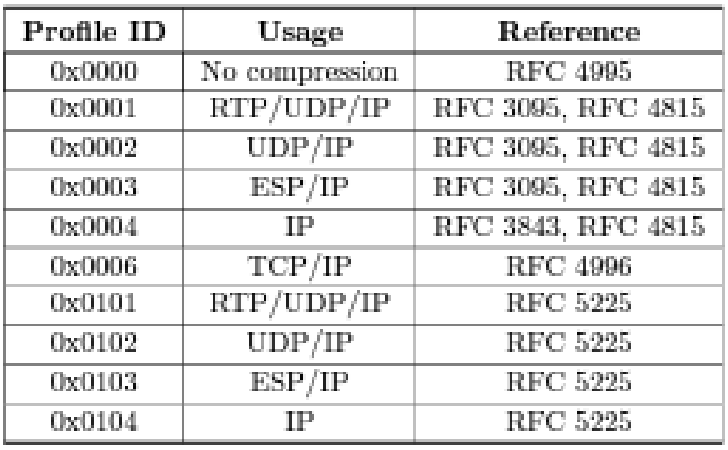
PDCP Data units

Header Compression :

The header compression protocol in LTE is based on the Robust Header Compression (ROHC) framework defined by the **Internet Engineering Task Force** (IETF) (12). PDCP entities are configured by upper layers to use header compression, which is only performed on user plane data. The requirement for header compression comes from the fact that all the services in LTE are IP-based, and are based on the framework of IP and other related IETF protocols.

However, these protocols bring 1 significant amount of header overhead at the network layer (IP), transport layer (TCP, UDP), and application layer (RTP), which contains redundant and repetitive information and necessarily consumes precious radio resources.

Therefore, an efficient header compression scheme is required, especially for VoIP services where the IP-related repetitive information in the header field is large relative to the in actual speech packets. There are multiple header compression algorithms, Galled profiles, defined for the ROHC framework. Each profile is specific to the particular network layer, transport layer, or upper-laver protocol combination, e.g-, TCP/IP and RTP/UDP/IP.



Profile ID	Usage	Reference
0x0000	No compression	RFC 4995
0x0001	RTP/UDP/IP	RFC 3095, RFC 4815
0x0002	UDP/IP	RFC 3095, RFC 4815
0x0003	ESP/IP	RFC 3095, RFC 4815
0x0004	IP	RFC 3843, RFC 4815
0x0006	TCP/IP	RFC 4996
0x0101	RTP/UDP/IP	RFC 5225
0x0102	UDP/IP	RFC 5225
0x0103	ESP/IP	RFC 5225
0x0104	IP	RFC 5225

Integrity and Ciphering :

The security-related functions in PDCP include integrity protection and ciphering. A PDCP PDU counter, denoted by the parameter COUNT, is maintained and used as 11 input to the security algorithm.

The format of COUNT is shown in Figure, which has a length of 32 bits and consists of two parts: the Hyper Frame Number (HFN) and the PDCP SN. The SN is used for reordering and duplicate detection of RLC packets at the receive end

The ciphering function includes both ciphering and deciphering. It is performed on both control plane data and user plane data. For the control plane, the data unit that is ciphered is the data part of the PDCP PDU and the MAC-I; for the user plane, the data unit that is ciphered is the data part of the PDCP PDU.

The ciphering is done by an XOR operation of the data unit with the ciphering stream. The ciphering stream is generated by the ciphering algorithm based on ciphering keys, the radio bearer identity, the value of COUNT, the direction of the transmission,

Figure 3: Format of COUNT

MAC/RLC Overview :

As there is close interaction between MAC and RLC sub layers 5,6, we discuss them together in this section. The RLC layer performs segmentation and/or concatenation of

PDCP PDUs the size indicated by the MAC. RIC the RLC PDUs once they are received out of order possibly due to H-ARQ processes in the MAC layer.

The RLC layer also supports in ARQ mechanism, which resides on top of the MAC layer H-ARQ and is used only when all the H-ARQ transmissions are exhausted and the RIO PDU has not yet been received without errors. As mentioned previously, at the transmitter and the receiver there is one RLC entity per radio bearer.

The MAC layer only performs the task of multiplexing and prioritizing the various radio bearers Associated with the UE. The MAC layer provides services to the RLC layer through logical channels, while it access the data transfer services provided by the PHY layer through transport channels.

Data Transfer Modes

Functions of the RIC layer are performed by RLC entities. Each RLC entity can be operated in three different modes: the Transparent Mode (TM), the Unacknowledged Mode (UM), and the Acknowledged Mode (AM).

The Transparent Mode (TM)

The TM mode is the simplest one. The RLC entity does not add any RLC header to the PDU and no data segmentation or concatenation is performed. This mode is suitable for services that do not need retransmission or are not sensitive to delivery order. Only RRC messages such is broadcast system information messages and paging messages use the TM mode. The TM mode is not used for user plane data transmission. The RLC data PDU delivered by a TM RLC entity is called the TM Data (TMD) PDU.

The Unacknowledged Mode (UM)

The UM mode provides in-sequence delivery of data that may be received out of sequence due to the H-ARQ process in MAC, but no retransmission of the lost PDU is required. This mode can be used by delay-sensitive and error-tolerant real-time applications, such us VoIP. The DTCH logical channel can be operated in the UM mode, and the RLC data PDU delivered by 10 UM RIC entity is called the UM Data (UMD) PDU.

At the transmit end, the UM RLC entity segments and/or concatenates the RIC SDU. According to the total size of RLC PDUs indicated by the MAC layer. Relevant RLC headers are also included in the UMD PDU. The receiving UM RLC entity performs duplicate detection, reordering, and reassembly of UMD PDUs.

The Acknowledged Mode (AM)

The AM mode is the most complex one, which requests retransmission of missing PDUs in addition to the UM mode functionalities. It is mainly used by CITOI-Sensitive and delay-tolerant applications.

The operation of the AMRIC entity is similar to that of the UM RLC entity, except that it supports retransmission of RLC data PDUs. The receiving AM RIC entity can send a STATUS PDU to inform the transmitting RLC entity about the AMD PDUs that are received successfully and that are detected to be lost.

Purpose of MAC and RLC Layers

The main services and functions of the RLC sub layer include

- Transferring /receiving PDUs from upper layers, i.e. from RRC for the CCCH logical channel or from PDCP for other cases
- Error correction through ARQ (only when the RLC is operated in the AM mode)
- Concatenation, segmentation, and reassembly of RLC SDUS (only for UM and AM data transfer)
- Re-segmentation of RLC data PDUs (only for AM data transfer)
- In-sequence delivery of upper-layer PDUs (only for UM and AM data transfer)

- Duplicate detection (only for UM and AM data transfer)
- Protocol error detection and recovery
- RLC SDU discard (only for UM and AM data transfer)
- RLC re-establishment

LTE defines two MAC entities:
one in the UE and one in the eNode-B. The exact functions performed by the MAC entities are different in the UE from those performed in the eNode-B. The main services and functions of the MAC sub layer include

- Multiplexing/de multiplexing of NAC SDUs belonging to one or different logical channels into from the same transport block
- Error correction through H-ARQ, which has tight interaction with ARQ in the RLC layer and will be discussed later in this section.

Transport format selection, i.e., the selection of the Modulation and Coding Scheme (MOS) for link adaptation

- Padding if a MAC PDU is not fully filled with data .

PDU Headers and Formats RLC PDU Formats

RLC PDUs can be categorized into RLC data PDUs and RLC control PDU.. As discussed in the previous subsection, RLC data PDUs are used by TM, UM. and AM RLC entities to transfer upper-layer PDUs, called the TM Data (TMD) PDU, the UM Data (UMD) PDU, and the AM Data (AMD) PDU, respectively. On the other hand, RLC control PDUs are used for peer-to-peer signalling between the AM RLC entities at the two ends for ARQ procedures.

The formats of different RLC Data PDUs are shown in Figure . The TMD PDU only consists of a Data field, as no RLC header is added. The RLC headers are different for UMD PDU and AMD PDU, but they contain common fields including

- Framing Info (FI) field: The FI Held indicates whether a RLC SDU is Segmented at the beginning and/or at the end of the Data field.
- Length Indicator (LI) field: The LI field indicates the length in bytes of the corresponding Data field element present in the UMD or AMD PDU.
- Extension bit (E) field: The E field indicates whether a Data field follows or a set of E field and LI field follows

SN field: The SN Held indicates the sequence number of the corresponding UMD or AMD PDU. It consists of 10 bits for AMD PDU, AMD PDU segments, and STATUS PDUs, and 5 bits or 10 bits for UMD PDU. The PDU sequence number carried by the RLC header is independent of the SDU sequence number, i.e., the PDCP sequence number

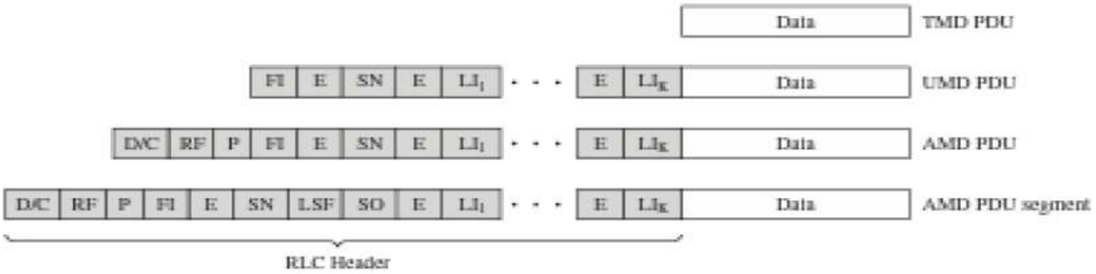


Figure 4: Formats of RLC Data PDUs

- **Data/Control (D/C) field**: The D/C field indicates whether the RLC PDU is an RLC Data PDU or an RLC Control PDU.
- **Re-segmentation Flag (RF) field**: The RF field indicates whether the RLC PDU is an AMD PDU or an AMD PDU segment.

- **Polling bit (P) field**: The P field indicates whether the transmitting side of an AM RLC entity requests a STATUS report from its per AM RLC entity. Additionally, the RLC header of an AMD PDU segment contains special fields including:
- **Segment Offset (SO) field**: The SO field indicates the position of the AMD PDU segment in bytes within the original AMD PDU.
- **Last Segment Flag (LSF) field**: The LSF Held indicates whether the last byte of the AMD PDU segment corresponds to the last byte of an AMD PDU.

The STATUS PDU is used by the receiving AM RLC entity to indicate the missing portions of AMD PDUs. The format of the STATUS PDU is shown in Figure 10.9, which Consists of the following fields:

Control PDU Type (CPT) field: The CPT field indicates the type of the RLC control PDU, and in Release the STATUS PDU is the only defined control PDU.

- **Acknowledg**ment SN (ACK SN) field: The ACK_SN field indicates the SN of the next not received RIC Data PDU, which is not reported is missing in the STATUS PDU.
- Extension bit 1 (El) field: The El field indicates whether a set of NACK_SN, El, and E2 follow us.
- Extension bit 2 (E2) field: The E2 field indicates whether a set of SO start and SO end follows.

Negative Acknowledgment SN (NACK SN) field: The NACK_SN field indicates the SN of the AMD PDU (or portions of it) that has been detected is lost at the receiving side of the AM RLC entity

- **SO start (SO start) field and SO end (SO end) field**: These two fields together indicate the portion of the AMD PDU with SN = NACK SN that has been detected is lost at the receiving side of the AM RLC entity.

Figure 5:The format of STATUS PDU

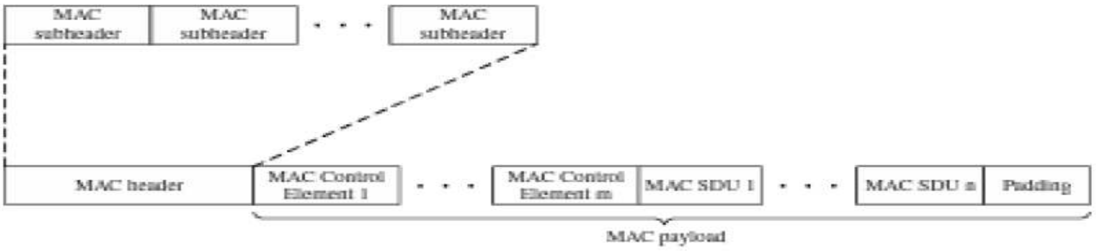


Figure 6: An example of MAC PDU consisting of MAC header

RRC Overview :

The RRC layer takes care of RRC connection management, radio bearers control, mobility functions, and UE measurement reporting and control. It is also responsible for broadcasting system information and paging. In this section, we discuss the two RRC states in LTE and the functions provided by the RRC protocol.

RRC States

Compared to UMTS, which has four RRC states, LTE has only two states RRC_IDLE und RRC.CONNECTED, is depicted in Figure 7 .This simplifies the RRC state machine handling and the radio resource management, which controls the RRC state.

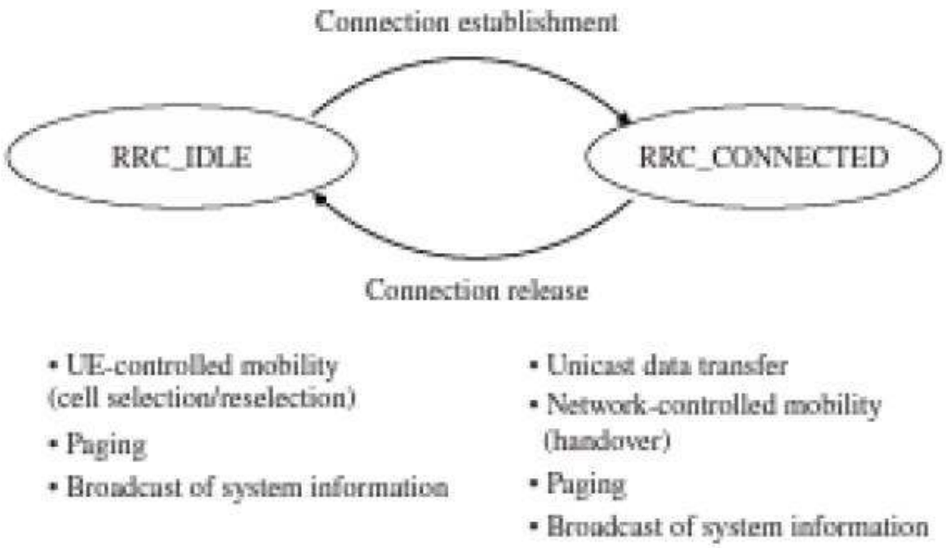


Figure 7: RRC states in LTE

In the RRC_IDLE state, the UE can receive broadcasts of system information and information. There is no signalling radio bearer established, so there is no RRC connection. In the RRC_IDLE state, the mobility control is handled by the UE, which performs neighbouring cell measurements and cell selection/reselection.

The system information mainly contains parameters by which E-UTRAN controls the cell selection/reselection POCK, such as priorities of different frequencies. The UE shall have been allocated an ID that uniquely identifies the UE is a trucking area. The UE also monitors a paging channel to detect incoming calls, and it specifies the paging Discontinuous Reception (DRX) cycle.

In the RRC_CONNECTED state, the UE has an E-UTRAN RRC connection and 1 context in the E-UTRAN, so it is able to transmit and/or receive data: to/from the network (eNode-B). The UE monitors control channels (PDCCH) Located with the shared data channel to determine if data is scheduled for it.

In the RRC_CONNECTED state, the network controls mobility,'handover of the UE.

RRC Functions

Before going into different functions provided by the RRC protocol, we first introduce the concept of Signalling Radio Beaers (SRBs). SREs are defined as radio bearers that ne used only for the transmission of RRC and NAS message. There are three different SRBs defined in LTE .

Broadcast of system information, which is divided into the Master Information Block (MIB) and a number of System Information Blocks (SIBs). The MIB includes a limited number of the most essential and most frequently transmitted parameters that are needed to acquire other information from the cell, and is transmitted on the BCH logical channel. SIBs other than SIB Type 1 are carried in System Information (SI) messages. SIB Type 1 contains parameters needed to determine if 1 cell is suitable for cell selection as well as information about the time-domain scheduling of the other SIBs. SIB Type 1 and all SI Messages are transmitted on DL-SCH.

RRC connection control includes procedures related to the establishment, modification, and release of at RRC connection, including paging, initial security activation, establishment of SRBs and radio bearers carrying user data, radio configuration control and QoS control, and recovery from the radio link failure.

Measurement configuration and reporting includes establishment, modification, and release of measurements, configuration, and (de-)activation of measurement gaps, and measurement reporting for intra-frequency, inter-frequency, and inter-RAT (Radio Access Technology) mobility.

Other functions include transfer of dedicated NAS information and non-3GPP dedicated information, transfer of UE radio A capability information, and support of self-configuration and self-optimization.

Mobility Management

LTE mobility management functions can be categorized into two groups a) mobility within the LTE system (intra-LTE mobility) and b) mobility to other systems such as other 3GPP systems (C. UMTS) and 100-3GPP systems (inter-RAT mobility). Intra LTE mobility can happen either over the Si interface or over the X2 interface. When the UE moves from one eNode-1 to another eNode-B within the same Radio ACCESS Network (RAN) attached to the same NME, the mobility takes place over the X2 interface.

The inter-RAT mobility essentially uses the Sl-mobility with the only difference being that in this case the PDCP context is not continued and the UE needs to re-establish its session once it Moves to the target non-LTE system.

Si Mobility : Si mobility is very similar to the UMTS Serving Radio Network Subsystem (SRNS) relocation procedure and consists of the following steps.

1. **Preparation Phase**: Once a decision has been made for a handover and a target MME and eNode-B have been identified, the network needs to allocate resources on the target side for the impending handover. The MME sends a handover request to the target eNode-B requesting it to set up the appropriate resources for the UE.

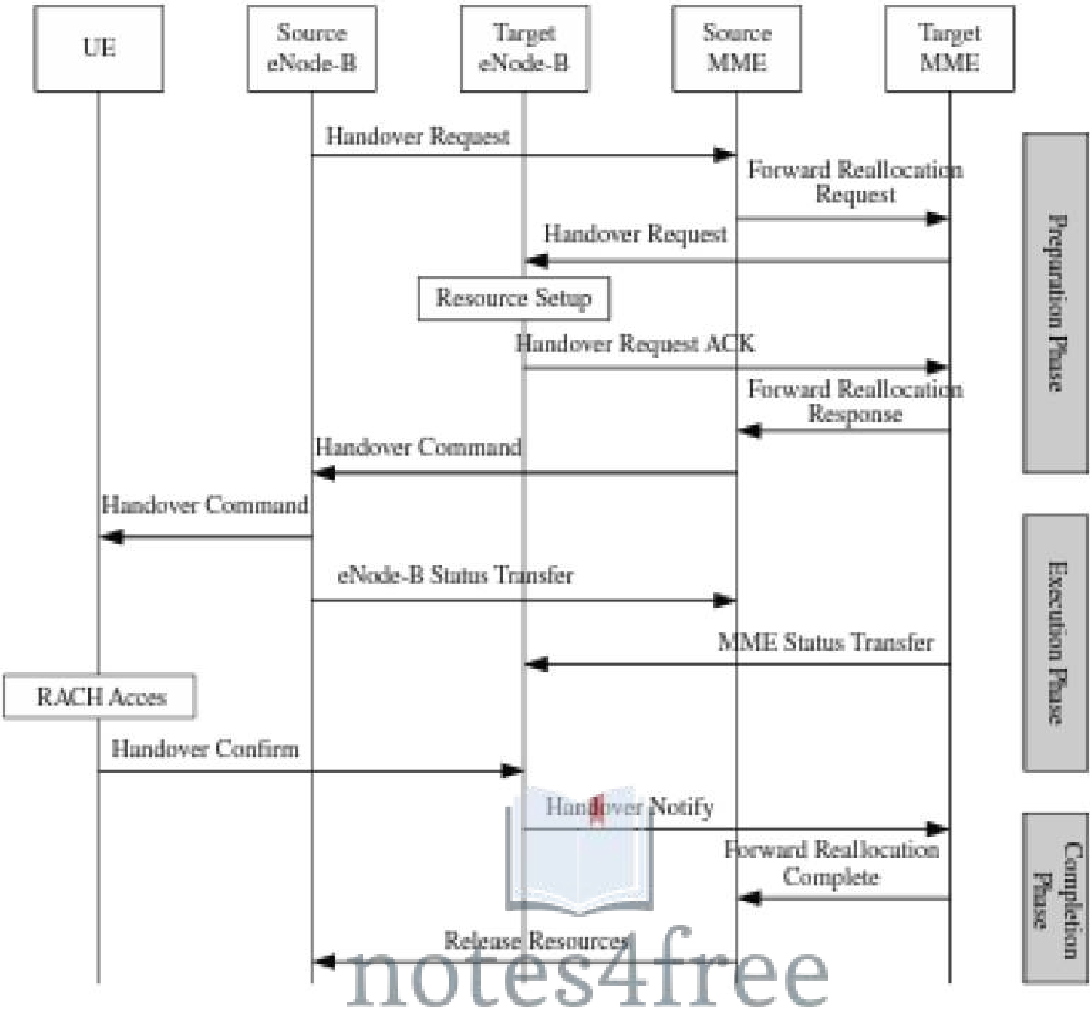


Figure 8 : Mobility Management over the SI interface

2. **Execution Phase**: Once the UE receives the handover command, it responds by performing the various RAN-related procedures needed for the handover including accessing the target eNode-B using the Random Access Channel (RACH). The RAN-related procedures of a handover are discussed in detail later in this section. While the UE performs the handover, the source eNode-B initiates the status transfer where the PDCP context of the UE is transferred to the target eNode-B.

3. **Completion Phase:** When the target eNode-B receives the handover confirm message, it sends a handover notify message to the MME. The MME then informs the source eNode-B to release the resources originally used by the UE.

X2 Mobility

The mobility over the X2 interface is the default mode of operation in LTE unless an X2 interface is not available between the source and target eNode-Es. When this is the arise, the mobility over Sl interface is triggered is mentioned in the previous section. Mobility over the X2 interface also consists of three steps :

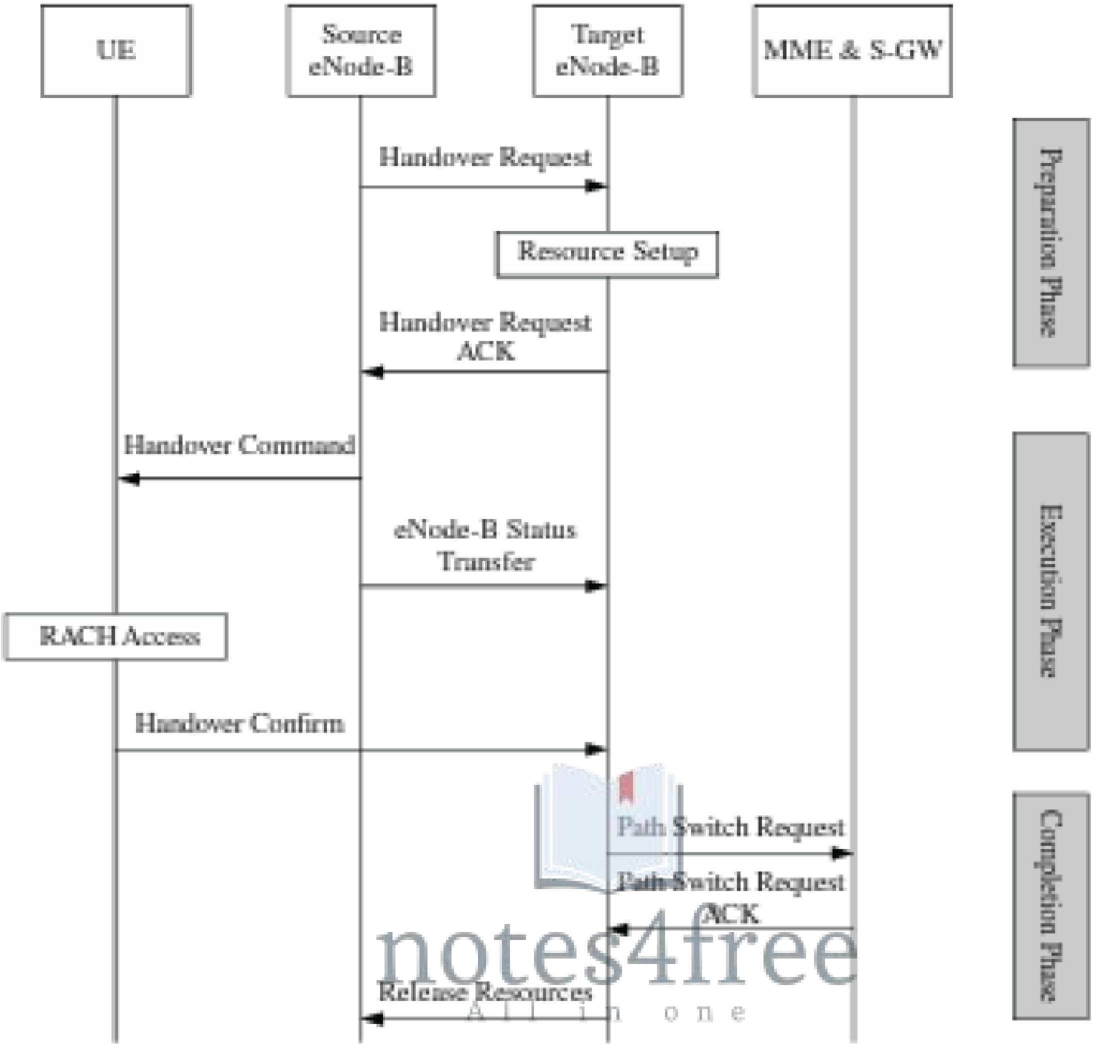


Figure 9: Mobility management over the X2 interface

1. **Preparation Phase**: Once the handover decision has been made by the source eNode-B, it sends a handover request message to the target eNode-B. The target eNode-B upon receipt of this message works with the NNE 2nd S-GW to set up the resources for the UE. In the case of mobility over X2 interface.
2. **Execution Phase**: Upon receiving the handover request ACK, the source eNode-B sends a handover command to the UE. While the UE completes the various RAN related handover procedures, the source eNode-B starts the status and data transfer to the target eNode-B. This is done on a per-RAB basis for the UE.
3. **Completion Phase:** Once the UE completes the handover procedure, it sends a handoff complete message to the target eNode-B. Then the target eNode-B sends a path switch request to the MME/S-GW and the S-GW switches the GTP tunnel from the source eNode-B to the target eNode-B. When the data path in the ser plane is switched, the target eNode-B sends a message to the source eNode-B to release the resources originally used by the UE.

Paging

Paging is a connection control function of the RRC protocol. The Paging message is used to inform the UEs in the RRC_IDLE or RRC CONNECTED state about a system information change and/or about an Earthquake and Tsunami Warning System (ETWS) notification.

The UE in the RRC_IDLE state also monitors a Paging channel to detect incoming calls. Change of system information only occurs at specific radio frames, and the concept of 1 Modification period is used. Within a modification period, system information can be transmitted a number of times with the same content.

Upon receiving a change notification contained in the Paging message, the UE knows that the current system information is valid until the next modification period boundary. After this boundary, the UE will re-acquire the required system information.

If the ETWS notification is indicated the UE that is ETWS capable will re-acquire the system information block related to ETWS immediately without waiting for the next system information modification boundary.

The paging information is carried on the PDSCH physical channel. In a certain PO, the UE is configured to decode PDCCH with CRC scrambled by the Paging-Radio Network Temporary Identifier (P-RNTI), and then decode the corresponding PDSCH for the paging information.

To reduce power Consumption, the UE may use Discontinuous Reception (DRX) in the idle mode, so it needs only to monitor one PO per DRX cycle.

After receiving the Paging message, the UE can switch off its receiver to preserve battery power. The DRX cycle is configured by the E-UTRAN .

Inter-Cell Interference Coordination

In cellular networks, each UE suffers Inter-Cell Interference (ICI) due to frequency reuse in other cells. Conventional cellular networks by design are interference-limited: if they were not, it would be possible to increase the spectrum efficiency by lowering the frequency reuse or increasing the average loading per cell. To meet the spectrum efficiency target, LTE will be deployed with universal frequency reuse, ie, the same spectrum will be reused in each cell.

This will cause a high level of ICI, especially for UEs at the cell edge. Meanwhile, LTE also has a mandate to increase cell edge throughput. Therefore, ICI control techniques must be applied (10.11, 13, 14, 17). In this section, we discuss ICI mitigation techniques for both downlink and uplink transmissions. ICI suppression through base station coordination, or networked MIMO, has been discussed in Section 5.9.2, where the associated opportunities and challenges were highlighted.

Downlink

ICI randomization. This is achieved by scrambling the codeword after channel coding with a pseudo-random sequence, With cell specific scrambling. ICI from neighbouring cells is randomized, and then interference suppression is achieved thanks to the processing main provided by the channel code. Without scrambling, the channel decoder might be equally matched to interfering signals us to the desired signals on the same radio resource. ICI randomization has been applied in systems such as UMTS.

ICI cancellation If a UE is able to decode the interfering signals, it can IC generate and then subtract them from the desired signal. This can be achieved with a multiuser detector |16 at the UE. However, to decode the interfering signal from neighbouring cells, the UE needs to know its transmission format, which is not available us the UE cannot decode the PDCCH from neighbouring cells.

ICI coordination/avoidance This is achieved by applying restrictions to the downlink resource management in 1 coordinated way between neighbouring cells. The restrictions can be on time/frequency resources or transmit power used at each eNode-B. It requires additional inter-eNode-B communication und UE measurements and reporting.

Static ICI coordination/avoidance This is mainly done during the cell planning process and does not require frequent reconfiguration. An example is static Fractional Frequency

Reuse (FFR), Static coordination strategy requires no or little inter-eNode-B signalling, but there is performance limitation as dynamic characteristics such as cell loading or user distributions are not taken into consideration.

Semi-static ICI coordination/avoidance Semi-static coordination typically requires reconfigurations on 1 time-scale of the order of seconds or longer, and inter-eNode-B communication over the X2 interface is needed. The information exchanged between neighbouring eNode-Bs can be transmission power and/or traffic load on different resource blocks. By considering such information at neighbouring eNode-Es, ICI suppression is more efficient.

Coordinated Multi-Point Transmission

In LTE-Advanced, to further improve cell-edge performance, advanced techniques with more sophisticated coordination will be developed for ICI mitigation. One such technique is called Coordinated Multi-Point (COMP) transmission/reception.

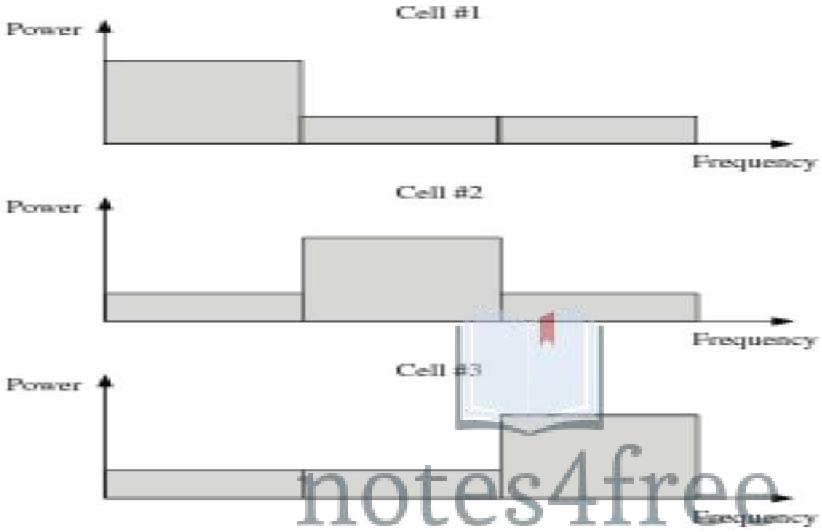


Figure 10: Possible downlink power levels of three neighbouring cells.

Uplink

- **ICI randomization** Similar to the downlink ICI :randomization in the uplink is achieved by scrambling the encoded symbols prior to modulation. Instead of cell specific scrambling as used in the downlink UE-specific scrambling is used in the uplink as ICI comes from multiple UEs in neighbouring cells.
- **ICI cancellation** ICI cancellation is more applicable in the uplink than in the downlink, as the eNode-B has higher Computational capability and usually more antenna elements.
- **Uplink power control** Power control is an efficient way to suppress ICI in the uplink. Fractional Power Control (FPC) is used in LTE.
- **ICI coordination/avoidance** Similar coordination techniques discussed for downlink can be applied in the uplink, such as FFR.

Coordinated Multi-Point Reception

Similar to the downlink, COMP reception will be developed for uplink in LTE-Advanced. This means coordinated reception at multiple eNode-Bs of transmitted signals from multiple geographically separated UEs in different cells. In contrast to downlink, uplink COMP reception is expected to have very limited impact on the radio-interface specifications. As uplink scheduling is performed at the eNode-B, coordinated inter-cell scheduling can be 1pplied to control ICI, which, however, will have impact on radio-interface specifications.